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Controlling Stormwater Quality with Filter Soil—Event and Dry Weather Testing

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Abstract: The use of filter soil is increasing for control of quality of stormwater runoff prior to infiltration or discharge. This study aimed to gain knowledge about treatment efficacy of filter soils at field scale. Percolate samples from swale-trench systems with filter soil based on agricultural till with/without limestone were monitored for 15 and 9 rain events respectively. Further, two curb extensions with filter soil based on landfill soil were monitored for 10 and 8 events. Pollutant concentrations in percolate were compared to influent samples from the catchment area. Additionally one of the curb extensions was tested twice by adding high-dose synthetic influent containing runoff pollutants of concern. Despite generally low influent pollutant levels, phosphorus, copper, zinc, lead and some polyaromatic hydrocarbons exceeded guiding criteria for protection of groundwater and freshwater. Concentrations in the percolate were in most cases reduced, but phosphorus increased and despite reduced concentrations copper, lead and benzo(a)pyrene still exceeded guiding criteria. Pollutants from the synthetic influent were efficiently retained, except the pesticide MCPA. Filter soil based on landfill soil tended to perform better than agricultural till. No impact of limestone was observed. Overall the filter soils performed well in retaining pollutants, despite simultaneous processes of mobilization and immobilization.

Keywords: bioretention; bioswales; heavy metals; infiltration; organic carbon; phosphorous; stormwater runoff; water quality

1. Introduction

For more than 25 years on-site management of stormwater runoff, often referred to as SUDS (sustainable urban drainage systems), LID (low impact development) or LSM (landscape-based stormwater management), has been practiced and developed as a supplement to conventional pipe-based drainage of urban areas [1]. Within this concept infiltration elements such as swales, rain gardens, and curb extensions are some of the most widespread and well-known SUDS [2]. Infiltration elements are designed to contribute to urban drainage by retaining stormwater runoff locally and thereby decreasing downstream flow rates and volumes. Additionally, the infiltration elements may function as stormwater treatment facilities because pollutants are retained by processes such as sedimentation, filtration, adsorption and in some cases degradation of pollutants present in the stormwater runoff that have accumulated during dry weather on the urban surfaces [3]. The infiltration capacity as well as the treatment capacity depends on the media used in the facility, and often an engineered soil mixture is used. The engineered soil layer can be based on the local soil in case of new developments, i.e., on bare land. In case of retrofitting an existing area the soil will have to

be transported to the site. To ensure proper treatment performance, filter soil guidelines have been developed in several countries, with recommendations on e.g., soil texture, soil layer thickness, pH and organic matter content. These guidelines differ among countries, and typically reflect the parameters that have driven the process for the on-site management such as hydraulic efficiency, runoff treatment or plant growth [4–8].

Germany has a long record of roadside infiltration facilities that also intentionally address water quality by utilizing an engineered soil media as described in the German DWA-guidelines [5]. The guidelines include, among other technical specifications, recommendations of a 30 cm top soil layer where pH should be 6–8, the saturated hydraulic conductivity no less than 10^{-5} m/s, the clay content not exceeding 10% and the organic content between 1% and 3% [9]. Since 2008 the practice of local infiltration of stormwater runoff by means of an engineered soil, based on the German guidelines, has gained ground in Denmark and is termed filter soil.

When increasing the drainage capacity of a city by means of on-site management of stormwater runoff, the risk of recipient contamination increases, both for surface waters like streams and rivers, and groundwater. Therefore the Danish environmental authorities increasingly require that the effluent leaving the filter soil does not deteriorate the recipient. According to Danish legislation, which is aligned with the EU legislation, stormwater runoff is considered wastewater, and it is compulsory to obtain a permit from the relevant environmental authorities to discharge (to sewer, marine or freshwater recipients) or infiltrate (to the soil) the runoff. No specific quality criteria exist that stormwater runoff has to comply with, and with the use of certain standard measures a permit will normally be granted as long as the runoff originates from normal urban surfaces such as roofs, minor roads and parking sites, squares, and parks. Authorities can only require a specific quality of the discharged or infiltrated water if the runoff is considered a risk for meeting the targeted environmental goals for a specific water body, i.e., good ecological and chemical quality as defined under the European Water Frame Directive (WFD) [10]. In such cases the authorities can define emission limit values that the runoff has to comply with before discharge or infiltration. Such limit values are local and individually decided, but the authorities may take into consideration the quality criteria for surface water bodies and the groundwater quality criteria summarized in Table 1. The groundwater quality criteria has been developed by the national environmental authorities in Denmark [11], to aid local authorities in defining requirements for when to release contaminated soil from further remedial measures like pumping of groundwater. Likewise, the quality criteria for surface freshwater bodies as listed in the departmental order 1070 under WFD [12] are not concerning discharge of stormwater runoff, but may be used as guidance in case there is a need to control a certain discharge of stormwater runoff.

Since authorities tend to assess stormwater discharges by concentrations rather than mass fluxes, it makes sense to evaluate stormwater treatment facilities based on what percolate concentrations they can achieve. As an example, the environmental authority from the city of Copenhagen has announced that stormwater runoff discharged to lakes in the municipality may contain no more than 0.08 mg phosphorus (P) per liter [13].

The retention of stormwater pollution in filter soils is controlled by precipitation, complexation and sorption processes. In most cases sorption processes control the distribution of pollutants between the solid and the solution phases. Sorption is used here as a collective term for various soil surface-related processes including surface complexation, ion exchange, and other processes related to binding by chemical or physical properties. The soil system is too complex to unravel the actual reactions controlling the specific pollutants.

Studies both under laboratory [14–17] and field conditions [18–22] have investigated the ability of engineered soils to retain pollutants from percolating water, focusing on heavy metals, polyaromatic hydrocarbons (PAHs), nutrients and suspended solids. Overall these studies show that the soil media perform well in retaining pollutants; however, there can be leaching of dissolved organic carbon (DOC) from the systems, as well as pollutants such as phosphorus (P) and copper (Cu). Further, the leaching of P and Cu is likely to be linked to DOC mobility [16,23]. No data on pesticides have been found.

Recognizing that there may be significant variations between laboratory and field scale as well as between local and regional field studies, the Danish environmental authorities have sought more documentation on performance of filter soil in field scale facilities. Thus, the aim of this study was to add to our knowledge about the treatment efficacy of filter soils at field scale in a Danish context. Improved understanding of treatment capacity and behavior of infiltration facilities will lead to better design guidance and hopefully also contribute to more sustainable urban water management internationally.

The specific objectives were:

(a) To monitor the treatment performance of Danish road runoff infiltration systems with filter soil during storm events, and to look for differences between filter soil based on modified local soil with/without limestone and unpolluted soil from a landfill, and

(b) To test the treatment performance of one of the systems under more extreme conditions using a synthetic road runoff solution with high yet realistic concentrations of a range of relevant pollutants.

Table 1. Danish and European Union quality criteria for groundwater and surface water, which may provide guidance when assessing filter soil treatment performance.

	Groundwater Quality Criteria [1] [µg/L]	**Short-Term Conc. Criteria for Surface Freshwater Bodies [2] (in Parenthesis the Long-Term Conc. Criteria) [µg/L]**
Reference	[11]	[12]
Cadmium (Cd) [3]	0.5	<0.45–1.5 (<0.08–0.25)
Chromium (Cr)		
Cr(III) + Cr(VI)	25	124 (17)
Cr(VI)	1	4.9 (3.4)
Copper (Cu)	100	2 (1)
Nickel (Ni)	10	34 (4)
Lead (Pb)	1	2.8 (1.2)
Zinc (Zn)	100	8.4 (7.8)
Acenaphthene	No criterion	3.8 (3.8)
Benzo(a)pyrene	0.01	0.027 (0.00017)
Fluoranthene	0.1	0.12 (0.0063)
Naphthalene	1	130 (2)
Phenanthrene	No criterion	4.1 (1.3)
Pyrene	No criterion	0.023 (0.0046)
Sum of polyaromatic hydrocarbons (PAHs)	0.1 [4]	No criterion
Single pesticide	0.1	No criterion
Sum of pesticides	0.5	No criterion
Linear alkylbenzene sulfonate (LAS)	No criterion	160 (54)

Notes: [1] Danish threshold values (total concentrations) for groundwater under polluted soils; [2] Dissolved concentrations. Short-term is defined as discharge in maximum 24 h once per month with minimum 6 days in between; [3] Depending on water hardness; [4] Sum of benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(g,h,i)perylene, indeno(1,2,3-cd)pyrene.

2. Materials and Methods

2.1. Locations

Two types of field-scale road runoff infiltration systems with filter soil were studied, including swale-trenches in the city of Odense and curb extensions in the Copenhagen area (Table 2). At the Odense site the filter soil was placed as the top layer in two infiltration swale-trenches receiving stormwater runoff from a newly established parking lot. For both trenches the filter soil was made from the local till soil by adding sand, to meet the DWA standard. The filter soil in one of the trenches was further modified by adding limestone, though not exceeding the prescribed pH. At the Copenhagen sites the filter soil was included as the top layer in curb extensions used to disconnect two streets located 10 km apart, Moellebakken and Lindevang, from the sewer system. At Moellebakken, there were four curb extensions, and at Lindevang, six curb extensions. Here the filter soil was made from unpolluted soil transported to the site from landfill storage (RGS 90 A/S). At Moellebakken the percolate from one out of a total of four curb extensions was monitored and at Lindevang the effluent from one out of a total of six- curb extensions was monitored.

Table 2. Description of test sites and sampling methods.

	Swale-Trenches—Odense		**Curb Extensions—Copenhagen**	
				
	Photo of One of the Swale-Trenches		**Photo of One of the Curb Extensions**	
	East (+limestone)	**West**	**Moellebakken**	**Lindevang**
Year of construction	Spring 2011		Fall 2012	
Catchment typology UTM	Parking lot for 200 cars 55°22′4.22″ N 10°25′26.74″ E		Residential road <5000 cars per day 55°42′16.83″ N 12°27′44.72″ E	Residential road <5000 cars per day 55°37′8.84″ N 12°24′59.75″ E
Design	0.3 m deep filter soil layer on top of a thin gravel layer and 0.5 m of infiltration trench made from stormwater boxes		Curb extension with a 0.4 m deep filter soil layer on top of 1.6 m soakaway made from stormwater boxes	
Infiltration area	1000 m^2	1180 m^2	20 m^2	16 m^2
Catchment area: infiltration area	5:1	5:1	33:1	21:1
Filter soil composition	Local topsoil mixed 1:1 with sand in grain size 0.02–2 mm and 3 kg of bryozo calcite [1] per m^3 of soil-sand mixture	Local topsoil mixed 1:1 with sand in grain size 0.02–2 mm	Made from RGS90 growth-topsoil (mixture 4) [2] from a landfill storage	
No. of influent samples	12		10	
Influent sampling method	Runoff samples collected via line drainage placed along the edge of parking lot connected to a sampling well		Runoff samples were collected from nearby road with similar traffic load (55°41′49.71″ N 12°27′50.74″ E) by means of a fraction collector placed in a road well equipped with 24 PE-containers of 0.5 L (ISCO 3700)	
No. of percolate samples	15	9	10	8
Percolate sampling method	From sampling wells (Quadro Control Fränkische) connected with the stormwater boxes via a longitudinal perforated pipe mounted along the top of the stormwater boxes, just below the filter soil, capturing fractions of the percolating water		From bottom of the stormwater boxes by vacuum pumping in a tube (Teflon™) lowered into the stormwater boxes through a vertical pipe bypassing the filter soil. As percolate ponded in the bottom of the trench for some time before ex-filtrating into surrounding soil it was considered mixed and representative of the filter soil percolate	
Monitoring period	June 2014–October 2014		July 2013–December 2014	October 2013–December 2014

Notes: [1] Mined bryozoan calcite from Faxe Limestone Quarry, Denmark, diameter range: 1–3 mm, bulk weight: 1250 kg/m^3, bulk porosity: 54%; [2] Homogeneous mixture of topsoil, sand and compost, according to the supplier's specification: Humus: 3%, clay: 6%, silt: 8%, fine sand: 38%, course sand: 44%, pH: 8.

2.2. Soil Samples

To document that the filter soils complied with the German DWA guidelines and were originally unpolluted, representative samples were obtained for analysis. From the swale-trench systems 20 samples of topsoil mixed with sand (prior to mixing with limestone) were obtained before the soil was placed in the trenches. These 20 soil samples were analysed for pollutant levels by an accredited laboratory. The 20 samples were then bulked to one sample for texture analysis. After mixing half of the topsoil with limestone, further samples were obtained for pH and plant-available P-measurements of the two filter soil types: with and without limestone. Regarding the curb extensions, filter soil was sampled from all four in Moellebakken and all six in Lindevang shortly after construction, by collection of 10 samples from 0 to 40 cm depth distributed over the surface area. The 10 subsamples from each curb extension were bulked into one sample used for texture analyses. Hereafter the four bulk samples from Moellebakken and the six bulk samples from Lindevang were bulked into one sample for each street, from which two subsamples were analysed for pollutant levels.

2.3. Soil Analyses

Texture was analysed by the hydrometer method [24] and the pH of the soil samples was determined using a combined glass electrode (Metrohm, 6.0228.000) in a solution of soil and a 0.01 M $CaCl_2$ solution with a ratio of 1:2.5. An accredited laboratory performed analysis of plant-available P in the swale-trench soil by the Olsen-method [25], and total P on curb extension soil, by the method SM 3120 on ICP-OES. Heavy metals (Cd, Cr, Cu, Ni, Pb, Zn) were analysed with ICP-OES after standard method 3120, total petroleum hydrocarbons with GC-FID after REFLAB method 1:2010 and PAHs (fluoranthene, benzo(b+j+k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene) with GC-MS after REFLAB method 4.

The hydraulic conductivity was measured by means of in situ single ring infiltration test with constant head following the method by [26]. In the swale-trenches infiltration measurements were done four times throughout 2013–2014 (two to three years after construction) at three different places in the trenches each time. The curb extensions were subjected to the infiltration tests at two places in each curb extension six months after construction.

2.4. Water Sampling Procedure

Precipitation data for the swale-trenches were recorded by a rain gauge nearby (UTM 55°20′36.5″ N 10°25′59.3″ E). For the curb extensions precipitation data were obtained from a rain gauge placed near the influent fraction collector (UTM 55°42′08.2″ N 12°27′55.2″ E), both operated by the Danish Water Pollution Committee and the Danish Meteorological Institute [27].

Pressure transducers were used to monitor the water level in the stormwater boxes underneath the filter soil and thus to control that stormwater generated percolate was sampled (swale-trenches: MJK Expert™ 7060 hydrostatic digital/analog logger; curb extensions: HOBO® Water Level Loggers).

In the swale-trenches influent samples were obtained from a line drainage placed in terrain along the parking lot edge. Due to practical reasons it was not possible to collect inlet samples at the curb extensions in Copenhagen. However, flow weighted samples of stormwater runoff were collected from a nearby road with a similar traffic load (Table 2). This was used to represent influent for both curb extensions.

Sampling procedures for percolate samples are described in Table 2. The samples were all collected in glass and plastic containers (dependent on compounds to be analysed), stored in the cold and dark, and sent to an accredited laboratory within 24 h.

Table 3. Schematic presentation of the compounds included in the monitoring program for each location. B = basic program (n = 5 for Moellebakken, n = 4 for Lindevang), E = extended program (n = 5 for Moellebakken, n = 4 for Lindevang), S = synthetic stormwater program. Compounds analysed are marked with X.

	Odense	Moellebakken			Lindevang		Method	Detection Limit
Monitoring program		B	E	S	B	E		
pH	X	X	X	X	X	X		
Electric conductivity	X	X	X	X	X	X	EN 27888	0.5 mS/m
Suspended solids	X	X	X		X	X	EN 872	0.5 mg/L
TOC/DOC	X		X		X	X	EN 1484	1 mg/L
P-total and dissolved	X	X	X	X	X	X	SM 4500-P (F)	0.005 mg/L
N-total	X		X		X	X	EN ISO 11905 auto mod Skalar	0.05 µg/L
NH_3+NH_4-N			X		X	X	SM 4500-NH3 (H)	0.005 mg/L
NO_3-N			X		X	X	SM 4500-NO3 (H)	0.1 mg/L
Cl		X	X		X	X	SM 4500-Cl (E)	1 mg/L
Al—total and dissolved		X	X	X	X	X	EN ISO 17294m: 2005 ICP/MS	30 µg/L
Cd—total and dissolved	X	X	X	X	X	X	EN ISO 17294m: 2005 ICP/MS	0.05 µg/L
Cr—total and dissolved	X	X	X	X	X	X	EN ISO 17294m: 2005 ICP/MS	0.5 µg/L
Cu—total and dissolved	X	X	X	X	X	X	EN ISO 17294m: 2005 ICP/MS	1.0 µg/L
Ni—total and dissolved[1]		X	X	X	X	X	EN ISO 17294m: 2005 ICP/MS	1.0 µg/L
Pb—total and dissolved	X	X	X	X	X	X	EN ISO 17294m: 2005 ICP/MS	0.5 µg/L
Zn—total and dissolved	X	X	X	X	X	X	EN ISO 17294m: 2005 ICP/MS	5.0 µg/L
Total petroleum hydrocarbons (TPH)		X	X				ISO 9377-2 mod.GC/FID	C6H6-C10: 2 µg/L C10-C25: 8 µg/L C25-C35: 10 µg/L
PAHs		X	X	X		X	GC/MS	0.01 µg/L
Pesticides: 2-(4-chloro-2-methylphenoxy) acetic acid (MCPA), Glyphosate				X			GC/MS, LC/MS/MS	0.01 µg/L
Anionic detergents				X			DS 237	0.15 mg/L

2.5. Water Analyses

Table 3 presents the parameters included in the monitoring program at each location. Samples collected in the swale-trenches were all analysed after the same program. For the curb extensions 4–5 samples were analysed after a smaller program referred to as a basic program (B) and the remaining samples after a more extended program (E). A synthetic influent applied to the curb extension in Moellebakken was analysed after a third program (S).

Due to practicalities only N, P and metals were measured as both total and dissolved; however, it should be noted that [28] has shown that this speciation can also be significant for the organic compounds such as PAHs.

2.6. Application of Synthetic Influent to One Curb Extension

To test the filter soil under conditions where a number of relevant contaminants (S-program in Table 3) are present at high but still realistic concentrations, a synthetic contaminant dose was added to the monitored curb extension at Moellebakken in dry weather. In all, 10–11 m^3 of contaminated water was added to the curb extensions during approximately six hours (detailed procedure and considerations are described in [29]). Bromide was included in the dose as a conservative tracer. The test with synthetic effluent was conducted twice two months apart.

3. Results

3.1. Filter Soil Characteristics

Texture, hydraulic conductivity and pollution levels in the filter soils of swales and curb extensions are presented in Tables 4 and 5 respectively. Since the same type of local soil was used for the two swale-trenches and the same type of landfill soil for the curb extensions, the results are bulked respectively. The only exception is pH and P for the swale-trenches, where separate results are given for the west and east ends.

In the swale-trenches, plant-available P was 0.8 mg/kg for the limestone-modified eastern trench (East) and 1.3 mg/kg for the western trench (West). In the curb extensions, the average of total P was 438 mg/kg, with a standard deviation of 34 mg/kg dry matter.

When compared all tested filter soils initially complied with the Danish soil quality criteria [11] (Table 5). These data can be used in the future to evaluate the accumulation of pollution in filter soil. It is noticed that the Copenhagen filter soil based on landfill soil contained slightly higher levels of Pb, Cu, Zn, hydrocarbons and PAHs compared to the farmland-based filter soil in Odense. The plant-available P-level in the landfill soil used in Copenhagen is in the range of 3–6 (information from the landfill soil provider, RGS90) and thus higher compared with the measured value of plant-available P of 0.8 in swale-trench East and 1.3 in swale-trench West in Odense.

Table 4. Soil characteristics (with standard deviation) of filter soils in the soils in Odense (texture $n = 1$, infiltration $n = 15$) and Copenhagen (texture $n = 4$, infiltration $n = 20$), compared with requirements in the DWA guidelines.

	pH	Texture (%)					Hydraulic Conductivity (m/s)
		Organic C	Clay	Silt	Fine Sand	Sand	
DWA [5]	6–8	1–3	Clay + Silt < 10				10^{-5}–10^{-3}
Odense Swale-Trenches	East 7.9 West 7.5	1.7	2.8	1.5	25.2	68.7	2×10^{-5} (1.6×10^{-5})
Copenhagen Curb Extensions	7.8 (0.04)	2.0 (0.3)	4.9 (1.1)	3.9 (1.1)	30.4 (1.8)	61.1 (2.2)	2.7×10^{-5} (3.0×10^{-6})

Table 5. Average soil pollutant concentrations (with standard deviations in parenthesis) for Copenhagen (n = 4) and Odense (n = 20), compared with Danish values for clean soil. b.d. = below detection limit. n.i. = not included.

Parameter	Odense Swale-Trenches	Copenhagen Curb Extensions	Soil Quality Criteria [1]
		[mg/kg DM]	
Cd	0.12 (0.02)	0.20 (0.03)	0.5
Cr	5.0 (0.6)	4.1 (0.4)	500 (20)
Cu	2.0 (0.4)	9.5 (0.4)	500
Ni	3.8 (0.4)	4.4 (0.4)	30
Pb	4.4 (0.7)	11 (0)	40
Zn	18 (2)	45 (3)	500
Sum of hydrocarbons	b.d.	25 (2.6)	100
Fluoranthene	b.d.	0.09 (0.03)	n.i.
Benzo(b+j+k)fluoranthene	b.d.	0.14 (0.04)	n.i.
Benzo(a)pyrene	b.d.	0.05 (0.02)	0.3
Indeno(1,2,3-cd)pyrene	b.d.	0.05 (0.02)	n.i.
Dibenzo(a,h)anthracene	b.d.	0.01 (0.004)	0.3
Sum of 7 PAHs [2]	b.d.	0.34 (0.1)	4

Notes: [1] If the soil quality criteria are met the soil is considered safe for use without fear of exposure in e.g., private gardens and on playgrounds [11]; [2] Sum of 7 PAHs fluoranthene, benzo(b)fluoranthene, benzo(j)fluoranthene benzo(k)fluoranthene, benzo(a)pyrene, dibenzo(a,h)anthracene and indeno(1,2,3-cd)pyrene.

3.2. Characterization of Rain Events

The rain events sampled represented significant but not extreme events. In Table 6 the rain depths for the sampled events are seen. As the arrival of percolate in the stormwater boxes is delayed compared to the stormwater runoff, and the percolate may originate from series of rains, it was decided to calculate rain depth in the 24 h preceding the percolate sampling time for the Odense sites. For the Copenhagen sites the rain depth corresponding to the influent water-sampling period was recorded. To look for correlations between the preceding dry weather period, the number of dry weather days before the event as well as the accumulated rain depth in the 7 days antecedent to the period were calculated.

Table 6. Rain characteristics for sampled events at the swale-trench systems in Odense (above) and the curb extensions in Copenhagen (below).

Odense											
Date (all 2014)	28/6	14/7	10/8	14/8	18/8	31/8	15/9	22/9	30/9	13/10	17/10	20/10
Rain depth antecedent 24 h [mm]	1.2	21.8	0.8	0.6	1.4	16.4	2.6	11.4	15.0	7.8	2.6	27.6
Antecedent dry days [d]	0	3	0	1	0	0	0	0	4	0	0	1
Antecedent 7 days rain depth [mm]	28.8	1.6	11.4	15.8	32.8	12.8	16.6	2.3	1.6	15.4	15.4	40.2

Copenhagen										
Date (all 2014)	7/5	9/5	8/8	29/8	30/9	7/10	13/10	24/11	5/12	12/12
Rain depth inlet sample [mm]	15.1	11.9	19.8	8.8	2.5	5.0	3.3	6.2	4.0	11.9
Antecedent dry weather [d]	13	0	4	7	6	6	1	1	11	2
Antecedent 7 days rain depth [mm]	0	17.9	30.4	5.2	7.0	9.2	11.2	8.2	0	14.0

3.3. Influent and Percolate Concentrations

The average values for influent compared to the concentrations in the percolate during rain events are listed in Table 7. Compounds that were below detection limit in all events in both influent and percolate (volatile organic carbon, total petroleum hydrocarbons, acenaphthene, naphthalene and fluorine) are left out.

Suspended solids and metals were plotted as a function of rain depths as well as antecedent dry weather periods. Only weak linear correlations could be observed (R^2-values between 0.1 and 0.4) and it is concluded that in this case there was little or no coherence between influent pollution levels and rain patterns.

Table 7. Characterization of inlet and percolate samples from filter soil systems. Average value is shown for each parameter, standard deviation given in brackets (detection limit used for samples with concentrations below detection limit; if all samples were below detection limit, there was no standard deviation). *n* = number of samples, n.a. = not analysed.

	Swale-Trench Systems			Curb Extensions		
	Odense Influent *n* = 12	**Odense East Percolate *n* = 15**	**Odense West Percolate *n* = 9**	**Copenhagen Influent *n* = 10 or *n* = 5 [1]**	**Moellebakken Percolate *n* = 10 or *n* = 5 [1]**	**Lindevang Percolate *n* = 8 or *n* = 4 [1]**
pH	7.0 (0.3)	8.2 (0.2)	8.1 (0.2)	7.5 (0.3)	8.5 (0.6)	8.0 (0.2)
EC [mS/m]	4.1 (1.6)	32.0 (9.4)	28.4 (14.4)	11.4 (3.8)	24.5 (8.0)	20.3 (3.7)
Susp. solids [mg/L]	16 (11)	8.6 (6.2)	8.9 (5.5)	26.7 (23.5)	5.5 (4.2)	n.a.
OC [2]	4.3 (2.7)	8.5 (3.4)	8.2 (3.6)	12.3 (14.5)	5.3 (1.1)	6.2 (2.1)
N tot. [mg/L]	1.2 (0.7)	1.2 (0.6)	1.2 (0.8)	1.6 (0.6)	1.3 (0.4)	1.1 (0.3)
NH_3+NH_4-N diss. [mg/L]	n.a.	n.a.	n.a.	0.3 (0.2)	1.5 (3.3)	0.02 (0.02)
NO_3-N diss.[mg/L]	n.a.	n.a.	n.a.	0.7 (0.4)	0.9 (0.4)	0.8 (0.3)
P tot. [mg/L]	0.1 (0.03)	0.2 (0.1)	0.2 (0.1)	0.1 (0.1)	0.2 (0.1)	0.2 (0.1)
P diss. [mg/L]	0.03 (0.02)	0.1 (0.1)	0.1 (0.1)	0.03 (0.02)	0.2 (0.1)	0.2 (0.1)
Cl diss. [mg/L]	n.a.	n.a.	n.a.	7.9 (9.1)	9.6 (5.7)	3.9 (1.6)
Al tot. [µg/L]	n.a.	n.a.	n.a.	793 (643)	348 (166)	271 (146)
Al diss. [µg/L]	n.a.	n.a.	n.a.	69.2 (113.0)	113 (68.2)	54 (37)
Pb tot. [µg/L]	1.8 (1.7)	1.8 (1.5)	1.2 (0.5)	2.4 (1.8)	0.8 (0.4)	0.8 (0.3)
Pb diss. [µg/L]	0.6 (0.5)	0.6 (0.1)	0.6 (0.2)	0.5	0.5 (0.03)	0.5
Cd tot. [µg/L]	0.1 (0.02)	0.1 (0.1)	0.2 (0.3)	0.1 (0.01)	0.1 (0.01)	0.1 (0.1)
Cr tot. [µg/L] [3]	5.0 (13. 6)	4.8 (3.1)	4.9 (5.4)	2.1 (1.5)	8.1 (10.3)	5.3 (10.4)
Cr diss. [µg/L]	2.5 (6.5)	1.8 (1.7)	1.3 (0.7)	0.7 (0.3)	7.2 (10.0)	4.9 (10.6)
Cu tot. [µg/L]	7.2 (4.6)	7.1 (3.6)	6.5 (3.1)	11.7 (5.1)	9.6 (6.9)	6.0 (2.5)
Cu diss. [µg/L]	5.1 (5.7)	5.7 (3.5)	6.4 (4.1)	6.2 (3.3)	6.6 (5.5)	4.3 (3.0)
Ni tot. [µg/L]	n.a.	n.a.	n.a.	7.2 (14.4)	2.2 (1.7)	1.4 (0.7)
Ni diss. [µg/L]	n.a.	n.a.	n.a.	1.4 (0.4)	2.0 (1.9)	1.2 (0.4)
Zn tot. [µg/L]	25.9 (15.3)	11.5 (9.9)	11.1 (7.7)	27.9 (12.1)	5.7 (1.0)	8.1 (5.4)
Zn diss. [µg/L]	18.4 (20.7)	6.1 (2.1)	5.8 (2.0)	12.1 (10.3)	5.0	5.8 (2.1)
Acenaphthene [µg/L]	n.a.	n.a.	n.a.	0.01	0.01	0.01 (0.01)
Naphthalene [µg/L]	n.a.	n.a.	n.a.	0.01	0.01	0.01 (0.005)
Phenanthrene [µg/L]	n.a.	n.a.	n.a.	0.02 (0.01)	0.01	0.01
Fluoranthene [µg/L]	n.a.	n.a.	n.a.	0.03 (0.03)	0.01 (0.004)	0.01
Pyrene [µg/L]	n.a.	n.a.	n.a.	0.03 (0.03)	0.01 (0.005)	0.01
Benzo (b+j+k)fluoranthene [µg/L]	n.a.	n.a.	n.a.	0.05 (0.06)	0.02 (0.01)	0.01
Benzo(a)pyrene [µg/L]	n.a.	n.a.	n.a.	0.02 (0.02)	0.01 (0.003)	0.01
Indeno(1,2,3-cd)pyrene [µg/L]	n.a.	n.a.	n.a.	0.02 (0.02)	0.01 (0.004)	0.01

Notes: [1] *n* depended on after which program samples were analysed by, see Table 3. Further, n deviated for SS Odense West: *n* = 10, Odense East: *n* = 4, naphthalene Møllebakken: *n* = 8 samples, and all PAH's Lindevang: *n* = 3, except naphthalene: *n* = 2; [2] DOC for Odense, TOC for Copenhagen; [3] Chromium showed significantly higher levels for the first samplings from both curb extensions, probably originating from concrete reinforcing walls surrounding the stormwater boxes. Furthermore a total Cr concentration of 48 µg/L was observed in one event in Odense, but considered a contamination of the sample since the dissolved Cr was below detection limit in the same sample. The value of 48 µg/L is not included in the calculations.

The EC measured in the influent water is comparable to other studies [30–32] and was seen to increase from influent to percolate, reflecting that the water mobilized various ions as it passed through the soil.

The observed concentration of less than 50 mg/L of SS in the influent from both Odense and Copenhagen (Table 7) is relatively low compared to other studies [30–32], but was most likely due to the low traffic level in the areas. In the swale-trench systems in Odense the SS measured in the percolate is half of what is observed in the influent. Comparing the influent concentrations of SS in Copenhagen with concentrations in the percolate from the Moellebakken curb extension, a five-fold reduction in SS is seen.

Phosphorus in influent exceeded the Copenhagen criterion of 0.08 mg P/L in 4 out of 12 events in Odense and in 7 out of 10 events in Copenhagen. In percolate, P concentrations were in general higher than in influent at all sites, and in all cases exceeding 0.08 mg P/L. Furthermore a larger fraction of P was found in the dissolved form compared to influent.

The observed levels of heavy metals and organic contaminants in influent and percolate from rain events are compared with the guiding values in Table 1. In some cases the concentration level of a compound is not critical compared to values in Table 1, which is true for Cd, Ni, acenaphthene, naphthalene, phenanthrene and fluoranthene. In other cases either the groundwater quality criteria or the criteria for discharge to freshwater may be the more critical, which is discussed below. Other pollutants included in the monitoring program, such as chloride (Cl), aluminum (Al), benzo(b,j,k)fluoranthene, and indeno(1,2,3-cd)pyrene have no guiding criteria. For heavy metals only, in a few cases, patterns for the distribution between dissolved and particulate forms are observed.

The Cr concentrations in the influent in most cases exceeded the value of 1 μg/L for Cr(VI), but not the criterion for total Cr. The percolate from all sites had higher Cr concentrations than the influent, and the observed level was at or exceeded the quality criterion for long-term discharge. Chromium leaching from the swale-trenches was bound to particles, whereas the Cr leaching from curb extensions was mostly on the dissolved form.

The criterion for Cu in groundwater is 100 μg/L, since the potential harmful effects of Cu to humans are limited. However, the short-term criterion for dissolved Cu in freshwater is 2 μg/L and the influent concentrations of Cu at both sites in all events exceeded this level. Half of the Cu detected in the influent was in the dissolved form at both sites. In the percolate from swale-trenches a large part of the Cu in the percolate was in the dissolved form and from both trenches exceeded 2 μg/L during every rain event. In the percolate from the curb extension in Moellebakken, Cu exceeded the freshwater criterion in all samples. In the percolate from the curb extension in Lindevang, Cu was detected in 7 out of 8 events, and all exceeded the freshwater criterion. Almost all Cu found in the percolate from the curb extensions were in the dissolved form.

In general, Pb was detected in the majority of the influent samples and particle bound (Odense: 10 out of 12 events, with 7 exceeding groundwater quality criteria; Copenhagen: 10 out of 10 events, with 9 exceeding same criterion). There was only a weak Pb reduction from influent to percolate, and several samples still exceeded the 1 μg/L criterion (lime-modified swale-trench East: all samples with 12 out of 15 exceeded groundwater quality criterion; swale-trench West: 7 out of 9 samples, with 5 exceeding same criterion; Moellebakken: 7 of 10 samples, with 3 exceeding same criterion; Lindevang: 4 of 8 samples, with 3 exceeding same criterion).

At both sites total Zn in all influent surpassed the short-term criterion for emissions to freshwater, whereas the dissolved Zn exceeded the criteria in 5 events in Copenhagen and 9 out 12 events in Odense.

Polyaromatic hydrocarbons were only measured in influent in Copenhagen and in percolate from the curb extension in Moellebakken. Some of the influent samples contained PAH in problematic concentrations, when comparing with the guidelines in Table 1. Pyrene was detected in 6 out of 10 influent samples and 4 of them exceeded the short-term freshwater emission criterion, but pyrene was only observed in 2 percolate samples, both below the criterion. Benzo(b,j,k)fluoranthene was

detected in 7 out of 10 events where the groundwater quality criterion was exceeded in 2, but not in any of the percolate samples. Benzo(a)pyrene (groundwater quality criterion of 0.01 µg/L) was detected in 4 out of 10 influent samples all with concentrations above the criterion, and was detected in the percolate in 2 out of 10 samples, both exceeding the criterion.

3.4. Test with Synthetic Influent

The results from the replicate experiment with addition of synthetic runoff with high yet realistic concentrations of selected pollutants are presented in Table 8. Since bromide is inert, the loss in bromide cannot be ascribed to the removal mechanisms operating in filter soil, but rather to diffusion of the solute into volumes of the filter soil or the soil matrix surrounding the facilities with non-mobile water [29,33]. Similar diffusion losses must be expected for other solutes, and without accounting for this loss, an over-estimation of pollutant removal efficiencies would occur. Adjustment to the observed effluent concentrations were made prior to calculating the contaminant removal efficiency by reducing the influent concentrations with the same reduction factor as observed for the conservative tracer bromide (named 'expected concentration' in Table 8).

Table 8. Characterization of synthetic influent added twice to the inlet of curb extension at Moellebakken, and resulting effluent. 'Expected effluent concentration' is the calculated concentration if the compound had been retained to the same degree as bromide, i.e., if there had been no impact of the filter soil. For P and heavy metals, dissolved fraction is given in italics. *n* = number of samples, n.a. = not analysed.

Parameter	First Addition			Second Addition		
	Influent	Expected Effluent Concentration	Observed Effluent Concentration	Influent	Expected Effluent Concentration	Observed Effluent Concentration
pH	7.8		8.2	8		8.3
Suspended solids	1.1		3.2	0.7		3.7
Br [mg/L]	3000		2100	3300		1600
P [µg/L]	390 *350*	273	250 *200*	380 *390* [1]	184	300 *300*
Cd [µg/L]	3.9 *3.8*	2.7	0.06 *<0.05*	4.6 *4.5*	2.2	<0.05 *<0.05*
Cr(VI) [µg/L]	36 *33*	25.2	26 *19*	23 *19*	11.2	9.8 *9.5*
Cu [µg/L]	51 *41*	35.7	8 *<1*	54 *45*	26.2	8.1 *2.7*
Ni [µg/L]	*No data* [2]	-	*No data*	20 *17*	9.7	1.2 *1.1*
Pb [µg/L]	18 *12*	12.6	1.6 *<0.5*	19 *15*	9.2	<0.5 *<0.5*
Zn [µg/L]	*No data* [1]	-	*No data*	190 *180*	92.1	6.4 *<5*
Acenaphthene [µg/L]	1.0	0.7	0.05	0.7	0.3	0.03
Naphthalene [µg/L]	0.8	0.6	0.02	0.8	0.4	0.02
Phenanthrene [µg/L]	0.8	0.5	<0.01	0.6	0.3	0.01
Glyphosate [µg/L]	0.9	0.6	0.09	0.8	0.4	0.08
MCPA [µg/L]	0.5	0.4	0.5	1.4	0.7	0.1
Linear alkylbenzene sulfonates [µg/L]	*No data* [1]	-	*No data*	130	63.0	<0.03

Notes: [1] The insignificant difference indicates that all P is dissolved; [2] For the first addition, contaminant dose interpretations cannot be made on Zn, Ni and LAS as these compounds apparently formed a precipitate in the stock solution used for preparing the synthetic influent. For the results of the second addition this is not an issue since the stock solutions were prepared differently.

To distinguish between percolate from rain events and percolate from this experiment with addition of synthetic runoff the term effluent is used for the latter.

As for the rain events, the SS were higher in effluent than in influent. Comparing the expected effluent concentration with the observed concentrations it is seen that P was not reduced from influent to effluent. In the second addition P in the effluent was higher than in influent. The cationic metals Cd, Cr, Cu, Ni, Pb and Zn were in all cases reduced from influent to effluent. The cationic Cr(VI) was not retained in the soil. PAHs and glyphosate concentration levels were reduced from influent to effluent as well as LAS. The pesticide MCPA was not reduced in the first addition, but retained in the second addition.

4. Discussion

The tested filter soil complied with the German DWA guidelines at all locations (Table 4). As the pH of the till soil is already in the more alkaline part of the spectrum, addition of limestone to one filter soil in the swale-trench only raised pH slightly from 7.5 to 7.9. Regarding the hydraulic conductivity it should be noted that in the curb extensions the measurements were completed shortly after construction, while in the swale-trenches they were carried out repeatedly throughout the first two years after construction. With time, soil can be more compacted and the hydraulic conductivity decreased, but results from [9] showed that German swale-trench systems up to 16 years old still complied with the guidelines. Here the vegetation is assumed to play a role in maintaining a good soil structure.

The observed influent concentrations at monitored sites in Odense and Copenhagen (Table 7) were generally low when compared with other studies [30,31,34]. Worth mentioning is that many organic contaminants such as pesticides, which proved to be problematic when added synthetically, were not included in the monitoring of rain events. While pH, EC, N-total, Cd, Cr, and Zn of the influent were at the same level, the concentrations of SS, OC, Pb and Cu tended to be higher in Copenhagen than in Odense (Table 7), which may be explained by more traffic in the residential streets of the Copenhagen site compared to the parking lot in Odense, where also the atmospheric deposition may be lower due to its more rural surroundings.

The correlation between pollution level in stormwater runoff and antecedent dry weather period that is often observed [35,36] was weak in this study with R^2 values below 0.4 when using 7-day antecedent rain depths (Table 6) as a measure of dry weather conditions. The lack of significant correlation is ascribed to the character of the catchment with low pollution levels in general. Other reasons may be that too few events were sampled, not capturing the annual variation. As shown by [37,38], a minimum of between 15 and 20 runoff events are necessary to have a statistically representative sample dataset of influent samples, which was not the case for any of the locations in this study. Further, no samples were collected during the winter period due to a dry winter, which could be the reason for no observations of high Cl concentrations.

When infiltrating runoff through the filter soil of 30–40 cm, a direct comparison between influent and percolate of an individual event does not make sense, since a part of the percolate will stem from previous rain events and furthermore from equilibrium reactions with the soil during the dry weather period. This is why only the average influent and percolate concentrations presented in Table 7 should be compared. Furthermore, when the initial soil moisture level is below field capacity, the soil will retain a fraction of the water which will later be lost through evapotranspiration. This loss can vary significantly depending on the pore size distribution, the soil moisture level, the plants present, as well as spatial and temporal climatic conditions. Nonetheless, this loss of water makes direct comparison of average influent and effluent concentrations somewhat inadequate as a clear measure of pollutant retention. Considering pollutant mass fluxes instead of concentrations alone would result in more positive retention results, due to the reduced water volume. However, quantification of the water budget in field-pilot facilities is a complex matter. Also, as water quality regulation is based

on threshold concentrations in the water bodies, it makes sense to limit this study to what effluent concentrations the soils in these particular facilities were able to produce.

The percolate pH was slightly more alkaline than the influent pH which is ascribed to the buffering ability of the filter soils (Table 7). Due to the original farmland soil having an alkaline pH, the addition of limestone to the soil in swale-trench East did not result in a significant difference compared to percolate from swale-trench West. When adding the synthetic stormwater runoff solution the pH in the effluent increased slightly, but not dramatically and the pH-values observed in these two experiments are in the same range as percolate pH observed during rain events (Table 8).

Removal of SSis crucial in treatment of urban stormwater runoff since the solids often carry a large part of the pollutant load [3]. Studies performed by [16] showed that even small particles are well retained in filter soil, and the main part of the particles present in the percolate at both locations are probably particles that have been mobilized in the filter soil, rather than the particles entering with the stormwater runoff. This mechanism of internal mobilization of particles is confirmed in the present study when the addition of particle-free synthetic influent resulted in effluent concentrations of SS in the same range as observed during rain events. When comparing the farmland-based swale-trench system with the landfill soil-based curb extensions there is a tendency that the concentration of SS in swale-trench percolate was higher than in curb extension percolate. The reason for this is unknown, but could either be due to the fact that the catchment area to filter soil area is much lower in the swale-trenches compared to the curb extensions (Table 2), providing more soil contact per percolate volume, or due to differences in aggregate stability between the local till soil and the oft-handled landfill soil.

The higher OC concentration in the percolate in Copenhagen compared to Odense (Table 7) may reflect slightly higher organic matter content in the filter soil of Copenhagen (Table 2), or it could be due to the fact that OC was measured as DOC in Odense and as TOC in Copenhagen. The OC found in percolates is likely to stem from mobilization of the internal organic pool in the soil [16], while incoming OC is retained. Unfortunately OC was not measured in effluent from the synthetic pulse addition, which could have given an idea of the mechanisms. When comparing the soil from swale-trenches and curb extensions it is observed that the local soil in the swale-trenches was leaching more OC than the landfill soil in curb-extensions, similar to what was observed for SS. Leaching of organic matter was also observed by [16] from German filter soil, 15 years old, but even young systems like the ones monitored here leach organic matter. Organic matter is not a pollutant as such, but can be a source of P and complex metals such as Cu and cause leaching of these e.g., [39,40]. When designing filter soil it is therefore relevant to look at the opportunities to improve the composition of the filter soil in order to retain organic matter.

It seems like the filter soil is removing particulate P while at the same time leaching dissolved P. As for SS and OC, this points to mobilization of the internal P-pool in the filter soil, as was also shown in the studies by Ingvertsen et al. [16]. In parallel with this, swale-trenches leached more particle-bound P than the low SS-leaching curb extensions, where P was mostly in dissolved form, probably reflecting the higher plant-available P in the landfill soil. The higher plant-available P found in swale-trench East did not result in more leaching of P compared to West. Besides the fact that particulate P and dissolved P are removed by different mechanisms, dissolved P will be more bioavailable for aquatic organisms and thereby pose a bigger risk for undesirable growth of algae [41]. Looking at the synthetic addition (Table 8), no significant reduction in P was observed either. Filter soil is concluded to retain P inefficiently.

Processes of immobilization of incoming P from the runoff could take place simultaneously with mobilization of the internal P-pool in the soil. Linear regression was conducted to elucidate whether the leached P was correlated with the leached organic matter. The correlation factors in Odense East of 0.6 for total P and 0.5 for dissolved P, with p-values from Pearson's test at 0.001 and 0.004 respectively indicated that there was a correlation. However, in Odense West a correlation factor of 0.5 for total P and 0.3 for dissolved P with p-values >0.05 showed no correlation. In Moellebakken the correlation

factor was 0.3 for total P and 0.6 for dissolved P, but the correlation was negative and in Lindevang the correlation between the organic matter was 0.2 for total P and 0.3 for dissolved for dissolved P. Thus no direct conclusions can be made about the correlation between leaching of organic matter and P. However, Odense East where the correlation is observed was also the location with the highest amount of samples (n = 15) and thus forms the best statistical basis.

Since it is not likely that Cr is present in runoff as Cr(VI) [42], the influent concentrations of Cr are considered to meet the criterion. Concentrations of Cr in the percolate from the swale-trenches were lower than Cr from the curb extensions. This is, however, likely to be due to some significantly higher levels of Cr in the very first samples from both curb extensions, probably originating from concrete reinforcing walls surrounding the stormwater boxes, which could be Cr(VI) [43]. Potential introduction of Cr during the construction of curb extensions is therefore something to be aware of. The retention of the applied Cr was very low and the majority of the Cr in the effluent was found as dissolved Cr, which is similar to what has been observed in laboratory column experiments [44,45]. Since the Cr added with the synthetic pulse was added as Cr(VI), no direct comparison with the stormwater data can be made.

The filter soils were not able to reduce the level of dissolved Cu to below the 2 µg/L level for any of the events. Percolate and influent concentrations were similar, and there seems to be a limited effect of the filter soil on total Cu and virtually no effect on dissolved Cu. However, when adding dissolved Cu in a concentration of approximately 50 µg/L, the effluent concentrations of dissolved Cu was significantly reduced to below the detection limit and to 2.7 µg/L, but with a total Cu concentration of 8 and 8.1 µg/L, indicating that the Cu found in the effluent stems from the soil. A linear correlation of R^2 of 0.5 (Pearson's correlation test p-value of 0.04) for swale-trench West, and 0.9 (Pearson's correlation test p-value < 0.001) for East between total Cu and DOC points to complexation of Cu by the mobile DOC as the mechanism, as also observed by [16,40]. This trend was, however, not observed at Moellebakken and Lindevang where the correlation between TOC and dissolved Cu was 0.2 and 0.4 respectively (Pearson's correlation test with both p-values of 0.27 and 0.3 respectively). It should be noted that in Moellebakken the TOC was only measured at five rain events, and thus the statistical basis is weak at this location.

For Pb, similar to the suspended solids pattern, the highest inlet concentrations and the lowest percolate concentrations were observed for the curb extensions compared to the swale-trenches, despite filter soils with lower original Pb content at the swale-trenches (Table 4). Knowing that Pb is often found associated with SS and OC, the leaching from the swales and especially from the limestone-amended swale is in good accordance with the leaching of SS and OC. Almost all Pb was retained by the filter soil, when adding synthetic influent with Pb in dissolved form in concentrations much higher than those in the monitored events. In the first addition, total Pb was observed in a concentration of 1.6 µg/L with no dissolved Pb and, in the second addition, no Pb could be observed in the effluent, which is somewhat unexpected considering the fact that particles were leached. Comparing the concentrations of Pb in the percolate with the low criterion of 1 µg/L, it is concluded that the Pb concentration can be critical.

Percolate concentrations of Zn from both swale-trenches and curb extensions were below the criterion in all events. Adding almost 200 µg dissolved Zn/L to the curb extension demonstrated a significant reduction to a value below 8.4 µg/L in the effluent. Thus the filter soil can retain Zn.

Of the three PAHs surpassing the guiding criteria in influent, only benzo(a)pyrene was not in all cases sufficiently reduced in the filter soil. A good retention of PAHs in filter soil was also observed in the test based on synthetic influent. Here acenaphthene, naphthalene and phenanthrene were applied in dissolved form in high concentrations compared to reports on stormwater runoff concentration levels, but low concentrations compared to the criteria, which are relatively high for these three PAHs (Table 1). Therefore the effluent concentrations of these 3 PAHs were in no case critical in relation to the criteria.

The LAS and pesticides were not measured during normal rain events in this study, but included in the synthetic runoff, since they frequently are observed in runoff [29,46,47]. The pattern for LAS is somewhat biased by the fact that the chemical precipitated in the stock solution in the first addition. In the second addition, 130 µg/L LAS was added, but nothing was observed in the effluent, which indicates a good retention of LAS in the filter soil. For the pesticides, a good retention of glyphosate, which is known to sorb strongly to soil iron and aluminum oxides [48] was observed with concentrations in the effluent of 0.08 and 0.09 µg/L just below the groundwater quality criterion of 0.1 µg/L. MCPA was not retained at all in the first addition, having an effluent concentration of 0.5 µg/L, whereas in the second addition the effluent concentration could comply with the criterion of 0.1 µg/L. The reason for these contradictive results is not known. At the pH conditions present in the filter soil MCPA is primarily found as an anion, known to be poorly sorbed in soils, and sorption is negatively correlated with soil pH and positively correlated with organic matter content [49]. A way to improve the filter soil towards sorption of MCPA could be to add more stable organic matter; however, this has to be considered jointly with the risk of increasing DOC leaching and associated P and Cu. In general the fate of pesticides and their degradation products in filter soil is not well described. More research into retention efficacy and fate of pesticides and their degradation products in filter soil is needed.

An overall comparison of the two different systems showed that the percolate concentrations of SS, OC and Pb in Table 7 from the landfill-based filter soils in Copenhagen tended to be slightly lower than in percolate from the farmland-based filter soils in Odense possibly due to the larger infiltration area:catchment ratio at the swale-trenches or higher stability of the filter soil used in the curb extensions. It should be noted that both the influent concentration levels and the original contaminant content of the filter soil tended to be highest in the Copenhagen sites. The lime amendment of filter soil in swale-trench East in Odense did not result in improved percolate concentrations compared to swale-trench West, which could be ascribed to potential DOC mobilizing effects of the slightly increased pH of the soil.

5. Conclusions

Influent concentrations during rain events were low and several of the compounds analysed could not be detected (TPH, anionic detergents, pesticides) or were at similar low levels in influent and percolate e.g., (Cd). Despite the generally low influent levels the following contaminants were observed to exceed one or more of the guiding quality criteria for groundwater and freshwater protection: P, Cu, Pb, Zn benzo(a)pyrene. This may call for the use of filter soil or other treatment mechanisms before infiltration of discharge of stormwater runoff, even in low traffic catchments.

Filter soil reduced the inlet levels of SS, Cu, Ni, Pb, Zn and PAHs, while the concentration of P was increased in the percolate. For Zn, filter soil reduced the percolate concentration to below the guiding criteria; however, Cu was not sufficiently retained for discharge to freshwater and Pb and benzo(a)pyrene exceeded the groundwater quality criterion. Phosphorous levels in the percolate exceeded the Copenhagen limit of 0.08 mg P/L for discharge to lakes. Thus, filter soil is best suited for protecting groundwater and less suited for protecting freshwater.

The addition of synthetic influent with high concentrations of dissolved compounds confirmed the generally good retention of cationic heavy metals in filter soil, and some reduction in organic contaminants (PAH, LAS, pesticides). It also confirmed that filter soil can be a source of P. The observed patterns of SS and OC suggest internal mobilization processes rather than influent concentrations to account for occurrences of SS and OC in percolate.

No marked difference between the swale-trenches built from local farm soil and the curb extensions made from landfill soil was observed; however, there was a tendency for higher concentrations of SS and OC in percolate from swale-trenches, possibly due to the larger infiltration area:catchment ratio at the swale-trenches, although differences in aggregate stability could also play

a role. The amendment of one swale-trench filter soil with limestone did not increase the retention capacity compared to the non-amended filter soil.

The replicated experiment with addition of synthetic runoff with high but still realistic concentrations of selected pollutants showed that filter soil efficiently retains the added contaminants with percolate concentrations for most compounds at the same level as observed for rain events. This indicates that the treatment capacity of the soil is sufficient, and that a filter soil could be used in highly trafficked areas as well. However, the pesticide MCPA was not well-retained and in future studies more focus should be put on retention of pesticides in filter soil. As for rain events, dissolved Cu was at a critical level compared to the criterion, and P was not sufficiently retained. DOC remains a complicating factor and no general conclusion can be drawn. Generally we conclude that filter soil used in raingardens, curb extensions and trenches is a step in the right direction when it comes to protecting water resources by local management of stormwater runoff.

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