Infiltration and treatment of urban stormwater: how well do swale-trench systems work?

Infiltration et traitement des eaux de pluie en zone urbaine: quelles sont les performances des systèmes « fossé-rigole » ?

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RÉSUMÉ

Cette étude vise à évaluer l'état des systèmes « fossé-rigole » allemands (Mulden-Rigolen) qui sont en place pour permettre l'infiltration des eaux de ruissellement en milieu urbain depuis 15 ans ou moins. Sept différents systèmes « fossé-rigole » situés sur différents sites en Allemagne (Hoppegarten, Dortmund et Hambourg) ont été sélectionnés pour cette évaluation. Ces systèmes ont tous été conçus selon les directives établies par l'Association Allemande pour l'Eau, les Eaux usées et les Déchets (DWA). Des tests d'infiltration ont été effectués sur place pour évaluer le taux d'infiltration des systèmes. Des carottes de sol ont été prélevées dans la couche supérieure du sol (25-30 cm) en dessous la rigole et ont été sous-divisées en trois sections selon la profondeur des échantillons .Ces échantillons ont ensuite été analysés pour déterminer leur pH, la concentration en matière organique, la texture du sol ainsi que la concentration en phosphore et en métaux lourds. Par ailleurs, huit colonnes de sol intactes ont été collectées et ramenées au laboratoire pour des tests supplémentaires. Ce document décrit les sites d'échantillonnage et le protocole ainsi que les expériences et analyses réalisées. Les résultats des tests d'infiltration, la détermination des paramètres de base des sols ainsi que les concentrations en métaux lourds et en phosphore sont présentés, alors que les travaux sur les colonnes de sol intactes sont toujours en cours et ne seront donc pas présentés dans cet article.

ABSTRACT

This study aims at evaluating the state of German swale-trench systems (Mulden-Rigolen) that have been used for infiltration of urban runoff for up to 15 years. Seven swale-trench systems from different sites in Germany (Hoppegarten, Dortmund and Hamburg) were selected for the evaluation. The systems have all been designed according to the guidelines set by the German Association for Water, Wastewater and Waste (DWA). Infiltration tests were performed on-site to assess the infiltration rates of the systems. Soil core samples were collected in the top soil layer (25-30 cm) below the swale, which were sub-divided into three depth sections. The samples was analysed for pH, organic content, and texture as well as the content of phosphorus and heavy metals. Furthermore, eight intact soil columns were collected and brought to the laboratory for further testing. This paper describes the sampling sites and protocol as well as the chemical analyses. Results for on-site infiltration tests, basic soil parameters as well as heavy metal and phosphorus concentrations are presented, whereas the work on the intact soil columns are still on-going and will not be presented in this paper.

KEYWORDS

Urban runoff, Infiltration, Heavy metals, Swale-trench, Treatment performance

1 INTRODUCTION

Conventional management of urban stormwater relies on the rapid transport of runoff from impervious surfaces into combined or separate sewer systems. However, due to climate change the amount and intensity of rain events has amplified resulting in increasingly frequent sewer overflows (IPCC 2007). As a consequence on-site stormwater management is being considered as an alternative approach in Denmark, where stormwater is disconnected from the sewer systems and the urban landscape is utilized for retention and infiltration of the water. Such facilities are typically termed sustainable urban drainage systems (SUDS). However, the quality of urban runoff is often poor and as a consequence there are restrictions for the types of runoff that can be disconnected through SUDS.

As the water flows across impervious surfaces such as roads, parking lots and building materials it picks up a variety of pollutants. Common pollutants found in urban stormwater runoff are suspended solids, heavy metals, xenobiotic organic compounds (e.g. PAH), nutrients, and pathogens. A range of low technology treatment facilities for stormwater runoff are available to control the quality of the water. Among these are bioretention facilities which include variations such as rain gardens, infiltration ponds and swales. The common feature for these facilities is that they consist of a vegetated surface and a well-defined top soil layer with good hydraulic capacity and high pollutant removal efficiency. Many studies have been carried out for such systems both in the field (i.e. Davis 2007 ; Hatt et al. 2009 ; Li et al. 2009) and in laboratories (i.e. Hsieh & Davis 2005; Hatt et al. 2006 ; Thompson et al. 2008) to determine the treatment performance and optimal composition of the soil. However, knowledge about the long term functioning of these systems is still lacking.

In Denmark it is not allowed to infiltrate road runoff in urban areas, which in some areas can be a major barrier when planning for on-site stormwater management. The reason for such restrictions is the concern for polluting the groundwater which has an almost sacred status as the all-important source of drinking water in Denmark. However, in Germany, where groundwater is also an important source of drinking water, there are several examples of stormwater infiltration facilities for road runoff constructed during the last 10 to 15 years, namely swale-trench (Mulden-Rigolen) systems (Fig. 1). Within this period of time on-site storm water management in Germany became standard within urban drainage, especially in newly developed urban areas, where infiltration and retention was being considered at an early stage. (Sieker, 2006). In the early period of establishing these infiltration systems, projects to evaluate the hydraulic efficiency and pollution reduction were initiated. Most of these studies only produced results up to 5 years after construction, though, one study with a longer perspective was undertaken in the commercial area of Dahlwitz-Hoppegarten (Sieker, 2001). However, no real long term evaluations have been carried out so far. In 1990 the German Association for Water, Wastewater and Waste (Deutsche Vereinigung für Waserwirtschaft, Abwasser, und Abfall, DWA) published a standard with guidelines for the construction of infiltration facilities (DWA, 2005). A schematic diagram of the German swale-trench systems can be seen in Figure 1.The guidelines include, among other technical specifications, recommendations for the 30 cm top soil layer with respect to pH, grain size, clay content and organic content. However, no guidelines exist for assessing when the top soil of swale-trench systems needs replacement.

The objectives of this study is to make a first evaluation of the German swale-trench infiltration systems that have received different kinds of urban runoff, including road runoff, for more than a decade. They will be assessed with respect to hydraulic properties and treatment performance. The spatial distribution of pollutants will not be adressed in this study. The information to be gained is interesting in a Danish context if the restrictions for infiltration of road runoff are ever to be reconsidered. In a German context the results can provide valuable information concerning the expected lifetime or maintenance requirements of swale-trench systems or help improve existing guidelines.

2 MATERIALS AND METHODS

2.1 Site descriptions

The swale-trench systems chosen for this study are based on their time of operation, knowledge about previous examinations and measurements as well as the expected pollutant loadings. Details about the location and the dimensions of the individual systems are left out here due to lack of space. Pictures of a few facilities can be seen in Figures 2a and 2b, while a comparison of the facilities is found in Table 1. However, detailed information about parameters such as the quality of the runoff, the exact composition of the initial soil mixtures and the conditions during the previous time of operation is also lacking and, thus, cannot be included in the discussion.

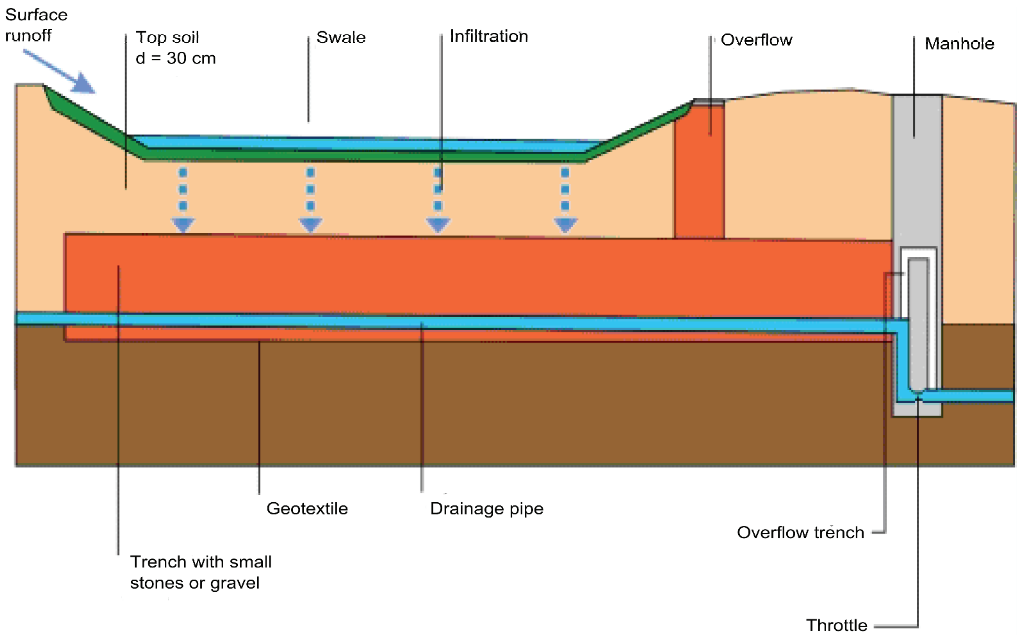

Fig. 1 Schematic diagram over the German swale-trench (Mulden-Rigolen) systems.

Table 1 Information about the seven sites to be investigated in this study.

Sampling site	Location	Runoff type	Traffic intensity (ADTF*)	Drainage area / infiltration area	Construction year
Site 1	UPS area, Hoppegarten	Road, parking area and roof	All incoming UPS trucks pass close by the swale.	7	1995
Site 2	Gewerbestrasse, Hoppegarten	Road runoff and sidewalk	6000 ADTF [a]	4	1997
Site 3a + 3b	Innodrain, Hoppegarten	Road runoff	2000 ADTF [a]	11 - 14	1998
Site 4	KiTA day care center, Dortmund	Roof, parking area and sidewalk	Very low	10	1994
Site 5	Glinder Strasse, Hamburg	Road runoff	20.000 ADTF [a]	4	2004
Site 6	An der Bucht, Rummelsburg, Berlin	Road and sidewalk	< 2000 ADTF [a]	4	1997
Site 7	Alt Stralau, Stralau, Berlin	Road and sidewalk	2500 ADTF [a]	6	1998

* Average Daily Traffic Frequency [a] Estimated value

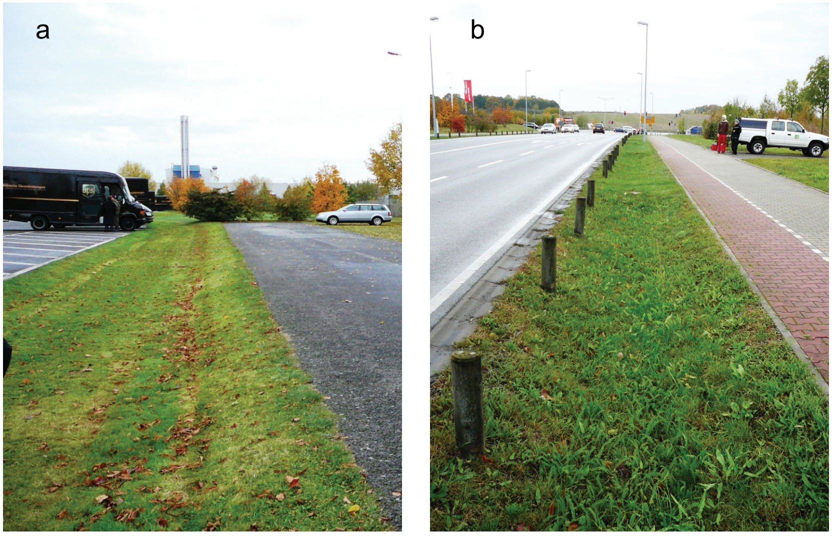

Fig. 2 a) UPS property, Hoppegarten, b) Gewerbestrasse, Hoppegarten

2.2 Sample protocol

Samples of the top soil layer were collected from all seven swale-trench systems whereas in two swales (site 1 and site 6) four intact soil columns were collected (eight in total) and brought to the laboratory. All sampling was carried out between the 26th of Oct. and the 8th of Dec., 2009.

2.2.1 Soil core samples

Soil core samples with a diameter of approximately 2 cm were collected from the top soil layer (25 cm) in the swales. 15 metres of the swale were selected for sampling. This area was divided into three sections of 5 metres each. In each 5 m section ten core samples were systematically sampled (Fig. 3). Immediately upon collection the core samples were sub-divided into three depth sections from 0-5 cm, 5-15 cm and 15-25 cm. The ten corresponding depth sections in each 5 m section were then mixed into three bulk samples so that each swale all in all yielded 9 bulk samples. This sample protocol ensured a good estimate of the overall concentration of pollutants. The spatial distribution in the swales was not considered a crucial parameter since most of the systems receive the road runoff along the entire length of the swale, and not just from few “point inlets”. Such an assessment would be more suited for a detailed study of one or a few swales.

2.2.2 Soil columns

Intact soil columns with an inner diameter of 15 cm and a length of 30 cm were collected from the swale at Gewerbestrasse in Hoppegarten and at An der Bucht in Rummelsburg. Four columns in each swale. The columns were collected by digging a hole leaving a monolith in the middle with a diameter of 20-30 cm. The vegetation layer was kept intact. On top of the monolith was placed a sharp stainless steel ring. With a knife the root zone was cut along the rim of the ring and all roots and pebbles were removed under the sharp edge. On top of the stainless steel ring the acrylic cylinder (column) was placed and the system was gradually pushed down through the soil profile while making sure that no rocks or roots got caught under the sharp edge of the ring which could create a preferential flow path along the rim of the column. Using a leveller the column was kept as vertical as possible through the proces. When there was approximately 5 cm of headspace left in the column the bottom was cut with a shovel and removed from the hole. The columns were capped and kept in an upright position.

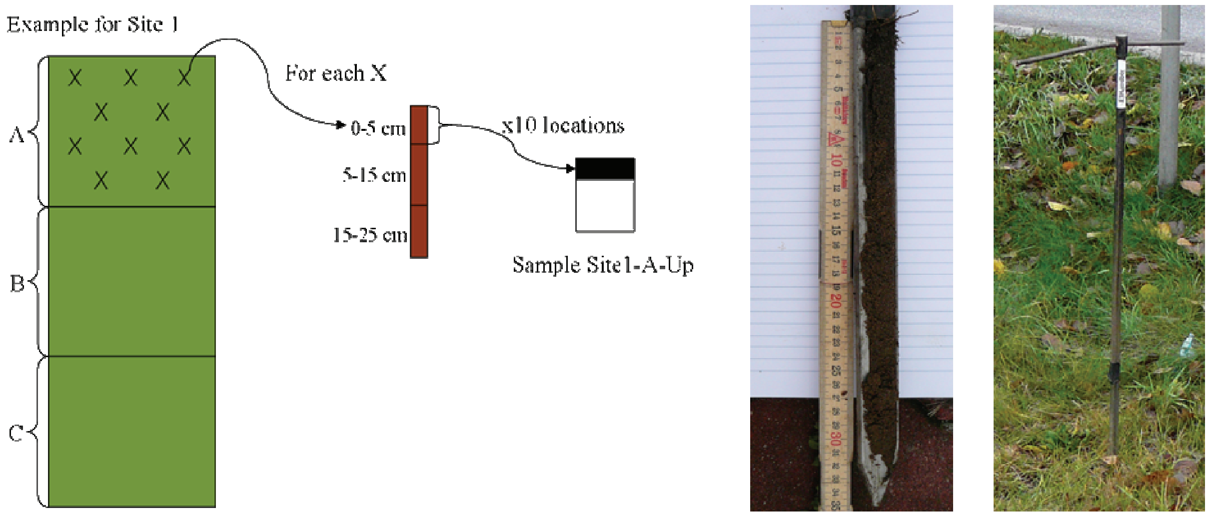

Fig. 3 Left: Sketch of the systematic sample collection in a swale seen from above. Ten soil cores were sampled from three sections of 5 m (30 core samples all in all). Each core was sub-divided into three depth sections. Middle: Picture of core sample before being sub-divided. Right: Picture of the core sampler.

2.3 Experiments and analyses

2.3.1 Open-end infiltration test

A German description of the Open-end infiltration test can be found in BMVBS (2008). The test can provide an on-site measurement of the infiltration rate in the swale or of the soil permeability. In this study the test was used to measure the infiltration rate through the vegetation layer. The test was performed by hammering a 50 cm metal tube (9.4 cm in diameter) straight into the bottom of the swale, approximately 15 cm. The tube was filled with water and the water allowed to infiltrate into the swale for a while. A floater was placed in the tube which was connected to a valve which added water to the tube in accordance with the floater height. When the addition of water through the valve was steady the infiltration rate was considered to be constant and measurements could begin. At five minute intervals the amount of water infiltrated was measured (per time unit). It was aimed to have at least 8 measurements per infiltration test. The k-value is then calculated as a function of the water flux divided by an empirical formula for the pressure of the water in the infiltration tube ($k = Q / (5.5 \times r \times H \times 6000)$, where Q is the water flux, 5.5 is an empirical factor, r is the radius of the infiltration tube and H is the height of water above ground in the infiltration tube). Three tests were performed in each swale.

2.3.2 Selection of soil analysis parameters

The basic parameters for the top soil layer such as pH, organic content, texture and clay content will be determined according to standard methods. This basic information is important for the assessment of treatment performance as well as lifetime expectancy. Moreover, these results can provide valuable inputs to the discussion of the pollutant contents measured and the treatment performance and flow capacity assessed by the soil column studies. There are numerous possible pollution substances to search for in top soil layers from urban stormwater infiltration facilities, i.e. a range of heavy metals, polycyclic aromatic hydrocarbons (PAH), pesticides, nutrients, pathogens, etc. Many organic substances are expensive to analyse. Heavy metals are in general cheaper to analyse, but still constitute good indicators of urban pollution, especially from trafficked areas. A review of typical stormwater runoff concentrations can be found in Göbel et al. (2007). Copper (Cu), cadmium (Cd), lead (Pb) and Zinc (Zn) are rather uncomplicated metals to analyse and often present in the urban environment at concentrations higher than background levels. Chromium (Cr) is not as well investigated (Göbel et al. 2007), although it often occurs in high concentrations in urban areas (Stotz 1987; Granier et al. 1990; Pitt et al. 1995; Thomson et al. 1995). Besides these heavy metals the soils were also analysed for basic elements such as iron (Fe), aluminium (Al), and manganese (Mn) as well as for the nutrient phosphorus (P) which is considered to be the most crucial parameter for eutrophication of Danish and German freshwaters.

2.3.3 Analytical methods

The bulk samples collected from different depths in the swale top soil layers were dried at 50 degrees Celsius and sieved through a 2 mm stainless steel sieve. For heavy metal and phosphorus analysis the soil samples were digested by microwave assisted (Anton Paar GMbH, Multiwave 3000) acid digestion according to the method of US EPA 3051A (USEPA 2007). Approximately one fourth of the dried, sieved and well mixed soil sample was pulverized prior to digestion. After digestion the heavy metal concentrations was analyzed by Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) (Perkin Elmer Optima 5300). The remaining three quarters of the sample was used for determining the other parameters according to standard methods.

2.3.4 Laboratory column experiments

The intact soil columns collected at selected sites were brought to the laboratory where they will be set up in a system to simulate the swale-trench system. This setup will be used for experiments to determine the saturated flow capacity and the long term treatment performance of the top soil layers. Furthermore, it is planned to conduct several tracing studies to examine and visualize flow patterns in such soils, as well as develop a method using fluorescent microspheres for simulating the behaviour of fine suspended solids in urban stormwater runoff. The distribution and breakthrough of the microspheres in the soil columns will provide new knowledge concerning the treatment efficiency towards particle associated pollutants in urban stormwater. Note that these experiments are ongoing and, thus, no results will be presented in this paper.

3 RESULTS AND DISCUSSION

3.1 Soil layer profiles

In each infiltration system a soil profile was dug to see whether any significant layering could be observed. Little detailed information has been found so far about the soil material that was used when constructing the systems. In general the upper 5-10 cm was darker than the rest of the profile, which can be explained by a higher concentration of organic matter in the root zone. Particularly at sites 3 and 7 were the top layers very blackish. Most roots were obviously concentrated in the upper 5 cm just below the vegetation, but in some of the profiles several fine and larger roots were observed throughout the entire depth profile. Other than that most of the profiles were rather uniform in their appearance, both with regards to colour and texture. There were noticeable differences in the biologic

Table 2. Soil and biology at the seven sites.

Site	Soil	Biologic activity / Vegetation cover
1	Dark top layer. Uniform deeper layer.	Few earthworms. Grass cover.
2	Dark top layer. Uniform deeper layer.	Great biologic activity and diversity (lots of earthworms and multiple plant species). Some deep running tap roots
3a	Very black, organic upper layer. Smell of sewage and water saturated soil.	Planted with bushes and small trees.
3b	Very black, organic upper layer.	Planted with bushes and small trees.
4	Uniform throughout the top 30 cm with no observed layering. Dark, sandy and loose soil.	Little biological activity. Cover: mixture of grass and mosses
5	Very distinct layering: organic rich top layer, more clayey layer in the middle and sand layer right above the trench. Presence of large rocks/gravels.	Grass cover. Little biological activity.
6	Dark top layer. Uniform deeper layer.	Few earthworms. Grass cover.
7	Two distinct layers: very black and organic-matter-rich upper layer of about 7 cm and black but looser deeper soil layer. Top soil seemed clogged. Very slow infiltration.	Lots of dead leaves and decomposing organic matter covering the swale.

diversity and activity in the different profiles. In all profiles we came across at least a few earthworms. A short description of the soil and biology at each of the seven sites can be seen in Table 2.

3.2 Open-end infiltration test

The results of the on-site Open-end infiltration tests are displayed in Table 3. The average infiltration rates measured varied from 1.4×10^{-7} − 3.6×10^{-5} m/s, values which, except for site 7, are within the acceptable range between 1×10^{-6} and 1×10^{-3} m/s. However, most soils are in the low end of this range, which could indicate a decrease in infiltration capacity since the time of construction. The highest variation was found in the swale along at the KiTA site in Dortmund, which also contained the highest amount of sand (Table 4).

It should be noted that this kind of on-site infiltration tests where the vegetation layer is included in the test is far from the same as a test of the hydraulic conductivity or permeability of the soil. The vegetation layer may in some cases be the rate limiting factor, whereas in other cases it may be the soil below that limits the infiltration. It will be interesting to perform measurements of the saturated hydraulic conductivity in the collected soil intact columns and compare the results with those of the on-site Open-end infiltration tests.

Table 3. Infiltration rates (10^{-6} m s^{-1})

	Test			
Site	1	2	3	Mean value
1	2,4 ± 0,4	2,7 ± 0,2	4,3 ± 0,2	3,2 ± 1,0
2	8,4 ± 0,1	5,8 ± 0,6	12,0 ± 1,0	9,0 ± 3,3
3a	1,2 ± 0,1	−	−	1,2 ± 0,1
4	35,0 ± 1,0	46,0 ± 3,0	27,0 ± 2,0	36,0 ± 9,0
5	6,3 ± 0,2	5,6 ± 0,3	42,0 ± 1,0	18,0 ± 21,0
6	4,8 ± 0,2	5,6 ± 0,5	5,9 ± 0,3	5,4 ± 0,6
7	0,13 ± 0,03	0,14 ± 0,03	−	0,14 ± 0,01

3.3 pH, organic matter and texture

Measured pH ranged from 7 – 8.5. According to the guidelines described by the DWA the pH of the soil pH should lie within the range of 6 – 8. Generally high pH-values ensure efficient retention of cationic heavy metals, but the effect can be different for anionic elements such as chromate (CrO_4^{2-}) and phosphate (PO_4^{3-}). It is not known whether or not the high pH measured at some of the sites is a product of the parent material used when the systems were constructed.

The soils' content of organic matter can be seen in Fig. 4 and as expected the top layer was always richest in organic matter. Organic compounds tend to maintain the aggregated structure of the soil and thus the permeability of the soil. However, when concentrations become too high organic matter can have the opposite effect and limit the flow. This could explain the poor permeability observed at sites 3 and 7 (Table 3). Considering the average content across the entire profile, then only sites 3a and 4 exceeded the DWA guideline of 3%. Nonetheless, the infiltration rate was acceptable at site 4.

The texture analysis was based on sedimentation and the use of a hydrometer to measure the density of the water column at certain times. The results can be seen in Table 4. All soils can be classified as *loamy sand* or *sand* according to the Danish soil classification system. The percentage of clay + silt is mostly around or exceeds 10%, which is the suggested maximum value in the DWA guidelines. There are no measurements available of the original soil material, so it is not possible to say for certain whether there has been an increase in fine particles or not. However, this rather high content of clay and silt could be a result of fine particulate matter being deposited in the swales with runoff or wind. These results correspond well with the measured infiltration rates (Table 3), except for site 7.

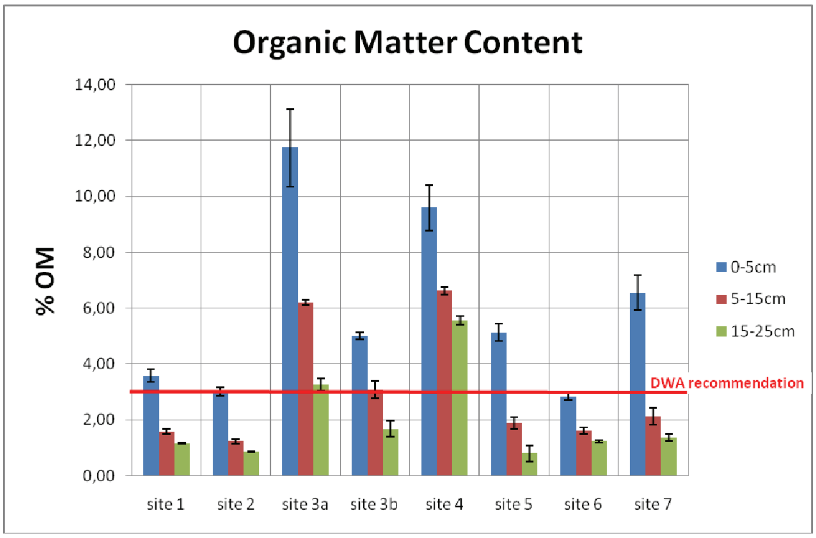

Figure 4 The content of organic matter in the three soil depths. The red line represents the German guideline of maximum 3% OM

Table 4 Percentage of clay, silt and sand as well as the corresponding soil type according to Danish soil classification system.

	% Clay	% Silt	% Sand	Soil Type
Site 1	5,5 ± 1,9	8,8 ± 1,3	85,7 ± 1,5	Loamy Sand
Site 2	5,1 ± 1,4	4,9 ± 1,3	90,0 ± 1,3	Loamy Sand
Site 3a	8,9 ± 3,1	13,0 ± 6,5	78,1 ± 6,3	Loamy Sand
Site 3b	7,0 ± 1,9	9,0 ± 4,3	84,0 ± 4,8	Loamy Sand
Site 4	4,8 ± 2,4	5,1 ± 2,1	90,1 ± 2,7	Sand
Site 5	5,5 ± 2,4	4,6 ± 1,7	89,9 ± 2,6	Loamy Sand
Site 6	5,7 ± 1,3	4,9 ± 1,1	89,4 ± 0,8	Loamy Sand
Site 7	5,4 ± 1,5	4,7 ± 1,5	89,9 ± 2,8	Loamy Sand

3.4 Heavy metals and phosphorus

The soil concentrations of the heavy metals Cd, Cr, Cu, Pb and Zn as well as phosphorus are shown in Fig. 6. The concentrations are compared to the Danish classification system for polluted soil as described by the regions of Sealand (Sjaellandsvejledningen 2001). Class 2 pollution corresponds to “slightly polluted soil” which doesn’t need treatment. Class 3, however, signifies polluted soil that should be cleaned depending on environmental and economical considerations. Concentrations of Cr, Cu and Zn were always below pollution class 2. Only at a few sites had the upper depth section (0-5 cm) significantly higher concentrations compared to the lower sections. This was often the case for site 3a and 7, which could indicate that heavy metals are being deposited in the top soil layer from road runoff and wind. For Cd and Pb pollution class 2 (and almost class 3) was exceeded at a few sites, particularly sites 1, 3a+b and 7. However, these concentrations are not yet critical according to the Danish guidelines, and the soils are only termed as slightly polluted. It should be noted that this is no guarantee for the treatment performance of the soils, which will be further investigated using the collected intact soil columns.

The concentrations of phosphorus ranged between approximately 200 and 1200 mg/kg and the depth distribution was more or less well correlated with that of basic elements such as iron, aluminium and manganese (not shown here) indicating association with these elements. Under aerobic condtions phosporus will be strongly bound to oxides or precipitated with carbonates (high pH). Similar concentrations have been reported in other studies on urban soils, i.e Zhang (2004).

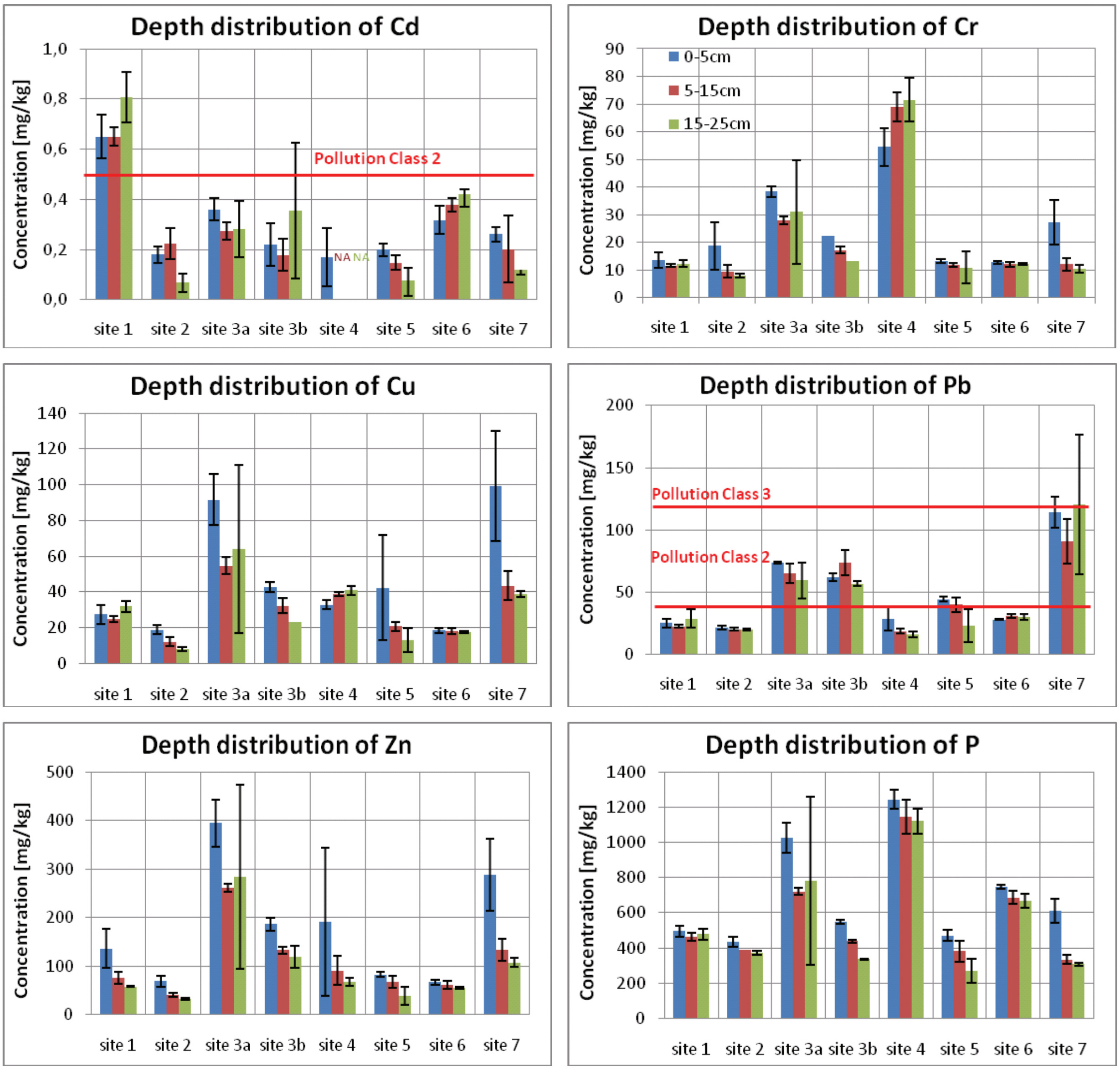

Figure 6 Soil concentrations [mg/kg] of heavy metals and phosphorus. Blue: 0-5 cm, Red: 5-15 cm, Green: 15-25 cm. Danish pollution classes are represented by the red line.

4 CONCLUSIONS

We have visited seven different swale-trench systems around Germany which infiltrate polluted urban runoff, including road runoff. The systems have been operating for 5-15 years, and so, to our knowledge, make up some of the longest running swale-trench facilities available. Soil samples have been collected from three different depths in the top soil layer (25 cm) of the swales. These samples have been analysed for heavy metals (Cd, Cu, Cr, Pb, and Zn), phosphorus, as well as for the basic soil parameters pH, soil texture, and organic content. Results revealed that the soil concentrations of heavy metals and phosphorus have not reached critical levels in terms of soil pollution. The basic parameters showed that the soils more or less comply with the German guidelines, except for a few sites where the content of organic matter was too high (>3%). Furthermore, the content of clay and silt was too high in most cases (>10%). This is in accordance with the results of the on-site infiltration tests which showed that almost all sites still have an infiltration rate that is within the acceptable range between 1×10^{-6} and 1×10^{-3} m/s, but the measured infiltration was generally in the low end of this range. It still remains to be investigated how well the soils work in terms of treatment efficiency. This work is on-going using the collected intact soil columns to test pollutant removal, flow capacity, vizualisation of flow patterns as well as removal and distribution of fine suspended solids. The information which will be obtained by these column studies is the core of this study.

5 ACKNOWLEDGEMENTS

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