Science of the Total Environment xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Spatial distribution of heavy metals in the surface soil of source-control stormwater infiltration devices – Inter-site comparison

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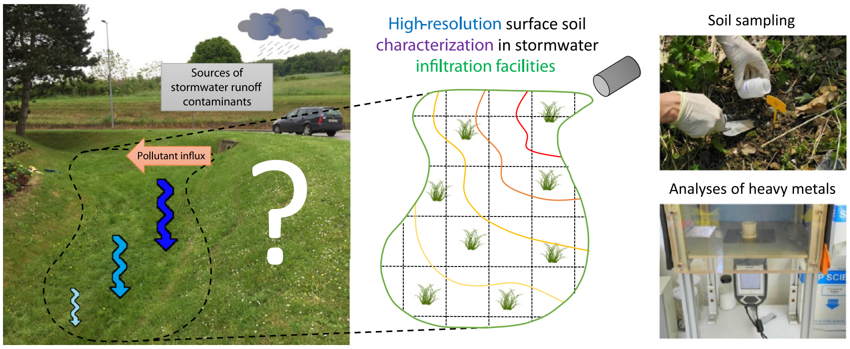
## HIGHLIGHTS

- Concerns about the fate of urban pollutants within the soil of infiltration devices.
- Experimental assessments of ten study sites with contrasting characteristics.
- Surface concentrations are spatially structured with respect to the inflow area.
- Contamination patterns bear the signature of non-uniform infiltration fluxes.
- These findings should be accounted for in SUDS design, maintenance, and modeling.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

*Article history:*
Received 13 July 2016
Received in revised form 28 October 2016
Accepted 30 October 2016
Available online xxxx

Editor: F.M. Tack

*Keywords:*
Contamination
Metals
Runoff infiltration
Soil
Spatial distribution
Sustainable urban drainage systems

## ABSTRACT

Stormwater runoff infiltration brings about some concerns regarding its potential impact on both soil and groundwater quality; besides, the fate of contaminants in source-control devices somewhat suffers from a lack of documentation. The present study was dedicated to assessing the spatial distribution of three heavy metals (copper, lead, zinc) in the surface soil of ten small-scale infiltration facilities, along with several physical parameters (soil moisture, volatile matter, variable thickness of the upper horizon). High-resolution samplings and *in-situ* measurements were undertaken, followed by X-ray fluorescence analyses and spatial interpolation. Highest metal accumulation was found in a relatively narrow area near the water inflow zone, from which concentrations markedly decreased with increasing distance. Maximum enrichment ratios amounted to >20 in the most contaminated sites. Heavy metal patterns give a time-integrated vision of the non-uniform infiltration fluxes, sedimentation processes and surface flow pathways within the devices. This element indicates that the lateral extent of contamination is mainly controlled by hydraulics. The evidenced spatial structure of soil concentrations restricts the area where remediation measures would be necessary in these systems, and suggests possible optimization of their hydraulic functioning towards an easier maintenance. Heterogeneous upper boundary conditions should be taken into account when studying the fate of micropollutants in infiltration facilities with either mathematical modeling or soil coring field surveys.

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http://dx.doi.org/10.1016/j.scitotenv.2016.10.226
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Please cite this article as: Tedoldi, D., et al., Spatial distribution of heavy metals in the surface soil of source-control stormwater infiltration devices – Inter-site comparis, Sci Total Environ (2016), http://dx.doi.org/10.1016/j.scitotenv.2016.10.226

## 1. Introduction

Land-use changes due to urban sprawl result in rising levels of impervious cover, which increases peak flows and volumes of runoff water to be drained away, and lessens infiltration into soils (Miller et al., 2014). Sustainable Urban Drainage Systems (SUDS), which contribute to the decentralization of stormwater management, have been proven to efficiently mitigate certain adverse impacts of urbanization on the water cycle, as they help control urban flooding, reduce combined sewer overflows, and participate in groundwater recharge (Dierkes et al., 2015; Zhou, 2014). While the use of facilities allowing for water infiltration is becoming a widespread approach in areas whose hydrogeological context enables it, their increasing implementation brings about some concerns about the fate of contaminants within these devices: given the micropollutant loads generated by urban watersheds (Gasperi et al., 2014), and the conservative behavior of several chemical species, long-term runoff infiltration may impair soil and/or groundwater quality (Mikkelsen et al., 1994; Pitt et al., 1999; Werkenthin et al., 2014). Operationally, the potential needs for soil maintenance or remediation to ensure a proper and sustainable functioning of infiltration-based SUDS are not clearly identified.

Previous experimental work led on such facilities revealed a significant accumulation of heavy metals (copper, lead, and zinc being among the most mentioned species) and hydrocarbons in the upper horizon of soil (El-Mufleh et al., 2014; Jones and Davis, 2013; Mikkelsen et al., 1996; Winiarski et al., 2006). It was often suggested that these systems exhibit a good potential for short- and mid-term pollution retention (Barraud et al., 2005; Napier et al., 2009). However, in most investigations, the sampling locations were not based on a preliminary analysis of the contaminant distribution in the surface soil – as recommended for example in the standard ISO 10381-5 (2005). Since surface concentrations have been shown to exhibit high variability at the scale of a whole infiltration basin (Le Coustumer et al., 2007; Dechesne et al., 2004a), the derived contamination profiles may not have the same representativeness from one study to another.

The studies which specifically addressed the horizontal distribution of soil contamination in infiltration systems are scarce (Tedoldi et al., 2016); moreover, authors who investigated the question generally used a rather “loose” sampling grid – *i.e.* $<2$ sampling points/100 $m^2$ (Le Coustumer et al., 2007; Dechesne et al., 2004a), 2.5 points/100 $m^2$ (Napier et al., 2009), and about 6 points/100 $m^2$ (Kluge and Wessolek, 2012) – which may be insufficient to capture the small-scale variability of the concentrations. Additionally, most of these assessments were carried out in large-scale or centralized facilities, as a result of which the spatial distribution of contaminants in “source-control” SUDS still suffers from a lack of documentation. Only Jones and Davis (2013) achieved a high-resolution characterization of a bioretention cell (about 75 sampling points/100 $m^2$), and thus evidenced noteworthy relationships between metal concentrations, distance from the inlet, and modeled cumulative infiltration. Although several sources of variability have been identified, among which topography, soil heterogeneities, “historical” accumulation, or the presence of technical installations (*e.g.* street lamps or barriers), the present literature does not allow to draw general conclusions regarding the contamination levels and typical size of the polluted areas in the upper horizon of SUDS.

Better appraising the pollutants' accumulation, and resulting distribution, in the surface soil of infiltration devices, would be of great value to (i) provide practical guidance regarding SUDS operation and potential needs for soil maintenance, (ii) optimize the representativeness of further vertical soil samplings, and (iii) understand the mechanisms controlling this distribution and accordingly derive possible improvements of the current modeling tools. For these purposes, the present work aimed to achieve high-resolution cartographies of the soil contamination, in a series of source-control infiltration devices with various hydrologic behaviors and runoff contamination potentials, focusing on heavy metals chronically associated to the urban- and traffic-sourced pollution (Gromaire-Mertz et al., 1999; Huber et al., 2016; Kayhanian et al., 2012).

## 2. Material and methods

### 2.1. Description of the study sites

A series of 10 infiltration-based SUDS, located in the Paris region (France), which had been in operation for at least 10 years except for one of them, were selected for their contrasting watersheds, characteristics, and morphologies (Table 1). Among these are four infiltration basins with different sizes, five infiltration swales, and one grassed filter strip. Photographs of the study sites are supplied as *Supplementary data*. The watershed characteristics, including the use of metallic construction materials and anthropic activities, are indicated in Table 1; the annual average daily traffic in the vicinity of the study sites is also reported when available, as it has been demonstrated to have a significant impact on the metal contents in the topsoil of several roadside swales (Horstmeyer et al., 2016). Watershed delimitation was achieved *via* field inspection, as-built drawings, and cadastral data supplied by the official French web mapping service *Géoportail*. The effective catchment area of each site – or sampled section in the case of longitudinal swales – was calculated as the weighted sum of the different surfaces composing the watershed, using the runoff coefficients proposed by Ellis et al. (2012). The average annual rainfall in the Paris region over the period 1981–2010 is ~640 mm (source: *Météo France*).

Inflow of water into the infiltration systems consists in either an inlet pipe (*Dourdan1*, *Greffiere*, *Alfortville*, *Dourdan2*, *Vaucresson*), or surface runoff directly flowing from the pavement (*Sausset1*, *Sausset2*, *Chanteraines*, *Vitry*, *Compans*). No dry weather flow was observed during the field campaigns, suggesting an absence (or limited amount) of illicit connections to the storm sewer system. In some devices, superficial outflow is possible in addition to infiltration (*Dourdan1*, *Chanteraines*, *Vitry*, *Compans*). In every study site except *Chanteraines* and *Sausset2*, a dark horizon – whose nature and formation process will be discussed later in this paper – could be distinguished at the soil surface (Fig. 1), and its thickness was noticed to be variable in space within the devices (0–30 cm). Most facilities were constructed with flat bottoms and sharp embankments, except *Chanteraines*, *Vitry*, and *Compans*, where the surface soil displayed a 5 to 15% slope perpendicular to the pavement, and *Alfortville*, which had a V-shaped transversal section. Local differences in topography resulted from the history of the devices (*e.g.* vegetation growth or fauna activity), which might cause heterogeneous flow pathways at the soil surface. Since it appeared difficult to make a fine topographical survey, it was rather decided to visualize the water distribution in the upper horizon by performing high-resolution measurements of the soil moisture (*cf.* Section 2.2).

### 2.2. Sampling and in-situ measurements

The field investigations were undertaken between April 2015 and May 2016. Samplings and measurements were carried out along a rectangular grid with $<3$ $m^2$ meshes whatever the study site. At each node: (i) the vegetation was removed if present, then approximately 50 g of surface soil (upper 2–3 cm) was composited from $\geq 4$ subsamples surrounding the sampling location, using a stainless steel trowel which was subsequently cleaned and rinsed twice with ultrapure water; (ii) soil moisture in the first 8 cm was measured (in triplicates, retaining the mean value) with a time-domain reflectometer (*Spectrum Technologies*, FieldScout probe TDR 100); (iii) a 30-cm-deep soil core was dug with a hand auger, so as to measure – when distinguishable – the thickness of the dark upper horizon. In *Dourdan1*, *Greffiere*, *Chanteraines*, *Vitry*, *Vaucresson*, and *Compans*, additional samples of raw sediment were collected on the nearby road pavement; such deposits could not be found in the immediate vicinity of the other study sites. All samples

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