Urban pollution control and soil contamination in Sustainable Drainage Systems: insights gained from an extensive field study

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Maîtrise de la pollution urbaine et contamination du sol dans les ouvrages de gestion à la source des eaux pluviales : bilan d'une campagne expérimentale approfondie

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RÉSUMÉ

Le développement du contrôle à la source des eaux pluviales urbaines, et notamment le recours croissant à des dispositifs d'infiltration, suscitent des interrogations sur la capacité du sol à jouer le rôle de « filtre » vis-à-vis des polluants présents dans le ruissellement. Cette question est abordée ici par une approche expérimentale, mise en œuvre sur 11 sites d'étude aux caractéristiques contrastées. Le sol de ces ouvrages a été échantillonné en deux phases successives, en élargissant la gamme de polluants et de paramètres pédologiques analysés entre la première et la seconde étape. Ceci a conduit à des cartographies de la contamination superficielle en éléments traces métalliques, puis à des profils verticaux de métaux et HAP, accompagnés de différentes variables explicatives. La distribution spatiale des métaux en surface, qui présente une structure caractéristique par rapport à la zone d'arrivée de l'eau, révèle le caractère non-uniforme de l'infiltration lors des événements pluvieux courants. Dans la zone la plus polluée des ouvrages, métaux et HAP présentent un enrichissement significatif sur 10 à 40 centimètres de profondeur. La contrepartie de cette rétention est une contamination qui, sur 7 sites, excède les teneurs maximales admissibles – telles que définies par différentes normes internationales – dans le sol de zones résidentielles. Dans ces ouvrages, la quantité de sol qui requiert une « intervention » après une dizaine d'années de fonctionnement représente en moyenne ~15 m^3 par hectare de bassin versant.

ABSTRACT

Sustainable Drainage Systems (SuDS) are increasingly used for stormwater management. However, the generalization of runoff infiltration in urban watersheds raises some concerns regarding the soil's ability to retain ubiquitous runoff pollutants. This question was addressed *via* experimental investigations on 11 study sites with contrasting characteristics. A two-phase sampling methodology was carried out, expanding the range of analyzed contaminants and soil parameters between the first and the second phases. This successively led to cartographies of metal contamination in the surface soil, and vertical profiles of metal and PAH contents, along with different explanatory variables. The spatial distribution of trace metals in the upper horizon displayed a systematic structure with respect to the inflow area, and revealed the time-integrated signature of non-uniform infiltration fluxes and flow pathways at the surface. In the most contaminated zone of the facilities, a significant enrichment of metals and PAHs was detectable until 10 to 40 cm depth. Soil acts as a "filter" towards these persistent urban contaminants, but in return, surface contents from 7 study sites exceeded "intervention thresholds" for multi-functional areas – as defined in various international soil clean-up standards. In these devices, the area which would require soil remediation after ≥ 10 years of operation was found to be laterally and vertically limited, and represented on average ~15 m^3 of polluted soil material per hectare of urban area.

KEYWORDS

Contaminant accumulation, Metals, Polycyclic Aromatic Hydrocarbons (PAHs), Runoff infiltration, Soil, Source-control stormwater management

1 INTRODUCTION

Source-control stormwater management is gaining popularity across the world, not only because of its widely recognized hydraulic and hydrologic improvements, but also considering more qualitative benefits such as urban heat island reduction or biodiversity aspects (Zhou, 2014). This new paradigm often leads to the dissemination of decentralized, infiltration-based techniques in urban areas – at least in the absence of specific proscription related to the hydrogeological context – which in turn may raise some concerns regarding the fate of runoff contaminants in soil, and their possible threat to groundwater. In addition to evaluating the potential for pollutant interception by the upper horizons of soil (Paus *et al.*, 2014), operational matters remain, especially concerning the identification of efficient guidelines to guarantee a proper and sustainable functioning of infiltration systems. This paper presents the insights gained from a comprehensive assessment of soil contamination by trace metals and polycyclic aromatic hydrocarbons (PAHs) in eleven source-control devices in France.

2 MATERIAL AND METHODS

2.1 Study sites and sampling methodology

Four small sized infiltration basins, five swales, and two vegetative filter strips in the Paris area, most of which had been in operation for ≥ 10 years, were selected for their contrasting morphologies, hydraulic configurations, catchments, and runoff contamination potentials. In the Paris region, the average annual rainfall depth is ~640 mm, and the rainfall distribution is dominated by small events: during the period 1993-2008, 60% of the daily rainfall depths were ≤ 10 mm, and 80% were ≤ 17 mm. A 10-year frequency event corresponds to 32 mm in 1 h, and 61 mm in 24 h (source: *Météo France*).

The levels and spatial extent of soil contamination were appraised *via* a two-stage sampling methodology (Figure 1). Firstly, a systematic, high-resolution sampling of the surface horizon (upper 2-3 cm) was carried out using a rectangular grid; the collected samples were analyzed for trace metals (section 2.2). After interpolation with universal kriging, areas with homogeneous contamination at the surface could be identified. Then, vertical sampling was undertaken in two or three of these areas, including the most and the least contaminated zones – referred to as "Zone 1" and "Reference", respectively –, and contingently an intermediate zone – "Zone 2". Four core samples were collected in each zone, and subdivided into six to nine depth sections with a higher resolution near the surface. For each depth, a composite sample was formed from the 4 corresponding subsamples.

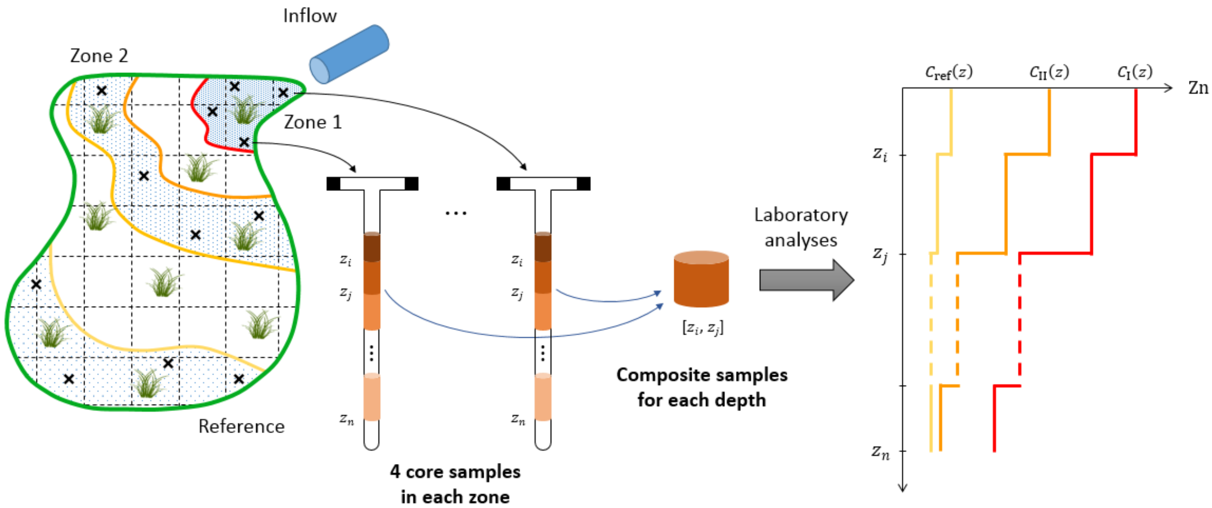

Figure 1 – Schematic representation of the two-step methodology for soil sampling and analysis (adapted from Tedoldi *et al.*, 2017).

2.2 Physicochemical analyses

The approach consisted of expanding the range of contaminants and soil parameters between the first and the second phases, with an increasing precision of the analytical methods. Hence, the elements of interest in the surface samples were Cu, Pb, and Zn, analyzed *via* X-ray fluorescence spectrometry, with 5 to 6 replicates on different subsamples. Subsequently, the analyses of the core samples covered 8 metals (Cu, Pb, Zn, Cd, Cr, Ni, Co, Mo) with a conventional determination of total contents (*i.e.* ICP-based analyses on acid-digested samples), 16 PAHs classified as priority pollutants by the US-EPA, pH_{water}, cation exchange capacity (CEC), volatile matter, and total carbonates.

3 RESULTS AND DISCUSSION

3.1 Typical patterns of soil contamination

Horizontal distribution. The spatial distribution of Cu, Pb and Zn in the surface horizon displayed a systematic structure with respect to the inflow area, characterized by a significant buildup in this zone followed by a marked decrease in contents with increasing distance. As to the other contaminants, the retained methodology implied that only one surface value per zone was available. Whatever the site, Cd, Mo, and PAH contents also followed the order Zone 1 > (Zone 2) > Reference, thus demonstrating – with a lower spatial resolution – a similar preferential accumulation of these contaminants near the water inlet. Given the characteristics of the pluviometry in the Paris area, for most rainfall events, water is likely to infiltrate before spreading over the entire systems – all of which have been designed for a ≥ 10-year frequency storm. Since water is the carrier medium of solutes and particles, the greatest part of the incoming pollutant fluxes would be essentially concentrated near the inflow area, or more exactly intercepted by the *first* permeable surface reached by stormwater runoff.

Vertical distribution. Contaminant profiles in the reference (*i.e.* least polluted) zone were approximately uniform below 5 to 10 cm depth, confirming that this area was marginally influenced by runoff-derived contamination (Figure 2). Conversely, in zones 1 and 2, the accumulation of metals and PAHs was visible over 10 to 40 cm, depending on the site. The most common trend for metals consisted of a continuous decrease in contents with increasing depth, whereas the highest PAH levels were not systematically found at the surface. The latter observation was attributed to the dissipation mechanisms which preferentially occur in the superficial, biologically active horizon of soil. Overall, the results demonstrate that the soil may act as an effective filter towards the incoming loads of metals and PAHs, thus preventing their downward transfer.

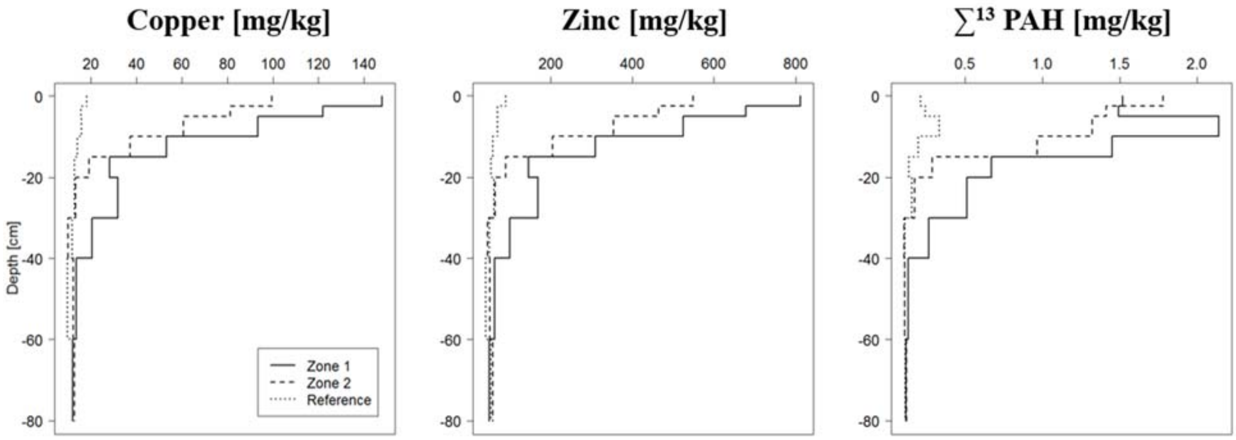

Figure 2 – Vertical distribution of copper, zinc, and PAH contents [mg/kg] in the three sampling zones of an infiltration basin located in a residential catchment (adapted from Tedoldi *et al*., 2017).

3.2 Contamination levels and operational outcomes

The inter-site variability of contamination has both a soil-related and a catchment-related components. The former could be linked to the soil properties, with strong correlations between metal contents and soil organic matter or CEC, and relatively low accumulation in swales with sandy soil. The latter was clearly associated to the contaminant sources within each drainage area, *i.e.*:

i. for Cu and Zn: road traffic, along with the use of zinc elements in building construction;
ii. for Pb: industrial activities, or leaded gasoline in case of ≥ 20-year-old roadside facilities;
iii. for PAHs: road traffic, or industrial / incineration activities in the vicinity of the sites.

As an illustration of the first two points, two recently built filter strips near a heavily trafficked road, which were among the most polluted sites with respect to Cu (> 300 mg/kg) and Zn (> 1200 mg/kg), displayed comparatively low Pb contents (< 70 mg/kg). Conversely, a roadside swale with relatively low traffic but > 25 years of operation had moderate Cu and Zn contents (at most 80 and 250 mg/kg, respectively), but was ranked third with respect to Pb contamination (230 mg/kg).

Although this accumulation appears beneficial to avoid groundwater quality impairment, the environmental impact of surface soil contamination should be evaluated as well. This is particularly important if SuDS are to be implemented within “multi-functional” spaces, and requires reflections about the optimal way to guarantee their long-term sustainability. In the absence of soil quality standards in the French regulations, the needs for intervention were evaluated according to various international soil clean-up standards; more specifically, the retained thresholds corresponded to the 1st quartile of the values synthesized by Provoost *et al*. (2006) for “residential land uses” (100, 270, 310, and 7 mg/kg for copper, lead, zinc, and cadmium, respectively). In 7 sites out of 11, a part of the devices was found to require soil remediation or excavation because of Cu and Zn contamination. The volume of polluted soil material which should be treated either way was estimated from the cartographies and profiles of metals, considering the extent of the surface horizon and maximum soil depth exceeding the thresholds.

The obtained values (Table 1) were evidently dependent upon the size of the devices, but interestingly, the normalized volume per unit surface of drainage area appeared to be fairly stable from one site to another. Assuming, as a first approximation – which obviously needs to be refined with additional data – that the retained panel of study sites might be considered representative of the infiltration practices and environments of the Paris suburban area, this approach provided a rough estimation of the volume of polluted soil material to be managed, as a mid- to long-term outcome of the generalization of source-control infiltration. The transposability of the results should be further investigated by including other panels of sites from different geographical regions, keeping in mind the need for harmonization in the experimental approaches in order to carry out a rigorous inter-study comparison.

Table 1 – Estimated volume of polluted soil (V_{soil}) with unacceptable metal contents for residential or multi-functional land uses; normalized value per unit surface of drainage area ($V_{soil}/S_{drainage}$).

Type of device	Infiltration basins			Swales		Filter strips	
Operating time [yr]	> 20	15	16	10	11	4	4
Device area [m^2]	120	65	130	20	30	35	35
V_{soil} [m^3]	9.4	4.0	27.5	0.3	> 0.6*	0.6	0.4
$V_{soil}/S_{drainage}$ [m^3/ha]	13	13	14	9	> 4*	25	16

*Since vertical investigations could not be carried out in this site, the given value corresponds to the surface soil only (3 cm) and thus provides a lower bound of the volume to be treated.

4 CONCLUSIONS

This paper reported a comprehensive assessment of mid- to long-term soil contamination in eleven infiltration systems in France. The two-step experimental methodology which was retained, consisting consecutively of horizontal and vertical investigations, guaranteed a suitable representativeness of the contamination profiles and enabled to achieve a precise, tri-dimensional vision of the extent of soil pollution. Overall, the results demonstrated that the soil may act as an efficient filter towards a series of ubiquitous runoff contaminants, including trace metals and polycyclic aromatic hydrocarbons. Their spatial distribution in the surface horizon emphasized the non-uniform nature of infiltration fluxes and settling processes at the soil surface, and provided a precise, time-integrated vision of the devices' actual hydraulic behavior. Even in the most polluted zone of each site, metal and PAH contents below 10 to 40 cm depth were comparable to the geochemical background. In several cases, copper and zinc accumulation had resulted in incompatible contents with residential or multi-functional land uses, according to various international soil clean-up standards. In two thirds of the sites, an average of ~15 m^3 of polluted soil material per hectare of urban area had to be managed (*e.g. via* remediation or excavation); this generally occurred after ≥ 10 years of operation, but this duration was reduced to 4 years in two sites with a high contamination potential. Similar assessments in other contexts, and especially other climates, would be valuable to gain insight into this need for maintenance – which ought to be kept in mind in the planning or retrofit of urban areas so as to definitely ensure the long-term sustainability of stormwater management.

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