The impact of stormwater on a soil profile in an infiltration basin

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Abstract The effects of urban stormwater on the soil of an infiltration/ holding basin were studied within the framework of research carried out by OTHU (Urban Hydrology Field Observatory of Lyon, France). The biophysicochemical impacts of stormwater from an industrial watershed on the local soil (to a depth of 4 m in the unsaturated zone) were measured. Several types of measurement (pH, organic matter, particle size, heavy metals content, and heterotrophic viable bacterial counts) for three vertical soil profiles were carried out. High concentrations of heavy metals and significant variations in pH and silt to a depth of 1.5 m were observed. The concentrations decreased as a function of distance from the stormwater discharge pipe. Changes in the bacterial population were also observed, varying in accordance with the depth and location of the profile.

Résumé Dans le cadre de la fédération de recherche OTHU (Observatoire de Terrain en Hydrologie Urbaine de Lyon) une étude sur l'impact des eaux pluviales sur le sol d'un bassin d'infiltration / rétention est présentée. Il s'agit d'évaluer l'impact biophysicochimique des eaux pluviales issues d'un bassin versant industriel sur une profondeur d'environ 4 m de zone non saturée. Pour cela plusieurs types de mesures ont été effectuées (pH, perte au feu, teneur en Cu, Pb, Cd, dénombrement bactérien) suivant trois profils verticaux. Les résultats montrent des concentrations importantes de métaux et des variations de pH jusqu'à 1.5 m de profondeur. De plus, les résultats montrent une variation suivant la position des points de prélèvements. Des modifications de la population bactérienne sont également observées suivant la profondeur et l'emplacement des profils.

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Resumen Se estudiaron los efectos de tormentas en zonas urbanas sobre el suelo de una cuenca retenedora/de infiltración dentro del marco de investigación llevado a cabo por OTHU (Laboratorio de Observación de Campo de Hidrología Urbana, Lyon, Francia). Se midieron los impactos biofisicoquímicos de la tormenta en una cuenca industrial sobre el suelo local (a una profundidad de 4m en la zona no saturada). Se llevaron a cabo varios tipos de mediciones (pH, materia orgánica, tamaño de partículas, contenido de metales pesados, y conteo de bacterias viables heterotróficas) en tres perfiles edáficos. Se observaron altas concentraciones de metales pesados y variaciones significativas en pH y limo a una profundidad de 1.5m. Las concentraciones disminuyeron en función de la distancia del tubo de descarga de las aguas de la tormenta. También se observaron cambios en las poblaciones de bacterias los cuales variaban en función de la profundidad y localización del perfil.

Introduction

The development of urban areas tends to increase the impermeable surface area, in turn increasing the amount of run-off water. This water is collected and transported by a compartmentalised or unitary urban drainage system, generally connected to the hydrological network. Due to the potential impact of this water on the environment to which it is directed, alternative techniques involving the infiltration of stormwater in the soil are used if the hydrological network is too far away or non-existent. The most common techniques involve the use of drainage ditches, infiltration wells, holding basins and/or infiltration basins.

Infiltration basins are particularly favoured in the eastern part of the Lyon area (France) due to the distance of this area from the local river (the Rhone) and the high permeability of the soil. Numerous basins of up to several hundred hectares in size collect and infiltrate stormwater from the surface (industrial and residential). This type of system may concentrate pollutants (heavy metals), resulting in a risk for the quality of both soil and groundwater

(Ford et al. 1992; Yousef and Yu 1992; Appleyard 1993; Mikkelsen et al. 1994). This risk is greater in urban and periurban areas due to the higher levels of pollutants in these areas (Pilgrim and Schroeder 1997).

The effect of a stormwater infiltration basin on the underlying porous matrix was studied at the Chassieu infiltration basin, which collects water from an industrial watershed to the east of Lyon (Fig. 1). The distribution of various physicochemical characteristics (pH, organic matter, grain distribution, heavy metal content) and of the viable heterotrophic bacterial population along a 4-m vertical profile in the soil were studied. Three vertical profiles were studied at different locations in the basin.

Description of the site

This system has been operational for about 20 years and currently consists of a holding basin, a holding/infiltration basin and a disused, clogged infiltration basin. Only the holding/infiltration basin (Fig. 2), which collects some of the water from the stormwater network and the water from the holding basin, was studied. The basin is approximately 5.5 m deep, with a bottom surface area of 7,406 m^2 and a bottom slope of 0.1%. It can hold up to 30,856 m^3 of water and can empty at a rate of approximately 0.5 m^{3}s^{-1}. The total surface area of the watershed drained is approximately 185 ha. The run-off coefficient is estimated to be 70 to 75%. The water table is approximately 13 m from the bottom of the basin, therefore the thickness of the unsaturated zone is significant. The drained surfaces are in a stabilised industrial area and the main pollutants involved are heavy metals, cyanides, inks, fats, hydrocarbons and solvents.

The underlying aquifer consists of a fluvio-glacial complex dating from the Quaternary period. The aquifer has a high speed of horizontal transfer (4 m/day). The hydraulic conductivity ranges from 7×10^{-3} to 9×10^{-3} m s^{-1} (Burgeap 1995) and transmissivity is from 0.0075 to 0.075 m^2 s^{-1}. The measured effective porosity is approximately 13%. The resource is estimated at 110,000 m^3 day^{-1} (rain and contribution to the underlying aquifer).
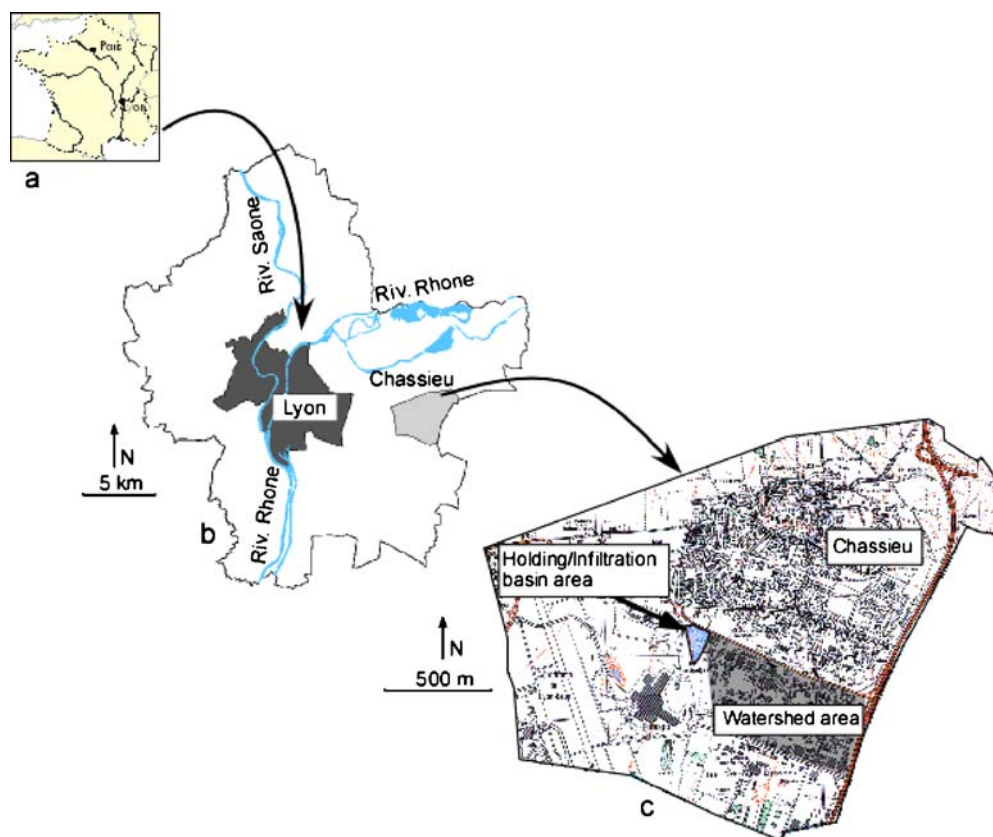
Materials and methods

Sampling

Three soil samples were taken in the current holding/infiltration basin (Fig. 2):

– Pt1: near the stormwater entry pipe
– Pt2: in the middle of the basin
– Pt3: at the southern extremity of the basin

Soil samples were collected by shovel and by hand auger every 0.05 to 0.10 m, to a depth of 0.5 m, and then

Fig. 1 **a** France, **b** Greater Lyon, **c** location of the study area at Chassieu, delineated by the *thick black line*
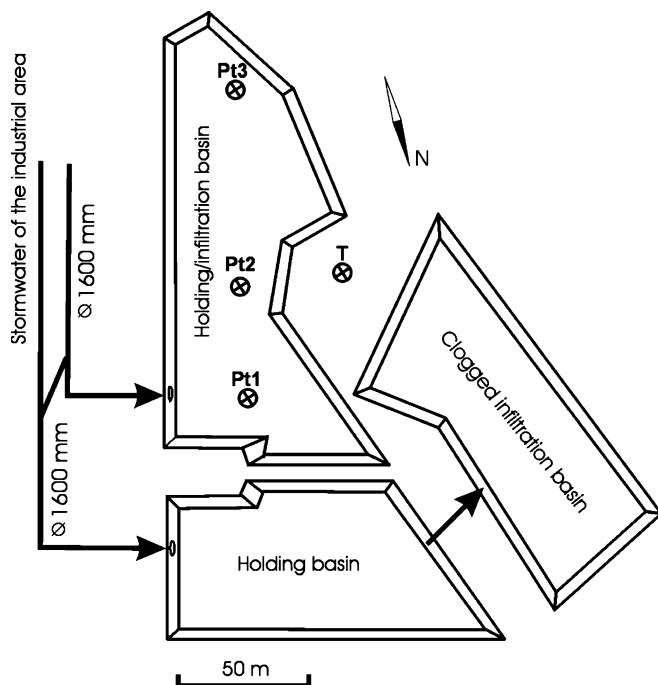
Fig. 2 Map of the holding/infiltration basin area, showing soil sampling points: *T* control; *Pt1* sampling point 1; *Pt2* sampling point 2; *Pt3* sampling point 3

by power shovel every 0.20 m, to a depth of 4 m. All the samples were homogenised on site before analyses and subsamples for microbial analysis were transported and stored at 4°C.

A fourth sample was taken with a power shovel from the area around the basin (sample point T in Fig. 2). This was used as a control sample not subjected to the impact of stormwater from the network. This was an averaged sample, corresponding to a homogenised mixture of the first 50 cm of the soil.

Measurements and methods used

The concentration of heavy metals was determined in samples dried at 60°C for 48 h. The dried samples (0.5 g) were sieved through a 2-mm screen and then mineralised by heating in a microwave oven with acid 7 ml of 65% HNO_3 (Suprapur Merck) and 3 ml of 48% HF (Ultrapur Merck; Hewitt and Reynolds 1990; Lamble and Hill 1998). The resulting solution was subjected to detailed analysis by graphite furnace atomic absorption spectrometry (GFAAS; Dean et al. 1998). Pb, Zn Cu, Ni, Cd and Cr contents were determined in the soil samples, because they are generally the heavy metals found in highest concentrations in urban stormwater (Marsalek et al. 1997; Mosley and Peake 2001). Only Pb, Cd and Cu profiles are given in this report. These three heavy metals have been chosen for their different reactivities with the soil and toxic properties. The retention of Pb is generally high, Cd is the most toxic metal and Cu is known for its affinity with organic matter. The replicability of the measurement was evaluated for 12 soil samples chosen randomly from

all the samples and the variability of the metal content for each sample was under 5%.

The grain size analysis of the particles less than 1 μm was carried out by laser granulometry (Malvern, Mastersizer S) as per ISO 13320 (2000). Four grain-size classes were chosen: less than 2 μm (fine clays), from 2 to 3.9 μm (clays), from 3.9 to 64 μm (silts), higher than 64 μm (sands). Water pH was determined as per ISO 10390 (1994). The combustible (organic) matter corresponds to the decrease in mass of the sample after heating as per EN 12879 (2000). Total carbonates content was determined as per ISO 10693 (1995).

Ten grams of dry sample were placed in a sterilized Waring Blender (Eberbach Corporation) and mixed with 50 ml of sterile saline solution (0.8% NaCl). The mixture was homogenized for 90 s. Homogenous soil suspensions were serially diluted in the sterile saline solution and 100 μl of appropriate dilutions were spread on the agar plates. Amphotericine B (Sigma) was used as an antifungal agent (2.5 mg L^{-1} final concentration). Three plates were inoculated for each dilution. Enumeration of Colony Forming Units (CFU) corresponding to viable heterotrophic bacteria was performed by plate count agar (PCA media, DIFCO) after 4 days incubation at 28°C (Ranjard et al. 1997). Counts were determined only for plates that contained from 30 to 300 colony-forming units (CFU). The data were expressed as the mean of triplicate determinations and variability was less than 10% for all the samples.

Results

Characterisation of the control soil

The soil taken from a depth of 0.5 m was rich in carbonates and alkaline (Table 1), as reported by Barraud et al. (2002) in a previous study. At 0.5 m depth, lead and copper concentrations were low and no cadmium was found above the detection limit. Grain-size distribution was as follows: 30% of particles had a diameter d>20 mm, 45% of the particles corresponded to gravel (20 mm>d>2 mm), 20% to sand (2 mm>d>0.2 mm) and 5% to fine sand (0.2 mm>d>0.08 mm; Barraud et al. 2002). The main characteristics of this size distribution were its discontinuity and the small proportion of particles from 1 to 10 mm while the quantity of particles <2 μm was insignificant (Fig. 3).

Table 1 Main characteristics of the control soil at 0.5 m (according to Barraud et al. 2002)

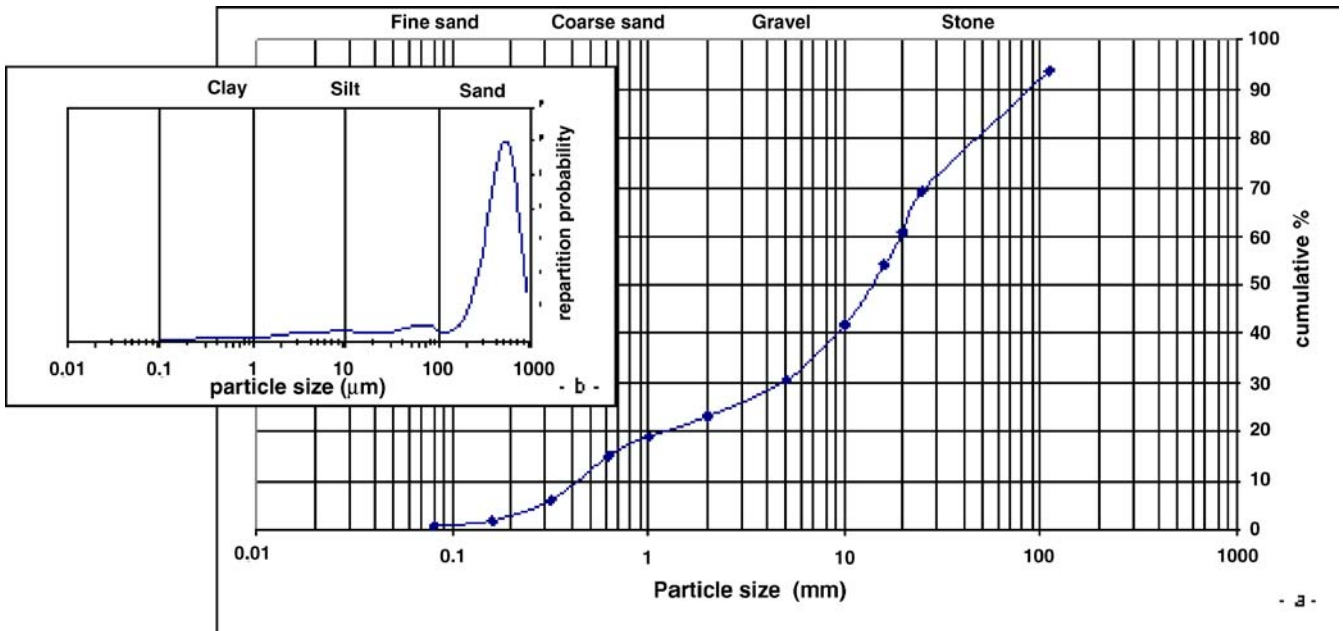| Main characteristics	Value	Unit of measurement
pH (1:10)	8.2	
Organic matter content	1.75	%
Carbonates	22.7	%
Total Pb	7	μg g^{-1} of dry soil
Total Cd	<0.5	μg g^{-1} of dry soil
Total Cu	10	μg g^{-1} of dry soil

Fig. 3 **a** Particle-size distribution of the total control soil, **b** particle size distribution of the part less than 1 mm

Physicochemical profiles

At Pt1, Pb and Cd concentrations were high to a depth of 1.5 m (Fig. 4) and significantly higher than those in the control soil (Table 1). Below 1.5 m, the concentrations of these elements were close to those in the control. The pH varied similarly, increasing steadily to a depth of 1.5 m and then stabilising at a value close to that of the control soil (pH 8.2). The quantity of combustible organic matter also showed a similar pattern. The provision of suspended matter, therefore, resulted in parallel increases in the concentrations of organic matter and total metals. Furthermore, the silts correlated very closely with the organic matter and metals.

A similar phenomenon was observed at Pt2 (Fig. 5), but for a lower depth, about 0.50 m (the same surface concentrations as Pt1). However, from 2.40–3 m, metal concentrations increased, pH decreased while organic matter content increased slightly and the silts correlated well with this parameter. This increase may be linked either to the presence of a particularly reactive horizon that captures the metals, or to greater lateral input due to the presence of preferential run-off channels.

There seemed to be less influence at Pt3 (Fig. 6). The soil at Pt3 was of similar quality to that of the control soil and only pH, silt distribution and organic matter content differed in the first few centimetres.
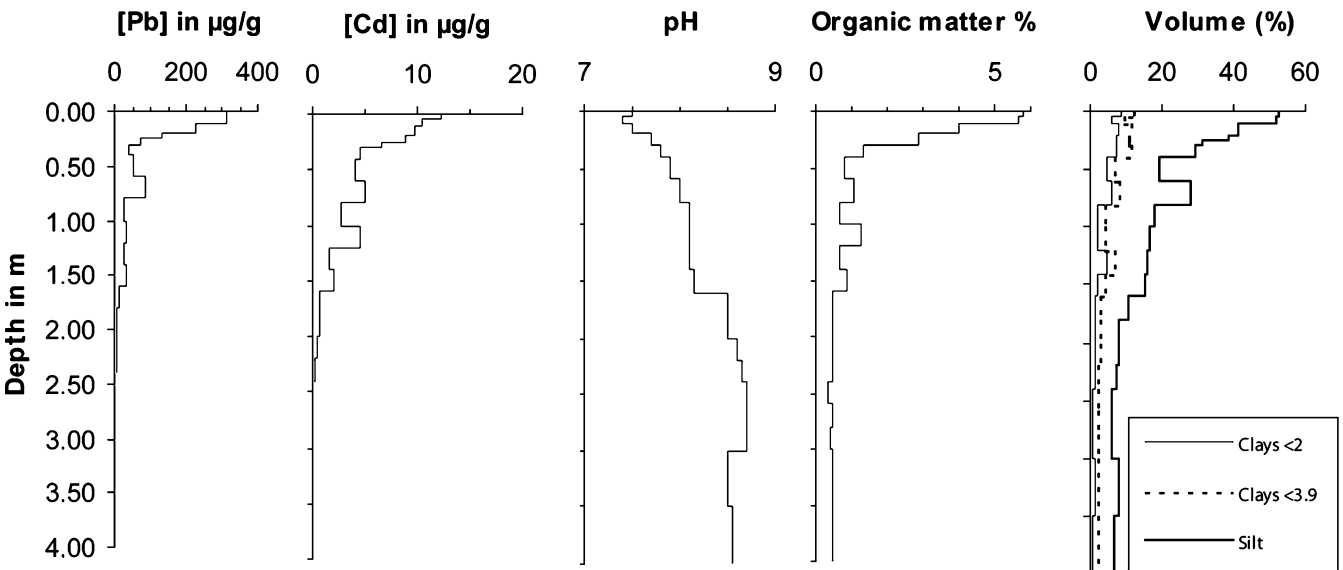

Fig. 4 Concentrations of heavy metals, pH, clays, silts and organic matter content along a vertical profile at Pt1
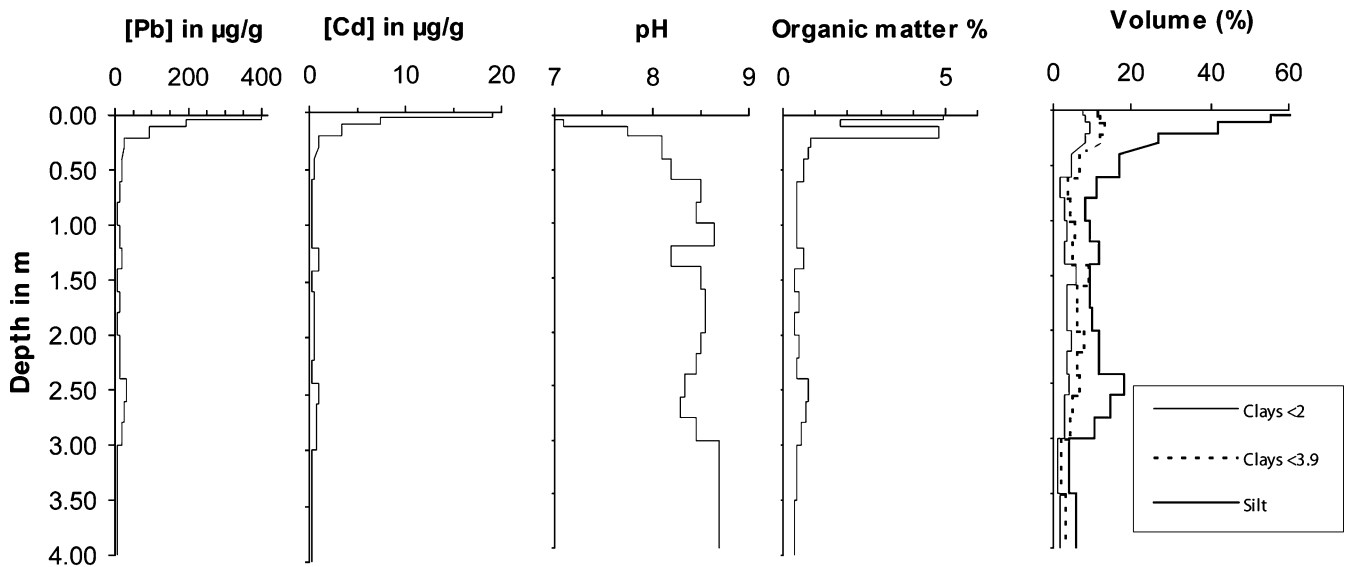
Fig. 5 Concentrations of heavy metals, pH, clays, silts and organic matter content along a vertical profile at Pt2

The overall difference in quality between these three points shows that the infiltration basin does not function uniformly across its entire surface. Indeed, pollutant concentrations are higher close to the site of stormwater entry (Pt1), because this sector is the most heavily used. Concentrations decreased markedly (Pt2) as a function of distance from this site until they became almost identical to those in the control soils (Pt3).

Profiles of the bacterial population

The bacterial population at the three sample sites was estimated to be from 10^4 to 10^7 CFU/g dry wt. (Fig. 7). Similar values have been reported for agricultural soils, in which the same techniques demonstrated the presence of 10^6–10^8 CFU/g dry soil (Metting 1992). Another study on soil from different sites, both contaminated and non-contaminated, gave from 10^5 to 10^7 CFU/g dry wt. of culturable bacteria (on different media as used here). A similar trend was observed compared with the physico-chemical parameters, bacterial population decreasing as a function of depth at the three sample sites. There was a two-log difference in the number of bacteria on the surface and at depth. However, it was noted that there was an increase in the bacterial population (clearly visible at Pt1) from 1.40 to 1.60 m depth. The control sample showed a bacterial population of 1.9×10^5 CFU/g dry wt. Surface samples were quite different from the control. A similar difference was observed between values estimated in Pt1 at 1.40 m depth and the control.
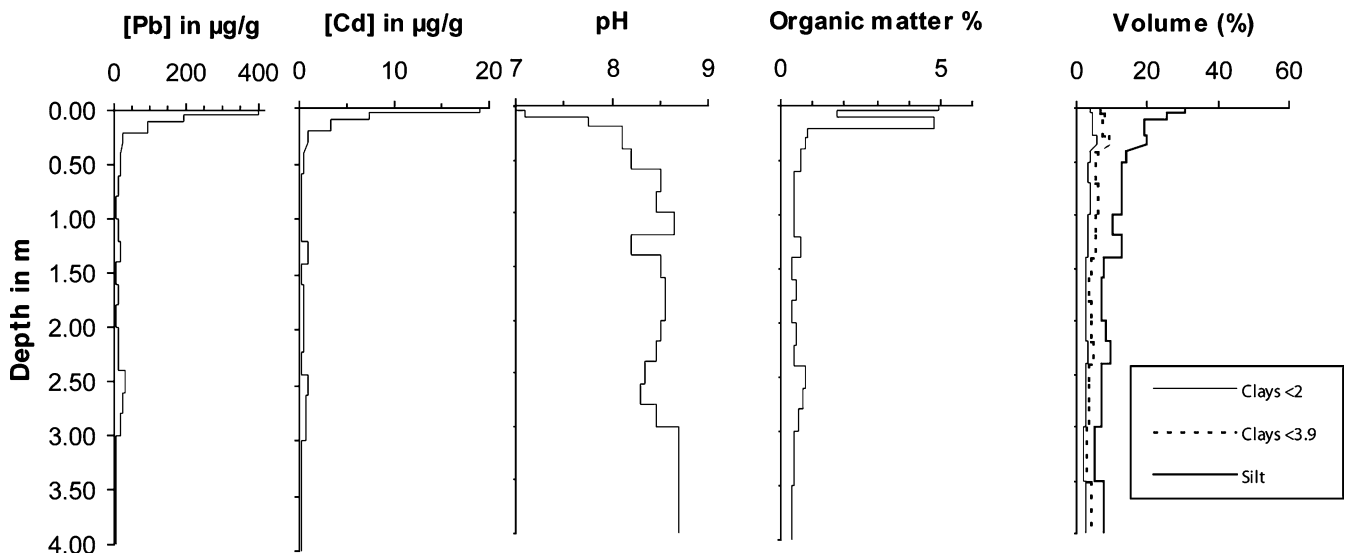

Fig. 6 Concentrations of heavy metals, pH, clays, silts and organic matter content along a vertical profile at Pt3
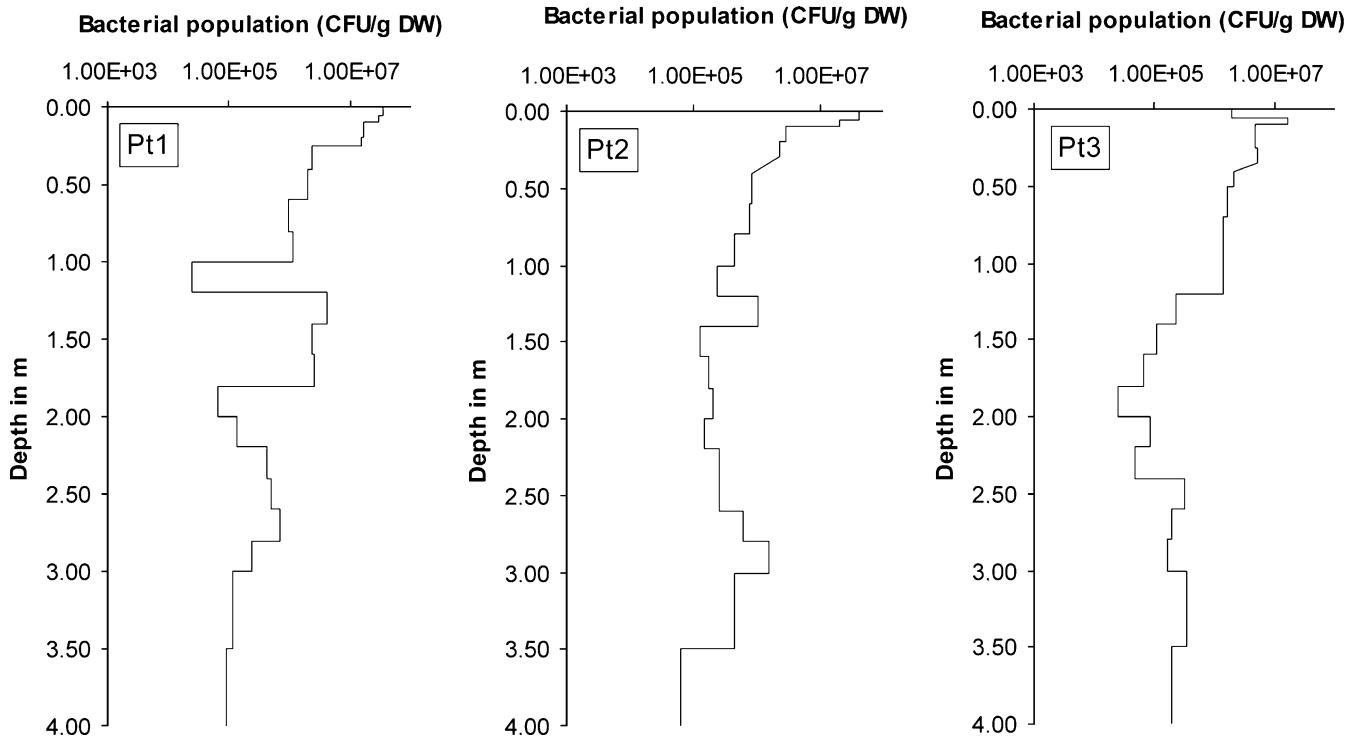
Fig. 7 Density of viable heterotrophic bacteria along vertical profiles at points *Pt1*, *Pt2* and *Pt3* (CFU/g dry wt.: colony forming units by gram dry wt.)
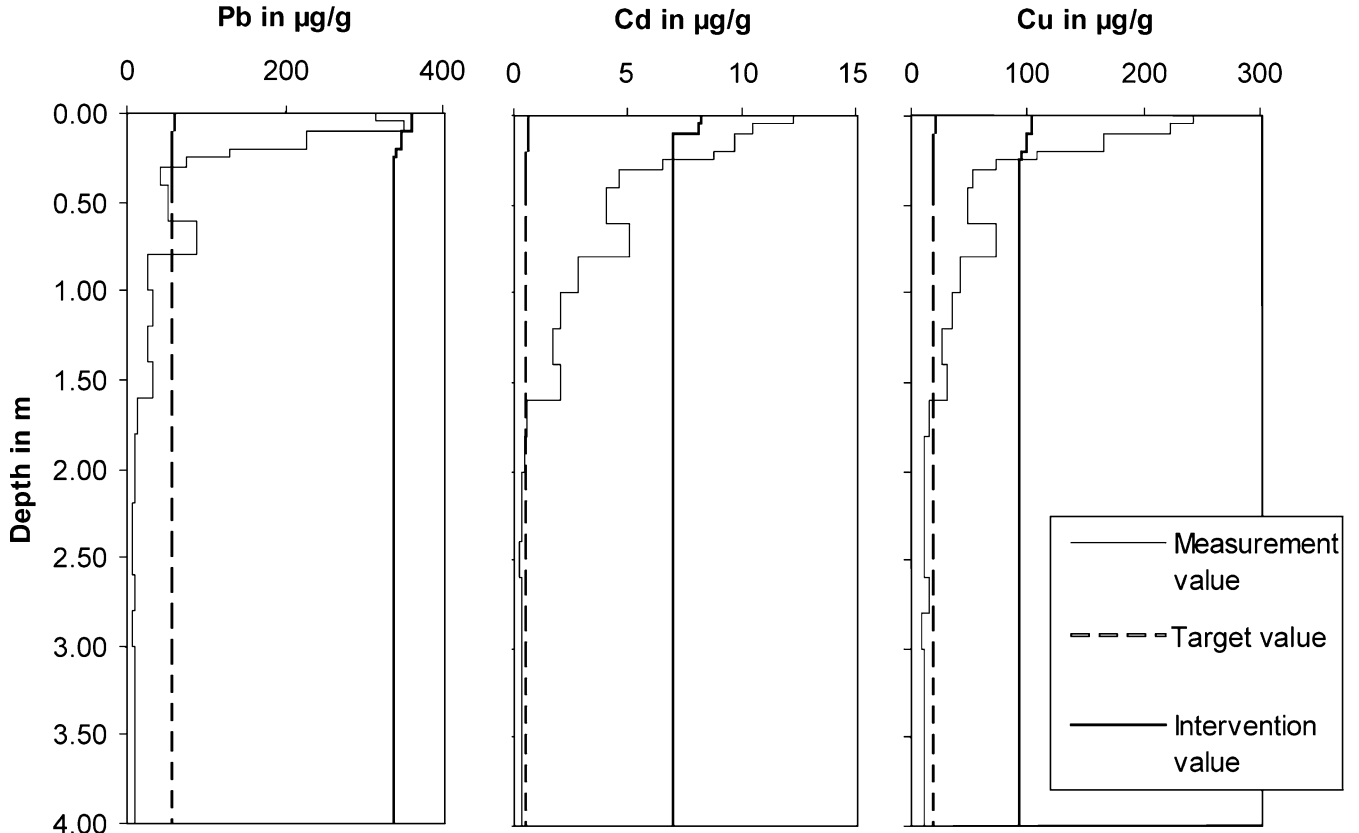

Fig. 8 Concentration of heavy metals with the target and intervention corrected values at sampling point Pt1
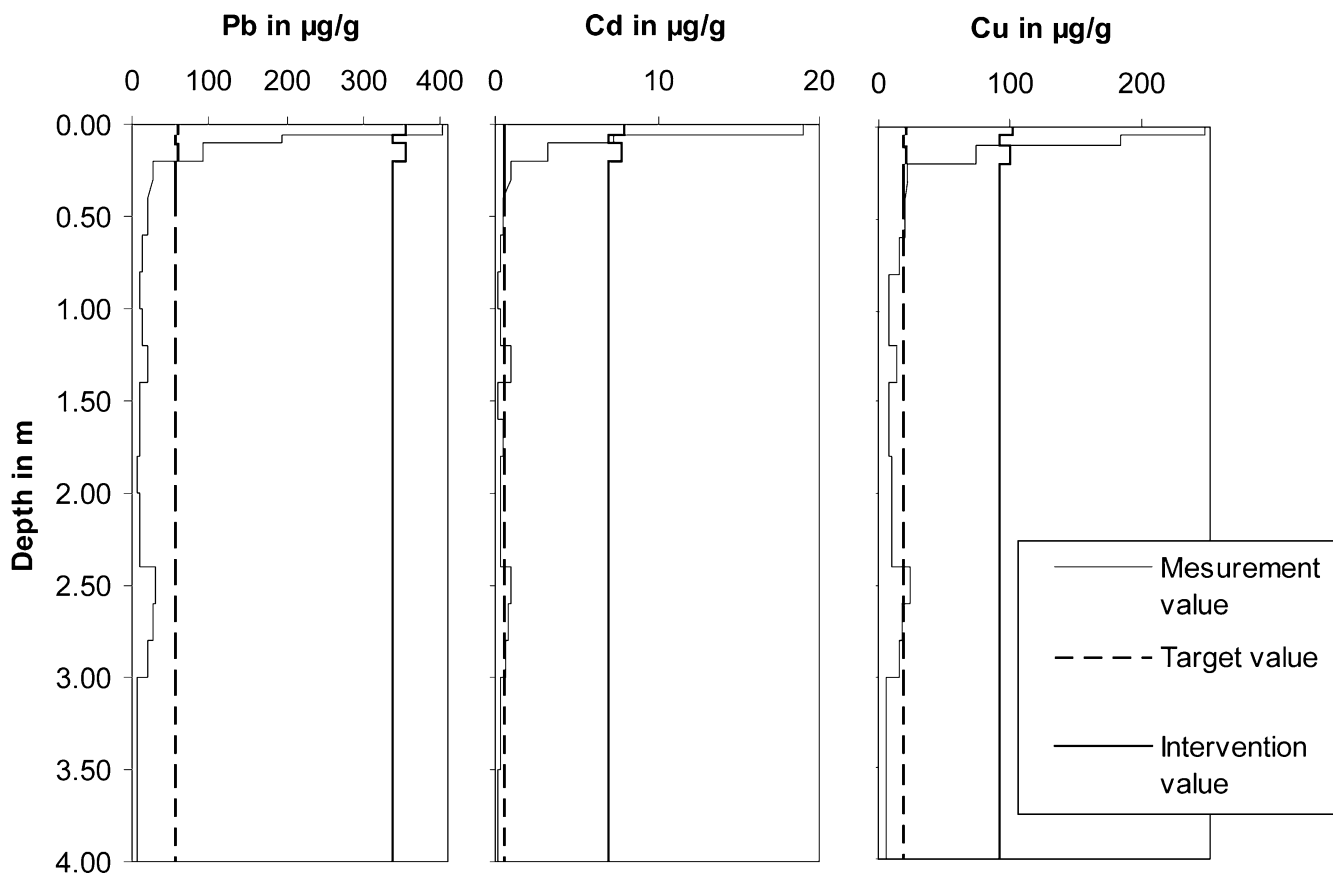
Fig. 9 Concentration of heavy metals with the target and intervention corrected values at sampling point Pt2

Discussion and conclusions

After 20 years infiltration, the concentrations of metals in the upper layers of the basin were many times higher than in the control soils. This could be explained by the presence of carbonates that can retain metallic cations through cation exchange reactions or by precipitation with dissolved carbonates (Bourg and Kedziorek 1999). Furthermore, the silt particles were correlated with the metals and organic matter. One means of transporting pollutants in urban water is in particulate form (Chebbo 1992). Retention could also be explained by the physical filtration of suspended solids present in the stormwater and the bacteria and organic matter contribute as aggregates to this quantity of silt. Thus, the contribution by the network and the development of organisms in situ may contribute significantly to the development of a biofilm and clogging of the basin. The supply of organic matter and microbial activity may contribute to soil acidification to a depth of 1.50 m (Paul and Clark 1996). The reactive hydroxyl and carboxyl sites in the organic matter contribute to the release of H^+ in the medium (Sposito 1989). These results show the high reactivity of this soil with heavy metals. This capacity of retention helps to protect the groundwater. The increase of heavy metal and organic content at point Pt2 from 2.40 to 3.00 m depth (Fig. 3) might be explained by preferential flows along seepage pathways. Despite the strong pollutant retention capacity of this soil, the presence of the accumulation zone shows that some of the pollutants can migrate through the unsaturated zone to the groundwater.

In order to evaluate pollution levels, Dutch standards (NMHSPE 2000) for the evaluation of polluted soils and the French guide for the management of the polluted sites (Ministère de l'Environnement 1997) were used. According to these references, the infiltration of stormwater running off an industrial watershed leads to significant pollution of the surface soils of infiltration basins. By taking into account the correcting factors defined in Eq. (1), which uses the hypothesis of a clay content value of 2% (default value), the lead, cadmium and copper contents measured in the first centimetres of profiles Pt1 and Pt2 were higher than the intervention value (Figs. 8 and 9). The evaluation concerning Pt3 is not shown because the heavy metal content was close to that of the control soil (Fig. 6).

Table 2 Substance dependent constants (A,B,C) for Pb, Cu, Cd and target values (SWsb) and soil remediation intervention values (IWsb). Values for soil have been expressed as concentration in a standard soil (10% organic matter and 25% clay; NMHSPE 2000)

Substance	A	B	C	SW_{sb}	IW_{sb}
Lead	50	1	1	85 µg g^{-1}	530 µg g^{-1}
Copper	15	0.6	0.6	36 µg g^{-1}	90 µg g^{-1}
Cadmium	0.4	0.007	0.021	0.8 µg g^{-1}	12 µg g^{-1}

The intervention value is defined as:

$$(SW, IW)_b = (SW, IW)_{sb}[(A + Bx) + y)/(A + 25B + 10C)] \quad (1)$$

where $(SW, IW)_b$ corresponds to the target value or intervention value for the soil to be assessed (values of A, B, and C are given in Table 2); $(SW, IW)_{sb}$ is the target value or intervention value for the standard soil and x is clay percentage measured (grain size <2 μm) in the soil to be assessed. If this value is negligible or <2%, the default value is 2% (Ministère de l'Environnement, 1997); y is the measured percentage of organic matter in the soil to be assessed. If this value is negligible or <2%, the default value is 2% (Ministère de l'Environnement) A, B, C: substance dependent constants for metals (Table 2). The lead concentrations in profile Pt1 measured in the first 70 cm are situated between the target and the intervention values. This agrees with a recognized pollution that does not require rapid intervention. The cadmium and copper concentrations measured are higher than the intervention value in the first 70 cm for cadmium and in the first 40 cm for copper. In both cases, pollution is recognisable to a depth of 1.5 m.

Consequently, these results show that the current practice of excavating the clogged upper layer of soil in the basins (several dozen centimetres, depending on the clogging of the basin) should be reviewed. Firstly, the excavated soil can be considered as a polluted soil and must be managed appropriately. Secondly, the thickness of the layer of the infiltration soil basin subject to pollution by stormwater can attain 1.5 m, making it necessary to treat very large volumes of soil to prevent the risk of polluting the groundwater.

Within the framework of the studies carried out by OTHU, the unsaturated zone of the infiltration basin will now be used as an experimental observation site. The key aim of this project is to measure the effects of urban runoff water on the quality of the subsoil and the water table in situ, as a function of the physical characteristics of the infiltration "field" and the type of input (volume of water, chemical composition, mass fluxes, etc.), by identifying the mechanisms of pollutant transformation and observing the interactions of these mechanisms with the solid matrix.

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