Spatial analysis and temporal evolution of pollutants in a stormwater infiltration basin – estimation of the mass of trapped pollutants

Répartition spatio-temporelle de la pollution dans les bassins d'infiltration – estimation de la masse de polluants piégés

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RESUME

Les systèmes d'infiltration pour la gestion des eaux pluviales sont largement utilisés en milieu urbain. Cependant leur réelle durabilité sur le long terme doit encore être étudié. L'un des risques majeurs liés à leur utilisation est une possible pollution de la nappe phréatique et des concentrations élevées en polluants à leur surface. Cet article étudie plus particulièrement les concentrations en métaux lourds rencontrées dans un bassin d'infiltration. Deux campagnes de mesures ont été effectuées à 10 mois d'intervalle et 200 échantillons ont été collectés et analysés pour le zinc, le plomb et le cuivre. Les analyses montrent des concentrations élevées à la surface de l'ouvrage, une accumulation des polluants entre les deux campagnes, notamment dans les parties les plus sollicitées hydrauliquement et des concentrations plus élevées dans la partie la plus ancienne de l'ouvrage. Enfin la masse totale de métaux lourds piégés dans les premiers centimètres du bassin est reconstituée.

ABSTRACT

Infiltration systems are widely used to manage stormwater in urban areas but questions about their long term sustainability need to be addressed. The possible pollution of the groundwater and the concentration of pollutant trapped in the soil are of major interest. This article focuses on the concentration of heavy metals found in the top layer of an infiltration basin. Two sampling campaigns had been undertaken 10 months apart and 200 samples were collected and analysed for lead (Pb), zinc (Zn) and copper (Cu). High concentrations are measured at the surface of the system; pollutant build up over time is clearly evident especially in the lower lying areas, as well as higher concentration in the oldest part of the system. Finally total mass of heavy metals trapped in the top layer of the systems are evaluated.

KEY WORDS

Efficiency, Heavy metals, Infiltration basin, Statistical analysis.

1 INTRODUCTION

Infiltration techniques are now widely used to manage stormwater in residential and industrial areas. These techniques are used and recognized for their many advantages, such as decreasing stormwater peak flows, reducing pollution of surface waters, recharging groundwater and enhancing urban landscape when infiltration systems are designed as playgrounds or parks for example (Dechesne *et al.* 2004 (a)). However they are still suspected to be unsustainable in the long term. Over time, two major problems are encountered: clogging of the system (Bouwer, 2002) and an eventual pollution of soil and groundwater (Dechesne *et al.*, 2004 (b)). It has been shown that the top soil layer is an effective pollutant barrier (Hutter *et al.*, 1998; Mikkelsen *et al.* 1994), but pollutant migration is still an issue. In order to prevent a possible effect of stormwater infiltration on the groundwater it is necessary to evaluate its ability to trap contaminants and thus its pollutant removal efficiency (Barraud *et al.,* 2005). Calculation of the efficiency of the system can be made by doing mass balances on conservative pollutants such as heavy metals. It is necessary to first evaluate the mass of pollutant brought to the system and the mass of pollutant trapped in the soil.

The main goal of the research presented in the paper is to study the spatial distribution of pollution in the top layer of an infiltration basin. It has two main objectives: i) the characterization of the quantity of pollutant trapped in the soil and ii) the possible impact of stormwater infiltration by assessing the pollutant removal efficiency of the system. The specificity of this study is to work on an operating system. An infiltration basin has been thus selected in the Greater Lyons Area (France) and is continuously monitored for various parameters (water flow, water depth in the different parts of the basin, pH, conductivity, turbidity and temperature with a two minute time step) in order to evaluate the quality of the inflow. The quantity of pollutant trapped in the soil has been assessed by two soil sampling campaigns, one in April 2005 and one in February 2006. Samples were then analysed for the main heavy metals found in stormwater runoff. Based on these data, a first qualitative analysis is made to evaluate the possible relations between contaminant spatial repartition, hydraulic behaviour, and history of the basin. Accumulation of pollutants in the top layer of the basin over time is evaluated and the mass of heavy metals is assessed.

2 METHODOLOGY

2.1 Site and environment

Description of the site is given in (Le Coustumer and Barraud, 2006).The catchment drained by the infiltration basin studied is an industrial area, located in Chassieu in the eastern suburbs of Lyons, France. It has a surface of 185 ha, with a flat topography (mean slope of 4 ‰) and an imperviousness of about 75 %. The catchment is drained by a separate stormwater system and its outlet is the basin structure called Django Reinhardt. The basin has been used for over twenty years and the design had been modified through its life. The latest configuration is presented in Figure 1. It comprises two compartments: i) a storage and settling basin and ii) an infiltration basin, of about 7000 m². The volumes of the two compartments are respectively 32000 m^3 and 61000 m^3. The runoff water flows successively through: i) the storage and settling basin, ii) a flow control device, iii) an outlet pipe equipped with a non return valve and iv) the infiltration basin.

The basin has been scrapped in December 2004 and sediments removed except in its south east corner (referred as the ‘Old part’, black area in Figure 1) where a thick

layer of sediments has been left. The lowest part of the infiltration basin and then the part that will be the more often flooded is also delimitated (shaded area in Figure 1).

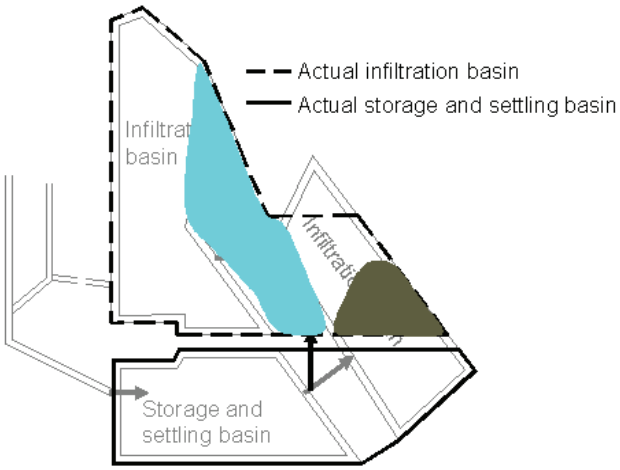

Figure 1 : View of the previous and actual configuration of the basin with the oldest and the lowest parts highlighted

The Django Reinhardt basin is located over quaternary fluvial and glacial deposits. The aquifer material, laid on an impervious substratum of crystalline formations (tertiary mollassic sands), has an approximate local thickness of 30-35 m and a permeability of about $7\text{-}9 \cdot 10^{-3}$ m/s. It is composed mainly of coarse material: 30 % of pebbles (diameter d > 20 mm), 45 % of gravels (20 mm > d > 2 mm), 20 % of coarse sand (2 mm > d > 0.2 mm) and 5 % of fine sand (0.20 mm > d > 0.08 mm) (Barraud *et al.,* 2002). Samples taken every meter had shown that there is a good homogeneity of the soil at the metric scale as deep as 26 m. The groundwater level is deep, about 13 m below the infiltration system.

2.2 Methods

- Sampling campaigns

The first sampling campaign was undertaken in April 2005 and the second one, 10 months later in February 2006. During the first and second campaign, 103 and 92 samples were respectively collected, based on a 10 by 10 meters grid. Samples were taken in the top 5 centimetres of the infiltration systems. All the samples were then oven dried at 105°C and sieved at 2 mm before analysis. In order to evaluate the spatial heterogeneity of the pollution and the mass of pollutant trapped in the soil an innovative and non-destructive method was used. For three major metals known to be found in stormwater (Zn, Pb, Cu), an X-ray fluorescence (XRF) portable analyser Niton XLt 700 Series Instrument (Clozel, 2006) was used to determine the concentration of pollutant.

- Pollutant mass assessment

The mass of pollutant trapped in the infiltration basin is estimated in order to do a balance of the accumulated pollution during its operation. To estimate the mass of pollutant trapped in the system, a discrete method is used. First, a mesh of the basin surface is created and then, each cell is assigned a pollutant concentration. The mass of pollutant m_i for each cell is calculated by :

$$m_i = \rho.s_i(f_1.e_{1i}.c_{1i} + f_2.e_{2i}.c_{2i}) \quad (1)$$

m_i: mass of the pollutant in cell i, ρ: soil density (kg/m^3), f_1: fine soil fraction percentage in the top layer, e_{1i}: soil layer thickness, c_{1i}: pollutant concentration in the top layer in cell i, f_2: fine soil fraction percentage in the deep layers, e_{2i}: soil layer thickness, c_{2i}: pollutant concentration in the deep layer in cell i.

The total pollutant mass is calculated by summing the masses in each cell. In the present work the masses trapped are calculated only in the top soil layer (5 cm deep). The cells concentrations are obtained by kriging of the concentrations in the soil sampled.

3 SPATIAL AND TEMPORAL EVOLUTION OF HEAVY METALS CONCENTRATION

3.1 Concentration of pollutants

- Results

Average concentration, median and coefficient of variation (Cv) of the concentration for each campaign are presented in Table 1; as well as the background concentration based on samples taken on the side of the basin (reference area) by (Winiarski *et al.*, 2001). When comparing the median values to the background concentration, we found that concentration of Zn are between 11 and 23 times higher, concentration of Cu are between 17 and 32 times higher and concentration of Pb are between 6 and 17 times higher. These high concentrations can be explained by the fact that heavy metals are highly particulate-bound (Chebbo 1992; Marsalek *et al.*, 1997) and are then trapped at the surface of the system. The heterogeneity is also quite important at the surface of the basin (see below)

Comparing the results with typical heavy metal concentrations found in infiltration systems (Ruban *et al*., 2005; Barraud *et al*., 2005; Lind *et al.*, 1995 for example), the concentrations are in the habitual range values found in the top layer of infiltration systems.

Date of sampling		Zn	Cu	Pb
Background concentration (Winiarski et al. 2001)		46	6	6
April 2005	Average / *Median*	735 / *505*	137 / *103*	473 / *33*
(N=102)	Cv (%)	90	69	77
Feb. 2006	Average / *Median*	1046 / *1045*	179 / *191*	146 / *104*
(N=92)	Cv (%)	55	52	100

Table 1 : Average concentration for 3 heavy metals (mg/kg of dry matter)

- Correlation between pollutants

Results from the first campaign show a good correlation between the different metals (Table 2) but unfortunately the correlation is much weaker for the second campaign. It seems that the different metals have not the same behaviour. Moreover, there is no correlation between the pollution positions from one campaign to the other.

	April 2005			February 2006			1st and 2nd Campaigns		
	Pb/Zn	Pb/Cu	Zn/Cu	Pb/Zn	Pb/Cu	Zn/Cu	Cu/Cu	Pb/Pb	Zn/Zn
r^2	0.88	0.90	0.73	0.09	0.36	0.65	0.14	1.5×10^{-4}	0.35

Table 2 : Coefficient of correlation between pollutants for the first and the second campaign

- Analysis of the spatial heterogeneity and pollution build up

Pollution evolution over the time gives the following results.

For copper (Table 3 and Figure 2): In 2005, concentrations are rather constant in the entire basin (Cv = 35%) except in the oldest part of the system where no scrapping of sediment deposits was done and where concentrations are more than twice higher. In 2006, concentration in the oldest part stays relatively constant. However pollution build-up is more particularly visible in the lowest part of the system. T-test conducted on log_{10}-transformed data show that Cu concentration are statistically higher ($p<0.001$) in 2006 that in 2005.

	2005	2006
Old part of the system	286 ±101 (35%)	216±107 (50%)
Rest of the system	116±72 (62%)	151±102 (67%)

Table 3 : Average concentration (mg/kg), standard deviation (mg/kg) and Cv (%) for Cu in different part of the system for both campaigns

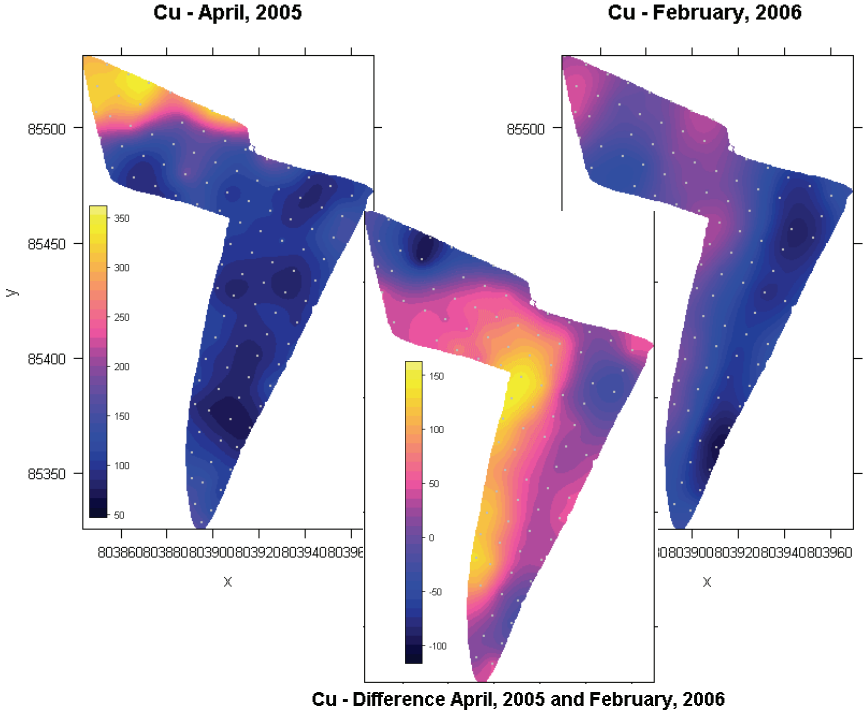

Figure 2 – Spatial distribution of copper concentrations in April 2005 (left), February 2006 (right), spatial distribution of differences between 2005 and 2006 (middle) - (mg/kg of dry matter)

For Lead (Table 4 and Figure 3): In 2005, concentrations are rather evenly distributed within the system, almost 3 times higher in the oldest part of the system. 10 months later the distribution of the pollution is clearly shown: the entrance of the system and the lowest point are much more polluted than the rest of the system. The concentration in the oldest part is slightly lower than in 2005. T-test conducted on

log_{10}-transformed data show that Pb concentration are statistically higher ($p<0.001$) in 2006 that in 2005.

	2005	2006
Old part of the system	110±37 (34%)	108±45 (42%)
Rest of the system	38±26 (68%)	133±154 (116%)

Table 4 : Average concentration (mg/kg), standard deviation (mg/kg) and Cv (%) for Pb in different part of the system for both campaigns

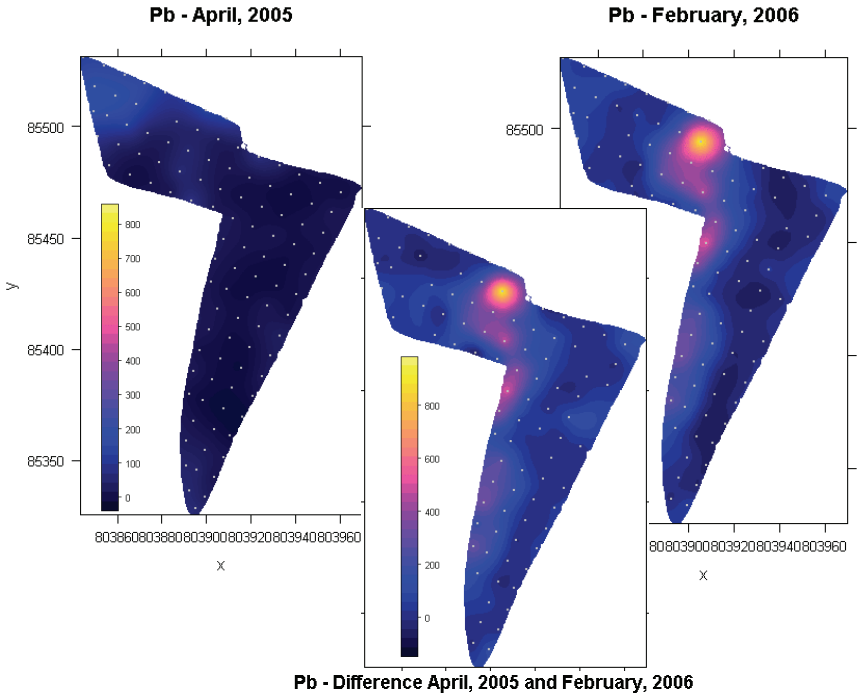

Figure 3 – Spatial distribution of lead concentrations in April 2005 (left), February 2006 (right), spatial distribution of differences between 2005 and 2006 (middle) - (mg/kg of dry matter)

For **zinc** (Table 5 and Figure 4): In 2005, higher concentrations are found in the oldest part of the system when concentrations are pretty constant in the rest of the system. The pollutants build up is also clearly shown but the distribution of pollutants with surface is not as obvious as for the other pollutants. Zinc seems to be the most mobile metal in space.

	2005	2006
Old part of the system	1986±898 (45%)	1869±754 (40%)
Rest of the system	550±354 (64%)	928±426 (46%)

Table 5 : Average concentration (mg/kg), standard deviation (mg/kg) and Cv (%) for Zn in different part of the system for both campaigns

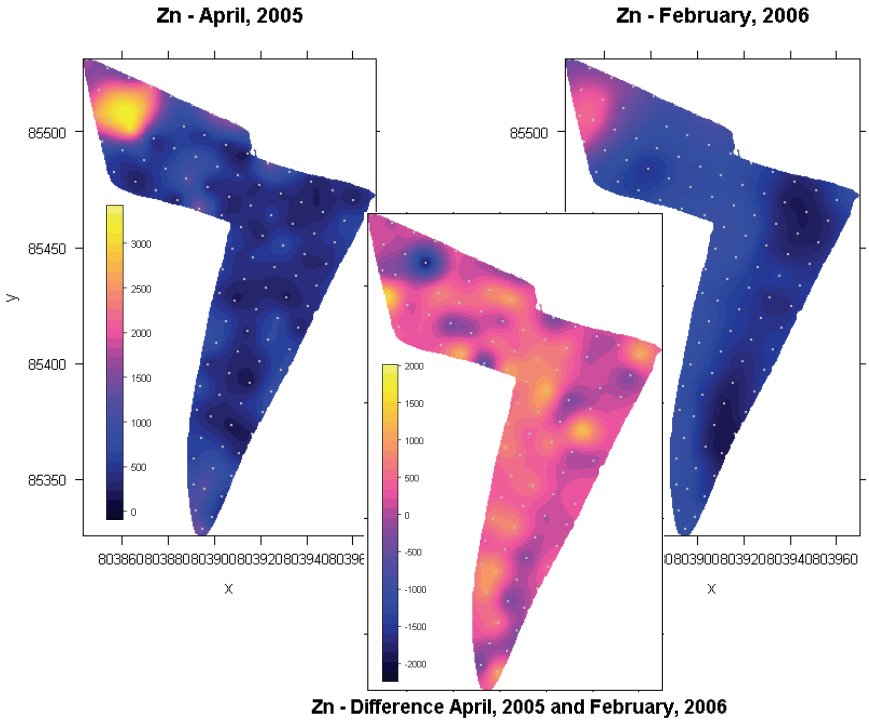

Figure 4 – Spatial distribution of zinc concentrations in April 2005 (left), February 2006 (right), spatial distribution of differences between 2005 and 2006 (middle) - (mg/kg of dry matter)

3.2 Assessment of pollutant mass trapped in the soil

The total mass trapped by the topsoil was calculated by equation 1, for each considered pollutant. The analysis considers a soil thickness of 5 cm.

The uncertainties of the mass estimation concern the pollution local variability, the uncertainties in the soil density, in the fine soil fraction percentage and in the thickness. The mass estimation and their uncertainties are shown in Table 6.

Trapped pollutants mass	Cu (kg)	Pb (kg)	Zn (kg)
April 2005	34± 15	11 ± 6	179± 58
February 2006	46 ± 21	39 ± 21	271± 88
Mass trapped by topsoil	12 ± 6	28 ± 15	91± 30

Table 6 : Evaluation of the mass of heavy metals in the top layer of the system

4 CONCLUSION

The two sampling campaigns undertaken show that the top layer of the infiltration system is highly polluted by heavy metals. The spatial heterogeneity is important and unfortunately, all the pollutants do not behave in the same way. Zinc is the most mobile in space.

The oldest area of the basin is often more polluted than the rest of the system. It highlights the fact that historical accumulation can be important and that soil pollution

should be accounted for the rehabilitation of such systems.

The zones that are more frequently flooded have higher concentration of heavy metals after 10 months and for all the metals. This point is interesting because it can be used for maintenance. Removing the sediments from the entire surface of the basin is quite expensive therefore it is rarely undertaken. But removing the sediments from a smaller part (about 25% of the surface in our case) which is the most polluted could be a good practice. The area to be frequently scrapped could be easily defined according to hydraulic considerations. Pollution build-up over a 10 month period is also demonstrated. The quantity of samples collected allows us to calculate the mass of each heavy metal with its uncertainty. It is the first step in order to do mass balances. Further work will include another sampling campaign that will be undertaken in order to confirm the pollutant build-up and evaluate the accumulation rate of pollutant over time. Heavy metals concentration in the inflow still needs to be assessed in order to do mass balance and evaluate the pollutant removal efficiency of such systems.

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