Characterization & main factors affecting clogging evolution of the bottom of stormwater infiltration systems

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ABSTRACT
The paper presents recent studies on spatial and temporal characterization of the clogging of a large infiltration system and main factors affecting its evolution. Thickness, organic content, density, particle size distribution, biomass and saturated hydraulic conductivity were then evaluated during 10 campaigns from September 2009 to February 2011. The results show that the sediment accumulation over the bottom is heterogeneous and more important in areas often flooded and in particular in the lowest part of the basin. In this part, the grain size is also the finest, the biomass and porosity the highest, the dry bulk density the lowest giving to the soil a peaty aspect. This part is also the more clogged. The heterogeneity of the characteristics of the bottom in time and space is high with no clear tendencies except for organic matter which has doubled in 1.5 years. In general, all the characteristics are in the same range than those observed on similar systems. The results also show a good spatial logarithmic regression in particular with porosity, organic matter, biomass content, and grain size D10 but an insufficient correlation to explain the evolution of clogging both in space and time.

KEYWORDS
In situ observation, stormwater, infiltration, clogging.

INTRODUCTION
Infiltration basins are frequently used for stormwater drainage. However their longevity is not certain and at the present time, long-term evolution is neither well understood nor controlled. One of a major problem encountered is clogging that compromises the hydraulic capacity of the basin and tends to increase risk of flooding.

Even thought, the clogging is attested and the overall phenomena well known (mainly the combination of physical and biological processes), the evolution over time, the composition and the dominant factors of its development have to be better analyzed, especially on real and large infiltration systems. For that purpose, long time series and observations of clogging and variables which are supposed to play a role have to be studied.

In this context, a stormwater infiltration basin representative of the majority of infiltration systems of Rhone Region (France) has been monitored for more than 6 years.

Previous works have shown that the major part of the clogging of large systems mainly occurred at the bottom (Gonzalez-Merchan et al., 2011a).

A second step was then explored and aimed at (i) studying the main characteristics of the clogged layer in space and time in terms of thickness, organic content, density, particle size distribution biomass, and saturated hydraulic conductivity and (ii) examining the potential correlation between clogging and these characteristics. This is the objective of the paper.
MATERIALS AND METHODS

Site description
The infiltration basin is situated at Chassieu, in the eastern suburbs of Lyons, France. The infiltration basin receives stormwater from an urban and industrialized watershed of 185 ha, with a rather flat topography (mean slope 0.4%) and an imperviousness coefficient of about 75%. The total area and the capacity of the basin is about 8,000 m² and 61,000 m³.

Before entering the infiltration basin, stormwater flows successively through a detention-settling compartment whose area and capacity are about 1 ha and 32,000 m³ respectively and through a flow control device limited to 350 L/s.

In the infiltration compartment, stormwater infiltrates through a fluvioglacial deposit substratum and flows into groundwater whose table is situated 13 m below the bottom of the basin. The basin has been functioning for more than thirty years. It has been rehabilitated in 2002 and totally scraped in April 2004 (sediments and the topsoil completely removed). At last from the end of 2006 to the beginning of 2007, the bare bottom of the basin has been progressively overgrown with spontaneous vegetation.

The site is monitored continuously in terms water inflows, turbidity allowing the estimation of TSS and COD concentrations with a 2 min time step as indicated in (Bertrand-Krajewski, 2004). Climatic factors (air, water temperature, solar energy & rainfall) are also monitored.

The basin bottom can be divided into different areas: (i) dry zones (which are more often dry) and where average soil humidity varies between 10 to 20 %, (ii) wet zones where the soil humidity ranges from 30 to 60 % and (iii) submerged zones which present a quasi-permanent ponding and where the soil is saturated. The locations of these areas can be found in Figure 1.

The complete description of the site and the monitoring system are given in Barraud et al. (2002) and Bertrand-Krajewski et al. (2008).

Methodology
The physical and biological parameters were measured during ten field campaigns (from September 2009 to February 2011) except for dry bulk density (measured twice: once in July 2010 and once in March 2011) and particle density (once in March 2011), both known to evolve slowly on such a short period (1.5 years).

All the parameters were measured in 8 points representative of the different zones of the basin (See Figure 1). The thickness was also measured more precisely during two campaigns (in May 2008 and April 2010) in about 100 points according to a regular 10 by 10 meter grid.

For each measure three replicates were done.

Physical characteristics
The Sediment thickness was determined as the difference between basin topsoil made of sediments and the fluvioglacial soil, the visual difference between these two layers being very contrasted and therefore very easy to distinguish.
The dry bulk density was evaluated through two different tests according to the grain size distribution. If the maximum grain size was less than 5 cm, the dry bulk density was measured according to the NF P 94-061-4 French standards (AFNOR, 1996), else with a calibrated cylinder (ISO NF X31-501, 1992).

The particle density was assessed with the NF P94-054 standards (AFNOR, 1991) and the soil porosity ($\varepsilon$) with the dry bulk density ($\rho_d$) and particle density ($\rho_s$) according to the following equation: $\varepsilon = 1 - \rho_d / \rho_s$.

Grain size distribution analysis was performed by Laser Particle Sizer (Malvern Mastersizer 2000 G). Due to the matter aggregation, the samples were submitted to ultrasounds during ten minutes before analysis. Grain size distribution (D10, D50, D90) was then evaluated.

The in situ saturated hydraulic conductivity has been evaluated using a single-ring test. The interpretation of the test was realized with the BEST method (Beerkan Estimation of Soil Transfer method) described in (Braud et al., 2005) and (Lassabatere et al., 2006). The results obtained for the saturated hydraulic conductivity were then corrected according to water temperature and normalized at 20°C.

Biological characteristics

Organic matter content were estimated by weighing soil samples before and after heating them at 450°C, according to standards (XP P94-047, 1998).

Biomass content (soil microbial biomass) was quantified on the basis of Ninhydrin-reactive N determined by the fumigation extraction method (Amato and Ladd, 1988). Sediment samples were fumigated with ethanol-free chloroform during 10 days. Extraction with 2M KCl was executed before and after fumigation. The dead organisms react with Ninhydrin (proteolysis process) and are then determined by colorimetry. For the estimation of the biomass-C, Ninhydrin-N results were multiplied by a conversion factor of 21 as obtained in the calibration experiment of Joergensen et al. (1996).

Correlation between the saturated hydraulic conductivity and physical & biological factors

In order to explain the evolution of clogging in space and time, correlation studies were performed. Considering each point and each campaign, a linear correlation was tested between the saturated hydraulic conductivity ($K_s$) and the different parameters supposed to play a role in the clogging process: organic matter ($OM$), biomass content ($BIO$), grain size ($D10$, $D50$ and $D90$), porosity ($\varepsilon$), sediment thickness ($e$), dry bulk ($\rho_d$) and particle density ($\rho_s$), solar energy accumulated during 3 and 7 days before the measure ($Sol-Ene3$, $Sol-Ene7$). A second correlation study was carried out with log-transformed (natural logarithm) variables. Stepwise regression was used to determine whether there was any significant relationship between the predictors and the dependent variable.

RESULTS AND DISCUSSION

Characterization of the clogged layer

Dry bulk density and porosity

The results are summarized in Table 1. Considering the soil type and according to the dry bulk density, the surface characteristics can be assumed as heterogeneous. The parts frequently submerged (points 2, 4, 6) show a peaty soil type, with the highest range of
porosity (between 0.42 to 0.73 m$^3$/m$^3$), high sediment thickness (from 7.5 cm to 14 cm) and low dry bulk density (between 630 to 765 kg/m$^3$).

In the parts 1, 3, 5, 7 and 8, the quaternary fluvial soil is still present in the topsoil. Therefore, the dry bulk density is higher (between 1778 and 2250 kg/m$^3$) and the porosity much lower (from 0.17 to 0.3 m$^3$/m$^3$) compared to the other parts of the basin (results significantly different with Wilcoxon test, $p$-value = 0.0002). The sediment thickness was also thinner (1 to 3 cm) in these parts.

**Grain size**

Table 1 shows mean values obtained during all the campaigns for each point and table 2 presents the mean values for each campaign. The results show a high variability over the time, (CV $>100\%$). The variation in space are less important but can range from 8 $\%$ to 176 $\%$. This heterogeneity in time and space had already been pointed out in other studies of infiltration system like (e.g. Gilbert-Jenkins et al., 2010). However, despite high variability, point 6, situated in the wet area and in the lowest part of the basin, has the finest grain size.

<table>
<thead>
<tr>
<th>Points</th>
<th>D10 (µm)</th>
<th>D50 (µm)</th>
<th>D90 (µm)</th>
<th>Ks $\times 10^5$ (m/s)</th>
<th>$\rho_d$ (Kg/m$^3$)</th>
<th>$\rho_s$ (Kg/m$^3$)</th>
<th>$\epsilon$ (m$^3$/m$^3$)</th>
<th>e (cm)</th>
<th>Soil type*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>53.0 (&gt;100%)</td>
<td>136.96 (&gt;100%)</td>
<td>547.9 (&gt;100%)</td>
<td>5.2 ± 1.5</td>
<td>1998 ± 5</td>
<td>2618 ± 5</td>
<td>0.24 ± 0.01</td>
<td>2.5</td>
<td>Mineral</td>
</tr>
<tr>
<td>2</td>
<td>43.2 (&gt;100%)</td>
<td>155.45 (&gt;100%)</td>
<td>420.7 (&gt;100%)</td>
<td>3.9 ± 0.1</td>
<td>669 ± 96</td>
<td>2349 ± 96</td>
<td>0.72 ± 0.03</td>
<td>14</td>
<td>Peaty</td>
</tr>
<tr>
<td>3</td>
<td>85.7 (&gt;100%)</td>
<td>237.1 (&gt;100%)</td>
<td>445.4 (&gt;100%)</td>
<td>4.6 ± 1.3</td>
<td>1778 ± 109</td>
<td>2533 ± 109</td>
<td>0.30 ± 0.01</td>
<td>3</td>
<td>Mineral</td>
</tr>
<tr>
<td>4</td>
<td>43.9 (&gt;100%)</td>
<td>135.5 (&gt;100%)</td>
<td>527.1 (&gt;100%)</td>
<td>2.4 ± 1.6</td>
<td>630 ± 38</td>
<td>2335 ± 38</td>
<td>0.73 ± 0.04</td>
<td>14.5</td>
<td>Peaty</td>
</tr>
<tr>
<td>5</td>
<td>50.9 (&gt;100%)</td>
<td>184.32 (&gt;100%)</td>
<td>427.9 (&gt;100%)</td>
<td>3.6 ± 1.2</td>
<td>2100 ± 109</td>
<td>2667 ± 109</td>
<td>0.21 ± 0.04</td>
<td>2</td>
<td>Mineral</td>
</tr>
<tr>
<td>6</td>
<td>7.9 (98%)</td>
<td>74.43 (&gt;100%)</td>
<td>370.4 (&gt;100%)</td>
<td>0.79 (49%)</td>
<td>765 ± 0.01</td>
<td>2400 ± 0.01</td>
<td>0.43 ± 7.5</td>
<td>Peaty</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>81.7 (100%)</td>
<td>185.78 (&gt;100%)</td>
<td>536.7 (&gt;100%)</td>
<td>4.6 ± 0.4</td>
<td>2140 ± 99</td>
<td>2638 ± 99</td>
<td>0.19 ± 1.5</td>
<td>Mineral</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>98.5 (100%)</td>
<td>180.51 (&gt;100%)</td>
<td>402.9 (&gt;100%)</td>
<td>6.6 ± 0.01</td>
<td>2250 ± 45</td>
<td>2720 ± 45</td>
<td>0.17 ± 1</td>
<td>Mineral</td>
<td></td>
</tr>
</tbody>
</table>

* According to density as proposed in (Musy and Soutter, 1991)

**Table 2.** Mean values of particle size D10, D50, D90 for each campaign, mean of saturated hydraulic conductivity ($K_s$), with their coefficient of variation (in brackets).

<table>
<thead>
<tr>
<th>Date</th>
<th>D10 (µm)</th>
<th>D50 (µm)</th>
<th>D90 (µm)</th>
<th>$K_s \times 10^5$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep-2009</td>
<td>38 (85%)</td>
<td>196 (75%)</td>
<td>688.7 (5%)</td>
<td>5.7 ± 1.6 (71%)</td>
</tr>
<tr>
<td>Nov-2009</td>
<td>12.1 (22%)</td>
<td>155.3 (74%)</td>
<td>799.6 (22%)</td>
<td>3.2 ± 1.0 (52%)</td>
</tr>
<tr>
<td>March-2010</td>
<td>20.9 (50%)</td>
<td>407.6 (67%)</td>
<td>882.1 (45%)</td>
<td>3.6 ± 1.0 (64%)</td>
</tr>
<tr>
<td>May-2010</td>
<td>13 (53%)</td>
<td>133 (117%)</td>
<td>710 (64%)</td>
<td>5.4 ± 1.2 (83%)</td>
</tr>
<tr>
<td>July-2010</td>
<td>305.6 (80%)</td>
<td>436 (73%)</td>
<td>541.1 (66%)</td>
<td>4.8 ± 2.1 (38%)</td>
</tr>
<tr>
<td>Sep-2010</td>
<td>1.9 (8%)</td>
<td>8.4 (9%)</td>
<td>29.7 (27%)</td>
<td>6.0 ± 1.7 (43%)</td>
</tr>
<tr>
<td>Oct-2010</td>
<td>2.3 (20%)</td>
<td>10.7 (62%)</td>
<td>45 (143%)</td>
<td>3.5 ± 1.2 (39%)</td>
</tr>
<tr>
<td>Nov-2010</td>
<td>2.1 (12%)</td>
<td>9.4 (12%)</td>
<td>46.3 (82%)</td>
<td>2.4 ± 0.99 (46%)</td>
</tr>
<tr>
<td>Jan-2011</td>
<td>2.0 (13%)</td>
<td>8.0 (32%)</td>
<td>164 (176%)</td>
<td>3.2 ± 1.09 (58%)</td>
</tr>
<tr>
<td>Feb-2011</td>
<td>185 (46%)</td>
<td>281.32 (64%)</td>
<td>692 (32%)</td>
<td>3.9 ± 0.78 (79%)</td>
</tr>
</tbody>
</table>

*Characterization & main factors affecting clogging evolution of the bottom of stormwater infiltration systems*
**Thickness of the clogged layer**

Figure 2 shows the spatial distribution of the thickness of the clogged layer in May 2008 & April 2010 and allows us to identify the zones where accumulation of the sediments is the more important.

The measures show than sediment thickness is more important in areas regularly exposed to runoff water (in particular in the area near the inflow point) and in the lowest parts in terms of topography. In these zones, the thickness layer reaches 14 cm (May 2008) and 20 cm (April 2010). Unsurprisingly, the sediment deposition depends on the geometry and flooding frequency of the bottom. However, sediment deposit is not uniform all over the bottom.

If we consider it as uniform, the mean sediment thickness accumulated between April 2004 (basin totally scraped) and April 2010 has been estimated to $59.3 \pm 15.4$ mm. The mean thickness was determined as the ratio of the total sediment volume accumulated during the period to the total basin area with a bulk density of $0.688 \, \text{t/m}^3 \pm 0.019 \, \text{t/m}^3$. The accumulation is therefore about 10 mm/year.

We can try to compare this mean thickness with the equivalent thickness of sediment brought to the system. The mass of sediment brought to the system can be derived from the continuous measurement of Total Suspended Solid (TSS) concentrations as already presented in Gonzalez-Merchan et al. (2011b). According to this study, TSS load (between April 2004 to April 2010) was found to be $132 \, \text{t} \pm 32 \, \text{t}$. Considering an average sediment density of $0.688 \, \text{t/m}^3 \pm 0.019 \, \text{t/m}^3$, a porosity of $0.62 \, \text{m}^3/\text{m}^3 \pm 0.04 \, \text{m}^3/\text{m}^3$ homogeneously distributed over the 8,000 m² of the basin, the thickness of the sediment accumulated after 6 years of operation should be about $39 \, \text{mm} \pm 6\,\text{mm}$ i.e. about 6.5 mm/year. The results are consistent, and the tendency very similar to the one found *in situ*.

![Figure 2](image)

**Figure 2.** The spatial distribution of the sediment thickness between May 2008 (a) and April 2010 (b)

**Biomass content**

Figure 3 (a) shows the temporal distribution of the biomass content and Figure 3(b) its spatial distribution for each of the 8 points. The previous studies had shown large fluctuations of the biomass over the time (Compton *et al.*, 2004; Devi and Yadave 2006; Badin *et al.*, 2011). Devi and Yadava (2006) reported high seasonal variations of biomass contents. Our study confirms rather high temporal variation for each point (the temporal coefficients of variation ranging from 41% to 79%). If we compare the mean values of biomass content obtained for each campaign with Kruskal-Wallis test, the variation is statistically significant ($p$-value = 0.0008). Figure 3 (a) shows that the average biomass content is higher in May and lower in July. Same results have been obtained by Badin *et al.* (2011) on the same site in 2006 and 2007.

The spatial heterogeneity is also noticeable for each campaign (the spatial coefficients of variation ranging from 12 to 120 %). In average, the higher values of biomass content are once again located in point 6. This point presents a clogged layer higher than 5 cm, a soil of peat type and is situated in the lowest part of the basin where the mean saturated hydraulic
conductivity is also the lowest (See Table 1). In organic layer of peat type, the biomass content reaches several thousand of µg-C/g DM (Chen et al., 2005). In our case 11,000µg/g DM has been the higher value obtained in point 6 for the campaign realized in May 2010. A consequent supply of nutrients and organic matter and water logically result in the high development of microorganisms.

Figure 3(a). Boxplot of the biomass content distribution for each campaign with the spatial coefficient of variation (% in brackets). (b) Boxplot of the biomass content distribution for each point and the temporal coefficient of variation (% in brackets). (c) Boxplot of the organic matter content (OM) distribution for each campaign and the spatial coefficient of variation (% in brackets). (d) Boxplot of the organic matter content (OM) values distribution for each point and the temporal coefficient of variation (% in brackets). On the boxplot, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points excluding outliers; outliers are plotted individually (dots on the figure).

**Organic matter**

Figure 3(c) shows temporal distribution of organic matter (OM) over the time and Figure 3(d) its spatial distribution for each of the 8 points.

The organic matter shows a little variability in space (coefficient of variation of about 28 % ranging from 17 % to 45 %), the Kruskal-Wallis test exhibiting a significant differences of the spatial distribution of OM ($p$-value = 0.0023). The higher values of OM are located in points 2, 4 and 6. They are all situated in the wet area. Their sediment layer is thicker than 5 cm with a low dry bulk density.

For each point, the temporal coefficient of variation ranges from 29 % to 35 %, with a mean of about 24 %. Between September 2009 and February 2011 the organic matter has increased (from 14 % in September 2009 to 27 % in February 2011); the Kruskal-Wallis test showing a significant increase in the variation of organic matter over the time ($p$-value = 0.0292). However between May 2010 and February 2011, the OM evolution is homogenously distributed over time (Kruskall-Wallis test, $p$-value = 0.751).
Correlation between hydraulic conductivity and physical or biological factors

The results of the correlations analysis are given in Table 3. The linear regression being unsatisfactory ($R^2 = 0.32$– $p$-value $< 0.05$), the results of logarithmic regression will only be discussed.

Over a period of 1.5 years, the most influential parameters are the logarithm of the porosity, organic matter, biomass content, and sediment thickness. However, the set of parameters is not able to explain completely the variation of the saturated hydraulic conductivity ($R^2=0.37$– $p$-value $<0.05$).

Table 3. Logarithmic regression between the saturated hydraulic conductivity $K_s$ and the different parameters: organic matter ($OM$), biomass content ($BIO$), grain size ($D_{10}$, $D_{50}$ and $D_{90}$), dry bulk ($\rho_s$), particle density ($\rho_d$), porosity ($\varepsilon$), sediment thickness ($e$) solar energy accumulated during 3 and 7 days before the measure ($Sol-Ene_3$, $Sol-Ene_7$).

<table>
<thead>
<tr>
<th>Dependant variable</th>
<th>Predictors</th>
<th>$R^2$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ln(K_s)$</td>
<td>$\ln(OM)$, $\ln(BIO)$, $\ln(D_{10})$, $\ln(D_{50})$, $\ln(D_{90})$, $\ln(\rho_d)$, $\ln(\rho_s)$, $\ln(\varepsilon)$, $\ln(e)$, $\ln(Sol-Ene_3)$, $\ln(Sol-Ene_7)$</td>
<td>0.47</td>
<td>$&lt;&lt;0.05$</td>
</tr>
<tr>
<td>$\ln(K_s)$</td>
<td>$\ln(OM)$, $\ln(BIO)$, $\ln(\varepsilon)$, $\ln(e)$</td>
<td>0.37</td>
<td>$&lt;&lt;0.05$</td>
</tr>
</tbody>
</table>

Considering the stepwise regression analysis, the correlation study is performed for each campaign (see results in table 4), except for May 2010, the regression is correct suggesting a good spatial correlation but not a good temporal one.

Table 4. Logarithmic regression between the saturated hydraulic conductivity $K_s$ and the: $\ln(OM)$, $\ln(BIO)$, $\ln(e)$ estimated for each campaign.

<table>
<thead>
<tr>
<th>Campaign</th>
<th>$R^2$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>sept.-09</td>
<td>0.69</td>
<td>0.034</td>
</tr>
<tr>
<td>nov.-09</td>
<td>0.74</td>
<td>0.026</td>
</tr>
<tr>
<td>march-10</td>
<td>0.88</td>
<td>0.010</td>
</tr>
<tr>
<td>may-10*</td>
<td>0.50</td>
<td>0.060</td>
</tr>
<tr>
<td>jul.-10</td>
<td>0.59</td>
<td>0.05</td>
</tr>
<tr>
<td>oct.-10</td>
<td>0.66</td>
<td>0.039</td>
</tr>
<tr>
<td>nov.-10</td>
<td>0.92</td>
<td>0.029</td>
</tr>
<tr>
<td>jan.-11</td>
<td>0.88</td>
<td>0.01</td>
</tr>
<tr>
<td>feb.-11</td>
<td>0.63</td>
<td>0.03</td>
</tr>
</tbody>
</table>

* Correlation not significant.

CONCLUSION

Previous works have shown that the major part of the clogging of large systems mainly occurred at the bottom. A second step was then explored aiming at (i) studying the main characteristics of the clogged layer in space and time in terms of thickness, organic content, density, particle size distribution biomass, and saturated hydraulic conductivity and (ii) examining the potential correlation between clogging and these characteristics.

The work was conducted on a real large basin continuously monitored for more than 6 years in particular in terms of inflow, TSS concentrations, water temperature and solar energy. To study the characteristics of the bottom 10 campaigns were carried out from September 2009 to February 2011.

The results show that the sediment accumulation over the bottom of large system is heterogeneous and unsurprisingly much more important in areas often flooded in particular in the lowest part of the basin. In the lowest part, the grain size is also the finest, the biomass and porosity the highest, the dry bulk density the lowest giving to the soil a non mineral feature but a peaty aspect. At last, this part is also the more clogged.

It clearly suggests that large infiltration systems should be partitioned in successive compartments in order to delimit “clogged” areas where maintenance could be done more often and more easily than the whole scrapping of the bottom.

Apart from that, the heterogeneity of the characteristics of the bottom in time and space is important with no clear tendencies except for organic matter which has doubled in 1.5 years and mainly at the beginning of the period. In general, the top soil has high values of organic matter. Globally, the characteristics are in the same range than those observed on similar systems (Winiarski et al., 2006; Barraud et al., 2005; Cannavo et al., 2010).
A correlation between the main characteristics of the top layer and the unsaturated hydraulic conductivity was tested to try to explain the evolution of clogging. The results show a good spatial logarithmic regression in particular with porosity, organic matter, biomass content, and sediment thickness but an insufficient correlation to explain the evolution of clogging both in space and time.

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