A method for evaluating the evolution of clogging: application to the Pampulha Campus infiltration system (Brazil)
S. Barraud, C. Gonzalez-Merchan, N. Nascimento, P. Moura and A. Silva

ABSTRACT
In order to evaluate the hydraulic performance of stormwater infiltration trenches, a study was undertaken to assess clogging and its distribution between the bottom and the sides. The method used was based on the calibration of the hydraulic resistance event by event according to Bouwer’s model and applied to a demonstration trench in Belo-Horizonte monitored in the framework of the European Project Switch. The calibration was performed by minimizing the distance between measured and modeled infiltration flow rates and by using continuous measurements of rainfall, inflow, water temperature and depth in the trench. The study showed that the methodology and particularly Bouwer’s model was able to produce satisfactory results. It revealed a significant clogging evolution within a year, with global resistance increasing by a factor of 9. A significant difference between the bottom and the sides was observed; the bottom being more rapidly prone to clogging. Sudden fluctuations of the hydraulic resistance of the bottom were found that could be explained by very high concentrations of total suspended solids from inflows (about 2,000 mg/L). Clogging of the sides evolves over the time but with a very low rate.

Key words | clogging, hydraulic resistance, infiltration trench, stormwater, sustainable urban drainage systems

INTRODUCTION
Infiltration systems and in particular source control practices are more and more used for their potential to: (i) mitigate flooding by reducing run-off volumes and peak flows, (ii) limit wet weather non-point source pollution, (iii) contribute to groundwater recharge, and (iv) generally enhance the local environment and landscape.

However infiltration techniques must perform these functions over the long-term, which is particularly dependent on their hydraulic performance. In order to understand the loss of infiltration performance due to clogging, different models have been proposed (e.g. Duchene et al. 1994; Browne et al. 2008; Freni et al. 2009; Wang et al. 2012) but few of them were verified on long periods in real conditions of operation with continuous measurements.

Field studies such as Schuh (1990), Lindsey & Roberts (1992), Warnaars et al. (1999), Gautier et al. (1999), Dechesne et al. (2005), Le Coustumer & Barraud (2007), Emerson et al. (2010) or Bergman et al. (2011) have shown that clogging of stormwater infiltration systems is an issue of major importance, resulting in increased overflows, reduced treatment capacity and accentuated nuisance associated with extended periods of ponded water. Some of them were developed to monitor all kinds of system in a continuous way but were not tested on a wide range of technical systems, some others were devoted to a specific kind of infiltration device but were not monitored continuously for long periods.

The objective of the present study is to: (i) apply a methodology based on the assessment of the hydraulic conductivity of any infiltration system with a continuous data acquisition, (ii) evaluate its suitability for small systems such as trenches, and (iii) estimate the performance of one small system simply designed and cost effective.

For that purpose, measurements carried out on a Brazilian demonstration infiltration trench (named Pampulha Campus trench) in the framework of the European (EU) Switch Project were used to evaluate both adequacy of the methodology and clogging evolution assessment.
The paper presents the experimental and monitoring system, the methodology used to estimate the global hydraulic resistance and its spatial distribution (clogging of sides and bottom), the results and discussion. It compares them to other experiments, either experiments using the same methodology but on larger systems or comparable experiments carried out on the same type of device (trench).

**DESCRIPTION OF THE EXPERIMENTAL SITE AND MONITORING SYSTEM**

The experimental site is an infiltration trench situated in the UFMG Pampulha university campus in Belo-Horizonte, located at Mergulhão watershed, affluent of the Pampulha lake.

As presented in Silva et al. (2010), the experimental system receives runoff flow from a portion of a four-way road separated in the middle by a vegetated median strip. This four-way road with a drainage area of 3,880 m² links Belo Horizonte centre to its Northern districts (Presidente Carlos Luz Avenue).

The run-off generated by this area is collected and conveyed by a pipe to a junction box, where the run-off is diverted to the experimental area. The junction box allows a division of inflow into two equal parts: one towards the infiltration trench, the other towards a detention trench unit not studied in the paper. The soil surrounding the trench is mainly composed of red–yellow latosol, of low density, according to studies provided by the Municipality (DRENURBS 2002). Its hydraulic conductivity was assessed by a pre-test with Ghelph permeameter and evaluated at $5 \times 10^{-5}$ m/s (180 mm/h), typical of silt soils. The groundwater table, according to geotechnical investigations, is deeper than 4 m (Silva et al. 2010).

The infiltration trench, designed for a 10-year return period rainfall event, is 20 m long, 1 m wide and 1.5 m deep with vertical sides. It is filled with crushed stone as shown in Figure 1 with a porosity of 30%. The infiltration trench was installed at the end of May 2008.

![Figure 1](image-url)
In order to analyze infiltration trench clogging evolution, the following monitoring system (Figure 1) was used aiming at measuring at a 4-min time step (Silva et al. 2010):

- rainfall intensity (measured with a tipping bucket rainfall sensor)
- inflow rate (measured by water pressure sensors set up in Parshall flumes)
- inflow water temperature
- water level in the trench (by water pressure sensors)
- water quality of soil and water (in this study only total suspended solids (TSS) concentrations sampled at the trench inlet were used).

Despite an installation at the end of May 2008 and except inlet collection of sediment deposits, no measurements were performed up to October 2008 due to the 6-month dry season typical of the local climate. Moreover, due to gaps in the measurement series or poor quality of data linked to technical problems, data series from January to February 2009 and from mid-March to September 2009 were not considered.

**METHODOLOGY**

In order to assess the evolution of clogging of the infiltration trench over the time, hydraulic resistance was estimated according to the Bouwer’s model (Bouwer 1969, 2002) and adapted to local conditions.

Estimation of hydraulic resistance

Global hydraulic resistance

Previous studies have shown that one method to evaluate clogging of an infiltration system is to estimate its global hydraulic resistance. The hydraulic resistance R represents the time it takes for a unit infiltration amount to move through the clogging layer at unit head loss (Bouwer 2002).

The hydraulic resistance can easily be estimated if some assumptions are made, in particular if: (i) the clogged layer is thin compared to the water depth, (ii) saturated whereas the underlying soil is considered to be unsaturated (in this case, the hydraulic flow in the soil is only due to gravity and the hydraulic gradient can be equal to one), (iii) the clogged layer has a small hydraulic conductivity compared to the underlying soil, and (iv) the pressure head is supposed to be constant in the vadose-zone.

According to these assumptions and applying Darcy’s law, the infiltration flow rate can be expressed as a function of water depth in the system:

\[ Q_{\text{inf,Bouwer}}(h_i) = K_c \cdot \frac{h_i - h_{cr}}{e} \cdot S_{\text{inf}}(h_i) = \frac{h_i - h_{cr}}{R} \cdot S_{\text{inf}}(h_i) \]  \hspace{1cm} (1)

where \( Q_{\text{inf,Bouwer}} \) is the infiltration flow rate (m³/s) according to Bouwer model, \( K_c \) is the hydraulic conductivity of the clogged layer (m/s), \( e \) is the thickness of the clogged layer (m), \( h_i \) is the water depth in the infiltration system (m), \( h_{cr} \) is the water pressure head in the unsaturated porous media (m), \( R \) is the hydraulic resistance (hr), and \( S_{\text{inf}}(h_i) \) is the infiltration surface (m²) depending on the water depth and the geometry of the trench.

\( h_{cr} \) can be estimated by guide values according to the type of soil (Bouwer et al. 1999).

The hydraulic resistance can be calculated event by event by minimizing the sum of the square differences between measured and the Bouwer’s infiltration flow rates:

\[ C = \sum_{i=1}^{n} \left[ Q_{\text{inf,mes}} - Q_{\text{inf,Bouwer}}(h_i) \right]^2 \]

\[ = \sum_{i=1}^{n} \left[ Q_{\text{inf,mes}} - S_{\text{inf}}(h_i) \cdot \frac{h_i - h_{cr}}{R} \right]^2 \]  \hspace{1cm} (2)

where \( Q_{\text{inf,mes}} \) and \( Q_{\text{inf,Bouwer}} \) are respectively the measured and the Bouwer’s infiltration flow rate at time step \( i \), \( n \) is the number of time steps during the emptying part of the hydrograph.

\( Q_{\text{inf,mes}} \) can be determined from the measurements of the inflow rate (\( Q_{ei} \)) and the volume stored in the system depending on the water depth by using the continuity equation:

\[ Q_{\text{inf,mes}} = Q_{ei} - \frac{V(h_i) - V(h_{i-1})}{\Delta t} \]  \hspace{1cm} (3)

where \( Q_{ei} \) is the inflow rate at time step \( i \), \( \Delta t \) is the time step duration, and \( V(h_i) \) is the volume stored depending on the water depth \( h_i \) and the geometry of the trench.

Evaluation of the part of the clogging of the bottom and the sides

The evaluation of the part of the global clogging due to the bottom and of that due to the sides can be assessed in the same way by dividing the infiltration rate into two parts.
leading to calibrate two hydraulic resistances: one for the bottom \((R_{\text{bottom}})\) and one for the sides \((R_{\text{sides}})\) (Equation (4)). Considering that the water table is horizontal in the trench (low slope), the flow perpendicular to infiltration surfaces, the characteristics of soil similar at the bottom and sides, the geometrical feature of the trench, the flow through the bottom and the sides can easily be expressed as function of the water depth \(h_i\) in the trench.

\[
Q_{\text{Bouwer}}(h_i) = Q_{\text{Bouwer}}(h_i)_{\text{sides}} + Q_{\text{Bouwer}}(h_i)_{\text{bottom}}
\] (4)

**Evolution of the hydraulic resistance**

The evolution over the time is assessed event per event and has to be compared on equivalent bases: a sufficient maximum water depth in the trench to calibrate the hydraulic resistance (a limit of 0.5 m was chosen), calibration of \(R\)-values on the emptying phases of the hydrographs in order to minimize the effect of water content (similar range of moisture conditions) and a correction of hydraulic resistance at 20 °C in order to account for the variation of the viscosity of water with temperature. The hydraulic resistance correction at 20 °C is calculated according to the following equation:

\[
R[20\, ^{\circ}\, C] = \frac{\nu_{\text{w}}[x\, ^{\circ}\, C]}{\nu_{\text{w}}[20\, ^{\circ}\, C]} R[x\, ^{\circ}\, C]
\] (5)

where \(R[20\, ^{\circ}\, C]\) and \(R[x\, ^{\circ}\, C]\) are respectively the hydraulic resistance normalized at 20 °C and hydraulic resistance calibrated at \(x\, ^{\circ}\, C\) (mean water temperature during the calibration event); and \(\nu_{\text{w}}[20\, ^{\circ}\, C]\) and \(\nu_{\text{w}}[x\, ^{\circ}\, C]\) are the kinematic viscosity at 20 °C \((1.005 \times 10^{-6} \text{ m}^2/\text{s})\) and \(x\, ^{\circ}\, C\).

The uncertainty of each \(R\)-value is calculated using Monte Carlo method as described in Le Coustumer & Barraud (2007).

![Figure 2](https://iwaponline.com/wst/article-pdf/69/6/1241/472285/1241.pdf)

**Figure 2** | Results of the calibration of \(R\)-values: (a) temporal evolution of the global hydraulic resistance, (b) hydraulic resistance on the bottom and sides with their uncertainties, (c) measured vs calibrated infiltration flow (e.g. event 29 November 2009), (d) hydrograph of the calibrated infiltration flow through the sides, the bottom and the whole system with the water level in the trench (emptying phase – event of the 29 November 2009).
RESULTS

Global clogging evolution

The calibration of $R$-values normalized at 20 °C was carried out for twelve events from November 2008 to December 2009. For these events, the total rain depth ranged from 5 to 66 mm, from 0.33 to 14 h in duration and from 0.5 to 12 days for antecedent dry period (Silva et al. 2010). For the rainfall events measured, all the return periods (calculated on the basis of their total rain depth and duration) were less or equal than 1 year, except for the 19 November 2008 event which presented a 2-year return period.

The water pressure head $-h_{cr}$ was taken equal to $-0.35$ m according to Bouwer’s guide values (1969) and to the preliminary characterization of the underlying soil of the trench reported in Silva et al. (2010).

The evolution of the global hydraulic resistance $R$ is plotted in Figure 2(a) and all the results are given in Table 1.

Comparing $R$-value evolution over 12 months (from November 2008 to October 2009), the hydraulic resistance has increased by a factor of about 9 (from 2.3 h at the beginning of the period up to 20.3 h at the end). The increase of the values between 2008 and 2009 is statistically significant (Wilcoxon-test; $p$-value = 0.0022; $p$-value < 0.05) and can be quite fast (from 4 h at the end of November 2008 to about 10 h a month later).

Temporal evolution of clogging of the bottom and sides

The $R$-values were calibrated for the bottom ($R_{\text{bottom}}$) and sides ($R_{\text{sides}}$), also normalized at 20 °C and for the same events. The results are presented in Table 1 and plotted in Figure 2(c).

Between 2008 and 2009 the annual mean $R_{\text{bottom}}$-value has increased significantly (Wilcoxon-test, $p$-value = 0.0087; $p$-value < 0.05). On the same period the increase of the hydraulic resistance of the sides was not so pronounced ($p$-value = 0.058).

DISCUSSION

Suitability of the method

The study on Pampulha Campus trench shows that the methodology and in particular Bouwer’s model was applicable to small infiltration systems like those developed in Belo Horizonte. The calibration for each event gave rather good fits ($r^2$) between calibrated and measured hydrographs in the range of 0.62–0.98 (mean value of 0.83) for global resistance and in the range of 0.76–0.97 (mean value of 0.84) for those of the bottom and sides (Table 1). Figures 2(a) and 2(b) present an example of the comparison of the calibrated and measured infiltration flow for the event of the 29 November 2009.

<table>
<thead>
<tr>
<th>Date</th>
<th>$R$ (h)</th>
<th>$U(R)$ (%)</th>
<th>$r^2$ (-)</th>
<th>$R_{\text{bottom}}$ (h)</th>
<th>$U(R_{\text{bottom}})$ (%)</th>
<th>$R_{\text{sides}}$ (h)</th>
<th>$U(R_{\text{sides}})$ (%)</th>
<th>$r^2$ (-)</th>
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<tr>
<td>17-Nov-08</td>
<td>2.3</td>
<td>38</td>
<td>0.97</td>
<td>10.6</td>
<td>32</td>
<td>1.1</td>
<td>34</td>
<td>0.83</td>
</tr>
<tr>
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<td>2.2</td>
<td>24</td>
<td>0.95</td>
<td>10.2</td>
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<td>28-Nov-08</td>
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<td>19.6</td>
<td>37</td>
<td>1.4</td>
<td>39</td>
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<tr>
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<td>1.3</td>
<td>43</td>
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</tr>
<tr>
<td>22-Dec-08</td>
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<td>0.74</td>
<td>13.1</td>
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<td>1.5</td>
<td>33</td>
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<tr>
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<td>33</td>
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<td>1.9</td>
<td>30</td>
<td>0.84</td>
</tr>
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<td>01-Mar-09</td>
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<td>11</td>
<td>0.64</td>
<td>17.4</td>
<td>19</td>
<td>2.8</td>
<td>30</td>
<td>0.81</td>
</tr>
<tr>
<td>11-Oct-09</td>
<td>15.3</td>
<td>33</td>
<td>0.98</td>
<td>19.5</td>
<td>28</td>
<td>2.2</td>
<td>30</td>
<td>0.84</td>
</tr>
<tr>
<td>29-Nov-09</td>
<td>21.0</td>
<td>38</td>
<td>0.8</td>
<td>19.9</td>
<td>29</td>
<td>1.2</td>
<td>34</td>
<td>0.84</td>
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<td>14-Dec-09</td>
<td>20.9</td>
<td>34</td>
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<td>20.8</td>
<td>30</td>
<td>2.0</td>
<td>30</td>
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<tr>
<td>19-Dec-09</td>
<td>20.3</td>
<td>31</td>
<td>0.76</td>
<td>22.1</td>
<td>30</td>
<td>1.8</td>
<td>32</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Global evolution of clogging

At the very beginning of the experiment (i.e. after 6 months of operation, mostly during the dry season of the year), $R$-values were quite low (a little more than 2 h) attesting that the trench was not globally clogged.

Rapidly, within a month, the hydraulic resistance reached values of around 10 h. However, they were still rather low and in the range of global hydraulic resistance of a large French infiltration basin after few months of operation (Gonzalez-Merchan et al. 2012) or trench (Proton & Chocat 2007).

Twelve months later $R$-values had grown up and reached 15.3 h (i.e. more than six times the values obtained on the first month). The trench began to get clogged at this period considering that a hydraulic resistance of more than 24 h generally indicates a serious clogging.

Spatial distribution of clogging

Clogging of the bottom

The bottom hydraulic resistance ranged from 10.6 to 22.1 h with a median value of around 15 h.

The evolution trend of the bottom hydraulic resistance is significant. In about 1 year this resistance nearly doubled (from around 10 h up to 20 h).

On other experiments, the same tendency was observed, the bottom being quickly prone to clogging. For example on other trenches $R_{\text{bottom}}$-values close to infinite were observed meaning a total clogging after 3 years (Emerson et al. 2010) or 6 years of operation (Proton & Chocat 2007) (see Table 2).

We can notice that initial values were already high (in the range of 10 h). It means that the bottom of the trench already presented a small initial clogging either as a result of the trench construction process or due to low local initial permeability. This level of initial value was also found on another infiltration experiment in Pennsylvania (Emerson et al. 2010) reporting an $R_{\text{bottom}}$ resistance of 8 h (Table 2).

Clogging of the sides

The hydraulic resistance of the sides ranges from 1 to 2.8 h with a median value of 1.8 h.

At the very beginning the $R_{\text{sides}}$-values were very low (from 1 to 1.4 h in November 2008), then they increased to values ranging from 1.2 to 2.8 h in 2009 (see Figure 2(b)).

Even if the level of clogging was still acceptable compared to the bottom, a slow increase was observed on a period of 1 year. This was not noticed on other experiments for which $R_{\text{sides}}$ were rather constant over greater periods (Table 2).

Comparison of clogging of bottom and sides

For the Pampulha Campus trench, the study shows a significant difference between the hydraulic resistance of the bottom and the sides, the bottom being more rapidly prone to clogging (Figure 2(b)).

However, and whatever the type of infiltration system (bare like swales or infiltration basins or covered by a granular materials like trenches) the bottom is the first part to clog. This has to be taken into account in the design procedure. It is interesting to notice that in some design standards, it was sometimes recommended to only take the bottom surface as infiltration area to integrate clogging effects (e.g. ATV 138 (2002), Leeflang & Monster (1995)).

For the Pampulha Campus trench, we can also notice rapid and sudden fluctuations in the evolution of the bottom on short periods of time. For example, in 9 days (from 19 to 28 November 2008), clogging of the bottom

Table 2 | Comparison of the results with other experiments carried out with similar methodologies to assess the hydraulic resistance of the bottom ($R_{\text{bottom}}$) and sides ($R_{\text{sides}}$). The last column aims at comparing results on trenches with a large system

<table>
<thead>
<tr>
<th>Sites</th>
<th>Infiltration trench</th>
<th>Infiltration basin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pampulha Campus</td>
<td>Pennsylvania-USA</td>
</tr>
<tr>
<td></td>
<td>(our study)</td>
<td>(Emerson et al. 2010)</td>
</tr>
<tr>
<td>Observation period (years)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$R_{\text{bottom}}$ (in h)</td>
<td>[10.2–22.1]</td>
<td>[8–10$^6$]</td>
</tr>
<tr>
<td>$R_{\text{sides}}$ (in h)</td>
<td>[1.1–2.8] (constant over time)</td>
<td>[11 h–12] (constant over time)</td>
</tr>
</tbody>
</table>
grew drastically from 10.2 to 19.6 h. These pulses of clogging observed on the trench could therefore be explained by the very high concentrations of TSS brought to the system associated with an intense rainfall. On this specific episode, the event of the 19 November 2008 was actually the one with the highest return period (2 years) in the rainfall series and TSS concentration also reached a high value (1,955 mg/L) (Silva et al. 2010). On the total experimental period, TSS concentrations were globally high (from 616 to 1,955 mg/L with an average of 1,500 mg/L) contributing to increase physical clogging.

These high concentrations could be explained by a high-level of erosion of the catchment due to the vegetated central strip of the road, probable inputs from its side slopes which are supposed to be drained by catch drains but overflow during heavy rains and at last by the damages observed on the road itself which usually lacks of maintenance particularly during the rainy season.

**CONCLUSION**

In order to evaluate clogging evolution of a small infiltration system designed as a very simple device (ditch filled of gravel), the global, bottom and side hydraulic resistance with their uncertainties were calculated for twelve events from November 2008 to October 2009. The method used is based on the calibration of the hydraulic resistance event by event under similar conditions according to Bouwer’s model. The calibration is carried out by minimizing the distance between measured and modeled infiltration flow rates and by using continuous measurements of rainfall, inflow, water temperature and water depth in an infiltration trench set up and monitored in the framework of the EU Project Switch.

The study on the Pampulha Campus trench shows that the methodology and in particular Bouwer’s model was applicable to small systems like those developed in Belo Horizonte with the local type of soil. Actually, the calibration for each event gave rather good fits.

It also demonstrated a significant evolution of clogging within a year, with global resistance increasing by more than nine times over this period.

As already exhibited in the literature, a significant difference between the hydraulic resistance of the bottom and the sides was observed; the bottom being more rapidly prone to clogging.

Rapid fluctuations in the evolution of the hydraulic resistance of the bottom on short periods of time were also detected. In 9 days, clogging of the bottom has increased by a factor of 1.9. These variations of clogging could be explained by the very high concentrations of TSS (around 2,000 mg/L) brought to the system associated with more intense rainfall events.

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