Evolution of clogging assessment applied to Pampulha Campus infiltration system (Brazil)

Estimation de l'évolution du colmatage appliqué au cas du système d'infiltration du Campus de la Pampulha (Brésil)

Sylvie Barraud[1], Carolina Gonzalez-Merchan[1], Nilo Nascimento[2], Priscilla Moura[2], André Silva[3]

[1]Université de Lyon ; INSA de Lyon ; Université Lyon 1 ; LGCIE, 69621 Villeurbanne, France
[2]Universidade Federal de Minas Gerais, Escola de Engenharia, Departamento de Engenharia Hidráulica e Recursos Hídricos
[3]Belo Horizonte Municipality, Av. Afonso Pena, 4000 – Belo Horizonte, Brazil, 30130-009
Corresponding author : sylvie.barraud@insa-lyon.fr

RÉSUMÉ

De manière à étudier la performance hydraulique sur le long terme de tranchées d'infiltration d'eaux pluviales, une étude a été entreprise visant à évaluer la résistance hydraulique globale ainsi que celles du fond et des parois. La méthode utilisée est basée sur le calage de résistances hydrauliques évènement pluvieux par évènement pluvieux selon le modèle de Bouwer et a été appliquée à une tranchée de démonstration dans un contexte brésilien. Le calage a été mené en minimisant les écarts entre débit d'infiltration mesuré et modélisé et en utilisant des données en continu de pluies, de débits d'entrée, de températures et de hauteurs d'eau dans la tranchée acquises dans le cadre du projet européen Switch. L'étude a montré que la méthodologie et notamment le recours au modèle de Bouwer donnaient de bons résultats. Elle révèle une évolution significative du colmatage sur une année. La résistance globale y a été multipliée par un facteur de plus de 6. Une différence significative a également été constatée entre résistance hydraulique du fond et des parois ; le fond étant le plus prompt au colmatage. Même si le niveau atteint par le colmatage des parois est acceptable par rapport à celui du fond, une augmentation de sa valeur a été détectée ; ce que l'on ne retrouve pas dans la littérature qui rapporte des valeurs plus constantes sur des périodes plus importantes. Des fluctuations brusques de résistance aussi bien pour le fond que pour les parois ont pu être observées qui pourraient être expliquées par des apports de matières en suspension élevés.

ABSTRACT

In order to evaluate the long-term hydraulic performance of stormwater infiltration trenches, a study was undertaken to assess their global hydraulic resistance and its distribution between the bottom and the sides. The method used was based on the calibration of the hydraulic resistance event per event according to Bouwer's model and was applied to a demonstration trench in a Brazilian context.

The calibration was carried out by minimizing the distance between measured and modelled infiltration flow rates and by using continuous measurements of rainfall, inflow, water temperature and water depth in the trench set up in the framework of the EU project Switch.

The study showed that the methodology and in particular the Bower's model was applicable with satisfactory results. It also revealed a significant clogging evolution within a year. The global resistance was multiplied by a factor of 6. A significant difference between the bottom and the sides was also observed; the bottom being more rapidly prone to clogging. Even if the level of clogging was still acceptable for the sides, an increase was detected, which is not usual, the literature reporting a relative stability of side resistance over greater periods. Rapid and sudden fluctuations of resistance both for sides and bottom were also found that could be explained by the very high concentrations of Total Suspended Solids brought into the system.

KEYWORDS

Clogging, Hydraulic resistance, Infiltration trench, SUDS, Stormwater

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1 INTRODUCTION

Infiltration systems and in particular source control practices are more and more used for their potential to: (i) mitigate flood by reducing runoff volumes and peak flows, (ii) limit wet weather non-point source pollution (iii) contribute to groundwater recharge and (iv) generally enhance local environment and landscaping (Azzout et al., 1994, Baptista et al*.,* 2005, CIRIA 2007, David & Sousa 2008, Tamoto & Sakakibara 2008, Pasche et al., 2009).

However infiltration techniques must integrate the expected long term performance and in particular the longevity of the hydraulic function.

Field studies such as Schuh (1990), Lindsey et al. (1992), Warnaars et al*.* (1999), Gautier et al. (1999), Dechesne et al*.* (2005), Le Coustumer et al. (2009), Emerson et al. (2010) or Bergman et al. (2011) have shown that clogging of stormwater infiltration systems was an issue of major importance because it does not only lead to flow rate reduction, it also reduces treatment capacity when they are equipped with bypass devices.

The objective of the present study is to: (i) apply a methodology based on the assessment of the hydraulic conductivity (ii) evaluate its adequacy to small systems such as trenches in a Brazilian context, (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 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 compare them to other experiments carried out on rather similar bases (same methodology, same type of design).

2 DESCRIPTION OF THE EXPERIMENTAL SITE AND MONITORING SYSTEM

The experimental site is an infiltration trench situated in the Pampulha university campus (UFMG), whose area is located at Mergulhão watershed, affluent of Pampulha lake.

As presented in (Silva et al., 2010), the experimental system receives runoff flow from a portion of a 4-way road of 3,880 m^2 contributing area, linking the centre of Belo Horizonte to its Northern districts (Presidente Carlos Luz Avenue).

The runoff generated by this area is collected and conveyed by a pipe to a junction box, where the runoff is diverted to the experimental area. The junction box (see figure 2) allows a division of inflow into two equal parts: one towards the infiltration trench, the other towards a detention 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 Belo Horizonte Municipality (DRENURBS, 2002). Its hydraulic conductivity was assessed by means of a pre-test with Ghelph permeameter and evaluated at 5×10^{-5} m/s (180 mm/h), typical of silt soils. Geotechnical investigations did not reveal presence of groundwater level in the first 4 meters depth (Silva et al., 2011).

The infiltration trench designed with a 10-year return period is 20 m long, 1 m wide, 1.5 m deep with vertical sides with a slope of 1%. 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.
In order to analyse infiltration trench clogging evolution, the following monitoring system was used aiming at measuring:

- Rainfall (with a tipping bucket rainfall sensor) for event detection
- Inflow rate (measured by water pressure sensors (Parshall flume presented in figure 3))
- Water level measured by water pressure sensors
- Water temperature of inflow for hydraulic resistance correction
- Water quality of soil and water (in the study only TSS concentrations sampled at inlet of the trench were used).

The data from continuous measurements were mainly acquired with a 4 min time step.

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.

The whole monitoring system and experiment conditions is described in (Silva et al., 2010 and 2011).

Figure 1. Configuration the experimental infiltration trench
(Silva et al., 2010)

Figure 2. Junction box: entrance (left) exit and flow tranquilizer (right) (Silva et al., 2011)

Figure 3. System with Parshall flumes for measuring inflows (Silva et al., 2011)

3 METHODOLOGY

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

3.1 Estimation of hydraulic resistance

3.1.1 Global hydraulic resistance

Previous studies have shown that one of a method to evaluate clogging is to estimate its global hydraulic resistance (e.g. Gautier et al., 1999; Dechesne et al., 2005 or Le Coustumer & Barraud 2007, Gonzalez-Merchan et al., 2012) on large systems or Emerson et al., 2010, Proton 2008, or Caramori *et al., 2*002) for small systems such as a trench).

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 (Bouwer, 1969), in particular if:

- the clogged layer has a small hydraulic conductivity compared to the underlying soil and the clogged layer is very thin compared to the water depth,
- the clogged layer is saturated but 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 is equal to one),
- the pressure head is supposed to be constant in the vadose-zone (Bouwer proposed guide values according to soil type (Bouwer et al., 1999)).

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:

$$Q_{inf\_Bouwer}(h_i) = K_c.\frac{h_i - h_{cr}}{e} \cdot S_{inf}(h_i) = \frac{h_i - h_{cr}}{R} \cdot S_{inf}(h_i) \qquad \text{Equation 1}$$

where Q_{inf_Bouwer} is the infiltration flow rate (m^3/s) according to Bouwer model, K_c the hydraulic conductivity of the clogged layer (m/s), e the thickness of the clogged layer (m), h_i the water depth in the infiltration system (m), h_{cr} the water pressure head in the unsaturated porous media (m), R the hydraulic resistance (h) and $S_{inf}(h_i)$ the infiltration surface depending on the water depth (m²) and the geometry of the trench.

As indicated before, 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 per event by minimizing the sum of the square differences between measured and the Bouwer's infiltration flow rates:

$$C = \sum_{i=1}^{n} \left[Q_{inf\_mes_i} - Q_{inf\_Bouwer_i}(h_i) \right]^2 = \sum_{i=1}^{n} \left[Q_{inf\_mes_i} - \frac{S_{inf}(h_i) \cdot (h_i - h_{cr})}{R} \right]^2 \qquad \text{Equation 2}$$

where $Q_{inf\_mes\ i}$, $Q_{inf\_Bouwer\ i}$ are respectively the measured and the Bouwer's infiltration flow rate at time step i, n the number of time steps during the emptying period

Q_{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:

$$Q_{inf\_mes_i} = \left[\frac{V(h_i) - V(h_{i-1})}{\Delta t} \right] - Q_{e\ i} \qquad \text{Equation 3}$$

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

3.1.2 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 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_{bottom}) and one for the sides (R_{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 from the bottom and from the sides can easily be expressed by functions of the water depth h_i in the trench.

$$Q_{Bouwer}(h_i) = Q_{\underset{sides}{Bouwer}}(h_i) + Q_{\underset{bottom}{Bouwer}}(h_i) \qquad \text{Equation 4}$$

3.1.3 Evolution of the hydraulic resistance

The evolution over time is assessed event per event and has to be compared on an equivalent basis. Some conditions have to be checked: similar range of water volume (similar range of rainfall and water depth), correction of hydraulic resistance at 20°C in order to account for the variation of the viscosity of water with temperature, calibration of R-values on the emptying parts of the hydrographs in order to minimize the effect of water content (similar range of moisture conditions).
The uncertainty of each R-value is calculated using Monte Carlo Method described in (Le Coustumer & Barraud, 2007).

4 RESULTS

4.1 The global clogging evolution

The calibration of *R* values normalized at 20°C was carried out for 8 events from November 2008 to October 2009. For these events, the total rain depth ranged from 4.2 mm to 62.6 mm, from 15 min to 420 min in duration and from 0.5 to 12 days for antecedent dry period (Silva et al., 2010).

The water pressure h_{cr} head was taken equal to -0.35 m according to Bouwer's guide values (1999) 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 is plotted in figure 4 and all the results are given in table 1. Comparing *R* value evolution over 11 months (from November 2008 to October 2009), the hydraulic resistance has increased significantly (*Wilcoxon-test*; p-value = 0.0003; p-value < 0.05 between values obtained in 2008 within a month and values evaluated in 2009). Moreover, the increase is quite fast (from 4 h at the end of November 2008 to 10 h one month later).

Table 1. Calibrated hydraulic resistance (*R*) for each of the 8 events, relative uncertainties (*Ur(R)*) and r^2 determination coefficient of the calibration of *R* value

Date	*R* (h)	*Ur(R)* (%)	r^2 *(-)*
17-Nov-08	2.3	38	0.97
19-Nov-08	2.2	24	0.95
22-Nov-08	7.1	47	0.74
28-Nov-08	3.5	37	0.91
29-Nov-08	4.1	43	0.75
27-Dec-08	9.9	33	0.62
01-mar-09	14.2	11	0.64
11-Oct-09	15.3	33	0.98

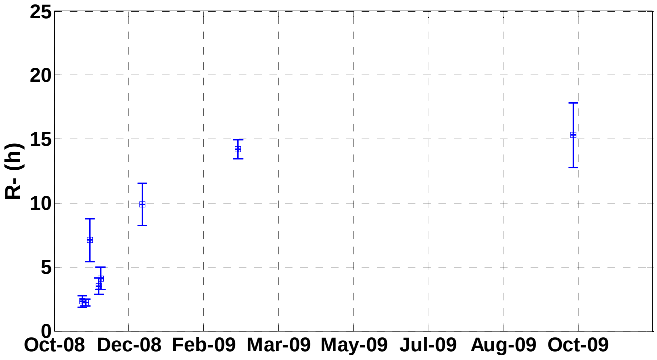

Figure 4. Temporal evolution of the global hydraulic resistance *R* (in h).

4.2 Temporal evolution of clogging of the bottom and sides

The *R* values were calibrated for the bottom (R_{bottom}) and sides (R_{sides}) also normalized at 20°C and for the same events. The results are presented in table 2, plotted in figure 5 and 6.

Table 2. Hydraulic resistance of the bottom (R_{bottom}) and sides (R_{sides}) normalized at 20°C with their relative uncertainties ($Ur(R_{bottom})$, $Ur(R_{sides})$) and *the* determination coefficient of the calibration r^2

Date	R_{bottom} *(h)*	$Ur(R_{bottom})$ *(%)*	R_{sides} *(h)*	$Ur(R_{sides})$ *(%)*	r^2 *(-)*
17-Nov-08	10.4	32	1.0	34	0.83
19-Nov-08	10.1	20	1.4	21	0.76
28-Nov-08	13.1	31	1.5	33	0.97
29-Nov-08	19.5	37	2.3	39	0.83
22-Dec-08	15.6	40	1.6	42	0.86
27-Dec-08	15.1	28	2.5	30	0.84
01-mar-09	17.3	19	2.8	9	0.81
11-Oct-09	19.6	28	2.1	30	0.84

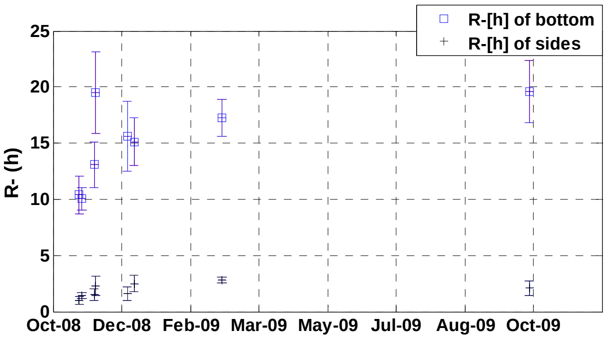

Figure 5. Temporal evolution of hydraulic resistance on the bottom and sides with their uncertainties

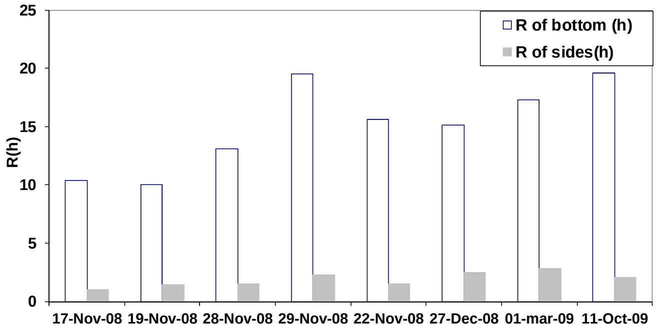

Figure 6. Comparison of hydraulic resistance of the bottom (R_{bottom}) and sides (R_{sides}) with their uncertainties

5 DISCUSSION

5.1 Regarding adequacy of the methodology

The study on Pampulha campus trench shows that the methodology and in particular the Bouwer's model was applicable to small systems like those developed in Belo Horizonte with the local type of soil. The calibration for each event gave rather good fits *(*r^2 between calibrated and measured hydrographs in the range of 0.62 to 0.98 for global resistance with a mean value of 0.82 (see table 1) and in the range of 0.76 to 0.97 for the hydraulic resistance of the bottom and sides with a mean value of 0.84 (table 2).

5.2 Global clogging evolution

At the very beginning of the experiment (i.e. after six months of operation and of dry season), *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 has 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, 2008).

One year later *R* values have grown up and reached more than six times the values obtained on the first month (15.3 h). It is clear that the trench began to get clogged at this period. It is generally admitted that a hydraulic resistance of more than 24 h indicates a complete clogging.

5.3 Clogging spatial distribution

5.3.1 Clogging of the bottom

The bottom hydraulic resistance ranges from 10 to 20 h with a median value of around 15 h.

The evolution tendency of the hydraulic resistance of the bottom is significant even if there are fluctuations in the increase. In about one year this resistance has nearly doubled (around 10 h in November 2008 up to 20 h in October 2009).

On other experiments, the same tendency was observed, the bottom being quickly prone to clogging. For example on other trenches R_{bottom} values close to infinite were observed meaning a total clogging after 3 years (Emerson et al., 2010) or 6 years of operation (Proton, 2008) (see table 3).

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 that could be due to defects during the construction of the trench or 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_{bottom} resistance of 8 h (table 3).

5.3.2 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.

It also evolves over time. At the very beginning the R_{sides} values were very low (from 1 to 1.4 h in November 2008), then they increased to values ranging from 2.1 to 2.8 h in 2009 (see Figure 2).

Even if the level of clogging was still acceptable compared to the bottom, a slow increase was observed on a period of one year. This was not noticed on other experiments for which R_{sides} were rather constant over greater periods (Table 3).

5.3.3 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. It also shows that the difference tends to get lower as time passes as shown in figure 6.

However and whatever the type of infiltration system (bare like swales or infiltration basin 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 (e.g. ATV 138 (2002), Leeflang et al. (1995)).

For the Pampulha Campus trench, we can also notice rapid and sudden fluctuations in the evolution of both sides and bottom on short periods of time. For example in one day (from 28 to 29 November 2008), clogging has increased drastically: R_{bottom} has grown from 13 h to 19.5 h and R_{sides} value from 1.5 h to 2.3 h. These pulses of clogging observed on the trench could therefore be explained by the very high concentrations of Total Suspended Solids (TSS) brought to the system. TSS accumulation are known to increase physical clogging mainly by filtration mechanisms (Baveye et al., 1998; Bouwer et al., 2002; Siriwardenne et al., 2007). Table 4 shows the range of TSS concentrations that were measured on the Pampulha Campus site on the same period (Silva et al., 2011).

Table 3. Comparison of the results with other experiments carried out with about the same methodology to assess the hydraulic resistance of the bottom (R_{bottom}) and sides (R_{sides}). The last column aims at comparing a large system

Sites	Pampulha Campus Infiltration trench (our study)	Infiltration trench Pennsylvania-USA (Emerson et al., 2010)	Infiltration trench Lyon-France (Proton, 2008)	Infiltration Basin Chassieu-France (Gonzalez-Merchan et al., 2012)
Observation period	1 year	3 years	6 years	7 years
R_{bottom} [min - max]	[10.4 h-19.6]	[8 h – 1 x 10^6 h]	[2.7 h - ∞]	[7.6-24.8]
R_{sides} [min - max]	[1 -2.8]	[11 h – 12 h] (constant over time)	~2 h (constant over time)	[0.6-1.3] (constant over time)

Table 4. Inflow TSS concentration (Silva et al., 2010)

Event	**Inflow TSS concentration (mg/L)**
31/10/2008	1596
7/11/2008	616
27/11/2008	1955
8/12/2008	1660
22/12/2008	1452
01/02/2009	1451
13/02/2009	1763

6 CONCLUSIONS

In order to evaluate clogging evolution of a small infiltration system designed in a very simple way (ditch filled of gravels), the global, bottom and side hydraulic resistance with their uncertainties were calculated for 8 events from November 2008 to October 2009. The method used is based on the calibration of the hydraulic resistance event per event on similar bases according to Bouwer's model. The calibration is carried out by minimizing the distance between measured and modelled infiltration flow rates and by using continuous measurements of rainfall, inflow, water temperature and water depth in the 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 the Bower'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 clogging evolution within a year. The global resistance has grown up and reached more than six times the values obtained on the first month indicating that the trench began to get seriously clogged on the 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 However it tends to get lower as time passes. Even if the level of clogging was still acceptable at the end of the experimentation for the sides compared to the bottom, a slow increase was detected on a period of one year. This was not noticed on other experiments for which hydraulic resistance of the sides was approximately constant over greater periods.

Rapid and sudden fluctuations in the evolution of both sides and bottom on short periods of time were also observed. In one day, clogging of the bottom could increase with a factor of 1.5 and 5 for the sides. These variations of clogging could be explained by the very high concentrations of Total Suspended Solids (around 2000 mg/L) brought to the system. In general the high TSS concentrations linked to a high level of erosion may also explain the observed rapid clogging of the trench surfaces.

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