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Hydraulic performance of biofilters: first lessons from both laboratory and field studies

Performance hydraulique des biofiltres : premiers résultats d'expériences en laboratoire et in-situ

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RESUME

Afin de mieux comprendre le fonctionnement des biofiltres pour les eaux de ruissellement pluviale, la Facility for Advancing Water Biofiltration (FAWB) a été créé à Monash University (Australie). L'un des buts de ce projet est d'améliorer la conception et la durabilité des systèmes d'infiltration. En effet il a été montré que de nombreux systèmes ne fonctionnent plus après quelques années de fonctionnement. Des tests sur des systèmes existants ont été effectués afin d'évaluer leur conductivité hydraulique ainsi que des expériences en laboratoire afin de comprendre les paramètres qui pourraient influencer le comportement des ouvrages. Il a été montré que 43% des biofiltres testés ont une conductivité hydraulique inférieure aux normes australiennes. Les premiers résultats des expériences en laboratoire montrent une forte décroissance de la conductivité hydraulique lors des premières semaines d'utilisation ($\mu=66\%$ de réduction), bien que la majorité reste à l'intérieur des limites acceptables. L'influence sur la conductivité hydraulique du ratio taille du bassin versant/ taille du biofiltre et du type de sol utilisé dans le système est aussi examiné.

ABSTRACT

In order to improve knowledge on stormwater biofiltration systems, the Facility for Advancing Water Biofiltration (FAWB) was created at Monash University in Melbourne, Australia. One of the aims of FAWB is to improve hydraulic performance of biofilters, given that there are numerous cases of infiltration devices failing after a few years of operation. Experiments were conducted in the field to evaluate the performance of existing systems, and in the lab to understand the factors that influence hydraulic behavior over time. The field experiments show that 43% of tested systems are below nominal Australian guidelines for hydraulic conductivity. The preliminary lab results show a decrease in hydraulic conductivity during the first weeks of operation ($\mu=66\%$ reduction), although most remain within acceptable limits. Influences of the size of the biofilter relative to its catchment and the importance of the type of media, on the evolution of hydraulic conductivity, are examined.

KEY WORDS

Biofiltration, Bioretentions, Clogging, Hydraulic conductivity, Sustainability

1 INTRODUCTION

Infiltration techniques are widely used around the world to manage stormwater in urban areas. These techniques are recognized for their many advantages, such as decreasing stormwater peak flows and reducing pollution of surface waters (Dechesne *et al.* 2004). However, there are still substantial questions over their long-term performance and sustainability, particularly the potential for clogging (Bouwer, 2002). A field survey by Lindsey *et al.* (1992) showed that only 38% of infiltration basins were functioning as designed after 4 years of operation, with 31% clogged. Schueler *et al.* (1992, in Barrett *et al.* 2004) showed that 50% of infiltration systems were not working due to clogging. Clogging is therefore an issue of primary importance for infiltration systems because it leads to more frequent overflows, an extended ponding time, reduced treatment capacity, and aesthetic problems.

In response to these concerns, recent developments have seen the inclusion of vegetation into the infiltration media, to form 'biofiltration' or 'bioretention' systems (Fletcher *et al.* 2005). The vegetation serves several roles, including the uptake of nutrients and other pollutants, the prevention of erosion on the soil surface, and the potential maintenance of soil hydraulic conductivity, through the creation of macropores as a result of root growth and senescence (Archer *et al.* 2002).

In 2005, the Facility for Advancing Water Biofiltration (FAWB) was established at Monash University in Melbourne, Australia, in order to improve knowledge on biofiltration systems to treat stormwater runoff. One of the aims of this project is to improve the design and long-term sustainability of infiltration systems, focusing on hydraulic performance of biofilters (FAWB, 2006).

This paper presents the first results of experimental work to evaluate the long-term hydraulic behavior of biofiltration systems and the parameters that influence it over time. The research was conducted in two phases. Firstly, a series of field experiments were conducted to assess the behavior of existing biofilters, and assess performance of biofilters relative to their age. Secondly, laboratory experiments were conducted to understand the different factors that influence hydraulic performance of biofilters over time. At completion of these experiments new guidelines will be defined to improve biofilter design, construction and maintenance.

2 METHODS

2.1 Field experiments

In order to measure the field hydraulic conductivity (K_{fs}) of biofilters, two different methods were used: a single ring infiltrometer and a deep ring infiltrometer. The two methods were compared, and used for cross-checking the measurements.

2.1.1 Single ring infiltration test (shallow test)

The single ring infiltrometer consists of a small steel ring, with a diameter of 10 cm that is driven 5 cm into the soil. It is a constant head test that is conducted for two different pressure heads (5 cm and 15 cm). The head is kept constant during all the experiments by pouring water in the ring. The frequency of readings of the volume poured depends on the soil. It varies from 30 seconds to 5 minutes. The experiment is stopped when the infiltration rate is considered steady (i.e. when the volume poured per time interval remains constant for at least 20 minutes).

In order to calculate K_{fs} a 'Gardner's' behaviour for the soil was assumed (Gardner, 1958 in Youngs *et al.* 1993):

$$K(h) = K_{fs} e^{\alpha h} \quad \text{Eq. 1}$$

where K - the hydraulic conductivity, h - the negative pressure head and α - a soil pore structure parameter (large for sands and small for clay). K_{fs} is then found using the following analytical expression (for a steady flow) (Reynolds and Elrick, 1990):

$$q = K_{fs} \left(1 + \frac{H}{\pi a G} \right) + \frac{\phi_m}{\pi a G} \quad \text{Eq. 2}$$

where q - the steady infiltration velocity, a - the ring radius, H - the ponding depth, ϕ_m - the matrix flux potential, and G a shape factor estimated as:

$$G = 0.316 \frac{d}{a} + 0.184 \quad \text{Eq. 3}$$

where d - the depth of insertion of the ring, and a - the ring radius.

The first term of Equation 2 represents the effect of gravity, the second term the effect of ponding, and the third the effect of capillarity in the soil (Angulo-Jaramillo *et al.* 2000). G is nearly independent of soil hydraulic conductivity (i.e. K_{fs} and α) and ponding, if the ponding is greater than 5 cm.

The possible limitations of the test are (Reynolds *et al.* 2000): (1) the relatively small sample size due to the size of the ring, (2) soil disturbance during installation of the ring (compaction of the soil), (3) possible edge flow during the experiments.

2.1.2 Deep ring infiltration test

A metal infiltration cylinder (diameter 13 cm) was driven into the filter media so that it reaches the gravel layer which underlies biofilters, to act as a drainage layer (Figure 1). It was assumed that there is zero pressure at the bottom of the cylinder (in the gravel) so that Darcy's law (Eq. 4) can be used to calculate the hydraulic conductivity.

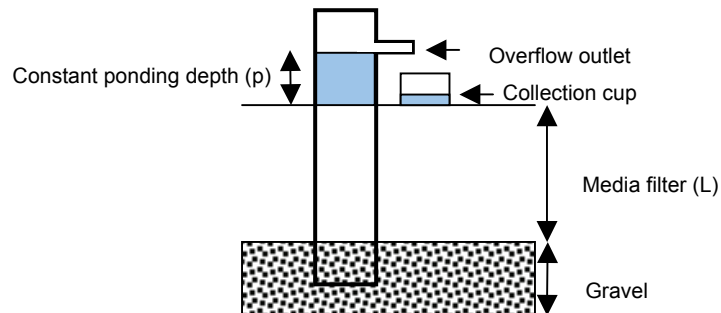


Figure 1: Sketch of the deep ring

The volume of water, to keep a constant head in the device, was recorded over short time intervals. When the infiltration rate was steady (i.e. when the volume poured per time interval remains constant for at least 20 minutes), the filter media was assumed to be saturated. Recorded values were corrected for temperature of 20°C.

We assumed that the soil is saturated when the infiltration rate is steady (i.e. after the initial saturation period), and that the pressure head in the gravel is zero. Therefore the hydraulic conductivity at saturation could be found using the Darcy's law:

$$Q = k \frac{dH}{L} S = k \frac{L+p}{L} S \quad \text{Eq. 4}$$

where L - the length of the media filter, p - the ponding depth, Q - the infiltration flow rate (i.e., added volume of water to keep a constant head divided by the time step) and S the cross section of the column.

Similar to the single shallow ring tests, the main limitations with the deep ring test are the possible compaction of the soil while the ring is driven into the soil and possible preferential flow on the side of the column. It is also possible that the assumptions of saturated conditions at the commencement of the experiment, and the free-draining behaviour of the underlying gravel, may not be true in all cases.

2.1.3 Biofilters Tests

Biofilters built over the past 8 years in three different states were tested: 11 in New South Wales, 25 in Victoria and 4 in Queensland. They had different characteristics: size and type of catchment, effective area/ size of biofilter ratio, age.

A few replicate tests are usually made at different locations in the same biofilter as hydraulic conductivity often varies from one point to another (even over quite small distances). The two different methods to measure K_{fs} (shallow vs. deep) were used at the same time on four different biofilters, while the deep method was mainly used.

Because we are still gathering the data on biofilter characteristics, only the site means, standard deviation and coefficient of variation (Cv) of K were calculated for each system.

2.2 Laboratory experiments

In order to understand the influence of design on the performance of the systems, 125 biofiltration testing columns of large dimension (diameter 375 mm, depth up to 900 mm) have been constructed. The influence of six different parameters on the behavior of the systems over a long period of time is tested:

- **Vegetation:** 5 different species are tested (*Carex apressa*, *Dianella revoluta*, *Microleana stipoides*, *Leucophyta brownii*, *Melaleuca ericifolia*)
- **Climate** (i.e. rainfall pattern): a sub-tropical climate and temperate climate;
- **Filter media depth:** 300 mm, 500 mm and 700 mm, plus 100 mm of sand and 100 mm of gravel drainage media in each case;
- **Type of media:** a sandy loam ('normal media'), a sandy loam with vermiculite and perlite (media 1), a sandy loam with "low" pH, mulch and compost (media 2) and a sandy loam with mulch and compost (media 3);
- **Pollutant inflow characteristics:** 'Typical' stormwater concentration (after Duncan, 1999): TSS = 150 mg/L, TN = 2.6 mg/L, TP = 0.35 mg/L, (as well as heavy metals) and 'High' concentrations = double the 'Typical' values.
- **Size of the biofilter relative to its catchment:** The inflow volume was varied: a standard volume (biofilter area = 2% of impervious catchment area), a double volume (biofilter = 1% of catchment), and a half-volume (biofilter = 4% of catchment).

There were five replicates for each case studied. Hydraulic conductivity (K) is measured on each column using the constant head method (based on ASTM D 2434-68, modified for the columns). Tests were first done before dosing the column with stormwater in order to determine the initial hydraulic conductivity. Columns are then tested 4, 8 and 14 weeks from the start of the dosing (stormwater was applied 2 times per week to mimic averaged drying and wetting

regime in Melbourne). The testing will be conducted over a 12 month period at approx 8 week intervals.

The data on K were \log_{10} -transformed to achieve normality (at Kolmogorov-Smirnov $p=0.05$) before analysis using analysis of variance (ANOVA).

3 RESULTS AND DISCUSSION

3.1 Field results

For the 75 conducted field tests the median K_{fs} was 88 mm/h (N=40) (Table 1) which is generally consistent with Australian design guidelines that recommend a hydraulic conductivity of 50-200 mm/h for biofilters (Melbourne Water, 2005). There are 43% of biofilters that have a K_{fs} less than 50 mm/h. This could be due to clogging, or possibly due to inadequate specification of the original filter media soil.

The resulting Cv in K_{fs} for one biofilter was between 34% and 83%, similar to values in the literature, for sandy loam. For example Bagarello *et al.* (2000) found a Cv between 90% and 160%, Mertens *et al.* (2002) observed a Cv of 200% and Vauclin *et al.* (1994) a Cv between 35% and 40%.

The two different methods gave very similar results (Table 1).

Site	Test type	N	K_{fs}	K_{fs}	Cv (%)
Streisand Dr, Brisbane, QLD	Shallow	2	62	47 [¶]	67
	Deep	2	33		
Saturn Cr Brisbane, QLD	Shallow	3	34	40 [¶]	58
	Deep	3	45		
Donnelly Pl Brisbane, QLD	Shallow	3	19	35 [¶]	83
	Deep	2	60		
Hoyland Dr Brisbane, QLD	Shallow	6	354	451 [¶]	65
	Deep	3	645		
Monash Car park, Clayton, VIC	Shallow	2 [#]		43, 48	
Cremorne St, Richmond, VIC	Deep	6 [#]		528, 444, 265, 298, 100, 202	
		3		211	34
		3		163	59
Aleyne St, Chelsea, VIC	Deep	3 [#]		5, 9, 8	
		2		6	
Point Park, Docklands, VIC	Deep	1		332	
		2		78	
Hamilton St, W. Brunswick, VIC	Deep	2 [#]		2, 1	
Avoca Cr, Pascoe Vale, VIC	Deep	3 [#]		11, 10, 6	
Parker st, Pascoe Vale, VIC	Deep	2 [#]		23, 1	
		3		56	48
Wolseley Pd, Vic Park, NSW	Deep	5 [#]		758, 822, 98, 280, 173	
Leyland Gr, Vic Park, NSW	Deep	5 [#]		355, 437, 359, 522, 311	
Tanzanite St, 2 nd Pond Creek, NSW	Deep	5		5	67
Ceres, West Brunswick, VIC	Deep	4		60	73

Cv: Coefficient of variation, N: number of experiments, [¶] Average K_{fs} from both methods, [#] Represents single readings taken for N separate biofilters (e.g. 2[#] = 1 reading taken in each of two biofilters), Vic: Victoria, NSW: New South Wales and QLD: Queensland

Table 1 : measured field hydraulic conductivity, K_{fs} , in mm/h

3.2 Laboratory results

3.2.1 Evolution of hydraulic conductivity with time

Hydraulic conductivity in the laboratory columns declined significantly over time (Table 2). The reduction is very quick during the first four weeks of experiments and then tends toward one value (Figure 2). ANOVA conducted on \log_{10} -transformed data show that hydraulic conductivity are statistically different ($p < 0.001$) from one experiment to another except for the measurements made on week 8 and 14 ($p = 0.857$). The overall average reduction of 66% of hydraulic conductivity with time (from 521 mm/h to 176 mm/h) is then statistically significant. However, the most important question is not the early rate of decline, but what is the value to which conductivity declines over the long-term (this will be answered over the course of the experiments)

Time	K mm/h	Std. Dev. (mm/h)	Cv (%)
Initial	521	325	62
4 weeks	235	143	61
8 weeks	189	117	62
14 weeks	176	103	58

*Number of points used = 124

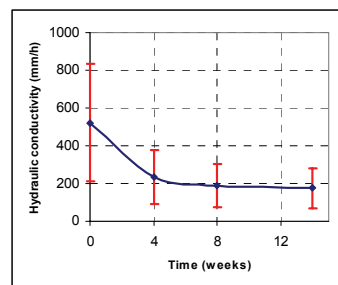


Table 2 and Figure 2: Mean hydraulic conductivity K (mm/h) with time, standard deviation and coefficient of variation. Results obtained from all the columns

3.2.2 Influence of design

The influence of design was evaluated by comparing hydraulic conductivity (after 14 weeks) of each design configuration (Table 3), using ANOVA. Systems with dense vegetation (specifically *Carex apressa*) have a higher hydraulic conductivity than those with sparse vegetation (*Melaleuca ericifolia*), shallow root systems (*Microleana stipoides*) or without any vegetation (Control). However these results are not statistically different at this early stage, and should be seen as initial trends only. We are therefore yet to make a conclusive finding on the role of vegetation in maintaining hydraulic conductivity of biofilters.

The columns that receive double storm volume (for the same vegetation type: *Carex apressa*) show lower hydraulic conductivity ($\mu \pm \sigma = 85 \pm 9$ mm/h) than those that receive standard storm volumes ($\mu \pm \sigma = 287 \pm 116$ mm/h), with the difference significantly different (i.e. $p < 0.05$). The results clearly show that undersizing a biofilter in relation to its catchment area will lead to a more rapid reduction of hydraulic conductivity due to high loading rates.

The systems with *Carex apressa* and with a media filter depth of only 300mm have a statistically lower K ($\mu \pm \sigma = 92 \pm 33$ mm/h) than the regular *Carex apressa* systems ($\mu \pm \sigma = 231 \pm 80$ mm/h), probably due to higher relative compaction of the media.

Media type also appears to be an important design parameter. Media 1 ($\mu \pm \sigma = 367 \pm 193$ mm/h) has one of the highest K of all the systems. It has vermiculite added which seems to maintain soil structure and conductivity over time.

Media 3 has 10% (by volume) of mulch and compost added, that should help vegetation growth and microbiological activity. Its hydraulic conductivity started relatively high and remained amongst the highest at week 14 ($\mu \pm \sigma = 393 \pm 84$ mm/h).

Media 2 is similar to Media 3, but has a marginally lower pH than all the other media types (as well as having compost and mulch added). However, it has a very low hydraulic conductivity ($\mu\pm\sigma=115\pm40$ mm/h). To achieve the lower pH, a different soil was used. Since the difference of pH is very small (pH=8 for the standard system, pH=7.4 for media 2), the difference in hydraulic conductivity could be explained by the nature of the source-soil more than the variation in pH. This clearly shows the importance of strict specification of the soil for use in biofilter media, since a small variation in soil characteristic can result in large differences in hydraulic conductivity. Further analysis will be undertaken in order to quantify the difference between the standard soil and Media 2, in order to provide further guidance on the exact soil properties that must be tested, before selecting a biofilter soil media.

Design type	Parameter tested	N	K (mm/h)	Std. Dev. (mm/h)	Cv (%)
Control*		5	161	46	29
Carex		5	231	80	35
Dianella	Vegetation	5	193	111	58
Microleana		5	136	15	11
Leucophyta		5	172	23	13
Melaleuca		5	151	57	38
Carex_s_V**			5	287	116
Carex_h_V***	Size of the biofilter relative to its catchment	5	85	9	11
Microleana_h_V***		5	141	62	44
Melaleuca_h_V***		5	150	53	35
Carex_500mm			5	109	31
Carex_300mm		5	92	33	36
Microleana_500mm	Length of media filter	5	206	78	38
Microleana_300mm		5	190	46	24
Melaleuca_500mm		5	168	144	86
Melaleuca_300mm		4	182	89	49
Media1			5	367	193
Media2	Media type	5	115	40	35
Media3		5	393	84	21

*No vegetation, **s_V : small volume (catchment 0.5 x standard), ***h_V: high volume (catchment 2x standard). The column with a specific media are planted with the species Carex apressa

Table 3: Hydraulic conductivity of selected design configuration after 14 weeks of experiments

4 CONCLUSION

Field experiments have shown that soil hydraulic conductivity of biofilters constructed around Australia varies greatly, with around 43% nominally below Australian guidelines. This finding supports the need for laboratory experiments to understand the parameters that influence this evolution of performance with time. First results from the lab show a significant decrease in the infiltration capacity of the systems in the first weeks of operation. An analysis of the different design configuration shows the importance of the volume of stormwater (i.e. an expression of the catchment: biofilter area ratio) and media type (presence of vermiculite, or organic matter) on the evolution of hydraulic conductivity with time. Future work will attempt to relate the K_{fs} of each existing biofilter in the field with characteristics of the catchment and the age of the systems. At this early stage, the effect of vegetation on hydraulic behaviour remains unclear. Laboratory experiments will be continued for 12 months, to better

understand the parameters that influence the evolution of infiltration capacity with time. It will be then possible to improve design guidelines in order to increase the life span of biofiltration and infiltration systems, and to decrease their failure rate.

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