Hydraulic performance of biofilter systems for stormwater management: lessons from a field study

Sébastien Le Coustumer, Tim D. Fletcher
Ana Deletic & Matthew Potter

Facility for Advancing Water Biofiltration, Department of Civil Engineering, Institute for Sustainable Water Resources, Monash University, Melbourne, Vic., 3800, Australia

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Contact details:

Sebastien.le.coustumer@eng.monash.edu.au

Tim.fletcher@eng.monash.edu.au

Ana.deletic@eng.monash.edu.au

matthew.potter@melbournewater.com.au

Executive summary

Biofiltration systems ('biofilters') are increasingly being used to manage polluted stormwater runoff in urban areas. However, there are significant concerns about their lifespan, particularly due to the possibility of clogging of the systems over time. A study of 37 biofilters constructed on the east coast of Australia during the last seven years, shows that 60% of constructed systems have a saturated hydraulic conductivity (K) which meets or exceeds the currently recommended range of 50 to 200 mm/h. It appears that the media used varied greatly between systems, perhaps because of a lack of available guidelines at the time of construction, or because of inadequate specification and quality control. However, this generally does not affect the treatment efficiency of the systems, as most systems surveyed were sufficiently sized (in filter area or ponding volume) such that their detention storage volume compensates for reduced media hydraulic conductivity (Figure 1). Consideration of the interaction between these three design elements – *hydraulic conductivity, filter area and detention (ponding depth)* – is critical (rather than consideration of one factor in isolation).

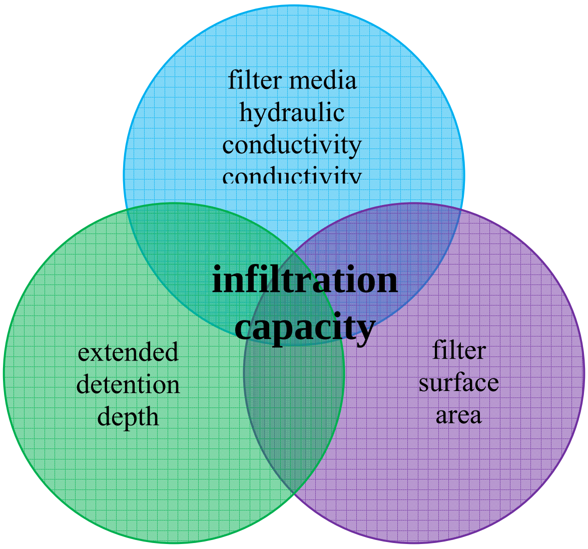

Figure 1. Interaction between media hydraulic conductivity and other design components, in determining infiltration capacity of the bioretention system.

The study broadly reveals two types of systems: some with a high initial K (>200 mm/h) and some with a low initial K (<20 mm/h). Significant reductions in K are evident for biofilters in the former group, although most are shown to maintain an acceptably high conductivity. For the second type of systems (with low initial K), little change occurs over time. Two hypotheses could explain this phenomenon: on one hand sediment depositions could be leading to the clogging of the surface of the system; another possibility is that the creation of macropores through root growth and dieback may help to minimise the reduction in K. The impact of surface clogging is proportionally greater in systems which started with a high initial K, most likely because the difference in particle size distribution between the original filter media and deposited sediments will be greater where the original media was coarse. In the systems with low initial K, the finer particle size distribution will be more similar to that of the inflow sediments (although still considerably larger), thus reducing the proportional impact of any surface clogging effect.

Site characteristics such as filter area as a proportion of catchment area, age of the system and inflow volume were not found to be useful predictors of media conductivity, with initial conductivity of the original media explaining the vast majority of variance. It is clear therefore, that strict attention must be paid to the specification of original filter media, to ensure that it satisfies current design requirements. Media should be tested after construction of the system.

Given the apparent difficult in specifying and maintaining hydraulic conductivity in biofiltration media, one approach is to use a "contingency factor" in the specification of hydraulic conductivity for biofiltration systems. For example, where the design intent is to use a soil media with a hydraulic conductivity of 180 mm/hr, sizing of the system should be undertaken assuming a hydraulic conductivity of 50% of the design value (ie. 90 mm/hr). In this way, if the media does not meet specifications, or shows a decline in hydraulic conductivity over time, the overall system performance will remain satisfactory.

Key words: Biofilters, clogging, stormwater management, hydraulic conductivity

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1 Introduction

Biofiltration systems (also called bioretention systems, biofilters or rain gardens) have been widely implemented in the last few years as a source control technique to manage stormwater runoff in urban areas (Melbourne Water, 2005). They form one technique in the suite of tools which aim to reduce the impact of urbanisation on watersheds (Dietz and Clausen, 2007).

In Australia, they are commonly used to treat runoff in urbanizing areas and as a retrofit technique in already-developed areas. With increasing societal pressure to protect and restore the environmental quality of aquatic ecosystem (Brown and Clarke, 2007), local water authorities are encouraging their development and construction.

Biofilters have been shown to be effective in the treatment of suspended sediments, heavy metals and nutrients (Zinger et al. 2007). However, there remain significant questions about the sustainability and long-term performance of biofilters, with little field data available.

Australian guidelines for biofilter design generally recommend a saturated hydraulic conductivity (K) of between 50 and 200 mm/h for the filter media (e.g. Melbourne Water, 2005). Biofilters are then designed in order to achieve pollutant removal efficiency for total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP), as described in Table 1. Curves giving the percentage of pollutant removal versus the size of biofilter for different detention depth have been developed, to determine required area and detention volume (Melbourne Water, 2005). As an example, in the Melbourne area, if a 300 mm detention depth is assumed, a biofilter has to be sized at approximately 1.65% of the impervious catchment in order to achieve a 45 % TN removal (the limiting performance target required by regulations in several Australian states).

Table 1: Quality objectives for stormwater treatment in Victoria (Victoria stormwater committee, 1999)

Pollutants	Objective
TSS	80% retention of annual loading
TP	45% retention of annual loading
TN	45% retention of annual loading

The potential for clogging of the surface of the systems is a real issue (Bouwer, 2002). A field survey of a number of ***infiltration systems*** (which unfortunately did not include raingardens or any other form of biofilters) conducted by Lindsey et al. (1992) showed that only 38% of infiltration basins were functioning as designed after 4 years of operation, with 31% considered to be clogged. Schueler et al. (1992) showed that 50% of infiltration systems were not working due to clogging. Clogging results in more frequent overflows and therefore a decrease in treatment capacity, since less of the annual flow volume filters through the media. Clogging may also cause problems of stagnant water and aesthetic problems, leading to difficulties in acceptance of biofiltration as a system integrated into the built environment.

To illustrate the impact of the variation of K on the performance of the system, the Model for Urban Stormwater Improvement Conceptualisation (MUSIC v3.02) software was used to model a hypothetical catchment of 1 ha (100% impervious) located in Melbourne, draining into a biofilter designed at 1% of the catchment area, and with a ponding depth of 10 cm. As shown in Figure 1, the percentage of mean annual flow treated (called 'hydrologic effectiveness'; Wong et al. 1999) decreases with K. For a K of 200 mm/h, the hydrologic effectiveness is 85%; falling to 58% for K of 50 mm/h and to 29% for K of 5 mm/h. When biofilters are severely clogged (for example when K is 5 mm/h), 71% of inflows are discharged effectively untreated to receiving waters.

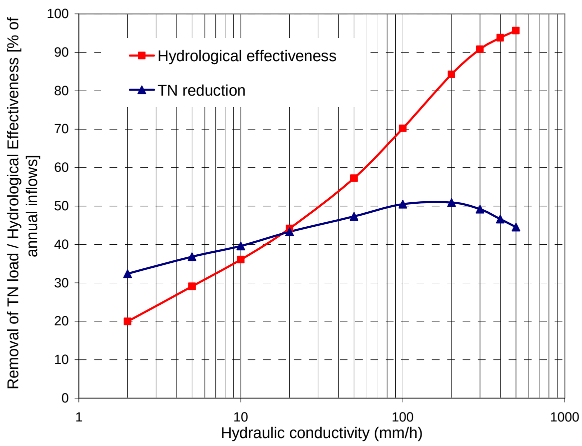


Figure 1 : Evolution of Hydrological effectiveness and TN reduction vs. Hydraulic conductivity

In this context, the objectives of this study are to:

- Evaluate the hydraulic conductivity and the design of a large number of systems already built in order to assess their performance regarding current guidelines,

- Assess the evolution of hydraulic conductivity in order to estimate the variation of their performance with time,

- Gather a large dataset on different systems in order to understand the possible influence of some factors (i.e. catchment size, biofilter size, age…) on their performance.

- Provide guidance on the design and construction of rain-gardens, based on findings of the survey.

2 Method

2.1 Sampling locations

Thirty-seven biofilters were sampled over 18 sites, in Melbourne, Sydney and Brisbane. Measurements were taken in order to represent as well as possible any spatial variability in hydraulic conductivity. Usually three measurements were taken in each biofilter, most of the biofilters tested being less than 40 m² in area (Table 2).

The sites were deliberately chosen to have different characteristics. Impervious catchment and biofilter size were measured for each. The distributions of the main characteristics of the sites (catchment location, type and size, and biofilter size) are presented in Table 2. The volume of water, the volume of water received by the system every year and the total volume of water per m² of biofilter were calculated with the following hypotheses: an average annual precipitation (Bureau of Meteorology):

- Melbourne: 650 mm/h
- Brisbane: 1200 mm/h
- Sydney: 1175 mm/h
- An annual runoff coefficient of 0.8 (to account for initial losses, etc).

Table 2: Site characteristics

Location	# of sites	Catchment use	# of sites	Catchment size	# of sites	Biofilter size	# of sites
Melbourne	30	Residential	18	< 100m²	6	< 40m²	31
Brisbane	4	Industrial	8	100–1000 m²	17	40–400 m²	4
Sydney	3	Parking	5	1000-10000 m²	9	> 400 m²	2
		Highway	4	> 10 000 m²	1		
		Low traffic road	2				

2.2 Sampling methodology

A number of alternative methods were used (for comparative purposes) for determination of hydraulic conductivity. ***Field hydraulic conductivity*** (K_{fs}) measurement of biofilters, have been conducted by two different methods (used for cross-checking the measurements):

(1) a single ring shallow infiltrometer (referred to herein as $\mathbf{K_{fs\ shallow}}$), and

(2) a deep ring infiltrometer (herein referred to as $\mathbf{K_{fs\ deep}}$).

Laboratory measurements of hydraulic conductivity were also conducted on two types of samples:

(1) surface samples ($\mathbf{K_{lab\ surf}}$), and

(2) samples taken from deep in the filter media (at a depth of approximately 150 mm below the surface - referred to as $\mathbf{K_{lab\ deep\ ini}}$)

Whilst the surface measurement reflects the current effective hydraulic conductivity of the system, the deep sample provides an estimate of the initial hydraulic conductivity of the media. Methods used for determining each of these measures are described in more detail in subsequent sections.

Single ring field infiltration test (shallow test)

The single ring infiltrometer test has been widely described in the literature (see Reynolds and Elrick, 1990, Youngs et al. 1993 for example) and thus only a brief summary is given here. This method measures the hydraulic conductivity at the surface of the soil (and thus is most appropriate when the hydraulic conductivity is controlled by a limiting layer at the media surface).

The single ring infiltrometer consists of a small plastic ring, with a diameter of 100 mm that is driven 50 mm into the soil (Figure 2). It is a constant head test that is conducted for two different pressure heads (50 mm and 150 mm). 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.

K_{fs} is then found using the following analytical expression (for a steady flow) (Reynolds and Elrick, 1990):

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

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

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

Where d - the depth of insertion of the ring, and a - the ring radius. G is considered to be independent of soil hydraulic conductivity (i.e. K_{fs} and α) and ponding, if the ponding depth is greater than 50 mm.

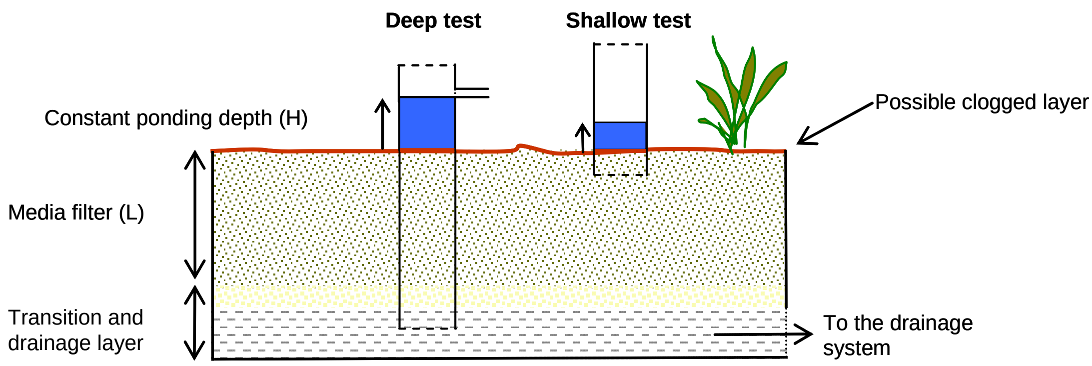


Figure 2: Sketch of a biofilter with the deep ring and the shallow ring

Deep ring field infiltration test

The deep ring method is based on the lysimetric method as explained in Daniel (1989), and may be more appropriate if the limiting hydraulic conductivity is found considerably below the surface. In order to measure the K_{fs} with this method it is necessary to have a free-draining outflow drain from which the discharge can be measured. Biofilters are built effectively as a lysimeter (i.e. with a drainage layer made of gravel and perforated pipe, both of which have a flow capacity several orders of magnitude higher than the overlying filter media), but it was not feasible to flood each biofilter and measure the outflow in the drain. However, by inserting a ring down to the drainage layer (Figure 2), it is then possible to apply Darcy’s law, assuming the following hypotheses: flow through the soil is uni-directional (vertical); soil is saturated, we can then assume that the wetting front is going down the drainage layer and will be as thick as the soil layer and there will be no pressure in the drainage layer (ie. free drainage is assumed).

Darcy's law (Eq. 4) can be then used to calculate the hydraulic conductivity.

$$K_{fs} = \frac{QL}{(H+L)A} \qquad \text{Eq. 4}$$

Where L - the length of the media filter, H - 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 A the cross sectional area of the column.

The cylinder used had a 130 mm internal diameter and was driven up to the gravel layer. This method is able to measure the hydraulic conductivity of the whole system, and can thus account for a limiting layer anywhere in the media depth profile.

Laboratory infiltration test

Soil samples were tested according to the Australian standard AS 4419-2003. Tests were undertaken on disturbed samples (by necessity). Surface samples (called *lab-surface*) were taken in the first centimetre of the soil and deep samples between 10 and 15 cm. Surface samples were used to compare the field and the laboratory method. Deep samples (called *lab-deep*) are assumed to represent 'the initial hydraulic conductivity' of the systems because soil has not been changed by sediment deposit (any fine sediment deposited on the filter is assumed to be trapped within the first few centimetres of the media (Hatt et al, 2006). The dimensions of samples tested during the experiments were 100 mm diameter and 85 mm deep.

Limitations of the sampling methods

For both field tests, the main limitations are the possible compaction or disturbance of the soil while the ring is driven into the soil and possible preferential flow on the side of the column. For the deep ring method, it is also possible that the assumptions of saturated conditions at the beginning of the experiment, and the free-draining behaviour of the underlying gravel, may not be true in all cases.

Laboratory measurements have inherent problem that samples are in all cases disturbed, and therefore impact of in-situ soil compaction can not be evaluated. Although it is clamed that these measurements will give 'the initial hydraulic conductivity', this is not exactly true since soil structure may have been changed over time (e.g. water flowing through the systems over time should have changed soil structure to some extent).

2.3 Data analysis

Data preparation

For each biofilter and when multiple tests were conducted, average hydraulic conductivity and its coefficient of variation were calculated for each method. Uncertainties were calculated using the law of propagation of uncertainty as explained in NIST, 1994. Data have been logged transformed before statistical analysis in order to respect the assumptions of normality, which was tested with Kolmogorov-Smirnov test (K-S test); normality accepted at $p>0.05$.

Comparison between methods

The results from the two different field methods are compared as well as field methods and laboratory methods. Paired t-Tests are conducted with results considered as statistically different when $p< 0.05$; coefficient of correlation (R^2) between methods is also calculated. The laboratory – field comparisons are only made for the lab-surface samples because it is assumed that lab-deep samples represent the initial hydraulic conductivity and not the current value (Hatt et al., 2006).

Determining clogging over time

As the initial hydraulic conductivity is unknown for all the systems tested, the measurement made on the lab-deep samples is assumed to represent the initial hydraulic conductivity ($K_{lab\ deep\ ini}$). This value is then compared with the field measurements ($K_{fs\ deep}$ and $K_{fs\ shallow}$) and with laboratory measurement made on the surface samples ($K_{lab\ surf}$).

Determining the influence of catchment characteristics

Ascendant Hierarchical Classification (AHC) was used to show group patterns in the dataset, and thus to tease out the factors which have significant explanatory power on the variation observed. It was conducted on the following parameters: $K_{fs\ shallow}$, $K_{fs\ deep}$, $K_{lab\ deep\ ini}$, age of the system, size ratio, volume of water per year, total volume of water and total volume of water per area (m^2) of systems.

Multiple regressions were used in order to explain the variation of $K_{fs\ shallow}$ as a function of explanatory variables ($K_{lab\ ini}$, age, size ratio, volume of water per year, total volume of water per m^2) in order to understand possible correlation between the current K and characteristics of the system and its catchment.

3 Results and discussion

3.1 Biofilter design

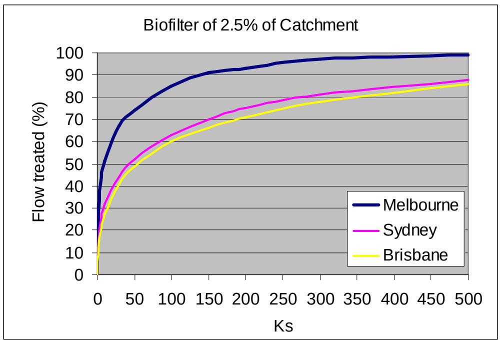
Most of the systems studied were not designed strictly according to current guidelines in term of ratio size of the system/size of the catchment (many were constructed prior to the availability of these current guidelines). For example, the Victorian (Melbourne Water, 2005) guidelines recommend a biofilter :catchment area ratio of at least 1.65 %, but the 30 Victorian systems surveyed show a ratio between 0.1% and 21.9%, with an average of 5.3 % and a median of 2.5% (Table 3). Biofilters are thus generally over sized, although the extended depths are often considerably less than the recommended range of 100-200mm. However, given their irregular geometry, exact measurement of the 'effective' or 'average' ponding depth was not feasible.

Field hydraulic conductivity measurement shows that 39% (using the shallow ring method) (42% using the deep ring method) of the biofilters have a K_{fs} below 50 mm/h, 44% (27%) between 50 and 200 mm/h and 17% (30%) above 200 mm/h (Table 3). In summary, most of the systems (~60%) have a hydraulic conductivity either within or exceeding the currently used guidelines (Melbourne Water, 2005; Wong et al., 2006).

Table 3: Data for each site: hydraulic conductivity value (different method), catchment characteristics and volume of water received

Sites	Hydraulic conductivity (mm/h)						Sites characteristics				Volume of water		
	$K_{fs\ shallow}$	ur(K) %	$K_{fs\ deep}$	ur(K) %	$K_{lab\ deep}$ (ini)	$K_{lab\ surf}$	Age (year)	Catchment area (m²)	Biofilter area (m²)	Ratio (%)	V. water/year (m3)	Total V. water (m3)	Total V./ m² (m)
Streisand Dr, Brisbane	61	29	32	99	399	238	0.5	1105	20	1.8	1060.8	530.4	26.5
Saturn Cr, Brisbane	34	20	38	10	17	9	0.5	675	20	3.0	648.0	324.0	16.2
Donnelly Pl, Brisbane	19	22	63	12	12		0.2	1130	32.2	2.8	1084.8	217.0	6.7
Hoyland Dr, Brisbane	204	16	667	6	65	146	5	17400	860	4.9	16704.0	83520.0	97.1
Monash Car park, Clayton	58	30	68	14	53		0.5	1500	15	1.0	780.0	390.0	26.0
	102	22	88	13	117		0.5	1500	15	1.0	780.0	390.0	26.0
	45	20	55	15	48		0.5	1500	15	1.0	780.0	390.0	26.0
Cremorne St, Richmond	71	31	406	12	582	31	3	366	14.5	4.0	190.3	571.0	39.4
	594	34	444	10	264		3	60	11	18.3	31.2	93.6	8.5
	129	34	265	9	462	98	3	560	4.5	0.8	291.2	873.6	194.1
	316	34	282	12	747	116	3	622	18	2.9	323.4	970.3	53.9
	98	32	100	17	113	28	3	400	10	2.5	208.0	624.0	62.4
	119	25	203	9	297	113	3	324	11	3.4	168.5	505.4	45.9
	53	26	202	17	151	4	3	84	6	7.1	43.7	131.0	21.8
	85	25	140	11	270	102	3	85	10	11.8	44.2	132.6	13.3
Aleyne St, Chelsea	49	27	5	50	10		2	68	12	17.6	35.4	70.7	5.9
	35	34	6	39	20		2	112	24.5	21.9	58.2	116.5	4.8
	5	29	9	79	21		2	213	17	8.0	110.8	221.5	13.0
	19	30	8	50	12		2	163	22	13.5	84.8	169.5	7.7
Point Park, Docklands	139	25	321	7	246		1	410	7	1.7	213.2	213.2	30.5
	135	20	77	47	306		1	370	7	1.9	192.4	192.4	27.5
Hamilton St, W. Brunswick	36	14	7	76	5		3	3200	4	0.1	1664.0	4992.0	1248.0
	137	34	11	63	11		3	91	1	1.1	47.3	142.0	142.0
Avoca Cr, Pascoe Vale	13	36	11	47	9		3	120	5	4.2	62.4	187.2	37.4
	26	34	10	51	11		3	200	4	2.0	104.0	312.0	78.0
	44	34	6	59	15		3	310	4	1.3	161.2	483.6	120.9
Parker St, Pascoe Vale	24	34	23	30	4		3	314	12	3.8	163.3	489.8	40.8
	19	21	56	13	16		3	157	14	8.9	81.6	244.9	17.5
	39	34	1	138	7		3	528	7	1.3	274.6	823.7	117.7
Ceres, West Brunswick	97	19	60		13		2	1257	21.75	1.7	653.6	1307.3	60.1
Bourke St tree pit, Melbourne	84	23			23	21	1	100	1.44	1.4	52.0	52.0	36.1
Hallam Bypass, Floret Pl	154	24			199	63	3		120				
Hallam Bypass, Wanke Rd	115	22			490	387	3		12				
Hallam Bypass, Wanke Rd basin	203	27			286	207	3		168				
Wolseley Pd, Vic Park (NSW)	159	18	425	5	376	560	7	1504	330	21.9	1413.3	9893.0	30.0
Leyland Gr, Vic Park (NSW)	237	17	398	4	151	224	7	1804	180	10.0	1695.8	11870.3	65.9
2nd Pond Creek (NSW)			5	21					2000		0		

The influence of this result on the system hydrologic effectiveness is shown by the MUSIC model results in Figure 3. For a system designed at 2.5 % of its catchment area in Melbourne (which is large by current standards), an extended detention depth of 30 cm and with a K of only 50 mm/h, 74% of the mean annual inflow is treated by the biofilter. If the system conformed with the recommended hydraulic conductivity (K of 180 mm/hr), it would intercept only 18% more of the mean annual flow. In other words, the observed frequent over-dimensioning of filter area compensates for the low hydraulic conductivity, even through detention depths are generally relative shallow in the systems tested. When K_{fs} drops to 5 mm/h, 44% of flow is treated (for a size of 2.5%) and 64% for a size of 5.3%. The key lesson is that over-sizing of biofilter area will help to 'buffer' against unintended reductions in hydraulic conductivity.



K(mm/h)/ Size ratio (%)*	1.65	2.5	5.3
180	85	92	98
50	63	74	90
10	40	51	71
5	34	44	64

** With Melbourne data*

Figure 3: Influence of the ratio biofilter/catchment size and of the K_{fs} on the 'hydrologic effectiveness'

At the time of this study, no Australian guidelines made explicit acknowledgement of this issue; the interaction of hydraulic conductivity, filter area and ponding depth, in determining the effective infiltration capacity of the biofiltration system (Figure 4). However, in response to this lack, the Facility for Advancing Water Biofiltration (FAWB) recently revised its filter media guidelines, to provide greater guidance on the interaction between design elements in determining infiltration capacity (Figure 4). Designers should not consider hydraulic conductivity in isolation, but rather, should design systems using an integrated approach.

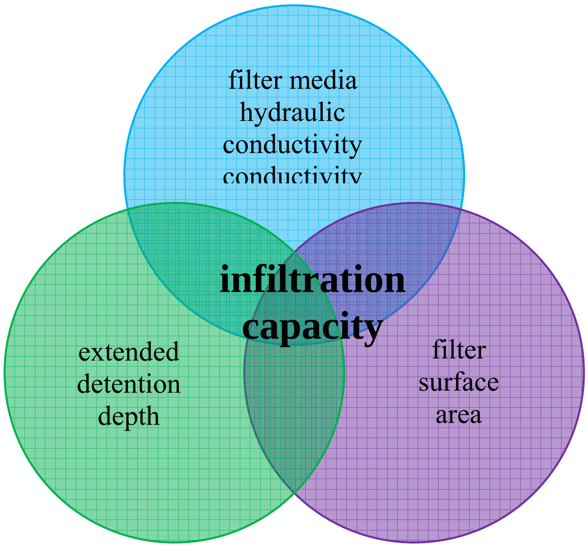
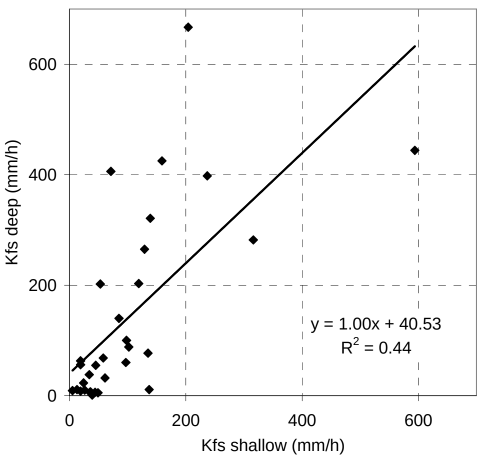


Figure 4. Design elements that influence infiltration capacity (source: www.monash.edu.au/fawb).

3.2 Comparing field methods

Statistically both methods give similar results (p=0.38 for n=32). Correlation between two methods is moderately strong with $R^2 = 0.44$ (Figure 5). This result can be explained by the similarity between the two methods, which are both a pressure test applied on the same surface of soil. The differences could be explained by the uncertainty on each reading (around 30% as shown in Table 3) and by the spatial variability in the systems. Contribution to uncertainty of the latter can be evaluated at 50% as shown in Table 4, based on repeated application of the hydraulic conductivity measurements in one system. Since tests have not been conducted in the same spot it could explain the moderate correlation.



	$K_{fs\ shallow}$	$K_{fs\ deep}$
Mean (mm/h)	100	140
σ (mm/h)	115	172
Cv (%)	115%	123%
n	32	
p	0.38*	

* logged transformed data to respect the normality for $K_{fs\ deep}$

Figure 5 : Correlation between field methods

Table 4 : K value and Cv for each site

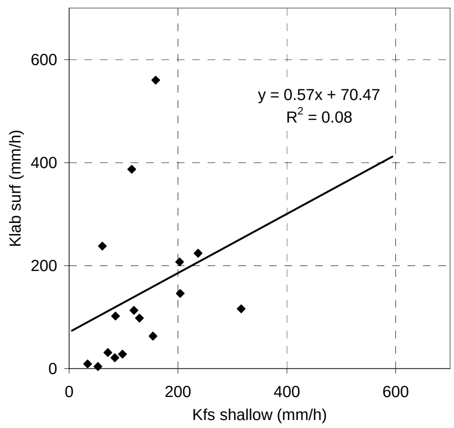
	Shallow method			Deep method		
Sites	n	K (mm/h)	Cv (%)	n	K (mm/h)	Cv (%)
Cremorne St, pod7, Richmond	3	119	29	3	203	32
Cremorne St, pod9, Richmond	3	85	55	3	140	54
Parker St, pod 2 Pascoe Vale	3	19	46	3	56	48
Ceres, Brunswick East	4	97	63	4	60	73
Hamilton St pod1, Brunswick West	3	36	52			
Monash car park, strip 1	4	58	34			
Monash car park, strip 2	3	102	58			
Monash car park, strip 3	3	45	33			
Point park car park, Docklands, pod2	3	135	28			
Alleyene st, Chelsea, pod4	3	19	140			
Tree pit, Docklands, pod7	3	84	78			
Hallam Bypass, Wanke Rd	3	115	55			
Hoyland St	6	204	59	3	667	32
Donnelly Pl	3	19	58			
Saturn dr	3	34	16	3	38	67
Wolseley Pd, Vic Park	5	159	63	5	425	80
Leyland Gr, Vic Park	5	237	55	5	398	21
2nd Pond Creek				9	5	67
Average		78	53		221	53

3.3 Comparing field and laboratory methods

The shallow field method gives results that are not statistically different from the measurement made in the laboratory on samples taken from the surface ($p=0.71$, $n=16$). The consequence of this is that there is very little bias introduced by the choice of method. It is therefore possible to compare measurement from the field (shallow method) and from the lab without effect of the method. These results are similar to that of Reynolds *et al.*(2000), which showed for a sand and a loam, that the hydraulic conductivity measured in the field (shallow method) does not vary significantly from laboratory measurements ($p>0.05$, $n=12$ for the sand, $n=10$ for the loam).

The correlation between methods is low (R^2=0.08). It can be explained by the spatial variability of the hydraulic conductivity and by the variations in compaction between the samples. In the laboratory, measurements are conducted on disturbed samples (inevitably during sampling) that have been re-compacted to a standard value which may be different than that which existed in the field. It may also be speculated that another reason for lower K found in the laboratory measurements is due to the samples being taken right at the surface; they therefore represent deposition formed over time (i.e. they are deposited stormwater sediment). In this way $K_{lab,\ surf}$ represents the hydraulic conductivity of the clogging layer on its own.

If we compare the results from the deep field tests and the laboratory tests, results are statistically different ($p<0.01$ n=11). Importantly, these methods cannot be directly compared, because they have a relatively low correlation (R^2=0.11).



	$K_{fs\ shallow}$	$K_{lab\ surf}$
Mean (mm/h)	133	147
σ (mm/h)	76	151
Cv (%)	57%	103%
n	16	
p	0.71	

Figure 6 : Correlation between field method and laboratory method on surface samples

3.4 Clogging of systems over time

Comparing results of the field experiments (which both provide an estimate of the current system conductivity) and laboratory measurements on deep samples (which provide an estimate of the initial conductivity) provides an indication of the evolution of hydraulic conductivity since construction. Sediment deposition is considered to be the principal cause of clogging (Bouwer, 2002) and can occur at the surface of the system with the creation of a clogged layer (surface clogging) or deeply, by filling of the pore space (interstitial clogging), as explained by Langergraber et al. 2003 and Winter et al.

(2003). Since both field measurements of the hydraulic conductivity give similar results (average value: $K_{fs\ deep}$ = 140 mm/h, Cv=123% and $K_{fs\ shallow}$ =100 mm/h, Cv=115%), it is evident that hydraulic conductivity of the system is controlled primarily by the top layer and that there is no deep 'clogging' of the soil media.

However, vegetation development and especially root growth, will lead to the creation of macropores. For example, Archer et al. (2000) showed that root growth increases hydraulic conductivity, as root dieback creates macropores which facilitate water movement in the soil. It is not yet clear whether this phenomenon will have a major impact on biofilter hydraulic conductivity; if clogging is primarily occurring on the surface, macropores below the clogged layer at the top may have little or no consequence.

Results of the Ascendant Hierarchical Classification show four groups with distinctly different behaviour. Group 1 has only one biofilter, which is undersized (0.1 % of the catchment); group 2 has three systems with very high K_{fs} ($K_{fs\ shallow}$ average = 200 mm/h) and very high initial K ($K_{lab\ deep\ ini}$ average = 197 mm/h). Groups 3 and 4 represent 88% of the systems tested. Biofilters from group 3 have a high initial K ($K_{lab\ deep\ ini}$ average = 241 mm/h, n=17), whilst group 4 systems have a low initial K ($K_{lab\ deep\ ini}$ average= 12 mm/h, n=11).

Systems with a high initial hydraulic conductivity (which can be explained by media with relatively coarse particles and a subsequently large pore space) will decrease substantially over time, and proportionally by a greater amount than will systems with a low initial hydraulic conductivity. This is demonstrated by the fact that the field shallow test results show a hydraulic conductivity on average 114 mm/h (n=17) lower than the laboratory deep tests as shown on Figure 7. This result is also confirmed by the difference between the laboratory tests taken on the deep and surface samples, with an average difference of 255 mm/h (n=9).

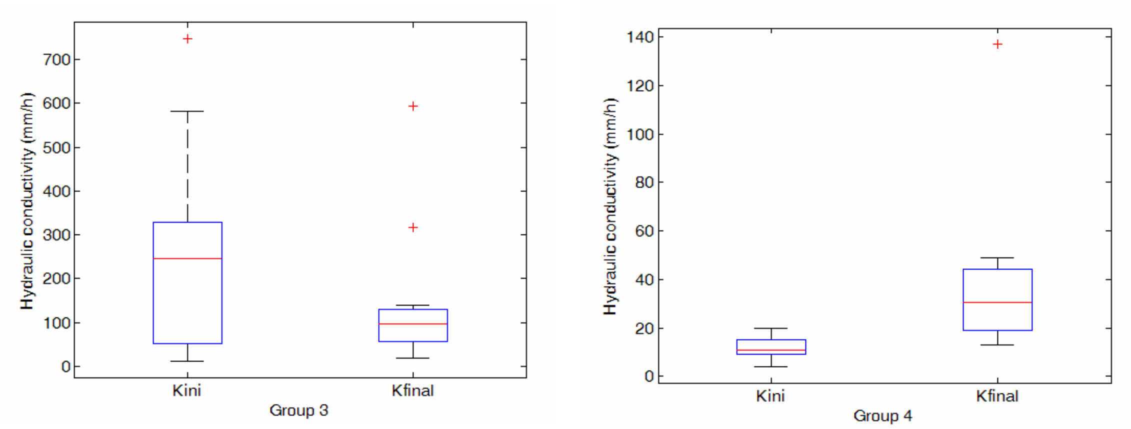


Figure 7 : $K_{lab\ deep\ ini}$ vs. $Kf_{s\ shallow}$ – white triangle, system with low initial hydraulic conductivity, black square, systems with high initial hydraulic conductivity

This decrease can be explained by sediment deposition at the surface. However, final hydraulic conductivities are still relatively high ($K_{fs\ shallow}$ = 127 mm/h, n=17), and likely to be adequate to ensure good pollutant removal performance. This observation may be either because the systems are only partially clogged, or because creation of macropores is having some effect in creating flow through the media, possibly even at the surface (for example, at the base of plant stems, where growing, senescence and even stem movement due to wind, may cause 'breaking up' of any clogging layer) (Figure 8).

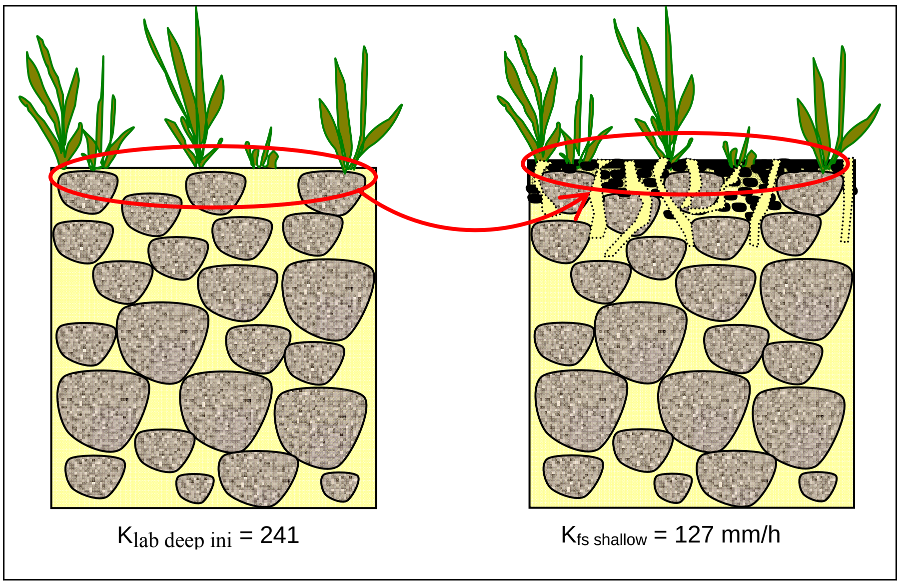


Figure 8 : Schematic representation of the evolution of the behaviour of biofilters with high initial K

Systems with low initial hydraulic conductivity (explained by a high concentration in fine particles and thus a low pore volume) show effectively no decrease over time (ΔK average = +25 mm/h, n=11; Figure 7). In part, this is because the relative difference in particle size of the filter media, and of the influent sediment, will be less, meaning that any buildup of sediment at the surface will have proportionally less impact. The slight increase could again be contributed to by macropore creation by roots (Figure 9), although further studies are required to test this hypothesis.

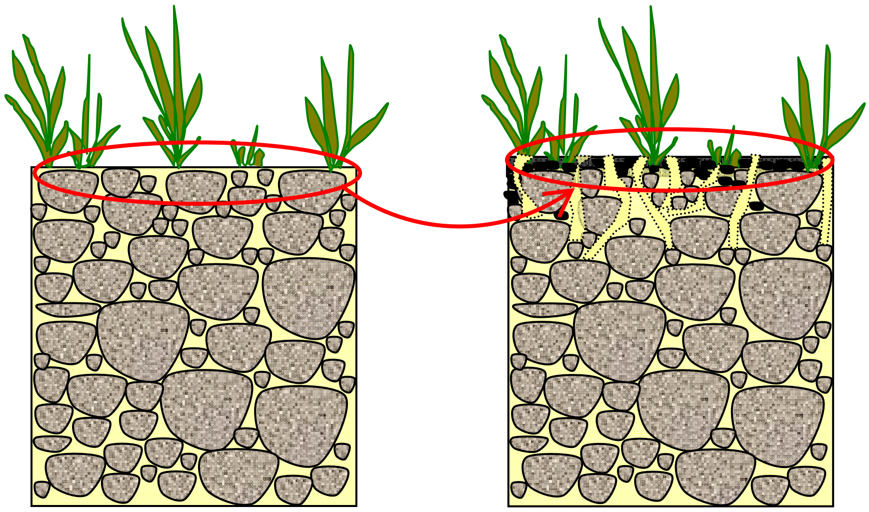


Figure 9 : Schematic representation of the evolution of the behaviour of biofilters with low initial K

3.5 Influence of system characteristics and hydraulic performance

Of all the factors tested – age of the biofilter, its initial hydraulic conductivity, the ratio between its size and the size of the catchment drained, the volume of water received per year and the volume of water received per m² of system since its construction – only the initial conductivity provided a statistically significant explanation of variability in current conductivity of the systems (Table 5).

Table 5: Regression between $K_{fs\ shallow}$ and various parameters

Field method	$K_{fs\ shallow}$
R^2	0.52
Parameters	P value
(Constant)	0.00
$K_{lab\ deep\ (ini)}$	0.00
Age	0.24
Ratio	0.34
Volume of water/year	excluded
Total volume/m²	0.49

Achleitner et al. (2006) reported a similar lack of correlation between hydraulic conductivity and site characteristics, and made the hypothesis that current K was mainly governed by the initial value. This result is in some ways unfortunate, because it provides little guidance to those charged with the maintenance of such systems, in being able to predict their lifespan and maintenance requirements. However, it does show the importance of correctly specifying the filter media during the biofilter design, and of having appropriate quality control to ensure that the supplied and installed media meets these specifications.

One approach is to use a “contingency factor” in the specification of hydraulic conductivity for biofiltration systems. For example, where the design intent is to use a soil media with a hydraulic conductivity of 180 mm/hr, sizing of the system should be undertaken assuming a hydraulic conductivity of 50% of the design value (ie. 90 mm/hr). In this way, if the media does not meet specifications, or shows a decline in hydraulic conductivity over time, the overall system performance will remain satisfactory.

4 Conclusions

Whilst biofilters have been demonstrated to provide effective stormwater quality treatment, their long-term hydraulic behaviour has to date not been studied, particularly in reference to real systems. This study provides a first attempt to evaluate performance of a range of constructed systems, with design and catchment characteristics.

From a measurement point of view, the different field methods used gave similar results, demonstrating that for these soil-based biofilters, hydraulic conductivity is governed by their surface layer. Field and laboratory experiments gave identical results.

Regarding system design and construction, three key messages are deduced.

Firstly, whilst many systems measured have a low hydraulic conductivity (lower than *currently* recommended values), a tendency by designers to over-dimension the systems (relative to guidelines) acts to compensate for the low conductivity. Critically, however, current guidelines do not address this relationship, and seem to pay no attention to the risks of diminished effectiveness when systems are either constructed with lower-than-desired conductivity, or when clogging causes conductivity to decline over time. In particular, this may occur as a result of poor construction management practices in the catchment, resulting in excessive sediment loading. Strict controls should be in place during the construction phase of development.

Secondly, proportional hydraulic conductivity reduction occurs mainly for systems with high initial value, but the resulting value ends up generally respecting the guidelines. Other systems, which have been constructed with low-conductivity soils, do not show evidence of further decline, possibly because the filter media particle size distribution is more similar to that of the influent sediment, than is the case for systems with high initial conductivity (and thus coarse media). Declines in conductivity over time are likely to occur by sediment deposition, which occurs at the surface of the systems. Whilst macropore creation by vegetation may limit the effect of clogging, further detailed research is needed to verify the reliability of this strategy in maintaining soil hydraulic conductivity within recommended guidelines.

Finally, it was not possible to predict a filter's current hydraulic conductivity from factors such as its size, the catchment size, or the inflow volume. The initial specified hydraulic conductivity is the critical determinant of its long-term hydraulic behaviour. Whilst this provides little help in predicting system lifespan or maintenance requirements, it does reinforce the criticality of specifying the correct hydraulic conductivity of systems at the time of construction. Perhaps most importantly, guidelines do not pay due attention to the importance of translating design specifications through the construction process. Contract hold-points should in place to ensure testing of the media during construction.

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