Hydraulic conductivity and impact on retrofit stormwater biofiltration - case study of the design, assessment and function of retrofit raingardens using different filter media in Sydney.

Impacts de la conductivité hydraulique sur la biofiltration des eaux pluviales : étude de la conception, du fonctionnement et du suivi de jardins d'eau utilisant différents systèmes de filtration à Sydney, Australie

Olof J. Jonasson[1], Peter Davies[1,2], Sophia Findlay[1]

1. Ku-ring-gai Council 818 Pacific Highway, Gordon NSW Australia 2072 jjonasson@kmc.nsw.gov.au,
2. Macquarie University - Macquarie University NSW 2109, Australia

RÉSUMÉ

Cet article présente une étude de cas sur la conception de divers systèmes de biofiltration au moyen de différents matériaux de filtration et de différentes méthodes de mesure de la conductivité hydraulique. La modélisation mise en œuvre dans le cadre de cette étude a montré que pour les petits systèmes, une conductivité hydraulique élevée entraîne globalement de meilleurs résultats. L'évaluation des performances hydrauliques des systèmes existants a été effectuée au moyen de deux méthodes différentes utilisant toutes deux un infiltromètre à anneau unique, mais selon deux formules différentes de calcul de la conductivité hydraulique. Les résultats ont montré, en comparant les deux méthodes, que la biofiltration sur argile sableuse donnait une conductivité hydraulique notablement plus basse que celle précédemment rapportée dans les essais en laboratoire. Tous les essais ont fait apparaître une large variabilité dans les résultats, suggérant un besoin de prudence quant à l'utilisation d'un seul test ou d'une seule méthode pour mesurer la conductivité hydraulique avec précision. Du point de vue de la conception et de l'exploitation, cette étude approuve l'utilisation de sable plutôt que d'argile sableuse comme milieu de filtration, particulièrement lorsqu'il n'y a pas assez d'espace pour dimensionner le système de biofiltration suivant les recommandations des bonnes pratiques.

ABSTRACT

This paper presents a case study of the design and performance of various biofiltration systems using different filter media and different methods to measure hydraulic conductivity. Modelling undertaken as part of this study indicated that for small systems a high hydraulic conductivity will result in a better overall performance. Assessment of the hydraulic performance of four biofiltration systems was carried out using two different methods, both using a single ring infiltrometer but using different formulas to calculate the hydraulic conductivity. The results showed that biofiltration using sandy loam reported significantly lower hydraulic conductivity using both methods than that previously reported in laboratory tests. In all testing there was great variability in the results suggesting the need for caution to rely on any single test or method to accurately report the hydraulic conductivity. From a design and operational perspective this study supports the use of sand over sandy loam as a filter media particularly where there is insufficient space to size the biofiltration system according to best practice guidelines.

KEYWORDS

Hydraulic conductivity, biofiltration, bioretention, raingarden, Water Sensitive Urban Design, stormwater modelling, stormwater quality, filter media, urban drainage

1 INTRODUCTION

In a fully developed catchment, retrofitting stormwater quality devices can be challenging due to space limitations and the presence of underground services such as electricity, water and gas. This is particularly so for biofiltration systems, also called raingardens or bioretention systems, where it can be difficult if not impossible to secure the necessary surface area required to comply with current design guidelines. When designing and assessing the performance of a biofiltration system, the hydraulic conductivity of the filter media is a vital design consideration. Current Australian design guidelines for biofiltration systems acknowledge the relationship between ponding depth, size and hydraulic conductivity of a filter media on the performance of a biofiltration system (FAWB 2008), but it is left to the individual designer to quantify the relationship between these design parameters.

While sand is effective in capturing TSS, TP and TN in a biofiltration application (Hatt et al 2007a), a filter media with a high hydraulic conductivity is unlikely to support plant growth (FAWB 2008). This is an important consideration as plants are a vital component of biofiltration systems (Bratieres et al., 2009, Hatt et al., 2007a, Henderson et al.,2007). Plant growth and root mass will counter the effect of compaction over time and help to maintain hydraulic conductivity (FAWB 2008). Sandy loam is therefore commonly used in biofiltration applications and is considered a suitable growing media (Henderson et al., 2007, Fletcher et al., 2007). However, much of the available research focuses on the efficiency of the filtration media in removing target pollutants with limited fieldwork being undertaken on existing systems to validate the relationship with other design parameters.

Since 2004, Ku-ring-gai Council has implemented a range of Water Sensitive Urban Design (WSUD) projects as part of its capital works and environmental programs. The Ku-ring-gai local government area (LGA) is located approximately 15 kilometres north of the Sydney CBD in New South Wales (NSW), Australia and covers an area of 85.4 km^2 (ABS 2006). It is predominately characterised by low density residential housing set on individual lots. A formalised drainage system is present across most of the developed area with the connected impervious percentage being approximately 29% (Davies et al, in review).

A focus of Ku-ring-gai Council's WSUD program is to quantify the performance of various devices installed to improve future design and operation and also to contribute to the applied research in this field of study. The performance of biofiltration systems for treating stormwater is assessed by water quality sampling before and after water passes through the filter and hydraulic conductivity testing using different methods (Le Coustumer et al. 2007, Bouwer 1986). This paper presents a case study of the design of various biofiltration systems using different filter media and field methods to measure hydraulic conductivity and to verify assumptions made during the design

2 BACKGROUND

Many organisations in Australia are using the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) as developed by the Australian Cooperative Research Centre for Catchment Hydrology (CRCCH) for the design and evaluation of biofiltration systems treating urban runoff. Hydraulic conductivity of the filter media is an important variable in the modelling and the use of realistic values is key for both design and during evaluation.

The specification of a soil media intended for biofiltration applications often includes a value for saturated hydraulic conductivity as tested by the supplier. However, time and financial constraints often limits the ability to test filter media supplied to site and figures provided by the supplier is often relied upon when making design decisions and evaluating the performance and benefits of a biofiltration system.

In 2006 Ku-ring-gai Council constructed a number of small biofiltration systems. These were designed in accordance with then current design guidelines (Ecological Engineering et al 2006). However once in operation problems were observed related to the hydraulic conductivity being considerably lower than what was designed and indicated as part of the soil specification. Performance was further compromised by having limited space in the developed catchment to construct larger systems, something that would have counteracted the decline in hydraulic performance. As a consequence, the majority of runoff was discharged to the receiving environment without any treatment at all. As a result of this, Council started to investigate alternative design approaches for biofiltration systems in a fully developed catchment.

Modelling undertaken in 2007 using MUSIC version 3.01 indicated that for small systems, using a filter media with a high hydraulic conductivity would result in improved overall treatment of stormwater runoff compared to filter media with a lower hydraulic conductivity. A hypothesis was developed that by utilising a sand filter media rather than sandy loam the overall performance of the system could be improved. This approach could support the use of systems with a smaller footprint than the traditional approach using a sandy loam media.

In order to assess the field performance of filtration media with a high hydraulic conductivity, a sand filter biofiltration system was constructed in 2008 at Kooloona Crescent, West Pymble (Latitude -33.7667, Longitude 151.1322) (Figure 1). Coarse washed river sand was used and was amended with water absorbing polymers in an attempt to provide some longer term water availability for the plants. The filter was densely planted with mix of *Juncus usitatus, Dianella caerulea* and *Iseolepsis sp.* Runoff that has passed through the system is collected at the base of the filter and discharge back to the drainage network. During construction the filter was unfortunately covered with decomposed granite containing fines that may have impacted on the overall hydraulic conductivity of the system.

Figure 1. Biofiltration system at Kooloona Crescent, West Pymble (Left), and at Nimbrin Street, Turramurra (Right)

When the vegetation was fully established in 2009, field testing of the hydraulic conductivity was performed to verify design assumptions. Two different methods were used and results were compared with field test results from three other biofiltration beds of a similar age constructed using filter media complying with design guidelines at the time of construction.

Three raingardens were constructed adjacent to Nimbrin Road, Turramurra (Latitude -33.7483, Longitude 151.1160) in 2008 (Figure 1). The gardens were designed in series, intended to focus most of the maintenance on the first bed (as this would receive the bulk of the sediment load). The first two gardens also included a small section of un-vegetated sand in an attempt to increase the hydraulic performance of the systems. Coarse washed river sand was used, the same sand as for the raingarden at Kooloona Crecsent, Gardens are planted with a mix of *Juncus usitatus, Dianella caerulea* and *Dichelachne micrantha*. All three gardens included a subsoil drainage system, collecting filtered water for reuse.

3 METHODOLOGY

3.1 Modelling of biofiltration systems

Modelling of a hypothetical system with different filter media characteristics and surface areas was performed using MUSIC version 3.01 to assess how a change in hydraulic conductivity is likely to impact on the overall performance of a biofiltration system. This computer model can assess the likely water quality improvements that can be expected from different stormwater quality improvement strategies (CRCCH 2005). Modelling parameters and values are presented in Table 1.

Extended detention depth		100mm
Seepage loss		0 mm/hr
Surface area/filter area		0.2-2.5% of connected impervious catchment
Filter depth		500mm
Depth below underdrain pipe		0 % of filter depth
Overflow weir width		2.00m
Filter specifications		
Ksat	**Median particle size**	**Source**
1000mm/hr	0.6mm	Median particle size from material specification (coarse sand)
750mm/hr	0.6mm	Median particle size from material specification (coarse sand)
315mm/hr	0.6mm	Median particle size from material specification (coarse sand)
170mm/hr	0.15mm	Median particle size from material specification (sandy loam)
40mm/hr	0.15mm	Median particle size from material specification (sandy loam)

Table 1. Input in MUSIC model assessing alternative filter media in biofiltration systems

3.2 Hydraulic conductivity measurement

Hydraulic conductivity of soil in laboratory was assessed using three different methods:

1. permeability testing as per Australian Standard AS4419-2003
2. *Hydraulic Conductivity Compaction Curve* (HCCC) developed by McIntyre & Jacobsen (1998)
3. method proposed by the Unite States Golf Association (USGA) (ASTM F1815 (2006)).

The field method recommended for use in Australia by FAWB 2008 and used in this study is the single ring, constant head infiltration test method (shallow test), as described by Le Coustumer et al. (2007). The test utilises a single ring infiltrometer inserted 50mm into the filter media and applies a constant head. The saturated hydraulic conductivity is calculated using flow rates from two different constant heads, 50mm and 150mm.

As a comparison, tests were also carried out using the field method described in Bouwer (1986) by an external consultant. This method uses a single ring infiltrometer similar to the shallow test described by Le Coustumer et al (2007) but this is inserted approximately 100mm into the soil media. Saturated hydraulic conductivity is calculated using flow rates from a constant head of approximately 150mm. The later method applies Darcy’s Law when calculating the saturated hydraulic conductivity as opposed to the shallow test method described by Le Coustumer et al (2007) that assumes a Gardner’s behaviour of the soil (Le Coustumer et al. (2007)).

In MUSIC version 3.01 the flow through rate of a bioretention system appears to be calculated using Darcy’s Law. Consequently the flow through rate will depend on the hydraulic conductivity as specified in the model, as well as filter depth and ponding depth. The flow through rate will increase with an increased ponding depth and will decrease with a deeper filter layer.

4 RESULTS

4.1 Modelling of biofiltration systems

MUSIC modelling indicated that for small systems where the available surface area of the biofiltration system is limited (with a surface area of 0.25%-0.75% of the upstream impervious catchment) a filter media with a higher hydraulic conductivity will result in an improved overall treatment performance in terms of percentage mass removal of pollutants. (Figure 2). The total % of pollutants removed is related to the volume of water that is treated (increases with an increased hydraulic conductivity) and the pollutant concentration reduction achieved (increases with a decrease in hydraulic conductivity

(Bratieres et al 2009)). Larger systems with a hydraulic conductivity of 40-315mm/hr are predicted to remove a greater percentage of target pollutants. This is consistent with current design guidelines, recommending a hydraulic conductivity of between 100-300mm/hr (FAWB 2008). These guidelines however assume that the biofiltration systems can be sized to be approximately 2% of the contributing catchment. This is not always possible in a developed catchment.

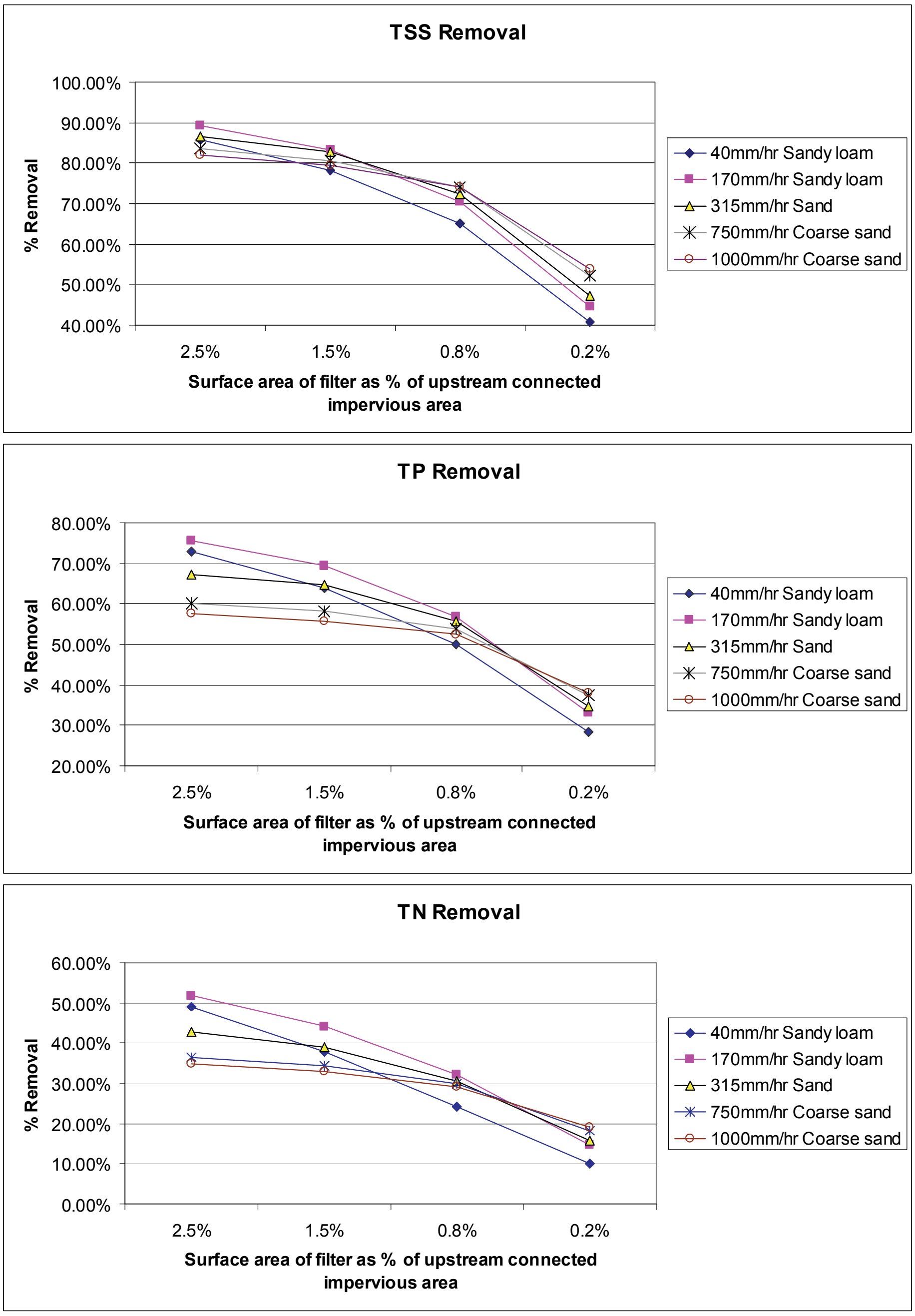

Figure 2. Results, MUSIC modelling of different filter media in biofiltration systems

4.2 Hydraulic conductivity

4.2.1 Laboratory testing of hydraulic conductivity

Results from laboratory testing of hydraulic conductivity for the sandy loams used for the filter gardens at Nimbrin Street were provided by the supplier. The sand media used at Kooloona Crescent was tested by an external laboratory. The results are presented in Table 2.

Filter media	Supplier Code	Site used	Saturated hydraulic conductivity (mm/hr)	Test method used	Comments
Sandy loam	M165	Nimbrin Street	460 (after 32 drops)	HCCC	Information from product specification. Three methods were used in assessing hydraulic conductivity of the soil media.
			400	AS 4419	
			332	USGA	
Coarse washed river sand	+425 Sand	Kooloona Crescent	740	USGA	Laboratory testing performed (by Sydney Environmental & Soil Laboratory, SESL) on actual sand delivered for use in biofiltration systems

Table 2. Hydraulic conductivity test results, laboratory testing

4.2.2 Field testing of hydraulic conductivity

Testing for all four biofiltration systems were carried out using both the single ring (shallow test) infiltrometer as described by Le Coustumer et al (2007) and by Bouwer (1986).

For comparative reasons a third calculations was carried out using the flow rates obtained from the single ring (shallow test) infiltration test as described by Le Coustumer et al. (2007), but applying Darcy's Law in calculating the hydraulic conductivity. This is in effect a variation of the method described in Bouwer (1986). Darcy's Law assumes that there is zero pressure head below the single ring infiltrometer. Even though this is unlikely to be the case the top layer of a bioretention system is often limiting the overall hydraulic performance of a biofiltration system as this layer is most susceptible to clogging from fine sediments washed into the system. For this reason it can be assumed that the underlying filter media has a higher hydraulic conductivity that the top layer, and applying Darcy's Law should give a conservative low result. The results for all three methods are presented in Table 3.

	Hydraulic conductivity Kfs (mm/h), Single ring infiltration test (shallow test) as described by Le Coustumer et al. (2007)	Hydraulic conductivity Kfs (mm/h), Single ring infiltration test as described by Bouwer (1986).	Hydraulic conductivity Kfs (mm/h), calculated by adopting Darcy's Law to flow rates obtained using Single ring infiltration test (shallow test, 50mm head) as described by Le Coustumer et al. (2007)	Hydraulic conductivity Kfs (mm/h), calculated by adopting Darcy's Law to flow rates obtained using Single ring infiltration test (shallow test, 150mm head) as described by Le Coustumer et al. (2007)	Hydraulic conductivity Kfs (mm/h) from laboratory test using USGA
Nimbrin St 1					
A (sandy loam)	46	87	91.7	80.2	
B (sandy loam)	18	207	105.4	66.5	
C (sandy loam)	N/A	70	N/A	N/A	
Washed sand section	-55	756	664.6	292	
Average (sandy loam):	*32*	*121*	*98.6*	*73.4*	*332*
Nimbrin St 2					

A (sandy loam)	17	426	213.1	119.2	
B (sandy loam)	18	190	105.4	66.5	
C (sandy loam)	N/A	84	N/A	N/A	
Washed sand section	2	N/A	520.2	261.3	
Average (sandy loam):	*17.5*	*233*	*159.25*	*92.9*	*332*
Nimbrin St 3					
A (sandy loam)	4	142	261.3	132.9	
B (sandy loam)	-6	173	348.4	170.7	
C (sandy loam)	-24	64	153.6	58.4	
Average (sandy loam):	*-8.7*	*126*	*254.4*	*120.7*	*332*
Kooloona Cr					
A (washed sand)	34	1009	634.8	342.6	
B (washed sand)	45	1077	325.4	196	
C (washed sand)	N/A	1127	N/A	N/A	
D (washed sand)	N/A	758	N/A	N/A	
Average (washed sand):	*39.5*	*993*	*480.1*	*269.4*	*740*

Table 3. Saturated Hydraulic conductivity as tested in the field using single ring infiltration test (shallow test) as described by Le Coustumer et al. (2007), field method described Bouwer (1986) and using flow rates obtained through (shallow test) method proposed by Le Coustumer et al (2007) (50 and 150mm head), adopting Darcy's Law. Results compared to laboratory test results using USGA

4.2.3 Field observations

The rain gardens at Nimbrin Street all have a rectangular shape with vertical walls. This allows the calculation of the hydraulic performance during a storm event with reasonable accuracy. Following a period of rainfall, the rate of which the water level dropped in Nimbrin 3 was recorded after inflow to the biofiltration bed had ceased. Nimbrin 3 is constructed using only M165 sandy loam. The water level was recorded as dropping by approximately 7mm every 10 minutes over a period of 30 minutes (from 103 to 81). Adopting Darcy's Law this would be equivalent to a hydraulic conductivity of approximately 35mm/hr.

During storm events at the Kooloona Crescent biofiltration system it was observed that water did pond on top of the filter during high inflows. Though no detailed recording was carried out of water levels and the rate of which the level dropped, it was observed that the water subsided rapidly (in a matter of minutes) once flow into the garden decreased.

5 DISCUSSION

5.1 Hydraulic conductivity

The four biofiltration systems were tested at multiple points (between two and four locations) using two different methods (refer to Table 3).

The hydraulic conductivity as measured using the single ring infiltration test (shallow test), as described by Le Coustumer et al. (2007) reported a high variability for the washed sand. This was inconsistent with field observations. The average hydraulic conductivity of the sandy loam between the four systems varied from -24mm/hr to 46mm/hr. The results did not compare favourably with the results obtained using the field method described by Bower (1986).

The single ring infiltration test (shallow test) as described by Le Coustumer et al. (2007) and recommended by current Australian guidelines (FAWB 2008) calculates the saturated hydraulic conductivity using a different equation than the field method described by Bower (1986), and utilises the difference in flow rate from 50mm and 150mm of head. Many of the tests carried out as part of this study showed only minor differences in flow between 50mm and 150mm head. The resulting hydraulic conductivity was calculated as low in these cases irrespective of the actual flow rate. During testing of Nimbrin 3, the results were calculated as negative using the method (shallow test) described by Le Coustumer et al. (2007), as a slightly higher flow rate was recorded at 50mm head compared to 150mm head. This raises suspicion that testing was not carried out long enough for the flow to stabilise. Testing in Nimbrin 3 was however carried out for a duration of 80 minutes for a head of 50mm, and a further 60 minutes for a head of 150mm. These were longer durations than the tests done for Nimbrin 1 and 2. The significant impact on the results where the difference in flow between the 50mm and 150mm heads is low is identified as a limitation of this method. This could potentially impact on the calculated effectiveness of the system during evaluation.

The method described by Bouwer (1986) appears to overestimate the hydraulic conductivity and is also inconsistent with field observations from Nimbrin 3. There are some questions whether the testing was carried out for a sufficient duration of time to achieve saturated conditions. This may have impacted on the test results. If a higher hydraulic conductivity is assumed as part of the design or evaluation process this may overestimate the performance of the treatment system.

The hydraulic conductivity is considerably higher when applying Darcy's Law to the flow rates measured during field testing than using the method (shallow test) described by Le Coustumer et al. (2007) (Table 3). Using the result from the 50mm head test to calculate the hydraulic conductivity using Darcy's Law resulted in the hydraulic conductivity being approximately twice that determined using the result from the 150mm head test. This shows some uncertainty in this method and indicates that multiple tests using different heads should be undertaken when Darcy's Law is used to calculate the hydraulic conductivity. The results are generally more in line with the results obtained by using the method described by Bouwer (1986) for all sandy loams, as would be expected. However this is not the case for the coarse sand used at Kooloona Crescent, where the results vary considerably between all methods used.

Le Coustumer et al (2007) and later in Le Coustumer et al (2008) reported variability in the hydraulic conductivity using shallow and deep tests on the same sites, noting that the deep test applied Darcy's Law. This is consistent to the results reported in this study. Whilst some of the differences can be attributed to variability within the individual systems, further noting that the hydraulic conductivity will vary over the life of the system (FAWB 2008), this presents difficulties for stormwater managers to evaluate the performance of their systems. The results obtained by using methods applying Darcy's Law appear to be more consistent. This method shows a clear difference in hydraulic conductivity between sand and sandy loam. This is not the case for results obtained using the (shallow test) method described by Le Coustumer et al. (2007).

Given the spatial and temporal variability of any system, it is appropriate to recommend multiple testing within each individual system and that testing is performed using different heads. Importantly, the results should be read as indicative rather than definitive.

5.2 Implications of using a sand filter media compared to sandy loam

Sand is effective in capturing TSS, TP and TN in a biofiltration application (Hatt et al 2007). As sand is likely to have a higher hydraulic conductivity than sandy loam, this would suggest that sand may be a preferred filter media where the size of the filter is limiting the overall performance of a biofiltration system.

Recent research undertaken by Monash University has further investigated the use of sand based filter media instead of the sandy loam media as recommended by current design guidelines (Bratieres et al 2009). The Monash study showed that sand based filter media has quite poor treatment performance for the first six months however the difference is less profound after one year. Bratieres et al (2009) also reported that a sand based filter media is less likely to leach nitrogen. Other studies have shown that soil based filter media used in biofiltration systems may be net producers of nitrogen (Hatt et al 2007), providing further support for using sand based filter media.

The findings by Bratieres et al (2009) support the hypothesis proposed that using sand based filter media have some benefits over a sandy loam filter media in certain applications. The poor performance during the first six months observed by Bratieres et al (2009) from the sand filter may be offset by the fact that a washed sand will contain less fines than a sandy loam and is thus less likely to export sediment during the initial period after installation. Such export has been observed from a number of biofiltration systems constructed using a sandy loam filter media across the Ku-ring-gai local government area. This observation is of some concern and is an area for more investigation. Anecdotal evidence from other councils in the Sydney region indicates that this is a common problem. There is little literature that reports on the amount and characteristic of exported sediment during the establishment phase of a biofiltration system and the potential impact this has on downstream ecosystem.

A filter media with a high hydraulic conductivity is however unlikely to support plant growth (FAWB 2008). As this is an important part of the effectiveness of a biofiltration system (Bratieres et al., 2009, Hatt et al., 2007a, Henderson et al.,2007) it may limit the use of sand as a filtration media, especially in areas regularly experiencing prolonged periods of drought. Measures such as incorporating water holding polymers or the use of a saturated zone can counteract some of these problems.

The long-term hydraulic performance of sand in a biofiltration application should also be considered. It is likely that fine sediment present in the stormwater runoff will be washed into the biofiltration system and reduce the hydraulic conductivity. This may transform the sand media to a sandy loam after prolonged exposure to urban runoff.

The overall capacity of the system to store captured pollutants should also be considered when designing systems that receive runoff from a large impervious catchment. A larger system will have more capacity to handle pollutant loads especially if maintenance is infrequent. Smaller biofiltration systems may not be advisable unless regular maintenance can be assured.

6 CONCLUSION

Modelling undertaken as part of the study indicates that for small biofiltration systems a high hydraulic conductivity will result in a better overall performance. The assessment of the hydraulic performance of existing systems showed that in biofiltration systems where sandy loam is used, the hydraulic conductivity was typically significantly lower than results from laboratory studies. Even though the assessment of hydraulic conductivity reported different results depending on the method applied, when compared with field observations it confirms that sand retains a significantly higher hydraulic conductivity compared to a sandy loam. Given the similar water quality improvement that can be expected from using sand compared to sandy loam in a biofiltration application (Hatt et al 2007), the findings from this study support the modelling results. In retrofit situations where available land is limited this is an important finding, and verifies the importance of considering all aspects of a system (hydraulic conductivity, size and ponding depth) during the design of new systems.

The field study has showed that the method used to assess hydraulic conductivity may significantly influence the results. The single ring infiltration test (shallow test) as described by Le Coustumer et al. (2007) will report a lower hydraulic conductivity than other methods where the difference in flow rate is small between 50mm and 150mm head. The method described by Bouwer (1986) on the other hand appears to consistently overestimate the hydraulic conductivity, however results are generally more consistent. When flow is measured over a longer period of time, results obtained applying Darcy's law are lower and highlight the importance of allowing the filter media to be truly saturated before recording the flow rates used to calculate the hydraulic conductivity.

Neither of the field methods used to measure hydraulic conductivity in sandy loam provided consistent results comparable to field observations. Where the hydraulic conductivity is high (sand media), using the method described by Bouwer (1986) (applying Darcy's Law), appear to provide a more reliable result.

When testing the hydraulic conductivity to verify modelling and quantify the benefits of biofiltration in a stormwater management system, results need to be critically assessed. Hydraulic conductivity test results should ideally be verified by field measurements, including flow gauging at the outflow of the system, or by comparison with anecdotal evidence to ensure they are representative of the function of the filter. Importantly, the results should considered as indicative not definitive.

LIST OF REFERENCES

ASTM F1815 (2006) *Standard Test Methods for Saturated Hydraulic Conductivity, Water Retention, Porosity, and Bulk Density of Putting Green and Sports Turf Root Zones*

Australian Bureau of Statistics (ABS), (2006). *2006 Census Community Profile series Ku-ring-gai (A) LGA 14500 Catalouge No. 2001.0*

Bouwer H., (1986) Intake *Rate: Cylinder Infiltrometer. Chapt 32* In: Klute A., (1986) Methods of Soil Analysis Part 1 Physical and Mineralogical Methods. 2nd Edn. Number 9 (Part 1) in the series Agronomy. American Soc of Agronomy, Inc., Soil Science Soc of America, Inc. Madison Wisconsin USA.

Bratieres, K., Fletcher, T. D., Deletic, A. (2009) *The advantage and disadvantages of sand-based biofilter medium; Results of a new laboratory trial*. Proceedings of The 6th International Water Sensitive Urban Design Conference and Hydropolis #3, 2009, Perth May 2009

CRCCH (2005) *MUSIC User manual*. Cooperative Research Center for Catchment Hydrology, Victoria Australia

Davies, P., Wright I.A., Findlay, S., Jonasson, O. J., Burgin, S. (2010) *Impact of urban development on aquatic macroinvertebrates in south eastern Australia: degradation of in-stream habitats and comparison with non-urban streams* Aquatic Ecology Published online: 07 January 2010

Ecological Engineering, Sydney Environmental & Soil Laboratory Pty. Limited (SESL), Dr Peter May (The University of Melbourne) 2006, *Guideline Specification for Soil Media in Bioretention Systems*. Facility for Advancing Water Biofiltration, Melbourne July 2006.

Facility for Advancing Water biofiltration (FAWB) (2008) *Guideline specification for soil media in bioretention systems Version 2.01*, Facility for Advancing Water Biofiltration, Melbourne March 2008.

Fletcher, T. D., Zinger, Y., Deletic, A,, Bratieres, K., (2007*). Treatment efficiency of biofilters; results of a large-scale column study,* Proceedings of The 13th International Rainwater Catchment Systems Conference, 5th International Water Sensitive Urban Design Conference Sydney, Australia August 2007

Hatt, B.E., Deletic, A., Fletcher, T. D.,(2007a). *Stormwater reuse: designing biofiltration systems for reliable treatment*. Water Science and Technology 55(4): 201-209.

Hatt, B.E., Lewis, J., Deletic, A., Fletcher, T. D.,(2007b). *Insight from the design, construction and operation of an experimental stormwater biofilter system*, Proceedings of The 13th International Rainwater Catchment Systems Conference, 5th International Water Sensitive Urban Design Conference Sydney, Australia August 2007

Henderson, C., Greenway, M., Phillips, I. (2007) *Removal of dissolved nitrogen, phosphorus and carbon from stormwater by biofiltration mesocosms*, Water Science and Technology 55(4): 183-191.

Le Coustumer, S., Fletcher, T. D., Deletic, A., Barraud, S (2007). *Hydraulic performance of biofilters for stormwater management: first lessons from both laboratory and field studies*. Water Science and Technology 56(10): 93-100.

Le Coustumer, S., Fletcher, T. D., Deletic, A., Potter, M (2008). *Hydraulic performance of biofilter systems for stormwater management: lessons from a field study*. Facility for Advancing Water Biofiltration, Melbourne April 2008.

McIntyre, Jakobsen (1998) Chapter 10 *Methodology for determining soil hydraulic conductivity in 'Drainage for Sportsturf and Horticulture'*, Horticultural Engineering Consultancy, Canberra

Standards Australia (2003). *AS4419 - 2003: Soils for landscaping and garden use.* Sydney, Australia, Standards Australia International Ltd.