FAWB
Facility for Advancing
Water Biofiltration

Advancing the Design of Stormwater Biofiltration

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Contributors

FAWB team

Lucie Alcazar	*Researcher*
Katia Bratières	*Researcher*
Peter Breen	*Researcher*
Rebekah Brown	*Project 2 Leader*
Kerrie Burge	*Researcher*
Jodi Clark	*Researcher*
Ana Deletic	*Research Manager*
Megan Farelly	*Researcher*
Tim Fletcher	*Project 1 Leader*
Belinda Hatt	*Project 3 Leader*
Nina Keath	*Researcher*
Sébastien Le Coustumer	*PhD Student*
Justin Lewis	*Project 4 Leader*
David McCarthy	*Researcher*
Peter Morison	*Researcher*
Peter Poelsma	*Researcher*
Jennifer Read	*Researcher*
Sally Boer	*Researcher*
Susan Van de Meene	*PhD Student*
Anke Wendelborn	*PhD Student*
Tricia Wevill	*Researcher*
Tony Wong	*C.E.O*
Yaron Zinger	*PhD Student*

International Collaborators

Sylvie Barraud	*Research Collaborator, INSA-Lyon, France*
Godecke Blecken	*PhD Student, Luleå University of Technology, Sweden*
Maria Viklander	*Research Collaborator, Luleå University of Technology, Sweden*

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1. Introduction

1.1 About FAWB

The Facility for Advancing Water Biofiltration (FAWB) was formed in mid-2005 as an unincorporated joint venture between the Institute for Sustainable Water Resources (ISWR), Monash University and EDAW Australia (previously Ecological Engineering). The following industry collaborators are also involved:

- Manningham City Council (Vic)
- Melbourne Water (Vic)
- Vic Roads (Vic)
- Landcom (NSW)
- Brisbane City Council (Qld)
- Adelaide and Mount Lofty Ranges Natural Resources Management Board (succeeding The Torrens and Patawalonga Catchment Water Management Boards) (SA)

The facility is run by a Board of Management, which is chaired by Professor Russell Mein. The work is carried out by over 20 staff and PhD students, and is managed by the following team:

- Chief Executive Officer: Dr Tony Wong, Ecological Engineering
- Research Manager: Associate Professor Ana Deletic, Monash University
- Business Manager: Mr John Molloy, Monash University
- Project Leaders: Dr Tim Fletcher, Monash University (Project 1), Dr Rebekah Brown, Monash University (Project 2), Dr Belinda Hatt, Monash University (Project 3), and Mr Justin Lewis, Monash University (Project 4)

FAWB also has active collaboration arrangements (on-going joint research projects) with INSA-Lyon, a leading Engineering School in France, and with Luleå University of Technology in Sweden.

FAWB is primarily funded through the Victorian State Government's Science, Technology and Innovation (STI) grant, industry cash contributions and a direct cash contribution from Monash University. The total value of the activities within FAWB, including both cash and in-kind contributions, is $4.3 million over three years.

1.2 Our Mission

FAWB's mission is to **provide proof of concept by developing and field-testing a range of biofilter systems that can be applied to specific market-based needs**. This includes the needs of catchment managers, environmental regulators, public utilities, local governments, land developers, and design engineers.

Water biofiltration is the process of improving water (stormwater and wastewater) quality through the processes of filtration through biologically influenced media. Stormwater biofiltration systems include bioretention systems, constructed surface flow wetlands and constructed sub-surface flow wetlands, however the focus of this document is on bioretention systems.

A typical biofiltration system consists of a vegetated swale or basin, overlaying a filter medium (usually soil-based) with a drainage pipe at the bottom (Figure 1). Small bioretention pods are often referred to as rain gardens, while linear systems are commonly referred to as bioretention swales. The design configuration of biofilters is flexible, and possible variations include removal of the underdrain (to promote exfiltration into the surrounding soil) and the inclusion of a permanently wet, anoxic zone at the bottom (to further enhance nitrogen removal).

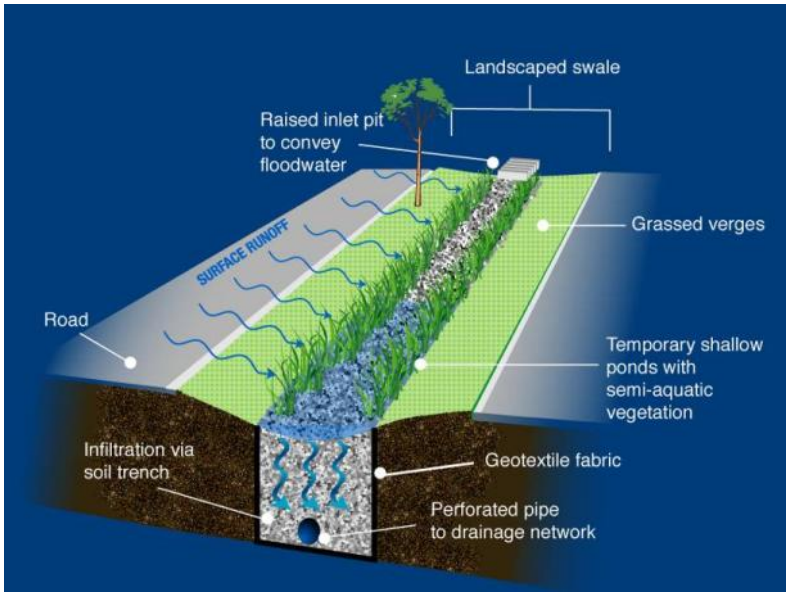

Figure 1. Schematic of a typical biofilter (bioretention system)

1.3 Structure of Research Program

To refine the design of biofilters and facilitate widespread adoption of these systems, the following research questions should be answered:

1. Technology questions:
   - How do biofilters work?
   - How should we design biofilters to work efficiently in a wide range of applications (e.g. pollution control, stormwater harvesting) and a range of site characteristics (e.g. different climate, pollutant loads)?

2. Adoption questions:
   - What are the factors (policy, regulation, risk, etc.) that advance their widespread implementation?
   - How do we quantify these factors and their relative significance?

To test the technology and enable its uptake, FAWB is also committed to:

- Develop adoption tools, such as design methods and adoption guidelines; and
- Demonstrate and test the technology, by supporting construction of a number of full scale systems.

The entire Research Program is divided into four highly interlinked Projects:

- **Project 1: Technology** aims to overcome technical barriers to wide adoption of the technologies;
- **Project 2: Policy and Risk** aims to develop methodologies/strategies to overcome institutional and social barriers to widespread adoption of the technologies;
- **Project 3: Adoption Tools** aims to develop design tools for practitioners, and
- **Project 4: Demonstration and Testing** aims to demonstrate the wide capability of novel, multi-functional designs (Figure 2).

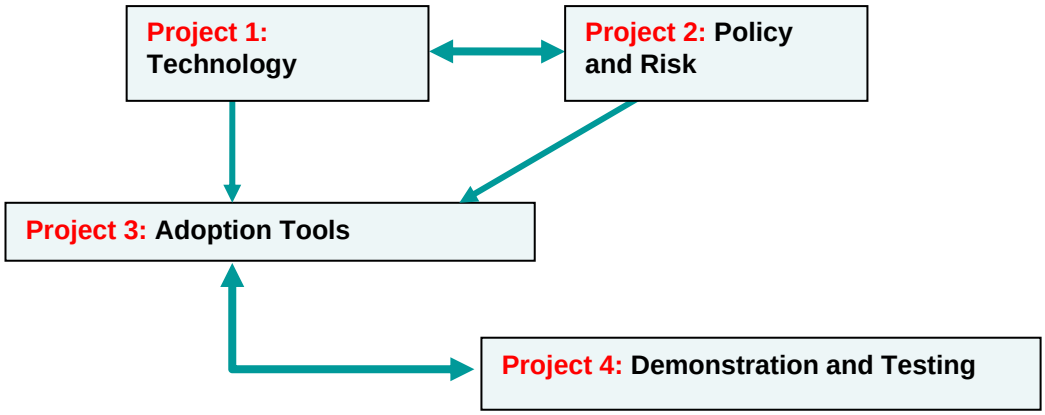

Figure 2. FAWB Projects

1.4 About this Document

The purpose of this document is to provide a summary of FAWB's findings to date on biofiltration **technologies** and it therefore focuses only on the findings **from Projects 1 and 4**. The document begins with an outline of the typical design of biofilters, then briefly explains the research methodology, followed by a summary of the key findings.

The findings from **Project 2** can be found in the following papers and reports:

- Brown, R.R. and Clarke, J.M. (2007). The Transition Towards Water Sensitive Urban Design: The Story of Melbourne, Australia, Report No. 07/01, Facility for Advancing Water Biofiltration, Monash University, June 2007, ISBN 978-0-98030428-0-2. (67pages).
- Brown, R. and Clarke, J. (2007). The transition towards Water Sensitive Urban Design: a socio-technical analysis of Melbourne, Australia, Proceedings of the 7th International Conference NOVATECH 2007, 25-27 June, Lyon, France, ISBN 2-9509337-7-7-7, V(1):349-356.
- Brown, R and Farrelly, M (2007). Institutional impediments to advancing sustainable urban water management: a typology, Proceedings of the 13th International Rainwater Catchment Systems Conference and the 5th International Water Sensitive Urban Design Conference, 21-23 August 2007, Sydney, Australia.
- Brown, R.R and Farrelly, M.A. (2007). Advancing Urban Stormwater Quality Management in Australia: A Survey of Stakeholder Perceptions of Institutional Drivers and Barriers, Report No. 07/05, National Urban Water Governance Program, Monash University, September 2007, ISBN 978-0-9804298-0-0. (128 pages).

2. Research Methodology

2.1 Project 1: Technology

The aim of Project 1 is to develop and test biofilter technologies that will be capable of treating stormwater runoff in a range of urban situations, and to overcome technical barriers to the utilisation of biofiltration technology. The specific aims are to:

1. Develop new biofilter designs to optimise performance and ensure long-term sustainability;
2. Determine design configurations that optimise treatment performance, and reduce the risk of soil media clogging;
3. Develop new filter media types for targeted pollutants (such as heavy metals, nutrients and pathogens);
4. Determine sustainable pollution loadings in order to make predictions about effective lifespan; and
5. Determine the performance and risk of using stormwater biofilters as a treatment device for stormwater harvesting.

Based on these aims, three Project Activities have been developed within Project 1:

Project Activity 1.01 Vegetation trials

Project Activity 1.02 Laboratory biofilter column experiments

Project Activity 1.03 Biofilter optimisation for stormwater reuse

Activity 1.01: Vegetation trials

Twenty species commonly used in rain garden design have been tested for removal of the key stormwater pollutants (Figure 3), including total suspended solids (TSS), key heavy metals, total phosphorus (TP) and total nitrogen (TN) and their species (for full details, see Read *et al.*, 2008). The list of plants tested is given in Table 1.

Table 1. Species used in experiments and their life form. All monocots were herbaceous. The life forms of the dicots are listed below: c, climber or scrambler; ms, mat-forming shrub; ss, small to medium shrub; l, large shrub to small tree.

MONOCOTS	DICOTS
Carex appressa R.Br. (Cyperaceae)	*Acacia suaveolens* (Sm.) Willd. (Mimosaceae) l
Dianella revolute R.Br. var. *revoluta* (Liliaceae)	*Banksia marginata* Cav. (Proteaceae) l
Ficinia nodosa (Rottb.) Goetgh., Muasya & D.A.Simpson (Cyperaceae)	*Correa alba* Andrews (Rutaceae) ss
Juncus amabilis Edgar (Juncaceae)	*Dodonaea viscosa* (L.) Jacq. (Sapindaceae) l
Juncus flavidus L.A.S. Johnson (Juncaceae)	*Goodenia ovata* Sm. (Goodeniaceae) ss
Lomandra longifolia Labill. (Dasypogonaceae)	*Hibbertia scandens* (Willd.) Dryand.(Dilleniaceae) c
Microlaena stipoides (Labill.) R.Br. (Poaceae)	*Kunzea ericoides* (A.Rich.) J. Thomps. (Myrtaceae) l
Poa labillardierei Steud. var. *labillardierei* (Poaceae)	*Leucophyta brownii* Cass. (Asteraceae) ss
	Melaleuca ericifolia Sm. (Myrtaceae) l
	Myoporum parvifolium R.Br. (Myoporaceae) ms
	Pomaderris paniculosa subsp. *paralia* N.G. Walsh (Rhamnaceae) ss
	Pultenaea daphnoides J.C.Wendl. (Fabaceae) ss

The plants were dosed with semi-synthetic stormwater for three months and their treatment performance assessed by analysing the treated stormwater. At the end of the dosing period, plant

biomass was measured and relate to plant performance. Plant stress was also monitored (including the impact of drought and shade) in a separate trial. We are still analysing the data.

Figure 3. Plant species trials

Activity 1.02: Laboratory biofilter column experiments

This is a large activity that involved several independent studies:

(a) ***Laboratory study of non-vegetated filters***. For 42 weeks, the soil-based filters were dosed with semi-synthetic stormwater under different drying and wetting regimes, during which time their treatment (removal of TSS, TP, TN, nutrient species, and heavy metals) and hydraulic performance (clogging rate) were monitored (Figure 4(a); see also Hatt *et al*., 2007a,b, 2008).

Figure 4. Laboratory biofilter column experiments: (a) non-vegetated soil filter media columns and (b) standard columns

Table 2 lists the media types that have been tested.

Table 2. Filter media types

Abbreviation	Filter Media	Depth (cm)	Rationale
S	Sand	80	Baseline design
SL	Sandy loam	80	Currently recommended
SLH	4:1 sandy loam: Hydrocell	80	Increase retention time
SLVP	8:1:1 sandy loam: vermiculite: perlite	80	Target heavy metals
SLCM	8:1:1 sandy loam: compost: light mulch	80	Enhance biological activity
SLCMCH	3:1:1 sandy loam: compost: light mulch	60	Enhance biological activity
	Charcoal	20	Sorb dissolved organics

(b) ***Optimisation of standard biofilter design*** (Figure 5(b)) was carried out using columns filled with four filter media types, non-vegetated and vegetated with five different plant species, and three different filter depths (300, 500 and 700 mm). The impact of different inflow concentrations and climate (Brisbane and Melbourne) was also studied. In total, 140 columns were dosed over ten months with semi-synthetic stormwater, and their treatment (removal efficiency of key pollutants) and hydraulic performance (change in hydraulic conductivity) monitored. Details of the experimental methods are reported in Bratieres *et. al.* (in press) and Fletcher *et al.* (2007). Details of the monitoring of hydraulic performance were reported in a joint lab/field study by Le Coustumer *et al.* (2007). Table 3 summarises the factors tested in the experiments.

Table 3. Factors tested in the column experiments

Variable	Factors
Vegetation (5+1)	*Carex appressa (C), Melaleuca ericifolia (ME), Microleana stipoides (MS), Dianella revoluta (D), Leucophyta brownii (L),* non-vegetated
Filter Media Type (3)	Sandy loam (SL), SL with 10% vermiculite and 10% perlite (SLVP), SL with 10% compost and 10% mulch (SLCM)
Filter Media Depth (3)	300 mm, 500 mm, 700 mm
Filter Area (3)	Biofilter sized to 1%, 2% or 4% of the catchment (i.e., double, standard or half dosing volume**)
Inflow Concentration (2)	'Typical' (Duncan, 1999; Taylor *et al.*, 2005) and 2 x 'Typical'

(c) The impact of a permanently ***submerged zone*** (with and without a carbon source) on biofilter performance was assessed using 18 advanced columns (Figure 5). The methods and the full set of results are reported in Zinger *et. al.* (2007b) and Blecken *et. al.* (under review). The impact of a wetting and drying regime on systems with and without a submerged zone was also examined (Zinger *et al.*, 2007a), where the systems were subjected to dry periods of between two days and seven weeks.

(d) The ***long term sustainability of soil media*** has been investigated in a separate laboratory study, where three selected soils were exposed to 15-20 years of continuous stormwater loading. The aim of this study was to assess break-through of pollutants;the laboratory work has recently been completed and the results are currently being analysed.

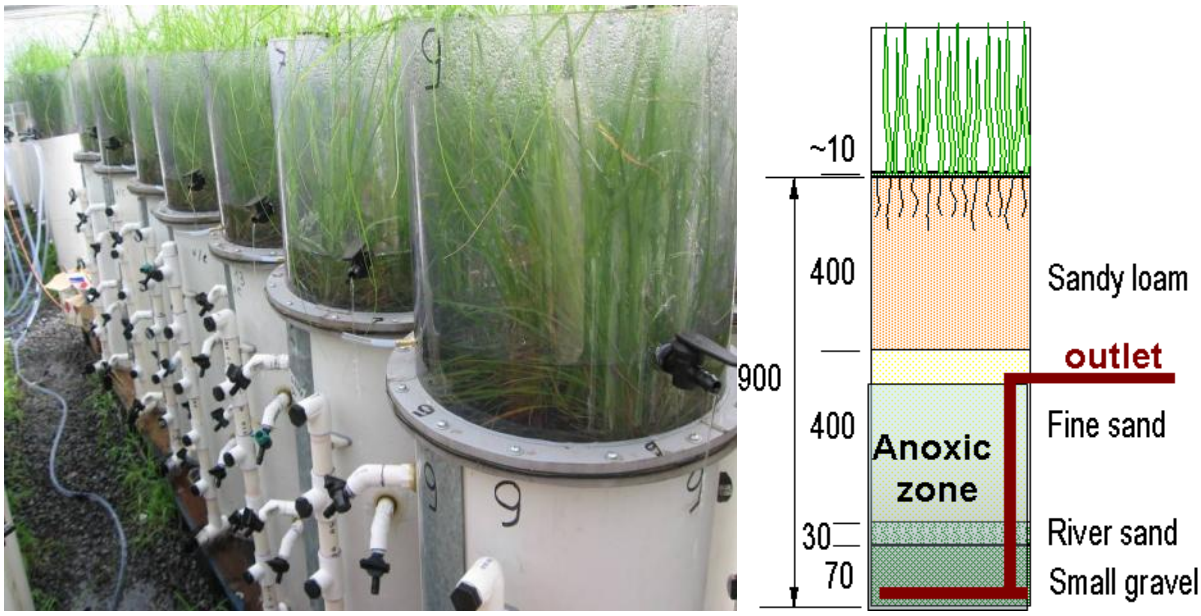

Figure 5. Testing the impact of a submerged zone, carbon source, and variable wetting and drying in the advanced columns

(e) The ***impact of temperature*** on the performance of biofiltration systems was studied in conjunction with Luleå University of Technology, Sweden. This work was performed in constant temperature rooms at Luleå University of Technology using the FAWB standard column design (Figure 4(b)) and experimental procedures. The results of this study, which focused primarily on cold climate issues and used non-Australian plants, are reported in Blecken *et. al.* (2007).

Activity 1.03: Biofilter optimisation for stormwater reuse

Pathogen removal by biofilters was tested using 30 standard columns (Figure 4(b)). Over three months, the columns were dosed with real stormwater spiked with pathogens and the removal of three common pathogen indicators (indicators of viruses, protozoa and bacteria) was monitored. The influence of soil type, plant species, submerged zone, carbon source, and variable wetting and dry on pathogen removal was observed. The papers and report on this study are currently in preparation, therefore only preliminary results are included in this document.

2.2 Project 4: Demonstration and Testing

Project 4 aims to complete a number of field trials of bioretention systems in Melbourne, Brisbane and Sydney, in order to;

1. Validate laboratory studies and address site specific issues;
2. Provide the basis for monitoring of long term robustness under real operating conditions;
3. Provide demonstrations of bioretention systems in a range of urban environments (streetscapes, greenfield, inner-city retrofits, etc.); and
4. Document construction procedures, for use in guidelines and standard drawings.

The focus of Project 4 is on testing the novel systems constructed in consultation with FAWB, as well as on testing a number of existing bioretention systems. The current activities include:

Activity 4.01	Second Ponds Creek Bioretention System, Sydney
Activity 4.02	Monash University Carpark Bioretention System, Melbourne
Activity 4.03	Wakerley Bioretention System, Brisbane
Activity 4.04	Testing existing bioretention systems (Melbourne, Brisbane and Sydney)
Activity 4.05	Saturn Crescent stormwater garden, Brisbane

Activity 4.01 Second Ponds Creek Bioretention System, Sydney

There is a need to study the long-term performance of stormwater bioretention systems constructed in the saline soils that are typical of the Western Sydney region, particularly given that construction of a large number of bioretention systems in this region is proposed in the near future. Two experimental bioretention systems were constructed at Second Ponds Creek in August 2004 (Figure 6, and Figure 7 (a)). One trench is unlined (i.e., the filter media is in direct contact with saline soils), while the other is fully lined. Both trenches are 20 m long, 3 m wide, and 0.9 m deep (0.6 m of filter media) and serve large catchment areas; it has been estimated that they represent only 0.01% of the total catchment area (both pervious and impervious).

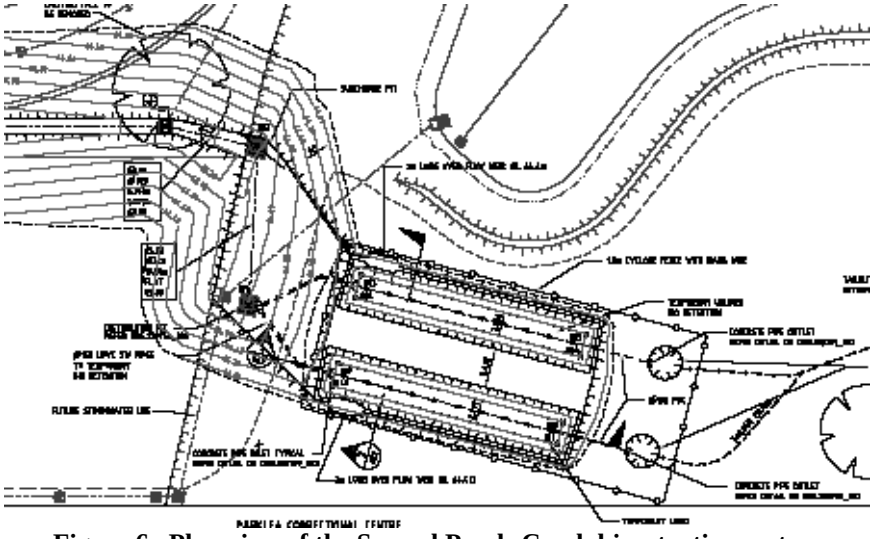

Figure 6. Plan view of the Second Ponds Creek bioretention system

The main research questions that we are aiming to answer by testing these systems are:

1. Will unlined stormwater bioretention systems built in saline soils interact with surrounding soil and export salt to receiving waterways?
2. Is the hydraulic performance of filter media used in the bioretention construction affected by its interaction with surrounding soil (e.g. could salt intrusion cause dispersion of the clay fraction and thus collapse of the soil structure)?

The *in situ* hydraulic conductivity (i.e., infiltration capacity) of the bioretention systems has been measured three times since completion of construction (most recently in October 2007). The filter media in the systems was found to be unstable (the soil structure had collapsed) and had to be replaced due to rapid failure of the hydraulic performance.

Figure 7. Second Ponds Creek bioretention system: (a) construction of the two bioretention trenches and (b) laboratory study of the performance of bioretention systems built in sodic soils

The system failed even after the soil replacement, therefore a full-scale laboratory investigation was conducted on the performance of unlined systems built in highly saline soils. The full details of this study are reported in Deletic and Mudd (2006) and are only briefly outlined here. The rig was set up to physically model the Second Ponds Creek biofilter (Figure 7(b)). Actual pre-treated stormwater was periodically added to the rig to simulate wetting and drying. During stormwater events, flow rate, electrical conductivity (EC), turbidity, pH, and water temperature were continuously recorded at the outflow. Samples were taken from the outflow and analysed for total dissolved solids (TDS) and major anions and cations.

The filter media at Second Ponds Creek has now been replaced with a material that meets the most recent FAWB specification for soil filter media and the systems are vegetated. The FAWB team will carry out final *in situ* tests of hydraulic conductivity and leaching in mid-2008.

Activity 4.02 Monash University Carpark Bioretention System, Melbourne

FAWB has built a full scale bioretention system in collaboration with the grounds department at the Clayton campus of Monash University. Runoff from the top level of a multi-level carpark (approximately 5000 m^2) drains into two 18 kL pre-treatment tanks. The water is then treated in the biofilter that contains three different biofilter cells, each 1.5 m wide, 10 m long, and 0.7 m deep (0.5 m of filter media), as shown in Figure 8. Treated water runs into an ornamental pond that acts as a store for the harvested stormwater (water from the pond is used to irrigate a nearby sports oval). The system was constructed in January 2006, and fully vegetated in March 2006.

The key research questions to be examined at this site include:

1. To what extent do different media types (in combination with vegetation) remove stormwater pollutants – sediment, nutrients, metals, carbon?
2. Does the addition of vermiculite and perlite improve removal of heavy metals and other cations (through increased cation exchange capacity)?
3. Does the addition of organic matter enhance nutrient removal (via increased biological activity)?
4. Does the pollutant removal rate change with time or varying seasons?
5. How does the hydraulic performance of the systems change with time?

To answer these questions the biofilter was configured to allow the testing of three different types of filter media (this was done before any findings from the laboratory studies were available):

- Cell 1: sandy loam (media currently recommended by design guidelines);
- Cell 2: sandy loam mixed with 10% vermiculite and 10% perlite (by volume); and
- Cell 3: sandy loam mixed with 10% compost and 10% light mulch (by volume).

Figure 8. Monash University carpark biofiltration system

The monitoring program and preliminary results are described in Hatt et al (2007b; in press). The system is fully equipped for monitoring both flow and water quality. Three V-notch weirs installed in the covered inflow chamber are used to monitor inflow into the biofilters. The outflow from each cell is monitored by three small separate V-notch weirs (Figure 9). Autosamplers collect water quality samples at both the inflow and outflow. The system also allows for easy testing with spiked inflows.

Figure 9. Monash carpark stormwater harvesting system

Activity 4.03 Wakerley Bioretention System, Brisbane

This regional scale bioretention system treats stormwater runoff from an 87 ha residential catchment. The system has been designed with three hydraulically separate filtration cells, each with a slightly different sub-surface drainage configuration and vegetation specification, thus providing a unique monitoring opportunity. A plan view is highlighted in Figure 10. The project has been split into two phases for funding reasons, with Phase 1 being built in 2006 and Phase 2 in 2007.

Figure 10. Plan view of the Wakerley bioretention system

The main research question to be investigated at this site is:

1. How effective is the submerged zone in this system at removing nitrogen from urban stormwater?
2. How do different vegetation types impact on performance?

Lessons learned from the construction phase of the system will inform adoption strategies.

Figure 11. Wakerley bioretention system

Brisbane City Council (BCC) is establishing a comprehensive monitoring program. The system is very complex and thus a challenge to monitor.

Activity 4.04 Testing existing bioretention systems

There is a need to study the long-term performance of established stormwater bioretention systems across Australia. The main aim is to collect knowledge on the adoption and long-term performance of existing systems. The following questions have been asked:

1. What is the hydraulic performance (e.g. field infiltration capacity) of the existing systems after years of operation, and can we simply assess its change with time?
2. Do toxicants accumulate in these systems and reach hazardous levels (e.g. heavy metals in the soil media)?
3. What is the quality of landscaping after years of operation?
4. What are the essential maintenance requirements?
5. Are there any observed construction and operational problems (including quality of landscaping)?

The infiltration capacities of thirty-seven biofilters have been tested *in situ*. Filter media samples were collected for laboratory measurements of hydraulic conductivity (using standard tests) and heavy metal concentrations (Figure 12). Over 18 sites in Melbourne, Sydney and Brisbane were included, and at least three measurements were usually taken at each biofilter, using two different field tests. A small part of this study has been reported on in Le Coustumer *et al.* (2007). The detailed study of hydraulic performance is reported in a joint FAWB/Melbourne Water report (Le Coustumer *et al.*, 2008; Le Coustumer *et al.*, under review-a).

Figure 12. Testing of existing biofilters

Activity 4.05 Saturn Crescent stormwater garden, Brisbane

This is currently the only system that has been fully built based on findings from the FAWB program and subsequently tested. The system is a relatively small bio-pod that was retrofitted into the urban landscape. It has a plan area of $20m^2$ and services a $900m^2$ catchment (the full design details of the system design are in Smith *et. al.* (2007)). The current FAWB soil filter media specifications were used, as were plant species recommended by FAWB (the system was initially trialled with some other plant species but later replanted using a FAWB specified plant species, Hatt *et al.*, in press).

The main questions asked were:

1. What is performance of the system built according to the latest findings from our research?
2. What is functionality of retrofitting the bioretention system into an existing urban landscape?

To date, five controlled experiments have been conducted (Figure 13), one before and four after the system was replanted (using FAWB specified plants). A design storm event was prepared and introduced to the system, the outflow rate measured and water quality samples collected and analysed for key pollutants. The hydraulic and treatment performance of the system has been tested as described in Smith *et. al.* (2007) and Hatt *et al.* (in press).

Figure 13. BCC and FAWB working together to test the Saturn Crescent bio-pod

3. Key Findings

The key results from Projects 1 and 2 are presented together in order to avoid repetition and are organised according to the design features of the biofilters. The outline of the recommended biofilter design is followed by findings on each system component. This document contains only very brief results, however details of the results from each separate research activity can be found in the papers and reports listed in the References section under specific topics.

3.1 Outline of the Biofilter Design

Two main configurations of biofilters are recommended, depending on the objectives of the system (e.g. target pollutants, site opportunities and constraints, etc.). They are:

- Standard biofilter design (Figure 14)
- Biofilter with a submerged zone (Figure 15)

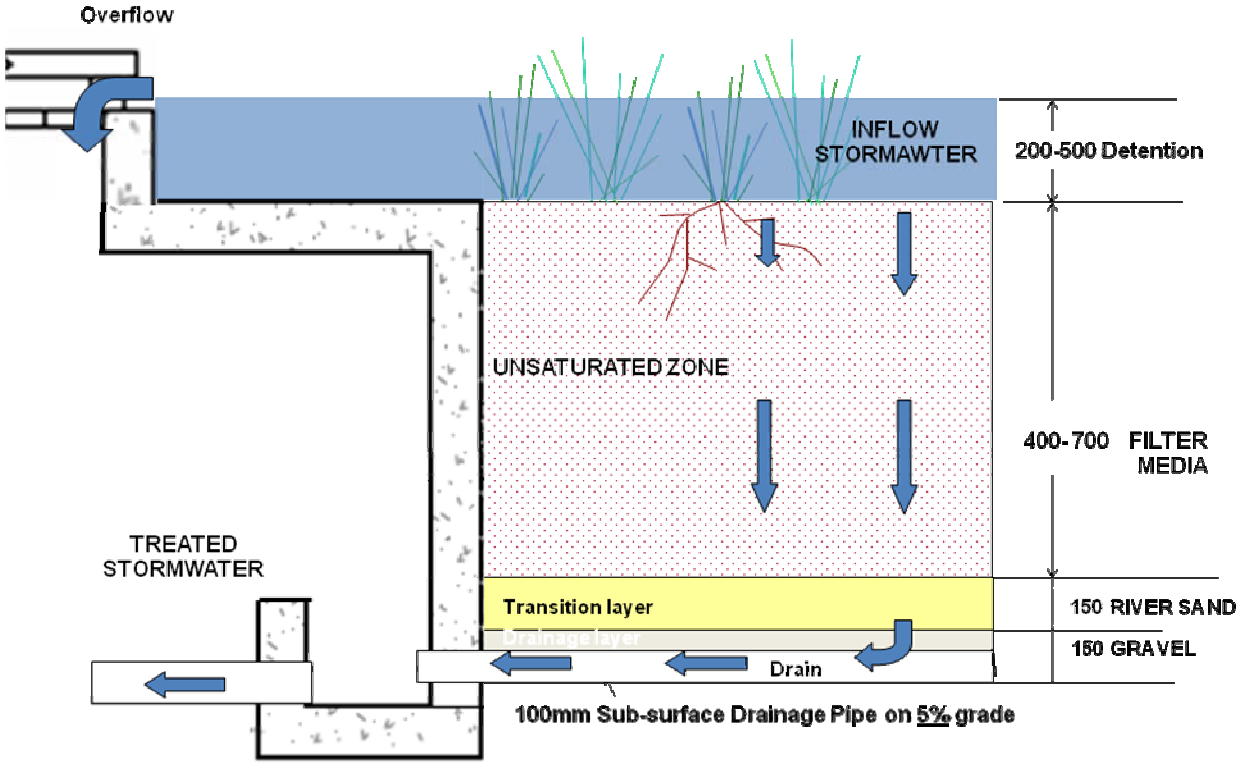

Figure 14. Conceptual outline of the design of a standard bioretention system

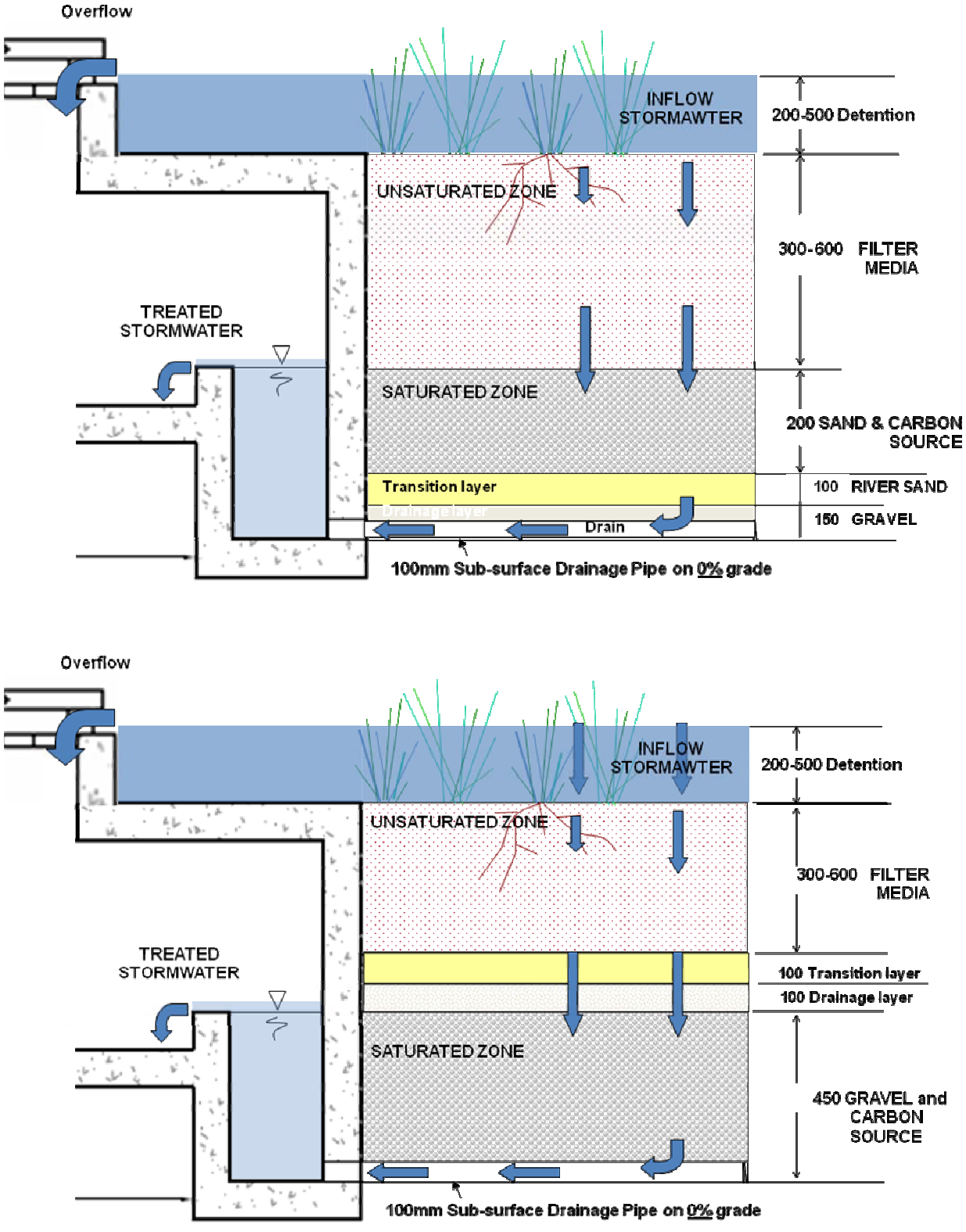

Figure 15. Conceptual outline of the design of bioretention systems with a submerged zone

The bioretention systems can have different shapes. Systems should be **unlined** to promote exfiltration wherever conditions allow (e.g. the systems are built far enough from foundations). Any reduction in volumes due to exfiltration will translate to a mean reduction in pollution loads, and will also reduce the impacts of changed hydrology inherent in urbanised catchments.

3.2 Soil Filter Media

To ensure reliable operation of bioretention systems, filter media specifications must be adhered to, in terms of both composition and hydraulic conductivity. FAWB has produced such guidelines, which are updated as required to reflect new and relevant research insights. The finalised version of these guidelines is included in Appendix A. FAWB has also produced guidelines on how to measure *in situ* hydraulic conductivity of bioretention systems, which are included in Appendix B.

The key findings on soil filter media are:

- A ***loamy sand*** should be used that is free of rubbish, deleterious material and toxicants, and not be hydrophobic;
- The ***hydraulic conductivity*** should be selected in conjunction with other design characteristics (i.e., the area of the bioretention system and its ponding depth), and climate conditions (i.e., rainfall characteristics). The hydraulic conductivity (Figure 17) of the ***maximum compacted media*** should be 100 – 300 mm/hour for a temperate climate and 100 – 600 mm/hr for a tropical climate;

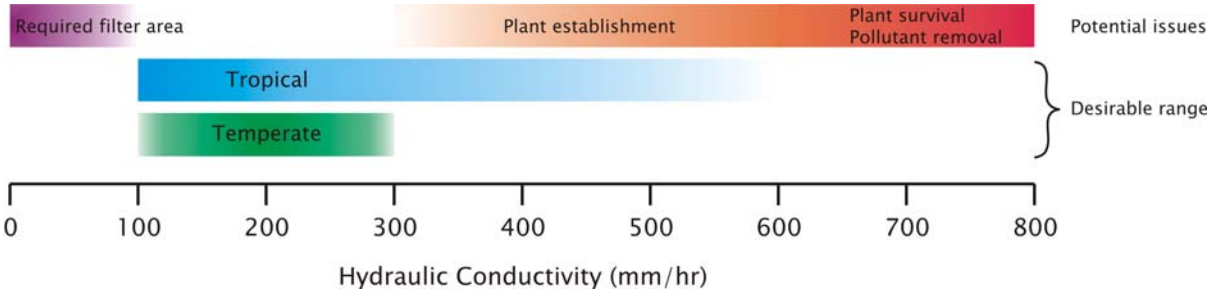

Figure 16. Recommended filter media hydraulic conductivity range and potential issues (FAWB, 2008)

- ***Particle Size Distribution*** (PSD): the clay and silt fractions (<5 μm) should be no more than 3% in total (w/w), and the distribution of other fractions should be continuous;
- ***Organic matter*** should be kept to a minimum (<5% (w/w));
- The ***total phosphorus*** content should be minimised, and be at least less than 100 mg/kg; and
- Soils used in bioretention systems should be ***structurally stable***, particularly in wet conditions.

Filter media that is placed 'uncompacted' will initially show a very high hydraulic conductivity, which will then rapidly decrease to the design value. ***It is therefore ESSENTIAL that testing of hydraulic conductivity be conducted on compacted filter media prior to installation.*** The hydraulic conductivity of potential filter media should be measured using the ASTM F1815-06 method (a standard soil test that is widely used in the USA). This test method uses a compaction method that best represents field conditions and so provides a more realistic assessment of hydraulic conductivity than other test methods. However, it should be noted that, if a hydraulic conductivity lower than 100 mm/hr is specified, this test method may be too harsh and so underestimate the actual hydraulic conductivity of the filter media.

While it is tempting to use media with a very high initial porosity (i.e., sand based filters), our study of the hydraulic performance of non-vegetated filter media showed that such soils are very prone to surface clogging. This is less prominent in loamy soils, however they do experience reduced hydraulic capacity due to compaction (Hatt *et al.*, 2008).

It has been shown that the addition of vermiculite and perlite (around 10% of each, by volume) to the soil media helps to maintain hydraulic conductivity, making the biofilter more robust to slight deviations from the specified filter media characteristics. It may also enhance the long-term adsorption capacity of the filter media, which is important for heavy metal removal.

Dispersive clays and silts (for example, sandy loam soils from the Western Sydney area) are unsuitable filter media materials, owing to their unreliability in maintaining a suitable hydraulic conductivity. The hydraulic testing of soil media under wet conditions should be able to detect such structural instability, and they should be avoided.

Soil media is a key factor for the removal of heavy metals. The good news is that all the sand, soil and soil-based filter media tested (in both laboratory and field studies) demonstrated high removal (over 90%) of heavy metals (Table 4). In a similar way, filter media is the key for removal of pathogens.

Table 4. Summary of load reductions (mean ± standard deviation) in the non-vegetated column study (see Activity 1.02 in the Research Methodology section and Figure 5(a)), as reported in Hatt *et. al.* (2008). Note: a negative load reduction indicates leaching of previously retained pollutants and/or native material.

Non-vegetated Media	Mean Load Reduction (%)							
	TSS	TP	TN	TOC	Cu	Mn	Pb	Zn
S	99 ± 1	97 ± 1	38 ± 1	59 ± 8	97 ± 1	94 ± 1	99 ± 1	99 ± 1
SL	93 ± 4	-65 ± 16	-18 ± 15	-103 ± 17	97 ± 1	-32 ± 54	99 ± 1	99 ± 1
SLH	92 ± 3	-143 ± 17	-37 ± 4	-146 ± 19	96 ± 1	-71 ± 19	99 ± 1	98 ± 1
SLVP	90 ± 3	-73 ± 15	-23 ± 12	-129 ± 22	94 ± 2	-26 ± 52	95 ± 2	96 ± 4
SLCM	92 ± 4	-409 ± 40	-111 ± 41	-178 ± 13	94 ± 1	-152 ± 100	97 ± 1	96 ± 1
SLCMCH	96 ± 1	-437 ± 50	-164 ± 14	-165 ± 5	93 ± 1	-178 ± 189	97 ± 1	96 ± 1

S Sand
SL Sandy loam
SLH 4:1 sandy loam: Hydrocell
SLVP 8:1:1 sandy loam: vermiculite: perlite
SLCM 8:1:1 sandy loam: compost: light mulch
SLCMCH 3:1:1 sandy loam: compost: light mulch Charcoal

To achieve a high removal rate of phosphorus, soils should have a low phosphorus content (FAWB guidelines recommend <100 mg/kg). This is clearly demonstrated by comparing TP removal in the non-vegetated small columns, which leached phosphorus (Activity 1.02(a), Table 4), to the non-vegetated standard columns (Activity 1.02(b), Figure 5(b)), which demonstrated effective phosphorus removal (Figure 17, Bratieres *et. al.*, in press; Fletcher *et. al.*, 2007).

The soil used in the small diameter columns contained substantially higher levels of phosphorus than that used in the larger columns. Similar findings are drawn when results from field tests of the Saturn Crescent bio-pod (designed using FAWB's filter media guidelines) are compared with the results from the Monash University carpark biofilter (where the filter media contains over 300 mg/kg of P), as shown in Hatt *et. al.* (in press).

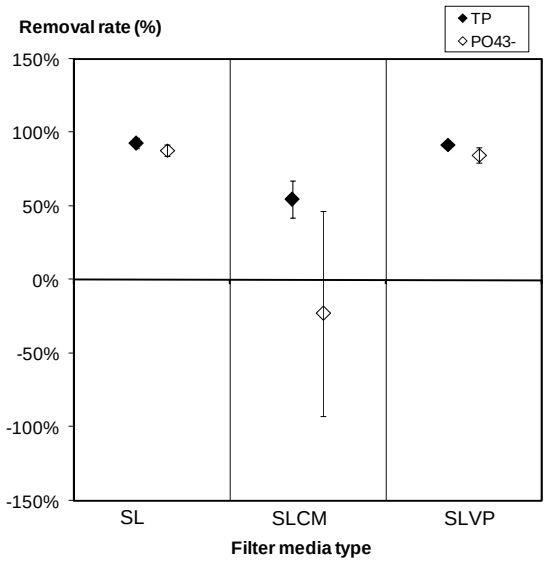

Figure 17. Mean and 95% confidence interval of removal rates for TP and PO_4^{3-} relative to filter media type during Sampling Run 2. SL – Sandy Loam, SLCM – Sandy Loam + Compost/Mulch, SLVP – Sandy Loam + Vermiculite/Perlite. (Source: Bratieres *et al.*, in press)

It was also found that plants have a positive effect on phosphorus removal. Columns planted with *C. appressa* performed better for both TP and PO_4^{3-} removal than both the non-vegetated columns and those planted with other plant species. This can be explained by the extensive root system of *C. appressa*, as well as the presence of root hairs. However, the difference between species is not of great practical significance, since good TP removal (>77%) was demonstrated for all configurations in the large column study (Activity 1.02(b)). In that study, it was shown that approximately 70% of incoming phosphorus was in particulate form, therefore it can be concluded that a high proportion of phosphorus is removed by filtration processes.

In contrast to the demonstrated consistent removal of phosphorus, without vegetation, most soils will naturally leach some nitrogen {Hatt, 2007 #692; Hatt, 2008 #779 and see Table 4}. The extent of leaching is influenced by the presence organic matter, but even more so by soil moisture content. It was found that, during dry spells, soluble nitrogen will accumulate in the soil and will then be washed out upon re-wetting (large spikes of TN have been recorded in non-vegetated soils). There is a strong correlation between the number of dry days prior to a storm event and leaching of nitrogen from soil filter media (Figure 18).

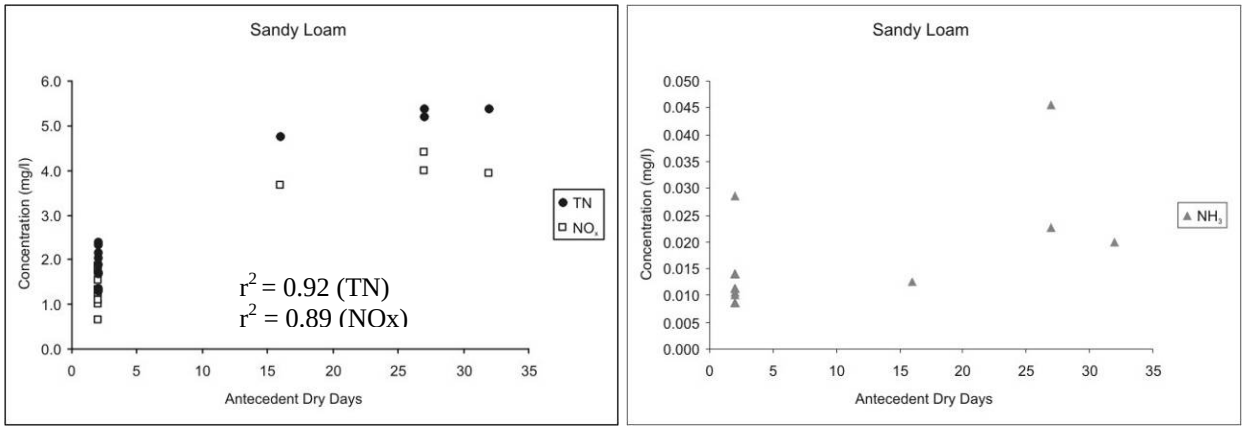

Figure 18. Mean outflow nitrogen concentrations from the sandy loam filter columns (Activity 1.02 (a)) relative to antecedent dry days. (Source: Hatt *et al.*, 2007a)

3.3 Vegetation

Bioretention systems rely strongly on vegetation and its symbiotic relationships with bacteria and fungi for the removal of nutrients from stormwater. However, ***there is marked variation in pollutant removal (including heavy metals) among plant species.*** Figure 19 illustrates the impact of vegetation type on nitrogen removal rates in the large column study (Activity 1.02 (b), Figure 5(b)).

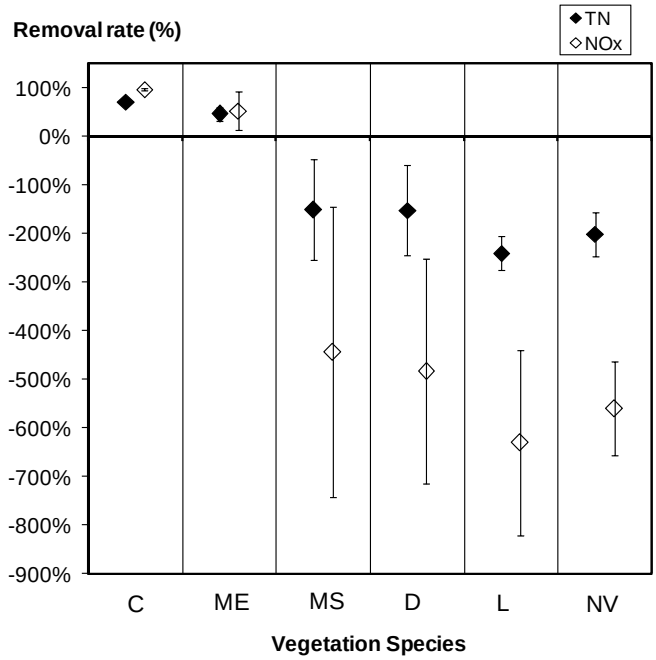

Figure 19. Mean and 95% confidence interval removal rates for TN and NO_x relative to vegetation species during Sampling Run 5. C- *Carex appressa*, ME - *Melaleuca ericifolia*, MS - *Microleana stipoides*, D - *Dianella revoluta*, L - *Leucophyta brownii*, NV - Non-vegetated. (Source: Bratieres *et al.*, in press)

For nitrogen and phosphorus (but not metals, which are generally effectively removed by any soil-based filter media), some of this variation (20-37%) could be explained by plant size (Fletcher *et al.*, 2007; Read *et al.*, 2008; Bratieres *et al.*, in press). However, there was still marked variation among plant species in pollutant removal per unit plant mass. We expect that some of this variation in pollutant removal will be due to differences among species in root architecture and physiology, leading to variation in uptake of pollutants as well as varying effects on soil physicochemistry and the associated microbial community.

Of the species tested extensively so far (*C. appressa*, *D. revoluta*, *M. stipoides*, *L. brownii* and *M. ericifolia)*, *C. appressa* is the best for nutrient removal (it is suggested that this is due to rapid spreading of roots throughout the soil media, and the role of symbiotic fungi around the root rhizosphere). In general, we are not in a position to definitively say which plants are "good" and "bad" for pollutant removal, but it is clear that plants which are well adapted to growing in the ephemeral wet/dry conditions of biofilters, and which have extensive root systems, are likely to be effective. Species tested to date which proven to be particularly effective for nutrient removal include ***Carex appressa, Melaleuca ericifolia, Juncus amabilis* and *Juncus flavidis.***

Biofilters planted with shallow-rooted plants (e.g. *M. stipoides*) appear to be ineffective for nutrient removal, particularly for nitrogen, as do those which have symbiotic relationships with nitrogen-fixing microbes (e.g. *A. suaveolens*), or those which are adapted to very dry conditions (e.g. *L. longifolia*, *B. marginata*). *L. brownii* was also consistently poor in nutrient removal, although

this may be due to its poor growth in the wet conditions that were used in the study so far (see future research section).

Interestingly, the other studied species (see Read *et al.*, 2008) all performed very similarly and did not appear to significantly influence nitrogen removal.

There was also an influence of time on the treatment performance of some plants. Figure 21 illustrates how *Melaleuca* started as not very good performer but over the span of less than 1 year (that past between sampling run 1 and 5) it became very efficient in TN removal (the results are from Activity 1.02(b) - the large column study, as reported in Bratieres et al, in press)

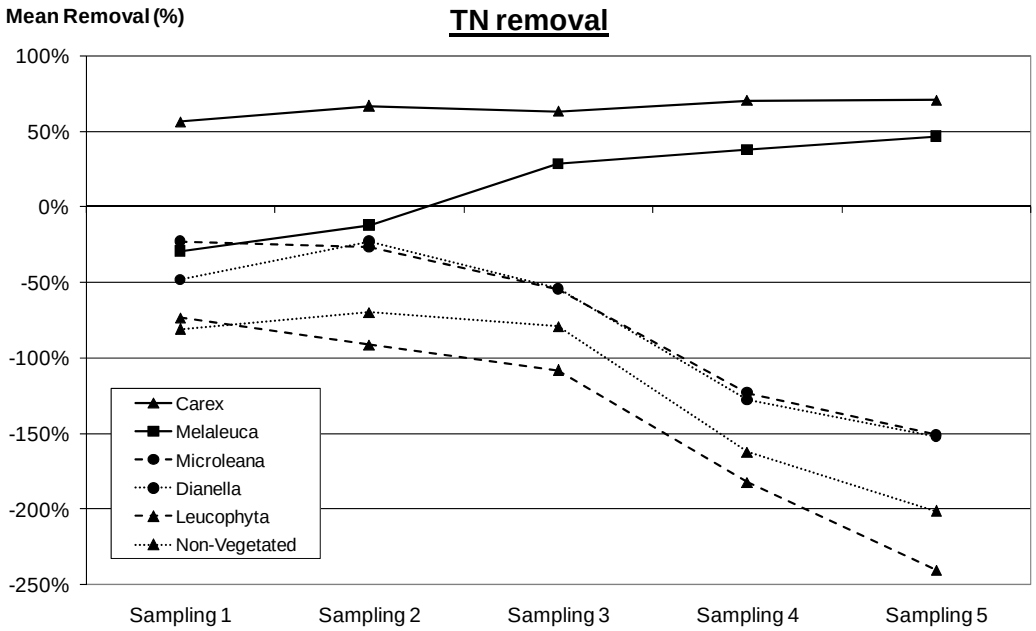

Figure 20. Mean removal rates over time (Sampling Runs 1 - 5) for TN relative to vegetation species (Source: Bratieres *et al.*, in press)

There was no evidence that plants were physiologically stressed by the application of stormwater in this experiment. However, measures of whole-plant performance may show effects that were not detected by fluorometry.

3.4 Submerged Zone and Carbon Source

The presence of an approximately ***450 mm deep, permanently submerged zone (consisting of sand or gravel) containing a carbon source such as hardwood chips (around 5% by volume)*** will largely improve nitrate/nitrite (NO_x) removal, by promoting denitrification (this zone becomes anoxic in some situations). The presence of this zone without a carbon source did not achieve improved NO_x removal (Figure 21).

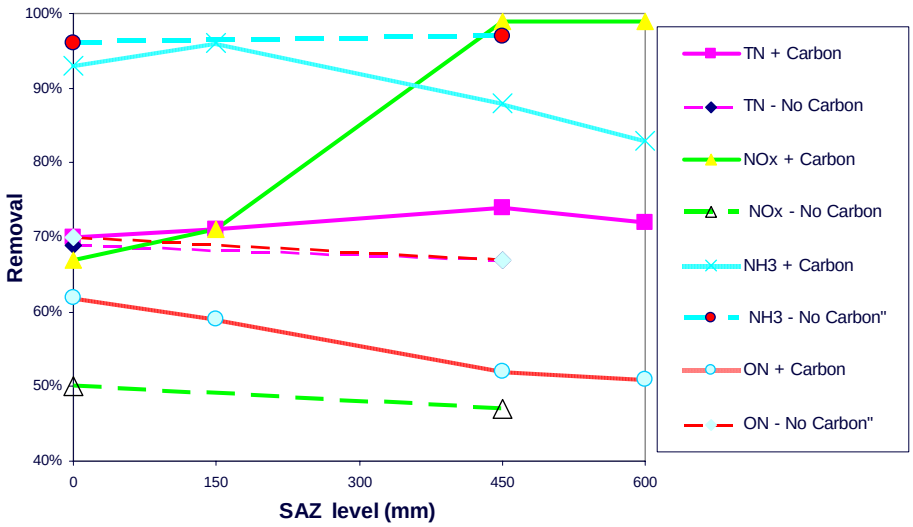

Figure 21. Nitrogen species removal under a range of SAZ levels (Source: Zinger *et al.*, 2007b)

A submerged zone with carbon is also beneficial for heavy metal removal (Blecken *et al.*, under review). This is particularly the case for copper (Cu), where only systems with this design feature were able ***to meet the ANZECC water quality targets*** for aquatic water health.

However, ***one of the most important benefits of these permanently wet zones is their ability to support plant survival during dry periods***. This has a large implication for treatment performance; the vegetated systems without a submerged zone and carbon, that removed over 60% of TN during regular wetting, began leaching TN after only ***three weeks of dry weather*** and took longer to recover upon re-wetting (Figure 22). The same systems with a submerged zone and carbon will 'fall-apart' ***only after seven weeks of dry weather***. Even then, they recover relatively quickly. It must also be noted that the response is not linear.

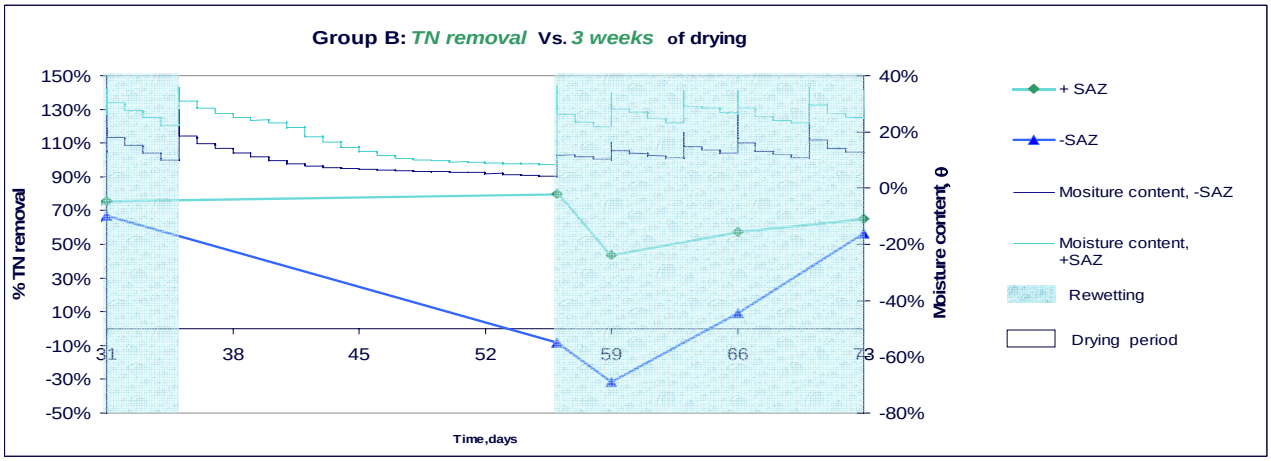

Figure 22. Impact of three weeks of drying on TN removal. Note: the change during the three week period is not linear and the first two points are joined for presentation reasons only. (Source: Zinger *et al.*, 2007b)

However, there are some side effects of incorporating submerged zones into bioretention systems. Low levels of ammonium production were observed, and they could be a source of some pathogens (very likely some viruses).

3.5 Hydrologic Performance

Infiltration Capacity

The use of appropriate soil media is an important factor in achieving reliable hydraulic functioning of the biofilters. ***If sized accordingly, systems with a hydraulic conductivity of around 100-300 mm/hour under compaction should be operational (under typical conditions) over a considerable period of time***. This was the main finding from the large survey of 37 field systems, that included systems that are over eight years old (Activity 4.04, Le Coustumer *et al.*, 2007; Le Coustumer *et al.*, 2008; Le Coustumer *et al.*, under review-a). The study broadly revealed two types of systems: some with a high initial hydraulic conductivity, K_{ini} (Figure 23 (left)), and some with a low (K_{ini} <25 mm/hr, Figure 23 (right)). Although reductions in K_s are evident for bioretention systems in the former group, most are shown to maintain an acceptably high conductivity (on average around 100 mm/hr, Figure 23 (left)). For the second type of system (with low initial K_s), little change occurred over time. It was therefore concluded that the main reason for low K_s is due to systems being built using soil with a low initial hydraulic conductivity. It is clear that strict attention must be paid to the filter media specification, to ensure that it satisfies current design requirements.

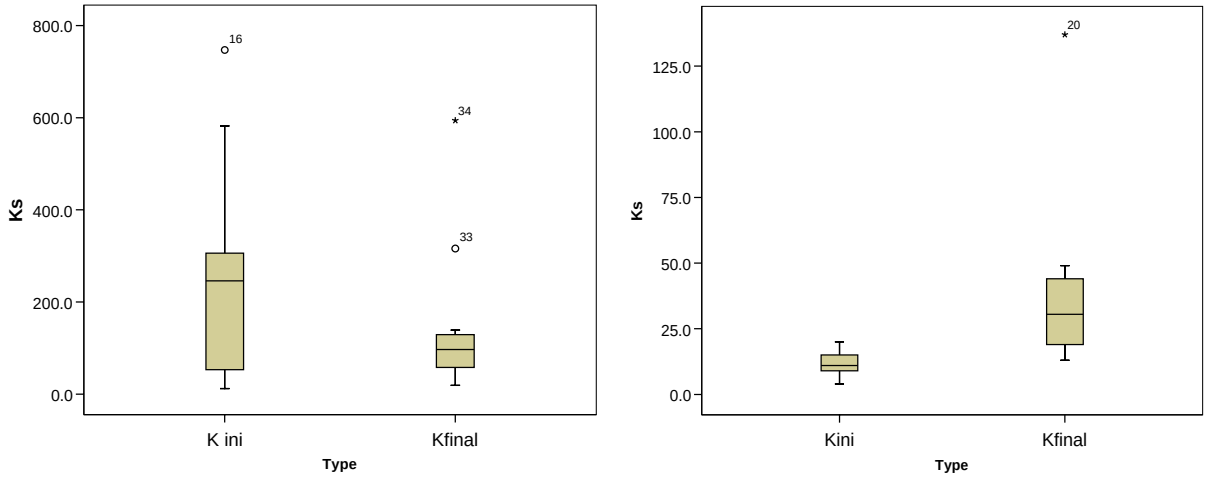

Figure 23. Evolution of hydraulic conductivity, K_s, in 37 field-scale bioretention systems: (left) Systems with an initial K_s that is within FAWB guidelines (mean K_{ini} = 241 mm/hr, n = 17) and (right) Systems with a very low initial K_s (mean K_{ini} = 12 mm/hr, n = 11). (Source: Le Coustumer *et al.*, under review-a)

In systems that are ***under-designed (too small for their catchment) or service catchments with high silt loads, surface clogging is an existing problem***. This is the key finding from our large column lab study, Activity 1.02(b) (see Figure 5 (b), Le Coustumer *et al.*, 2007; Le Coustumer *et al.*, under review-b). As illustrated in Figure 24 (left), systems that are sized to 4% of the impervious catchment were operational after 40 weeks, while systems that presented only 0.7% of the impervious catchment clogged very quickly (Le Coustumer *et al.*, under review-b). Similarly, Figure 24 (right) shows that systems that received higher inflow sediment concentrations experienced faster clogging. However, it must be noted that this laboratory study had some limitations, since the plants became pot-bound towards the end and it was felt that the results may not be directly scalable.

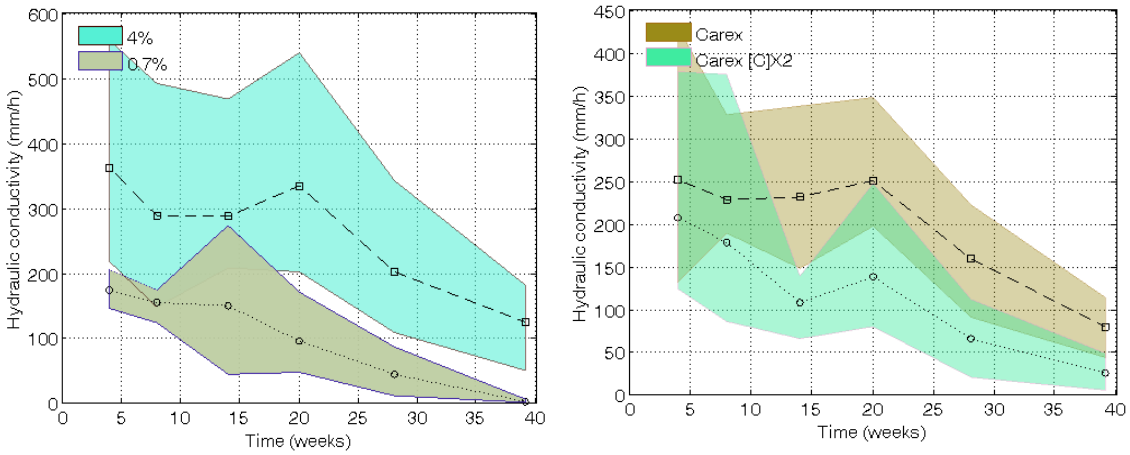

Figure 24. Hydraulic conductivity of the laboratory columns used in Activity 1.02 (b) relative to time: (left) Impact of the size of the system (4% of the impervious catchment and 0.7% of the impervious catchment) and (right) Impact of the inflow sediment concentration (Carex received average inflow concentrations with Carex[C]x2 receive double concentrations. (Source: Le Coustumer *et al.*, under review-b)

It was clear from all the investigations into hydraulic conductivity that bioretention systems will experience a ***drop in hydraulic conductivity immediately following construction***, due to compaction and, to a small extent, surface clogging. However, one of the key findings from the Monash carpark bioretention system (Activity 4.02, Hatt *et al.*, 2007b; Hatt *et al.*, in press) is that ***hydraulic conductivity will recover over time***. At the Monash system, the hydraulic conductivity was initially 300 mm/hr and decreased to less than 50 mm/hr in the first six months, but then recovered to >200 mm/hr within one year (Figure 25). We believe that plant growth is the cause of this recovery (through the creation of macropores by plant roots).

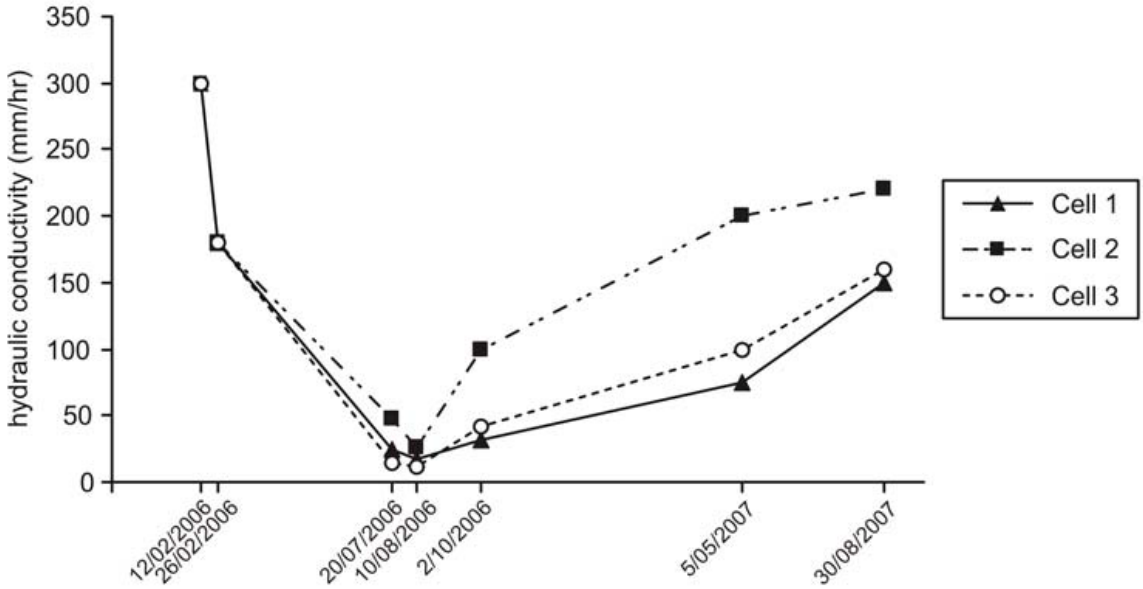

Figure 25. Hydraulic conductivity of the three cells of the Monash carpark bioretention system relative to time. SL - Sandy Loam, SLVP - Sandy Loam with Vermiculite/Perlite, SLCM - Sandy Loam with Compost/Mulch. (Source: Hatt *et al.*, in press)

Another key finding from the large column laboratory study is that it is likely that plants with large diameter roots, such as *M. ericifolia*, may 'work better as de-clogging agents' than thin rooted plants (Le Coustumer *et al.*, under review-b). In that study, it was found that, even when

pot-bound, the hydraulic conductivity of systems vegetated with *M. ericifolia* increased from 155 (±53) mm/hr after four weeks of operation to 295 (±112) mm/hr after 39 weeks of operation (while all columns planted with fine-rooted species showed a decline in K_s).

Flow Reductions

Based on the results of all field flow monitoring programs, it was evident that substantial reductions in flow peaks by bioretention systems are guaranteed. Based on results from the Saturn Crescent system (Activity 4.05), reductions in flow peaks of the 1 in 3 month storm event will vary between 80 and 86% (Table 5), depending on antecedent conditions (i.e., how long since it last rained). The reduction in flow peaks at the Monash University bioretention system (Activity 4.02) was of a similar magnitude and depended on the inflow peak (Figure 26 (left)). As a rule of thumb, ***outflow peaks should not be more than 20% of inflow peaks***.

Table 5. Total volumes and losses for the Saturn Crescent bioretention system during simulated storm events. ADWP - duration of antecdent dry weather period. (Source: Hatt *et al.*, in press)

Events	Inflow (L)	Outflow (L)	Loss (L)	ADWP (days)	Peak Q_{out} (L/s)	Peak Q_{out} (as % Q_{out})
25 October 2006	3000	2593	407 (14%)	3	0.48	14
19 June 2007	3000	2097	903 (30%)	11	0.48	14
23 October 2007	3000	2226	774 (26%)	12	0.66	20
24 October 2007	3000	2670	330 (11%)	0	0.50	15

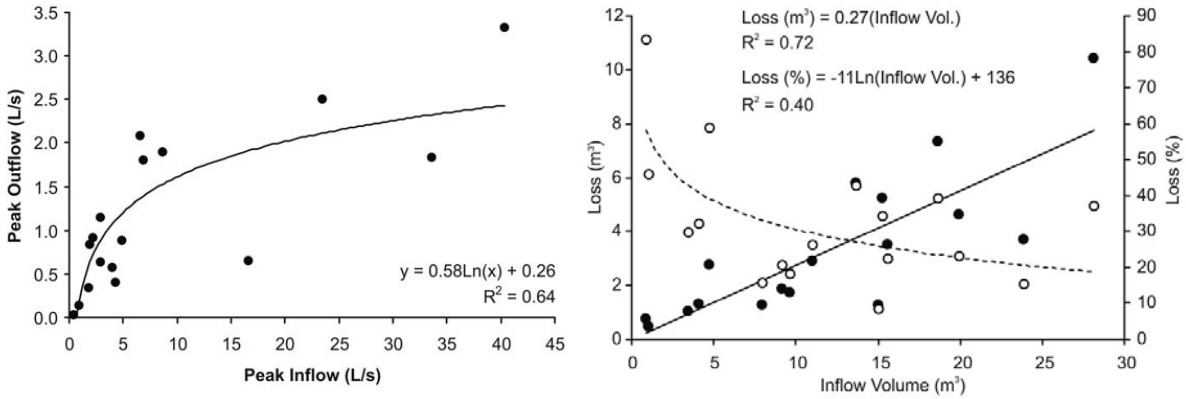

Figure 26. Monash University bioretention system: (left) Reduction in flow peaks and (right) Relationship between inflow volume and losses (Source: Hatt *et al.*, in press)

If built for pollution control, ***the systems should be built to promote exfiltration whenever possible***, since this will contribute to restoring catchment hydrology back towards its pre-development state, as well as result in reductions in pollution loads. Exfiltration losses will depend on the permeability of the surrounding soils and should be modelled accordingly.

However, even fully lined systems will have high losses due to evapotranspiration. The field studies at the Monash University bioretention system in Melbourne (Activity 4.05, Figure 26 (right)) and the Saturn Crescent stormwater garden in Brisbane (Activity 4.02, Table 5) both show ***that, on average, 20-30% of inflow volumes will be lost during typical storm events due to evapotranspiration***. Results from the Saturn Crescent bioretention system show that, even where relatively large events occured on consecutive days, inflow volumes for the second event were still reduced by 10%, while losses increased to 25% when the system was dry for more than ten days (Table 5). Losses are also overwhelmingly dependent on the size of the event (Figure 26 (right)), with small events being almost totally absorbed by biofilters.

3.6 Treatment Performance

If designed according to FAWB specifications, bioretention systems should be effective for the treatment of stormwater, reducing inflow ***TSS and TP by more than 90 and 80%***, respectively (Table 6 and Table 7).

To achieve this high removal rate of TP, it is crucial that the filter media meets the FAWB soil filter media guidelines. Soils with a high phosphorus content will leach TP, as shown by both the large scale column test (Table 6) and the field tests (Table 7).

On average, 50% removal of nitrogen is also achievable, if the right vegetation is selected (Figure 20 and Table 6). For nitrogen and phosphorus removal, *C. appressa* and *M. ericifolia* are very effective, however *M. ericifolia* will take longer to mature. Selecting filter media which do not have excessive levels of organic matter will also help to prevent nutrient leaching. The main cause of variations in TN removal is variable wetting and drying (with treatment efficiency decreasing substantially after long dry spells, Figure 22). ***TN concentrations reductions will be maintained at a high level*** and possibly enhanced ***by introducing a submerged zone***. This zone will provide a water source to sustain plants and microbes during dry spells as well as promote denitrification and therefore a high level of NO_x reduction (>90%, Figure 21). However, high load reductions could also be achieved simply by promoting exfiltration (i.e., not lining the system). Therefore, it is recommended that the advantages and disadvantages of lining a system be evaluated (if lining is not required for any other reason than creating a submerged zone).

Removal of heavy metals is consistently high and the standard bioretention system configuration ***will reduce Zn, Pb, and Cd concentration by more than 90%*** {e.g. Table 7, \Hatt, in press #780 and see also \Blecken, under review #805; Le Coustumer, under review #810}, and will ensure that the treated stormwater meets at least ***the ANZECC freshwater guidelines*** (Blecken *et al.*, under review). ***Removal of up to 60% of Cu can be expected using the standard design configuration, and over 90% if a submerged zone is incorporated***. While the standard design configuration just misses meeting the ANZECC standard for Cu, systems with a submerged zone can be expected to meet these high targets.

Preliminary results also show that ***bioretention systems may be very effective for the removal of bacteria (E. coli was used as an indicator), viruses (FRNA phages) and protozoa (C. perfringens)*** (Table 8). However, bacteria removal (i.e., *E. coli*) is considerably reduced following dry spells. Introduction of a submerged zone improved *E. coli* removal (Table 9) by buffering against the impact of dry weather spells, but resulted in a considerable decrease in removal of viruses (FRNA phages, Table 9). The preliminary results suggest that, if bioretention systems are to be used for treatment of harvested stormwater, and very high levels of pathogens in the inflow are present (the cases tested in Activity 1.03), additional disinfection may be required (to achieve water quality for safe use). However, disinfection may not be necessary if inflows have rather modest levels of pathogens (although this is still to be tested).

Importantly, treatment performance will also be reduced if the bioretention system is small relative to its catchment. Whilst no definitive guidance is yet available, ***a sizing of around 2% of the catchment area appears to give satisfactory treatment performance***.

Table 6. Results from the large laboratory study (Activity 1.02 (b)): Mean (coefficient of variation shown in parentheses) of five sampling runs for inflow and outflow for every column configuration. Inflow data are given as concentrations, while outflow data are given as both concentrations and concentration reduction rates. (Source: Bratieres *et al.*, in press)

INFLOW

Inflow concentration (mg/L)	TSS	TN	NO_x	TP	PO_4^{3-}
'Standard' concentration	160.0	2.21	0.79	0.427	0.127
'High' concentration	244.3	3.74	1.40	0.747	0.261

OUTFLOW *

Factors tested	Vegetation	Inflow volume	Filter media depth	Filter media type	Inflow conc.	TSS		TN		NO_x		TP		PO_4^{3-}	
						Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)
Vegetation	None	Std.	700	SL	Std.	1.3 (29)	99 (0.2)	6.68 (12)	-201 (18)	5.23 (12)	-560 (14)	0.083 (15)	81 (4)	0.064 (15)	50 (15)
	Carex	Std.	700	SL	Std.	1.3 (38)	99 (0.3)	0.65 (11)	71 (4)	0.03 (45)	96 (2)	0.023 (22)	95 (1)	0.013 (21)	90 (2)
	Dianella	Std.	700	SL	Std.	1.4 (46)	99 (0.4)	5.58 (30)	-152 (49)	4.62 (32)	-484 (39)	0.092 (19)	78 (5)	0.072 (16)	44 (20)
	Microleana	Std.	700	SL	Std.	1.1 (36)	99 (0.3)	5.56 (33)	-151 (55)	4.30 (44)	-443 (54)	0.074 (12)	83 (3)	0.050 (22)	61 (14)
	Leucophyta	Std.	700	SL	Std.	1.7 (35)	99 (0.4)	7.54 (8)	-241 (11)	5.78 (21)	-630 (24)	0.098 (9)	77 (3)	0.076 (13)	40 (19)
	Melaleuca	Std.	700	SL	Std.	4.2 (34)	97 (0.9)	1.19 (21)	46 (24)	0.38 (65)	52 (60)	0.070 (17)	84 (3)	0.034 (35)	74 (13)
Volume	Carex	Low	700	SL	Std.	3.0 (45)	98 (0.9)	0.84 (33)	62 (21)	0.16 (>100)	79 (40)	0.024 (48)	94 (3)	0.013 (45)	90 (5)
	Carex	High	700	SL	Std.	2.5 (73)	98 (1.1)	0.77 (33)	65 (18)	0.27 (99)	66 (51)	0.046 (12)	89 (1)	0.027 (28)	79 (8)
	Microleana	High	700	SL	Std.	3.0 (97)	98 (1.9)	4.56 (6)	-106 (12)	3.66 (6)	-362 (8)	0.104 (9)	76 (3)	0.087 (8)	32 (17)
	Melaleuca	High	700	SL	Std.	4.6 (54)	96 (3.6)	1.49 (54)	33 (>100)	0.79 (86)	0 (>100)	0.078 (29)	82 (7)	0.045 (39)	64 (22)
Filter media depth	Carex	Std.	500	SL	Std.	1.5 (58)	99 (0.5)	0.61 (26)	72 (10)	0.05 (25)	93 (2)	0.032 (26)	93 (2)	0.016 (24)	87 (4)
	Carex	Std.	300	SL	Std.	1.3 (27)	99 (0.2)	0.82 (46)	63 (27)	0.40 (81)	50 (82)	0.038 (22)	91 (2)	0.022 (18)	83 (4)
	Microleana	Std.	500	SL	Std.	0.9 (11)	99 (0.1)	4.90 (10)	-121 (18)	3.98 (11)	-403 (13)	0.078 (14)	82 (3)	0.062 (17)	52 (16)
	Microleana	Std.	300	SL	Std.	1.0 (73)	99 (0.5)	3.24 (33)	-46 (>100)	2.60 (37)	-229 (53)	0.078 (6)	82 (1)	0.053 (6)	58 (4)
	Melaleuca	Std.	500	SL	Std.	3.5 (63)	98 (1.4)	1.87 (78)	16 (>100)	1.15 (>100)	-45 (>100)	0.060 (39)	86 (6)	0.033 (60)	74 (21)
	Melaleuca	Std.	300	SL	Std.	5.3 (52)	96 (3.0)	1.26 (45)	43 (59)	0.79 (75)	0 (>100)	0.050 (40)	88 (5)	0.024 (79)	81 (18)
Filter media type	Carex	Std.	700	SLVP	Std.	4.0 (>100)	97 (2.6)	0.84 (41)	62 (25)	0.29 (>100)	64 (62)	0.040 (31)	91 (3)	0.021 (35)	83 (7)
	Carex	Std.	700	SLCM	Std.	2.4 (30)	98 (0.5)	4.44 (85)	-101 (>100)	2.04 (>100)	-158 (>100)	0.264 (48)	38 (78)	0.226 (49)	-78 (>100)
Inflow Conc.	Melaleuca	Std.	700	SL	High	7.2 (50)	95 (4.2)	2.06 (59)	45 (72)	1.12 (>100)	20 (>100)	0.068 (24)	91 (2)	0.030 (34)	96 (1)
	Microleana	Std.	700	SL	High	2.2 (44)	99 (0.4)	5.88 (26)	-57 (71)	4.94 (28)	-253 (39)	0.064 (14)	91 (1)	0.049 (17)	93 (1)
	Carex	Std.	700	SL	High	2.8 (62)	99 (0.7)	0.79 (30)	79 (8)	0.21 (87)	85 (15)	0.028 (30)	96 (1)	0.015 (35)	98 (1)
	None	Std.	700	SL	High	1.7 (24)	99 (0.2)	7.66 (11)	-105 (21)	6.80 (12)	-386 (15)	0.086 (6)	88 (1)	0.065 (6)	91 (1)

* Outflow concentrations (in mg/L) are provided together with the coefficient of variation (in %) in parentheses.
Similarly, removal data (expressed in %) is followed by the coefficient of variation (in %) in parentheses.

Table 7. Pollutant removal performance for seven storm events at the Monash University bioretention system (Activity 4.02) and four storm simulations at the Saturn Crescent rain garden (Activity 4.05). Note: the Monash University system was NOT built according to the FAWB soil filter media guidelines, while the Saturn Cresecent system was. (Source: Hatt *et al.*, in press)

Load Reduction (%)

	Monash University, Melbourne	**Saturn Crescent, Brisbane (FAWB soil spec)**			
	(mean ± standard deviation)	25 Oct 2006	19 Jun 2007	23 Oct 2007	24 Oct 2007
TSS	76 ± 25	91	97	88	94
TP	-398 ± 559	85	90	82	87
FRP	-1271 ± 1067	91	96	75	58
TN	-7 ± 72	17	66	28	31
NO_x	-13 ± 93	-41	33	-47	-33
NH_4^+	64 ± 42	98	99	86	99
DON	-129 ± 232	53	59	73	32
PON	38 ± 55	61	83	88	82
Cd	-	89	94	91	89
Cu	67 ± 23	97	99	98	97
Mn	38 ± 53	-	-	-	-
Pb	80 ± 15	97	99	98	98
Zn	84 ± 26	99	99	99	99

Table 8. Pathogen removal (unpublished preliminary results from Activity 1.03)

Indicator	**Inflow Conc.**	**Overall Average Removal**	**After Wet Period**	**After Dry Period**
C. Perfringens	$1.4\times10^3 – 4\times10^4$	99.7% (CV =1.1%)	99.6% (CV=1.6%)	99.8% (CV=0.2%)
E. coli	$7.6\times10^4 – 5.2\times10^5$	82.1% (CV =38.5%)	98.2% (CV=2.7%)	68.4% (CV=54.5%)
FRNA phages	$3.8\times10^3 – 9\times10^7$	96.1% (CV=31.3%)	99.6% (CV=2.5%)	93.3% (CV=43.0%)

Table 9. Impact of a submerged zone on pathogen removal (unpublished preliminary results from Activity 1.03)

Indicator	**Inflow Concentrations**	**Overall Average Removal**	**Only SZ Columns**	**Overall Average Excluding SZ Col.**
C. Perfringens	$1.4\times10^3 – 4\times10^4$	99.7% (CV =1.1%)	99.0% (CV=2.7%)	99.9% (CV=0.3%)
E. coli	$7.6\times10^4 – 5.2\times10^5$	82.1% (CV =38.5%)	97.3% (CV=7.0%)	79.5% (CV=42.1%)
FRNA phages	$3.8\times10^3 – 9\times10^7$	96.1% (CV=31.3%)	73.6% (CV=104.3%)	99.99% (CV=0.1%)

3.7 Construction and Maintenance

Some degree of leaching of fine sediment and nutrients from the soil filter media will usually occur during the establishment phase, until the soil has stabilised and plant roots have occupied the soil volume (this will typically take 2 – 6 months, Deletic and Mudd, 2006).

Effective communication between designers and construction contractors is essential throughout all stages of the project. It is imperative that quality control issues are addressed in planning and design, construction, and maintenance throughout the life of the biofiltration system, and that the design intent is communicated to the contractors at a pre-construction briefing.

Maintenance requirements could be high during the establishment phase; frequent weed removal is required and juvenile vegetation should be watered during extended dry periods. However, the need for this level of maintenance reduces significantly as the vegetation matures. The

development of mosses on the surface should be discouraged, as these can reduce the infiltration capacity of the system. Dense planting of the preferred plants at the time of construction will help to minimise the extent of weed invasion, and minimise any moss growth.

3.8 Building Bioretention Systems in Sodic Soils

Bioretention systems constructed in sodic soils without an impermeable lining are not at risk of exporting salt from *in situ* soil into local streams. Even after six months of intensive flushing under controlled, laboratory conditions, they did not leach salt from the surrounding soils (Deletic and Mudd, 2006).

3.9 Future Research

While we have shown that some species are more effective than others in terms of pollutant removal (primarily for nitrogen), it is not certain that the same trends among species will occur in differing environments, or when plants are grown in competition with other species. We are currently testing the same species under varied wetting and drying regimes, to determine whether certain species, which are not effective in nitrogen removal in frequently-wet environments, perform better under drier conditions.

Engineered media (instead of naturally sourced media) should be tested prior to widespread adoption. They may provide a solution to the problem of ensuring media stability and satisfactory initial hydraulic performance, but they still need to be tested for leaching and clogging. FAWB is currently undertaking research in conjunction with Melbourne Water to test the performance of engineered soil filter media.

We are also awaiting results on break-through of heavy metals to assess the long-term sustainability of the soil media. The FAWB specified filter media has been exposed to more than 20 years of stormwater inflows and soon we will be able to estimate when Zn, Cu, Pb and Cd will start leaching from the systems. We therefore hope to be able to provide guidance on how many years a system may operate for, before the media becomes saturated and starts leaching.

Clogging issues, as well as soil structural changes and stability, are long-term processes that will require monitoring over a number of years. We are continuing to test the infiltration capacity of Monash University bioretention system, as well as a number of other systems.

The long-term impact of incorporating a submerged zone also requires assessment. The length of time for which the specified carbon source will last is hypothesized, and ongoing testing is needed to verify these predictions.

Further testing of bioretention systems in field conditions is essential. It is important to monitor new systems (hopefully built according to the findings presented above) in order to verify the specified design. These systems, if not designed correctly, may act as sources of pollution and therefore should be carefully designed, constructed and monitored.

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Appendix A:
Guidelines for Soil Filter Media in Bioretention Systems

GUIDELINES FOR SOIL FILTER MEDIA IN BIORETENTION SYSTEMS (Version 2.01) March 2008

The following guidelines for soil filter media in bioretention systems have been prepared on behalf of the Facility for Advancing Water Biofiltration (FAWB) to assist in the development of bioretention systems, including the planning, design, construction and operation of those systems.

NOTE: This is a revision of the previous FAWB guideline specifications (published in 2006). It attempts to provide a simpler and more robust guideline. FAWB acknowledges the contribution of EDAW Inc., Melbourne Water Corporation, Dr Nicholas Somes (Ecodynamics), Alan Hoban (SEQ Healthy Waterways Partnership), and STORM Consulting to the preparation of the revised guidelines.

Disclaimer

1 GENERAL DESCRIPTION

The bioretention filter media guidelines require three layers of media: the filter media itself (400-600 mm deep or as specified in the engineering design), a transition layer (100 mm deep), and a drainage layer (50 mm minimum underdrainage pipe cover). The bioretention system will operate so that water will infiltrate into the filter media and move vertically down through the profile.

The filter media is required to support a range of vegetation types (from groundcovers to trees) that are adapted to freely draining soils with occasional flooding. The material should be based on natural soils or amended natural soils and can be of siliceous or calcareous origin. In general, the media should be a **loamy sand** with an appropriately high permeability under compaction and should be free of rubbish, deleterious material, toxicants, declared plants and local weeds (as listed in local guidelines/Acts), and should not be hydrophobic. The filter media should contain some organic matter for increased water holding capacity but be low in nutrient content.

Maintaining an adequate infiltration capacity is crucial in ensuring the long-term treatment efficiency of the system. The ability of a bioretention system to detain and infiltrate incoming stormwater is a function of the filter surface area, extended detention (ponding) depth, and the hydraulic conductivity of the filter media (Figure 1). Most importantly, design of a bioretention system should optimize the combination of these three design elements.

For a bioretention system in a temperate climate with an extended detention depth of 100-300 mm and whose surface area is approximately 2% of the connected impervious area of the contributing catchment, the prescribed hydraulic conductivity will generally be between 100-300 mm/hr in order to meet best practice targets (Figure 2). This configuration supports plant growth without requiring too high a land space. In warm, humid (sub- and dry- tropical) regions the hydraulic conductivity may need to be higher in order to achieve the required treatment performance using the same land space (i.e., ensuring that the proportion of water treated through the media meets requirements).

Where one of these design elements falls outside the recommended range, the infiltration capacity can still be maintained by offsetting another of the design elements. For example, a filter media with a lower hydraulic conductivity may be used, but the surface area or the extended detention depth would need to be increased in order to maintain the treatment capacity. Similarly, if the available land were the limiting design element, the system could still treat the same size storm if a filter media with a higher hydraulic conductivity were installed. Where a hydraulic conductivity greater than 300 mm/hr is prescribed, potential issues such as higher watering requirements during the establishment should be considered. Bioretention systems with a hydraulic conductivity greater than 600 mm/hr are unlikely to support plant growth due to poor water retention, and may also result in leaching of pollutants. However plant survival might be possible if the outlet pipe were raised to create a permanently submerged zone.

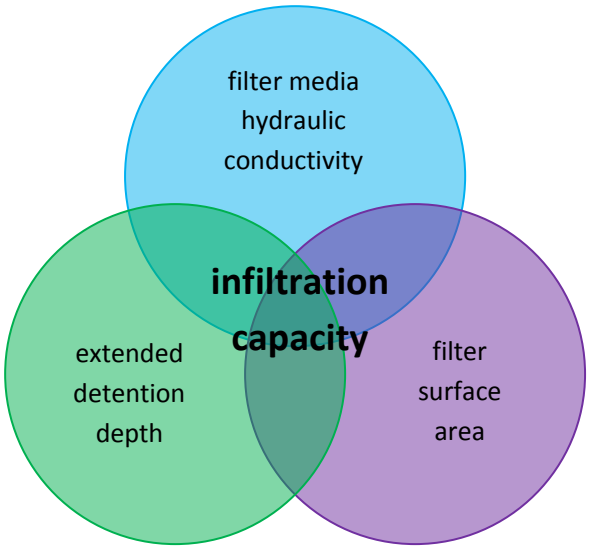

Figure 1. Design elements that influence infiltration capacity

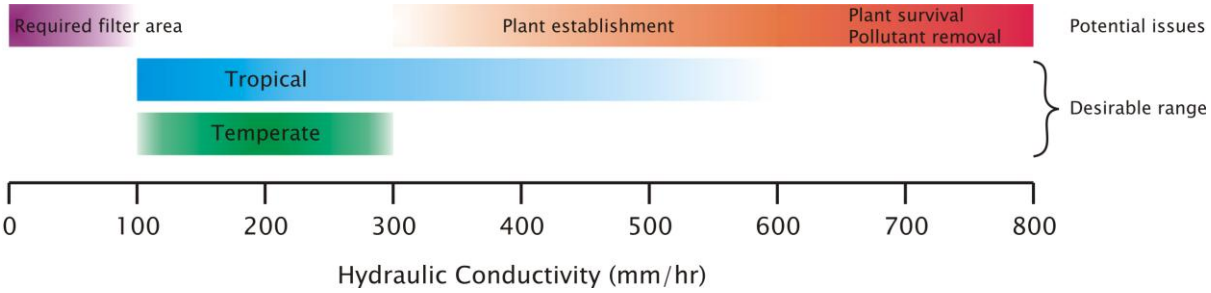

Figure 2. Recommended filter media hydraulic conductivity range and potential issues

The infiltration capacity of the bioretention system will initially decline during the establishment phase as the filter media settles and compacts, but this will level out and then start to increase as the plant community establishes itself and the rooting depth increases (see Appendix A). In order to ensure that the system functions adequately at its eventual (minimum) hydraulic conductivity, a safety co-efficient of 2 should be used: i.e., *designs should be modelled using half the prescribed hydraulic conductivity*. If a system does not perform adequately with this hydraulic conductivity, then the area and/or ponding depth should be increased. It may also be desirable to report sensitivity to infiltration rate, rather than simply having expected rate. This is important when assessing compliance of constructed systems as systems should ideally meet best practice across a range of infiltration rates.

2 TESTING REQUIREMENTS

2.1 Determination of Hydraulic Conductivity

The hydraulic conductivity of potential filter media should be measured using the ASTM F1815-06 method. This test method uses a compaction method that best represents field conditions and so provides a more realistic assessment of hydraulic conductivity than other test methods.

Note: if a hydraulic conductivity lower than 100 mm/hr is prescribed, the level of compaction associated with this test method may be too severe and so underestimate the actual hydraulic conductivity of the filter media under field conditions. However, FAWB considers this to be an appropriately conservative test, and recommends its use even for low conductivity media.

2.2 Particle Size Distribution

Particle size distribution (PSD) is of secondary importance compared with hydraulic conductivity. A material whose PSD falls within the following recommended range does not preclude the need for hydraulic conductivity testing i.e., it does not guarantee that the material will have a suitable hydraulic conductivity. However, the following composition range (percentage w/w) provides a useful guide for selecting an appropriate material:

Clay & Silt	<3%	(<0.05 mm)
Very Fine Sand	5-30%	(0.05-0.15 mm)
Fine Sand	10-30%	(0.15-0.25 mm)
Medium to Coarse Sand	40-60%	(0.25-1.0 mm)
Coarse Sand	7-10%	(1.0-2.0 mm)
Fine Gravel	<3%	(2.0-3.4 mm)

Clay and silt are important for water retention and sorption of dissolved pollutants, however they substantially reduce the hydraulic conductivity of the filter media. This size fraction also influences the structural stability of the material (through migration of particles to block small pores and/or slump). It is essential that the total clay and silt mix is **less than 3% (w/w)** to reduce the likelihood of structural collapse of such soils.

The filter media should be well-graded i.e., it should have all particle size ranges present from the 0.075 mm to the 4.75 mm sieve (as defined by AS1289.3.6.1 – 1995). There should be no gap in the particle size grading, and the composition should not be dominated by a small particle size range. This is important for preventing structural collapse due to particle migration.

2.3 Soil Properties

2.3.1 AS4419 – 2003 (Soils for Landscaping and Garden Use)

Filter media that do not meet the following specifications should be rejected:

i. Organic Matter Content – less than 5% (w/w). An organic content higher than 5% is likely to result in leaching of nutrients.

ii. pH – as specified for 'natural soils and soil blends' 5.5 – 7.5 (pH 1:5 in water).

iii. Electrical Conductivity (EC) – as specified for 'natural soils and soil blends' <1.2 dS/m.

iv. Phosphorus – <100 mg/kg. Soils with phosphorus concentrations >100 mg/kg should be tested for potential leaching. Where plants with moderate phosphorus sensitivity are to be used, phosphorus concentrations should be <20 mg/kg.

Optional testing:

v. Dispersibility – this should be carried out where it is suspected that the soil may be susceptible to structural collapse. If in doubt, then this testing should be undertaken.

2.3.2 Soil Nutrition

Potential filter media should generally be assessed by a horticulturalist to ensure that they are capable of supporting a healthy vegetation community. This assessment should take into consideration delivery of nutrients to the system by stormwater. Any component or soil found to contain high levels of salt (as determined by EC measurements), high levels of clay or silt particles (exceeding the particle size limits set above), or any other extremes which may be considered retardant to plant growth should be rejected.

3 TRANSITION AND DRAINAGE LAYERS

Transition layer material shall be a clean, well-graded sand/ coarse sand material containing little or no fines.

The drainage layer is to be clean, fine gravel, such as a 2-5 mm washed screenings.

Geotextile fabrics are not recommended for use in bioretention systems due to the risk of clogging. An open-weave shade cloth can be placed between the transition layer and the drainage layer to help reduce the downward migration of smaller particles if required, however this should only be adopted where there is insufficient depth for transition and drainage layers.

4 INSTALLATION

It is recommended that filter media be lightly compacted during installation to prevent migration of fine particles. In small systems, a single pass with a vibrating plate should be used to compact the filter media, while in large systems, a single pass with roller machinery (e.g. a drum lawn roller) should be performed. Under no circumstance should heavy compaction or multiple-passes be made. Filter media should be installed in two lifts unless the depth is less than 500 mm.

5 FIELD TESTING

It is recommended that field testing of hydraulic conductivity be carried out at least twice: 1. one month following commencement of operation, and 2. in the second year of operation to assess the impact of vegetation on hydraulic conductivity.

The hydraulic conductivity of the filter media should be checked at a minimum of three points within the system. The single ring, constant head infiltration test method (shallow test), as described by Le Coustumer *et al.* (2007), should be used. Given the inherent variability in hydraulic conductivity testing and the heterogeneity of the filter media, the laboratory and field results are considered comparable if they are within 50% of each other. However, even if they differ by more than 50%, the system will still function if both the field and laboratory results are within the relevant recommended range of hydraulic conductivities.

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Appendix

Figure A.1 illustrates the change in hydraulic conductivity during the establishment phase of a Melbourne bioretention system containing a sandy loam filter media. The hydraulic conductivity initially declines as the filter media is compacted under hydraulic loading, but recovers back to the design value (as indicated by the dashed horizontal line) as plant growth and increased rooting depth counters the effects of compaction and clogging.

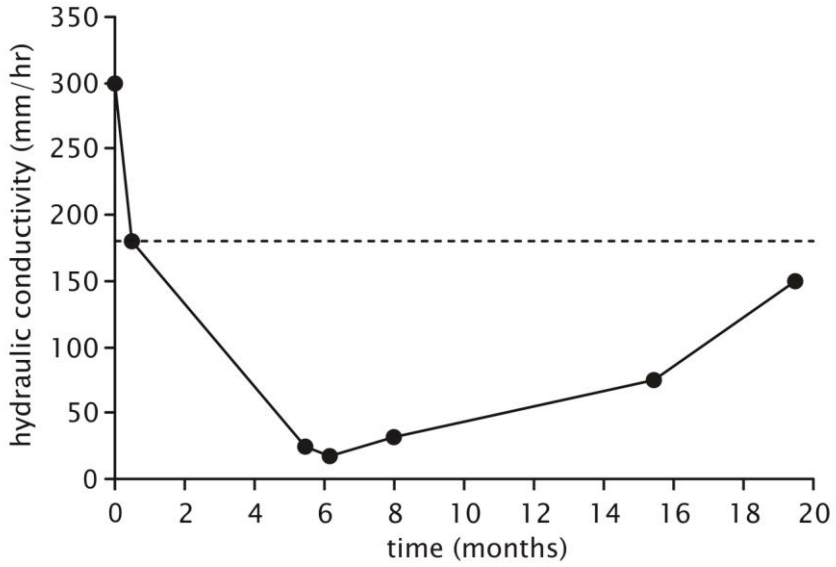

Figure A.1 Evolution of hydraulic conductivity during the first 20 months of a bioretention system

Appendix B:
Practice Note 1: *In Situ* Measurement of Hydraulic Conductivity

CONDITION ASSESSMENT AND PERFORMANCE EVALUATION OF BIORETENTION SYSTEMS

PRACTICE NOTE 1: *In Situ* Measurement of Hydraulic Conductivity

Belinda Hatt, Sebastien Le Coustumer

April 2008

The Facility for Advancing Water Biofiltration (FAWB) aims to deliver its research findings in a variety of forms in order to facilitate widespread and successful implementation of biofiltration technologies. This Practice Note for *In Situ* Measurement of Hydraulic Conductivity is the first in a series of Practice Notes being developed to assist practitioners with the assessment of construction and operation of biofiltration systems.

1. SCOPE OF THE DOCUMENT

This Practice Note for *In Situ* Measurement of Hydraulic Conductivity is designed to complement FAWB's Guidelines for Soil Filter Media in Bioretention Systems, Version 2.01 (visit http://www.monash.edu.au/fawb/publications/index.html for a copy of these guidelines). However, the recommendations contained within this document are more widely applicable to assessing the hydraulic conductivity of filter media in existing biofiltration systems.

For new systems, this Practice Note ***does not*** remove the need to conduct laboratory testing of filter media prior to installation.

2. DETERMINATION OF HYDRAULIC CONDUCTIVITY

The recommended method for determining *in situ* hydraulic conductivity uses a single ring infiltrometer under constant head. The single ring infiltrometer consists of a small plastic or metal ring that is driven 50 mm into the soil filter media. It is a constant head test that is conducted for two different pressure heads (50 mm and 150 mm). The head is kept constant during all the experiments by pouring water into the ring. The frequency of readings of the volume poured depends on the filter media, but typically 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 30 minutes). This method has been used extensively (e.g. Reynolds and Elrick, 1990; Youngs *et al.*, 1993).

Note: This method measures the hydraulic conductivity at the surface of the soil filter media. In most cases, it is this top layer which controls the hydraulic conductivity of the system as a whole (i.e., the underlying drainage layer has a flow capacity several orders of magnitude higher than the filter media), as it is this layer where fine sediment will generally be deposited to form a "clogging layer". However this shallow test would not be appropriate for systems where the controlling layer

is not the surface layer (e.g. where migration of fine material down through the filter media has caused clogging within the media). In this case, a 'deep ring' method is required; for further information on this method, please consult FAWB's report "Hydraulic performance of biofilter systems for stormwater management: lessons from a field study", available at www.monash.edu.au/fawb/publications/index.html.

2.1 Selection of monitoring points

For bioretention systems with a surface area less than 50 m^2, *in situ* hydraulic conductivity testing should be conducted at three points that are spatially distributed (Figure 1). For systems with a surface area greater than 50 m^2,an extra monitoring point should be added for every additional 100 m^2. It is ***essential*** that the monitoring point is flat and level. Vegetation should not be included in monitoring points.

Figure 1. Spatially distributed monitoring points

2.2 Apparatus

The following is required:

- 100 mm diameter PVC rings with a height of at least 220 mm. The bottom edge of the ring should be bevelled and the inside of the ring should be marked to indicate 50 mm and 150 mm above the filter media surface (Figure 2).
- 40 L water
- 100 mL, 250 mL and 1000 mL measuring cylinders
- Stopwatch
- Thermometer

- Measuring tape
- Spirit level
- Hammer
- Block of wood, approximately 200 x 200 mm

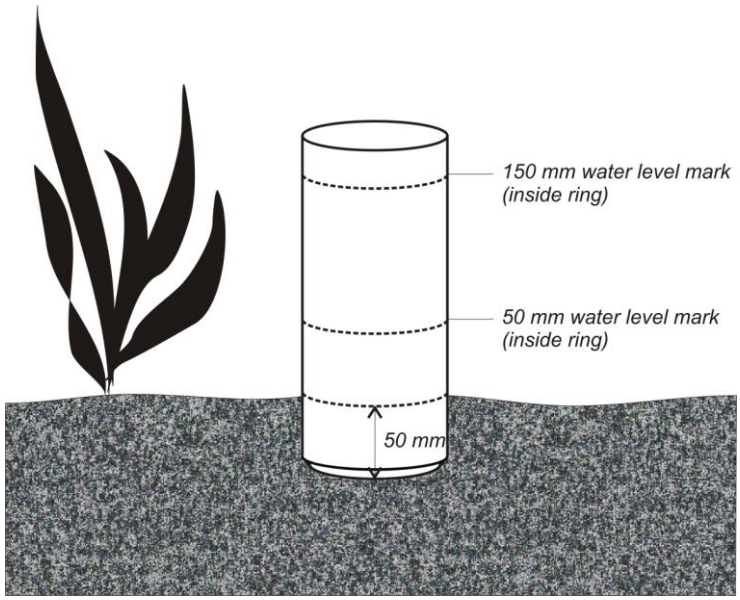

Figure 2. Diagram of single ring infiltrometer

2.3 Procedure

a. Carefully scrape away any surface covering (e.g. mulch, gravel, leaves) ***without disturbing*** the soil filter media surface (Figure 3b).

b. Locate the ring on the surface of the soil (Figure 3c), and then place the block of wood on top of the ring. Gently tap with the hammer to drive the ring 50 mm into the filter media (Figure 3d). Use the spirit level to check that the ring is level.

   Note: It is ***essential*** that this the ring is driven in slowly and carefully to minimise disturbance of the filter media profile.

c. Record the initial water temperature.

d. Fill the 1000 mL measuring cylinder.

e. Using a different pouring apparatus, slowly fill the ring to a ponding depth of 50 mm, taking care to minimise disturbance of the soil surface (Figure 3f). Start the stopwatch when the water level reaches 50 mm.

f. Using the 1000 mL measuring cylinder, maintain the water level at 50 mm (Figure 3g). After 30 seconds, record the volume poured.

g. Maintain the water level at 50 mm, recording the time interval and volume required to do so.

Note: The time interval between recordings will be determined by the infiltration capacity of the filter media. For fast draining media, the time interval should not be greater than one minute however, for slow draining media, the time between recordings may be up to five minutes.

Note: The smallest measuring cylinder that can pour the volume required to maintain a constant water level for the measured time interval should be used for greater accuracy. For example, if the volume poured over one minute is 750 mL, then the 1000 mL measuring cylinder should be used. Similarly, if the volume poured is 50 mL, then the 100 mL measuring cylinder should be used.

h. Continue to repeat Step f until the infiltration rate is steady i.e., the volume poured per time interval remains constant for at least 30 minutes.

i. Fill the ring to a ponding depth of 150 mm (Figure 3h). Restart the stopwatch. Repeat steps e – g for this ponding depth.

Note: Since the filter media is already saturated, the time required to reach steady infiltration should be less than for the first ponding depth.

j. Record the final water temperature.

k. Enter the temperature, time, and volume data into a calculation spreadsheet (see "Practice Note 1_Single Ring Infiltration Test_Example Calculations.xls", available at www.monash.edu.au/fawb/publications/index.html, as an example).

2.4 Calculations

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

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

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

$$K_{fs} = \frac{G}{a}\left(\frac{Q_2 - Q_1}{H_2 - H_1}\right) \qquad \text{Eqn. 2}$$

where a is the ring radius, H_1 and H_2 are the first (50 mm) and second (150 mm) pressure heads, respectively, Q_1 and Q_2 are the steady flows for the first and second pressure heads, respectively, and G is a shape factor estimated as:

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

where d is the depth of insertion of the ring and a is the ring radius.

G is nearly independent of soil hydraulic conductivity (i.e. K_{fs} and α) and ponding, if the ponding is greater than 50 mm.

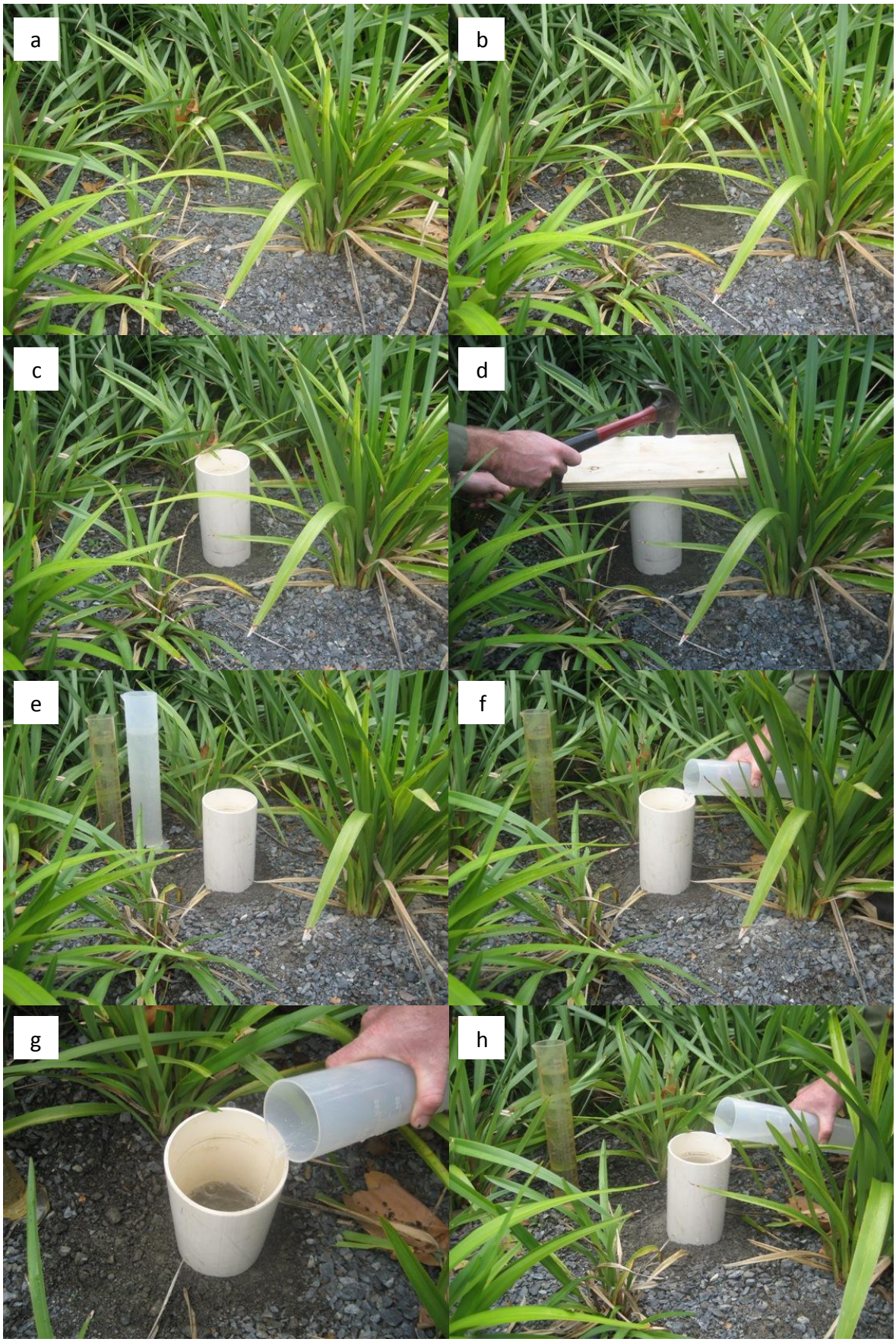

Figure 3. Measuring hydraulic conductivity

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), and (3) possible edge flow during the experiments.

3 INTERPRETATION OF RESULTS

This test method has been shown to be relatively comparable to laboratory test methods (Le Coustumer *et al.*, 2008), taking into account the inherent variability in hydraulic conductivity testing and the heterogeneity of natural soil-based filter media. While correlation between the two test methods is low, results are not statistically different. In light of this, laboratory and field results are deemed comparable if they are within 50% of each other. In the same way, replicate field results are considered comparable if they differ by less than 50%. Where this is not the case, this is likely to be due to a localised inconsistency in the filter media, therefore additional measurement should be conducted at different monitoring points until comparable results are achieved. If this is not achieved, then an area-weighted average value may need to be calculated.

4 MONITORING FREQUENCY

Field testing of hydraulic conductivity should be carried out at least twice: (1) One month following commencement of operation, and (2) In the second year of operation to assess the impact of vegetation on hydraulic conductivity. Following this, hydraulic conductivity testing should be conducted every two years or when there has been a significant change in catchment characteristics (e.g., construction without appropriate sediment control).

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Single Ring Infiltration Test

Site: ____

Date: ____

Constant water level = 50 mm		
Time (min)	Volume (mL)	Q (mL/s)

Constant water level = 150 mm		
Time (min)	Volume (mL)	Q (mL/s)