University of Southern Queensland
Faculty of Engineering and Surveying

Bioretention Basin
Best Practice Design Guidelines

A dissertation submitted by

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Abstract

A 'best practice' design guideline for a bioretention basin is concluded by comparing and critically evaluating existing design guidelines, along with studies on their performance. Further, an appropriate naming convention for a bioretention basin is sought and concluded.

Bioretention basins (which are an aspect of Water Sensitive Urban Design) seek to maintain near-to natural flow levels at storm water receiving waters (by retention of storm runoff) and treat storm runoff to remove pollutants at-source in urbanised areas. This minimises the consequences on receiving waterways caused by urbanisation. The increase in impervious area in an urbanised area causes disruption to the natural hydrologic cycle and an increase in stormwater pollutant load.

Many different guidelines exist for bioretention basin design due to simultaneous evolution of the technology in various locations around the world. A consensus on 'best practice' design principles is needed.

The design guidelines of bioretention basins are easily divided into separate design elements. This enables comparison and critical evaluation to be undertaken in terms of each design element to conclude an overall 'best practice' design guideline for the system. Recommendations for further research into some of these design elements are presented due to conflicting information in the publications reviewed or a lack of information. Twelve design guidelines and twelve studies from the USA and Australia are used as a source of information.

The naming convention is also compared in the various publications reviewed and other literature. The most appropriate term for a bioretention basin is 'bioretention' followed by either 'basin', 'system', 'cell', 'area' or 'facility'.

A 'best practice' design guideline has been concluded. It shares many similarities to some of the existing design guidelines, giving it some merit. Field testing is recommended to research its effectiveness.

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ENG4111 Research Project Part 1 & ENG4112 Research Project Part 2

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I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature

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Date

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Nomenclature

TSS	Total Suspended Solids
TN	Total Nitrogen
TP	Total Phosphorus
O/G	Oil and Grease
WSUD	Water Sensitive Urban Design
LID	Low Impact Development
SUDS	Sustainable Urban Drainage Systems
PVC	Polyvinyl Chloride
AG	Agricultural
HDPE	High-density Polyethylene

Chapter 1 Introduction and overview

1.1. Introduction

This study seeks to compare existing bioretention basin design guidelines, along with any studies on bioretention basin performance, to develop a 'best practice' design guideline. An appropriate naming convention for bioretention systems will also be sought as consistency is lacking in various publications. It will focus on urban stormwater drainage systems.

Storm runoff is directed in bioretention basins by gravity. Bioretention basins detain and treat the storm runoff to remove pollutants. They consist of a vegetated area with a fine media layer underneath which filters the runoff as it percolates downwards. Underdrains, at the bottom of the basin, collect the treated runoff and transport it into the constructed stormwater conveyance system. It eventually discharges to receiving waterways downstream (Brisbane City Council 2005a).

Bioretention basins are a relatively new system of stormwater drainage treatment and detention. They have simultaneously evolved in different ways and with different names at various locations around the world (Minton 2007). Inconsistency in their naming convention therefore exists.

1.2. Background

1.2.1 Urbanisation impacts

Urbanisation changes the quality and quantity of storm water reaching receiving waters from that in the natural environment. Urbanised areas contain greater impervious area (due to paving and roofs) and a constructed storm water conveyance system (usually piped). These intercept and divert storm runoff. Flow across impervious areas causes an increased runoff pollutant load. Conveyance time to receiving waterways is decreased. Environmental damage to some waterways results due to this hydrological cycle modification (Victoria Stormwater Committee 1999).

In the natural environment, the discharge of storm runoff to the downstream receiving body is more gradual than in the urbanised environment. Infiltration, biological uptake, transpiration and evaporation reduce the amount of runoff in natural systems. Groundwater is recharged through percolation to aquifers. Around 70% of the runoff ends up as atmospheric moisture (Argue & Hogan n.d.).

Increased impervious area results in a reduction in infiltration, biological uptake, transpiration and evaporation. This causes an increase in the quantity of runoff (Victoria Stormwater Committee 1999). Pipes and channels convey this increased quantity of runoff much faster than it would be conveyed in a natural system, resulting in a reduction in lag time (time between peak rainfall and peak discharge at outfall). Peak flows in receiving waterways increase along with scour and erosion (Argue & Hogan n.d.). Frequency of high flow events also increases. The morphology of creeks and rivers can be altered as a result (ed. Wong 2006). More regular high flow events can also degrade the aquatic ecology by destroying habitat. Refer to Figure 1.1 for a flood hydrograph showing lag time.

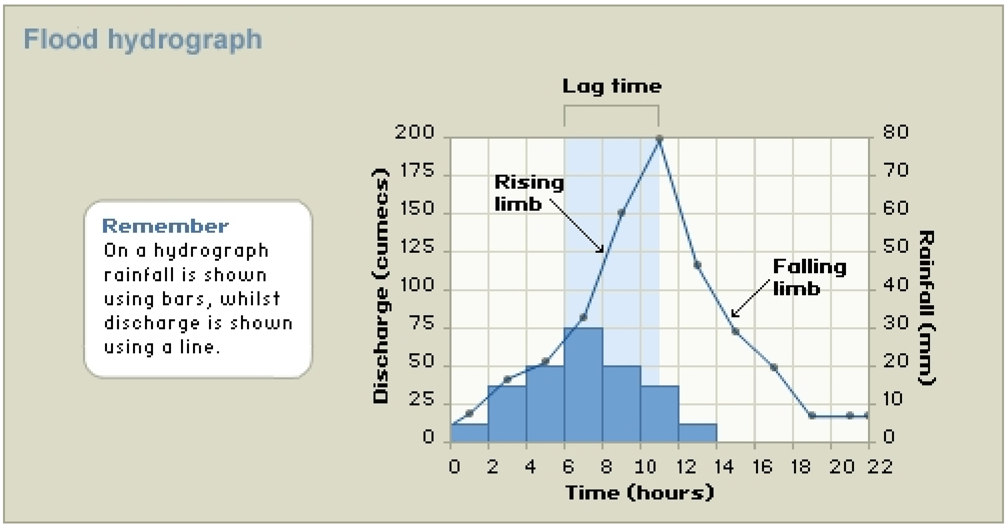

Figure 1.1 Flood hydrograph lag time

(BBC 2008, p. 1)

Storm water runoff collects and mobilises many pollutants as it flows across impervious surfaces in urban areas. Conventional drainage systems transport these to waterways downstream. These pollutants include nutrients, heavy metals and sediment which can have significant adverse impacts on waterways (Argue & Hogan n.d.).

Sediment can increase turbidity in water bodies, reduce the usefulness of the water and destroy ecological habitats (Davis & Cornwell 1998).

Toxic metals can become concentrated in the food chain and degrade the ecology (Davis & Cornwell 1998).

Nutrients of primary concern are nitrogen and phosphorus. In water bodies, excessive amounts can lead to algal blooms which deplete oxygen in the water body as they die and decompose. Organic suspended solids can also increase oxygen demand on a water body, adversely impacting on the ecology (Davis & Cornwell 1998). Eutrophication can be a result of increased nutrient load in waterways.

1.2.2 Water sensitive urban design (WSUD)

Water sensitive urban design (WSUD) seeks to minimise changes to the natural hydrological system through retention and detention of storm runoff at its source (Victoria Stormwater Committee 1999). Pollutant removal is also an aim of WSUD. Pervious areas of a catchment behave the same after development as before development, therefore only impervious areas of catchments need to be managed (Argue & Hogan n.d.).

Originally the basis of stormwater design was to collect it and transport it from its area of origination to an area of disposal as quickly as possible (Pearce, cited in Argue & Hogan n.d.). It is important to do this to protect the safety of the public and the integrity of property and also to minimise any nuisance caused by a storm event (University of Southern Queensland 2007). Problems have been encountered due to this philosophy with increased downstream flooding at the place of disposal of the stormwater and the pollution of the receiving waterways (Argue & Hogan n.d.) leading to the introduction of WSUD.

WSUD results in a runoff hydrograph that is similar before and after development. Detention and retention of storm runoff before it enters the constructed storm water conveyance system lessen peak flows. With the implementation of WSUD the size of the constructed system's elements can therefore be reduced saving costs (Victoria Stormwater Committee 1999).

Treatment of runoff at its source is a viable means of protecting receiving waterways from the adverse environmental impacts of pollutants. Vegetated swales and other WSUD systems filter pollutants and facilitate infiltration (Victoria Stormwater Committee 1999).

There also exist similar systems overseas. WSUD is known as Low Impact Development (LID) in the USA. Sustainable Urban Drainage Systems (SUDS) is the UK term. Hager (2003) describes LID as a stormwater management approach that treats rainfall on-site to attempt to maintain hydrological function. Neil Weinstein (cited in Hager 2003), executive director of the Low Impact Development Center in Beltsville, MD, describes LID as a "distributed source-control approach designed to treat and manage runoff at the source."

Some WSUD elements currently in use include:

- bioretention basins;
- bioretention swales;
- sand filters;
- sediment basins; and
- wetlands.

This study will focus on bioretention basins. Bioretention swales and sand filters have many similarities to bioretention basins and will be briefly outlined. Studies and guidelines relating to these systems have been considered as they may apply to bioretention basins depending on content.

1.2.3 Bioretention basins

Bioretention basins use the processes of filtration, detention and biological uptake to remove sediments, nutrients and other pollutants (Melbourne Water 2005). Refer to Figure 1.2 for a typical section through a bioretention basin. Refer to Figures 1.3 and 1.4 for photographs of bioretention basins located in Melbourne.

Bioretention basins usually consist of a top layer of vegetation where water is ponded in a storm. The vegetation aids in preventing erosion. Its roots break up the soil, improved by wind blowing on the plants causing sway and movement in the roots. This aids in maintaining the desired hydraulic conductivity of the media below and preventing clogging of the system (Melbourne Water 2005). Biofilms on its roots absorb some pollutants. Temporary ponding increases the volume of treated runoff (Gold Coast City Council 2007).

The storm runoff then filters through several layers of different media, where pollutants are removed through filtration and other means, to slotted underdrains below. It is then conveyed to the conventional piped storm water system. Exfiltration from the bioretention basin to the surrounding soil can be encouraged if desired.

An overflow or bypass system is incorporated for high flows. This may be in the form of a grated pit with a cover level a few hundred millimetres above the surface of the bioretention basin or an overflow along a kerb and channel to a side-entry pit, if the basin is located alongside a roadway (Melbourne Water 2005).

The shape and size of bioretention basins is very adaptable so they can be used in a variety of locations. Clogging, however, can occur if exposed to certain materials, for example excess silt from a construction site (Melbourne Water 2005).

Bioretention basins can also form part of an attractive streetscape (Melbourne Water 2005).

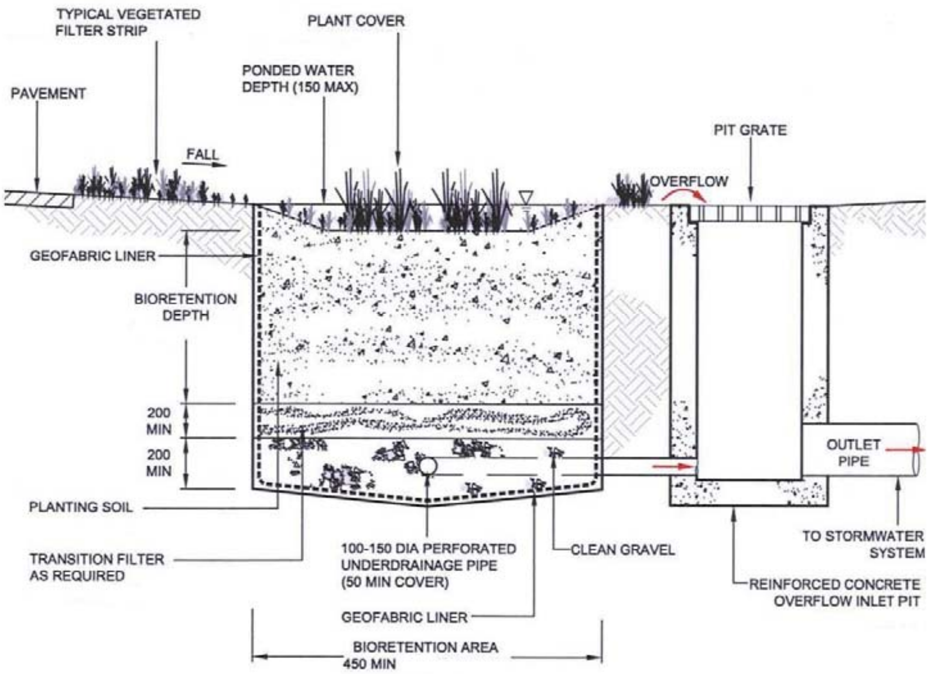

Figure 1.2 Bioretention basin typical section

(URS Australia Pty Ltd 2004, p. 5-31)

Figure 1.3 Photograph of a bioretention basin in Melbourne

(Melbourne Water 2005, p. 17)

Figure 1.4 Photograph of a bioretention basin in Melbourne

(Melbourne Water 2005, p. 17)

Bioretention basins have been shown to cause substantial reductions in peak flows, with a study by the Facility for Advancing Water Biofiltration (2008a) resulting in between 80 % and 86 % reduction. Evapotranspiration contributes to this reduction by around 20 % to 30 % depending on climatic factors.

Bioretention basins have the advantage over some other WSUD systems of being able to fit in relatively small spaces and being able to take on various shapes (Department of Water and Swan River Trust 2007). This makes them adaptable enough to be incorporated into roadside verges, median strips and parkland areas.

Bioretention is so-called as biomass is introduced to absorb and retain nutrients and other pollutants. Natural cleansing processes occur in the soil, mulch and vegetation areas of the bioretention basin (Prince George's County 2002).

1.2.4 Bioretention swales

Bioretention swales are similar to bioretention basins, but they convey water. They consist of similar elements, but are in the shape of a longitudinal trench below a vegetated swale (Melbourne Water 2005). No bypass system is required. Refer to Figure 1.5 for a photograph of a bioretention swale located in Melbourne.

Figure 1.5 Photograph of a bioretention swale in Melbourne

(Melbourne Water 2005, p. 15)

1.2.5 Sand filters

Sand filters are also similar to bioretention basins but they are not vegetated. They include sandy filter media with slotted underdrains underneath and a bypass system for very high flows. Water can pond on the surface and be retained while percolation occurs. Because they have no vegetation they can be installed underground and do not require a filter media that supports vegetation (Melbourne Water 2005). The lack of vegetation, however, means that the porosity of the filter media is not maintained by the vegetation's root system and lateral movements in the wind. The porosity of the filter media need to be maintained in another way to avoid clogging of the system, resulting in the requirement for regular maintenance (Melbourne Water 2005). Pre-treatment to remove litter and coarse sediment is usually needed (Melbourne Water 2005). Refer to Figure 1.6 for a photograph of a sand filter located in Melbourne.

Figure 1.6 Photograph of a sand filter located in Melbourne

(Melbourne Water 2005, p. 18)

1.3. Project aims

This study aims to review and compare existing design guidelines for bioretention basins and establish a 'best practice' design guideline. Focus will be on bioretention basins adjacent to roadways and car parks. Studies will also be reviewed.

Some industry leaders claim there is an inadequate amount of literature on detailed design procedures for WSUD (ed. Argue 2004).

Currently there exist many design guidelines for bioretention basins. Several Australian states have their own, sometimes with many in each state. There also exist guidelines in other countries. These design guidelines use different approaches to design, essentially, the same systems.

Research has been undertaken on the performance of bioretention basins. Some design recommendations have resulted. These will also be considered.

The guidelines that will be considered are from:

- Melbourne Water;
- Brisbane City Council;
- Upper Parramatta River Catchment Trust;
- Gold Coast City Council;
- Hobart City Council;
- Moreton Bay Waterways and Catchments Partnership;
- Department of Water and Swan River Trust;
- Shire of Augusta, Margaret River;
- Facility for Advancing Water Biofiltration, Monash University;
- Prince George's County, Maryland;
- North Carolina State University;
- California Stormwater Quality Association;
- City of Reno; and
- North Carolina Cooperative Extension Service.

Several studies will be reviewed. They are:

- Facility for advancing water biofiltration 2008a, *Advancing the design of stormwater biofiltration*, Monash University, Victoria.
- Le Coustumer, S, Fletcher, TD, Deletic, A & Potter, M 2008, H*ydraulic performance of biofilter systems for stormwater management: lessons from a field study*, Monash University, Victoria.
- Hatt, BE, Fletcher, TD & Deletic, A 2007, 'Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes', *Water science and technology*, vol. 56, no. 12, pp. 11-19.
- Hatt, BE, Fletcher, TD & Deletic, A 2008, 'Hydraulic and pollutant removal performance of fine media stormwater filtration systems', *Environmental science and technology*, vol. 42, no. 7, pp. 2535-2541.
- Le Coustumer, S, Fletcher, TD, Deletic, A & Barraud, S 2007, 'Hydraulic performance of biofilters for stormwater management: first lessons from both laboratory and field studies', *Water Science & Technology,* vol. 56, no. 10, pp. 93-100.
- Bratieres, K, Fletcher, TD, Deletic, A & Zinger, Y 2008, 'Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study', *Water Research* (2008), doi:10.1016/j.watres.2008.06.009.
- Read, J, Wevill, T, Fletcher, T & Deletic, A 2008, 'Variation among plant species in pollutant removal from stormwater in biofiltration systems', *Water Research*, vol. 42, pp. 893-902.
- Sharkey, LJ 2006, *The performance of bioretention areas in North Carolina: a study of water quality, water quantity and soil media,* North Carolina State University, USA.

- Hunt, WF, Jarrett, AR, Smith & Sharkey, LJ 2006, 'Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina', *Journal of irrigation & drainage engineering*, vol. 132, no. 6, pp. 600-608.

- Hunt, WF, Smith, JT, Jadlocki, SJ, Hathaway, JM & Eubanks, PR 2008, 'Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, N.C.', *Journal of Environmental Engineering*, vol. 134, no. 5, pp. 403-408.

- Hsieh, C & Davis, A 2005, 'Evaluation and optimization of bioretention media for treatment of urban storm water runoff', *Journal of Environmental Engineering*, vol. 131, no. 11, November, pp. 1521-1531.

- Hong, E, Seagren, EA & Davis, AP 2006, 'Sustainable oil and grease removal from synthetic stormwater runoff using bench-scale bioretention studies', *Water Environment Research*, vol. 78, no. 2, pp. 141-155.

- Davis, AP, Shokouhian, M, Sharma, H & Minami, C 2006, 'Water quality improvement through bioretention media: nitrogen and phosphorus removal', *Water Environment Research*, vol. 78, no. 3, pp. 284-293.

- Hunt III, WF 2003, *Pollutant removal evaluation and hydraulic characterization for bioretention stormwater treatment devices*, Pennsylvania State University, USA.

1.4. Specific objectives

The specific objectives of this study are outlined:

1. Research existing design guidelines for bioretention basins and studies into bioretention basin performance.

2. Undertake a literature review of this information.

3. Compare the different design guidelines and study findings.

4. Critically evaluate the different design guidelines and study findings.

5. Establish a ‘best practice’ design guideline for bioretention basins.

6. Submit an academic dissertation including:
    - An overview of water sensitive urban design and stormwater treatment measures.
    - An overview of the different bioretention basin design guidelines, comparing their basis, and studies into bioretention basin performance.
    - A critical evaluation of the different design guidelines and studies.
    - A definition of a bioretention basin.
    - A best practice design guideline for a bioretention basin.
    - Recommendations for further research.

Refer to the Project Specification in Appendix A.

1.5. Methodology

This study aims to investigate the different existing design guidelines and critically evaluate them. It is a desk-top analysis. Each design aspect of a bioretention basin is identified, compared and evaluated. Studies into bioretention basins are considered. A critical evaluation is conducted. A 'best practice' design guideline is concluded.

An overview of WSUD is researched in published literature and on the internet. Organisations involved in WSUD are used as sources of knowledge. Guidelines published by various authorities, including water authorities, local councils and stormwater organisations, are sourced on the internet. These are readily available. Published literature is also readily available.

Many different bioretention basin design guidelines exist. It is important to be able to compare each of these using a theoretical analysis. The design procedures will be divided into categories for ease of comparison. Comparison and critical evaluation would be difficult otherwise. These categories are:

- catchment area requirements;
- design flows establishment procedure;
- detention volume establishment procedure;
- depth of ponding requirements;
- sizing of basin surface area;
- pretreatment measures;
- vegetation specification;
- mulch layer design procedure;
- planting layer design procedure;

- filter media design procedure;
- transition layer design procedure;
- drainage layer design procedure;
- nitrogen removal zone design procedure;
- infiltration rate of system calculation procedure;
- perforated underdrain design requirements;
- inspection requirements;
- impervious liner requirements;
- groundwater considerations;
- bypass system requirements and design procedure;
- inlet design procedure;
- traffic lane flow widths checking procedure;
- inlet scour requirements; and
- scour across vegetation layer checking procedure.

Research is conducted into the performance of bioretention basins. This is necessary to evaluate the different design guidelines. Research is sought from books and scientific journals as well as from stormwater and engineering organisations.

The design guidelines and studies, once categorised, are compared. They are then critically evaluated and a 'best practice' concluded for each design element.

With different guidelines on their design, varying naming conventions for bioretention basins also exist. These are compared, along with any available literature on naming conventions, and critically evaluated to establish the most appropriate name for the system. An appropriate naming convention should be established for use across the whole industry. This would avoid confusion.

Once critically evaluated, 'best practice' design guidelines for a bioretention basin are concluded. Further research may be required. Recommendations for further research evident are stated.

Chapter 2 Bioretention basin publications reviewed

Twelve design guidelines and twelve studies on bioretention basins are reviewed in this study. These are outlined below and their bases noted.

2.1. Name of publication

For simplification, each publication is given a code number.

The format for the code number is,

***XN-YZ*-Country**,

where,

X represents whether the document is a guideline (*G*) or a study (*S*).
N represents an identification number.
Y represents whether the publication is by an authority, organisation or government (*A*) or by a university (*U*).
Z represents the university the publication may be affiliated with. It is omitted if it is a publication by an authority as there is only one publication by each used in this study. There is often more than one publication affiliated with a particular university, however. This notation highlights which publications have come from the same university or people associated with that university, where,

M represents Monash University,
N represents North Carolina State University
R represents University of Maryland
P represents Pennsylvania State University, and
L represents University of Lyon.

Country is denoted AUS for Australia, USA for USA and AUS/F for Australia and France together.

For example, G8-UM-AUS is guideline number 8. It is from a university, which is Monash University. It is from Australia.

Tables 2.1.1 and 2.1.2 outline the codes for each publication. These are then used throughout this document.

Table 2.1.1 Publications (guidelines)

Code	**Publication**
G1-A-AUS	Melbourne Water 2005, *WSUD engineering procedures: stormwater*, CSIRO publishing, Collingwood.
G2-A-AUS	Brisbane City Council 2005a, *Draft Water Sensitive Urban Design Engineering Guidelines: Stormwater,* City Design, Fortitude Valley, Queensland.
G3-A-AUS	URS Australia Pty Ltd 2004, *Water sensitive urban design technical guidelines for Western Sydney*, Upper Parramatta River Catchment Trust (UPRCT), Parramatta.
G4-A-AUS	Gold Coast City Council 2007, *Water Sensitive Urban Design (WSUD) Guidelines*, Gold Coast City Council, Queensland.
G5-A-AUS	Hobart City Council 2006, *Water sensitive urban design site development guidelines and practice notes,* Hobart City Council, Tasmania
G6-A-AUS	Moreton Bay Waterways and Catchments Partnership 2006, *Water sensitive urban design technical design guidelines for South East Queensland*, Healthy Waterways, South East Queensland.
G7-A-AUS	Department of Water and Swan River Trust 2007, *Structural controls, stormwater management manual for Western Australia*, Department of Water and Swan River Trust, Perth, Western Australia.
G8-A-AUS	Shire of Augusta – Margaret River 2006, *Council's standards and specifications for subdivisions and developments*, Shire of Augusta – Margaret River, Western Australia.
G9-UM-AUS	Facility for advancing water biofiltration 2008b, *Guidelines for soil filter media in bioretention systems*, Version 2.01, Monash University, Victoria.
G10-A-USA	Prince George's County, Maryland 2002, *Bioretention manual*, Prince George's County, Maryland, USA. Prince George's County, Maryland n.d., *Bioretention design specifications and criteria*, Prince George's County, Maryland, USA
G11-UN-USA	North Carolina State University, Stormwater Engineering Group 2001, *Designing rain gardens (bio-retention areas)*, North Carolina State University, USA
G12-A-USA	California stormwater quality association 2003, *California stormwater BMP handbook, new development and redevelopment,* California stormwater quality association, USA
G13-A-USA	Kennedy/Jenks Consultants 2004, *Truckee Meadows structural controls design manual*, City of Reno, USA.
G14-A-USA	Hunt, WF & Lord, WG 2006, *Bioretention performance, design, construction, and maintenance*, North Carolina Cooperative Extension Service, USA.

Table 2.1.2 Publications (studies)

Code	Publication
S1-UM-AUS	Facility for advancing water biofiltration 2008a, *Advancing the design of stormwater biofiltration*, Monash University, Victoria.
S2-UM-AUS	Le Coustumer, S, Fletcher, TD, Deletic, A & Potter, M 2008, H*ydraulic performance of biofilter systems for stormwater management: lessons from a field study*, Monash University, Victoria.
S3-UM-AUS	Hatt, BE, Fletcher, TD & Deletic, A 2007, 'Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes', *Water science and technology*, vol. 56, no. 12, pp. 11-19.
S4-UM-AUS	Hatt, BE, Fletcher, TD & Deletic, A 2008, 'Hydraulic and pollutant removal performance of fine media stormwater filtration systems', *Environmental science and technology*, vol. 42, no. 7, pp. 2535-2541.
S5-UM/L-AUS/F	Le Coustumer, S, Fletcher, TD, Deletic, A & Barraud, S 2007, 'Hydraulic performance of biofilters for stormwater management: first lessons from both laboratory and field studies', *Water Science & Technology*, vol. 56, no. 10, pp. 93-100.
S6-UM-AUS	Bratieres, K, Fletcher, TD, Deletic, A & Zinger, Y 2008, 'Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study', *Water Research* (2008), doi:10.1016/j.watres.2008.06.009
S7-UM-AUS	Read, J, Wevill, T, Fletcher, T & Deletic, A 2008, 'Variation among plant species in pollutant removal from stormwater in biofiltration systems', *Water Research*, vol. 42, pp. 893-902.
S8-UN-USA	Sharkey, LJ 2006, *The performance of bioretention areas in North Carolina: a study of water quality, water quantity and soil media,* North Carolina State University, USA
S9-UN-USA	Hunt, WF, Jarrett, AR, Smith & Sharkey, LJ 2006, 'Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina', *Journal of irrigation & drainage engineering*, vol. 132, no. 6, pp. 600-608.
S10-UN-USA	Hunt, WF, Smith, JT, Jadlocki, SJ, Hathaway, JM & Eubanks, PR 2008, 'Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, N.C.', *Journal of Environmental Engineering*, vol. 134, no. 5, pp. 403-408.
S11-UR-USA	Hsieh, C & Davis, A 2005, 'Evaluation and optimization of bioretention media for treatment of urban storm water runoff', *Journal of Environmental Engineering*, vol. 131, no. 11, November, pp. 1521-1531.
S12-UR-USA	Hong, E, Seagren, EA & Davis, AP 2006, 'Sustainable oil and grease removal from synthetic stormwater runoff using bench-scale bioretention studies', *Water Environment Research*, vol. 78, no. 2, pp. 141-155.
S13-UR-USA	Davis, AP, Shokouhian, M, Sharma, H & Minami, C 2006, 'Water quality improvement through bioretention media: nitrogen and phosphorus removal', *Water Environment Research*, vol. 78, no. 3, pp. 284-293.
S14-UP-USA	Hunt III, WF 2003, *Pollutant removal evaluation and hydraulic characterization for bioretention stormwater treatment devices*, Pennsylvania State University, USA.

2.2. Basis of publication

Some guidelines reviewed state their bases. These are summarised in Table 2.2.1.

Table 2.2.1 Bases of guidelines reviewed

G1-A-AUS	Not known
G2-A-AUS	WSUD Engineering procedures: stormwater (Melbourne Water guidelines)
G3-A-AUS	(ARC 2003), Stormwater Management Devices: Design Guidelines Manual, Revision of Technical
G4-A-AUS	Not known
G5-A-AUS	WSUD Engineering procedures: stormwater (Melbourne Water guidelines) and Water Sensitive Planning for the Sydney Region (Upper Parramatta River Catchment Trust and others).
G6-A-AUS	Water Sensitive Urban Design Engineering Guidelines: Stormwater (Brisbane City Council guidelines which are based on Melbourne Water guidelines) and Water Sensitive Urban Design Technical Guidelines for Western Sydney (Upper Parramatta River Catchment Trust).
G7-A-AUS	Cooperative Research Centre for Catchment Hydrology 2003, *Model for Urban Stormwater Improvement Conceptualisation (MUSIC) User Guide*, Version 2.0, December 2003. Davis, A.P., Shokouhian, M., Sharma, H. and Minani, C. 1998, *Optimisation of Bioretention for Design for Water Quality and Hydrologic Characteristics*, Final Report to Prince George's County, Maryland, United States of America.
G8-A-AUS	Not known
G9-UM-AUS	Facility for advancing water biofiltration 2008a, *Advancing the design of stormwater biofiltration*, Monash University, Victoria. This includes results from studies undertaken on biofiltration systems. Contributions by Melbourne Water Corporation, Dr Nicholas Somes (Ecodynamics), Alan Hoban (SEQ Healthy Waterways Partnership), and STORM Consulting.
G10-A-USA	Field experience, literature research, experimentation, and professional collaboration with individuals.
G11-UN-USA	Not known
G12-A-USA	Not known
G13-A-USA	Not known
G14-A-USA	North Carolina State University, Stormwater Engineering Group 2001, *Designing rain gardens (bio-retention areas)*, North Carolina State University, USA. Research by North Carolina State University (on-site monitoring).

It is difficult to compare the bases of the various guidelines. Many of them do not state their bases. It is noted that four of the guidelines state a basis on Melbourne Water's guidelines (G1-A-AUS). As they are all published by respected sources they all have some merit.

The bases of the studies reviewed are outlined in Table 2.2.2.

Table 2.2.2 Bases of studies reviewed

S1-UM-AUS	On-site monitoring and laboratory experiments.
S2-UM-AUS	On-site monitoring and laboratory experiments.
S3-UM-AUS	Laboratory experiments.
S4-UM-AUS	Laboratory experiments.
S5-UM/L-AUS/F	On-site monitoring and laboratory experiments.
S6-UM-AUS	Laboratory experiments.
S7-UM-AUS	Laboratory experiments.
S8-UN-USA	On-site monitoring and laboratory experiments.
S9-UN-USA	On-site monitoring.
S10-UN-USA	On-site monitoring.
S11-UR-USA	On-site monitoring and laboratory experiments.
S12-UR-USA	Laboratory experiments.
S13-UR-USA	On-site monitoring and laboratory experiments.
S14-UP-USA	On-site monitoring and laboratory experiments.

The studies reviewed are all based on testing. This is performed either in the laboratory or in the field (or both). This gives their design recommendations some merit.

Chapter 3 Identification of a bioretention basin

The existence of various names for a bioretention basin means that care must be taken when selecting publications to review. It must be ensured that they focus, indeed, on the same system.

A comparison of the publications is undertaken reviewing the name of the system, physical elements included in it and pollutants removed.

Table 3.1 outlines the various names used in each guideline reviewed. All systems either include the word 'bioretention' in their naming convention for the system or 'rain garden.' Those that include the word 'bioretention' in their name call the system a basin, system, facility, column, area or cell. G12-A-USA also refers to the system as 'bioretention best management practice.'

Table 3.1 Name of system in guidelines reviewed

G1-A-AUS	Bioretention basin.
G2-A-AUS	Bioretention basin.
G3-A-AUS	Non-conveyance (off-line) bioretention system.
G4-A-AUS	Bioretention basin.
G5-A-AUS	Bioretention system or rain garden (usually designed as a landscape feature).
G6-A-AUS	Bioretention basin.
G7-A-AUS	Bioretention basin.
G8-A-AUS	Bioretention basin.
G9-UM-AUS	Bioretention system.
G10-A-USA	Bioretention facility or bioretention column, rain garden describes small bioretention inside allotment.
G11-UN-USA	Rain garden.
G12-A-USA	Bioretention best management practice (BMP), bioretention area/cell/system/facility
G13-A-USA	Bioretention system.
G14-A-USA	Bioretention cell/rain garden

The names used in the studies reviewed are outlined in Table 3.2. All studies either include the word 'bioretention' or 'biofiltration' in their naming convention for the system. These are also a basin, system, facility, area or cell.

Table 3.2 Name of system in studies reviewed

S1-UM-AUS	Bioretention basin. (Bioretention systems include bioretention swales and bioretention basins).
S2-UM-AUS	Biofiltration system (biofilter).
S3-UM-AUS	Bioretention system (biofilter).
S4-UM-AUS	Fine media stormwater filtration systems, Biofiltration systems/rain gardens (if systems are vegetated).
S5-UM/L-AUS/F	Biofiltration/bioretention system (biofilter).
S6-UM-AUS	Biofiltration system/biofilters/rain gardens
S7-UM-AUS	Biofiltration system.
S8-UN-USA	Bioretention cell
S9-UN-USA	Bioretention area
S10-UN-USA	Bioretention cell.
S11-UR-USA	Bioretention facility
S12-UR-USA	Bioretention facility, bioretention system.
S13-UR-USA	Bioretention area.
S14-UP-USA	Bioretention cell, Bioretention stormwater treatment device

In this study a bioretention basin is defined as a system that includes vegetation, filter media, underdrains and a drainage layer. It at least removes TSS, TP, TN and metals by means of filtration, absorption and biological uptake (and possibly other means).

The elements described as part of these systems in each publications reviewed are outlined in Table 3.3. The pollutants removed by the system are also considered. These are described in Table 3.4 for each publication selected. The means of removal are outlined in Table 3.5.

Table 3.3 Physical elements included in system for each publication reviewed

	Grass buffer strip	Vegetation	Organic or mulch layer	Planting layer	Filter media	Transition layer or geotextile fabric	Drainage layer	Nitrate removal zone	Perforated underdrains	Impervious liner	Pervious filter fabric (around)	Sand layer (along walls of system)	Bypass system
G1-A-AUS		✓			✓	✓	✓		✓	✓			✓
G2-A-AUS		✓			✓	✓	✓		✓	✓			✓
G3-A-AUS		✓		✓	✓	✓	✓		✓	✓			✓
G4-A-AUS		✓			✓	✓	✓		✓	✓			✓
G5-A-AUS		✓			✓				✓				
G6-A-AUS		✓			✓	✓	✓		✓	✓			✓
G7-A-AUS		✓			✓	✓	✓		✓	✓			✓
G8-A-AUS		✓			✓	✓	✓		✓				✓
G9-UM-AUS		✓			✓	✓	✓		✓				
G10-A-USA		✓	✓	✓	✓	✓	✓		✓	✓	✓		✓
G11-UN-USA			✓										
G12-A-USA	✓	✓	✓		✓				✓			✓	
G13-A-USA		✓	✓		✓		✓		✓				✓
G14-A-USA								✓					
S1-UM-AUS		✓			✓	✓	✓	✓	✓				✓
S2-UM-AUS													
S3-UM-AUS		✓			✓			✓	✓				
S4-UM-AUS		✓			✓		✓	✓					
S5-UM/L-AUS/F		✓			✓								
S6-UM-AUS		✓			✓	✓	✓	✓	✓				
S7-UM-AUS		✓			✓				✓				
S8-UN-USA		✓	✓		✓	✓	✓		✓	✓			✓
S9-UN-USA		✓			✓		✓		✓				
S10-UN-USA		✓	✓					✓	✓				
S11-UR-USA		✓	✓		✓		✓	✓	✓				
S12-UR-USA		✓	✓		✓								
S13-UR-USA		✓	✓		✓			✓	✓				
S14-UP-USA		✓	✓		✓		✓		✓				✓

Table 3.4 Pollutants removed by system in each publication reviewed

	Pollutants	Litter/ debris	Organic matter	Small particles	TSS	TP	TN	Nutrients	Nitrates	Ammo-nium	Hydro-carbons	O/G	Metals	Bacteria	Pathogens
G1-A-AUS					✓	✓	✓								
G2-A-AUS					✓	✓	✓								
G3-A-AUS	✓											✓	✓		
G4-A-AUS	✓														
G5-A-AUS					✓			✓					✓		
G6-A-AUS					✓	✓	✓								
G7-A-AUS				✓	✓	✓	✓						✓		
G8-A-AUS				✓				✓							
G9-UM-AUS															
G10-A-USA					✓	✓			✓						
G11-UN-USA		✓			✓	✓	✓						✓	✓	✓
G12-A-USA			✓		✓	✓	✓				✓		✓		
G13-A-USA	✓														
G14-A-USA					✓	✓	✓						✓	✓	✓
S1-UM-AUS					✓	✓	✓						✓		✓
S2-UM-AUS															
S3-UM-AUS					✓	✓	✓						✓		
S4-UM-AUS					✓	✓	✓						✓		
S5-UM/L-AUS/F															
S6-UM-AUS					✓	✓	✓						✓		
S7-UM-AUS					✓	✓	✓						✓		
S8-UN-USA		✓				✓	✓					✓	✓	✓	
S9-UN-USA					✓	✓	✓						✓		
S10-UN-USA					✓	✓	✓					✓	✓	✓	✓
S11-UR-USA					✓	✓	✓			✓		✓	✓		✓
S12-UR-USA						✓	✓						✓		
S13-UR-USA					✓	✓	✓						✓		
S14-UP-USA					✓	✓	✓						✓		

Table 3.5 Means of pollutant removal by system in each publication reviewed

	Physical processes	Filtration	Absorption	Biological uptake	Extended detention	Sedimentation	Chemical processes	Nitrification	Denitrification	Volatisation	Ion exchange	Decomposition	Degradation	Phytoremediation	Bioremediation	Thermal attenuation	Sunlight & drying	Precipitation	Surface complexation	Evapotranspiration	Biotransformation	Other
G1-A-AUS		✓	✓	✓																		
G2-A-AUS		✓	✓	✓																		
G3-A-AUS		✓		✓			✓															
G4-A-AUS		✓	✓	✓																		
G5-A-AUS		✓	✓	✓																		
G6-A-AUS		✓	✓	✓																		
G7-A-AUS		✓	✓	✓					✓													
G8-A-AUS																						
G9-UM-AUS																						
G10-A-USA		✓	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓						
G11-UN-USA		✓	✓	✓		✓							✓									
G12-A-USA		✓	✓	✓		✓				✓		✓	✓									
G13-A-USA	✓			✓			✓															
G14-A-USA		✓				✓		✓	✓								✓					
S1-UM-AUS		✓																				✓
S2-UM-AUS																						
S3-UM-AUS		✓	✓	✓		✓																
S4-UM-AUS		✓	✓								✓							✓	✓			
S5-UM/L-AUS/F																						
S6-UM-AUS		✓		✓	✓																	
S7-UM-AUS			✓	✓									✓									
S8-UN-USA			✓			✓		✓					✓				✓					
S9-UN-USA																						
S10-UN-USA																	✓					✓
S11-UR-USA		✓	✓			✓												✓				✓
S12-UR-USA		✓	✓																	✓		✓
S13-UR-USA		✓	✓																	✓	✓	✓
S14-UP-USA			✓			✓	✓						✓									

Based on consensus, the main pollutants removed by bioretention basins are generally TSS, TP, TN and metals. TN and TP are nutrients so the 'nutrients' column needs consideration in conjunction with these. The main removal means are filtration, absorption and biological uptake. Sedimentation and degradation are also often listed as pollutant removal means.

For some studies, the elements listed are those that are described as being included in a bioretention basin. Not necessarily all elements were actually included in the experiments undertaken in these studies. In experiments, certain elements may have been singled out for testing. This comparison is simply to identify if they are studies on the same system. That is why this approach is taken.

For biological uptake to take place, vegetation is required. Without vegetation in a bioretention basin, there is no bioretention. Vegetation also keeps the filter media porous and enhances filtration (Brisbane City Council 2005a). This element must be included for the system to be considered a bioretention basin.

Most treatment in a bioretention basin is through fine filtration (Brisbane City Council 2005a). This occurs in the filter media layer, making this element necessary in a bioretention basin.

The general consensus is that bioretention basins are designed to collect the treated runoff for disposal at downstream waterways or at storage areas (Brisbane City Council 2005a). For this to occur, a drainage system is needed at the bottom of the basin. Perforated underdrains collect the treated runoff. A drainage layer is required to prevent clogging of these perforations (Hsieh & Davis 2005). These two elements are therefore crucial for the functioning of a bioretention basin. They must be included in a bioretention basin.

Only G12-A-USA includes a grass buffer strip in a bioretention basin. This is considered, therefore, to not be an element that defines the system.

Organic or mulch layers are specified in ten out of the twenty-eight publications reviewed. Mulch may aid the filter media in its functioning (Hsieh & Davis 2005). It may help prevent clogging of the filter media. It may aid the filter media in providing nutrients to support the vegetation. Moisture may be maintained in the basin better with the inclusion of a mulch layer. Its provision is therefore subjective and up to the discretion of the designer. It is optional and is therefore not an element that must be included to define the system.

The planting layer also may aid the filter media in its functioning. Vegetation sustenance can be enhanced by its inclusion (URS Australia Pty Ltd 2004). It is considered optional (North Carolina State University, Stormwater Engineering Group 2001). This element is not necessary for inclusion to define a system as a bioretention basin.

The transition layer is required only if there exists the possibility of filter media migration into the drainage layer due to particle size distribution (Gold Coast City Council 2007). It is therefore optional and is not considered to be an essential element in defining a bioretention basin.

Only one guideline incorporates a nitrate removal zone in its bioretention basin (G14-A-USA). This guideline suggests that it appears to reduce total nitrogen. All the other publications that include a nitrate removal zone are studies, most undertaken in the last couple of years. This is a recent proposal and this element is not considered essential to define a bioretention basin.

Impervious liner is optional and depends on the objectives of the bioretention basin and the hydraulic conductivity of the in-situ soil (Department of Water and Swan River Trust 2007). A system which does not include impervious liner can still be considered a bioretention basin.

Only one guideline reviewed includes a pervious filter fabric around the walls of the bioretention basin (G12-A-USA). This is therefore considered optional.

A bypass system is usually included in a bioretention basin to divert flows above that which the basin is designed to accept to prevent damage to vegetation and the surface as well as to maintain safe traffic passage (if adjacent to a road). Twelve of the twenty-eight publications include a bypass system as part of the bioretention basin. Most of these are guidelines. Studies may not have mentioned a bypass system, but this does not mean that one is not usually included. It is not considered a defining element in identifying the system in this case.

The elements that must be included to identify a system as a bioretention basin in the reviewed publications are vegetation, filter media, drainage layer and perforated underdrains. Guillette (2007) describes a bio-retention cell as a recessed landscaped area with a specialised soil mixture, an underdrain, vegetation and an aggregate base which is consistent with the definition found.

Twelve of the publications do not have all of these necessary elements listed. Most are studies rather than guidelines. Many of these studies do not give detailed descriptions and so some elements were simply not mentioned. It cannot be assumed that the description is not of a bioretention basin simply based on the elements omitted. These twelve publications are investigated further in order to identify them as bioretention basins or not.

G5-A-AUS, G12-A-USA, S3-UM-AUS, S7-UM-AUS and S13-UR-USA include the elements required except for the drainage layer. The systems described remove the main pollutants and use almost all of the pollutant removal mechanisms outlined as major. It is concluded that these publications describe bioretention basins.

Publications S12-UR-USA and S5-UM/L-AUS/F include the main elements except for the drainage layer and the perforated underdrains. The S12-UR-USA system removes most of the main pollutants and uses most of the main pollutant removal mechanisms and is identified as a bioretention basin. Publication S5-UM/L-AUS/F does not mention pollutants removed and mechanisms. Some of the authors of this study are affiliated with Monash University. Systems in other studies from Monash University (e.g. S1-UM-AUS) are already identified as bioretention basins therefore this system is assumed to be a bioretention basin also.

Publications S2-UM-AUS and S4-UM-AUS are also from Monash University. These are thus identified as bioretention basins by affiliation.

Guideline G11-UN-USA refers to rain gardens (also known as bioretention areas) pioneered in Prince George's County Maryland. Publications from Prince George's

County Maryland include G10-A-USA, which is already identified as being on bioretention basins. Guideline G11-UN-USA is identified as a bioretention basin design guideline by association.

Guideline G14-A-USA does not list many physical elements in the system described. The system removes the four major pollutants by means of two of the main mechanisms. It is identified as a bioretention basin for the purposes of this study.

Study S10-UN-USA describes a system that does not include the four major elements outlined. One author is affiliated with study S9-UN-USA, which is identified as a bioretention basin study. Study S10-UN-USA is also identified as a bioretention basin by affiliation.

All publications listed are classified for the purposes of this study as bioretention basins. Other design elements can therefore be compared. No publication was found with the name ‘bioretention’, ‘biofiltration’ or ‘rain garden’ that was not identified to be the same system.

Chapter 4 Bioretention basin naming convention

Bioretention basins go by many names. They are also known as bioretention systems, bioretention cells, bioretention columns, bioretention facilities, biofiltration systems, biofilters, bioretention stormwater treatment devices, organic filters and rain gardens. In this study a bioretention basin is concluded to be a system that includes vegetation, filter media, underdrains and a drainage layer as a minimum. It at least removes TSS, TP, TN and metals by means of filtration, absorption and biological uptake (and possibly other means).

Minton (2007) expresses concerns that WSUD currently includes duplicative and badly-defined technical terms. He claims some treatment systems that are the same have names that are entirely different. Some systems that are different are known by the same name. He calls for a consistent naming convention.

In this study no publication was found with the name ‘bioretention’, ‘biofiltration’ or ‘rain garden’ that was not identified to be the same system. This conflicts with the views held by Minton (2007).

Guillette (2007) describes a rain garden as not having the same engineered features as a bioretention cell, such as the underdrains and specialised soil mixture. Only one publication reviewed referred to a bioretention basin as a rain garden it is therefore not considered an appropriate name for the system.

Minton (2007) refers to an example whereby some manuals describe an organic filter as having a media of sand covered by the same depth of organic matter. Some manuals describe a bioretention system with underdrains as being made up of media of half sand and half organic matter. The depth of media of each is around the same and both may have a cover of grass. Minton (2007) claims that these two systems have entirely different names, but are essentially identical. This is contrary to the bioretention basin definition in this study. It is found that a bioretention basin must have an underdrain. The two systems Minton (2007) discusses here are different in that respect as an organic filter does not have one. He goes on to state that the sizing procedures outlined for each system are also contrasting. The organic filter sizing procedure uses Darcy’s Law, whilst the bioretention filter with underdrains is sized using principles applied to an infiltration system (Minton 2007). This is also contrary to findings in this study. Darcy's Law is used in all seven of the methods outlined in the reviewed publications for calculating the infiltration rate of the system and is concluded to be 'best practice' for the design of bioretention basins (refer to Section 5.14 for details). The claims of Minton (2007) appear unfounded.

Most publications reviewed in this study incorporate the word 'bioretention' in their naming convention for a bioretention basin. So what is bioretention? Plant roots uptake nutrients and metals from their host media. That means that bioretention occurs wherever plants exist. Minton (2007) claims that bioretention, therefore, is not exclusive to bioretention basins and also would occur in other WSUD systems including wet ponds and wetlands.

Minton (2007) proposes that bioretention should be considered as a mechanism of pollutant removal, such as filtration, flotation or sedimentation. Therefore, in his proposed naming convention, the terms bioretention and biofiltration are no longer used to refer to particular systems, but may be used to describe processes

Minton (2007) proposes a simplified system of categorisation of type and design criteria of treatment systems. He proposes a hierarchical system in which categorisation consists firstly of:

- **family**, being a group displaying common key characteristics of basins, swales, filters, infiltrators and screens;
- then **system**, comprising a unit or several units;
- **unit operation**, being the processes that may occur in a single unit or part of a system, for example in a sand filter alone sedimentation and filtration occur;
- **unit process**, being the mechanism used in the process, eg. filtration, screening, sedimentation, etc.; and
- **principles**, being the foundation of the processes used in the treatment, categorised as either chemical, biological or engineering.

Minton (2007) suggests that the name of a unit operation or system includes a descriptive term conveying its basic characteristic. An example he gives is a filter swale.

Milton (2007) proposes that those units in which the stormwater is infiltrated into the soil be called infiltrators (at least, when this is the main process of the unit). He proposes that a more accurate term for a bioretention basin be an infiltration cell as infiltration is its main function. This complies with the naming convention outlined earlier. Brisbane City Council (2005a) state that the filter media performs the majority of the pollutant removal in a bioretention basin through fine filtration and through supporting the vegetation, which enhances filtration and provides nutrient and contaminant uptake. Vegetation is therefore also a very important feature of a bioretention basin and the function of biological uptake is also. If a bioretention basin is referred to as an infiltration cell as per Minton's suggestion, the name does not even insinuate that vegetation exists in the system. A sand filter could also be called an infiltration cell as filtration is its main function. Both systems cannot be described as such as they offer different applications and treatment mechanisms. On the other hand, the name bioretention basin does not suggest that fine filtration is the main function of the system either.

Only five of the twenty-eight publications in this study did not include the word 'bioretention' in the name given to describe a bioretention basin, meaning it is widely accepted. This is not as confusing and conflicting, therefore, as Minton claims.

Bioretention basins are sometimes referred to as 'rain gardens'. Rain gardens, according to Hager (2003), consist of small depressions in individual lots to detain water and allow it to infiltrate. No special filter media is used. 'Rain garden' is not therefore an appropriate term for a bioretention basin.

The conclusion of this study is that the naming convention 'bioretention' is appropriate, whether it be followed by 'basin', 'system', 'cell', 'area' or 'facility'. 'Rain garden' is not an appropriate term for a bioretention basin.

Chapter 5 Bioretention basin design elements

The bioretention basin design procedure is divided into elements for ease of guideline and study comparison. Each of these elements is discussed in the following sections. The requirements outlined in various design guidelines are discussed as are the design recommendations of studies on bioretention basins. Each is analysed in an attempt to conclude a 'best practice' design procedure.

The design elements are outlined in the typical section of a bioretention basin shown in Figure 5.1.

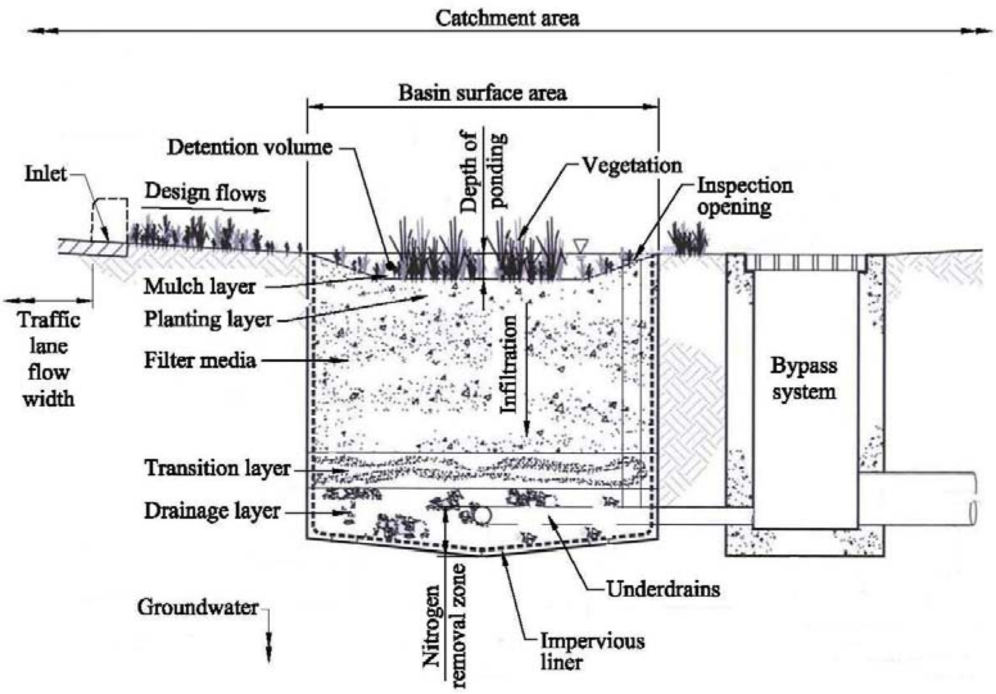

Figure 5.1 Typical section of a bioretention basin showing design elements

5.1. Catchment area requirements

The recommended size of catchment area for a bioretention system is outlined in Table 5.1.1.

Table 5.1.1 Recommended catchment area

G10-A-USA	Catchment area should be limited to 1 to 2 acres. Preferred catchment area is less than 1 acre. Catchment area is limited to one acre if underdrains are omitted.
G12-A-USA	Catchment area should be between 0.1 and 0.4 hectares (0.25 and 1.0 acres).
G13-A-USA	Preferred catchment area is less than 1 acre.

Based on consensus a conservative recommendation for maximum catchment area for one bioretention basin is 0.4 hectares (1.0 acre).

5.2. Design flows establishment procedure

The recommended methods for determining design flows for bioretention basins are outlined in Table 5.2.1.

Table 5.2.1 Design flow calculation method

G1-A-AUS	Design flows found using the Rational Method.
G2-A-AUS	Design flows found using the Rational Method, but for catchments greater than 50 ha runoff routing model is to be used.
G4-A-AUS	Design flows found using the Rational Method, but for large catchments or if bioretention system is to form part of a retention basin a runoff routing model is to be used.
G6-A-AUS	Design flows found using the Rational Method, but for large catchments or if bioretention system is to form part of a retention basin a runoff routing model is to be used.

Based on consensus design flows should be found using the Rational Method, unless the catchment is greater than 50 ha. Then a runoff routing model should be used. This is supported by engineering manuals as a recommended method of flow estimation. Haestad Methods (2007) recommend the Rational Method for small drainage basins. They state that for larger areas a runoff hydrograph is required to calculated flow rate versus time and runoff volume. This could be achieved by runoff routing modelling.

The design storm used will depend on the requirements of the local authority. It may vary from a 1, 2, 5 or 10 year ARI storm. Variations may be found in temperate and sub-tropical areas due to the differences in sizes of storms in these areas. Melbourne Water (2005) (in a temperate climate) require a bioretention basin accommodate a 5 year ARI storm while Brisbane City Council (2005a) (in a sub-tropical climate) require it accommodate a 2 year ARI storm.

5.3. Detention volume establishment procedure

The methods of determining the detention volume for a bioretention basin in the reviewed publications are outlined in Table 5.3.1.

Table 5.3.1 Detention volume calculation method

G1-A-AUS	The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Filter media characteristics are initially assumed. Local rainfall data should be used. Modelling is performed using MUSIC (preferred), or design charts from MUSIC and regionalisation factors (if necessary).
G2-A-AUS	The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Filter media characteristics are initially assumed. Local rainfall data should be used. Modelling is performed using MUSIC (preferred), or design charts from MUSIC and regionalisation factors (if necessary).
G3-A-AUS	Determined using: $V_{treat} = (ROD/1000) \times A$ where, V_{treat} = Treatable volume (m^3) ROD = Runoff Depth (mm) A = Catchment Area (m^2) For a capture period of 24 and 48 hour, and a capture rate of 60% of annual average runoff volume, the treatable volume per hectare to be provided are 150 m^3/ha for a 24 hour period and 200 m^3/ha for a 48 hour period. Determined from: Mean inter-event dry period (from rainfall data) of 24 hours to 48 hours, 60 % average annual rainfall volume filtration time through filter media.
G4-A-AUS	The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Modelling is performed using MUSIC.
G6-A-AUS	The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Modelling is performed using MUSIC.

G10-A-USA	Storage volume required is derived from a graph using existing and proposed runoff curve numbers. This volume is the volume of detention required to maintain the existing runoff volume leaving the site prior to development. The runoff curve numbers are calculated from pervious and impervious areas. A chart is also used to derive the detention required to maintain the predevelopment peak runoff rate. The desirable percentage of the site required to be used for bioretention is then storage required to maintain predevelopment peak runoff plus storage required to detain predevelopment runoff volume. If this is not achievable, only some of the predevelopment runoff volume is detained.
G11-UN-USA	The rain garden may be made large enough to accommodate the runoff from the first inch of rain on the catchment. The runoff depth is calculated using a formula from the Natural Resources Conservation Service. This uses the CN value to calculate the runoff depth in the catchment from one inch of rain. The CN value is the curve number which is a measure of how much rain will infiltrate in the catchment. This is determined by soil type and land use (i.e. percentage of pervious and impervious areas) and is derived from a standard table. Runoff depth in inches = (P - 0.2 S)2)(P + 0.8 S), where, P = precipitation (typically use 1 inch) and, S = 1,000 ÷ CN – 10. CN = Curve Number. Runoff volume is then determined. Runoff volume (cubic feet) = Area × Runoff depth
G12-A-USA	Size should be such that design storm runoff may be captured.
G13-A-USA	The Water Quality (WQ_V) method is used to determine the detention volume. This method is based on the following formulae: $WQ_V = [(P)(RV)(A)]/12,$ and, $R_V = 0.05 + 0.009I$ where, WQ_V = water quality volume (ft3) P = the 90th percentile precipitation depth (0.60 inches) R_V = watershed runoff coefficient I = percent of watershed impervious area A = drainage area (ft2) 12 = units conversion constant

There are various methods of calculating the required storage volume for a bioretention basin. Five out of nine publications focus on the pollutant removal objectives. Of these, four use a modelling approach. Four focus on capturing a certain amount of runoff.

MUSIC is an acronym for 'Model for Urban Stormwater Improvement Conceptualisation.' It is a conceptual design tool developed by Melbourne Water in Victoria, Australia. MUSIC is capable of estimating stormwater pollutant generation and the performance of stormwater treatment measures (Melbourne Water 2004). MUSIC can be used to determine the pollutant removal capabilities of stormwater treatment devices. Treatment objectives specified by Melbourne Water (2004) are;

- 45% reduction in total nitrogen (TN) from typical urban loads
- 45% reduction in total phosphorus (TP) from typical urban loads
- 80 % reduction in total suspended solids (TSS) from typical urban loads
- 70% reduction in litter from typical urban loads
- Maintain discharges for the 1.5 year ARI event at pre-development levels.

These targets, however, may vary depending on the requirements for and nature of the receiving waterway downstream.

The guidelines reviewed that recommend the use of modelling for sizing bioretention basins recommend using MUSIC.

A modelling approach is ideal for determining the dimensions of a bioretention basin due to its variable and complex nature (ed. Wong 2006). Modelling is able to consider local rainfall data, individual catchment characteristics, runoff volume, peak runoff flow, pollutant removal, filter media characteristics and basin dimensions. Whether it be MUSIC or and equivalent modelling approach, this is the best option for sizing of bioretention basins.

5.4. Depth of ponding requirements

The methods of determining the ponding depth for a bioretention basin in the reviewed publications are outlined in Table 5.4.1.

Table 5.4.1 Ponding depth calculation method and requirements

G1-A-AUS	The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Filter media characteristics are initially assumed. Local rainfall data should be used. Modelling is performed using MUSIC (preferred), or design charts from MUSIC and regionalisation factors (if necessary).
G2-A-AUS	The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Filter media characteristics are initially assumed. Local rainfall data should be used. Modelling is performed using MUSIC (preferred), or design charts from MUSIC and regionalisation factors (if necessary).
G4-A-AUS	The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Modelling is performed using MUSIC Temporary ponding to be up to 300 mm deep over surface of filter media. This is controlled by the level of the overflow pit.
G6-A-AUS	The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Modelling is performed using MUSIC Temporary ponding to be up to 300 mm deep over surface of filter media. This is controlled by the level of the overflow pit.
G10-A-USA	Preferred depth 76 mm (3 inches) to 102 mm (4 inches). Maximum depth 152 mm (6 inches). Maximum may be increased as long as surface ponding dewaters in 3 to 4 hours so as to not limit potential plant species chosen.
G11-UN-USA	Typically 229 mm (9 inches), but may be between 152 mm (6 inches) and 305 mm (12 inches). Deeper limits plant selection diversity.
G12-A-USA	Maximum depth 152 mm (6 inches). This maximum is recommended to not restrict plant selection. Surface ponding to dewater in 3 days to restrict breeding of mosquitos and other insects.
G13-A-USA	Maximum depth 152 mm (6 inches) (recommended). Surface ponding to dewater in less than 7 days to prevent mosquito breeding.

The functions of surface ponding include; to slow flow velocity to reduce vegetation scour; to increase storage volume; and to ensure the ponded water is not a hazard to the public (Moreton Bay Waterways and Catchment Partnership 2006) as well as allowing time for evaporation and sedimentation (Pince George's County, Maryland 2002).

Six of the eight publications reviewed that present requirements for ponding depth deliver a maximum depth. Three recommend a maximum depth of around 300 mm and three recommend a maximum depth of 152 mm (6 inches). Those that recommend a 152 mm (6 inches) maximum do so to prevent the diversity of plant selection from being diminished. The length of time for surface ponding dewatering affects the types of plants that may be suitable. G10-A-USA allows the depth to be increased as long as the surface ponding dewaters in 3 to 4 hours. The longer the time submerged, the less plant species can survive.

The treatable volume must be contained in the ponding depth and the surface area of the bioretention basin. Changing any of these design parameters affects the other two. The ponding depth must therefore be suitable to contain the volume to be treated.

A suitable maximum recommendation for ponding depth is therefore 300 mm, however, the time of dewatering must be suitable for appropriate vegetation sustenance and to limit the chance of mosquito and other insects breeding. Maximum dewatering time appropriate to prevent mosquito and other insects breeding is 3 days (North Carolina State University, Stormwater Engineering Group 2001). Maximum dewatering time to suit vegetation depends on the type of vegetation. This must be a consideration in the design of ponding depth. Four of the eight publications determine the ponding depth using modelling. The surface area and volume to be treated are considered in this method. Modelling is a suitable means for determining the dewatering time and suitable ponding depth because the system can be analysed as a whole.

5.5. Sizing of basin surface area

The recommended surface areas for a bioretention basin are outlined in Table 5.5.1.

Table 5.5.1 Recommended surface area

G1-A-AUS	Surface area required can be found from volume and ponding depth. The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Filter media characteristics are initially assumed. Local rainfall data should be used. Modelling is performed using MUSIC (preferred), or design charts from MUSIC and regionalisation factors (if necessary).
G2-A-AUS	Surface area required can be found from volume and ponding depth. The catchment area is modelled to determine the bioretention basin dimensions to meet pollutant removal objectives. Filter media characteristics are initially assumed. Local rainfall data should be used. Modelling is performed using MUSIC (preferred), or design charts from MUSIC and regionalisation factors (if necessary).
G3-A-AUS	Surface area required can be found from volume and ponding depth. Calculate the surface area of the bioretention system using the following equation: $A = \frac{V_T \times d}{(k \times (h + d) \times t)}$ where: A = minimum surface area of the system (m^2) V_T = Treatment Volume (m^3) k = filter media hydraulic conductivity (m/day) t = filtration time (days) h = average depth of water above the filter media (i.e. half d_{max} depth) and d = filter media depth (m) For initial sizing, use the following data: t = 1 day minimum, 2 days maximum k = (can use approx. 1 m/day assuming a sandy organic soil and some clogging) h = 0.075 m d = 1 m nominal
G4-A-AUS	MUSIC modelling can be used to establish the bioretention system treatment area required to provide the appropriate level of stormwater treatment. Surface area required can also be found from volume and ponding depth.
G6-A-AUS	MUSIC modelling can be used to establish the bioretention system treatment area required to provide the appropriate level of stormwater treatment. Performance curves generated in MUSIC are also provided as an indication of area required. Surface area required can also be found from volume and ponding depth.
G10-A-USA	Detention volume can be calculated directly. Size of basin can then be determined.
G11-UN-USA	Detention volume can be calculated directly. Size of basin can then be determined from volume and depth of ponding. Rain garden surface area = Rain garden volume ÷ Average depth of water (typically 229 mm or 9 inches). Alternatively basin is sized so that surface area is 5 % to 7 % of catchment area. May be 3 % to 8 %.

G12-A-USA	Size should be such that design storm runoff may be captured. Minimum size 12.2 m by 4.6 m (40 feet by 15 feet). Facilities wider than 6.1 m (20 feet) should be twice as long as they are wide.
G13-A-USA	Detention volume can be calculated directly. Size of basin can then be determined. Minimum size 12.2 m by 4.6 m (40 feet by 15 feet). Preferred size 15.2m by 7.6 m (50 feet by 25 feet). Facilities wider than 6.1 m (20 feet) should be twice as long as they are wide (promotes distribution of flow and discourages concentrated flow).
S1-UM-AUS	If basins are too small for their catchment or if the catchment has high silt loads surface clogging can occur. Systems that are 4% the size of the impervious catchment perform better than those that are only 0.7% which clogged very quickly. A size of around 2% performs satisfactorily.
S6-UM-AUS	Minimum size 2 % of catchment area. Size to be maximised and considered in conjunction with ponding depth and hydraulic conductivity.

An undersized bioretention basin surface area can result in clogging of the system (Facility for Advancing Water Biofiltration 2008a). The recommended minimum surface area for satisfactory performance of a bioretention basin is 2% of the catchment area in both studies reviewed. One guideline sets a minimum size of 3 % of catchment area. A minimum size of 12.2 m by 4.6 m is also recommended in two of the guidelines reviewed. These minimums may be adopted as 'best practice' by consensus. Size should, however, be maximised to improve performance (Bratieres et al 2008).

Surface area is directly related to treatable volume and ponding depth. It can either be calculated from these or found using modelling. URS Australia Pty Ltd (2004) recommends the following equation,

$$A = \frac{V_T \times d}{\left(k \times \left(h + d\right) \times t\right)},$$

where,

A = minimum surface area of the system (m^2)

V_T = Treatment Volume (m^3)

k = filter media hydraulic conductivity (m/day)

t = filtration time (days)

h = average depth of water above the filter media (i.e. half d_{max} depth) and

d = filter media depth (m)

For initial sizing, use the following data,

t = 1 day minimum, 2 days maximum

k = (can use approx. 1 m/day assuming a sandy organic soil and some clogging)

h = 0.075 m

d = 1 m nominal

Modelling is preferred due to it being more suitable for such a variable and complex system.

5.6. Pretreatment measures

The recommended pretreatment measures for a bioretention basin are outlined in Table 5.6.1.

Table 5.6.1 Recommended pretreatment measures

G1-A-AUS	In larger applications than streetscapes pretreatment upstream of the bioretention basin is recommended.
G2-A-AUS	In larger applications than streetscapes pretreatment upstream of the bioretention basin is recommended.
G4-A-AUS	A coarse sediment forebay is to be included in the design where there is no prior coarse sediment management of the stormwater runoff.
G6-A-AUS	A coarse sediment (1 mm or more) forebay is to be included in the design where there is no prior coarse sediment management of the stormwater runoff.
G10-A-USA	Vegetated buffer strips may be provided for pre-treatment but are optional. Pretreatment is not compulsory because the initial ponding of water layer allows settling and filtering of sediment and suspended solids at the mulch layer prior to the water entering the filter media.
G11-UN-USA	Use grass buffer strips (1.52 m (5 feet) long typically) if TSS load is possible.
G12-A-USA	Grass buffer strip.
G13-A-USA	Vegetated buffer strips may be provided for pre-treatment but are optional.
G14-A-USA	Pretreatment is recommended (three types are outlined below). Gravel verge (thin strip) with sod surrounding the perimeter: Gravel verge to be 203 mm (8 inches) wide. Sod (a grassed filter strip) to be installed downslope of the verge and to be 1.22 m to 1.52 m (4 feet to 5 feet) wide with a minimum of 0.91 m (3 feet). The sod prevents erosion. Grass swale: Most sediment has been observed to be removed in the first 3.05 m to 4.57 m (10 feet to 15 feet) of a grass swale. Minimum length depends on catchment area and composition and swale slope, width and cover. Forebays: Suitable for large bioretention cells. Forebay should be adequate to still runoff. Depth to be between 457 mm and 762 mm (18 inches and 30 inches). Suitable where standing water does not cause safety issues. Gravel verge of grass swale are preferred. Runoff in forebay should not be able to directly enter underdrains.
S1-UM-AUS	If high levels of pathogens are present in stormwater disinfection may be required.

By consensus small bioretention basins, such as those located in a roadside, do not generally require pretreatment. Other bioretention basins may need pretreatment depending on the expected coarse sediment load from the catchment. A mulch layer in the bioretention basin may prevent sediment clogging the filter media if pretreatment is not used (Prince George's County, Maryland 2002). Modelling in MUSIC may be used to determine if the bioretention basin requires pretreatment or if it is capable of achieving acceptable pollutant removal levels without it.

Recommended pretreament devices include the inclusion of a grassed buffer strip (with or without a preceding gravel verge), a grass swale or, for large bioretention basins, a forebay.

A grassed buffer strip should be a minimum of 0.91 m (3 feet) wide. If a gravel verge is implemented, it should be upstream of the grassed buffer strip. 200 mm is a suitable width. This pretreatment helps to prevent scour of the bioretention basin surface as well as trapping pollutants (Hunt & Lord 2006). Figure 5.6.1 shows a photograph of a grassed buffer strip with a gravel verge.

Figure 5.6.1 Photograph of a grassed buffer strip with a gravel verge

(Hunt & Lord 2006)

Grassed swales remove most suspended sediment in the first 3.05 m to 4.57 m (10 feet to 15 feet). The required minimum length depends on the characteristics of the catchment and the slope, width and cover of the swale (Hunt & Lord 2006). Figure 5.6.2 shows a photograph of a grassed swale.

Figure 5.6.2 Photograph of a grassed swale

(Hunt & Lord 2006)

A forebay may be used for pretreatment for large bioretention basins (Hunt & Lord 2006). It is a depressed bay with an outlet to the bioretention basin. It should be large enough to still runoff before it enters the bioretention basin. Depth should be between 5.49 m and 9.14 m (18 inches and 30 inches). A forebay must be isolated from underdrains to avoid untreated runoff entering them. Lining may be utilised for this purpose (Hunt & Lord 2006). Figure 5.6.3 shows a photograph of a forebay.

Figure 5.6.3 Photograph of a forebay

(Hunt & Lord 2006)

5.7. Vegetation specification

Vegetation serves many purposes in a bioretention basin. It traps sediment and other pollutants at the surface (Melbourne Water 2005). Plants reduce flow velocities and limit erosion. Biofilms in the root zone aid in the removal of pollutants. Plants' roots help maintain the functionality of the filter media by reducing soil compaction. Vegetation also serves as a landscape feature and to enhance local biodiversity.

The design requirements listed for vegetation in a bioretention basin are many. Some guidelines include lists of appropriate plants. These are usually specific to the local region of the author. It is therefore not suitable to provide a list of appropriate plant species in the 'best practice' design guidelines.

Other vegetation requirements in the guidelines reviewed are outlined in Table B.1 in Appendix B. Studies' recommendations are outlined in Table B.2 in the same appendix.

The recommendations of the publications reviewed are compared and reviewed. For 'best practice,' vegetation shall:

- be tolerant of the hydrologic regime (short periods of inundation and long severe dry periods);
- suit the extended detention depth;
- be dense enough to prevent preferred flow paths from developing, scour and re-suspension of sediments;
- cover entire surface of bioretention media;
- be able to withstand design flows;
- suit the region, climate, soil type (freely draining filter media) and other abiotic elements;

- be selected considering aesthetics, community character and landscaping (a landscape architect should be consulted);
- have ecological value and provide habitat;
- be suitable for crime prevention and traffic visibility;
- be selected considering maintenance requirements;
- be appropriate for pollutant removal;
- be appropriate for preventing filter media blockages;
- be native species (preferred) (exotic species may also be used);
- be species that will not become noxious weeds;
- be protected from invasion of weeds;
- have extensive root systems, preferably with large diameter roots, but not such that will interfere with underdrains and not root-matting (or water will not be able to penetrate);
- be perennial rather than annual;
- be partially or all evergreen species;
- be a mix of various species (to maximise pollutants removed and decrease susceptibility to disease);
- be a mix of ground covers, trees and shrubs (to create a microclimate and discourage weeds);
- not include turf; and

- not include trees and shrubs near the inlet.

Many guidelines include a list of recommended plant species. The designer may consult an appropriate guideline for their area.

Most guidelines recommend dense planting, but guideline G14-A-USA recommends that planting should not be dense to optimise pathogen removal. Pathogens are removed through sunlight exposure. Other guidelines recommend dense plantings to prevent erosion and preferred path establishment, ensure a uniform root zone, aid in weed control, prevent re-suspension of sediments, break up the surface of the filter media and maintaining porosity through root growth and agitation (through wind) (Brisbane City Council 2005a). The vegetation also facilitates pollutant removal through biofilms growth on plant roots. Consensus dictates that 'best practice' is to have dense planting.

Five of the studies reviewed found that some plants perform well in nutrient removal from the storm runoff. Some species perform better than others. Cares, C. appressa and M. eticifolia perform well in nutrient removal (S6-UM-AUS). Juncus performs well also, but is not useful in removing lead. Melaleuca is effective in removing some pollutants (S7-UM-AUS). Further research may be required in this area. The designer may consider the use of these plants to enhance nutrient removal.

5.8. Mulch layer design procedure

The requirements for an organic or mulch layer in a bioretention basin are outlined in Table 5.8.1.

Table 5.8.1 Mulch layer requirements

G10-A-USA	Aged mulch is to be used (stockpiled for more than 12 months). Shredded hardwood only is to be used. Mulch not to be mounded around plants (encourages disease and pest damage). Maximum depth of 76 mm (3 inches) (so that oxygen flow to roots is not restricted).
G11-UN-USA	Mulch should be hardwood (double-shredded works well). Mulch may be pine straw. Minimum depth of 51 mm (2 inches). Preferable depth 76 mm to 102 mm (3 inches to 4 inches).
G12-A-USA	Mulch should be fine shredded hardwood or shredded hardwood chips. Preferable depth 51 mm to 76 mm (2 inches to 3 inches)
G13-A-USA	Approximate depth 76 mm (3 inches).
S11-UR-USA	Mulch should have TSS filtering ability, high permeability (d_{10} > 0.1 mm) and uniformity (a d_{60} / d_{10} value less than 4).
S12-UR-USA	A 30 mm layer of mulch was found to capture, sorb and totally degrade (in 3 to 10 days through microbial activity) the oil and grease tested.

The mulch layer filters pollutants and keeps the soil moist and intact. It is a medium for biological growth and it absorbs heavy metals, oil and grease (O/G). Micro-organisms reside in this layer and degrade petroleum-based solvents and other pollutants (Prince George's County, Maryland 2002). It filters TSS, helping to prevent clogging of the filter media. Nutrients for vegetation are supplied from the mulch layer and it aids in maintaining moisture for plant sustenance in dry episodes (Hsieh & Davis 2005).

Based on consensus mulch is optional, but beneficial. Depth of mulch should be around 50 mm to 75 mm. It is to be made of shredded hardwood (or double-shredded), hardwood chips or pine straw. Mounding around plant trunks should be avoided. Mulch should have high permeability (d_{10} > 0.1 mm) and uniformity (a d_{60} / d_{10} value less than 4).

5.9. Planting layer design procedure

The requirements for a planting layer in a bioretention basin are outlined in Table 5.9.1. The planting layer is provided in addition to and above the filter layer.

Table 5.9.1 Planting layer requirements

G3-A-AUS	Only required if filter media is not suitable for planting. Minimum thickness 100 mm. 5% by weight of particles must be less than 0.7mm, otherwise, a transition layer between the planting layer and filter media may be provided with less than 5% fines. This transition layer must meet the above grading and it hydraulic permeability must be equal to or more than the filter media. It should be 200 mm deep.
G10-A-USA	Topsoil to be sandy loam, loamy sand or loam. Maximum clay content is less than 5%. Media shall be 50% to 60% sand, 20% to 30% leaf compost and 20% to 30% topsoil. Material to be free from noxious weeds.
G11-UN-USA	Material to be sandy loam with organics (typical). Depth to be 76 mm to 152 mm (3 inches to 6 inches) (typical).
S11-UR-USA	<u>If planting layer is employed (best pollutant removal):</u> Depth to be 250 mm to 300 mm. Media to meet the requirements of the vegetation.

The provision of a planting layer is optional. It is only required if the filter media is not suitable for sustaining vegetation.

If necessary, the planting layer should be between around 75 mm and 300 mm. It should ideally be sandy loam, loamy sand or loam with a clay content less than 5 %. Sand content should be 50 % to 60 %. Leaf compost should be included at 20 % to 30 % and 20 % to 30 % should be topsoil. The hydraulic permeability of the planting layer must be equal to or more than that of the filter media. It should meet the requirements of the vegetation and be free from noxious weeds.

5.10. Filter media design procedure

The filter media performs the majority of pollutant removal in a bioretention basin (Brisbane City Council 2005a). It performs fine filtration of the storm runoff and supports the vegetation (unless a separate planting layer is included for this purpose).

The design recommendations for filter media from the guidelines reviewed are summarised in Table C.1 in Appendix C. The design recommendations for filter media from the studies reviewed are summarised in Table C.2 in Appendix C.

5.10.1 Hydraulic conductivity

A graph of the recommended hydraulic conductivity for filter media from the various publications is shown in Figure 5.10.1.

All the recommended hydraulic conductivities are within a similar range except that for S11-UR-USA, which is considerably higher. This could be because the hydraulic conductivity given for the media is the initial hydraulic conductivity with 150 mm head. Initial hydraulic conductivity with a 150 mm head cannot be readily compared to the other hydraulic conductivities. Head is a multiplier in Darcy's equation for determining hydraulic conductivity, therefore the hydraulic conductivity calculated with 150 mm head would be higher than that with less head. That recommended in S11-UR-USA is therefore omitted and the results are graphed in Figure 5.10.2.

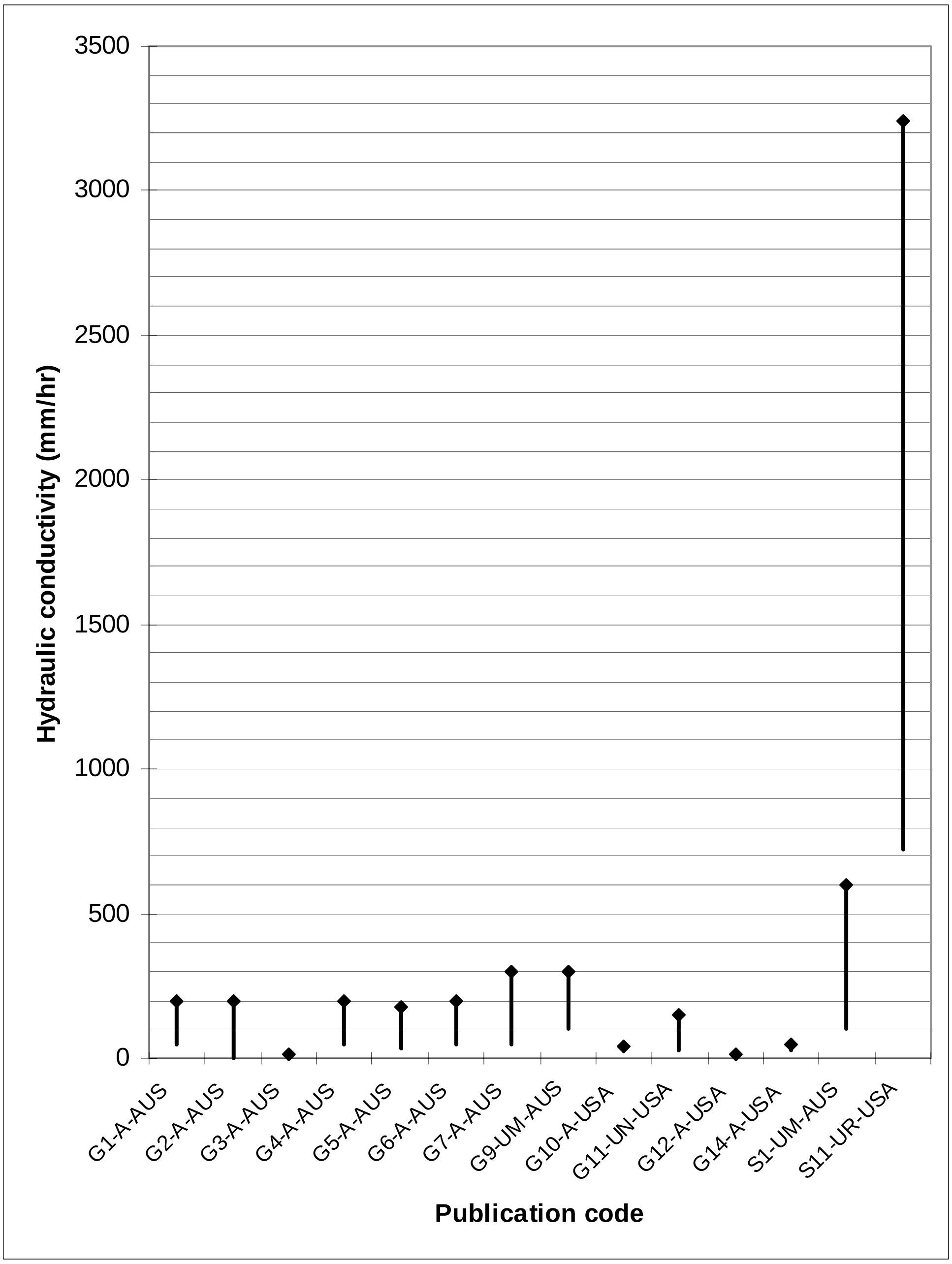

Figure 5.10.1 Graph of recommended filter media hydraulic conductivity (If only a minimum is specified, it is shown as a diamond shape, without a vertical line).

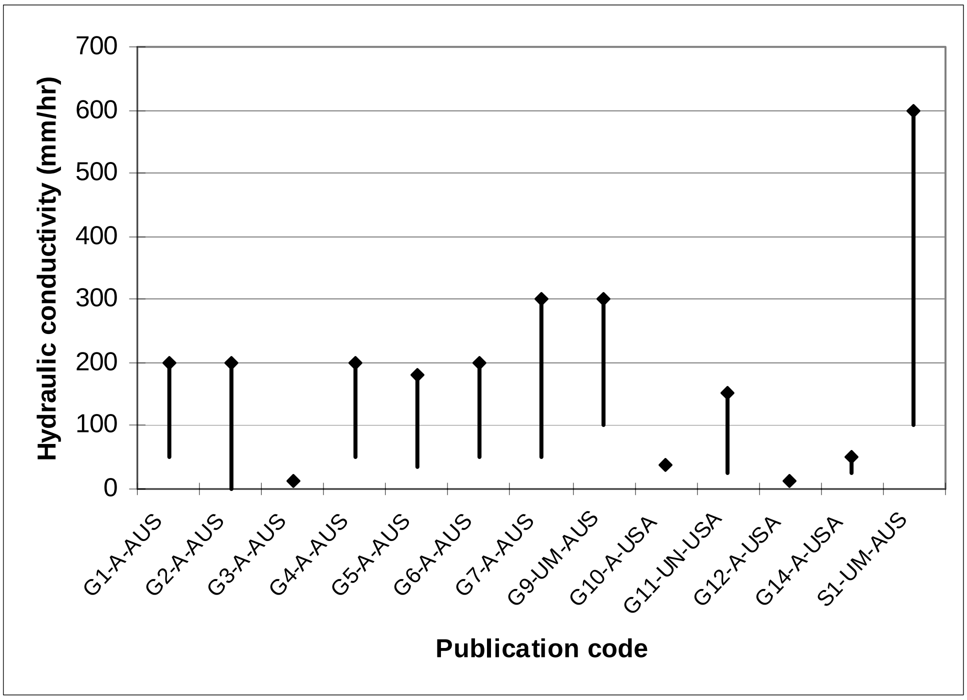

Figure 5.10.2 Graph of recommended filter media hydraulic conductivity omitting S11-UR-USA recommendations (If only a minimum is specified, it is shown as a diamond shape, without a vertical line).

Some publications only recommend a minimum hydraulic conductivity. These are shown in Figure5.10.2 as a diamond shape (without a vertical line). G14-A-USA recommends a minimum of 25 mm/hr with a preferred hydraulic conductivity of 51 mm/hr. So the maximum recommended value is not given in this case.

G3-A-AUS recommends that the hydraulic conductivity be calculated with the Hazen Formula and then reduced by a factor of ten. The Hazen Formula gives an approximate value for the coefficient of permeability based on the D_{10} effective particle size (Craig 2004). G9-UM-AUS recommend a safety coefficient of 2 for hydraulic conductivity design to account for decreasing conductivity over time, as does study S2-UM-AUS. This may make these recommendations for a minimum hydraulic conductivity more conservative than some others although the range recommended by G9-UM-AUS appears to be around the general consensus range.

A study by the Facility for Advancing Water Biofiltration (2008a) reveals that the hydraulic conductivity of a bioretention basin declines as the basin becomes established. It then increases again due to plant activity. Figure 5.10.3 illustrates the change in a bioretention basin in Melbourne. This may mean that safety factors are unnecessary.

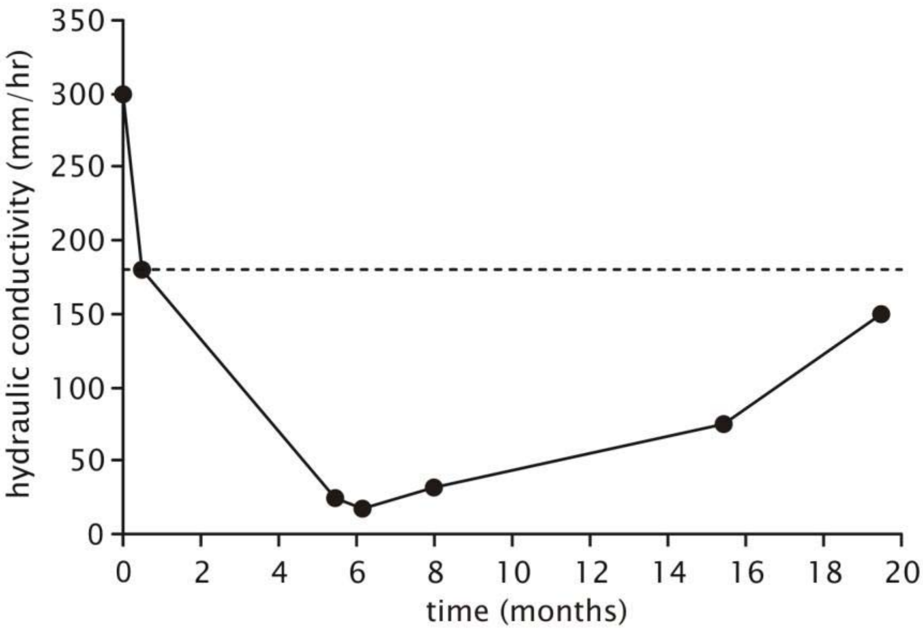

Figure 5.10.3 Change in hydraulic conductivity over 20 months in a bioretention basin in Melbourne (Facility for advancing water biofiltration 2008a)

Some publications give absolute maximums above the recommended range of hydraulic conductivity. G4-A-AUS gives an absolute maximum of 500 mm/hr, as does G6-A-AUS. G9-UM-AUS recommends a maximum of 600 mm/hr due to difficulties supporting vegetation in soil with a higher hydraulic conductivity.

G9-UM-AUS has different suggested filter media hydraulic conductivities depending on if the bioretention basin is to be located in a temperate (100 mm/hr to 300 mm/hr) or tropical (higher hydraulic conductivity may be required) climate. This is to ensure the design storm for the basin is treated by a bioretention basin with a similar area. Design storms in a tropical climate may produce more storm runoff than that in a temperate climate. Study S1-UM-AUS agrees with these guidelines. The amount of storm runoff to be treated by a bioretention basin, however, is accounted for when the storm data is obtained for the design storm. The bioretention basin is then designed to this capacity. The different hydraulic conductivity suggestions presented by these publications are therefore considered as a guide rather than as a requirement.

G11-UN-USA has a different hydraulic conductivity requirement depending on the in-situ soil at the bioretention basin location. The minimum is 25 mm/hr in sandy soils.

For clayey soils, the hydraulic conductivity is to be between 25 mm/hr and 152 mm/hr. This is possibly due to the higher expected exfiltration in sandy soils.

G12-A-USA and G13-A-USA both require the basin drain within a certain time. These times are 3 days and 7 days respectively. Guideline G11-UN-USA requires that the facility dewaters to 610 mm (2 feet) below the surface in less than 48 hours. Possible reasons for this are; to ensure the bioretention basin is ready for a subsequent storm; to prevent the reproduction of mosquitoes; or to minimise any hazard caused by ponded water in the system. These requirements would need to be checked at the design stage.

Another guideline, G14-A-USA recommends different optimum filter media hydraulic conductivities for different target pollutants. For TSS, the rate is to be greater than 51 mm/hr. For TP, the rate is to be greater than 25 mm/hr, with 51 mm/hr as the recommended rate. For TN removal the rate is to be 25 mm/hr. These may need to be considered in design when there is a particular target pollutant for the bioretention basin. Usually, TSS, TN and TP are all required to be removed by the system. Other factors affecting pollutant removal may need to be considered in conjunction with these guidelines when deciding the desired hydraulic conductivity required. Pre-treatment such as forebays or grass swales may reduce the TSS load before the storm runoff reaches the bioretention basin. Vegetation may be able to uptake TP and TN. A permanently saturated zone in the basin may reduce TN through denitrification. All of these elements may lessen the need of the filter media to be at these suggested optimum hydraulic conductivities.

It is difficult to determine a consensus on what hydraulic conductivity is suitable for a bioretention basin. There are many other factors that need to be considered at the same time. Consideration of the interaction between hydraulic conductivity, filter area and ponding depth is crucial (Le Coustumer et al 2008). If hydraulic conductivity is low, a bioretention basin may be able to compensate by having a larger filter area or a deeper ponding depth. The system may need to be modelled to determine the required balance between these elements. Exfiltration and ability to support plant life are other considerations as well as those mentioned above. In general, most recommended hydraulic conductivities fall within the range of 25 mm/hr to around 180 mm/hr (refer to Figure 5.10.2). This would be a suitable recommended range with the maximum set at around 500 mm/hr (as outlined by G4-A-AUS and G6-A-AUS), although a filter media with this hydraulic conductivity may have difficulty sustaining vegetation (G2-A-AUS).

The hydraulic conductivity would be best determined by testing. The Hazen Williams formula is only approximate.

The designer should consider, filter area, ponding depth, detention time, exfiltration rate, expected storm frequency, and target pollutant optimum rate when designing hydraulic conductivity required for filter media.

5.10.2 Organic content

The recommended organic content range for filter media given in the studies and guidelines sampled are shown in Figure 5.10.4.

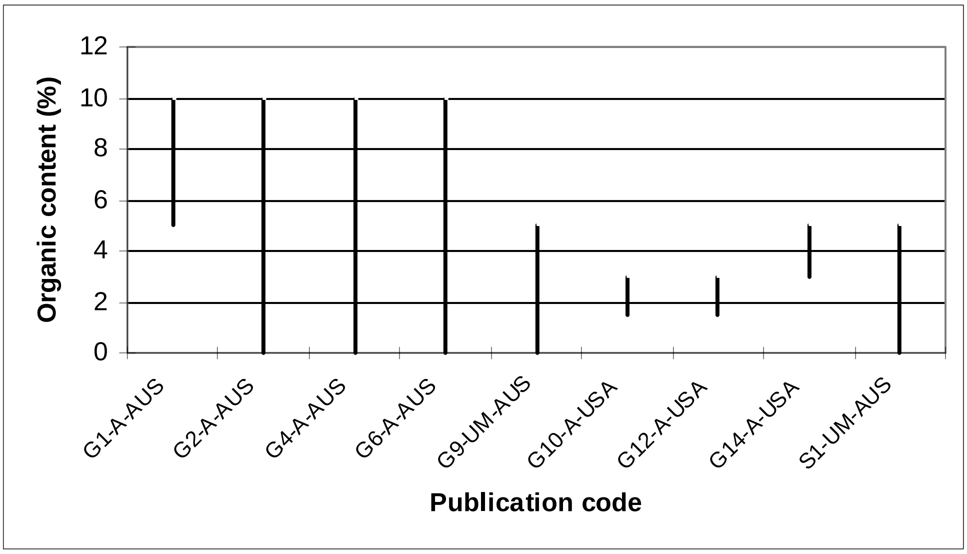

Figure 5.10.4 Graph of recommended organic content range in filter media.

It is assumed all are in units of percentage by weight although not all specify.

It is preferable to have some organic content in the filter media (at least initially) as it aids in nutrient absorption and plant growth according to Department of Water and Swan River Trust (2007). Established vegetation should produce its own organic matter which is contributed to the bioretention system (Hatt, Fletcher & Deletic 2008). This organic content in a bioretention basin, however, may be applied to the system in another element, such as in the mulch or planting layer (if these elements are included). This should be considered when specifying organic content in the filter media.

Studies/guidelines G2-A-AUS, G4-A-AUS, G6-A-AUS, G9-A-AUS and S1-UM-AUS give no minimum requirement for organic content. Only a maximum value is given.

Guideline G10-A-USA has one of the lower recommended ranges for organic content in filter media, being 1.5 % to 3 %. This guideline also recommends a planting layer and a mulch layer to be included in the system. Organic content would be found in these other two elements which could account for the lower range recommended for inclusion in the filter media. Guideline G12-A-USA also has a recommended range of 1.5 % to 3 % and also includes a mulch layer in the bioretention basin. Guideline G14-A-USA has the same recommended range, but does not mention a mulch or planting layer in the overall system. This does not necessarily mean that one should not be included in this case. This guideline was brief and only focused on a few aspects of the bioretention basin. The assumption may be made that if the range is 1.5 % to 3 % in the filter media, a planting or mulch layer (or both) should be included in the basin to account for a higher overall organic content.

In several guidelines/studies it is noted that different organic contents and/or materials are suitable for the removal of nitrogen and phosphorus. The requirements given are vague and a 'best practice' cannot be concluded.

Study S5-UM/L-AUS/F recommends the filter media contains organic matter or vermiculite (clay used for soil conditioning) for the purpose of improving the decline of hydraulic conductivity over time.

Guideline G7-A-AUS recommends red mud, or blast furnace slag and laterite or zeolite to absorb phosphorus and other inorganics. It recommends woodchips for nitrogen removal as they have more longevity than sawdust. Guideline G14-A-USA recommends newspaper or peat moss. Target pollutant removal is a consideration in determining what to use as organic material in filter media.

It is recommended that organic carbon content to be less than 5 % and overall organic content is to be less than 10 % in guidelines G4-A-AUS and G6-A-AUS. Half can be organic carbon. The other publications reviewed do not mention organic carbon content. It is unclear as to its importance. Mulch layers may also include organic carbon. This also needs to be considered.

A conservative filter media organic content recommend range would be 3 % to 5 % if no planting or mulch layer is included and 1.5 % to 3 % if a planting or mulch layer is included. Woodchips are suitable for nitrogen removal and red mud, or blast furnace slag and laterite or zeolite are suitable for phosphorus and other inorganics' removal. A mixture of these may be able to be used to cover a broad range of pollutant removal.

5.10.3 Depth requirements

The various depth requirements outlined in the guidelines and studies reviewed are represented graphically in Figure 5.10.5. Those guidelines/studies that only recommended a minimum depth have the minimum shown as a diamond shape on the graph.

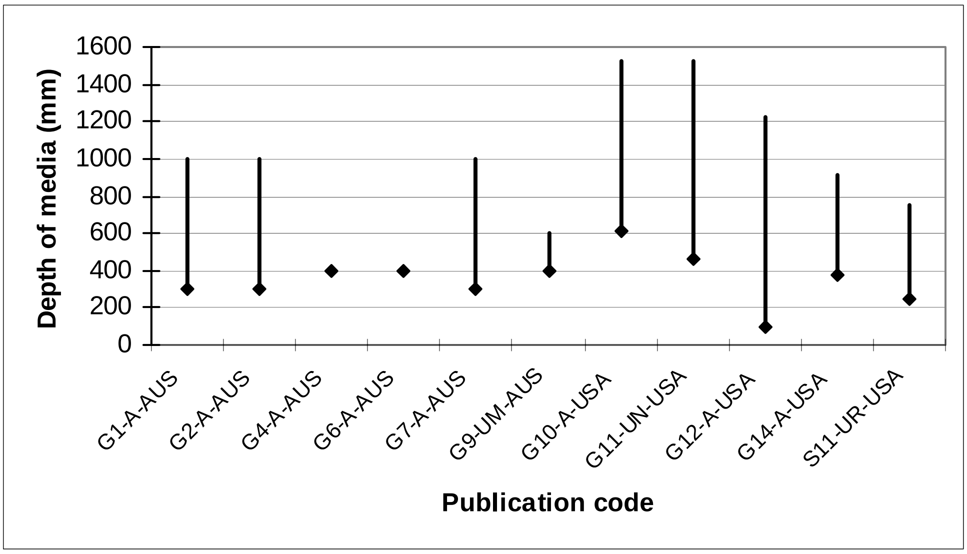

Figure 5.10.5 Graph of recommended filter media depth (If only a minimum is specified, it is shown as a diamond shape with no vertical line).

Most guidelines recommend the depth of filter media based on vegetation requirements. The minimum depths shown in Figure 5.10.5 may not be sufficient for some types of vegetation, such as trees.

G12-A-USA has a much lower minimum depth shown on the graph. This minimum is 102 mm, but the specification requires that the media depth is 102 mm deeper than the bottom of the largest root ball, therefore 102 mm is not considered the actual minimum depth of the filter media. This requirement is omitted.

The next lowest depth is from study S11-UR-USA and is 250 mm. This is the minimum depth only if a planting layer is employed in the basin design. The minimum depth for a bioretention basin with no planting layer is recommended to be 550 mm.

The other minimum depths vary from 305 mm to 610 mm (1 foot to 2 feet). G14-A-USA specifies that 457 mm (18 inches) is an adequate depth for metal removal. This guideline does not have a planting or mulch layer which possibly would aid metal removal. It also specifies 762 mm (30 inches) minimum for optimum TN removal (with 914 mm (36 inches) as a preferred depth). 305 mm (1 foot) may be recommended as long as it is deep enough to support the vegetation and if there exists a planting or mulch layer to aid in metal removal. Otherwise, 450 mm minimum may be required. If TN removal is required and no other mechanism for nitrogen removal is included, 760 mm minimum may be required.

Maximum depths vary from 600 mm to 1.52 m. The importance of specifying a maximum seems negligible.

Some guidelines recommend a greater minimum depth of filter media for trees. A minimum depth for trees of 800 mm is specified in three guidelines, 1.22 m is specified in one and 914 mm is specified in one. 800 mm may be suggested as a minimum depth for trees as long as it is verified by an expert that this depth is adequate for the species to be planted.

5.10.4 Planting/mulch layer inclusion

The following guidelines and studies include a separate planting layer in the design of bioretention basins:

- G3-A-AUS (only if filter media not suitable to support vegetation);
- G10-A-USA;
- G11-UN-USA; and
- S11-UR-USA (in one option only).

Refer to Section 5.9 for further information on the planting layer requirements.

The inclusion of a planting layer means that the filter media itself does not have to be able to support vegetation and may include less organic material.

The following guidelines and studies include a separate mulch/organic layer in the design of bioretention basins:

- G10-A-USA;
- G11-UN-USA;
- G12-A-USA;
- G13-A-USA; and
- S11-UR-USA.

Refer to Section 5.8 for further information on the mulch/organic layer requirements.

The inclusion of a mulch/organic layer means that the filter media may include less organic material.

5.10.5 pH

pH requirements are given in some of the guidelines reviewed. None of the studies reviewed mention a recommended pH. The ranges given are outlined in Figure 5.10.6.

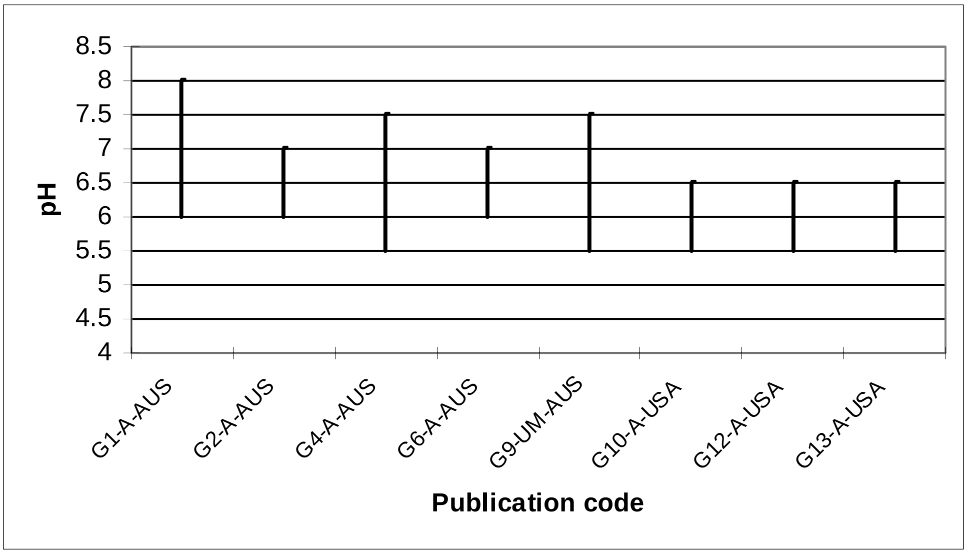

Figure 5.10.6 Graph of recommended pH range in filter media.

Guideline G1-A-AUS recommends pH to be 6 to 7.5, 7 to 8 to optimise denitrification or lower if siliceous materials are used. TN removal is a consideration in pH of filter media.

Guideline G12-A-USA recommends between 5.5 and 6.5 as microbial activity will flourish in this range aiding in pollutant removal.

No studies reviewed outlined optimal pH. More research may be required in this area.

From general consensus, pH should be approximately 5.5 to 7. If denitrification is to be encouraged to aid in the removal of TN, a pH of 7 may be more suitable.

5.10.6 Salt content

Most guidelines that mention a limit on salt content specify that salt content is to be less than 0.63 dS/m for low clay content soils. The guidelines stating this requirement are G2-A-AUS, G4-A-AUS & G6-A-AUS. Two of these guidelines are known to be based on Melbourne Water guidelines. G9-UM-AUS sets a limit on electrical conductivity as 1.2 dS/m. G12-A-USA limits soluble salt content to 500 ppm (0.781 dS/m).

Based on consensus a conservative recommendation is that salt content should be below 0.63 dS/m. Some studies into this would be beneficial.

5.10.7 Type of soil

Various requirements for the type of soil are presented in the guidelines and studies reviewed. The specified types of soil to be used as filter media are represented in Figure 5.10.7.

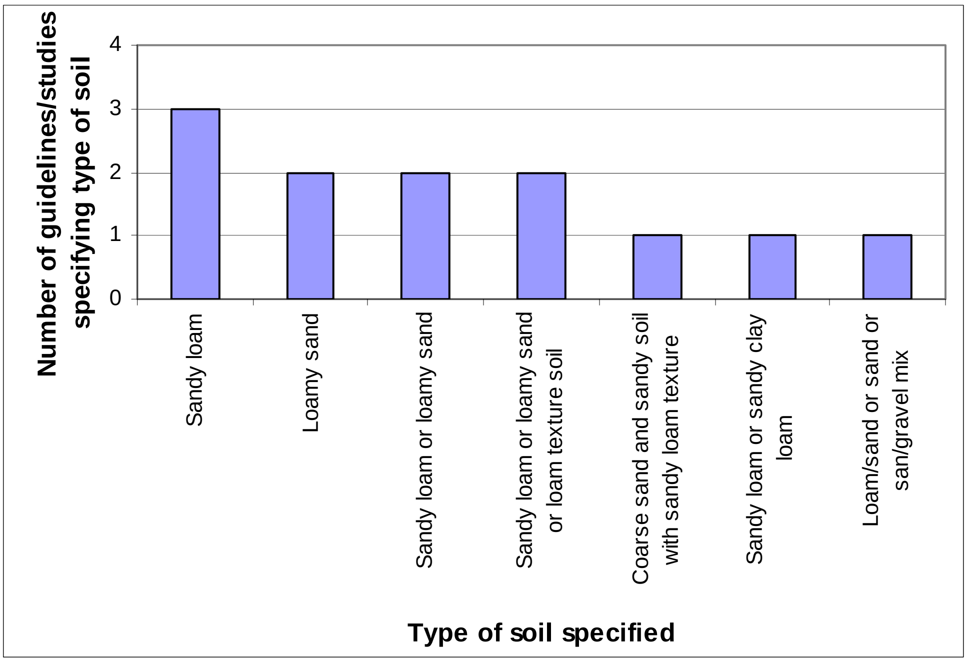

Figure 5.10.7 Graph of different soil types recommended.

Sandy loam or loamy sand is generally the soil type specified.

Coarse sand and sandy soil with sandy loam texture is only specified in study S11-UM-USA and is based on laboratory and field studies giving it some merit. This study suggests media to be coarse sand and sandy soil with sandy loam texture at a ratio of 20 % to 70 % by mass if filter media is to act as planting media or at a ratio of 50% if a separate planting layer is employed. This mix was found to have very good pollutant removal in a study aimed at optimising bioretention media for treatment of urban storm water runoff.

On this basis all of the soil types outlined in Figure 5.10.7 may be acceptable as long as they meet the other design criteria such as hydraulic conductivity and ability to support vegetation (if there is no planting layer).

Requirements relating to fines/clay content are:

- less than 15 % clay content (in guidelines G1-A-AUS and G2-A-AUS);
- less than 25 % clay (by mass) (in guideline G3-A-AUS);
- less than 5 % clay content (in guideline G10-A-USA);
- to include enough fines (clay) to support plant growth and capture pollutants (in guideline G11-UN-USA);
- to include 10 % to 25 % clay content (in guideline G12-A-USA);
- to include 8 % to 12 % fines (in guideline G14-A-USA);
- to include less than 3 % clay and silt (in study S1-UM-AUS); and
- to include less than 3 % clay and silt (for structural purposes) (in guideline G9-UM-AUS).

It is unclear what the optimum clay content is. Clay content should be enough to ensure the media is structurally stable of course. Other than that, more research may need to be conducted in this area. Mentioned in study S1-UM-AUS is that the media is to be structurally stable. This is a reasonable requirement and should be considered important due to safety concerns.

Requirements relating to sand properties and content are:

- grain size of sand used to be 0.508 mm to 1.02 mm (in guideline G10-A-USA);
- to include 85 % to 88 % sand (in guideline G14-A-USA); and
- to include 75 % to 85 % sand (in study S1-UM-AUS).

It is unclear what the optimum sand content is. Perhaps it should be in the range 75 % to 88 %. More research may need to be conducted in this area.

Requirements relating to grading are:

- soil to be well-graded and have continuous distribution of other fractions (in study S1-UM-AUS);
- soil to be well-graded and present from the 0.075 mm to the 4.75 mm sieve (for structural purposes) (in guideline G9-UM-AUS); and
- soil not to be dominated by small particles (for structural purposes) (in guideline G9-UM-AUS).

It makes sense that in order to prevent particle migration and to trap pollutants that the soil should be well-graded. The requirement that the soil should present from the 0.075 mm to the 4.75 mm sieve for structural stability is also valid.

Requirements relating to addition of vermiculite or perlite are:

- vermiculite or perlite may be added (approximately 10 % by volume) to maintain hydraulic capacity and absorption capacity (in study S1-UM-AUS); and

- vermiculite may be added (or organic matter) to maintain hydraulic capacity (in study S5-UM/L-AUS/F)

It is unclear whether the addition of perlite or vermiculite is necessary. As mentioned previously a study by the Facility for Advancing Water Biofiltration (2008a) reveals that the hydraulic conductivity of a bioretention basin declines as the basin becomes established. It then increases again due to plant activity. Refer to Figure 5.10.3. On this basis these suggested additives may be unnecessary. Further research may need to be performed to confirm this.

5.10.8 Phosphorus content

Various recommendations exist in some of the guidelines and studies reviewed for phosphorus content of the filter media.

Both G9-UM-AUS and S1-UM-AUS recommend a phosphorus content of less than 100 mg/kg. G9-UM-AUS also recommends this be lowered to less than 20 mg/kg if the selected plants are sensitive to phosphorus. This guideline and study are both from the same department at Monash University.

Other guidelines and studies from the USA recommend phosphorus content in terms of P-Index of the soil. P-Index can be related to Melich 3 Extractable P (M3P) in units of milligrams phosphorus per kilogram soil with the following equation,

$$M3P = \frac{1.2 \times PI}{w/v},$$

where,
PI = P-Index
and,
w/v = weight to volume ratio of soil (Cox, cited in Sharkey 2006).

Without knowing the weight to volume ratio of the soil, it is difficult to make a direct comparison between P-Index and phosphorus content in mg/kg. In Sharkey (2006) a filter media with a P-Index of 40 was said to contain 37 mg-P/kg-soil.

The recommended P-Indices for filter media are outlined in Figure 5.10.8. G14-A-USA is the only guideline with a recommended P-Index. It recommends between 25 and 40 or, if phosphorus is a target pollutant, between 10 and 30. S3-UM-AUS recommend that phosphorus content be minimised to enable adequate phosphorus removal from the storm runoff. The range given in S9-UN-USA is much lower than that given in the others, being 4 to 12. This study focuses on nutrient removal by bioretention basins in the field. Only two are compared for Phosphorus removal. One has a P-Index of 86 to 100 and more phosphorus is found in the outflow than inflow. The media with P-Index of 4 to 12 successfully removed phosphorus. No conclusions were drawn on any media with P-Index between these values.

Guideline G14-A-USA and study S8-UN-USA recommend a maximum P-index of 40 or 30 if phosphorus is a target pollutant. Study S14-UP-USA recommends a maximum P-Index of 50.

A conservative recommendation would be to recommend a P-Index less than 40 or phosphorus content less than 100 mg/kg, whichever is the lowest. If phosphorus is a target pollutant, a maximum P-Index of 30 may be more appropriate.

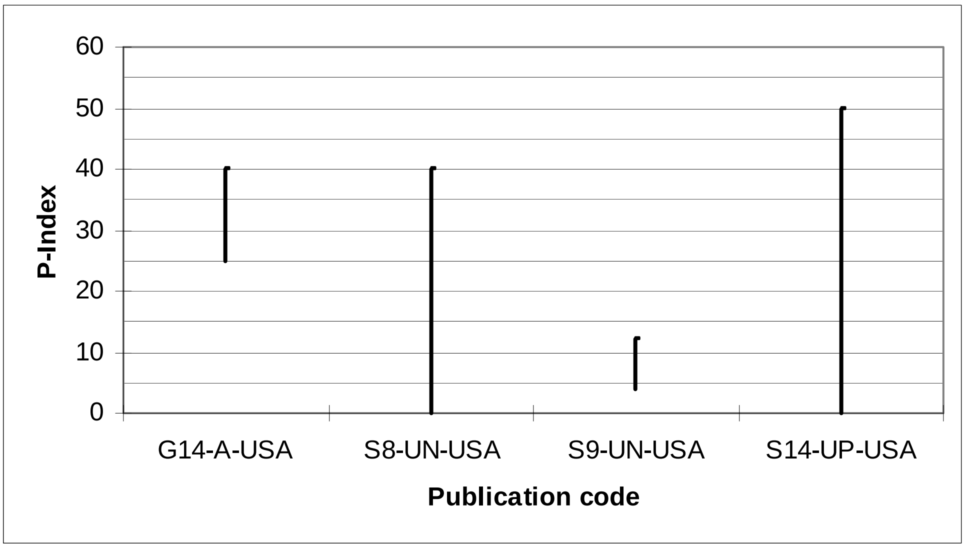

Figure 5.10.8 Graph of recommended P-Index range in filter media.

5.10.9 Other requirements

Other requirements presented in the publications reviewed are:

- Material must not be retardant to plant growth.
- Material must not be retardant to denitrification.
- Material must not contain fire ants or be from a fire ant restricted area.
- Surface to be horizontal.
- Material to be free from woody material over 25 mm in size.
- Material to be free from brush or noxious plant seeds.
- Material must not be susceptible to breakdown.
- Material not to contain rubbish or other deleterious material.

- Material must meet geotechnical requirements.

- Material to be placed and lightly compacted.

- Material to have cation exchange capacity (CEC) exceeding 10 (to aid in the capture and retention of phosphorus and other pollutants).

- Material to not be hydrophobic.

All of these requirements have valid reasons for existence and all are included in the recommended ‘best practice’ design guidelines.

5.11. Transition layer design procedure

The transition layer is placed between the filter media and the drainage layer. Its function is to prevent the migration of filter media particles into the drainage layer and underdrains (Brisbane City Council 2005a). The requirements for the transition layer found in the different publications reviewed are summarised in Table D.1 in Appendix D.

Four of the guidelines reviewed recommend that the transition layer is only required if the size differential between the filter media and the drainage layer is more than one order of magnitude. Since the transition layer exists in order to prevent migration of particles between these layers, it stands to reason that their particles size differences be considered in this manner. If the order of magnitude is less than one, particle migration is not expected and the transition layer is not required (Brisbane City Council 2005a).

Three of the guidelines state that if the drainage layer is fine gravel (2 mm to 5 mm) rather than coarse sand (1mm), then a transition layer is required. This is because if fine gravels are used in the drainage layer, the order of magnitude of the average particle size of the drainage layer is likely to be more than two compared to the average particle size of the filter media (Gold Coast City Council 2007).

Based on consensus between publications the transition layer thickness should be between 100 mm and 200 mm.

Four publications require that the transition layer material be sand or coarse sand, one specifies pea gravel and one specifies choking stone with a layer of sand above it. Based on consensus the material should be sand or coarse sand with particle size distribution based on Unimin specifications (or well-graded with minimal or no fines). An example of a typical sand/coarse sand grading based on Unimin specification is 100 % passing 1.4 mm sieve, 80 % passing 1.0 mm sieve, 44 % passing a 0.7 mm sieve and 8.4 % passing a 0.5 mm sieve (Gold Coast City Council 2007).

A permeable geotextile fabric may be used in lieu of a transition layer, however, it is more likely to clog. The minimum permittivity rate recommended in G10-A-USA is 3.06 $m^3/min/m^2$ (75 $gal/min/ft^2$). A transition layer is preferable if depth is available.

Whatever material is used, its hydraulic conductivity needs to be greater than that of the filter media to prevent disruption to the system.

5.12. Drainage layer design procedure

The drainage layer exists underneath the transition layer or underneath the filter media if there is no transition layer. It houses the perforated underdrains and allows free drainage to these (Hsieh & Davis 2005). The requirements for the drainage layer outlined in the publications reviewed are summarised in Table 5.12.1.

Table 5.12.1 Drainage layer requirements

G1-A-AUS	Coarse sand (1 mm) or fine gravel (2mm to 5 mm). Minimum thickness 150 mm. Desirable thickness 200 mm.
G2-A-AUS	Sand (1 mm) is preferred, but smallest particle size must be compatible with underdrain slot sizes, otherwise fine gravel (2 mm to 5 mm) may be used. Minimum thickness 200 mm.
G3-A-AUS	Fine to coarse gravel. Generally, uniform size of 10 mm nominal, free from silt and clay and deleterious matter. Provide 50 mm cover over drain.
G4-A-AUS	Sand is preferred, but smallest particle size must be compatible with underdrain slot sizes, otherwise fine gravel may be used. Minimum thickness 150 mm. Desirable thickness 200 mm. Soil must not contain fire ants or be from fire ant restricted areas.
G6-A-AUS	Either coarse sand (1 mm) or fine gravel (2 mm to 5 mm). Sand is preferred, but smallest particle size must be compatible with underdrain slot sizes, otherwise fine gravel may be used. Minimum thickness 200 mm. Soil must not contain fire ants or be from fire ant restricted areas. Media to be washed to remove fines.
G7-A-AUS	Either coarse sand (1 mm) or fine gravel (2 mm to 5 mm). Typical thickness 150 mm. The material size differential between adjacent layers should not be more than one order of magnitude. Reject soil which contains rubbish or other deleterious material. Media must meet hydraulic conductivity requirements. Media must meet geotechnical requirements.

G9-UM-AUS	Media to be clean, fine gravel (2 mm to 5 mm washed screenings typically). Providing 50 mm cover to underdrain.
G10-A-USA	Material shall have a hydraulic capacity greater than the filter media infiltration rate. Preferred material is river-run washed gravel. Material shall be no greater than 13 mm to 38 mm (½ inch to1½ inches). Gravel stone to be blue stone, double washed #57 stone 25 mm to 38 mm (1 inch to 1½ inches). Depth to be less than 305 mm (12 inches). Pea gravel (small, smooth, rounded stones) may be used in lieu of the drainage layer, but it must be ensured that the underdrain perforations do not exceed 6.4 mm (¼ inch). Pea gravel to be 6.4 mm to 13 mm (¼ inch to ½ inch) in size.
G11-UN-USA	Material to be washed gravel (such as #57 stone) Depth to be 152 mm to 305 mm (6 inches to 12 inches).
S6-UM-AUS	Drainage layer to prevent leaching of fine materials.
S11-UR-USA	Media to be sand. Depth to be 50 mm. This layer prevents soil particles clogging the underdrain.

The different material types recommended are represented graphically in Figure 5.12.1.

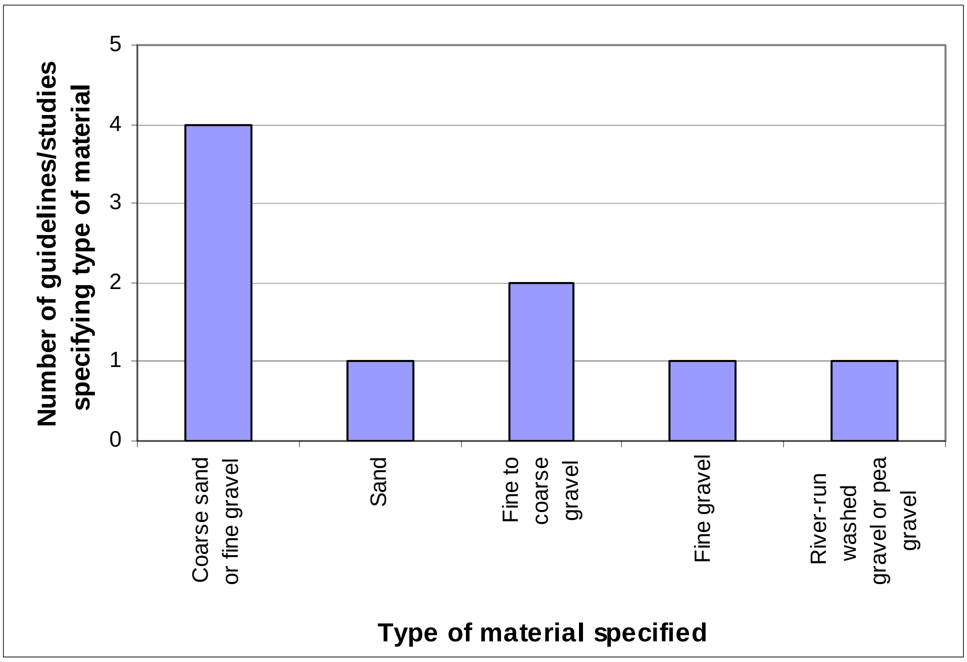

Figure 5.12.1 Recommended drainage layer material types

All publications recommend the material used be either sand or gravel of various descriptions. The smallest particle size must be such that it is compatible with the slot sizes in the underdrains otherwise it may enter and clog them (Gold Coast City Council 2007). Two of the guidelines that recommend coarse sand or fine gravel state coarse sand as the preferred material as long as it meets underdrain slot size requirements. But there are close-to an equal number of recommendations for sand or gravel in the publications. Either is therefore considered acceptable. The material size differential between the drainage layer and the adjacent layer shall be no more than one order of magnitude to prevent migration of particles and clogging of the system (Department of Water and Swan River Trust 2007).

Various drainage layer depths are recommended in the publications reviewed. All range from 150 mm to around 300 mm. S11-UR-USA recommends a depth of 50 mm, but this is based on a bioretention basin that does not contain a perforated underdrain within the drainage layer. An underdrain would not fit in a 50 mm drainage layer as most specified are 100 mm or 150 mm in diameter (refer to Section 5.15). This is discounted and the ‘best practice’ drainage layer depth recommendation is between 150 mm and 300 mm based on consensus between the other publications. Two publications also recommend 50 mm cover to underdrains. It is important to have some cover to underdrains for the drainage layer to serve its purpose of preventing migration of the upper layers’ material into the underdrains. This is therefore adopted as ‘best practice’ also.

Other requirements of note are:

- Material to be free from silt and clay (G2-A-AUS).
- Material to be free from deleterious matter (G2-A-AUS).
- Soil must not contain fire ants or be from a fire ant restricted area (G4-A-AUS).
- Material to be washed to remove fines (G6-A-AUS).
- Material must meet hydraulic conductivity requirements (G7-A-AUS).

- Material must meet geotechnical requirements (G7-A-AUS).

Silt and clay particles would most likely migrate into underdrain perforations and may result in clogging. The material should therefore be free of these. Washing the material to remove fines would therefore be recommended if necessary.

Deleterious matter may cause damage to the bioretention system or the vegetation therein and should be excluded from the drainage layer material.

Fire ants are not to be imported to the construction area as they are detrimental to the local ecology and attempts are being made to manage their localities.

The material should meet hydraulic conductivity requirements so as to not hinder the function of the filter media and the system by clogging.

Material should meet geotechnical requirements to ensure it is stable and does not affect surrounding structures.

5.13. Nitrogen removal zone design procedure

Some of the publications reviewed incorporate a submerged zone to remove nitrogen and prevent the onset of nitrogen leaching after extended dry periods in the bioretention basin. These zones house anaerobic bacteria and allow denitrification in the system. The requirements for these nitrogen removal zones from various publications are outlined in Table 5.13.1.

Table 5.13.1 Nitrogen removal zone recommendations

G14-A-USA	It appears that a permanently saturated anaerobic zone may reduce TN. This layer should be at least 457 mm (18 inches) from the surface of the bioretention cell 610 mm (24 inches) (recommended). This is to avoid the surface area that collects most metals and phosphorus from becoming saturated resulting in release of these elements via solution.
S1-UM-AUS	Approximately 450 mm deep submerged zone of sand or gravel as well as a carbon source (e.g. approximately 5% by volume of hardwood chips) largely improves nitrate/nitrite removal by denitrification and is beneficial for heavy metal removal (especially copper). A submerged zone supports plant life during dry periods and delays the onset of nitrogen leaching during these same periods (from three weeks to seven in tests performed). Upon re-wetting a system with a submerged zone recovers more quickly than one without (note that the response is not linear). A submerged zone may, however, produce low levels of ammonium which could be a source of pathogens (likely some viruses).
S3-UM-AUS	Anaerobic sumps designed to catch nitrogen enhance nitrogen removal from storm runoff according to preliminary results of experiments (Zinger et al, cited in Hatt, Fletcher & Deletic 2007). These zones mean that the system causes nitrification and denitrification.
S4-UM-AUS	An anaerobic zone may enhance nitrogen retention (Zinger et al cited in Hatt, Fletcher & Deletic 2008).
S6-UM-AUS	Studies have shown that nitrogen removal is improved by incorporating a permanently saturated carbon-enhanced anaerobic zone (Zinger et al cited in Bratieres et al 2008). Further testing is required.
S10-UN-USA	Nitrogen reduction may be enhanced by the inclusion of an internal water storage area (Dietz & Clausen cited in Hunt et al 2008).
S11-UR-USA	Layer to be below filter media and above drainage layer. Media to be sandy loam or coarse sand mixed with and organic material (Hunt et al cited in Hsieh & Davis 2005). Depth to be 100 mm to 300 mm. Layer may be kept submerged (Kim et al cited in Hsieh & Davis 2005). Nitrate removal is poor unless this layer is included. It is believed this layer promotes denitrification but results are so far inconclusive.
S13-UR-USA	An anoxic cell could aid in the removal of TN through denitrification, especially nitrate which is the most difficult form to address (Kim et al cited in Davis et al 2006)

In a bioretention basin aerobic metabolism converts organic nitrogen to nitrate through nitrification (Davis et al 2006). Upon re-wetting after extended dry periods, this nitrate can be washed from the system (Hatt, Fletcher & Deletic 2007). This causes a marked increase in concentrations of nitrogen leaving the system. The publications recommending a submerged zone be incorporated in bioretention basins propose that it causes anaerobic conditions and hence denitrification, addressing the problem of nitrate concentrations. A submerged zone has been found to delay the onset of nitrate leaching (from three weeks to seven weeks) in the study by the Facility for Advancing Water Biofiltration (2008a).

The underdrain keeps the soil in an aerobic state by allowing the media to drain at an acceptable rate. The vertical position of the underdrain can be lifted to create an anaerobic zone to encourage nitrogen removal through denitrification (Prince George's County, Maryland 2002).

The following recommendations currently exist for the location of the submerged zone:

- Saturated zone should be at least 457 mm (18 inches) from the surface of the basin to avoid the area that collects most metals and phosphorus to avoid saturation releasing these elements via solution (G14-A-USA).

- Saturated zone to be below filter media and above drainage layer (S11-UR-USA).

These submerged zone location requirements are both similar and it can be concluded that the submerged zone should be located such that is does not overlap with the area that collects the most metals and phosphorus i.e. the top 450 mm of the filter media.

The requirements outlining depth of submerged zone are as follows:

- Saturated zone should be approximately 450 mm deep (S1-UM-AUS).

- Depth to be 100 mm to 300 mm (S11-UR-USA).

These depth requirements are conflicting and it is difficult to conclude the most desirable depth requirement. The minimum should at least be 100 mm perhaps.

Materials suggested include:

- Sand, gravel and carbon source (such as 5 % by volume hardwood chips) (S1-UM-AUS);

- Zone to be carbon-enhanced (S6-UM-AUS); and

- Media to be sandy loam or coarse sand mixed with organic material (S11-UR-USA).

Several studies require than a carbon source be included in the submerged zone with S11-UR-USA stating that nitrate removal without it is poor. Sand, gravel or sandy loam are concluded to be appropriate materials.

Study S1-UM-AUS states that a submerged zone may produce low levels of ammonium which could be a source of pathogens.

Results in studies undertaken into incorporation of a submerged zone are promising, but as yet inconclusive (Hsieh & Davis 2005). Further research is required and as such the inclusion this design element is not included in the ‘best practice’ guidelines.

5.14. Infiltration rate of system design procedure

The recommended methods for calculating the infiltration rate of the system are summarised in Table 5.14.1.

Table 5.14.1 Recommended methods for calculating the infiltration rate of a bioretention basin

G1-A-AUS	Darcy's equation used to determine maximum filtration rate.
G2-A-AUS	Darcy's equation used to determine maximum filtration rate and to then size underdrains.
G3-A-AUS	Darcy's equation used to determine maximum filtration rate.
G4-A-AUS	Darcy's equation used to determine maximum filtration rate and to then size underdrains.
G6-A-AUS	Darcy's equation used to determine maximum filtration rate and to then size underdrains.
G7-A-AUS	Darcy's equation used to determine maximum filtration rate and to then size underdrains. Infiltration modelling software may be required if the influence of groundwater level and infiltration capacity needs to be considered, especially for pervious systems.
G11-UN-USA	Darcy's equation used to determine maximum filtration rate.

Darcy's equation relates flow velocity to the permeability of the soil (Haestad Methods 2007). It is as follows,

$$Q_{max} = \frac{A \times k \times (h_{max} + d)}{d},$$

where,

Q_{max} = maximum outflow from the system (m^3/s)

A = surface area of the system (m^2)

k = filter media hydraulic conductivity (m/s)

h_{max} = maximum depth of water above the filter media

d = filter media depth (URS Australia Pty Ltd 2004).

All seven methods outlined by the publications reviewed recommend Darcy's equation for calculation of the infiltration rate of the system. This is therefore concluded to be the 'best practice' method.

5.15. Perforated underdrains design requirements

Perforated underdrains drain the bioretention basin. They are usually located at the bottom of the basin, but may be elevated to produce a saturated zone for enhanced nitrogen removal (Prince George's County, Maryland 2002). They allow the system to drain and must be able to accommodate the expected flow or the system will back up. The perforated underdrain design requirements outlined in the publications reviewed are summarised in Table E.1 in Appendix E.

The consensus between the reviewed publications is that the maximum filtration rate of the bioretention basin is used to size the underdrains. Guideline G11-UN-USA is the only guideline to have an alternate recommendation. It recommends that the capacity of the underdrain be one order of magnitude higher than the maximum infiltration rate. This is considerably higher than the consensus. It states that the underdrains must drain water from the drainage layer substantially faster than the water enters from the layer above, but it does not explain why. All other guidelines do not have this requirement; therefore the 'best practice' procedure adopted is to size the underdrains for maximum filtration rate of the system as a minimum.

The various publications recommend the use of Manning's equation (four publications), Colebrook-White equation (one publication) or either of the two (one publication) to check the underdrain has the desired capacity. Although Manning's equation is recommended in more publications, the Colebrook-White equation is also suitable. Normally the Colebrook-White equation is used for full pipes under pressure, but it can be used for pipes not under pressure. This is done by assuming that the hydraulic gradient is equal to the pipe gradient in the equation (Chadwick, Morfett & Borthwick 2004). In 'best practice' either may be used.

The perforations must be checked to ensure they also accommodate the maximum infiltration rate (Brisbane City Council 2005a). Five out of the six guidelines that mention this check, recommend the use of the sharp-edged orifice equation and the other does not specify an equation. The sharp-edged orifice equation is widely used in engineering for the purpose of determining flow capacity through an orifice and is deemed appropriate. Its use is outlined in various engineering manuals including

Haestad Methods (2007), Chadwick, Morfett & Borthwick (2004) and Nalluri & Featherstone (2001). All of the five publications reviewed that recommend the sharp-edged orifice equation mention applying a blockage factor of 50 % to account for blockages of the perforations by drainage layer material. This is reasonable and a consensus and is therefore adopted as 'best practice.'

Guideline G10-A-USA recommends the exact dimensions of the perforations. This is unnecessary as the perforations of the pipes used are checked for suitability. The perforation sizes also depend on what perforated pipes are readily available commercially.

The pipe is to have no perforations in the 1.52 m (5 feet) closest to the drainage outfall structure according to guideline G10-A-USA. The publication states that this is to avoid piping problems. It is unclear why this is necessary. It is not required by any other guidelines reviewed and is disregarded.

Five of the publications recommend that a check be performed to ensure that the perforations would not allow migration of drainage layer material into the underdrains. This may cause clogging and is therefore a reasonable expectation. This is adopted as 'best practice.'

Pipe size should be 150 mm maximum as this is acceptable in three of the publications.

The maximum spacing of underdrains should be 1.5 m, except where catchment is greater than 100 m^2, then spacing may be increased to 2.5 m to 3 m. The minimum grade is to be 0.5 %. Maximum grade is to be 4 %. Underdrain to have a minimum cover of 50 mm drainage material. This ensures the drainage layer serves its purpose of protecting the underdrain from being clogged with migratory particles from the transition or filter layers above.

Pipe materials that are acceptable include polyvinyl chloride (PVC), perforated pipes such as agricultural (AG) pipes or corrugated high-density polyethylene (HDPE) pipe. Based on consensus, the pipe surface is to be smooth to minimise surface beading. Surface beading may attract tree roots, which may then intrude into the pipe causing blockages and damage.

Only guideline G3-A-AUS requires a back-flushing system be installed to clean the underdrains. This is therefore considered optional but may be considered for maintenance purposes.

Guideline G7-A-AUS recommends that root barriers be installed around underdrains if trees are planted. This may be considered for 'best practice' design but is optional.

Underdrains are not required where in-situ soil has an hydraulic conductivity greater than 25 mm/hr (1 inch), the water table is greater than 610 mm (2 feet) below the bottom of the bioretention basin and the catchment area is less than one acre, according to guideline G10-A-USA Guidelines G12-A-USA and G13-A-USA both recommend that an underdrain is not required if the in-situ soil has an hydraulic conductivity greater than 13 mm/hr (0.5 inches per hour). The recommended minimum hydraulic conductivities for filter media in these guidelines are 38 mm/hr (G10-A-USA) and 13 mm/hr (G12-A-USA and G13-A-USA). The recommendations in G12-A-USA and G13-A-USA mean that if the hydraulic conductivity of the in-situ soil is the same or greater than that of the filter media (and therefore the whole bioretention basin), then an underdrain is not required. The treated runoff would reach the bottom of the bioretention basin and infiltrate through the in-situ soil at a rate which would not back up the system and affect is function. This seems acceptable, but caution would need to be exercised that the hydraulic conductivity of the in-situ soil remains the same and is not affected by seasonal groundwater levels. Guideline G10-A-USA, however, allows the in-situ soil to have a hydraulic conductivity less than the possible hydraulic conductivity of the bioretention basin filter media (and therefore the whole system). This would mean that the basin may back up from its invert where it abuts the in-situ soil. This may affect the function of the bioretention basin, depending on how far it backs up and how long it takes to drain. Modelling of the system may be necessary to determine the likely outcome. The backed up water may affect the microbial activities in the bioretention basin. It may also cause some pollutants to become re-suspended in it.

Guideline G10-A-USA suggests that if the underdrain is omitted the catchment area should be limited to one acre and the groundwater should be more than 610 mm (2 feet) below the invert of the basin. Limiting the catchment area means that the underdrain may only be omitted in small bioretention basins. Reasons are not given. Maybe there is too much uncertainty and unpredictability involved in the effects of omitting the underdrains. It seems conservative to recommend this, so it is adopted as 'best practice' for bioretention basins without underdrains that the catchment area should be no more than on acre. The groundwater at 610 mm (2 feet) below the invert of the basin would minimise the affect of the groundwater on the hydraulic conductivity of the soil. This is also adopted as 'best practice' for bioretention basins without underdrains.

Underdrains are not to be located within the groundwater zone of saturation other they would constantly be draining groundwater. This would have local effects on the groundwater table.

Perforations are normally placed near the invert of the basin (Prince George's County, Maryland 2002), but they may be placed near the top of the pipe to induce a submerged zone if required.

5.16. Inspection requirements

Some guidelines require inspection openings be incorporated into the design of the underdrains. The various requirements are summarised in Table 5.16.1.

Table 5.16.1 Inspection requirements

G2-A-AUS	Underdrains to be extended vertically to the surface of the system for ease of inspection and maintenance. Inspection shaft to be capped. Perforations are not required in this section.
G3-A-AUS	Include an inspection well to check efficiency of system.
G4-A-AUS	Extend underdrains to surface for inspection and maintenance purposes. Use unperforated pipes for vertical section. Cap, construct concrete surround and label as "Flush Point."
G6-A-AUS	Extend underdrains to surface for inspection and maintenance purposes. Use unperforated pipes for vertical section.
G10-A-USA	An observation/cleanout standpipe is to be installed if depth is greater than 610 mm (2 feet) or if an underdrain exists. Material to be rigid non-perforated PVC pipe, 102 mm to 152 mm (4 inches to 6 inches) in diameter. Location to be the centre of the structure. Standpipe to be capped flush with the surface.

The general consensus on inspection requirements is to install an inspection opening to underdrains. This is to be a section of unperforated and vertical pipe from the underdrains to the surface. The inspection opening is to be capped at the surface. It is required for inspection and maintenance providing easy access for cleaning of the underdrains. This may prolong the life of the bioretention basin. In 'best practice' design it is therefore required.

5.17. Impervious liner requirements

An impervious liner may be included around the walls or along the bottom (or both) of the bioretention basin. The various requirements outlined in the publications reviewed for provision of impervious liner are summarised in Table 5.17.1.

Table 5.17.1 Impervious liner requirements

G1-A-AUS	Impervious liner required at bottom of basin. Impervious liner required at sides if surrounding soils have a saturated hydraulic conductivity less than one order of magnitude less than the filtration media. System can be designed to encourage exfiltration and have no impervious liner where stormwater volume reduction is important. System can be designed to not allow exfiltration and have impervious liner where in-situ soils are not suitable or where system is near a significant structure. In roadside locations, drainage trenches often exist which would collect seepage from systems. In some terrain care is to be taken when considering impervious liner inclusion. A fully lined system may act as a barrier causing an increase in groundwater levels in areas of shallow groundwater. Depth to groundwater, chemical composition of soils (e.g. sodic soils) and proximity to structures are other considerations. Impervious liner may be flexible membrane of concrete.
G2-A-AUS	Impervious liner required at drainage layer sides and bottom if surrounding soils have a saturated hydraulic conductivity less than one order of magnitude less than the filtration media. System can be designed to recharge groundwater with no liner and no underdrains. Depth to groundwater, chemical composition of soils (e.g. sodic soils) and proximity to structures are other considerations. Impervious liner may be flexible membrane of concrete.
G3-A-AUS	Geofabric shall be provided along the side walls and base to prevent migration of fine soils from surrounds. Low permeability liner to be provided where salinity is a hazard.
G4-A-AUS	Impervious liner required at basin sides and bottom if surrounding soils have a saturated hydraulic conductivity less than one order of magnitude less than the basin media. (Likely to only be needed at base and sides of drainage layer). Groundwater, hydraulic conductivity of in-situ soils, site terrain and proximity to structures should be considered when exfiltration is considered.
G6-A-AUS	Impervious liner may be required at sides and bottom of basin if surrounding soils have a saturated hydraulic conductivity less than one order of magnitude less than the basin media. (Likely to only be needed at base and sides of drainage layer). Flexible membrane or concrete casing may be used. Groundwater, hydraulic conductivity of in-situ soils, site terrain, salinity and proximity to structures should be considered when exfiltration is considered.

G7-A-AUS	If a pervious system is required and the saturated hydraulic conductivity of the surrounding soil is more than one order of magnitude higher than the filtration media an impervious liner should be incorporated along the sides of the basin, but not the base (ex-filtration to occur at base). If an impervious system is required and the saturated conductivity of the surrounding soil is lower than the filtration media an impervious liner should be placed typically across the base of the system. A liner may also be required on the sides of the drainage layer. When considering whether to install an impervious liner groundwater, salinity and the proximity of nearby infrastructure should be considered.
G10-A-USA	In areas where groundwater protection is required an impervious liner is used. An impervious liner can aid in containment if an accidental spill was to occur. Liner to extend below underdrain invert. Permeable filter fabric may be placed along the walls of the facility to encourage flow direction downwards through the facility. This will help protect adjacent pavements by reducing lateral flow. Proximity to structures should be considered. 1.52 m (5 feet) setback from foundations or a slab is required without liner. If a basement exists, 7.62 m (25 feet) setback downhill is required and invert of system should be lower than basement floor level.
S1-UM-AUS	Preferably unlined where possible (e.g. where system is far enough from foundations). Exfiltration should be encouraged as it reduces pollutant loads on the bioretention system and serves to restore the original hydrological conditions in the area somewhat. Hydraulic conductivity of surrounding soils must be considered in exfiltration.
S8-UN-USA	Exfiltration should be encouraged as a system which reduces stormwater runoff volume as well as pollutant loads performs better in overall stormwater treatment than one which does not reduce stormwater runoff volume. Even clayey surrounding soils reduce stormwater runoff volume in systems.
S9-UN-USA	Unlined bioretention cells are preferable. They reduce outflow and pollutant load entering the stormwater system.
S13-UR-USA	Promotion of water infiltration from the bioretention basin to surrounding soils is important and should be promoted. Water that leaves the system through infiltration will encounter increased soil contact time and longer reaction time in the surrounding soils. This will help reduce nutrient loads.

Three of the seven guidelines reviewed suggest an impervious liner is required at the basin sides and bottom if the surrounding soil has a saturated hydraulic conductivity less than one order of magnitude less than the filter media. This is said to typically be required on the base and sides of the drainage layer only (G4-A-AUS). Guideline G1-A-AUS requires an impervious liner at the bottom regardless of surrounding soils and at the sides if the saturated hydraulic conductivity of the surrounding soil is less than one order of magnitude less than the filter media. One of the guidelines requires and impervious liner where the saturated hydraulic conductivity of the surrounding soil is lower than the filter media (G7-A-AUS). This is again suggested to be at the base and at the sides of the drainage layer only. These requirements are designed to prevent storm runoff from exfiltratating the basin it is unlikely to occur (or is likely to be minimal) if the surrounding soil has a saturated hydraulic conductivity less than the filter media (Gold Coast City Council 2007). Exfiltration is most likely to occur at the base of the bioretention basin as the difference in hydraulic conductivity between the filter media and the surrounding soils direct the water through the path of least resistance, down through the system to the base. Gravity also influences the water to take this path and encourages exfiltration through the base.

The system can be designed with the intent of exfiltration. In this case no impervious liner is used (G1-A-AUS & G2-A-AUS). Guideline G7-A-AUS requires no impervious liner at the base in such a system, but requires one be placed at the sides of the basin if the hydraulic conductivity of the surrounding soil is more than one order of magnitude higher than the filtration media. This would allow exfiltration through the bottom of the system only. This is to prevent filter media from being bypassed. This is adopted as 'best practice' for a system designed to exfiltrate.

Consideration of hydraulic conductivity of surrounding soils is necessary to consider according to study S1-UM-AUS.

Most of the guidelines reviewed recommend the bioretention basin disallow exfiltration by incorporating an impermeable liner. The benefits of disallowing exfiltration are outlined:

- Exfiltration adjacent to structures may cause problems for foundations (six of seven guidelines, one of four studies).

- Chemical composition of surrounding soils (e.g. sodic soils) may be a reason against allowing exfiltration (four of seven guidelines).

- Protects groundwater against accidental spills (one of seven guidelines).

In contrast, all of the studies reviewed recommend that bioretention basins not include an impervious liner, if possible. The benefits of not lining the basin are outlined:

- Exfiltration reduces pollutant loads on bioretention basins (S1-UM-AUS, S8-UN-USA, S9-UN-USA).

- Exfiltration results in longer soil contact time and longer reaction time for stormwater runoff, helping to reduce nutrient loads (S13-UR-USA).

- Exfiltration aids in restoring the original hydrological conditions in the area (S1-UM-AUS).

- Exfiltration reduces stormwater runoff volume which causes the bioretention basin to perform better. (Even clayey in-situ soils reduce stormwater volume) (S8-UN-USA, S9-UN-USA).

- In areas of shallow groundwater, an impermeable liner may act as a barrier causing groundwater level to rise (four of seven guidelines).

- Roadside drainage trenches often exist which would collect seepage from basins (one of seven guidelines).

These studies are based on field and laboratory testing giving them some merit. On this basis it is preferable to not line bioretention basins with impervious material unless required to due to vicinity of structures, chemical composition of soils or protection of possible accidental spills is required. If adjacent soils have a hydraulic conductivity one order of magnitude higher than the filter media, liner may be used on the sides of the basin to prevent stormwater runoff bypassing the filter media and thus the main area of pollutant removal.

G3-A-AUS require the basin be lined (walls and base) with a permeable geofabric. This is to prevent migration of fine soils from the surrounds into the basin. If salinity is high, it suggests a low permeability liner be used. G10-A-USA also suggests the use of a permeable filter fabric along the walls. This is to encourage flow downwards to protect adjacent structures from lateral flow. Filter fabrics of various permeability, rather than a totally impermeable membrane, may produce the results desired in respect to preventing/minimising exfiltration, water migration control in saline soils, soil migration control, and protection of adjacent structures. The hydraulic conductivity of the filter fabric, the surrounding soil and the filter media would need to be compared to establish if there is adequate control with the selected filter fabric. The path of least resistance is the like path for the stormwater runoff (Gold Coast City Council 2007).

5.18. Groundwater considerations

The proximity of groundwater may have some impact on bioretention design. Requirements from the publications reviewed are outlined in Table 5.18.1.

Table 5.18.1 Groundwater considerations

G1-A-AUS	A fully lined system may act as a barrier causing an increase in groundwater levels in areas of shallow groundwater.
G4-A-AUS	Shallow groundwater may mean a flexible membrane of concrete casing should be provided to prevent excessive exfiltration.
G6-A-AUS	Shallow groundwater may mean a flexible membrane or concrete casing should be provided to prevent excessive exfiltration.
G7-A-AUS	Annual maximum groundwater level should be considered in selection of bioretention system. Shallow groundwater may mean a flexible membrane should be provided to prevent excessive exfiltration.
G10-A-USA	Seasonally high groundwater table should be 0.61 m (2 feet) below system (minimum).
G11-UN-USA	In areas with high water table a small stormwater wetland may be better suited than a bioretention basin as plant growth may be hindered.
G12-A-USA	Water table must be more than 1.83 m (6 feet) below ground level.
G13-A-USA	Seasonally high water table must be more than 1.52 m (5 feet) below ground level or bioretention basin is not suitable.

By consensus the groundwater table should be lower than the base of the bioretention system or it must be lined. A different WSUD device may be more suitable in this situation. Guideline G11-UN-USA recommends that in areas of high water table a small stormwater wetland may be better suited then a bioretention basin. This is because plant growth may be hindered. This recommendation should therefore be considered. If a better WSUD alternative exists, it should be implemented. Lining the basin is discussed in Section 5.17. It is less desirable than an unlined bioretention basin, but may be considered.

Recommended depths of groundwater vary and are outlined:

- Seasonally high water table to be 0.61 m (2 feet) below system (G10-A-USA).
- Water table to be 1.83 m (6 feet) below ground level (G12-A-USA).
- Seasonally high water table to be 1.52 m (5 feet) below ground level (G13-A-USA).

As the depth of the system itself may vary, groundwater depth requirements are better described relative to the base of system rather than the surface level. 'Best practice' design may be to recommend that the seasonally high water table is to be 0.61 m (2 feet) below than base of the bioretention basin.

5.19. Bypass system requirements and design procedure

A bypass system is required as part of a bioretention basin design. This is to capture and transport high flows around the basin and applies to storms greater than the design storm for the treatment system. This ensures an afflux is not created on the adjacent street surface adversely affecting traffic flow (if the basin is adjacent to a roadway) and provides protection of vegetation from scour (Melbourne Water 2005). It also acts to prevent scour of filter media (Shire of Augusta, Margeret River 2006) and erosion of surrounding soils due to uncontrolled overflow (North Carolina State University, Stormwater Engineering Group 2001).

The level of the bypass system inlet controls the ponding depth in the bioretention basin (Brisbane City Council 2005a).

The bypass system requirements presented in the various publications reviewed are summarised in Table 5.19.1.

Table 5.19.1 Bypass system requirements

G1-A-AUS	Grated pit: Broad-crested weir equation (free flow conditions) and orifice equation (drowned conditions) are used to check grated pit flow capacity. The larger flow of the two is adopted. Invert to be at least 100 mm below street gutter invert. Side-entry pit (downstream of basin inlet): Usual method for sizing street drainage side-entry pits is used. Purpose: to ensure a minor flood does not cause an afflux in street surface drainage flow, does not affect traffic flow and does not pass through too much vegetation.
G2-A-AUS	Grated pit: Broad-crested weir equation (free flow conditions) and orifice equation (drowned conditions) with 50% blockage factor are used to check grated pit flow capacity. The larger flow of the two is adopted. Invert to be at least 100 mm below street gutter invert. Side-entry pit (downstream of basin inlet): Usual method for sizing street drainage side-entry pits is used. Purpose: To ensure a minor flood does not cause an afflux in street surface drainage flow. Other notes: Pit crest to be above surface of filter media. Minimum 100 mm head over overflow pit required to facilitate discharge. Invert of pit to be minimum 100 mm below gutter invert.
G3-A-AUS	Overflow pit required.
G4-A-AUS	Grated pit: Broad-crested weir equation (free flow conditions) and orifice equation (drowned conditions) with 50% blockage factor are used to check grated pit flow capacity. The larger flow of the two is adopted. Minimum of 100 mm head over the overflow pit. Overflow pit to be up to 0.3 m above filter media surface. Overflow pit to be placed near inflow zone (to prevent high flows over filter media). Dome type grates are preferred. A high flow bypass is provided for storms greater than the design storm. A weir is provided for overflow using the weir flow equation.
G6-A-AUS	Grated pit: Broad-crested weir equation (free flow conditions) and orifice equation (drowned conditions) with 50% blockage factor are used to check grated pit flow capacity. The larger flow of the two is adopted. Minimum of 50 mm head over the overflow pit. Overflow pit to be up to 0.3 m above filter media surface. Overflow pit to be placed near inflow zone (to prevent high flows over filter media). Dome type grates are preferred. Inlet to bypass system must not suffer blockage, flow conveyance issues or public safety issues.
G7-A-AUS	Grated pit: Broad-crested weir equation (free flow conditions) and orifice equation (drowned conditions) with 50% blockage factor are used to check grated pit flow capacity. The larger flow of the two is adopted.
G8-A-AUS	Overflow pit to be placed near inflow zone (to prevent high flows over filter media).
G10-A-USA	Outlet to be provided if there is no safe overflow path.
G11-UN-USA	If surrounds are virgin or have unaltered soil with turf, overflow may leave the system overland at several locations. If the surrounds of the system are disturbed during construction, the soil is likely to erode if overflow is allowed. A designated overflow can be incorporated with rock or turf reinforcement mats.

	In commercial or industrial settings or in clay soils a vertical overflow pipe or drop box is installed with the top at the height of proposed ponding. It can be placed in the middle of the system.
G13-A-USA	Weir overflow: Broad-crested weir equation. Orifice overflow: Orifice equation. Pipe: Manning's equation. Overflow to be discharged into the conventional stormwater system.

The options for a bypass system presented in the publications reviewed are a grated pit or other outlet pit (in or adjacent to the basin), a side-entry pit (in the roadway downstream of the basin inlet), or a designated overland overflow.

Only guideline G11-UN-USA recommends an overland overflow. These may be unprotected overflows at several locations if the surrounds are undisturbed and turfed, but are to be protected with rock or turf reinforcement mats if the surrounds are disturbed and likely to erode. As only one guideline of ten recommends this option, it is not considered 'best practice' based on consensus.

Most guidelines recommend a grated pit or outlet pit of some kind. The pit is connected to a piped outlet to the constructed stormwater system. Sizing of the pit is undertaken using the broad-crested weir equation and the orifice equation with 50 % blockage factor. The broad-crested weir equation sizes the pit in free flow conditions, where it would behave as a weir of length equal to the perimeter of the pit. The orifice equation is used to determine if the grate can account for the flow capacity required under submerged conditions. A 50 % blockage factor is used to account for any blockages that may exist in the grate. These may include litter, vegetation overhang, leaf litter and mulch. The pit used is to be the larger of the two found using these methods. Both of these equations are published in engineering manuals such as Haestad Methods (2007) and are suitable for their specified purposes in this case. This type of bypass system and method of sizing is therefore adopted as 'best practice.'

Two of the guidelines recommend an alternative to a grated pit for roadside bioretention basins. A side-entry pit downstream of the basin can act as a bypass system directly into the usual constructed stormwater network. A roadside bioretention basin would have an inlet through a depressed section of kerb. Upon filling up to the inlet level in a storm greater than that which the system is designed to take, the water would overflow back into the kerb and channel and be conveyed by gravity to the downstream side-entry pit. This seems a reasonable alternative to a grated pit in the system and would save cost if a side-entry pit already exists nearby to a new basin. Vegetation and filter media scour would still be avoided as well as erosion of surrounding soil. The side-entry pit is designed using the usual method employed by the local authority in charge of the stormwater network. It therefore should not pose problems for traffic flow in a storm.

A grated pit or a side-entry pit connected to the constructed stormwater system is therefore considered the 'best practice' design options for a bioretention basin bypass system. A side-entry pit bypass system is suitable for roadside bioretention basins where a side-entry pit exists downstream of the basin.

Other requirements identified as 'best practice' based on guideline consensus for a grated pit bypass system include:

- Pit crest to be above filter media at the height of proposed ponding;
- Invert of pit to be minimum 100 mm below bioretention basin inlet invert (to allow for head over grated pit to facilitate discharge);
- Pit to be placed near inflow zone (to minimise scour over system); and
- Pit to discharge into conventional stormwater system.

For all bypass systems:

- The inlet system is not to suffer blockage.
- It should not cause conveyance or public safety issues.

5.20. Inlet design procedure

If a bioretention basin is located adjacent to a kerbed roadway or paved area (such as a car park), the inlet to the system may be a depressed length of kerb. Some guidelines offer requirements for the design of these inlets. A summary is provided in Table 5.20.1.

Table 5.20.1 Kerb inlet design requirements

G1-A-AUS	Broad-crested weir equation is used to design the kerb opening width at entrance to basin.
G2-A-AUS	Broad-crested weir equation is used to design the kerb opening width at entrance to basin. For small basins, where there is no pretreatment, care must be taken to ensure litter and debris is removed at inlet.
G4-A-AUS	Broad-crested weir equation is used to design the kerb opening width at entrance to basin.
G6-A-AUS	Broad-crested weir equation is used to design the kerb opening width at entrance to basin.
G11-UN-USA	Leave a 51 mm to 76 mm (2 inch to 3 inch) drop from edge of pavement to surface of rain garden (eventual plant growth may otherwise cause a damming effect at the inlet).
G13-A-USA	Slotted kerb or kerb cuts.

Guideline G11-UN-USA recommends a drop of between 51 mm to 76 mm (2 inches to 3 inches) between edge of pavement and basin surface. This may conflict with previously discussed ponding depth requirements and/or bypass system requirements and is concluded to not be ‘best practice.’

By consensus, the broad-crested weir equation is to be used to design the kerb opening width at the inlet of the bioretention basin where it is adjacent to a kerbed pavement. Slotted kerbs or kerb cuts may be used as long as they meet capacity requirements.

5.21. Traffic lane flow widths checking procedure

Some guidelines recommend a check be performed on bioretention basins adjacent to roadways to ensure that flow width in the road will not interfere with traffic in a storm greater than that for which the basin is designed to cater. Excessive stormwater spread across roadways can be hazardous to traffic. It can cause hydroplaning of vehicles and loss of visibility due to spray (Haestad Methods 2007). Guideline requirements are summarised in Table 5.21.1.

Table 5.21.1 Traffic lane flow width checking procedure recommendations

G1-A-AUS	Manning's equation is used to check flow width on road at entry to basin to avoid interference with traffic in a minor storm.
G2-A-AUS	Manning's equation is used to check flow width on road at entry to basin to avoid interference with traffic in a minor storm. Flow spread across roadway must be preserved in accordance with relevant standards.
G4-A-AUS	Manning's equation is used to check flow width on road at entry to basin to avoid interference with traffic in a minor storm.
G6-A-AUS	Manning's equation or Izzard's equation is used to check flow width on road at entry to basin to avoid interference with traffic in a minor storm. Flow must not exceed the lower of top of kerb or road crest to be acceptable.

Manning's equation is a well-known engineering equation to use for this purpose. It is detailed in many engineering manuals including Haestad Methods (2007). Izzard's equation is also generally used for this purpose and is specified in engineering manuals such as University of Southern Queensland (2007). Either equation may be used in 'best practice' bioretention basin design.

Guidelines G2-A-AUS specifies flow spread requirements must be in accordance with relevant standards. Guideline G6-A-AUS specifies that the flow must not exceed the lower of top of kerb or road crest to be acceptable. University of Southern Queensland (2007) suggests that the flow spread standards vary in accordance with the function of the road and expected traffic flows. It recommends flow width be limited to 0.45 m at pedestrian crossings and bus stops and 2.5 m otherwise. For pedestrian safety, the product of flow depth at kerb invert and average flow velocity in the kerb is generally to be less than 0.4 m^2/s or less than 0.6 m^2/s for a major storm. The designer may need to check with the relevant road authority as to their standards regarding flow spread allowances in roadways.

5.22. Inlet scour requirements

Scour can occur at the inlet to a bioretention basin (Melbourne Water 2005) and therefore many of the guidelines reviewed have requirements to avoid it. A summary of requirements is provided in Table 5.22.1.

Table 5.22.1 Inlet scour requirements

G1-A-AUS	Rock beaching is recommended to avoid scour at inlet.
G2-A-AUS	Check flow velocities and provide scour protection.
G4-A-AUS	Rock beaching or other scour protection is required to avoid scour at inlet.
G5-A-AUS	Care must be taken to avoid scour caused by high velocity flow.
G6-A-AUS	Scour (rock) protection is required to avoid scour at inlet.
G7-A-AUS	Rock beaching or dense vegetation is required to avoid scour at inlet.
G10-A-USA	Energy dissipaters such as landscape stone, surge stone, rip-rap or gabion mattresses can be used.
G11-UN-USA	Rock beaching and a level spreader (which turns water flow into sheet flow) is required to avoid scour at inlet. If system is receiving concentrated flow from a large catchment (at least 1 acre) stilling areas may be required. If flow is not greater than 0.30 m/s or 0.61 m/s (1 or 2 feet per second), erosion is unlikely.
G12-A-USA	Site must be graded so as to minimise erosion from sheet flow.
G13-A-USA	Slotted kerb or kerb cuts are used as an inlet. These slow the velocity of the runoff and evenly distribute it along the length of the bioretention system.

Guideline G11-UN-USA suggests that erosion at inlet is unlikely unless flow is greater than 0.61 m/s (2 feet per second). Guideline G2-A-AUS suggests flow velocities should be checked. Regardless of the results, both guidelines, along with nine others recommend scour protection at the inlet. It is therefore 'best practice' to include scour protection at the inlet to a bioretention basin. Rock beaching is the most recommended solution. Others suggested include:

- Dense vegetation;
- Energy dissipators such as landscape stone, surge stone, rip-rap or gabion mattress;
- Rock beaching and a level spreader;

- Stilling areas (if catchment is large and flow is concentrated);

- Slotted kerbs or kerb cuts as inlets (because they slow and evenly distribute flow into bioretention basin); and

- Site to be graded to minimise erosion from sheet flow.

Rock beaching is recommended based on consensus, but no reason is presented as to why the designer cannot include any of the other types of scour protection mentioned as long as it serves to adequately protect the inlet from scour.

5.23. Scour across vegetation layer checking procedure

Most of the guidelines reviewed require vegetation scour checks be performed and maximum flow velocities across vegetation be observed. A summary of there requirements is presented in Table 5.23.1.

Table 5.23.1 Scour across vegetation layer recommended checking procedures

<table>
<tr><td>G1-A-AUS</td><td>Flow velocity checks are performed: Flow is divided by cross sectional area of ponding at maximum depth.

Acceptable parameters:
Less than 0.5 m/s for 5 year ARI;
and, less than 1.0 m/s for 100 year ARI.</td></tr>
<tr><td>G2-A-AUS</td><td>Flow velocity checks are performed: Flow is divided by cross sectional area of ponding at maximum depth. If inlet to basin controls flow, then this is used as a maximum to check velocities.

Acceptable parameters:
Less than 0.5 m/s for 2 year ARI;
and, less than 2.0 m/s for 50 year ARI.</td></tr>
<tr><td>G3-A-AUS</td><td>Flow velocity checks are performed.

Acceptable parameters:
To be less than those outlined in Table DS4.1 (NSW Department of Housing cited in URS Australia Pty Ltd 2004) (reproduced below) depending on the erodibility of the soil and the type of ground cover.

<table>
<tr><th rowspan="3">Ground cover</th><th colspan="3">Maximum velocity (m/s)</th></tr>
<tr><th colspan="3">Soil erodability</th></tr>
<tr><th>Low</th><th>Moderate</th><th>High</th></tr>
<tr><td>Mat or sword grasses with UV stabilised mesh</td><td>3.0</td><td>2.7</td><td>2.4</td></tr>
<tr><td>Kikuyu grass</td><td>2.5</td><td>2.2</td><td>1.9</td></tr>
<tr><td>Couch grass, carpet grass, rhodes grass, sword forming grasses</td><td>2.0</td><td>1.8</td><td>1.4</td></tr>
<tr><td>Other improved perennials</td><td>1.6</td><td>1.3</td><td>0.9</td></tr>
<tr><td>Tussock grasses</td><td>1.3</td><td>0.9</td><td>0.5</td></tr>
</table>

(NSW Department of Housing cited in URS Australia Pty Ltd 2004)</td></tr>
<tr><td>G4-A-AUS</td><td>Flow velocity checks are performed: Flow is divided by cross sectional area of ponding at maximum depth. If basin controls flow, then this is used as a maximum to check velocities and less than 0.5 m/s is acceptable.

Acceptable parameters:
Less than 0.5 m/s for 2 to 10 year ARI;
and, less than 2.0 m/s for 100 year ARI.</td></tr>
<tr><td>G5-A-AUS</td><td>Care must be taken to avoid damage to vegetation by high velocity flow.</td></tr>
<tr><td>G6-A-AUS</td><td>Flow velocity checks are performed: Flow is divided by cross sectional area of ponding at maximum depth. If basin controls flow, then this is used as a maximum to check velocities and less than 0.5 m/s is acceptable.

Acceptable parameters:
Less than 0.5 m/s for 2 to 10 year ARI preferred;
and, less than 1.5 m/s for 50 to 100 year ARI preferred.</td></tr>
<tr><td>G12-A-USA</td><td>Site must be graded so as to minimise erosion from sheet flow.</td></tr>
</table>

Based on consensus, a flow velocity check shall be performed for flow over the vegetated area of a bioretention basin. Flow velocity is calculated by dividing flow by cross sectional area of ponding at maximum depth.

Acceptable flow velocities are less than 0.5 m/s for 2 to 10 year ARI storm and (conservatively) less than 1.0 m/s for 100 year ARI storm. Some guidelines in Queensland allow 1.5 m/s or 2.0 m/s for 100 year ARI storm. The velocity allowed may depend on the location due to the variation in size of 100 year ARI storm. Vegetation should still be protected from scour, however. URS Australia Pty Ltd has more specific allowances for various ground covers (refer to Table 5.23.2). Allowances should be in accordance with this table for the specified ground covers.

Table 5.23.2 Maximum velocity allowed over vegetation in bioretention basin

Ground cover	Maximum velocity (m/s)		
	Soil erodability		
	Low	Moderate	High
Mat or sword grasses with UV stabilised mesh	3.0	2.7	2.4
Kikuyu grass	2.5	2.2	1.9
Couch grass, carpet grass, rhodes grass, sword forming grasses	2.0	1.8	1.4
Other improved perennials	1.6	1.3	0.9
Tussock grasses	1.3	0.9	0.5

(NSW Department of Housing cited in URS Australia Pty Ltd 2004)

Chapter 6 Best practice design guidelines

The various bioretention basin design publications reviewed are critically evaluated and compared. The 'best practice' design guidelines are presented in this section.

A bioretention basin is a storm runoff treatment and detention system that includes vegetation, filter media, a drainage layer, underdrains, scour protection and a bypass system (as a minimum). It removes pollutants such as TSS, TP, TN, sediment, O/G and metals by means such as filtration, absorption and biological uptake (and other means). Figure 6.1 outlines some of the various design elements and requirements on a typical section of a bioretention basin.

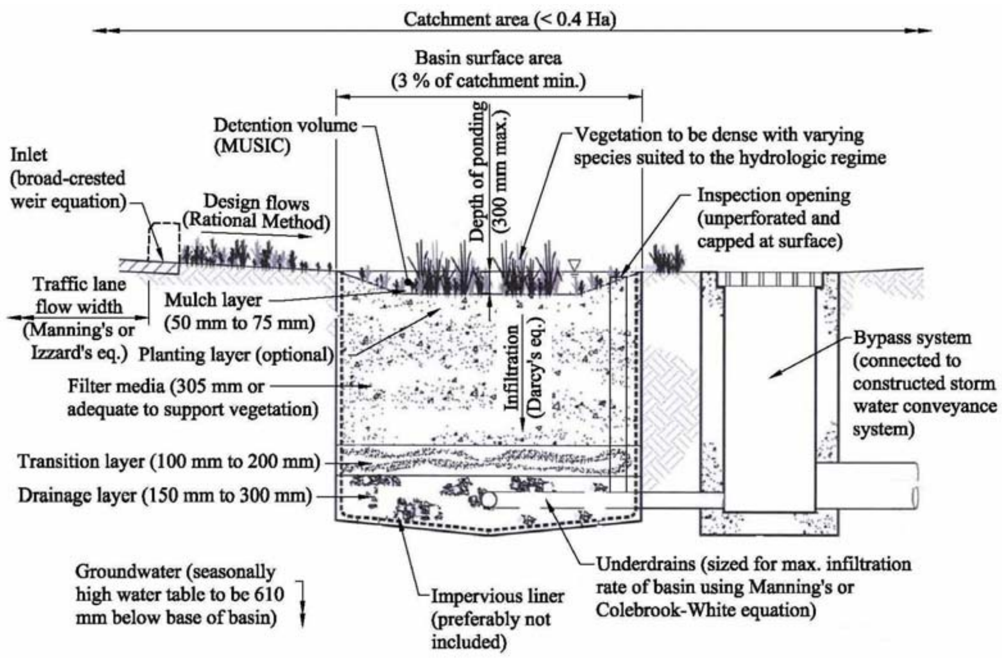

Figure 6.1 Typical section of a bioretention basin showing design elements

The concluded 'best practice' design guidelines resemble some of the design guidelines reviewed, in particular G4-A-AUS and G6-A-AUS. G1-A-AUS and G2-A-AUS are also very similar to the concluded 'best practice' design guidelines. This gives the findings some merit.

6.1. Catchment area requirements

Maximum catchment area for one bioretention basin is 0.4 hectares (1.0 acre).

6.2. Design flows establishment procedure

Design flows should be found using the Rational Method, unless the catchment is greater than 50 ha. Then a runoff routing model should be used. This establishes the treatable volume for the bioretention basin. The design storm used will depend on the requirements of the local authority. It may vary from a 1, 2, 5 or 10 year ARI storm. Variations may be found in temperate and sub-tropical areas due to the differences in sizes of storms in these areas.

6.3. Detention volume establishment procedure

A modelling approach (such as MUSIC) should be used for determining the dimensions of a bioretention basin due to its variable and complex nature (ed. Wong 2006). Modelling is able to consider local rainfall data, individual catchment characteristics, runoff volume, peak runoff flow, pollutant removal, filter media characteristics and basin dimensions.

6.4. Depth of ponding requirements

The treatable volume calculated must be contained in the ponding depth and the surface area of the bioretention basin.

The maximum ponding depth is 300 mm

The time of dewatering must be suitable for appropriate vegetation sustenance and to limit the chance of mosquito and other insects breeding. Maximum dewatering time appropriate to prevent mosquito and other insects breeding is 3 days (North Carolina State University, Stormwater Engineering Group 2001). Maximum dewatering time to suit vegetation depends on the vegetation reviewed. This must be a consideration in the design of ponding depth.

Modelling is a suitable means for determining the dewatering time and the suitable ponding depth. MUSIC may be used.

6.5. Sizing of basin surface area

The bioretention basin surface area is to be a minimum size of 3 % of the catchment area or a minimum size of 12.2 m by 4.6 m, whichever is the larger. Size should, however, be maximised to improve performance (Bratieres et al 2008).

Surface area is directly related to treatable volume and ponding depth. It can either be calculated from these or found using modelling. Modelling is preferred due to it being more suitable for such a variable and complex system.

Alternatively, the following equation may be used,

$$A = \frac{V_T \times d}{\left(k \times \left(h + d\right) \times t\right)},$$

where,

A = minimum surface area of the system (m^2)

V_T = Treatment Volume (m^3)

k = filter media hydraulic conductivity (m/day)

t = filtration time (days)

h = average depth of water above the filter media (i.e. half d_{max} depth) and

d = filter media depth (m)

For initial sizing, use the following data,

t = 1 day minimum, 2 days maximum

k = (can use approx. 1 m/day assuming a sandy organic soil and some clogging)

h = 0.075 m

d = 1 m nominal

(URS Australia Pty Ltd 2004)

6.6. Pretreatment measures

Small bioretention basins, such as those located in a roadside, do not generally require pretreatment. Other bioretention basins may need pretreatment depending on the expected coarse sediment load from the catchment. A mulch layer in the bioretention basin may prevent sediment clogging the filter media if pretreatment is not used (Prince George's County, Maryland 2002). Modelling in MUSIC may be used to determine if the bioretention basin requires pretreatment or if it is capable of achieving acceptable pollutant removal levels without it.

Recommended pretreament devices include the inclusion of a grassed buffer strip (with or without a preceding gravel verge), a grass swale or, for large bioretention basins, a forebay.

A grassed buffer strip should be a minimum of 0.91 m (3 feet) wide. If a gravel verge is implemented, it should be upstream of the grassed buffer strip. 200 mm is a suitable width. This pretreatment helps to prevent scour of the bioretention basin surface as well as trapping pollutants (Hunt & Lord 2006). Figure 6.6.1 shows a photograph of a grassed buffer strip with a gravel verge.

Figure 6.6.1 Photograph of a grassed buffer strip with a gravel verge

(Hunt & Lord 2006)

Grassed swales remove most suspended sediment in the first 3.05 m to 4.57 m (10 feet to 15 feet). The required minimum length depends on the characteristics of the catchment and the slope, width and cover of the swale (Hunt & Lord 2006). Figure 6.6.2 shows a photograph of a grassed swale.

Figure 6.6.2 Photograph of a grassed swale

(Hunt & Lord 2006)

A forebay may be used for pretreatment for large bioretention basins (Hunt & Lord 2006). It is a depressed bay with an outlet to the bioretention basin. It should be large enough to still runoff before it enters the bioretention basin. Depth should be between 5.49 m and 9.14 m (18 inches and 30 inches). The forebay must be isolated from underdrains to avoid untreated runoff entering them. Lining may be utilised for this purpose (Hunt & Lord 2006). Figure 6.6.3 shows a photograph of a forebay.

Figure 6.6.3 Photograph of a forebay

(Hunt & Lord 2006)

6.7. Vegetation specification

Vegetation shall:

- be tolerant of the hydrologic regime (short periods of inundation and long severe dry periods);

- suit the extended detention depth;

- be dense enough to prevent preferred flow paths from developing, scour and re-suspension of sediments;

- cover entire surface of bioretention media;

- be able to withstand design flows;

- suit the region, climate, soil type (freely draining filter media) and other abiotic elements;

- be selected considering aesthetics, community character and landscaping (a landscape architect should be consulted);

- have ecological value and provide habitat;

- be suitable for crime prevention and traffic visibility;

- be selected considering maintenance requirements;

- be appropriate for pollutant removal;

- be appropriate for preventing filter media blockages;

- be native species (preferred) (exotic species may also be used);

- be species that will not become noxious weeds;

- be protected from invasion of weeds;
- have extensive root systems, preferably with large diameter roots, but not such that will interfere with underdrains and not root-matting (or water will not be able to penetrate);
- be perennial rather than annual;
- be partially or all evergreen species;
- be a mix of various species (to maximise pollutants removed and decrease susceptibility to disease);
- be a mix of ground covers, trees and shrubs (to create a microclimate and discourage weeds);
- not include turf; and
- not include trees and shrubs near the inlet.

Many guidelines include a list of recommended plant species. The designer may consult an appropriate guideline for their area.

Vegetation may aid in removal of nutrients, with some species performing better than others. Cares, C. appressa and M. eticifolia perform well in nutrient removal (S6-UM-AUS). Juncus performs well also, but is not useful in removing lead. Melaleuca is effective in removing some pollutants (S7-UM-AUS). The designer may consider the use of these plants to enhance nutrient removal.

6.8. Mulch layer design procedure

Inclusion of a mulch layer is recommended. It is optional, but beneficial. Depth of mulch should be around 50 mm to 75 mm. It is to be made of shredded hardwood (or double-shredded), hardwood chips or pine straw. Mounding around plant trunks should be avoided. Mulch should have high permeability (d_{10} > 0.1 mm) and uniformity (a d_{60} / d_{10} value less than 4).

6.9. Planting layer design procedure

The provision of a planting layer is optional. It is only required if the filter media is not suitable for sustaining vegetation.

If necessary, the planting layer should be between around 75 mm and 300 mm. It should ideally be sandy loam, loamy sand or loam with a clay content less than 5 %. Sand content should be 50 % to 60 %. Leaf compost should be included at 20 % to 30 % and 20 % to 30 % should be topsoil. The hydraulic permeability of the planting layer must be equal to or more than that of the filter media. It should meet the requirements of the vegetation and be free from noxious weeds.

6.10. Filter media design procedure

6.10.1 Hydraulic conductivity

Consideration of the interaction between hydraulic conductivity, filter area and ponding depth is crucial (Le Coustumer et al 2008). If hydraulic conductivity is low, a bioretention basin may be able to compensate by having a larger filter area or a deeper ponding depth. The system may need to be modelled to determine the required balance between these elements. Exfiltration and ability to support plant life are other considerations as well as those mentioned above. The recommended hydraulic conductivity is within the range of 25 mm/hr to 180 mm/hr. The maximum is 500 mm/hr. The designer should note that filter media with a hydraulic conductivity near the maximum may have difficulty sustaining vegetation.

The designer is to ensure the bioretention basin dewaters in suitable time to be prepared for a subsequent storm, to prevent the reproduction of mosquitoes; and to minimise any hazard caused by ponded water in the system. The maximum dewatering time to prevent mosquito breeding is 3 days.

If the bioretention basin is to target a specific pollutant such as TSS, TN or TP, the optimum filter media hydraulic conductivities for each are:

- For TSS, the rate is to be greater than 51 mm/hr.
- For TP, the rate is to be greater than 25 mm/hr, with 51 mm/hr as the recommended rate.
- For TN removal the rate is to be 25 mm/hr.

Usually, TSS, TN and TP are all required to be removed by the system. Other factors affecting pollutant removal may need to be considered in conjunction with these guidelines when deciding the desired hydraulic conductivity required. Pre-treatment such as forebays or grass swales may reduce the TSS load before the storm runoff reaches the bioretention basin. Vegetation may be able to uptake TP and TN. All of these elements may lessen the need of the filter media to be at these suggested optimum hydraulic conductivities.

The hydraulic conductivity of the material to be used should be determined by testing.

The designer should consider, filter area, ponding depth, detention time, exfiltration rate, expected storm frequency, and target pollutant optimum rate when designing hydraulic conductivity required for filter media. Modelling using MUSIC or an equivalent program is recommended.

6.10.2 Organic content

It is preferable to have some organic content in the filter media (at least initially) as it aids in nutrient absorption and plant growth according to Department of Water and Swan River Trust (2007). Established vegetation should produce its own organic matter which is contributed to the bioretention system (Hatt, Fletcher & Deletic 2008). This organic content in a bioretention basin, however, may be applied to the system in another element, such as in the mulch or planting layer (if these elements are included). This should be considered when specifying organic content in the filter media.

If the filter media organic content is in the range of 1.5 % to 3 % a planting or mulch layer (or both) should be included in the basin to account for a higher overall organic content.

Additives that may be used to increase organic content of the filter media are:

- Vermiculite (clay used for soil conditioning) for the purpose of improving the decline of hydraulic conductivity over time.
- Red mud, or blast furnace slag and laterite or zeolite to absorb phosphorus and other inorganics.
- Woodchips for nitrogen removal as they have more longevity than sawdust.
- Newspaper or peat moss.

Target pollutant removal is a consideration in determining what to use as organic material in filter media.

The filter media organic content recommended range is 3 % to 5 % if no planting or mulch layer is included and 1.5 % to 3 % if a planting or mulch layer is included.

6.10.3 Depth requirements

A filter media depth of 305 mm (1 foot) is recommended as long as it is deep enough to support the vegetation and if a planting or mulch layer exists to aid in metal removal. Otherwise, 450 mm minimum is required. If TN is the target pollutant and no other mechanism for nitrogen removal is included, 760 mm minimum depth is recommended. A depth of 800 mm is suggested as a minimum depth for trees as long as it is verified by an expert that it is adequate for the species to be planted.

6.10.4 Planting/mulch layer inclusion

The inclusion of a planting layer means that the filter media itself does not have to be able to support vegetation and may include less organic material.

If a mulch/organic layer is included in the bioretention basin the filter media may include less organic material.

6.10.5 pH

Filter media pH should be in the range of 5.5 to 7. If denitrification is to be encouraged to aid in the removal of TN, a pH of 7 would be more suitable.

6.10.6 Salt content

Salt content should be below 0.63 dS/m.

6.10.7 Type of soil

Filter media is generally to be sandy loam or loamy sand. Other media that may be used, as long as all other filter media criteria are met, include; loam textured soil; coarse sand and sandy soil with sandy loam texture; sandy clay loam; sand; or sand/gravel mix.

Clay content should be between 3 % and 25 %. Media must be structurally stable.

Suggested sand content is between 75 % and 85 %.

Requirements relating to grading are:

- soil to be well-graded and present from the 0.075 mm to the 4.75 mm sieve (for structural purposes); and
- soil not to be dominated by small particles (for structural purposes).

6.10.8 Phosphorus content

Filter media to have a P-Index less than 40 or phosphorus content less than 100 mg/kg, whichever is the lowest. If phosphorus is a target pollutant, a maximum P-Index of 30 may be more appropriate.

P-Index can be related to Melich 3 Extractable P (M3P) in units of milligrams phosphorus per kilogram soil with the following equation,

$$M3P = \frac{1.2 \times PI}{w/v},$$

where,
PI = P-Index
and,
w/v = weight to volume ratio of soil (Cox, cited in Sharkey 2006).

6.10.9 Other requirements

Other filter media requirements are listed:

- Material must not be retardant to plant growth.
- Material must not be retardant to denitrification.
- Material must not contain fire ants or be from a fire ant restricted area.
- Surface to be horizontal.
- Material to be free from woody material over 25 mm in size.
- Material to be free from brush or noxious plant seeds.
- Material must not be susceptible to breakdown.
- Material not to contain rubbish or other deleterious material.
- Material must meet geotechnical requirements.
- Material to be placed and lightly compacted.
- Material to have cation exchange capacity (CEC) exceeding 10 (to aid in the capture and retention of phosphorus and other pollutants).
- Material to not be hydrophobic.

6.11. Transition layer design procedure

A transition layer between the filter media and the drainage layer is only required if the size differential between them is more than one order of magnitude.

The transition layer thickness is to be between 100 mm and 200 mm.

The material should be sand or coarse sand with particle size distribution based on Unimin specifications (or well-graded with minimal or no fines). An example of a typical sand/coarse sand grading based on Unimin specification is 100 % passing 1.4 mm sieve, 80 % passing 1.0 mm sieve, 44 % passing a 0.7 mm sieve and 8.4 % passing a 0.5 mm sieve (Gold Coast City Council 2007).

A permeable geotextile fabric may be used in lieu of a transition layer, however, it is more likely to clog. The minimum permittivity rate recommended is 3.06 $m^3/min/m^2$ (75 $gal/min/ft^2$). A transition layer is preferable if depth is available.

The hydraulic conductivity of the transition layer is to be greater than that of the filter media to prevent disruption to the system.

6.12. Drainage layer design procedure

The drainage layer material it to be either sand or gravel. The smallest particle size must be such that it is compatible with the slot sizes in the underdrains otherwise it may enter and clog them (Gold Coast City Council 2007). The material size differential between the drainage layer and the adjacent layer shall be no more than one order of magnitude to prevent migration of particles and clogging of the system (Department of Water and Swan River Trust 2007).

The drainage layer depth is to be between 150 mm and 300 mm. Cover over underdrains is to be 50 mm.

Other requirements are:

- Material to be free from silt and clay.
- Material to be free from deleterious matter.
- Soil must not contain fire ants or be from a fire ant restricted area.
- Material to be washed to remove fines.
- Material must meet hydraulic conductivity requirements.
- Material must meet geotechnical requirements.

6.13. Nitrogen removal zone design procedure

Results in studies undertaken into incorporation of a submerged zone are promising, but as yet inconclusive (Hsieh & Davis 2005). This design element is therefore not included.

6.14. Infiltration rate of system design procedure

Darcy's equation is to be used for calculation of the infiltration rate of the system,

$$Q_{max} = \frac{A \times k \times (h_{max} + d)}{d},$$

where,

Q_{max} = maximum outflow from the system (m^3/s)

A = surface area of the system (m^2)

k = filter media hydraulic conductivity (m/s)

h_{max} = maximum depth of water above the filter media

d = filter media depth (URS Australia Pty Ltd 2004).

6.15. Perforated underdrains design requirements

Underdrains are to be sized for maximum filtration rate of the system as a minimum.

Either Manning's equation or the Colebrook-White equation may be used to check the capacity of the underdrains. Normally the Colebrook-White equation is used for full pipes under pressure, but it can also be used when the pipe is not under pressure. This is done by assuming that the hydraulic gradient is equal to the pipe gradient in the equation (Chadwick, Morfett & Borthwick 2004).

The perforations must be checked to ensure they accommodate the maximum infiltration rate (Brisbane City Council 2005a). The sharp-edged orifice equation should be used with a blockage factor of 50 %. A check should also be performed to ensure that the perforations do not allow migration of drainage layer material into the underdrains.

Pipe size is to be 150 mm maximum.

Maximum spacing of underdrains should be 1.5 m, except where catchment is greater than 100 m^2, then spacing may be increased to 2.5 m to 3 m. Minimum grade is to be 0.5 %. Maximum grade is to be 4 %. Underdrain to have a minimum cover of 50 mm drainage material.

Pipe materials that are acceptable include polyvinyl chloride (PVC), perforated pipes such as agricultural (AG) pipes or corrugated high-density polyethylene (HDPE) pipe. The pipe surface is to be smooth to minimise surface beading.

Root barriers may need to be installed around underdrains if trees are planted.

Underdrains are not required where in-situ soil has a hydraulic conductivity greater than that of the filter media, the water table is greater than 610 mm (2 feet) below the bottom of the bioretention basin and the catchment area is less than one acre. Caution would need to be exercised however that the hydraulic conductivity of the in-situ soil remains the same and is not affected by seasonal groundwater levels. Modelling of the system may be necessary to determine the likely outcome.

Underdrains are not to be located within the groundwater zone of saturation.

6.16. Inspection requirements

An inspection opening to underdrains is to be installed. This is to be an unperforated and vertical section of pipe between the underdrains and the surface. The inspection opening is to be capped at surface.

6.17. Impervious liner requirements

It is preferable to not line bioretention basins with impervious material unless required to due to vicinity of structures, chemical composition of soils or protection of possible accidental spills is required. If adjacent soils have a hydraulic conductivity one order of magnitude higher than the filter media, liner may be used on the sides of the basin to prevent stormwater runoff bypassing the filter media and thus the main area of pollutant removal. Filter fabrics of various permeability, rather than a totally impermeable membrane, may produce the results desired in respect to preventing/minimising exfiltration, water migration control in saline soils, soil migration control, and protection of adjacent structures. The hydraulic conductivity of the filter fabric, the surrounding soil and the filter media would need to be compared to establish if there is adequate control with the selected filter fabric.

6.18. Groundwater considerations

The groundwater table should be lower than the base of the bioretention system or it must be lined. A different WSUD device may be more suitable in this situation such as a small stormwater wetland.

The seasonally high water table is to be 0.61 m (2 feet) below than base of the bioretention basin.

6.19. Bypass system requirements and design procedure

A grated pit or a side-entry pit, connected to the constructed stormwater system, is to be implemented for bioretention basin bypass. A side-entry pit bypass system is suitable for roadside bioretention basins where a side-entry pit exists downstream of the basin.

Sizing of a grated pit is to be undertaken using the broad-crested weir equation and the orifice equation with 50 % blockage factor. The broad-crested weir equation sizes the pit in free flow conditions, where it would behave as a weir of length equal to the perimeter of the pit. The orifice equation is used to determine if the grate can account for the flow capacity required under submerged conditions. A 50 % blockage factor is used to account for any blockages that may exist in the grate. The pit to be specified is to be the larger of the two found using these methods.

Other requirements for a grated pit bypass system include:

- Pit crest to be above filter media at the height of proposed ponding.
- Invert of pit to be minimum 100 mm below bioretention basin inlet invert (to allow for head over grated pit to facilitate discharge.
- Pit to be placed near inflow zone (to minimise scour over system).
- Pit to discharge into conventional stormwater system.

A side-entry pit downstream of the basin can act as a bypass system directly into the usual constructed stormwater network. A roadside bioretention basin would have an inlet through a depressed section of kerb. Upon filling up to the inlet level in a storm greater than that which the system is designed to take, the water would overflow back into the kerb and channel and be conveyed by gravity to the downstream side-entry pit. This would save cost if a side-entry pit already exists nearby to a new basin. The side-entry pit is designed using the usual method employed by the local authority in charge of the stormwater network.

The inlet system is not to suffer blockage. It should not cause conveyance or public safety issues.

6.20. Inlet design procedure

The broad-crested weir equation is to be used to design the kerb opening width at the inlet of the bioretention basin where it is adjacent to a kerbed pavement. Slotted kerbs or kerb cuts may be used as long as they meet capacity requirements.

6.21. Traffic lane flow widths checking procedure

Either Manning's equation or Izzard's equation may be used to check the traffic lane flow widths for a bioretention basin adjacent to a roadway.

The designer may need to check with the relevant road authority as to their standards regarding flow spread allowances in roadways. Allowable widths may vary depending on the traffic flow on the road. For pedestrian safety, the product of flow depth at kerb invert and average flow velocity in the kerb is generally to be less than 0.4 m^2/s or less than 0.6 m^2/s for a major storm.

6.22. Inlet scour requirements

Scour protection is to be included at the inlet to a bioretention basin. Rock beaching is the most recommended solution. Others suggested include:

- dense vegetation;
- energy dissipators such as landscape stone, surge stone, rip-rap or gabion mattress;
- rock beaching and a level spreader;
- stilling areas (if catchment is large and flow is concentrated);
- slotted kerbs or kerb cuts as inlets (because they slow and evenly distribute flow into bioretention basin); and
- site to be graded to minimise erosion from sheet flow.

6.23. Scour across vegetation layer checking procedure

A flow velocity check shall be performed for flow over the vegetated area of a bioretention basin. Flow velocity is calculated by dividing flow by cross sectional area of ponding at maximum depth.

Acceptable flow velocities are less than 0.5 m/s for 2 to 10 year ARI storm and less than 1.0 m/s for 100 year ARI storm. Some guidelines in Queensland allow 1.5 m/s or 2.0 m/s for 100 year ARI storm. The velocity allowed may depend on the location due to the variation in size of 100 year ARI storm. More specific allowances for various ground covers are outlined in Table 6.23.1). Allowances should be in accordance with this table for the specified vegetation.

Table 6.23.1 Maximum velocity allowed over vegetation in bioretention basin

Ground cover	Maximum velocity (m/s)		
	Soil erodability		
	Low	Moderate	High
Mat or sword grasses with UV stabilised mesh	3.0	2.7	2.4
Kikuyu grass	2.5	2.2	1.9
Couch grass, carpet grass, rhodes grass, sword forming grasses	2.0	1.8	1.4
Other improved perennials	1.6	1.3	0.9
Tussock grasses	1.3	0.9	0.5

(NSW Department of Housing cited in URS Australia)

Chapter 7 Limitations, recommendations and conclusions

7.1. Study limitations

Establishing a best practice design guideline for bioretention basin design based on the procedure used may not be the optimum method. Dividing the design procedure into elements makes analysis easier, but not considering the procedure/system as a whole may leave some conclusions of questionable reliability. The method of analysis assumes that the optimum design procedure for the system is the same as the optimum design procedure for each separate element put together. This assumption could prove to be incorrect. Many of the requirements for design elements do, however, consider the attributes of other design elements. For example, the transition layer media requirements have to be suitable when compared to the adjacent layers to prevent media migration, the basin dimensions are considered together to treat the required volume, the underdrains consider the infiltration rate and the migration of drainage layer particles, etc. The elements are therefore not entirely considered individually in this study. The concluded 'best practice' design guidelines resemble some of the design guidelines reviewed, alleviating the suspicion that the methodology is ineffective.

Due to time constraints, this study focuses on publications from Australia and the USA only. Publications from other countries around the world do exist and may have presented valuable information. The publications total twenty-eight, which also limits the amount of information reviewed.

Some of the studies reviewed here are laboratory studies. Hatt, Fletcher & Deletic (2008) explain that laboratory scale columns may not be reflective of actual field conditions but are, however, valuable for improving our understanding of the system's processes. Testing of the findings needs to be conducted in the field. It therefore cannot be concluded that the findings in this study, based on laboratory studies, is entirely accurate.

7.2. Recommendations for further research

Research on the recommended 'best practice' design guidelines is recommended to assess its reliability. Although it does align reasonably well in most design elements with some of the existing guidelines, field testing is recommended to assess its effectiveness as a whole system. This study is a desk-top study only. Further research would give the 'best practice' design guideline more merit.

7.2.1 Vegetation

Five of the studies reviewed found that vegetation aids in removing nutrients, with some species performing better than others. Further research is required to see how these plants perform when planted together (S7-UM-AUS) and to identify morphological or physiological reasons as to why some plants perform better than others (S6-UM-AUS).

7.2.2 Filter media

Hydraulic conductivity

A study by the Facility for Advancing Water Biofiltration (2008a) reveals that the hydraulic conductivity of a bioretention basin declines as the basin becomes established. It then increases again due to plant activity. This needs to be verified with further studies.

Organic content

In several guidelines/studies it is noted that different organic contents and/or materials are suitable for the removal of nitrogen and phosphorus. Study S9-UN-USA states that if nitrogen removal is required, the organic content in the filter media is to be suitable for this purpose, but does not state what "suitable" is. For phosphorus removal optimisation, S6-UM-AUS recommends a sandy loam with no additional organic matter added as organic matter depletes phosphorus removal capabilities. This does not give very sound guidelines as to the actual organic content required for optimal phosphorus removal, but implies that it should be minimised. Study S4-UM-AUS also stated that sandy loam with a low organic content is preferred as it removes TSS, TP and heavy metals better than sand filters. This is still to vague to put an exact figure on organic content to optimise phosphorus removal. Further research is recommended.

Guidelines G4-A-AUS and G6-A-AUS also recommend that organic carbon content to be less than 5 %. In both of these guidelines, overall organic content is to be less than 10 %. Half can be organic carbon. Other guidelines and studies reviewed do not mention organic carbon content. Further studies are recommended to verify the optimum organic carbon content for filter media and to understand its importance.

Woodchips are suitable for nitrogen removal and red mud, or blast furnace slag and laterite or zeolite are suitable for phosphorus and other inorganics' removal. Research may be useful into whether a mixture of these can be used to cover a broad range of pollutant removal and what the optimum combination of these materials is.

pH

No studies reviewed outlined optimal pH. More research is recommended in this area.

Salt content

Salt content should be below 0.63 dS/m. Some studies into this would be beneficial as not many of the publications reviewed recommended a maximum salt content.

Type of soil

Clay content should be between 3 % and 25 % according to the publications reviewed. This is quite a wide range. Further research into optimum clay content would be beneficial.

The optimum sand content for filter media is unknown. Further research may need to be conducted in this area.

It is unclear whether the addition of perlite or vermiculite is necessary to maintain hydraulic conductivity of the filter media. As mentioned previously, a study by the Facility for Advancing Water Biofiltration (2008a) reveals that the hydraulic conductivity of a bioretention basin declines as the basin becomes established. It then increases again due to plant activity. Refer to Figure 5.10.3. On this basis these suggested additives may be unnecessary. Further research is suggested to investigate the benefits of these additives.

7.2.3 Nitrogen removal zone

Studies have been undertaken into incorporation of a submerged zone for nitrogen removal. The results are thus far inconclusive (Hsieh & Davis 2005). Further research is required to determine the specifications for such a zone, its effectiveness in removal of nitrogen and whether it is in fact necessary.

7.3. Conclusions

Publications on the design of bioretention basins were reviewed, compared and critically evaluated and a 'best practice' design guideline has been concluded. An appropriate naming convention for bioretention basins was also found, based on consensus between publications and a review of literature on the naming convention of these systems. Some need for further research has become evident.

Many different terms exist that describe what we refer to in this study as a bioretention basin. An appropriate naming convention was explored and it was concluded that 'bioretention' is the most appropriate term to describe these systems. The word 'bioretention' may be followed by 'basin', 'system', 'cell', 'area' or 'facility'. These descriptions are all suitable to describe the same system, a bioretention basin.

Twenty-eight publications from Australia and the USA on the design of bioretention basins were reviewed. The design of a bioretention basin was broken down into many separate design elements. For each design element, comparison and critical evaluation of the publications was conducted. A conclusion on 'best practice' design was achieved for each of these elements. Assembling each design element together, a 'best practice' design guideline was concluded for the whole system.

The concluded 'best practice' design guideline resembles some existing design guidelines. This gives it some merit, although field testing is recommended to assess its performance as a complete system.

During this study, information on some bioretention basin design elements was found to be vague or conflicting between different publications. Therefore, some recommendations for further research became evident.

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Appendix A

Appendix A

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **Selina BOSKOVIC**

TOPIC: WATER SENSITIVE URBAN DESIGN – RUNOFF TREATMENT BEST PRACTICE USING RAIN GARDENS

SUPERVISORS: Dr. Ian Brodie

SPONSORSHIP: -

PROJECT AIM: To review and compare existing design guidelines for runoff treatment using rain gardens and establish a best practice solution for runoff treatment in a roadway.

PROGRAMME: **(Issue A, 10th March 2008)**

1. Research existing design guidelines for rain gardens used in water sensitive urban design.
2. Undertake a literature review of rain gardens.
3. Compare the different design guidelines to identify common design elements.
4. Critically evaluate the different design elements.
5. Establish a best practice treatment for a new roadway using a rain garden.
6. Submit an academic dissertation including
    - An overview of water sensitive urban design and stormwater treatment measures.
    - An overview of the different design guidelines, comparing their basis.
    - A critical evaluation of the different design guidelines.
    - A definition of a rain garden.
    - A best practice treatment for a new roadway using a rain garden.
    - Recommendations for further research.

As time permits:

7. Establish a standard treatment for a new roadway applicable to the Mildura, Victoria area using modelling.
8. Perform a risk assessment on the best practice treatment for a new roadway established.
9. Perform a cost analysis on various alternatives for the best practice solution for a new roadway if necessary in the evaluation process.

AGREED: ______ (Student) ______, ______ (Supervisors)
Date: 12/03/ 2008 Date: / / 2008 Date: 27/07/ 2008

Examiner/ Co-examiner: ______

Appendix B

Table B.1 Bioretention basin vegetation requirements in guidelines reviewed

G1-A-AUS	Vegetation shall: Be able to tolerate the hydrologic regime (short periods of inundation and longer severe dry periods). Suit the extended detention depth. Be either erect or prostrate (for groundcover plants). If prostrate, be low mat-forming stoloniferous or rhizomatous (typically) (e.g. Couch Grass, Cynodon dactylon, Phyla nodiflora, Dichondra repens). If erect, typically rhizomatous with simple vertical leaves (e.g. Rush, Juncus spp.; Carex spp.). Be spreading rather than clumped (preferred). Be perennial rather than annual. Have deep fibrous roots. Form an understorey if also grown with shrubs and trees. Be aesthetically pleasing and functional. Be either a single species or mixed. Meet landscape objectives, biodiversity objectives, conservation objectives and have ecological value. (Native plants are well adapted to local conditions and attract regional fauna). Suit the region, climate, soil type and other abiotic factors. Be species that will not become weeds. Be dense vegetation to a height equal to the extended detention depth. Be such that 70 % to 80 % cover is achieved after two growing seasons. Be dense ground cover vegetation with or without trees and shrubs used for aesthetics. Such that plant roots should not interfere with underdrains. List of suitable plants provided but not exhaustive. List outlines requirements for effective growth of vegetation, but does not mention pollutant removal characteristics. Consultation with landscape architect recommended.
G2-A-AUS	Vegetation shall: Be able to tolerate the hydrologic regime (short periods of inundation and longer severe dry periods). Suit the extended detention depth. Be spreading rather than clumped (preferred). Be perennial rather than annual. Have deep fibrous roots. Be turf, prostrate or tufted (groundcover plants). If prostrate, be low mat-forming stoloniferous or rhizomatous (typically) If tufted, typically rhizomatous with simple vertical leaves. Meet landscape objectives, biodiversity objectives, conservation objectives, be aesthetically pleasing and have ecological value. Suit the region, climate, soil type and other abiotic factors. Be dense vegetation to a height equal to the extended detention depth. Be such that 70 % to 80 % cover is achieved after two growing seasons. Must be suitable for growth in the filter media. Vegetation must be appropriate for sediment removal, erosion protection, stormwater treatment and preventing filter media blockages. Vegetation is to cover entire surface of filter media. Dense ground cover vegetation is essential. Must be dense enough to prevent preferred flow paths developing, scour and resuspension of pollutants. The greater the density and height (enhances sedimentation and adsorption of pollutants) of vegetation, the better the storm runoff treatment. It must integrate with its surrounding environment. It must meet requirements of crime prevention and traffic visibility. It must serve purposes such as shade, amenity, character, buffers, glare reduction, place making and habitat. It must be able to withstand minor and major design flows.

	List of species provided including species' height, shade tolerance, salt tolerance and soil moisture requirements.. Consult with landscape architect (recommended).
G3-A-AUS	List of species provided,
G4-A-AUS	Vegetation shall: Cover the whole filter media surface; Be able to withstand design flows; And, be dense enough to prevent preferred flow paths from developing, scour and re-suspension of sediments. The greater the density and height of ground cover vegetation, the better. Turf is not suitable vegetation. While meeting stormwater quality objectives, the landscape design must also consider road visibility, public safety and community character and habitat.
G5-A-AUS	Native vegetation is preferable. Exotic species may be used to fit in with landscaping.
G6-A-AUS	Vegetation shall: Cover the whole filter media surface; Be able to withstand design flows; And, be dense enough to prevent preferred flow paths from developing, scour and re-suspension of sediments. The greater the density and height of ground cover vegetation, the better. Turf is not suitable vegetation. The landscape design must also consider road visibility, public safety and community character and habitat. It must integrate with its surrounding environment. Consult with landscape architect (recommended).
G7-A-AUS	Vegetation shall: Cover the whole filter media surface; Be able to withstand design flows; And, be dense enough to prevent preferred flow paths from developing, scour and re-suspension of sediments. Be appropriate for the site climatic and watering conditions. Sedges and tuft grass are preferred to turf (due to mowing causing compaction of filter media). Taller and denser vegetation is best.
G8-A-AUS	Vegetation shall: Be dense. Be water tolerant and not root-matting (so that water can penetrate).
G9-UM-AUS	Vegetation shall: Range from groundcovers to trees. Be suitable for freely draining soils. Be tolerant of the hydrologic regime.
G10-A-USA	Vegetation shall: Be tolerant of the hydrologic regime. Be varied (to decrease susceptibility to insect and disease and to create a microclimate which reduces heat and drying winds). Be layered (to discourage weeds and create a microclimate) List of species provided.
G11-UN-USA	Vegetation shall: Be tolerant of the hydrologic regime. Not have aggressive roots that may damage drainage pipes. Not be any type of cherry tree (these emit a poison that kills the tree when inundated).

	Be partially or all evergreen species (to maintain colour in winter). Consult with landscape architect, county Extension agent or nursery specialist.
G12-A-USA	Vegetation shall: Improve the landscape and meet landscaping requirements of local authorities. Include one tree or shrub per 4.65 m^2 (50 square foot) of bioretention area and may include ground cover such as grasses or legumes. Include a tree to shrub ratio of 1:2 to 1:3. Include three species of trees and three species of shrubs (recommended). Be tolerant of hydrologic regime. Be tolerant of pollutant loads. Have suitable maintenance requirements. Be protected from invasion from non-native invasive species (such as by providing a soil breach). Be placed at irregular intervals (replicating natural vegetation). Include trees placed on the perimeter for shade and shelter. Be placed away from inlet (trees and shrubs).
G13-A-USA	Vegetation shall: Include one tree or shrub per 4.65 m^2 (50 square foot) of bioretention area. Be selected considering aesthetics, maintenance, native versus non-native species, invasive species and regional landscaping practice. Include trees placed on the perimeter for shade and shelter.
G14-A-USA	Vegetation should not be dense to optimise pathogen removal (through sunlight exposure). Grass-only bioretention cells are not recommended. If TN removal is required and designed for the system may be too wet to maintain grass-only planting. Consult a horticulturalist for plant selection.

Table B.2 Bioretention basin vegetation requirements in studies reviewed

S1-UM-AUS	Vegetation should: Be tolerant of hydrologic regime. Have extensive root systems (vegetation with shallow roots are ineffective in removing nutrients). Have large diameter roots (as these work better in preventing clogging of the media). Some plants aid in nitrogen removal.
S4-UM-AUS	Vegetation may enhance nitrogen retention (Zinger et al cited in Hatt, Fletcher & Deletic 2008).
S6-UM-AUS	A mixture of species is suitable (to maximise the spectrum of pollutants removed). Some plant varieties perform well at removing nitrogen and phosphorus (Carex) (Read et al cited in Bratieres et al 2008). Juncus performs well in removing nutrients, but not lead (Read et al cited in Bratieres et al 2008). C. appressa and M. ericifolia performed markedly better than other species tested in nutrient removal. Further research is recommended to identify morphological or physiological reasons as to why different plant species perform differently in pollutant removal. Some plants aid in nitrogen removal. Plants also need to be tolerant to the hydrologic regime.
S7-UM-AUS	A mixture of species is suitable (to maximise the spectrum of pollutants removed). Carex, Melaleuca and Juncus spp showed effectiveness in reducing some pollutants. Juncus spp was effective at removing TN and TP, but not lead. Species with high growth rates often do not retain leaves for long periods leading to prompt return of nutrients to the soil (Salt et al cited in Read et al 2008). Plant size at maturity should also be considered as a shrub with low pollutant removal ability might still have more considerable effect on overall pollutant removal than a smaller plant with better pollutant uptake ability. More research needs to be undertaken on the interaction of these plants when planted together and in competition for space before recommendations for planting can be made.
S13-UR-USA	Vegetation can remove a large portion of TN and TP. Its growth and harvesting needs to be managed.

Appendix C

Table C.1 Summary of recommended filter media requirements from the guidelines reviewed

G1-A-AUS	Hydraulic conductivity 50 to 200 mm/hr. Particle size to meet infiltration requirements. Sandy loam or loamy sand-type material or equivalent. Clay content to be less than 15 %. Silt content to be less than 30 %. Organic carbon content to be equal to or higher than 5 %. Organic content to be 5 to 10%. pH to be neutral (6 to 7.5) or 7 to 8 (optimum for denitrification) or lower if siliceous materials are used. Depth to be able to support vegetation (300 mm to 1000 mm). Reject if material contains high levels of salt or other extremes that retard plant growth. Surface to be horizontal. Material to be free of rubbish and other deleterious material.
G2-A-AUS	Hydraulic conductivity to meet desired requirements. Maximum saturated hydraulic conductivity to be 500 mm/hr. Preferred saturated hydraulic conductivity to be 200 mm/hr (to enable vegetation to be sustained). Sandy loam or sandy clay loam may be used. Clay content to be less than 15 %. Silt content to be less than 30 %. Organic carbon content to be equal to or higher than 5 %. Organic content to be not more than 10%. pH to be between 6 and 7.

	Depth to be able to support vegetation (300 mm to 1000 mm, minimum 800 mm for trees). Reject soil which may be a retardant to plant growth and denitrification. Salt content to be less than 0.63 dS/m for low clay content soils. Soil must not contain fire ants or be from fire ant restricted areas. Surface to be horizontal or as close to horizontal as possible (for uniform distribution).
G3-A-AUS	If filter media is to be planting media also, material shall be able to promote and sustain vegetation. Hydraulic permeability min. 0.3 m/day (to account fot likely reductions from roots and trapped particles) (estimate with Hazen formula, then reduce by factor 10). Loam/sand or sand of sand gravel mix may be used. To contain less than 25% clay (by mass). Free from woody material over 25mm in size. Free from brush or noxious plant seeds. Material not susceptible to breakdown.
G4-A-AUS	Saturated hydraulic conductivity should remain between 50-200 mm/hr (absolute maximum 500 mm/hr). Organic content to be not more than 10%. pH to be between 5.5 and 7.5. Minimum depth of 400 mm for grasses and shrubs. Minimum depth of 800 mm for trees. Optimal filter media (based on hydraulic conductivity) and detention depth is found using a continuous simulation modelling approach such as MUSIC. Reject soil which may be a retardant to plant growth. Reject soil which contains high levels of salt. Salt content to be less than 0.63 dS/m for low clay content soils. Organic carbon content to be less than 5%. Soil must not contain fire ants or be from fire ant restricted areas. Surface to be horizontal. Soil hydraulic conductivity, water holding capacity, particle size distribution and AS4419-2003 parameters must be met.
G5-A-AUS	Hydraulic conductivity approximately 36 to 180 mm/hr.

	Usually sandy loam.
G6-A-AUS	Optimal filter media (based on hydraulic conductivity) and detention depth is found using a continuous simulation modelling approach such as MUSIC. Saturated hydraulic conductivity should preferably be 50 to 200 mm/hr (absolute maximum 500 mm/hr). Organic content to be not more than 10%. pH to be between 6 and 7. Minimum depth of 400 mm for grasses and shrubs. Minimum depth of 800 mm for trees. Reject soil which may be a retardant to plant growth. Reject soil which contains high levels of salt. Salt content to be less than 0.63 dS/m for low clay content soils. Organic carbon content to be less than 5%. Soil must not contain fire ants or be from fire ant restricted areas. Surface to be horizontal. Well-graded particle size distribution with a combined clay and silt fraction of less than 12% required for structural stability.
G7-A-AUS	Hydraulic conductivity should typically be 50 to 300 mm/hr (sandy loam). Depth of 300 mm to 1000 mm typically. The material size differential between adjacent layers should not be more than one order of magnitude. Treatment media may be used (organic materials to absorb nutrients, red mud or blast furnace slag and laterite or zeolite to absorb phosphorus and other inorganics). For nitrogen removal woodchips are preferable to sawdust due to their longevity. Reject soil which contains rubbish or other deleterious material. Media must meet hydraulic conductivity requirements. Media must meet geotechnical requirements. Material to be placed and lightly compacted.
G8-A-AUS	Surface to be horizontal.
G9-UM-AUS	Generally, loamy sand. A safety coefficient of 2 for hydraulic conductivity should be used when modelling designs to account for changes in hydraulic conductivity over time.

	Hydraulic conductivity should be appropriately high. In temperate climates, typically 100mm/hr to 300mm/hr. In warm, humid (sub-tropical and dry-tropical) regions the hydraulic conductivity may need to be higher. The filter surface area or extended detention depth may be altered to allow for other soil hydraulic conductivities and still treat the desired runoff. If soil with hydraulic conductivity higher than 300mm/hr is used, high watering in establishment phase should be considered. Soil with hydraulic conductivity higher than 600mm/hr is unlikely to support plant growth and may result is pollutant leaching. The hydraulic conductivity of potential filter media should be measured using the ASTM F1815-06 method (as it is appropriately conservative and best represents field conditions). To prevent structural collapse, soil shall: Have total clay and silt mix less than 3% (w/w). Be well-graded and present from the 0.075 mm to the 4.75 mm sieve (AS1289.3.6.1 – 1995). Not be dominated by small particles (to prevent collapse by migration of small particles). Organic content to be less than 5% (w/w) pH to be between 5.5 and 7.5. Electrical conductivity to be less than 1.2 dS/m. Phosphorus content to be less than 100 mg/kg (otherwise tested for phosphorus leaching) or less than 20 mg/kg if selected plants are sensitive to phosphorus loading. Depth of 400 mm to 600 mm or as specified. Reject soil which contains rubbish or other deleterious material, toxicants, declared plants and local weeds. Soil should not be hydrophobic. Media to be assessed by a horticulturalist to ensure it is capable of supporting vegetation. Media having properties which are retardant to plant growth should be rejected.
G10-A-USA	Hydraulic conductivity to exceed 38 mm/hr (1.5 inches/hour). Less than 5% clay content. Organic content to be between 1.5% and 3%.

	pH to be between 5.5 and 6.5. Minimum depth 762 mm +/- 152 mm (2.5' +/- 0.5'). Additional depths required to accommodate trees. Depth for trees and large shrubs 1.22 m to 1.52 m (4' to 5'). Depth for shallow-rooted plants 457 mm (1.5'). Sand to be clean and free of deleterious materials. Grain size to be 0.508 mm to 1.02 mm (0.02" to 0.04").
G11-UN-USA	Hydraulic conductivity to exceed 25 mm/hr (1" per hour) for system in sandy soils. Hydraulic conductivity to be 25 mm/hr to 152 mm/hr (1" per hour to 6" per hour) for system in clayey soils. Facility to dewater to two feet below surface in less than 48 hours. Material to be sandy loam or loamy sand (typical) Minimum depth to be 914 mm (3'). Preferable depth 1.22 m to 1.52 m (4' to 5'). Depth may be 457 mm (1.5') if grass is the only vegetation. Material must have enough fines (clay) to support plant growth and capture pollutants.
G12-A-USA	Hydraulic conductivity to exceed 13 mm/hr (0.5 inches per hour). Area to drain within 72 hours. Area should drain completely within 72 hours. 10% to 25% clay content. Organic content to be between 1.5% and 3%. pH to be between 5.5 and 6.5 (microbial activity can flourish). Soluble salt content to be less than 500 ppm. Planting soils should be sandy loam, loamy sand or loam texture soil. Depth should be 102 mm (4 inches) deeper than the bottom of the largest root ball Overall depth should be 1.22 m (4 feet).
G13-A-USA	Area to drain within 7 days.

	pH to be between 5.5 and 6.5.
G14-A-USA	Infiltration rate to be greater than 51 mm/hr (2 inches per hour) for optimum TSS and metal removal. Infiltration rate to be 25 mm/hr (1 inch per hour) for optimum TN removal. Infiltration rate to be greater than 25 mm/hr (1 inch per hour) (recommended 51 mm/hr or 2 inches per hour) for optimum TP removal. Media to contain 3 to 5 percent organic matter. (newspaper mulch or peat moss has been used successfully). Organics will encourage initial nitrogen removal and plant growth. After a time the vegetation layer is expected to contribute organic matter to the system. Media to contain 85 to 88 percent sand. Media to contain 8 to 12 percent fines (this may vary depending on the infiltration rate required for the target pollutant). Media to have a P-Index between 10 and 30 if phospohorus is a target pollutant otherwise P-Index may be 25 to 40. Media to have cation exchange capacity (CEC) exceeding 10 to enhance the system's ability to capture and retain phosphorus and other target pollutants. Depth of media to be suitable for plant species selection. Grasses require 381 mm to 457 mm (15 to 18 inches), small trees may require 914 mm (36 inches), most shrubs require minimum 610 mm (24 inches). Depth need not exceed 457 mm (18 inches) for adequate metal removal. Depth to be 762 mm (30 inches) (recommended) or 914 mm (36 inches) (preferred) for optimum TN removal.

Table C.2 Summary of recommended filter media requirements from the studies reviewed

S1-UM-AUS	Media to be loamy sand. Dispersive clays and silts are unsuitable (due to their hydraulic conductivity). In temperate climates, typically 100mm/hr to 300mm/hr. In warm, humid (sub-tropical and dry-tropical) regions the hydraulic conductivity may need to be higher (up to 600 mm/hr). The filter surface area or extended detention depth may be altered to allow for other soil hydraulic conductivities and still treat the desired runoff. Immediately after construction, hydraulic conductivity drops (due mainly to compaction), but recovers over time (due to plant roots creating macropores it is believed). The hydraulic conductivity of potential filter media should be measured using the ASTM F1815-06 method (as it is appropriately conservative and best represents field conditions). Particle size distribution: Have total clay and silt mix less than 3% (w/w). Be well-graded and have continuous distribution of other fractions. Organic content to be less than 5% (w/w). Phosphorus content to be minimised and to be less than 100 mg/kg. Vermiculite may be added (approximately 10% of volume). Perlite may be added (approximately 10% of volume). These help to maintain hydraulic conductivity and may also improve the long-term absorption capacity of the media (important for removal of heavy metal). Media to be structurally stable. Media to be clean and free of deleterious materials, toxicants and rubbish. Media to not be hydrophobic.
S2-UM-AUS	A contingency factor in the specification of hydraulic conductivity may be used for media with high initial hydraulic conductivity. This may be 50 %. This would account for a loss in hydraulic conductivity of filter media due to clogging or use of media that does not meet specifications.
S3-UM-AUS	Phosphorus content of filter media should be minimised to enable adequate phosphorus removal from storm runoff.
S4-UM-AUS	Sandy loam with a low organic content is the preferred media. It removes TSS, TP and heavy metals better than sand filters.
S5-UM/L-AUS/F	Media should have organic matter or vermiculite. This improves the decline of hydraulic conductivity over time.
S6-UM-AUS	Media to be sandy loam with no additional organic matter (organic matter is detrimental to phosphorus removal).
S8-UN-USA	Media to be sandy loam or loamy sand and contain between 75% and 85% sand. Media to have a P-Index no greater than 40.

S9-UN-USA	Media to have a low P-Index (possibly 4 to 12) if in a phosphorus sensitive watershed. If nitrogen removal is required, organic content and hydraulic conductivity of media needs to be suitable.
S11-UR-USA	<u>If no planting layer is employed (more cost-effective design):</u> Media to be coarse sand (e.g. d_{10} > 0.3 mm) and sandy soil with sandy loam texture (soil ratio 20 % to 70 % by mass depending on plant species requirements). Media depth to be 550 mm to 750 mm. This soil has a high infiltration rate (initially 720 mm/hr to 3240 mm/hr at 150 mm head, 4 to 6 times faster than sandy loam) and very good pollutant removal. Expected pollutant removal is 96 % TSS, 96 % oil and grease, 98 % Pb, 24 % to 70 % TP, 6 % to 9 % nitrate and 11 % to 20 % ammonium. <u>If planting layer is employed (best pollutant removal):</u> Media to be coarse sand (e.g. d_{10} > 0.3 mm) and sandy soil with sandy loam texture (soil ratio 50 %). Media depth to be 250 mm to 500 mm. This soil also has a high infiltration rate (initially 720 mm/hr to 3240 mm/hr at 150 mm head, 4 to 6 times faster than sandy loam) and the best pollutant removal in all the studies performed. The advantage of this design is that the filter media can be optimised for pollutant removal without considerations for vegetation sustainability. Expected pollutant removal is 96 % TSS, 96 % oil and grease, 98 % Pb, 74 % TP, 9 % nitrate and 20 % ammonium.
S14-UP-USA	Media to have a P-Index no greater than 50.

Appendix D

Table D.1 Transition layer requirements

G1-A-AUS	Transition layer required if drainage layer is fine gravel (2mm to 5mm) rather than coarse sand (1mm). Material to be sand or coarse sand (0.7 mm to 1 mm) based on Unimin 16/30 FG sand grading. Geotextile fabric may be used but it must not be too fine or it will clog. Caution must be exercised when adopting this option. Minimum thickness 100 mm.
G2-A-AUS	If order of magnitude of the material size differential is more than one between drainage layer and filter media, transition layer is required. If drainage layer is fine gravel (2mm to 5mm) rather than coarse sand (1mm), transition layer is generally required. Particle size distribution based on Unimin specification. Minimum thickness 100 mm.
G3-A-AUS	15% by weight of material should be less than or equal to 4 times the particles size for which 85% of particles of the filter media are smaller. Desirable thickness 200 mm.
G4-A-AUS	If order of magnitude of the material size differential is more than one between drainage layer and filter media, transition layer is required. Particle size distribution based on Unimin specification. Material to be sand or coarse sand. Desirable thickness 150 mm.
G6-A-AUS	If order of magnitude of the material size differential is more than one between drainage layer and filter media, transition layer is required. Material to be sand or coarse sand. Desirable thickness 100 mm.
G7-A-AUS	If drainage layer is fine gravel, transition layer is required between the filter media and the drainage layer. Alternatively a suitable geotextile fabric may be used. Typical thickness 100 mm to 150 mm. The material size differential between adjacent layers should not be more than one order of magnitude. Reject soil which contains rubbish or other deleterious material. Media must meet hydraulic conductivity requirements. Media must meet geotechnical requirements.
G9-UM-AUS	Media to be clean, well-graded sand or coarse sand with minimal or no fines. Typical thickness 100 mm. Where depth is an issue an open-weave shade cloth may be placed between the transition layer and drainage layer to aid in the prevention of migration of smaller particles.
G10-A-USA	A pea gravel diaphragm is preferred over a filter fabric (due to clogging). It has greater porosity and is less likely to block. If filter fabric is used, minimum permittivity rate is 3.06 $m^3/min/m^2$ (75 $gal/min/ft^2$). Minimum thickness 76 mm to 102 mm (3 inches to 4 inches). Maximum thickness 203 mm (8 inches).

G11-UN-USA	Permeable geotextile.
G14-A-USA	A permeable filter fabric may be used where the bioretention cell is to be installed is stable. A thin layer of choking stone (such as #8 stone) may be used with a thin 51 mm to 102 mm (2 inch to 4 inch) layer of pure sand above it. The choking material to be used must satisfy the following equations: D15 open-graded base ÷ D50 choke stone < 5 and D50 open-graded base ÷ D50 choke stone > 2
S6-UM-AUS	Transition layer to prevent leaching of fine materials.

Appendix E

Table E.1 Perforated underdrain design requirements from publications reviewed

G1-A-AUS	Maximum filtration rate used to size underdrains. Sharp-edged orifice equation (with partial blockage factor of 50 %) used to check that the perforations in the underdrain can accommodate the maximum infiltration rate. Colebrook–White equation (or Manning's equation) used to check that underdrain can convey the maximum infiltration rate. Size of underdrain perforations are compared to the hydraulic conductivity of the drainage layer to determine if the slots would prevent sediment entering (otherwise a transition layer is required between the drainage layer and the underdrains). Maximum pipe size 100 mm diameter. Maximum spacing of underdrains is 1.5 m. Material to be polyvinyl chloride (PVC) or perforated pipe such as AG pipe.
G2-A-AUS	Maximum filtration rate used to size underdrains. Sharp-edged orifice equation (with partial blockage factor of 50 %) used to check that the perforations in the underdrain can accommodate the maximum infiltration rate. Manning's equation used to check that underdrain can convey the maximum infiltration rate. This assumes the pipe is full, but not under pressure. Size of underdrain perforations are compared to the hydraulic conductivity of the drainage layer to determine if the slots would prevent sediment entering (otherwise a transition layer is required between the drainage layer and the underdrains). Max. spacing of underdrains 1.5 m, except where catchment is greater than 100 m^2, then spacing can be 2.5 m to 3 m. Grade to be minimum 0.5 %. Maximum pipe size 100 mm. Material to be polyvinyl chloride (PVC) or perforated pipe such as AG pipe.
G3-A-AUS	Maximum filtration rate used to size underdrains. Minimum pipe size 100 mm, maximum 150 mm. Drainage layer to cover underdrain by 50 mm. Backflushing system required to clean underdrain.
G4-A-AUS	Maximum filtration rate used to size underdrains. Sharp-edged orifice equation (with partial blockage factor of 50 %) used to check that the perforations in the underdrain can accommodate the maximum infiltration rate.

	Manning’s equation used to check that underdrain can convey the maximum infiltration rate. Ensure size of underdrain perforations prevent sediment entering from the drainage layer. Maximum spacing of underdrains 1.5 m, except where catchment is greater than 100 m², then spacing can be 2.5 to 3 m. Grade to be minimum 0.5 %. Maximum pipe size 100 mm. Pipes to be smooth to reduce water surface beading and reduce tree root intrusion.
G6-A-AUS	Maximum filtration rate used to size underdrains. Sharp-edged orifice equation (with partial blockage factor of 50 %) used to check that the perforations in the underdrain can accommodate the maximum infiltration rate. Manning’s equation used to check that underdrain can convey the maximum infiltration rate. Ensure size of underdrain perforations prevent sediment entering from the drainage layer. Maximum spacing of underdrains 1.5 m, except where catchment is greater than 100 m², then spacing can be 2.5 m to 3 m. Grade to be minimum 0.5 %. Maximum pipe size 100 mm. Pipes to be smooth to reduce water surface beading and reduce tree root intrusion if necessary.
G7-A-AUS	Maximum filtration rate used to size underdrains. Sharp-edged orifice equation (with partial blockage factor of 2) used to check that the perforations in the underdrain can accommodate the maximum infiltration rate. The Colebrook-White equation used to check that underdrain can convey the maximum infiltration rate. Ensure size of underdrain perforations prevent sediment entering from the drainage layer. Maximum pipe size 150 mm. Root barriers may need to be installed around underdrains if trees are planted.
G8-A-AUS	Grade to be maximum 4 %. Maximum pipe size 100 mm.
G10-A-USA	Underdrains not required where surrounding soil has infiltration rate higher than 25 mm/hr (1 inch per hour) and water table is more than 610 mm (2 feet) below the proposed invert of the bioretention basin. In this case the in-situ material must be tested to confirm infiltration rate and the catchment area is limited to one acre. Perforations to be 6.35 mm to 12.7 mm (¼ inch to ½ inch) openings, 152 mm (6 inches) centre to centre. The flow capacity through all openings combined shall exceed the flow capacity of the underdrain. If an anaerobic zone is desired, perforations may be placed near the top of the pipe instead of near the invert or the underdrain invert may be placed above the drainage

	layer invert. Material to be polyvinyl chloride (PVC) or ADS (corrugated high-density polyethylene (HDPE) pipe). Underdrains not to be located within the groundwater zone of saturation. Pipe to have no perforations in the 1.52 m (5 feet) closest to the drainage outfall. Minimum pipe size 102 mm (4 inches). If pea gravel is used as the drainage layer, the underdrain perforations must not exceed 6.35 mm (¼ inch).
G11-UN-USA	Capacity to be one order of magnitude higher than the maximum infiltration rate. Manning's equation used to size the underdrain for a capacity one order of magnitude higher than the maximum infiltration rate. Material to be corrugated and perforated plastic. Typical pipe size 102 mm to 152 mm (4 inches to 6 inches).
G12-A-USA	Underdrain should be provided where surrounding soil has permeability less than 13 mm/hr (0.5 inches per hour).
G13-A-USA	Underdrain should be provided where surrounding soil has permeability less than 13 mm/hr (0.5 inches per hour).