Finding the Right Bioretention Soil Media

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Abstract

The successful functioning of a bioretention system depends on the use of suitable soil media. Predictive computer modelling of a bioretention system (e.g. using the MUSIC software) assumes specific characteristics of the soil media to achieve a certain level of stormwater treatment. Therefore, the soil media used in the construction of a bioretention system must exhibit the required characteristics. The use of inappropriate soil media can result in failure of a bioretention system, ranging from a reduced level of stormwater treatment through to a total lack of infiltration through the soil media and the associated ponding of water on the surface of the system.

This paper describes the soil media characteristics that are critical to the successful functioning of a bioretention system and outlines the methodology behind the development of the Guideline Specifications for Soil Media in Bioretention Systems (FAWB, 2006). Some of the challenges associated with obtaining soil media that meet the specifications are addressed, including: (i) determining the acceptable range of saturated hydraulic conductivity for the filter media; (ii) assessing the suitability of on-site topsoil for use as filter media; (iii) accounting for the variability in laboratory soil test results; (iv) relating laboratory soil test results to likely performance in a constructed system; (v) assigning responsibility for obtaining and verifying soil media, and; (vi) sourcing appropriate soil media from suppliers. The importance of good soil media design specifications, quality controls for the supply of soil media, and detailed construction procedures are stressed.

Bioretention systems for stormwater treatment

Pollutants are removed from stormwater both on the surface of the bioretention system and within the filter media. When large storm inflows cause temporary ponding on the surface of the system, pollutants are removed from the stormwater through sedimentation and particulate adhesion onto the stems and leaves of the vegetation. As stormwater percolates down through the filter media, fine particulates and some soluble pollutants are removed through processes such as adhesion on to the surface of the filter media particles, biological transformation of pollutants by biofilms growing on the surface of the filter media particles, and biomass uptake through the root systems of the vegetation.

Key aspects of bioretention soil media

Bioretention systems are typically comprised of three soil layers (see Figure 1): (i) filter layer; (ii) transition layer; and, (iii) drainage layer. All three layers must exhibit structural integrity and must not be prone to structural collapse. These soil layers are critical to the successful functioning of a bioretention system:

- Filter Media - The filter media must be capable of sustaining healthy vegetation, whilst also exhibiting a suitably high permeability (saturated hydraulic conductivity) to ensure a significant proportion of the incoming stormwater runoff infiltrates through the soil layers.
- Transition Media - The transition media needs to have a particle size distribution that prevents the downward migration of filter media particles.
- Drainage Media - The drainage media must have a sufficiently high saturated hydraulic conductivity to allow infiltrated water to flow horizontally across the base of the bioretention system towards the under-drainage pipes. The drainage media must also have a particle size distribution that prevents the downward migration of transition media particles.
Development of the Guideline Specifications for Soil Media in Bioretention Systems

The selection of appropriate soil filter media is crucial in terms of both water quality treatment function (pollutant removal) and long term sustainability. The Facility for Advancing Water Biofiltration (FAWB) has developed the ‘Guideline Specifications for Soil Media in Bioretention Systems’ that outline the key parameters of bioretention soil media, based on current knowledge and understanding. This document aims to assist in the selection of appropriate filter media by outlining the key parameters that should be considered during the selection process. It is important to note that the guidelines are based on current knowledge and understanding and as new findings come to light they will be incorporated into the guidelines.

The FAWB guidelines outline filter media specifications in light of two key factors: achieving and maintaining the prescribed hydraulic conductivity and supporting healthy plant growth. The overall objective being the provision of adequate long term pollutant load reduction. However, there is a wide array of competing factors that have been considered in the final specification (such as heavy metal uptake, prevention of nutrient leaching, maintenance of soil moisture for long term plant growth) and these are outlined in more detail below.

Key characteristics of an appropriate soil filter media

1. Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (or Ksat) is a crucial parameter of the soil media specification. The design saturated hydraulic conductivity (or range of hydraulic conductivities – see below for further details) is determined during the modelling phase and directly influences the treatment efficiency of a bioretention system. For this reason it is crucial that the actual hydraulic conductivity within the constructed bioretention system be within the design range determined during modelling.

The permeability test for AS4419-2003 can be used as a preliminary guide to choosing suitable soil media. However, it is recommended (SESL, 2006) that a laboratory test that examines the saturated hydraulic conductivity of a soil under a range of compaction levels (e.g. HCCC method by McIntyre and Jakobsen 1998) should be used to determine whether a soil is suitable for use as bioretention filter media. The acceptable range specified for the
saturated hydraulic conductivity of the filter media needs to include the level of compaction used in the laboratory test (e.g. “the saturated hydraulic conductivity of the bioretention filter media must be 200 - 500 mm/hr at the highest level of compaction (i.e. 32 drops), as tested by the McIntyre & Jakobsen 1998 HCCC method”).

While a range of hydraulic conductivities may be suitable for achieving a particular treatment efficiency (as modelled using MUSIC), the model assumes that the system is well vegetated and therefore it is important to ensure the suite of plants specified can tolerate the hydraulic conductivity of the media. For example, media with an extremely high hydraulic conductivity may result in conditions that are only suitable for very hardy (drought tolerant) plants.

2. **Particle size distribution (PSD)**

An appropriate PSD is crucial for the long term maintenance of hydraulic conductivity and prevention of structural collapse of the soil profile. Previously, soils with higher proportions of smaller particle sizes (including the silt plus clay range) have been prone to structural collapse in the field, with hydraulic conductivities reducing to <10 mm/hr. An appropriately specified PSD (particularly at the lower end of the particle size range – silt and clay) also assists in the maintenance of soil moisture (important for plant survival).

Soils with the following PSD are expected to have appropriate hydraulic conductivities while also maintaining their structural integrity (SESL, 2006 - adapted from United States Golf Association: Method of Putting Green Construction, 1993). Critically, the combined silt and clay content of the filter media must be less than 12% to reduce the likelihood of structural collapse.

<table>
<thead>
<tr>
<th>Particle description</th>
<th>% of mix (w/w)</th>
<th>Particle size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>2-4%</td>
<td>(&lt;0.002 mm)</td>
</tr>
<tr>
<td>Silt</td>
<td>4-8%</td>
<td>(0.002-0.05 mm)</td>
</tr>
<tr>
<td>Very Fine Sand</td>
<td>5-10%</td>
<td>(0.05-0.15 mm)</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>10-25%</td>
<td>(0.15-0.25 mm)</td>
</tr>
<tr>
<td>Medium to Coarse Sand</td>
<td>60-70%</td>
<td>(0.25-1.0 mm)</td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>7-10%</td>
<td>(1.0-2.0 mm)</td>
</tr>
<tr>
<td>Fine Gravel</td>
<td>&lt;3%</td>
<td>(2.0-3.4 mm)</td>
</tr>
</tbody>
</table>

3. **AS4419-2003 – Soils for landscaping and garden use**

The adoption of specifications from the AS4419-2003 standard for soils for landscaping and garden use ensures that a chosen soil will be suitable for healthy plant growth. As discussed previously, healthy plant growth is an important aspect of the pollutant removal efficiency of a bioretention system. It is recommended the same ranges be used for each parameter specified in AS4419-2003 for soils for landscaping and garden use unless otherwise stated. The parameters for which the bioretention filter media specification differs from the AS4419-2003 specifications are organic matter content and phosphorus.

4. **Organic matter content**

Organic matter content is important to sustain healthy plant growth, particularly during the establishment phase, when *in situ* organic litter will be limited. Fine organic matter also helps to improve the water holding capacity and therefore improve plant survival during dry periods. This may be particularly important in regions likely to experience extended dry
spells. Organic matter can also enhance the adsorption capacity of filter media for the uptake (removal) of heavy metals.

While an adequate supply of organic matter is important it is also important that the bioretention system does not have excess amounts, to avoid the potential for leaching of nutrients from the filter media as the material is broken down (FAWB 2006a). The suggested range for organic matter content is between 3 and 10% w/w. However, unless a specific application requires a high organic content (e.g. for additional heavy metal removal) it is generally recommended that the organic matter content be closer to the low end of this range.

5. Phosphorus
While the AS4419-2003 suggests a low phosphorus content, it is understood this is in response to the phosphorus sensitivity of some plants. As a result, a wider range of acceptable phosphorus concentrations have been suggested in the FAWB guidelines. The phosphorus concentration of the filter media for a specific site should take into account any phosphorus sensitive plants proposed. Where plants with moderate phosphorus sensitivity are to be used, phosphorus concentrations should be <20 mg/kg.

Based on some preliminary testing the Facility for Advancing Water Biofiltration (FAWB), soils with phosphorus concentrations up to 100mg/kg are unlikely to result in leaching. Soils with phosphorus concentration >100mg/kg should be tested for potential leaching.

6. Water Holding Capacity
The water holding capacity of a soil is influenced by a number of factors including the PSD of the smaller size particles and the organic matter content. It is suggested that the media be tested to ensure adequate water holding capacity if the PSD does not meet specifications but silt + clay content is <12%. Water holding capacity should also be tested in regions likely to experience extended dry spells. The water holding capacity should be at least 15 – 20% by volume at 300 mm of suction using the McIntyre and Jakobsen method (1998).

Recommended procedure for the specification, supply & installation of soil media

**Step 1. Test stormwater treatment performance under a range of filter media saturated hydraulic conductivities**

The accepted method of assessing the ability of a proposed stormwater treatment train to meet the required pollutant removal targets is computer model simulation using the MUSIC software developed by the CRC for Catchment Hydrology.

Saturated hydraulic conductivity is one of the key design parameters of a bioretention system and it is important to understand that this parameter will be subject to natural variation as the properties of the soil change over time. The inherent variation of a treatment system that utilises natural processes needs to be acknowledged and tested. As such, it is good practice to test the pollutant removal performance of the bioretention system over a range of saturated hydraulic conductivities. A graph showing the influence of saturated hydraulic conductivity on the treatment performance of a typical bioretention system is shown in Figure 2.
Step 2. Develop a customised specification for bioretention soil media
The ‘Guideline Specifications for Soil Media in Bioretention Systems’ developed by FAWB provides a basis for a customised specification. The FAWB specification covers all of the important items, but does not provide values for certain parameters that are specific to the design of an individual bioretention system. Therefore, the purpose of a customised soil media specification is to provide values and ranges for these undefined parameters. Aside from the depth of the individual soil media layers, the key parameters that need to be defined are the acceptable range for the saturated hydraulic conductivity of the filter media and drainage layer, along with the bridging criteria for the soil layers. Commercial products can also be incorporated into the filter media to target specific pollutants.

Site specific saturated hydraulic conductivity range of the filter media
The saturated hydraulic conductivity of the filter media should be specified as an acceptable range. Suitable filter media will exhibit saturated hydraulic conductivity, as tested by laboratory procedures outlined in the FAWB specification, which falls within this specified range. As well as the MUSIC testing outlined in Step 1 (above), the acceptable range specified for the saturated hydraulic conductivity of the filter media will be informed by the issues described below.

Lower limit for saturated hydraulic conductivity
As the saturated hydraulic conductivity of the filter media is reduced, the proportion of stormwater runoff that exceeds the infiltration capacity and forms the overflow component is increased. The MUSIC software assumes significant removal of suspended solids from these overflows that pass through the system via the overflow pit(s) or weir. The actual removal of suspended solids is dependent on the positioning of the overflow structures in relation to the inflow point and the associated potential for short-circuiting of these overflows. It is considered prudent to ensure that at least 70% of the stormwater that enters a bioretention system infiltrates through the filter media rather than simply passing through the system via
the overflow structures. This ensures the stormwater treatment objectives can be achieved even if the actual removal of suspended solids is less than that assumed by MUSIC. For example, it has been found that for a typical bioretention system in Brisbane, the saturated hydraulic conductivity of the filter media must be at least 100 mm/hr to ensure the overflow component does not exceed 30% of the total stormwater inflow. The upper limit for saturated hydraulic conductivity will generally be determined by factors such as moisture holding capacity and plant growth requirements.

**Saturated hydraulic conductivity of drainage media**

The key purpose of the drainage layer is to convey infiltrated flows horizontally across the base of the bioretention system into the slotted under-drainage pipes. The drainage layer is typically comprised of fine gravel (2 - 5mm), with a minimum saturated hydraulic conductivity of 4000mm/hr.

**Bridging criteria for soil media**

The key purpose of the transition layer is to prevent the filter media from migrating down into the drainage layer. The transition layer is typically comprised of coarse sand (1 – 2mm). A particle size distribution for the sand will need to be obtained and compared to the particle size distribution of the filter media to confirm that it will prevent the downward migration of the filter media. One method of assessing this is to specify a ‘bridging’ criterion such as:

\[
\text{Bridging Factor: } D_{15} \text{ (lower layer)} \leq 8 \times D_{85} \text{ (upper layer)}
\]

The ‘bridging’ criteria is based on engineering principles that rely on the largest 15% of the filter media particles ‘bridging’ with the smallest 15% of the sand particles. This results in smaller voids, which prevent the migration of filter media particles into the sand.

In a similar manner, the drainage media needs to prevent the transition media from migrating down into the drainage layer and into the under-drainage pipes. Therefore, a particle size distribution for the drainage media will also need to be obtained to ensure that it meets the ‘bridging’ criteria when assessed against the transition media.

**Addition of commercial product for target pollutants**

The media specification described above is designed for applications where the types and concentrations of pollutants are expected to be similar to ‘normal’ urban pollutant loads. In some cases, receiving waters may be more sensitive or target pollutants may differ (excessive heavy metals or increased nutrient concentrations for example). For sensitive sites or where the runoff is expected to have a composition that differs from general urban pollutant loads, media can be further amended to increase treatment efficiency. For example, activated carbon (or another material with a high adsorption capacity) can be added where high concentrations of heavy metals are expected; the organic matter content of the media can be increased for sites where nitrogen is the target pollutant (and therefore denitrification is the target process); commercial products with high adsorption capacity that target specific pollutants such as phosphorus can also be added to the media where required.

**Step 3. Identify and assess potential sources of bioretention soil media**

It is recommended that a suitable filter media be identified first. This is because the transition media and the drainage media both depend on the particle size distribution of the filter media. In general, the options for sourcing bioretention media will include:
utilising on-site materials (e.g. topsoil for filter media)
- blending on-site material with imported material
- importing material (e.g. from a soil supplier or quarry)

The first of these is typically the cheapest option. The available quantity of on-site topsoil needs to be assessed, bearing in mind that the depth of topsoil may only be in the order of 200mm, in which case topsoil would need to be stripped from an area that is substantially larger than the footprint of the bioretention system. It is also necessary to consider the need to undergo a rigorous screening process to remove debris, rocks, roots and other large particles from the topsoil.

Where on-site soils may be generally suitable, but a higher hydraulic conductivity is required, a suitable sand (0.25 – 1.0 mm) could be blended in to achieve the desired hydraulic conductivity. The blended material would require testing.

Some soil suppliers will recommend a product they refer to as bioretention soil. It is important to check that the characteristics of this bioretention soil do in fact match the FAWB specification and requirements described above. It is important to communicate the desired characteristics to the soil supplier and allow them to ascertain whether they either have a product that is suitable or whether they can develop a product.

Ultimately, a cost analysis of the available options should be undertaken, with the level of detail of the analysis reflecting the size of the bioretention system in question. Experience has shown that the second option is not necessarily more cost effective than the third option, due to the significant cost associated with providing sufficient mixing of the two materials.

**Step 4. Assess suitability of proposed media**
Regardless of whether media is to be sourced on-site or from a supplier, samples of the media will need to be tested for compliance with the customised specification developed in Step 2. In some instances, a soil supplier will already have test results for particular soil media. If this is the case, it is recommended that additional testing is completed on samples taken from the actual stockpile that will form the supply. If on-site topsoil is to be utilised for the filter media, the consistency of the topsoil needs to be determined, with tests undertaken on samples sourced from various locations and stockpiles.

Where test results vary from specifications, a suggested 90% compliance could be accepted.

**Step 5. Installation of soil layers**
Quality assurance checks are recommended to ensure the correct bioretention soil media is supplied, delivered and installed. Procedures should be established, and responsibilities assigned, for assessing laboratory test results, signing off deliveries of soil media (e.g. checking supply dockets), and verifying correct installation. Testing of soil samples from delivered stockpiles is recommended on large projects.

The procedure for installing the soil layers should be agreed through collaboration between the designer of the system and the contractor responsible for construction. The key consideration is to ensure that the soil layers are not subject to significant compaction, which may reduce the infiltration capacity. Recommended methods for placing and spreading the soil media are: (i) a long-arm excavator operating from the side of the system; (ii) a ‘pozitrack’ bobcat (or similar) operating within the system; and, (iii) construction personnel
working with hand tools. Heavy machinery should be prohibited from driving over the soil layers. Once the soil layers have been installed, light and even compaction of the filter media is required to remove air pockets. This can be achieved by hydraulically loading the system with water or making a single pass with a ‘pozitrack’ bobcat.

Once the bulking out of a bioretention system is complete and the installation of the under-drainage pipes and soil layers has commenced, the bioretention system will be particularly susceptible to storm damage. Therefore, once construction of a bioretention system has commenced, it must be completed as soon as possible to minimise the risk of storm damage. If there will be a delay between the installation of the filter media and implementation of temporary protective measures (e.g. silt fences, bunds, diversions), the entire system should be covered with geofabric to protect it from storm damage.

**Conclusions**
The successful application of bioretention systems for stormwater treatment requires informed design, careful specification of materials and appropriate construction supervision. The specification of a range for hydraulic conductivity is important in being able to select a suitable media material. Appropriate testing of media is essential to obtain a sustainable outcome in terms of plant growth, long term hydraulic conductivity of the media and stormwater quality treatment objectives.

**References**


