Assessment of International Bioretention Soil Media: Guidelines and Experiences

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1. INTRODUCTION

Stormwater runoff from urban areas presents one of the greatest threats to water quality due to the numerous contaminants that it often contains. The US Environmental Protection Agency found that urban stormwater runoff is the leading cause of water quality impairments in estuaries and the third most significant source of degradation to lakes (US EPA 2003). Most forms of stormwater pollution are anthropogenic, resulting from transportation, construction, agriculture, and industry (Shaver et al 2007). Pollutants are often deposited on impervious surfaces by human activities or atmospheric deposition and then mobilized during a rainfall event. Severe pollution can be harmful to aquatic ecosystems, can compromise drinking water supplies, and can make surface water bodies unsafe for recreation (US EPA 2003).

In response to these negative effects, many governments have enforced permits that require new construction to provide treatment of stormwater runoff. Local governments may also retrofit existing pollution-generating surfaces, like roadways, with treatment systems. These treatment systems, referred to as Best Management Practices (BMPs) in the United States or Sustainable Urban Drainage Systems (SUDS) in the United Kingdom, capture a specific amount of runoff and remove contaminants through a variety of mechanisms. Over the last decade there has been a growing movement toward providing small-scale, decentralized treatment near the pollution source, rather than large “end-of-pipe” solutions (PGCDER 2007). A central feature of this movement has been the use of engineered soils in shallow, vegetated depressions, which clean stormwater through a combination of physical, chemical, and biological processes. This approach is variously referred to as “bioretention” in the U.S and the U.K. and “biofiltration” in Australia, though the systems are often colloquially known as “rain gardens”. This paper will use the term “bioretention” to describe this system and “soil media” to describe the engineered soil mix in which most treatment occurs. The use of these facilities has increased due to their high treatment capacity, hydrologic benefits, low cost, and aesthetic appeal (PGCDER 2007). A typical bioretention facility with an outlet underdrain is shown in Figure 1.

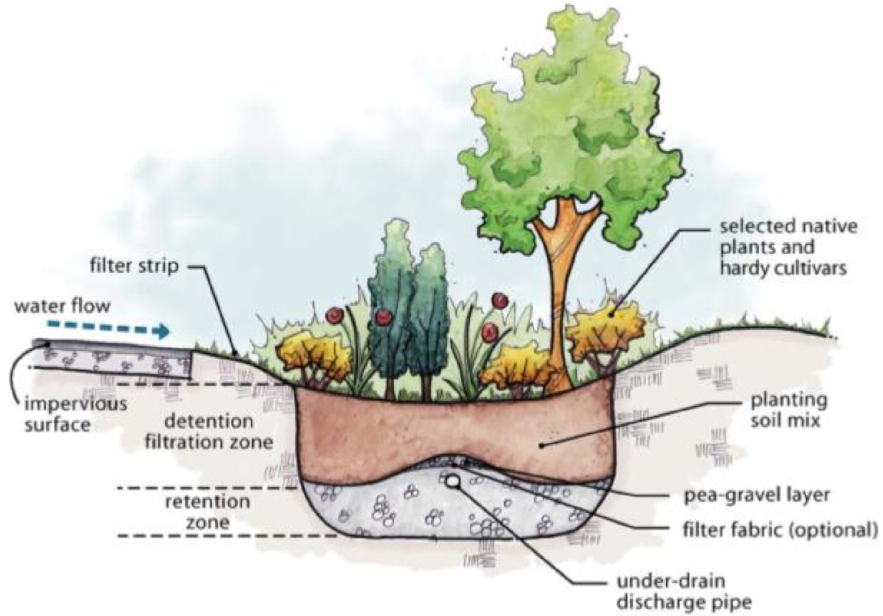

Figure 1 - Typical Bioretention System (Hinman 2005)

Over the last decade, a substantial amount of research has focused on the performance of these facilities in regards to the removal of many common pollutants, including total suspended solids (TSS), heavy metals (Pb, Cu, Zn, Cd), nutrients (nitrogen and phosphorus), hydrocarbons, pathogens, and xenobiotic organic compounds (XOCs). Much of the early research on bioretention facilities was performed in universities in the mid-Atlantic region of the United States, including the University of Maryland and North Carolina State University. These pioneering studies were used by local environmental agencies to create some of the first construction specifications and guidelines for bioretention systems (PGCDER 2002). Elements of these guidelines were then adopted by other regulatory agencies throughout the U.S. and abroad (MPCA 2005; CIRIA 2007; ARC 2003). Since these initial studies, a large body of further research has greatly expanded knowledge of these systems but has been slow to be incorporated in many design guidelines. As a result, design recommendations are often contradictory or omit features that have been shown to be important in the scientific literature.

The focus of the paper is on the engineered soil media component of bioretention systems, as it is the primary element that determines treatment effectiveness. The paper provides a review of the relevant scientific literature on bioretention with a summary of the major findings that have contributed to an improved understanding of these systems. A review and comparison of bioretention soil media design guidelines published by regulatory entities in the United States, Australia, Canada, the United Kingdom, Denmark, and Germany is then conducted. A comparison of design guidelines helps determine the criteria that are important to the proper construction of bioretention systems. By comparing various bioretention design guidelines against an overview of the current scientific knowledge on the subject, the strengths and weaknesses of the standards is determined.

2. BACKGROUND

Bioretention systems remove and degrade pollutants through several processes, including filtration, sedimentation, adsorption, plant uptake, and microbial degradation. The specific removal mechanism varies significantly among pollutants, and some mechanisms tend to be much more effective than others. The performance of different facilities can be quite variable and depends on many factors, including soil media composition, media depth, pollutant loading rate and frequency, hydrologic loading rate and frequency, facility age, vegetation type and maturity, etc.

The variability of the many design considerations makes it difficult to compare performance results among different facilities and studies. Additionally, the use of percent-removal as the only performance metric in many studies makes comparison challenging. Percent-removal may not provide an adequate basis to compare facilities as it is primarily a function of inflow concentrations and does not indicate if effluent concentrations are acceptable (Jones et al 2008). For this reason, facility performance will often be described qualitatively. Some specific removal results from various studies will be included, but for a comprehensive review of bioretention pollutant removal performance, refer to Davis et al 2009.

2.1. Pollutants and Removal Mechanisms

Total Suspended Solids (TSS) – TSS is one of the pollutants that are most effectively removed by a bioretention system. Newer systems have been observed to temporarily leach some silt and clay particle, decreasing the TSS removal efficiency (Hsieh and Davis 2005). Many mature systems have been observed to provide a 96% reduction of TSS or greater, with typical effluent concentrations ranging between 1.3-20 mg/L (Hsieh and Davis 2005; Bratieres et al 2008; Davis et al 2009). Suspended solids are removed from stormwater primarily by filtration through the soil matrix and sedimentation at the soil surface (Hunt et al 2012).

Heavy Metals – The presence of lead, copper, zinc, cadmium, and chromium in stormwater can be toxic to wildlife and humans in sufficiently high concentrations. Heavy metal pollution is typically caused by the wearing of vehicle tires and brake pads, the leaching of building materials, and atmospheric deposition (Davis et al 2003; Li and Davis 2008). Metals can be found in both dissolved and particle-bound forms and they do not degrade, making them difficult to treat by conventional methods (Li and Davis 2008). Metals are effectively removed from stormwater through a combination of filtration and adsorption and most removal occurs in the upper layers of the soil media (Li and Davis 2008). Removal by plant uptake has also been shown to account for up to 8% of the metal accumulation in a bioretention system (Muthanna et al 2007). Estimates of the long-term accumulation of metals in soil media have indicated that harmful concentrations are typically not reached for 15 years or more, depending on loading, background metal concentration, and the specific toxicity risk criteria used to assess the soil contamination (Davis et al 2003; Ingvertsen et al 2012a).

Total Phosphorus – Phosphorus is a pollutant of concern as it can lead to eutrophication issues in receiving streams and lakes. Typical phosphorus concentration in stormwater range from 0.02 to 9.4 mg-P/L and are the result of fertilizer use, vegetation decay, and soil erosion (Davis et al 2006). Bioretention systems remove phosphorus through filtration of particle-bound P and adsorption of soluble P (Hunt et al 2012). Phosphorus removal by bioretention systems is notoriously unpredictable, though effluent concentrations as low as 0.025 mg/L have been achieved (Bratieres et al 2008). The variability in removal efficiency can be attributed to the leaching of phosphorus from soils with high initial phosphorus content, which is often embodied in organic matter (Hunt et al 2012). High phosphorus removal has been observed using soils with little organic matter and appropriate plant selection (Bratieres et al 2008).

Total Nitrogen (TN) – Stormwater containing high levels of organic nitrogen, ammonia, or nitrate can also contribute to eutrophication issues. Organic nitrogen and ammonia can be effectively removed by bioretention systems, apparently through adsorption with organic material and biological degradation (Davis et al 2009). Nitrate is the most detrimental form of nitrogen in stormwater and it is also poorly removed by soil media due to its high solubility (Shaver et al 2007). Nitrate is primarily removed by denitrifying microorganisms and plant uptake (Hunt et al 2012). These processes require anoxic subsurface conditions and vegetative growth to be effective, leading to variable performance. As with phosphorus, the break down of organic matter in a soil media can cause nitrogen leaching (Hunt et al 2012).

Oils, Grease, and Polycyclic Aromatic Hydrocarbons (PAH) – Oils, grease, and PAHs typically enter stormwater runoff from vehicles or pavement sealants (Diblasi et al 2009). This category of pollutants is also effectively removed by filter soil media, usually within the first few centimeters, due to partitioning onto organic matter and adsorption onto soil particles. Microbial breakdown and phytodegradation can eliminate hydrocarbons, leading to a mass load reduction of 87% or more (Diblasi et al 2009; Davis et al 2009).

Pathogens – Pathogens, such as protozoa, bacteria, and viruses, are found in stormwater runoff as the result of natural sources and human and animal wastes. Pathogens can pose a risk to human health in recreational waters and can interfere with aquacultural operations. There is limited data on pathogen removal in bioretention facilities, however recent studies have shown that bioretention cells can effectively remove bacterial, viral, and protozoan indicator species (Li et al 2012). Viruses and protozoa can be reduced by a factor of 1000, likely due to filtering of protozoa and of particle-bound viruses. Bacteria can be reduced by a factor of 10-100, though removal efficiency seems to be lower in vegetated systems (Li et al 2012).

2.2. Components and Characteristics of Soil Media

The pollutant removal efficiency of the system is largely determined by the characteristics of the soil media. The soil media is often generally specified as a sandy loam or loamy sand per USDA texture classifaction or a blend of this soil type with sand and/or compost (CIRIA 2007; NHDES 2008; MDE 2009). The sandy loam and loamy sand texture classes roughly describe soils that are 55-90% sand, 0-35% silt, and 0-20% clay (Figure 2). The sorption potential of the soil, which is critical in removing dissolved pollutants like metals and nutrients, is a function of the soil's clay and organic matter content as well as the amount of iron and aluminum oxides it contains (Borggard and Elberling 2004).

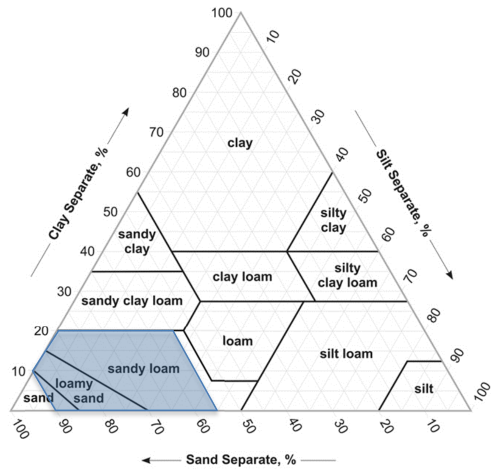

Figure 2 - USDA Soil Texture Triangle with typical bioretention soil textures highlighted

There are many trade-offs involved in a soil media mix design. High clay content will increase cation adsorption but will reduce soil permeability and can cause cracking and the formation of macropores that allow water to bypass treatment. Increased organic matter content will also improve sorption, soil structure, and is beneficial to vegetation, but will decompose over time and leach nutrients and pollutants adsorbed to dissolved organic carbon (DOC). Cation exchange capacity (CEC), DOC, and metal mobility are also pH dependent so an intermediate pH must be attained that maximizes sorption potential and minimizes pollutant solubility (Borggaard and Elberling 2004; Ingvertsen 2012b). Many early bioretention design guidelines focused on the permeability of the soil and the sorption benefits of organic matter, but ignored the more advanced chemical parameters (CEC, pH, iron and aluminum oxide content) that contribute to optimal performance.

Sand – Sand makes up the largest portion of the soil mix by mass and ensures the high permeability that is necessary for the soil's proper hydraulic function. It can mechanically filter particulate pollutants but does not contribute to the adsorption potential of the soil media. Laboratory columns studies have found that a bioretention media composed entirely of sand can provide better removal of oil and grease, TSS, and Pb than soil-based medias (Hsieh and Davis 2005). This is likely due to the fact that these pollutants are primarily removed by filtration in the top layers of a soil media.

Clay – Clay is a major contributor to the adsorption potential of the media, but it reduces soil pore size and can swell in the presence of moisture, drastically lowering hydraulic conductivity. Low hydraulic conductivity negatively affects the hydraulic performance of the facility but increases hydraulic retention time, which is important for the removal of many pollutants (Hunt et al 2012). During periods of extended drought, soils with high clay content may also dry out and crack. Water will preferentially flow through cracks and fissures, bypassing the soil matrix where a majority of treatment occurs. In some design procedures, the size of bioretention facilities is dictated by the infiltration rate of the media (WSDOE 2012). Therefore, the infiltration rate must be maximized with respect to the pollutant removal goals to optimize the system performance. Clay and silt are also important to the retention of nutrients, which are necessary for plant growth.

Organic Matter – Soil organic matter is composed of living and dead microorganisms, plant, and animal material and is more than half carbon by mass (Borggaard and Elberling 2004). It is one of the most chemically active constituents in soil and contributes to its sorption capacity. Microbial cells have been shown to have higher sorption values for metals than clay, illustrating the important contribution organic material makes toward a soil's CEC (Gadd 2008). Organic matter is also an important carbon source for microorganisms, promotes vegetative growth, and helps buffer soil pH (Borggaard and Elberling 2004). For these reasons, many bioretention soil media specifications have called for amendment with vegetative compost.

Recent research efforts have challenged the importance of organic matter, showing that organic matter may cause leaching of nutrients and long-term export of metals. In an early optimization study, organic matter content could not be correlated with TP removal (Hsieh and Davis 2005). A later optimization study showed that a sandy loam soil media with 20% compost and mulch caused a net production of nitrate and phosphate over time and performed much worse for TP and TN removal than a sandy loam soil media (Bratieres 2008). This was attributed to the leaching of phosphate and nitrate from decomposing organic material. The study did not look at metal removal, which theoretically should be improved by organic material, especially for more soluble metal ions like copper and zinc (Li and Davis 2008). Recent studies in the U.S. have cautioned against high organic matter content and have recommended upper limits on soil phosphorus content that are based on vegetation nutritional requirements (Hunt and Lord 2006; Hinman 2009). Additionally, the breakdown of organic matter produces DOC, which may cause the leaching of heavy metals bound to DOC (Li and Davis 2008; Ingvertsen 2012b).

pH – The pH of a soil media greatly determines sorption potential of many pollutants. Acidic soils cause a decrease in phosphorus and metal sorption but an increase in DOC sorption, which is tied to metal sequestration (Davis et al 2006; Ingvertsen et al 2012b). Additionally, CEC increases with pH (Borggaard and Elberling 2004). Soil pH can be raised with the addition of lime and lowered with the addition of iron sulfate. Most guidelines specify a pH range of approximately 5.5-7.0 to encourage pollutant sorption and microbial activity (PDEP 2006). This range is perhaps too acidic as many metals become much more soluble when soil pH is below 6 (Borggaard and Elberling 2004). A target pH of 6.5 has been suggested to balance DOC mobility with heavy metal adsorption (Ingvertsen et al 2012b).

Aluminum and Iron Hydroxides – Aluminum and iron hydroxides in a soil media can effectively bind metals, DOC, and can precipitate phosphorus (Hinman 2012; Hunt et al

2012; Ingvertsen et al 2012b). However, this important contributor to soil media sorption has been neglected from design guidelines until very recently. It has been suggested that iron and aluminum oxide soil content can be increased by amending soils with water treatment residuals (Hunt et al 2012). However, these substances are fine-textured and can cause a reduction in soil permeability (Hinman 2012). Also, there is a risk of aluminum leaching, especially if anoxic conditions occur in the soil media.

Other Additives – The addition of additives to improve permeability and adsorption potential has been little explored but could improve soil media retention of metals, DOC, or nutrients. Australian researchers at the Facility for Advancing Water Biofiltration (FAWB) at Monash University, Melbourne have added two minerals, vermiculite and perlite, to soil media to increase CEC. The additives have demonstrated a marginal improvement in metal removal but not nutrient removal (Hatt 2007; Brateries 2008).

2.3. Other Design Considerations

Media Depth – Theoretically, the media depth should play an important role in the effectiveness of the bioretention system since a thicker soil section will provide more opportunities for adsorption, filtration, and contact with decomposing microorganisms. Several studies have shown that most removal of TSS, heavy metals, oils, greases, and hydrocarbons occurs in the first 20 cm of the media (Davis et al 2003; Li and Davis 2008; Davis et al 2009). The results of early studies suggested that phosphorus, total Kjeldahl nitrogen (TKN), and ammonia removal were dependent on media depth and increased up to a depth of 60–80 cm (Davis et al 2006). These results were contradicted by later studies, which could find no correlation between media depth and TSS, ammonia, organic nitrogen, or TP/phosphate removal (Bratieres et al 2008; Khan et al 2012). In some tests, deeper soil mixes were shown to actually leach more nitrate. The same tests showed that the performance of deeper soil media did improve over time, suggesting that a shallow media layer may become saturated with pollutants and start leaching earlier than a deeper section (Bratieres et al 2008).

Many guidelines require a moderate soil media depth of approximately 50 cm but recommend deeper sections for enhanced pollutant removal or to support tree roots

(CIRIA 2007; MDE 2009; Hinman 2012). The soil media depth requirement is important not only for water quality goals but also for hydraulic considerations. By requiring an unnecessarily deep soil section, regulators might make bioretention infeasible for many projects that do not have adequate elevation difference between the water inlet and point of discharge. There are also additional construction costs and potential groundwater impacts associated with deeper soil media layer.

Mulch Layer – Many bioretention guidelines require a thin layer of vegetated wood mulch to be spread across the surface of bioretention cell. The mulch layer is typically specified to be shredded or chipped hardwood and often has an age requirement of 6 to 12 months. These guidelines recommend the surface mulch layer for various reasons including protection from weeds, erosion, and desiccation. The mulch also acts as an easily removed and replaced layer that contains a large portion of the accumulated metals and PAHs (Li and Davis 2008; Diblasi et al 2009). Some studies suggest that the surface mulch is instrumental in the removal of TKN and oils and greases (Davis et al 2006; Davis 2007). Hydrophobic compounds like hydrocarbons readily partition into the organic matter in the mulch where they are broken down by microbial activity and sunlight.

Vegetation – Healthy vegetation is important to the success of the system as roots improve soil structure and maintain long-term soil infiltration capacity (Davis et al 2006). Also, plant uptake of phosphate and nitrate represents an important removal pathway for these two intractable pollutants. Plant selection has been shown to make an enormous difference in nitrate and phosphate removal in column studies, with average percent-removal greater than 90% for both nutrients (Bratieres et al 2008). Also, trimming and removal of vegetation provides an important sink of nitrogen, phosphorus, and metals (Davis et al 2006; Muthanna et al 207).

2.4. Development of Bioretention Design Guidelines

The stormwater bioretention system was developed in the early 1990s in Prince George County, Maryland, where stormwater pollution to the Chesapeake Bay is a high-priority environmental concern (Hinman 2005). In the years that followed its development, a shift toward integrated urban stormwater management was observed in many regions. Paradigms like Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS), and Water Sensitive Urban Drainage (WSUD) became popular in the U.S, U.K. and Australia, respectively. The bioretention system became a central tool in many of these movements due to its ability to treat and infiltrate stormwater. In the early and mid-2000s, many environmental authorities throughout the world had adopted elements of the preliminary design guidelines that were in effect in Maryland (ARC 2003; UPRCT 2004; Hinman 2005).

Meanwhile, ongoing research efforts have investigated the hydrologic and water quality performance of bioretention systems. Much of the early research published on bioretention came from the University of Maryland and focused on proof-of-concept testing though some optimization studies were made (Davis et al 2001; Davis et al 2003; Hsieh and Davis 2005; Davis et al 2006). In the mid-2000s, there were renewed efforts to optimize bioretention soil media, motivated partly by poor nutrient removal performance in many field studies (Hunt et al 2006; Hunt and Lord 2006; Bratieres et al 2008; Hatt et al 2009). Most of this research has come from North Carolina State University and the University of Monash, Melbourne. Other recent research efforts from various institutions have attempted to improve bioretention performance by taking into consideration local environmental conditions like cold climates, native vegetation, and local soil and aggregate quality (Roseen 2006; Hinman 2009; Read et al 2010).

The findings of research efforts are often first incorporated into the design guidelines of the nearest regulatory entity. For instance, findings from researchers at North Carolina State University were first included in the North Carolina Stormwater BMP Manual, but these have since been adapted by the City of Toronto and the State of Washington (Hunt and Lord 2006; NCDENR 2007; TRCA 2010; Hinman 2012). There is an inherent time lag between when the results of a study are published and when they are included in regulatory guidelines. Also, many regulatory entities update their codes infrequently, further increasing the time lag between scientific understanding and regulatory enforcement.

3. METHODS

The selection of the most relevant bioretention design guidelines was based on an extensive review of the scientific literature on the subject, relevance in internet searches, and the experience of the author and project supervisor with stormwater design in the U.S. and Europe. The selection was mostly limited to publicly available guidelines that were published in English. Ten bioretention soil media guidelines were selected for comparison. Five of the ten are from the United States. These were selected because they are among the most relevant guidelines in the U.S. and they represent different regions (West Coast, Midwest, East Coast). Five additional guidelines were chose from authorities in Australia, Canada, Denmark, Germany, and the U.K. The analysis has been conducted from a U.S. perspective, and as such the guidelines have been organized into a "U.S." group and an "International" group. Table 1 lists the jurisdictional location, publication name and year, and responsible entity for the guidelines considered in this study. Figures 3 and 4 show the geographical location of the various guidelines' authority.

This paper is primarily focused on the soil media component of bioretention facilities and does not consider hydrologic sizing, pretreatment, or structural elements like underdrains, liners, or overflows. Additionally, a saturated, anoxic zones below the soil media have been shown to increase nitrate removal, however, this design variation is not explored (Kim et al 2003). Vegetation plays an important role in performance of bioretention facilities and is generally discussed, but plant selection is not explored in detail as this is highly dependent on climate, region, and end-user maintenance and aesthetic preferences.

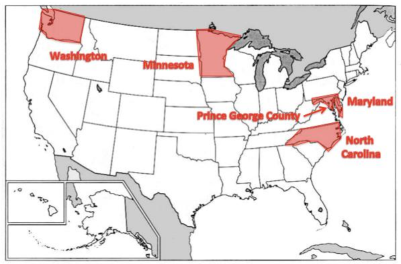

Figure 3 - Locations of U.S. Bioretention Guidelines

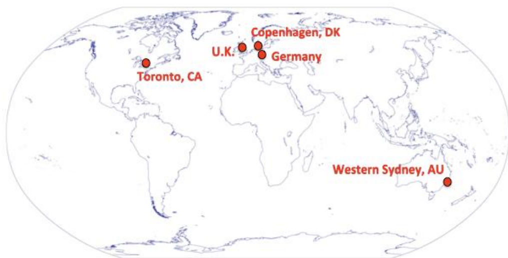

Figure 4 – Locations of International bioretention guidelines

Location	Publication Name	Publication Year	Authority/Author
Minnesota State, USA	The Minnesota Stormwater Manual	2005	Minnesota Pollution Control Agency (MPCA). (2005)
North Carolina State, USA	Stormwater Best Management Practices Manual	2007	North Carolina Department of Environment and Natural Resources (NCDENR)
Prince George County, USA	Bioretention Manual	2009	Prince George County Department of Environmental Resources (PGCDER).
Maryland State, USA	2000 Maryland stormwater design manual, volumes I and II (revised 2009)	2009	Maryland Department of the Environment (MDE).
Washington State, USA	Low Impact Development Technical Guidance Manual for Puget Sound	2012	Curtis Hinman. Washington State University Pierce County Extension
Western Sydney, Australia	Water Sensitive Urban Design Technical Guidelines for Western Sydney	2004	Upper Parramatta River Catchment Trust (UPRCT).
Germany	Standard DWA-A 138E	2005	German Association for Water, Wastewater and Waste (DWA)
United Kingdom	The SUDS Manual	2007	Construction Industry Research and Information Association (CIRIA)
City of Toronto, Canada	Low Impact Development Stormwater Management Planning and Design Guide	2010	Toronto and Region Conservation Authority (TRCA)
Copenhagen, Denmark	Regnbede (Rain Beds)	2011	Københavns Kommune

Table 1 – International Bioretention Guidelines

Two of the most referenced design manuals in Australia are "Water Sensitive Urban Drainage Systems Engineering Procedures: Stormwater" (2005) by Melbourne Water and "Australian Runoff Quality: A guide to Water Sensitive Urban Design" (2006) by Engineers Australia. These manuals are only available for purchase and could not be included in this study. The manual "Water Sensitive Urban Design Technical Guidelines for Western Sydney" (2004) by the Upper Parramatta River Catchment Trust has been used instead, though it does not appear to have the same level of authority in Australia as the other manuals. Furthermore, the Facility for Advancing Water Biofiltration (FAWB) at Monash University, Melbourne has contributed a large amount of quality research toward the recent study of bioretention systems, but it is unclear where that research is represented in Australian regulatory guidelines. Most of the FAWB's research has been published since the publication dates of the Melbourne Water and Engineers Australia manuals.

Most bioretention guidelines have requirements for soil media depth, media composition (sand, silt, clay, compost, etc.), organic matter content, pH, infiltration rate, and a surface mulch layer. Recently updated guidelines may also have requirements for cation exchange capacity, phosphorus index, and iron and aluminum oxide content. As has been previously discussed, these factors are critical to the pollutant removal performance of bioretention systems and they have therefore been chosen as comparison categories. Most manuals include extensive discussions of site selection and appropriateness, facility sizing, piping appurtenances, and landscaping, however these topics have been mostly excluded from this paper.

4. RESULTS AND DISCUSSION

The soil media requirements from each of the guidelines have been summarized in Tables 2 and 3. Table 2 summarizes the five U.S. guidelines considered and Table 3 summarizes the international guidelines.

4.1. United States Bioretention Soil Media Guidelines

The most outstanding feature among the U.S. bioretention guidelines is the high content of compost in the media composition specifications. Four of the five specifications require the mix to be approximately one-third compost. The compost is included to encourage healthy vegetation and microbial activity and to increase adsorption potential, but as has been discussed, compost amendment has been linked to nutrient export and long-term leaching of DOC-bound heavy metals (Bratieres 2008; Ingvertsen 2012b). The mix design recommended in the Washington guidelines might be difficult to achieve, given the high compost content (35-40% by volume) and the low organic matter content (1-8% by mass). The North Carolina specification does not recommend mixing with compost and instead requires relatively low organic matter content (1-3% by volume). The North Carolina guidelines were influenced by the research of Hunt and Lord (2006) who linked poor nutrient removal with compost-rich soil medias that have a high phosphorus-index value. This explains why North Carolina is the only U.S. State to specify an upper and lower limit on the phosphorus content in the soil. North Carolina recommends a phosphorus content in the soil that is theoretically high enough to

Table 2 – Summary of U.S. Bioretention Soil Media Guidelines

	Media Composition (percent content is by mass unless otherwise noted)	Organic Matter (by mass)	pH	Soil Depth (cm)	Permeability (cm/hr)	Other Requirements
Minnesota State (MPCA 2005)	A) Sand (55-65%)[a], sandy loam, loamy sand, or loam topsoil (10-20%)[a], organic leaf compost (25-35%)[a] B) Sand (50-70%)[a], organic leaf compost (30-50%)[a]	-	5.2 – 7.0	76 – 132[g]	-	
North Carolina State (NCDENR 2007)	Sand (85-88%)[b], silt + clay (8-12%)[b], organic matter (3-5%)[b]	1.5 – 3[c]	-	61 – 91[g]	2.5 - 15	• Soil media must have a phosphorus index of 10-30 • The silt + clay content can be increased to provide better N removal
Prince George County (PGCDER 2009)	Sand (50-60%)[b], topsoil (20-30%)[b], leaf compost (20-30%)[b]. Less than 5%[a]	-	5.5 – 6.5	>46	2.5 – 25[d]	
Maryland State (MDE 2009)	A) loamy sand (60-65%)[a], compost (35-40%)[a] B) sandy loam (30%)[a], coarse sand (30%)[a], compost (40%)[a] Less than 5%[a] clay	>10%[a]	5.5 – 7.0	61 – 122[g]	-	
Washington State (Hinman 2012)	Sand[f] (60-65%)[b], mature, stable compost (35-40%)[b]	1-8%	5.5 – 7.0	46 – 61[g]	2.5 – 30[e]	• CEC greater than 5meq/100g dry soil • Molar ratio of ammonia oxalate extracted P to ammonia oxalate extracted Fe and Al less than 0.25

a – percent is not specified as “by volume” or “by mass”
b – percent is by volume
c – percent is estimated by converting volume percentage to mass percentage
d – permeability is described as “infiltration rate”
e – permeability is described as “saturated hydraulic conductivity”
f – sand with 2-5% silt + clay content, by mass.
g – depth varies per plant requirements. Trees require deeper soil section.

Table 3 – Summary of International Bioretention Soil Media Guidelines

	Media Composition (percent content is by mass unless otherwise noted)	Organic Matter (by mass)	pH	Soil Depth (cm)	Permeability (cm/hr)	Other Requirements
Western Sydney (UPRCT 2004)	A) Loam/sand (35-60% sand) B) Sand or sand/gravel Less than 25% clay	-	-	100[e]	-	If a sand or sand/gravel mix is used a 10 cm planting soil mix must be included at the top of the media.
Germany (DWA 2005)	Fine or medium sand No coarse sand or gravely material Less than 10% clay + silt	1 - 3	6 - 8	10 – 30	greater than 3.6[c]	
United Kingdom (CIRIA 2007)	Sandy loam or loamy sand conforming to: Sand (35-60%)[a], silt (30-50%)[a], clay (10-25%)[a]	0 – 4%[a]	5.2 – 7.0	100 – 150[d]	greater than 1.3	A 30 cm sand filter is required below the soil media
City of Toronto, Canada (TRCA 2010)	Sand (85-88%), silt + clay (8-12%), organic matter (3-5%)	3-5%	5.5 – 7.5	50 – 125[d]	greater than 2.5[b]	• CEC greater than 10meq/100g dry soil • Soil media must have a "phosphorus index" of 10- 30 ppm
Copenhagen, Denmark (København 2011)	Topsoil mixed with coarse sand (50%)[a] and compost (20-30%)[a]. Less than 10%[a] clay	-	5.5 – 6.5	55 - 85	-	A 5-10 cm layer of top soil is placed over a 50-75 cm "growth soil"

a – percent is not specified as "by volume" or "by mass"
b – permeability is described as "infiltration rate"
c – permeability is described as "saturated hydraulic conductivity"
d – depth varies per plant requirements. Trees require deeper soil section.
e – minimum depth not provided. 100 cm included as this was the initial assumed value in example calculations

support plant growth without leaching excess P (Hunt and Lord 2006). The guideline provides no about the test procedure used to determine the P-index and it is unclear what the P-index actually represents.

Another major issue with the soil composition specifications is the inconsistent or omitted information on whether percentages are by mass or volume. Minnesota and Maryland do not indicate anywhere in their guidelines if the soil/compost blend is by mass or by volume. This is of critical importance since compost is approximately half as dense as soil (Hinman 2012). The ambiguity could increase or decrease soil organic matter content by a factor of 2 relative to the intended mix design. Prince George County, Washington, and North Carolina all use a volume-based mix specification since this is often a contractors preferred method for calculating soil amendment ratios. However, the North Carolina specification provides gradation information (sand, silt, clay, and organic mater), which is typically quantified by mass. Given the difficulty in determining the volume of the different soil gradations, it is likely that the guideline erroneously calls for the mix to be by volume. The mix specification was based on recommendations in Hunt and Lord 2006, but this study does not state if it is to be by volume or mass. The City of Toronto has also used the recommendations of Hunt and Lord 2006 in its guidelines, but it has interpreted the mix as mass based (refer to Table 3). This apparent error will likely cause confusion among contractors and could lead to underperforming bioretention systems.

The U.S. guidelines have similar required soil media depths. The North Carolina, Maryland, and Minnesota manuals require deeper sections that could limit their use in vertically constrained projects. The North Carolina manual justifies the deeper soil media by claiming improved N removal, which has not been conclusively demonstrated in laboratory or field studies. Given that much of the metal, hydrocarbon, and TSS removal occurs in the upper layers of the mix, the deeper soil sections might be excessive and counterproductive (Li and Davis 2008).

The specifications have many similarities, which is likely due to the influential nature of early pioneering studies in Maryland. Each of the guidelines requires or recommends a thin mulch layer at the surface, though the reasons for it vary. Common explanations include weed and erosion control, protection from desiccation, and pretreatment. The guidelines also specify a similar soil pH range of approximately 5.5 to 7.0. This allows soils that are too acidic and could lead to metal leaching, especially in Minnesota which allows soil acidity up to 5.2. All of the guidelines that specify an infiltration rate use the same lower limit (2.5 cm/hr), but Washington and Prince George County allow higher infiltration rates. The higher upper limits are justified by citing studies like Davis et al 2003 and Hsieh and Davis 2005, which found good removal of several pollutants using high permeability soil media.

The Washington guidelines have additional requirements that relate to the soils adsorption capacity and long-term nutrient and metal retention. The guidelines require that the soil have a minimum cation exchange capacity of 5 milliequivalents per 100 g of dry soil. Cation exchange capacity is determined by clay and organic matter content, so the CEC requirement should be achieved by meeting the soil composition mix design. The CEC requirement is therefore a second measure to ensure that the soil will properly remove and sequester metals and other cations. The Washington guidelines also have a provision to ensure that the molar ratio of ammonia oxalate extracted P to ammonia oxalate extracted Fe and Al be less than 0.25. This ensures that the soil has capacity to adsorb and precipitate P by maintaining a surplus of iron and aluminum oxides. Soils that do not meet the requirement can be improved through the addition of water treatment plant residuals, which typically are composed of Al and Fe precipitates. The manual cautions that water treatment residuals are fine textured and can potentially clog the soil media, so it recommends infiltration tests be performed if the residuals are to be added. This is an innovative use of a waste product to improve bioretention soil performance, but there appears to be limited understanding of how the addition of Fe and Al precipitates might interact with other factors like permeability or how it will behave if anoxic conditions develop.

4.2. International Bioretention Soil Media Guidelines

The international bioretention guidelines differ from the U.S. guidelines in that they tend to simply specify a soil texture class (most often loamy sand, sandy loam or a combination thereof) instead of a blend of soils, sands, and organic materials. The Danish guideline is the exception, requiring a blend of soil, sand, and compost in similar proportions to the Prince George County specification. As with the U.S. guidelines, the Danish specification could cause nutrient leaching over time

The U.K. and Western Sydney guidelines have many shortcomings and appear to be outdated. The guidelines call for an excessively thick soil media, which could limit their application. They also allow high clay content (25%), which could compromise the permeability of the soil media. The U.K. guideline references an early U.S. bioretention design manual (Clayton and Schueler 1996), which fell out of favor in the U.S. in the mid-2000s because the high clay content it recommended caused failure of many systems (Davis et al 2009). The Western Sydney guideline refers to the Auckland, New Zealand stormwater manual soil specification (ARC 2003). Upon further investigation, the New Zealand guideline also references the Clayton and Schueler 1996 manual, explaining the high upper limit on clay content. The U.K. and Western Sydney guidelines are based on outdated material and are likely leading to the construction of low-permeability bioretention cells. The Western Sydney guideline also allows for a sand and gravel media with an upper 10 cm thick planting layer. The sand and gravel layer will likely not provide sufficient filtration or adsorption of pollutants and the thin planting layer may provide low pollutant removal and will be too thin for many plant species.

As was mentioned previously, the Toronto guideline uses the recommendations of Hunt and Lord 2006, including the P-index limits and minimum CEC. The Toronto manual states that the P-index range be 10-30 ppm, interpreting the values suggested in Hunt and Lord 2006 as concentration and not as a unitless index. Hunt and Lord are vague on the testing procedure needed to determine P-index, but a P content of 10-30 ppm is moderate for most soils and the City of Toronto’s interpretation may not be a cause for concern. The soil composition specification roughly describes a loamy sand with low organic content. A soil media that complies with this specification should have high permeability and filtration capacity as well as low potential for metal or nutrient leaching. The recommended soil media depth is 100 cm but a minimum depth of 50 cm is allowed for constrained sites, allowing design flexibility. This soil media specification appears to be promising and is well defined.

The German soil specification describes a sand or loamy sand with a very low organic matter content. It should therefore provide good filtration and little leaching, however, may not be suitable for vegetative growth or pollutant sorption. Excessive accumulation of metals in the soil could also be an issue, given the thin media depth. The German guidelines allow soil acidity up to a pH of 8. Basic soils such as these will not provide much retention of DOC and could possibly limiting vegetative growth. The German guidelines do not allow soil acidity to be as high as other guidelines, which should improve heavy metal retention. The thin soil section may also have a reduced life expectancy due to its lower capacity to retain accumulated pollutants.

4.3. General Discussion

As bioretention guidelines are updated and improved, it is likely that more will require a minimum cation exchange capacity and limits on P content. These are convenient quality control parameters that can help ensure the high removal of TSS, heavy metals, and hydrocarbons, without the leaching of nutrients that has been observed in many performance studies. Requirements on the amount of iron and aluminum hydroxides in bioretention soils could further improve nutrient, metal, and DOC retention in soils. There seems to be a growing consensus in the literature that optimum treatment performance can be achieved by using a loamy sand or sandy loam soil with low organic matter and proper plant selection (Hunt and Lord 2006; Bratieres et al 2008). The soil specifications used in the relatively new North Carolina and Toronto manuals are the result of this shift in thinking. As new bioretention facilities are constructed per these new guidelines, performance monitoring and plant survivability will help confirm if compost amendment is a necessary component of bioretention soil media.

As soil media specifications become more complicated and demanding, there could also be a problem with compliance. There are many characteristics of a soil media that must be balanced (clay content vs permeability, organic matter content vs P–index) and the more parameters that are constrained the harder it will be for a contractor to meet a specification. This could lead to an increase in the cost of bioretention systems and decreased popularity among developers and designers.

Due to the wide variety of plants, soil characteristics, and precipitation patterns experienced throughout the world, there is not a single bioretention guideline that can be universally adopted. For instance, plants in Australia are better adapted to low-nutrient conditions, so bioretention soils should have a lower P content than in other parts of the world. In the Pacific Northwest of North America, dry summer seasons can cause desiccation of soil media and lead to the formation of cracks in soils with too much clay. Significant pollutant removal reduction has been observed following protracted dry periods (Blecken et al 2009; Li et al 2012). Systems in drought-prone areas could prevent dry out by having less vegetation. Bioretention guidelines will have to be further refined to reflect the environmental conditions of the relevant region.

There is also little discussion in the guidelines about the specific water quality concerns that are being addressed by stormwater treatment facilities. The design of a bioretention facility should be targeted toward the pollutants of concern in the receiving water body or aquifer. Systems that discharge to a eutrophic water body may need additional design elements and increased complexity to provide enhanced nutrient removal. Systems that infiltrate into underlying soils may target heavy metals to avoid contamination of aquifers. The specific target pollutant has major implications for the soil media composition, and therefore the cost and testing required to prove compliance.

There is also limited knowledge about the life expectancy of bioretention systems. Older bioretention systems will accumulate metals and some PAHs over time, possibly to harmful concentrations. Estimates of bioretention system life expectancy suggest that they can operate for more than 16 years before pollutant accumulation becomes a problem but there is little knowledge of mature systems (Davis et al 2003; Ingvertsen 2012a). None of the guidelines included in this study had recommendations for the replacement or decommissioning of old bioretention systems, pointing to the fact that this is an area that needs improved understanding. Many guidelines, particularly in the U.S., require replacement of the mulch layer every two to three years. It has been shown that the mulch layer and the first few centimeters of the soil media contain a high percentage of accumulated metals and PAHs, so this maintenance activity could indefinitely extend the life of bioretention facilities (Hunt et al 2012).

5. CONCLUSIONS

The widespread popularity of concepts like Low Impact Development and Water Sensitive Urban Design have driven the use of bioretention systems throughout the world. Since the first bioretention systems were installed, knowledge about their performance and design has evolved significantly. However, this knowledge has not been incorporated into many regulatory guidelines, leading to sub-optimal systems. Many guidelines, such as Western Sydney and the U.K. SUDS Manual, have not been updated in many years or rely heavily on outdated research. The rate of scientific inquiry into the topic has increased but some regulatory entities have kept pace, providing a paradigm for other jurisdictions throughout the world.

Bioretention systems effectively remove TSS, hydrocarbons, and heavy metals, though they often have low removal of nutrients. Inconsistent nutrient removal is beginning to be attributed to nutrient leaching, caused by high organic matter content in the soil media. Some design guidelines, like North Carolina State and the City of Toronto, have been updated to require lower organic matter in the hopes of improving performance. These guidelines also include new requirements for phosphorus content testing and cation exchange capacity, to ensure that the pollutant removing properties of the soil media are maintained despite the reduced organic matter. Washington State has also requires soils have a relatively high amount of aluminum and iron hydroxides, which improve sorption and pollutant retention. Further research will explore the feasibility of using water treatment byproducts that are high in aluminum and iron hydroxides to amend soils.

Though universal design guidelines for bioretention systems may not be appropriate given the variability of global environmental conditions, certain physical, chemical, and biological properties must be controlled to optimize system performance. A thorough bioretention design manual should provide recommendations for soil composition, clay content, organic matter content, pH, required media depth, CEC, P-index, and iron and aluminum oxide content. Though imperfect, the most recent guidelines from the City of Toronto and Washington State incorporate much of the current thinking on bioretention systems and should stand as an example to other regulatory authorities. Understanding of these systems is ever evolving and it is anticipated that substantial design improvements will continue to develop for decades.

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