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Filter Media Specifications for Low Impact Development: A Review of Current Guidelines and Applications

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LID 시설 여재에 관한 기술지침 및 적용에 관한 고찰

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Abstract

A primary aspect of low impact development (LID) design that affects performance efficiency, maintenance frequency, and lifespan of the facility is the type of filter media as well as the arrangement or media profile. Several LID guidelines providing media specifications are currently available and numerous studies have been published presenting the effectiveness of these systems. While some results are similar and consistent, some of them still varies and only a few focuses on the effect of filter media type and arrangement on system performance. This creates a certain level of uncertainty when it comes to filter media selection and design. In this review, a synthesis of filter media specifications from several LID design guidelines are presented and relevant results from different laboratory and field studies are highlighted. The LID systems are first classified as infiltration or non-infiltration structures, and vegetated or non-vegetated structures. Typical profiles of the media according to classification are shown including the different layers, materials, and depth. In addition, results from previous studies regarding the effect of filter media characteristics on hydraulic and hydrologic functions as well as pollutant removal are compared. Other considerations such as organic media leaching, clogging, media washing, and handling during construction were also briefly discussed. This review aims to provide a general guideline that can contribute to proper media selection and design for structural LIDs. In addition, it also identifies opportunities for future research.

Key words : LID facilities, filter media spec, guidelines, media selection, performance

요 약

LID 시설의 성능, 유지관리 빈도 및 수명에 가장 큰 영향을 미치는 1차적인 인자는 여재의 형태 및 구성(깊이 및 profile)일 것이다. 여재 스펙에 관련된 규정 및 정보를 제공하는 지침이 있으며 여재의 효과를 입증하려는 수많은 연구가 진행되고 있다. 일부의 연구결과는 서로 유사하거나 일관성이 있으나 일부는 전혀 다른 결론에 도달하고 있으며 매우 적은 연구가 여재의 형태 및 조성이 성능에 미치는 영향에 초점을 맞추고 있는 실정이다. 이와 같은 상황은 오히려 여재의 선정이나 설계하는데 불확실성과 혼란을 유발하고 있다. 이와 같은 관점에서 본 논문에서는 다양한 문헌과 실험실 및 현장 경험을 토대로 여재 스펙 및 구성을 종합적으로 분석하여 제시하였다. 먼저 LID 시스템을 침투 및 비침투 구조, 그리고 식생형 및 비식생형으로 분류하였다. 분류에 따르면 일반적인 여재 Profile을 여재층의 구성, 재료 및 깊이에 따라 고찰하였다. 또한 여재특성이 수리 및 수문학적 기능뿐 만 아니라 오염물질의 저감에 미치는 영향을 비교 분석하여 제시하였다. 유기물질의 침출로 인한 막힘, 여제 세척, 시공 중의 취급 등 기타 고려사항에 대해 간략하게 서술하였다. 본 고찰의 목표는 LID 시설을 설계할 때 적절한 여재를 선정하는데 일조하기 위함이며 또는 장래에 필요한 여재연구방향을 제시하는데 있다.

핵심용어 : LID 시설, 여재스펙, 여재층, 지침, 여재의 선정, 여재성능

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1. Introduction

Rapidly increasing urban expansion has disturbed and replaced natural pervious landscapes with impervious surfaces causing several issues regarding stormwater runoff management (Dietz, 2007; USEPA, 2001). The ensuing alterations in natural hydrologic systems and their processes have become apparent through frequent flooding, declining base flows, and surface water quality impairment (Brabec, 2002; Sharma, 2017; Shuster et al., 2005). This has led stormwater engineers towards green and sustainable solutions such as low impact development (LID) in the US with similar concepts known as Water Sensitive Urban Design (WSUD) in Australia and Sustainable Drainage System (SUD) in the UK. The underlying basic principle to this approach is to keep post-development hydrology close to pre-development conditions by using decentralized small-scale practices to manage the runoff volume and flow on-site and avoid transporting diffuse contaminants into receiving waters (USEPA, 2017).

One major aspect in LID design that affects performance efficiency, maintenance frequency, and lifespan is the type and configuration of the media profile within the system (Fassman-Beck et al. (2015). Aside from facilitating physical, chemical, and biological processes that improves the quality of stormwater runoff passing through, the media also defines the hydraulic capability of the structure which determines how it will function under different flow conditions (Brown and Hunt, 2011). Moreover, they also provide other structural and aesthetic benefits.

While numerous types of literature are available summarizing LID performance in different parts of the world, only a few provides a review that focuses on the filter media and the effect of filter media selection and configuration on system performance (Pitt and Clark, 2010). That said, the optimum media type, depth, and arrangement should vary because of varying drainage area and rainfall characteristics as well as hydraulic and water quality goals. Other factors to consider include the type of vegetation, potetial leaching of organic matter and nutrient, clogging, and handling of the media during transport and construction. Therefore, a synthesis of recent literature is needed to be able to provide a general guideline that can contribute to proper media selection and design of the media profile for structural LIDs. This review highlights past and current research results focusing on filter media as well as opportunities for future research.

2. Roles and functions of filter media in structural LIDs

The media within a structural LID system has several main functions. The voids and pores between and within the media provides temporary storage of stormwater which helps reduce runoff and attenuate peak flows. They provide space for growth of microorganisms, support for roots, as well as retain moisture for plants. The media also trap solids, heavy metals, organic compounds, and other particle-associated pollutants by filtration, settling, and adsorption (Hsieh and Davis, 2005; Hunt and Lord, 2006). In addition, they provide an environment for biological processes to occur and in cases where organic media is present, they can release sufficient carbon needed for complete nitrogen removal through denitrification (Chen, 2015; Hurley, 2017; Saeed and Sun, 2011). With the right design, the media facilitates proper drainage to avoid premature clogging. Furthermore, materials that are placed on the surface of the system can control erosion and facilitate oxygen transfer (Tetra Tech, 2011).

Depending on the type of LID, the material and layout of the filter media varies. As show in Fig. 1, structural LIDs can be classified according to function as either infiltration or non-infiltration and by whether or not they are vegetated or non-vegetated. Both infiltration and non-infiltration LIDs provide a level of stormwater treatment and are used to improve the quality of runoff before discharge. However, infiltration LIDs are primarily designed to reduce runoff volume and peak

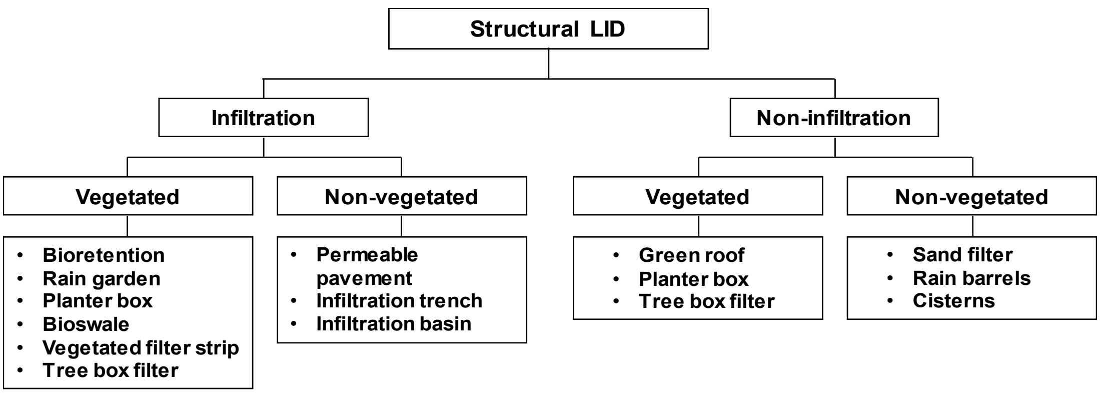
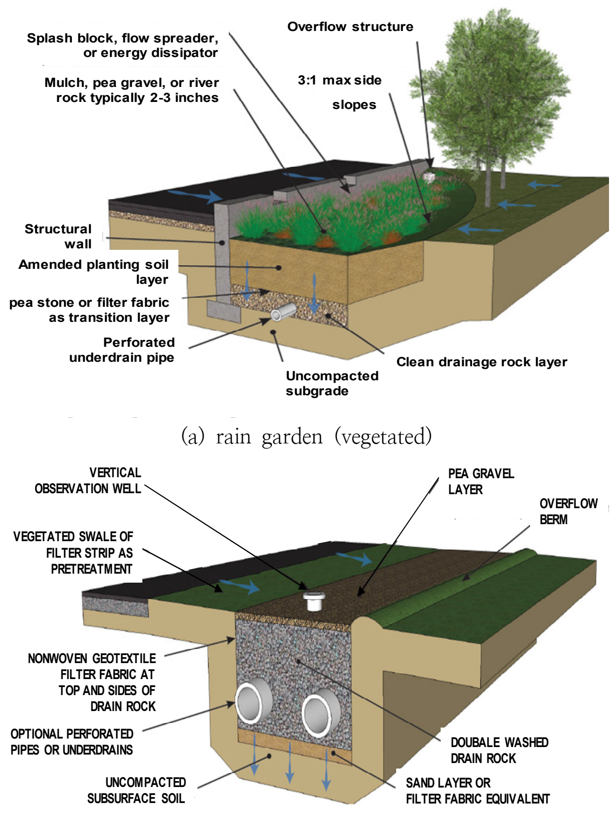


Fig. 1. Classification of structural LIDs

flow by percolation and groundwater discharge. As such, the media in this types of LID should have sufficient voids and pore spaces to be able to provide temporary storage of runoff. On the other hand, non-infiltration LIDs are more focused on physically straining runoff and effectively trapping particles and particle-associated contaminants. They provide filtration through smaller pore spaces and can reduce fine and even soluble constituents through sorptive processes. In this regard, infiltration LIDs tend to have larger-sized media as compared to non-infiltration type. Examples of infiltration LIDs are permeable pavements and infiltration trenches while non-infiltration LIDs include green roofs and tree box filters. It must be noted, however, that the infiltration function depends on the target function. Some structures like stormwater planters can either be designed as infiltration or non-infiltration depending on whether or not the site is safe for groundwater recharge.

Vegetation also plays a role on the type and size of the media. Employing plants or trees for pollutant uptake and added landscape aesthetics entails that soil be present for them to be able to grow and function. For example, bioretention systems are vegetated structures that typically allows infiltration. Thus, the media includes soil as well coarse sand or gravel that are strategically layered to enable filtration, storage, and infiltration in one structure. As a result, transitional layers such as sand or geotextile are often times added in between the small and larger-sized media to prevent premature clogging due to transport of smaller-sized media particles within the voids of the larger ones (City of Edmonton, 2011; Geosyntec, 2014; LADPW, 2014; SEMCOG, 2008; Tetra Tech, Inc., 2011).

For example and comparison, Fig. 2 is provided showing the layout of filter materials in typical infiltration structures. Rain gardens (Fig. 2(a)) which are vegetated typically employ a planting soil layer as the main media. A layer of drainage rocks is placed underneath to facilitate drainage and infiltration and provide temporary storage while the treated stormwater is being discharged slowly. Smaller-sized stones such as pea gravel is placed on top of the soil to act as energy dissipator and to prevent erosion of the soil surface although in most cases, mulch is used since they have the added benefits of retaining moisture and providing oxygen transfer among others. On the other hand, an infiltration trench (Fig. 2(b)) would normally employ a single layer of gravel or crushed rocks and sometimes topped with a pea gravel layer. In both types of LID, the placement of the transition layer also differs. For vegetated types, either filter fabric or pea stones are placed above the drainage layer, between the soil and gravel, to separate the media. Meanwhile in non-vegetated types, filter fabric or sand placed at the bottom of the rock layer to separate it from the underlying in-situ soil.



(a) rain garden (vegetated)

(b) infiltration trench (non-vegetated)

Fig. 2 Filter media profile according to LID type (adapted from AECOM, 2013)

A lot of materials have been investigated as filter media for LID in experimental as well as field studies (Hunter, 2012; Pitt and Clark, Robertson, 2010). The ones that are most commonly suggested in the currently existing design guidelines include ammended topsoil, sand, gravel, and woodchip or mulch. Therefore, experimental and field performances of these materials as well as other types of materials for LID will be discussed in the following sections.

3. Media specifications according to LID type

3.1 Vegetated Structures

The most common type of a vegetated LID structure with infiltration function is the rain garden most often called bioretention. Bioretentions are small-scale water quality and quantity control practices within a shallow depression that utilizes the chemical, biological, and physical properties of plants, microbes, and soils for the removal of pollutants from stormwater runoff (City of Edmonton, 2011; Prince George's County, 2007; USEPA, 1999b). They are generally used to treat runoff from impervious surfaces in urbanized residential and commercial settings (Dietz, 2007, but can also be used for agricultural runoff (Dietz, 2016; Ergas et al., 2010). Some of the processes that take place in a rain garden facility include sedimentation, adsorption, filtration, volatilization, ion exchange, decomposition, phytoremediation, bioremediation, and storage capacity (Prince George's County, 2007).

An example of bioretention design is shown in Fig. 3 as depicted in the LID Manual for Puget Sound, Washington. Typical media configuration includes 3 major parts. A surface layer, the main filtration media, and the bottom layer that facilitates drainage and also serves as a bedding if an underdrain is present. Depending on the in-situ soil infiltration rate and physical constraints, the system may be designed without an underdrain for full infiltration, with an underdrain for partial infiltration, or with an impermeable liner on the sides and an underdrain for filtration only, which can be referred to as a biofilter (CVC, 2010). An advantage of having an underdrain is that the space between the invert and the bottom of the bioretention creates a saturated zone that provides anaerobic conditions conducive for nitrogen removal (Hunter, 2012).

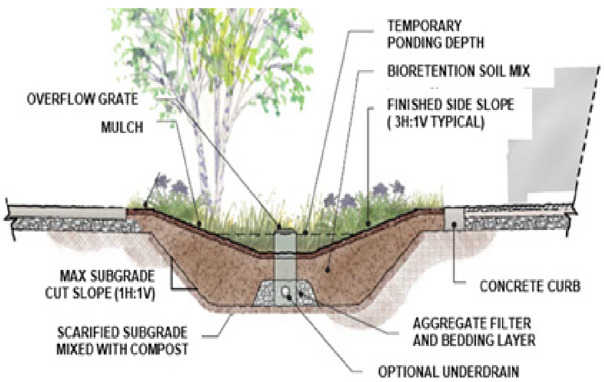


Fig. 3 Bioretention with primary design elements (adapted from Hinman, 2012)

Table 1 shows the different guidelines for these layers in terms of material, depth, and size. It can be seen that the suggested surface layer should be made of 5-10 cm of mulch, the main media should be 50-122 cm soil, and the bottom layer should be up to 30 cm of gravel or stones that are around 4 cm in diameter. Additional features such as gravel strips function as pretreatment especially for structures that receive sheet flow. One key element in most bioretention structures is the transition layer that separates the main media and the drainage layer which are two very different material in terms of size. To prevent bridging, or the movement of soil particles to lower layers of the media profile, a 30-100 cm thick layer of rocks not more than 3 cm in size are placed between the soil and the drainage gravels. As an alternative, a geotextile or filter fabric can also be employed. Filter fabrics placed on top of the drainage gravel bed are used to control sediment transport into the gravel bed, which could otherwise become clogged. According to the Prince George County's (2007) bioretention manual, this filter fabric must meet a minimum permittivity rate of 75 gal/min/ft^2 and must not impede the infiltration rate of the soil medium. If bioretention is used for areas that require protection from groundwater contamination and lateral flows that can potentially damage nearby roads and structural foundations, a low permeability geomembrane liner is applied on the sides and bottom of the structure. It also prevents seepage of saline groundwater into the bioretention as this could affect the integrity of the soil profile and propagation of plants (Hunter, 2012).

Another common type of vegetated infiltration LID is the planter box. A planter box, sometimes called stormwater planter or box planter, is a box-like structure made of concrete, brick, clay, or other stable material and contains soil, gravel, and vegetation. It functions similarly to a bioretention system in terms of using plants, soil, and microbes to minimize runoff and reduce pollutants from stormwater runoff. However, they are typically enclosed either above or below ground on the side of buildings or along sidewalks. They are typically design to accommodate and treat more frequent, smaller rainfall events (City of Edmonton, 2011) and are more practical for steep slope applications where they can be terraced. Planter boxes receiving runoff from rooftop areas must be located reasonably close to downspouts of the structures generating the runoff. This makes it an ideal application to disconnect impervious surfaces and provide on-site stormwater treatment and natural green aesthetics in tightly confined urban environments (Tetra Tech, 2011).

There are three types of planter boxes which may or may not have a lined or concrete bottom depending on whether or not it is design for infiltration, and therefore affects the type of media employed as shown in Fig. 4. Contained planters, as the name implies, are completely contained without infiltration or underdrains. Outflow goes only through a weep hole or an overflow structure so this type only uses soil as media and filter fabric. Infiltration and flow-through planters both employ a gravel drainage layer and a soil layer with filter fabric in between. The difference between the two is that infiltration planters drain to the underlying soil and provides groundwater recharge while flow-through planters collect treated stormwater in the underdrain that is connected to the local storm drains. It should be noted however that in some US states like California and Florida, planter boxes are only flow-through types in terms of being contained within an impermeable structure with an underdrain as they are typically applied in ultra urban settings (Geosyntec, 2014; LADPW, 2014; Tetra Tech, 2011). In addition, systems connected to building downspouts or other conveyance systems may also

Table 1. Specifications for the media profile in bioretentions

Design Guideline	Surface Layer	Filter Layer	Drainage Layer	Transition or Additional Layer	Drawdown Time
San Diego, California, USA (2011)	mulch (5-10 cm)	planting soil (61-122 cm)	drainage stones (30 cm max.)	Gravel strip on the side for pre-treatment	〈 48 hr
Los Angeles, California, USA (2014)	mulch (5-10 cm)	planting soil (61 cm min.; 122 cm preferred)	gravel (optional)	Geomembrane liner on the side	〈 96 hr
Edmonton, Canada (2011)	mulch (7-8 cm)	amended topsoil (50-100 cm)	〉 4-cm dia. washed rock (10 cm)	1.6-2.6 cm dia. washed rock (30-100 cm) between topsoil and drainage rocks	〈 36 hr
Orange County, Florida, USA (2014)	mulch (5-7.6 cm)	amended soil (46-122 cm)	3.8-cm dia. double-washed gravel	-	〈 72 hr
Michigan, USA (2008)	mulch or leaf compost (5-7.6 cm)	native soil (46-122 cm)	drainage stones (optional)	Sidewall material e.g. RAP for structural support	-
Prince George's County, Maryland, USA (2008)	mulch - raw hardwood (7.6-10 cm)	soil - sand, topsoil, compost mix (76-122 cm)	13-25 mm dia. gravel (30 cm max.)	6-13mm dia. pea gravel diaphragm (20 cm max.); impervious liner	

Source: City of Edmonton (2011); Geosyntec (2014); LADPW (2014); Prince George's County (2007); SEMCOG (2008); Tetra Tech, Inc. (2011)

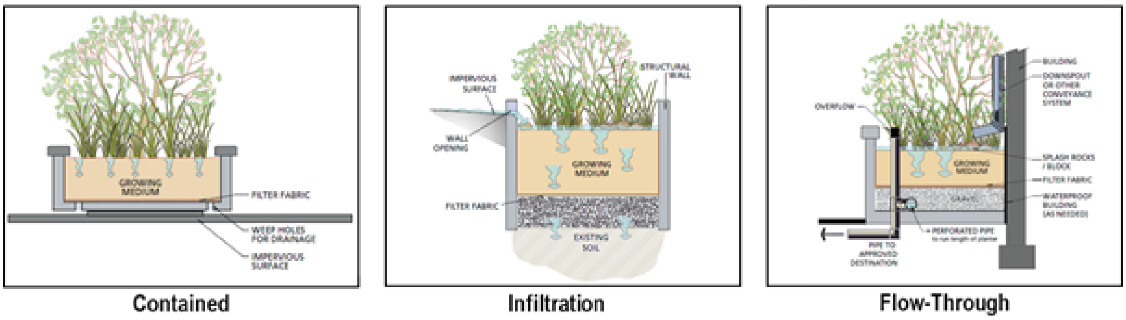


Fig. 4. Planter box types with different design elements (adapted from City of Portland, 2004)

require splash rocks on top of the soil media for flow energy dissipation (Geosyntec, 2014; SEMCOG, 2008).

Similar to bioretention structures, the media profile in planter boxes also consist of 3 major layers: the surface layer, the main media layer, and the drainage layer (Table 2). The surface layer may consist of 5-10 cm of finely shredded hardwood mulch, sod, splash rocks and other erosion control materials. As they only accommodate relatively smaller rainfall events, the soil medium thickness can be as low as 30-45 cm in LA and Michigan in USA as well as in Edmonton in Canada but was preferred to be 122 cm in San Diego and Florida USA just like in bioretention systems. The drainage layers are 10-30 cm gravel that should be allow drawdown times of 10 to 96 hours.

On the other hand, bioswales or vegetated swales are long, narrow, and gently sloping conveyance channels with vegetations on the sides and bottom. Treatment occurs as the stormwater flows along the length of the channel where the vegetation and occasional check dams slow the water down allowing sediments to settle or be filtered while encouraging infiltration to the ground. With narrow widths of 2-8 ft, bioswales are ideal for applications in the right-of-way of linear transportation corridors and along borders or medians of parking lots (Tetra Tech, 2011).

Typically planted with grasses, shrubs, or trees, the filter media is composed of planting soil at a depth of at least 46 cm topped with either mulch, sod, small-sized gravel stones, or erosion control mat (Table 3). The selection of the surface layer depends on the inflow rate which is typically limited to 1 ft^3/s for mulch and up to $3ft^3/s$ for sod. The difference is due to the fact that mulch is much more light weight than sod and is prone to floating. All design guidelines suggested a layer of gravel for drainage with depths ranging from 15 cm in Canada and between 30 and 61 cm in the US. This necessitates a transition layer of either geotextile or pea gravel to avoid transition of soil media to the drainage layer and

Table 2. Specifications for the media profile in planter boxes

Design Guideline	Surface Layer	Filter Layer	Drainage Layer	Transition or Additional Layer	Drawdow Time
San Diego, California, USA (2011)	Sod or finely shredded hardwood mulch (7.6 cm)	planting soil (122 cm)	drainage stones (30.4 cm)	filter fabric; bentonite clay liner; geomembrane liner	10-48 hr
Los Angeles, California, USA (2014)	mulch (5-10 cm)	soil mix (30.4-45.8 cm)	gravel (15.2 - 30.4 cm)	geomembrane liner or aggregate layer	〈 96 hr
Edmonton, Canada (2011)	-	amended topsoil or gradated gravel filter (30-45 cm)	clean gavel for additional storage	compacted clay	〈 96 hr
Orange County, Florida, USA (2014)	shredded hardwood mulch (5-7.6 cm)	planting soil (122 cm)	gravel (30 cm)	3.8-cm dia. gravel	〈 48 hr
Michigan, USA (2008)	mulch; splash rocks, erosion control mats	Soil or compost mix (30.4 cm)	Infiltration bed (9.6 - 15.8 cm)	geotextile fabric	~ 12 hr

Source: City of Edmonton (2011); Geosyntec (2014); LADPW (2014); SEMCOG (2008); Tetra Tech, Inc. (2011)

Table 3. Specifications for the media profile in bioswales

Design Guideline	Surface Layer	Filter Layer	Transition Layer	Drainage Layer	Drawdown Time
San Diego, California, USA (2011)	Sod or finely shredded hardwood mulch (5-10 cm)	planting soil (61 cm)	filter fabric or geomembrane liner	drainage stones (30.4 cm)	48 - 72 hrs
Riverbank, California, USA (2013)	small-sized gravel, stones, or erosion blankets	amended planting soil (46 cm)	non-woven filter fabric	clean drain rock	-
Orange County, Florida, USA (2014)	shredded hardwood mulch (5-7.6 cm)	Amended planting soil	absorption media (15.2 cm)	3.8-cm dia. gravel	〈 72 hr
Toronto, Canada (2010)	mulch (7.5 cm) or erosion control mat	planting soil mix	geotextile, filter fabric, or pea gravel	gravel (15.2 cm)	〈 24 hr
Michigan, USA (2008)	sod or grass	permeable soil (76.2 cm)	non-woven geotextile	2.54 - 5 cm dia. uniformly-graded aggregate (30.4-61 cm)	-

Source: AECOM (2013); CVC (2010); Geosyntec (2014); SEMCOG (2008); Tetra Tech, Inc. (2011)

eventual clogging. Drawdown times are within 24 hours in Canada and up to 72 hours in the US.

3.2 Non-vegetated structures

The two most common types of non-vegetated LID structures are infiltration trench and permeable pavement. An infiltration trench is a long, narrow, channel-like subsurface excavation filled with gravel that provides large pore spaces for stormwater detention and eventual infiltration to the ground. They are applied to reduce stormwater runoff volume and improve water quality by capturing sediment loads. As such, they require pretreatment upstream such as filter strips in order to prevent clogging by sediment over time. Table 4 provides the specifications for the media profile in infiltration trenches. As opposed to the previous structures that were discussed, gravel or stones are typically employed in the top layer instead of mulch because no vegetation is planted within the system. However, if the trench is designed to be covered by grass for aesthetic purposes, a soil layer in the surface can be provided. In other design guidelines such as in Tucson, Arizona, the gravel storage layer should be exposed with the surrounding area graded to it with a slope of 3:1 or flatter so no surface layer is required (City of Tucson, 2015).

The filter layer is typically composed of washed stone, gravel, or construction aggregate with size ranging from 4-8 cm in Arizona (City of Tucson, 2015) and Alaska (USKH, Inc., 2008) or 5-15 cm in Los Angeles, California (LADPW, 2014) and with a void ratio of 0.4 (Table 4). In San Diego, however, the design guideline for infiltration trenches suggests soil or sand medium that is highly permeable with at least 0.5 in/hr hydraulic conductivity (Tetra Tech, 2011). Interestingly, infiltration trenches with gravel filter layers require a drainage

Table 4. Specifications for the media profile in infiltration trenches

Design Guideline	Surface Layer	Filter Layer	Transition Layer	Drainage Layer	Drawdown Time
San Diego, California, USA (2011)	gravel or decorative stones	Soil or sand bed (61-122 cm)	hydraulic restriction material or soil media barrier	drainage stones (30.4 cm)	10 – 48 hr
Los Angeles, California, USA (2014)	pea gravel (5 cm) or filter fabric if no pretreatment	5-15.2 cm dia. clean stone (92-152 cm), e*=0.3-0.4	non-woven geomembrane liner	sand filter (15.2 cm)	〈 96 hr
Michigan, USA (2008)	Soil (15.2 cm)	Uniformly graded construction aggregate, e*=0.4	permeable non-woven geotextile	-	48-72 hr
Tucson, Arizona, USA (2015)	-	3.8-7.6 cm dia. uniformly graded and washed gravel, e*=0.4 (122 cm max.)	filter fabric (optional)	sand filter (optional)	-
Anchorage, Alaska, USA (2008)	crushed stone, pea gravel, or soil and grass (15.2 cm)	3.8-7.6 cm dia. stone, e*=0.4	filter fabric	sand filter (15.2 cm)	24 – 48 hr

Source: City of Tucson (2015); LADPW (2014); SEMCOG (2008); Tetra Tech, Inc. (2011); USKH (2008)
*e = void ratio

Table 5. Specifications for the media profile in permeable pavements

Design Guideline	Surface Layer	Bedding layer	Structural Layer	Liner
San Diego, California, USA (2011)	Pervious concrete W/C²=0.35-0.45 e¹=0.15-0.25 (4-8 10-20 cm)	-	coarse gravel ASTM No. 57 or 1.9 cm dia., compressive strength = 2.8-8 MPa	geotextile
	Porous asphalt e = 0.15-2.0 (7.6-17.8 cm)	-		
	PICP³ openings = 8-20% of surface area (3.8-7.6 cm)	fine gravel ASTM⁴No.8or 3.8-7.6 cm dia.		
	Plastic geocells or turf pavers	sand, load bearing capacity = 13.8 – 38 MPa		
Los Angeles, California, USA (2014)	Pervious concrete e=0.16; Porous asphalt (5-10 cm) Modular blocks	crushed stone ASTM No. 8 or 3.8-7.6 cm dia. (61-122 cm)	coarse gravel ASTM No. 57 or 1.9 cm (15.2 cm min.)	geotextile liner or impermeable liner
Michigan, USA (2008)	Pervious concrete Porous asphalt (6.4 cm) Permeable paver blocks Reinforced turf/gravel	stone bed AASHTO⁵No.57or〈38mmuniformlygraded,cleancoarse aggregate,e=0.4	coarse aggregate AASHTO No. 3 or 25-50 mm dia. (30.4-92 cm)	Non-woven geotextile filter fabric

[1]e = void ratio; [2]W/C= water to cement ratio; [3]PICP=PermeableInterlockingConcretePavement; [4]ASTM = American Society for Testing and Materials; [5]AASHTO=American Association of State Highway and Transportation Officials
Source: LADPW (2014); SEMCOG (2008); Tetra Tech, Inc. (2011)

layer composed of sand, while those employing fine medium should have stones or gravel for drainage but either way, a transition layer made of filter fabric of geotextile is recommended. The resulting configuration has varying drawdown times from up to 48 h in San Diego and Alaska, up to 72 h in Michigan, and up to 96 h in Los Angeles.

On the other hand, permeable pavement offers an alternative to conventional impervious concrete or asphalt pavement by employing pervious materials for urban surfaces such as parking lots, driveways, and other lightly traveled areas. The main purpose is to reduce runoff volume and peak flows by allowing percolation and temporarily hold water, therefore a storage layer or bedding is required underneath the permeable pavement. Also, since they are load-bearing, a structural layer is necessary and must be designed to avoid failure of the system. Permeable pavements can either be non-infiltrating with an underdrain and impermeable liners along the sides and bottom, or infiltrating with or without underdrains (partial or full infiltration). Therefore, aside from volume and peak flow reduction, it can also provide reduction of sediments, heavy metals, oil and grease, and bacteria.

The surface pavement material may vary depending on the design and porosity that is desired. As seen in Table 5, there are several types of permeable pavements available including those that are poured in place such as pervious concrete and porous asphalt, and modular systems such as interlocking concrete pavers and plastic geocells. They must be durable and designed to support the maximum anticipated traffic load but should not be used in areas with heavy traffic to avoid breakage. The bedding layer which serves as the reservoir is typically 4-8 cm diameter gravel conforming to the standards of the American Society for Testing of Materials (ASTM) or the American Association of State Highway and Transportation Officials (AASHTO).

4. Media specifications according to function and results from literatures

4.1 Hydraulic and Hydrologic Functions

For vegetated infiltration systems, coming up with the proper soil media is crucial to be able to meet the hydraulic and hydrologic design objectives while also providing other functions related to plant growth and water quality. Specifically, infiltration rates are important because they affect the runoff reduction, retention time, and pollutant removal. For that matter, planting soils are typically mixed with sand and compost or other organic matters to produce ammended topsoil which is sometimes called engineered media.

Table 6 summarizes the soil mixes that are suggested in several LID design manuals in the US. Each soil mix is believed to be capable of achieving the corresponding infiltration rates that are shown in the table. From the table, a soil mix that is 30-80% sand can achieve up to 2.54 – 305 mm/hr indicating that the higher the sand, the higher the infiltration rate. This is close to the findings of Hsieh and Davis (2005) who investigated laboratory columns as well as existing bioretention systems and concluded that an effective media is a mixture of coarse sand and sandy soil. However, their expected infiltration rates using this design were much higher at 720-3240 mm/hr (1.5-5.4 cm/min). Meanwhile, the specifications for fines, clay, or silt content varies, with some guides specifying 5%, others suggesting 8-12% while others specifically not referencing it.

High infiltration rates are advantageous when it comes to preventing excessive bypass and targeting a specific runoff volume reduction. In the literatures, LIDs employing sandy soils have been reported to achieve relatively high runoff reduction. Davis et al. (2001) and Davis (2007) reported up to 100% volume reduction from lab-scale bioretention columns and an existing bioretention employing 50% construction sand. A retrofit bioretention cell with 88% medium sand was able to treat 97% of runoff from a parking lot (DeBusk and Wynn, 2011). Meanwhile, a bioretention system with 70% gravelly sand was able to achieve relatively lower values of 48-74% which was attributed to the sizing of the system (Chapman and Horner, 2010). In addition, a study of different mixes of engineered media have reported that a sand-dominant media (84-90% v/v) was comparatively less prone to changes in saturated hydraulic conductivity (Ks) caused by compaction and changes in moisture content as compared to media mixes with only 30% sand and >30% v/v organic content (Fassman-Beck et al., 2015).

Directly affected by infiltration rates are drawdown times which are set not only to avoid flow bypass but also to provide adequate contact time for contaminant removal without attracting public concern over extended durations of ponded water (Fassman-Beck et al., 2015). In some design manuals,

Table 6. Specifications of the soil media for LID

Reference LID Manual	Soil Mix	Infiltration rate
Anchorage, Alaska (2008)	60-65% loamy sand, 35-40% compost or 20-30% loamy sand, 50-60% coarse sand, 20-30% compost	7.6-203 mm/hr
Michigan (2008)	20-30% topsoil, 30-50% sand, 20-40% compost	2.54-254 mm/hr
Los Angeles, California (2014)	60-80% sand, 20-40% compost	127-305 mm/hr
San Diego, California (2011)	85% coarse sand, 10% fines, 5% organic	25.4-51 mm/hr
Orange County, Florida (2014)	40% sand, 20-30% topsoil, 30-40% compost	12.7-51 mm/hr
Puget Sound, Washington (2012)	60-65% sandy mineral aggregate, 35-40% compost	25.4-305 mm/hr
North Carolina (2009)	85-88% sand, 8-12% clay and silt, 3-5% organic matter	
Prince George's County, Maryland (2007)	50-60% sand, 20-30% topsoil, 20-30% leaf compost	>25.4 mm/hr

Source: Geosyntec (2014); Hinman (2012); LADPW (2014); Perrin et al. (2009); Prince George's County (2007); SEMCOG (2008); Tetra Tech, Inc. (2011); USKH, Inc. (2008)

the infiltration rate and permeability of the soil should allow for ponding and drawdown time of 2-24 h (ARC, 2003; Atchison et al., 2006). In more recent manuals, a maximum of 24-36 h is allowed in Canada (City of Edmonton, 2011; CVC, 2010) while 48-96 hours is allowed in the US (Tetra Tech, 2011; Geosyntec, 2014; LADPW, 2014). While not much has been mentioned in the literatures with regards to target drawdown times, infiltration rates of at least 20 mm/h have been suggested to achieve adequate retention time within the LID (LeFevre et al., 2014). Others have associated pollutant removal with minimum infiltration rates. Hunt and Lord (2006) suggested at least 20 mm/hr for total phosphorus removal, 20-50 mm/hr for total nitrogen, and 50-150 mm/hr for total suspended solids, heavy metals, and pathogens.

Several works demonstrated that amending topsoil with organic materials such as compost can alter soil properties and help increase infiltration rates, retention of moisture, and decrease peak flows (Pitt et al., 1999; Hunt et al., 2008; Gülbaz and Kazezzyilmaz-Alhan, 2016). As such, most design guidelines suggests the use of soil media with compost. The fraction of organic material should be limited though due to its tendency to leach certain amounts of nutrients. This will be discussed in the following section.

For structures like infiltration trenches that are typically non-vegetated and primarily designed for temporary stormwater storage, groundwater recharge, and preserving base flows, the main media is stone aggregate composed of 2.5-7.6 cm inch clean stone (USEPA, 1999a). In this design, the removal of most pollutants happens as runoff infiltrates the surrounding soils while increasing the groundwater recharge and base flow. However, the potential for groundwater contamination must be carefully considered and therefore, an extensive site investigation must be done early in the planning process to determine the suitability of such gravel-filled infiltration facility.

4.2 Pollutant reduction

There is a vast information in the literature regarding pollutant reduction both in laboratory and field studies. Several studies have investigated the effect of the type of media not only on runoff volume and peak flow attenuation but also on pollutant reduction. For vegetated infiltration LIDs, design guidelines suggests the use of amended topsoil with compost component as filter media (Table 1-3). The amount of compost should be limited though due to its tendency to leach certain amounts of nutrients. Pitt et al. (1999) mentioned higher concentrations of these pollutants in the runoff from sites with amended soils as compared to regular topsoils. The saturated condition during rainfall, especially in extended periods of time, encourages leaching of soluble nutrients such as NH_4^+,NO_3-N,and from such compost-amended bioretention mixes (Hurley et al., 2017). However, in other cases, saturated condition is pursued because it provides anaerobic conditions conducive for denitrification that lead to lower levels of NO_3-N (Kim et al., 2003; Hsieh and Davis, 2005). Therefore, one such solution for this is to optimize the amount and positioning of the organic material in the media profile in such a way that is conducive for effective bioretention performance.

Another material that seems to play an important role in bioretention soil mixes is sand. Hsieh and Davis (2005) investigated laboratory columns as well as existing bioretention systems and concluded that an effective media is mixture of coarse sand and sandy loam where the soil ratio is 20-70% by mass depending on the requirement for plant growth. The resulting infiltration rate and pollutant removal capacity in this type of soil were 1.2-5.4 cm/min, >96% of TSS, >70% of TP, and >98% of Pb. In addition, a study of different mixes of engineered media have reported that a sand-dominant media (84-90% v/v) was comparatively less prone to changes in saturated hydraulic conductivity (Ks) caused by compaction and changes in moisture content as compared to media mixes with only 30% sand and >30% v/v organic content (Fassman-Beck et al., 2015).

Aside from the type of material, filter media depth also plays an important role in the effectivity of LID structures. Recommended depths for bioretention typically range between 0.6 to 1.2 meters with 1.2 m being the preferred depth as per the design manuals. In an overview provided by Davis et al. (2009), it was however identified as one of the design considerations that needs more research. Table 7 shows recommended depths fro the removal of specific pollutants as provided by the guidelines from Los Angeles (LADPW, 2014). There were no required minimum depth for TSS since they are mostly captured in the upper 20 cm of the media or in the pre-treatment structure if available. Heavy metals require at least 45 cm whule TN and TP requires at least 61-91 cm to be effectively removed.

Shallower systems are preferable in terms of cost because of savings in material and excavation. However, in terms of runoff and pollutant reduction, deeper systems are more advantageous. Exfiltration to surrounding soil as well as evapotranspiration is expected to be much higher in deeper media cells because of greater storage volume, retention time, and more exposure to side walls (Brown and Hunt, 2011). Consequently, higher exfiltration results to decreased outflow volume and increased pollutant load reduction.

That being said, the optimum depth of a vegetated LID structure seems to be determined by site characteristics as well as its function and pollutant of concern. For instance, in North

Table 7. Recommended depth of soil media for the removal of specific pollutants

Pollutant	Minimum Depth	Remarks
TSS	no minimum depth required	If high TSS influent, frequent maintenance is required
TN	At least 30 inches (76 cm); 36 inches (91 cm) preferred	-
TP	24 inches (61 cm)	low phosphorus content (P-index 15-30)
Metals	18 inches (45 cm)	Must keep top layer from saturating for extended periods of time
Pathogens	no minimum fill depth required	Limiting plant coverage allows more direct sunlight to kill pathogens
Temperature	At least 36 inches (91 cm); 48 inches (120 cm) preferred	-

Carolina, the type of vegetation determines the media depth. Facilities planted with grass or herbaceous plants can have a minimum media depth of 0.6 m while those planted with trees and shrubs require at least 0.9 m to accommodate plant roots (NCDEQ, 2018). In terms of pollutant reduction, studies have shown that effective filtration of suspended particles require no specific depth because nearly all of them are removed by filtration through the top portion of the media and mulch layer. If pre-treatment is provided, nearly all TSS removal occurs prior to water entering the system. Similarly, bacteria and pathogens are believed to die off at the surface of the facility where the stormwater is exposed to sunlight and the soil can dry out. Studies have shown that certain heavy metals such as Cu, Pb, and Zn are removed in the first 20 cm of the facility (Li and Davis, 2008; Davis et al., 2003). Hence, LID structure designed specifically for heavy metal capture need not be deeper than 45 cm (Perrin et al., 2009). On the other hand, nutrients especially nitrogen, require longer retention time thus, deeper media layer preferably at least 0.9 m, to make time for biological processes that transforms and removes them (Hsieh and Davis, 2005). Some studies have also introduced adding an internal water storage (IWS) zone, a saturated layer at the bottom portion of the media, to create an anaerobic condition which is conducive to reducing NO_3-N and consequently, TN. Field and laboratory investigations have shown that vegetated LID structures are generally effective in removing nutrients, however, results still vary and uncertainties arise which were attributed to leaching from the media itself, influx from the surrounding soil, and lack of anaerobic zone to promote denitrification.

5. Organic media versus inorganic media

Within the media profile of a structural LID, the materials can be classified as either inorganic or organic. Inorganic materials include gravel, crushed rock, volcanic stone, zeolite, and anthracite among others, while organic materials include woodchip, compost, mulch, and filter fabric. Chen (2015) conducted a column experiment comparing organic and inorganic media and reported that the type of material does not affect TSS removal. However, a similar study by Niu (2016) showed lower TSS removals from wetlands containing woodchip during the first five rainfall events due to the breakage of the woodchip material. Meanwhile, the column with woodchip was observed to have the lowest removal of COD but with the highest removal of NO_3-N (Chen, 2015). It was concluded that this media released organic materials from the beginning of the experiments which became a carbon source for denitrification of NO_3-N. This is consistent with the findings of Saeed and Sun (2011) who conducted experiments using laboratory-scale hybrid wetlands (vertical flow and horizontal flow) and reported that eucalypt wood mulch provided a carbon source for the removal of NO_3-N via denitrification and that the effluent NO_3-N concentration increased with the decrease of effluent COD concentration.

Moreover, NH_4-N removal, which can sometimes be a limiting factor for eliminating nitrogen was also observed to increase in the wood mulch wetlands due to its higher oxygen transfer capacity providing sufficient DO for nitrification. Therefore, simultaneous nitrification and denitrification can be observed within a media containing organic materials. In the same study, zeolite, which is inorganic, was also found to efficiently removed NH_4-N. The high cation exchange capacity as well as the porous nature of the substrate allowed adsorption of NH_4-N and subsequent nitrification by the nitrifying bacteria attached to the surface under aerobic conditions. However, biodegradable organics were greatly removed and this limited the denitrification of the generated NO_3-N. These results show that both organic and inorganic materials are capable of removing nitrogen but inorganic materials can be limited by insufficient carbon source.

In terms of selecting the proper material for carbon source, age seems to be an essential factor. Robertson et al. (2010) conducted experiments comparing the NO_3-N removal rate of fresh woodchips versus aged woochip. It was observed that the denitrification capacity of fresh woodchips was lowered to 50-79% after 2 years and 40-59% after 7 years. Although the decrease was significant during the initial stage, the slight difference in these values indicates that wood particle media can deliver stable NO_3-N removal rates over a period of time after the initial usage of the leached organics.

6. Conclusions

From the comparison of specifications from currently existing design guidelines, the type, depth, and profile of the media are not that different except when they are classified according to infiltration function and vegetation. The most commonly suggested media for all the LID structures are ammended soil, gravel or crushed stones, mulch, and compost or other types of organics. Specifications for the ammended soil is typically governed by the desired infiltration rate and that 50-80% sand and 20-40% compost ratios can achieve 200-300 mm/hr of infiltration rate. On the other hand, media depth is mostly governed by the target water quality especially if nutrients and heavy metals are of concern. Based on literatures, 90-120 cm media depth is sufficient to effectively reduce most pollutants but it can still be subject to site-specific constraints such as existing pipelines and risk of groundwater contamination. Except for non-vegetated infiltration LIDs, most structure types require a mixture of organic and inorganic media which serves different functions within the media profile. However, careful consideration should be done when deciding the amount of organics to avoid excessive COD in the effluent.

Despite the availability of design guidelines and published studies most prominently in the US where LID is being widely implemented, there is still insufficient information to be able to develop a single filter media specification which can consistently deliver the design objectives. However, this means that there are still a lot of opportunities for research in the future.

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