Factors affecting the hydrological response of substrate material for green roofs and bioretention

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Abstract: Green roof and bioretention have been frequently used as stormwater management practices to address urban hydrology issues, and researches regarding these technologies are increasing lately. However, a knowledge gap remains in characterizing the hydraulic properties of these practices. The hydrological process of green roof and bioretention is mainly determined by the substrate media of the practices. Based on current studies, this paper discussed factors affecting the hydrological response of substrate material for green roofs and bioretention. Most researches provide qualitative information on water movement within substrate, but few have further investigated the theoretical explanations on the hydrological process of substrate and give quantitative data. This study proposed that following factors affecting water flow dynamics of substrate media: type of materials and composition of the materials; depth of the substrate media; pore structure/network of the substrate materials. Many investigations focus on the effect of a single factor and generalizing the other, but the hydrological process of the substrate material is mostly under the effect of multiple factors simultaneously. And under different study conditions and different designs of green roof or bioretention, the importance of these factors to the hydrological performance of substrate media is different. In addition, interrelationships exist among the factors, changes in one factor could influence other factors. Current research on the factors influencing the hydrological process of the substrate material needs to be related. Future study needs to consider the effect of multiple factors and their interrelations, to create integrated approaches for a better understanding of the hydrological process of the substrate material, and for modeling the hydrological performance of the green roof and bioretention more accurately and designing the practices more efficient.

1. Introduction
Rapid urbanization process has adverse effects on urban hydrology, including increased runoff magnitude and frequency, decreased infiltration and underground water recharge and decreased water quality (Chen et al., 2017; Ntelekos et al., 2010; Walsh et al., 2012; N. Zhang et al., 2018). Additionally, the conventional urban stormwater drainage system is designed to convey urban runoff from the city to its surrounding environment as quickly as possible, therefore, the increased runoff magnitude and frequency would cause deterioration of the environment in receiving water body or stream of urban runoff (Fletcher et al., 2014; Jeng et al., 2005).

Since the concept of sustainable development is widely accepted, integrated water management approaches such as low impact development (LID), water sensitive urban design (WSUD), Green
Infrastructure (GI), and best management practices (BMPs) have been adopted to address the urban hydrology issues (Ahiablame et al., 2012; Davis et al., 2009; Wong and Brown, 2009). Despite the differences in the terminology and primary focus of these approaches, the core principle remains the same, that is reducing the number of grey infrastructures, increasing impervious area in the city, and to restore the original hydrological cycle close to its pre-development condition.

Those approaches manage the urban stormwater runoff by implementing a series of stormwater control measures (SCMs) in urban area. Green roofs and bioretention (or bioinfiltration system) are commonly used SCMs facilities to create more pervious area in the city by using soils and other porous materials as the substrate material and promoting infiltration and evapotranspiration of stormwater, bringing the hydrological condition closer to the predevelopment status (Davis et al., 2009; DeBusk et al., 2011; Oberndorfer et al., 2007). Additionally, green roofs and bioretention can improve stormwater quality (Allen P. Davis et al., 2006; Czemiel Berndtsson, 2010; Davis et al., 2012; Hatt et al., 2009; Jia et al., 2015), and green roof could also reduce the heat flow from the roof and mitigate the urban heat-island effect (Costa et al., 2018; Getter and Rowe, 2006). While increasing numbers of green roofs and bioretention have been studied and constructed globally (Davis et al., 2009; Hatt et al., 2009; Jia et al., 2017a, 2017b; Shafique and Kim, 2018; Vijayaraghavan et al., 2012), the lack of in-depth understanding of hydrological response and hydraulic properties of substrate material create challenges for designing efficient SCMs and accurately modeling their hydrologic processes. For example, studies have pointed out that properties of substrate material such as particle-size distribution, dry bulk density, particle density, porosity, and saturated hydraulic conductivity contributes to assessing material’s performance in stormwater control and to simulating the hydrologic process within these SCMs systems (Fassman-Beck et al., 2015; Liu and Fassman-Beck, 2016, 2017a), but the correlation between material’s properties and its hydrological performance is not well-established, as well as the related water flow mechanism. Studies show the substrate layer of green roofs and bioretention is the main function layer that mitigates the runoff magnitude and frequency, as well as improves the runoff water quality (Ahiablame et al., 2012; Davis et al., 2009; Muerdter et al., 2018). However, the hydrological process of the substrate layer is not well known, and questions remain about how to compositing the substrate materials to efficiently achieve the benefits listed above. Thus, understanding the fundamental mechanisms of the hydrological process and response of green roofs and bioretention under rain event is essential in attaining its goals.

This paper reviews current studies regarding this topic and summarized the factors affecting the hydrological process of substrate material for green roof and bioretention, including the pore structure and network, composition of the media, and depth of the substrate material. The needs for further investigation on this subject are also explored.

2. Factors affecting the hydrological performance of substrate material for green roof and bioretention

For both system, substrate material plays a critical role as the main functioning layer to regulate flow and improve water quality, it also provides nutrients, water and air to support plant growth, it is also the main structural layer of these practices as shown in Figure 1 and 2. Therefore, the substrate material has significant impact on the hydrological performance of green roof and bioretention.

![Figure 1 Cross section of a typical green roof system](image)
Figure 2 Cross section of a typical bioretention system

Dominate factors which influence the hydrological response and water retention capacity of the substrate of green roof and bioretention including: type of materials and composition of the materials; the depth of the substrate media; porosity, pore network and pore structure of the substrate materials.

Other conditional factors such as weather conditions (intensity and duration of rain event, climate), geometry conditions (shape, slope) and vegetation also affect the runoff dynamic and water holding ability of the substrate of green roof and bioretention. But this paper only focuses on the studies regarding the factors listed above, which are directly linked to the properties of the substrate media and its layer designing and materials composing.

2.1. Type of materials and composition of the materials

The types of the substrate material and its composition largely determines the hydrological performance of the green roof and bioretention, therefore, many studies have focused on this aspect by laboratory experiments or field monitoring. Substrate layer for green roof and bioretention is typically comprised by the mix of two or more materials, which is carefully composed with the intention to provide specific physical, hydraulic, and hydrologic functions (lightweight, well-drained, slowly infiltrate and ponding, etc. Many current studies focused on the effect of different materials and the mix of materials on the hydrological performance of the substrate. Based on the laboratory experiments of six different sand and soil based biofiltration media compositions (fine sand (S), sandy loam (SL), 80% sandy loam, 20% Hydrocell (SLH), 80% sandy loam, 10% vermiculite, 10% perlite (SLVP), 80% sandy loam, 10% compost, 10% mulch (SLCM), and 60% sandy loam, 20% compost, 20% mulch on a charcoal drainage layer (SLCMCH)), Hatt et al. (2008) found that other than SLCMCH, all media types showed significant reduction in infiltration capacity, and different filters demonstrated different level of reduction. The SLCMCH only intercepted 8% of inflow, while the intercepted inflow by other filter compositions ranging from 84%-27%. Authors suggest that the reason for the poor reduction performance of SLCMCH is likely due to the inherent high porosity of the filter media as well as cracking and the creation of macropores during dry periods. Thompson et al. (2008) evaluated physical and hydraulic properties of eleven composite mixtures of sand, soil, and compost in different volumetric proportions for bioretention, results show that an increase in the ratio of sand to compost significantly improved the infiltration rate for mixtures with no soil and with 20% sandy soil, but provided little explanation for mixtures with 20% silt loam soil. Differs from infiltration, compost additions consistently reduced the bulk densities of the all mixtures measured in this study. They suggest that compost controlled the physical density of the mixtures initially, the textural class of the mineral component may provide a more dominant control over the movement of water into these mixtures. As for water holding capacity, it increased with the percentage of compost, and generally decreased with an increase in the ratio of sand to compost of all mixtures regardless of their respective components, this is likely attribute to an increase in porosity and surface area. Zhang et al. (2018) simulated the hydrological benefits of three different mixtures of quartz sand and blast furnace slag with different permeability and gradation parameters in Storm Water Management Model (SWMM) software. The reduction rate of three mixtures ranging from 63.6%-80.2% when the rainfall return period is 2 years, and ranging from 37.4%-49.1% when the rainfall return period is 100 years. Authors suggest that the permeability of bioretention soil media is the key factor that affects its hydrological performance. Fassman and Simcock (2012), based on the laboratory and field experiments of five different blends of four substrate materials, describe the development of a mixed substrate material that promotes stormwater retention while balancing structural
load and providing sufficient plant cover with limited maintenance. Substrate particle size distribution (PSD) and quality control along the supply chain were identified as the key design and specification criteria affecting weight and saturated permeability. Hill et al. (2016) surveyed thirty-three extensive green roofs in southern Ontario, Canada, and conducted hydrological laboratory analyses of the green roof media samples recovered from these sites. Results show the dominance of organic matter in the physical and chemical properties of the media, and higher organic matter content increases the water retention capability of the substrate. The influence of organic matter on infiltration rate is limited, but media with larger minimum particle sizes increase infiltration rates due to a more open pore network. Yio et al. (2013) also found that higher organic content in green roof substrate increases the water holding capacity, by adding 5% of organic matter to the mineral substrate, the substrate runoff delay time increased from 4min to 20min. Eksi and Rowe (2016) explored the possibility of using recycled crushed porcelain and foamed glass as green roof substrate media. Both materials met the German FLL guideline for green roofs, but due to the higher percentage of larger particles contained in these media, the water holding ability of these materials is lower than recommended. Graceson et al. (2013) tested the water retention capabilities of three different materials mixed with composted green waste in different particle size, results show that the water holding capacity of the mixtures were observed to be significantly different and inorganic substrate particle size distribution also influenced water holding capacity greatly. Based on the results, they suggest that inter-particle and intra-particle pore space which was determined by particle size distribution are determining factors that affect the water retention capacity of green roof substrate. Voyde et al. (2010) monitored an extensive living roof in Auckland, New Zealand, they did not find statistically significant differences with regard to runoff reduction between three different substrate types (Pumice, Zeolite and Expanded Clay) or two different media depths (50mm and 70mm). However, one plot (plot 2) proved the exception, showing statistically significant differences to other plots. This is because that plot 2 used a pre-grown sedum mat to establish vegetation, while other plots were planted with plugs using a combination of native and non-native (sedum) species. The mat had coconut coir fiber mat which retained an additional 4.7 mm of water over and above the retention capabilities of the substrate alone.

From laboratory experiments and field monitoring about the effect of different substrate media compositions on hydrological performance of substrate layer, design methods for substrate media were given, and relationships between material properties and substrate hydrological process were interpreted. Other than commonly used material such as compost, sand, sandy loam and pumice, more new materials were investigated, such as ready-to-use commercial material and recycled materials. However, most of the studies only provide qualitative information regarding the interrelationship between different materials and hydrological process of the substrate, which cannot be use directly for the designing and modeling of hydrological performance for the substrate layer. Further research to explore the correlation between material properties and hydraulic parameters is needed to provide quantitative information on this aspect for better designing and modeling.

2.2. Thickness of the substrate layer

The depth of the substrate media was identified as one of the important factors that affect the performance of the bioretention and green roof, because the thickness of the substrate layer significantly determines the amount of substrate material used, which directly affect its water detention capacity. (Czemiel Berndtsson, 2010; Davis et al., 2009; Wong and Jim, 2014). Li et al. (2009) evaluated the hydrologic performance of six bioretention cells in Maryland, United States of America. The depth of the substrate ranges from 50-120cm. Results suggest that thicker media provide greater hydrologic benefit in terms of flow peak and volume reduction because larger runoff storage capacity is provided. They suspect that substrate depth is the dominant factor controlling the hydrologic performance of bioretention. Brown and Hunt (2011) monitored two bioretention cells of two media depths (60 and 90cm, located in Nashville, North Carolina, United States of America, to examine the effect of the media thickness on their performance. Results indicate that deeper substrate depths improve exfiltration and achieve better reductions in runoff volume. The data show that the goal of 24h volume reduction is met
more frequently in the deeper (90 cm) media depth (44% of events) compared to the shallower (60 cm) media depth (21%). Several studies examine the impact of substrate thickness on green roof hydrological performance (Buccola and Spolek, 2011; Nardini et al., 2012; Soulis et al., 2017), the depth of the media ranges from 5cm to 20cm. They observed that increasing media depth increases the runoff reduction and water retention ability, different substrate depths show different runoff reduction (40%–90%). The effects of media depth on green roof performance are also investigated by VanWoert et al. (2005), three media depths (2.5, 4.0, and 6.0 cm) were tested. They conclude that increasing media depth normally increases water retention, this conclusion consists with the previous studies mentioned above, however, they reported that it is only valid at one slope, their data show green roof at 2% slope with a 4cm media depth had the greatest mean retention (87%). Therefore, they suggest that to maximize the water retention ability of green roof, the depth and the slope of the substrate should be both addressed. Feitosa and Wilkinson (2016) model the water retention of green roofs and efficiency in rain-flow attenuation. The stormwater retention efficiencies of different substrate depths (5, 10, 20, 40, 80, and 160cm) were modeled by HYDRUS-1D software. The governing water flow equations of HYDRUS-1D describe the correlation between media depth and hydraulic properties (Simunek, et al., 2013), which makes this software suitable for the modeling of the impact of media depth on substrate hydrological process. Results show that the runoff retention capacity increased with the media depth according to a linear pattern, under different total rainfall conditions, for green roof 5, 10, 20, 40, 80, and 160cm, the average stormwater retention efficiencies of 28%, 29%, 32%, 36%, 44%, and 60% was observed. They suggest that in consideration of extra loads applied to roof structures, a substrate of 40 cm depth provides a better overall performance than other depths modeled. Meng et al. (2014) modeled hydrologic performance of two bioretention cells by HYDRUS-1D, with simulation results verified by field data. Results indicated that thicker the substrate layer, better the water detention capacity, but show little effect the water retention, which the authors suggest is likely attributed to the impervious surroundings of their experiment set-up. Researches on the effect of substrate layer depth on its hydrological performance confirm that thicker the layer, higher the water storage capacity of the substrate. But consider the cost to construct a deeper substrate layer and the benefits it brings, it is not always the best to choose the thicker layer, cost-effective depth should be used.

2.3. Porosity, pore network and pore structure of the substrate materials

The pore space of the substrate materials allows the water to percolate the substrate layer and hold a certain amount of water within. Therefore, the porosity, pore network and pore structure of the substrate material can affect the hydrological performance of the substrate material directly. In order to improve the understanding of the hydrological process in coarse-grained porous media used for green roofs, Pallà et al. (2009) used the SWMS-2D model, based on Richards’ law and the Van Genuchten–Mualem functions, to simulate the variably saturated flow within the green roof system. Results indicated that the mechanistic model which based on a single porosity approach is demonstrated to be suitable to describe the hydrologic performance of a green roof. After monitoring and analyzing the hydrological performance of three different bioretention sites locate in three different states in United States of America, Davis et al. (2012) brought up the concept of Bioretention Abstraction Volume (BAV), which is the storage volume for a bioretention cell that will fill before the occurrence of underdrain or overflow discharge, and is directly related to available media porosity and storage in the surface bowl. The BAV is recommended as a primary design parameter for bioretention design, and predictive design equations are given for the BAV for different bioretention configurations. For bioinfiltration system without underdrain, the average BAV is given as Equation 1, for bioinfiltration system with underdrain, the average BAV is given as Equation 2:

\[
\text{Ave } \text{BAV} = \text{Bowl Vol.} + \text{RZMS} \times (\text{SAT} - \text{WP})
\]

\[
\text{Ave } \text{BAV} = \text{RZMS} \times (\text{SAT} - \text{WP}) + \text{LMS} \times (\text{SAT} - \text{FC})
\]

where Bowl Vol. is bowl volume, RZMS is Root Zone Management System which represents the available media storage within the root zone, LMS is the lower media storage, FC is the field capacity, and SAT and WP are moisture contents of the media at saturated (SAT) and wilting point (WP)
conditions, respectively. Dal Ferro et al. (2014) found that the water retention curves had significant differences between volcanic porous media and were affected by their origin and size. Three volcanic porous materials were examined (pumice, lapillus, and zeolite), among the same volcanic substrates, the powders held less water than large aggregates at saturation. Pumices held more than 0.8 m$^3$ m$^{-3}$ of water in aggregates and around 0.7 m$^3$ m$^{-3}$ of water in powders, lapillus held more than 0.7 m$^3$ m$^{-3}$ of water in aggregates and less than 0.6 m$^3$ m$^{-3}$ of water in powders, and zeolites held almost 0.7 m$^3$ m$^{-3}$ of water in aggregates and less than 0.6 m$^3$ m$^{-3}$ of water in powders. Liu and Fassman-Beck (2017) investigate the water flow mechanism of engineered media for green roofs and bioretention. In the five media used in the study, two media with bimodal pore size distributions were observed with preferential flow. Uniform flow existed in the other three media (two media with bimodal pore size distributions and one with unimodal pore size distribution). They suggest that the occurrence of preferential flow is likely attributed to the interaction between the bimodal pore structure and the initial water content. In another study, Liu and Fassman-Beck (2018) measured the water retention characteristic (WRC) for 14 substrate materials for green roofs. And they used WRCs of these materials to investigate their pore structure and estimate hydraulic conductivities. Results show that complex interactions between intra-aggregate and interaggregate pores were involved in the water retention dynamics in 10 pumice-based media, for which the commonly used van Genuchten function is not suitable. They suggest the use of the Richards equation for the media with radii less than 1 mm. They also suggest that predictive unsaturated hydraulic conductivity ($K$) function based on WRC and Mualem’s approach tends to underestimate $K$ at low water contents. Researches on how pore network/structure of the substrate material affect the hydrological performance of the substrate material explore further on the water movement in substrate media. Provide more fundamental knowledge about how water flow through pore space, help improve model accuracy, and create new model approach. Given the complexity of the pore structure, more research is needed to investigate hydrological process of substrate material with complex pore systems under different flow patterns.

3. Conclusion

The green roof and bioretention have become widely used SCMs around the world, however, they are still new applications and more research are needed to better understand their performance. As a major component of the green roofs and bioretention, the substrate layer largely determines their hydrological performance. In general, the factors listed above all play important roles in regard to water movement within the substrate material of green roof and bioretention. Most of the studies focused on the effect of one or two factors, however, the example of contradictory results reported in different researches indicates that the hydrological process of the substrate material is under the effect of multiple factors simultaneously. And under different study conditions and different designs of green roof or bioretention, the importance of these factors to the hydrological performance of substrate media is different. The hydrological process of the substrate layer needs to be further investigated and the interrelation of various factors that affect the process explored.

Further investigation on hydrological response of substrate material is needed to provide knowledge for the designing of green roof and bioretention and modeling of their performance, and to explore other aspects and parameters involved in the water flow in substrate media, to modify the current model and design efficient. Conclusions and assumptions from most of the studies reviewed are made from observation of existing practices or simulate experiments, summarizing the data from field observation or laboratory experiment, which provide qualitative information on factors affecting substrate hydrological performance. However, further explain and explore the hydrological process of the substrate layer theoretically is need, to provide quantitative information for the designing and modeling.

Existing studies have identified that type of the material, the thickness of the material, and the pore structure/network of the material are important factors that affecting the hydrological response of the substrate layer directly. Further investigations on the relations between these factors and hydrological process of the substrate could gain more fundamental knowledge of the water movement within the substrate, which can be used for better predication of the hydrological performance of the substrate and
more efficient designing of substrate layer. Following aspect needed more in-depth research in both laboratory and field study:

- Relationship between the material properties and hydraulic parameters, which can help to further understand how different properties of material affect the water flow mechanism, give quantitative information for compositing substrate and modelling the hydrological performance of media, and provide a theoretical basis for studying the water movement through the substrate;
- The interrelationship among the factors that influence the hydrological process of the substrate media, and the importance of different factors under different designs of green roof or bioretention and different conditions to the water movement process. These researches could help to understand the effect of one factor on others, and ultimately, the influence on the hydrological response of the substrate, and help to identify the direct and indirect influence factors, minimizing the parameters needed to characterizing the hydrological process, simplifying the model and improving its accuracy. For example, understand the role of media thickness in the hydrological response and how it related with other factors could help to achieve the best hydrological performance with appropriate substrate depth.

Models with higher accuracy and efficient design suggestion could be given by focusing on these areas. While studies exploring conditional factors such as weather conditions, geometry conditions, and plant selection are also important for a better understanding on the hydrological process of the green roof and bioretention.

Specialists from different areas of study should be working together to address these needs, focusing on the research of these questions can be very helpful in terms of developing more accurate models for predicting the hydrological performance of the green roof and bioretention and more efficient design guidelines for green roof and bioretention implementation.

Acknowledgement
The authors appreciate the support from Yunnan Erhai Lake Ecosystem Observation and Research Station [Grant No. 2020ZZ01].

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