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Bioretention Performance – Multi-year Analysis of Hydrological and Water Quality Performance

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Bioretention Performance –

Multi-year Analysis of Hydrological and Water Quality Performance

by

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Abstract

Low Impact Development (LID) aims to mitigate and prevent the negative impacts of urbanization on the hydrology and water quality of the natural water bodies. Bioretention systems are some of the most popular LID systems that offer various benefits, including reduction of peak runoff, attenuation of excess runoff volume, retention of various pollutants, as well as aesthetic and habitat benefits. This research provides a comprehensive investigation of bioretention performance using mesocosms and controlled runoff application. The research site for this project was constructed in the Town of Okotoks, Alberta, in 2016/2017. The site consists of 24 lined mesocosms that were designed to receive no natural runoff and were drained by pumping through a perforated standpipe. There were three different bioretention media and three different vegetation types. Among the media, there was a unique mix of clay-loam and wood chips, as an alternative to the conventional sand-based bioretention media. The mesocosms were analyzed for their hydrologic and water quality performance using 72 simulated runoff events over four growing seasons. The mesocosms with different media exhibited significant differences in water retention at the onset of the study period yet became increasingly similar over time, whereas the differences in vegetation impacts increased over time. The water quality analytes include Total Phosphorus (TP), Reactive Phosphorus (RP), Total nitrogen (TN), Nitrate-Nitrogen (NO_3-N), and Total Organic Carbon (TOC). The research revealed significant leaching of nutrients and organics over four years. The leaching of nitrogen and organic compounds decreased over time, whereas phosphorus leaching persisted. This research also monitored the infiltration rate of the mesocosms, and an overall increasing trend in the infiltration rate was observed. Among the three media types, the clay-loam media had the highest infiltration rates, showing promise for future implementation. Soil respiration was measures as an indirect method of quantifying root activity, where the greatest respiration was associated with the clay-loam media. This research showcased the variability and changes in bioretention performance over time, as well as highlighted the role of the media and vegetation in various aspects of performance.

Preface

The following chapter have been published in, submitted to, and to be submitted to peer-reviewed journals:

Chapter 2 - Skorobogatov, He, J., Chu, A., Valeo, C., & van Duin, B. (2020). The impact of media, plants and their interactions on bioretention performance: A review. *The Science of the Total Environment*, *715*, 136918–136918. https://doi.org/10.1016/j.scitotenv.2020.136918

The following chapter has been submitted to *Water Research*:

Chapter 3 - Skorobogatov, He, J., Chu, A., Valeo, C., & van Duin, B. The Hydrologic Performance of Bioretention Mesocosms – Impacts of Design Parameters and Their Temporal Evolution. *Water Research.*

The following chapters have been reviewed by the co-authors and will be submitted to a journal:

Chapter 4 – Skorobogatov, He, J., Chu, A., Valeo, C., & van Duin, B. Multi-year analyses of bioretention mesocosm performance – Effect of design factors over time on leaching of nutrients and organics.

Chapter 5 - Skorobogatov, He, J., Chu, A., Valeo, C., & van Duin, B. Bioretention System Infiltration: Temporal evolution and Impacts of Design Parameters.

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Lastly, I would like to thank my committee members Dr. Patrick Hettiaratchi, Dr. Edward Johnson, Dr. Kerry Black, and Dr. William Zhang for contributing their time and efforts to the success of this research.

Dedication

I dedicate this to my wife Jessica and my family, who have been by my side through the years and endured the journey.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ADD	Antecedent Dry Days
ANOVA	Analysis of Variance
BMP	Best Management Practices
CL	Clay-loam/wood chip media
CoC	City of Calgary
CSA	Canadian Standards Association
DO	Dissolved Oxygen
DON	Dissolved Organic Nitrogen
EC	Electrical Conductivity
ET	Evapotranspiration
IP	Impervious to Pervious (in reference to areas)
IQR	Inter-quartile Range
IWS	Internal Water Storage
KS	Kolmogorov-Smirnov
LID	Low Impact Development
LMM	Linear Mixed Methods
ML	Maximum Likelihood
PET	Potential Evapotranspiration
PLR	Percentage of Load Retention
PWR	Percentage of Water Retention
SW	Shapiro-Wilk
TOC	Total Organic Carbon
VWR	Volume of Water Retention

Chapter 1: Introduction

1.1. Research Background

To address the negative consequences of land development and to overcome the limitations of conventional stormwater practices, an alternative approach that focuses on mimicking pre-development hydrologic condition was developed. This approach is known as Low Impact Development (LID). The defining feature of LID is installing multiple engineered systems near the source of stormwater runoff throughout the catchment and allowing the processes of infiltration, filtration, detention, storage, and evapotranspiration (ET) to reduce the total runoff volume and to remove runoff contaminants. Capturing runoff near its source can eliminate or reduce the costs associated with infrastructure necessary to collect and deliver runoff to a stormwater pond, while also providing the benefits of restoring the hydrological balance throughout the catchment.

Typical LID systems include bioretention systems, bioswales, permeable pavements, and green roofs (Dietz, 2007). A bioretention system utilizes vegetated depressions to detain stormwater runoff and to facilitate infiltration, groundwater re-charge, and ET processes (Roy-Poirier et al., 2010). Bioretention systems are typically characterized by having an inlet, ponding space, vegetation, an overflow system, a permeable growing media layer, a drainage layer, and an optional underdrain system below their surface (Figure 1.1). It has been acknowledged that well-designed bioretention systems can enable hydrological and water quality enhancements and offer additional benefits including a small footprint size relative to the catchment, not requiring irrigation and fertilizing, providing habitat benefits, and allowing seamless integration into the urban fabric (Hunt et al., 2015).

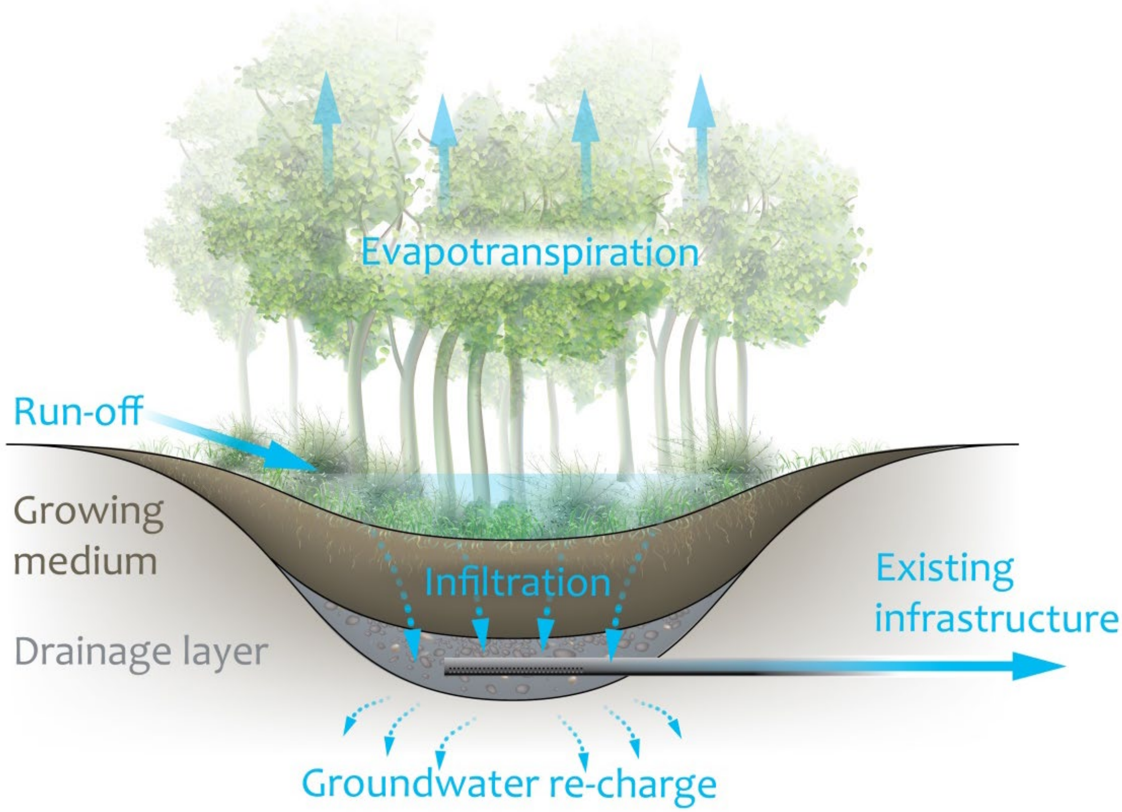


Figure 1.1. Diagram of a typical bioretention system.

In the context of stormwater management, bioretention performance has often been assessed from two main aspects: hydrology and water quality. Hydrologic performance metrics typically include reduction in peak flow, delay in peak flow timing, and reduction in runoff volume, whereas water quality performance metrics include removal efficiencies and mass loadings of common urban pollutants including sediment, nutrients, organics, metals, and pathogens (Davis, 2007 and 2008). Bioretention systems are generally accepted as being effective at removing TSS and attenuating peak flow, while variable results have been reported regarding the effectiveness of reducing the volume of runoff and removing nutrients, metals, and organics. For example, there is a dramatic variation in the volumetric reductions reported for various bioretention systems, as it depends strongly on the design of the systems and their climactic exposure (Kratky et al., 2017). Similarly, nutrient removal ranges from over 90% removal to over 200% leaching, although TSS removal efficiencies of 80-90% are generally reported (Fassam, 2012; Brown and Hunt, 2011; Kratky et al., 2017). When it comes to nutrient removal, there is a consensus forming that the removal of phosphorus (P) is mostly a function of the media properties and sorption, whereas nitrogen (N) removal in bioretention systems is more complex due to the biologically controlled nitrification and denitrification processes, N leaching from soil organic matter, as well as potentially significant plant uptake (Glaister et al., 2017).

Therefore, it is expected that the bioretention can be largely affected by the design parameters including media, vegetation, and hydrologic loading. However, the majority of research done on bioretention performance is focused on the role and properties of the growing media (Liu, 2014). Most studies have focused on utilizing coarsely textured media, as multiple lab-scale studies in the early 2000s have indicated that media with higher percentage of fines are prone to reduced infiltration, which leads to deteriorating functionality (LeFevre et al., 2014; Funai and Kupec, 2017). However, typically such conclusions are drawn based on short-term (often less than 12 months) studies on bioretention systems without vegetation, which are not representative of real-life bioretention systems. Furthermore, contrasting results have been reported in the presence of vegetation (Bratieres et al., 2008; Lucas and Greenway, 2008; Henderson et al., 2007). Nevertheless, more recent papers published are still focusing on analyzing unvegetated columns (Yan et al., 2017) and batch testing (Hurley et al., 2017) with the expectation that comparable results would be seen in the field.

Although many bioretention studies have not taken the role of vegetation into consideration when evaluating the performance of bioretention systems, several studies have investigated the role of vegetation by comparing the performance of bioretention systems with and without vegetation and among different vegetation species. Henderson et al. (2007) utilized mesocosm systems to analyze the difference in removal of dissolved nutrients when using three different media (gravel, fine sand, and sandy loam) and the presence/absence of vegetation. They found vegetated systems removed substantially more nutrients than non-vegetated systems. The study used the same plant mix for all treatments and did not investigate the plant-specific effects on performance. The work of Read et al. (2008) takes, perhaps, the most systematic approach to date at attempting to analyze a broad (20 species) plant palettes and their impact on bioretention performance from the nutrient removal perspective. This study found significant variation in the performance and attributed the variation to different plant-specific characteristics. The same research group then took their investigation a step further to look at specific plant traits and their correlation to the performance (Read et al., 2009). The finding was that root traits, such as the length of the longest root, rooting depth, and rooting mass, correlate strongly with nutrient removal. However, these experiments utilized small (Ø15 cm) columns as growing containers (limiting to plant growth), applied water in a fixed volume at regular time intervals, and excluded sediment from the inflow, which is not representative of conditions typical of bioretention systems. This experiment also lasted 22 weeks, which is likely too short to observe some of the effects of certain plant species, especially trees and shrubs, which require years to mature.

Furthermore, the role of trees and woody species has been represented poorly in the stormwater field (Berland et al 2017), even though there are multiple characteristics of woody plants that might be beneficial to bioretention performance. Multiple ecology and ecohydrology sources report greater runoff associated with transitions from a woody species-dominated system to a herbaceous one (Chang, 2013), attributing greater water retention to landscapes with woody vegetation. An article by Scharenboch et al. (2016) suggested that trees might be the best type of vegetation for LID applications based on the transpiration rates and the pronounced impact on the water budget. In addition, woody species tend to have larger roots that penetrate deeper into the soil, whereas grasses tend to have smaller fibrous roots that enmesh the soil close to the surface (Timlin and Ahuja, 2013).

Bioretention systems owe much of their functionality to the process of infiltration. It is widely acknowledged that infiltration is impacted by soil texture and structure, among which only soil texture can be easily controlled at the time of construction. This fact makes the selection and manipulation of media texture prevail in the study of bioretention. The role of media texture in controlling infiltration rate is undeniable due to its impacts on soil porosity, especially at the beginning stages of bioretention lifespan. Moreover, roots have been shown to increase infiltration in laboratory settings, for example in a study done by Bratieres et al. (2008). The key finding was that only plants with thick roots could maintain or even increase hydraulic conductivity of the media over time and in the presence of accumulating sediment. The concept that plants can create macropores and thus enhance infiltration in as short of time as 1 to 2 years has been reviewed in detail by Beven and Germann (1982 and 2013), yet a working understanding and appreciation of the phenomena is still lacking and it is unclear how to translate it into bioretention systems. A more recent study conducted by Hart (2017) investigated the root-related infiltration changes in bioretention systems and concluded that there is a positive correlation between root morphology and infiltration rates as well as seasonal variability in infiltration linked to root traits. Unfortunately, the study did not address the impact of sediment accumulation in relation to root-induced infiltration variation/ change. Without considering the role of plant roots, USEPA (2000) recommends replacing bioretention media every 5 to 10 years, based on the idea of clogging and deteriorating functionality of bioretention. If plants can counteract the deteriorating infiltration due macropore creation over time, a much longer lifespan can be expected from a bioretention system. There are other factors that need to be considered when investigating the impact of plant selection on bioretention performance. For plants to play a significant role in nutrient removal, low infiltration rates are preferable so that the microbial community surrounding plant roots could immobilize the nutrients for future plant use (Clark and Pitt, 2012). Therefore, an ideal bioretention system has infiltration rates sufficiently high to prevent long-term surface ponding and yet sufficiently low to allow effective treatment. Cameron and Schipper (2012) stated that the efficiency of nitrate removal depends on flow short-circuiting due to the presence of large, connected pores and heterogeneous flow. Plants produce macropores over time, which may counter-act clogging, but it may also lead to lesser nutrient removal. Plant roots also exert pressure on the surrounding soil, causing soil consolidation and an increase in soil bulk density (Cardon and Whitbeck 2007), which could further contribute to preferential flow. Overall, a non-uniform flow, such as one described by Jarvis (2007) is expected to be taking place most of the time in a bioretention setting, and yet for practical reasons, most bioretention system designers prefer to treat media as a uniform porous matrix that enables uniform flow. An additional factor that impacts preferential flow and therefore nutrient removal is soil moisture, as drier soil exhibit greater preferential flows due to water repellency (Hardie et al., 2011). Drier soils also cause plant roots to shrink, creating additional space for water to travel through the soil profile (Timlin and Ahuja, 2013). These notions contradict the intuitive idea of replenishing growing media storage via soil drying as beneficial to the bioretention performance.

There is also an emerging realization of how a static approach, in which the influencing factors are assumed to have constant effects, is not optimal for designing bioretention systems and predicting their performance (Traver and Ebrahimian, 2017). In practice, soil media storage and ponding volume are primarily used as the guiding parameters in the static approach. In reality, especially as it relates to infiltration, the texture of the media itself becomes less relevant when the system begins to receive sediment, especially since the sediment has colloidal particles which can fill the pore spaces and effectively halt infiltration. Soil structure may be the more important long-term consideration as soil structure is controlled by the ability of soil particles to aggregate, which is greatly facilitated by plant roots and associated microorganisms (Ritz and Young, 2011). The temporal evolution of infiltration would in turn impact the temporal evolution of the overall bioretention performance. Therefore, a more dynamic approach, in which the temporal evolution of bioretention performance is taken into consideration under the interactions of soil, vegetation, and hydrologic inputs, is desired when designing bioretention systems.

To summarize, bioretention performance is conventionally defined by the characterizing the media and the magnitude of a design precipitation event. Therefore, it is logical to assume that knowing the composition of media and design event magnitude, bioretention performance can be predicted. However, this approach does not take into account the fact that the properties of bioretention media are not static over time, as plants and associated organisms could alter the soil structure at rates sufficiently high for the impacts to be observable within years. Both plants and media are expected to influence bioretention performance. Thus, the investigation of the effect of the variables associated with media and plants is of great interest to better understand the dynamic performance of bioretention systems. Furthermore, identifying the most important factors contributing to the dynamic nature of such systems will aid in engineering design of bioretention and predicting its performance more accurately.

1.2. Research Objectives

The proposed research was intended to further the knowledge and understanding of bioretention performance in field conditions, especially the impacts of bioretention design parameters including growing media, vegetation, and hydrologic loading on bioretention performance, and the temporal variations and the physical mechanisms leading to the evolution of bioretention performance. The overarching objective of the proposed research is focused on the significance of the impacts of bioretention media and vegetation on a selected set of bioretention performance metrics and the investigation whether there is an observable change in these impacts or their inter-relationship over multiple years. To address this overarching research question, data were collected from the experimental bioretention beds receiving synthetic runoff which mimics typical stormwater runoff quality and average seasonal hydrologic loading (over the growing season) of the study area. The bioretention beds were exposed to operational conditions similar to those of real-world bioretention systems. Accordingly, the findings can be translated to recommendations and design tools for bioretention systems.

The detailed research objectives are:

1. To investigate the effect of bioretention design parameters on runoff retention as well as quantify and qualify the role of media storage and ET.
2. To investigate the effect of bioretention design parameters on water quality performance as well as quantify and qualify the effects for nutrients and total organic carbon (TOC).

3. To analyze the temporal effects of bioretention design parameters on bioretention performance
4. To quantify and qualify the effects of the interactions of bioretention design parameters on bioretention performance.
5. To investigate the evolution of infiltration capacity as it relates to the bioretention design parameters.

In this research, the bioretention beds were viewed as a dynamic system, thus special consideration was made towards the temporal variations in bioretention performance and factors that result in the variation. This research investigated lined systems, which excludes the potential impacts on groundwater recharge. This research will not address the differences in runoff caused by catchment heterogeneity, and pollutant loadings will be estimated based on a predefined catchment size, typical event magnitude and pollutant loading rate.

1.3. Dissertation Layout

This dissertation consists of six chapters. The first chapter (Chapter 1) provides an overview of the state of the research, as well as gaps in the understanding and practice that ultimately led to the development of the research objectives. The following four chapters (Chapters 2 through 5) are presented as journal articles, either already published, under review, or in preparation for publication. As such, each of these chapters is structured as a manuscript with the relevant sections for each topic. Chapter 2 was published as a review paper and provides an in-depth literature review that served as the foundation for the remainder of the research. Chapter 3 is focused on the impacts of the design parameters on hydrological performance of bioretention mesocosms, limitations of media storage, and evolution of volumetric retention over time. Chapter

4 is focused on the impact of design factors on the water quality performance of the bioretention mesocosms, leaching of nutrients and organics, temporal variability and some of the underlying processes. Chapter 5 is focused on the impacts of the design factors on infiltration performance as it impacts the overall bioretention functionality and is a major consideration for long-term performance. Chapter 6 provides an overview of the conclusions and recommendations for future research endeavors. Lastly, the appendix section includes additional information on experimental design, relevant materials and methods, as well as additional details of experimental setup and simulated event regime.

Chapter 2: The impact of media, plants and their interactions on bioretention performance: a review

2.1. Introduction

Stormwater management is becoming increasingly more important as urbanization and the associated land development transform natural landscapes (Eckart et al., 2017). The ensuing imperviousness and pollution generate excess runoff with varying degree of contamination, which can lead to flooding, erosion, and water quality impairment in the receiving water bodies (LeFevre et al., 2015). Low Impact Development (LID) is an approach to stormwater management that aims to utilize natural processes and minimize the negative impacts of urbanization (Liu et al., 2014a). Bioretention systems are some of the most commonly utilized LID practices, which have gained popularity due to their ability to reduce peak runoff flows and volumes, remove urban runoff contaminants, and provide aesthetic and ecological benefits (Li and Davis, 2009). The original concept of bioretention systems was built on the integrated effect of the ecological, physical, chemical, and biological functions of soil, plants, and microorganisms (Roy-Poirier et al., 2010b). When designing a bioretention system, one can vary its shape, size, media, underdrain, and/or vegetation, yet the overarching goal is invariably to capture a portion of stormwater runoff and to treat select runoff contaminants. Reduction of peak flows and removal of suspended solids by bioretention systems have been shown to be highly successful (DeBusk and Wynn, 2011; Li and Davis, 2016; Trowsdale and Simcock, 2011), while removal of dissolved contaminants is highly variable and capture of dissolved contaminants can be a challenge (Liu et al., 2017). An even greater challenge is understanding and predicting the long-term performance and the ultimate benefits of bioretention systems due to the relative novelty of the LID approach as well as the multifunctional nature of bioretention systems (Kratky et al., 2017; Lucke et al., 2017; Willard et al., 2017). A greater insight into the interactions between the media and the living components of bioretention systems could improve the ability to predict the long-term performance and the potential benefits of bioretention systems. Some of the relevant interactions that will be explored in this paper are related to water and nutrient balance, as well as the impact of plants on the physical and chemical properties of the media. Figure 2.1 highlights some of the interactive processes that will be discussed in this review.

Numerous media optimization studies have been conducted with the focus of identifying the most effective combination of materials to maximize pollutant concentration reductions and/or improve other aspects of the performance, such as hydraulic conductivity, residence time, or moisture retention capacity. However, such studies were often conducted over a relatively short period of time (weeks to months) and in the absence of vegetation (Fassman-Beck et al., 2015; Kim et al., 2018; Mei et al., 2018; Segismundo et al., 2017). Vegetation plays a key role in controlling wetting and drying cycles, the composition of the microbial community, and has a direct impact on soil physics and chemistry (Gobat et al., 2004). Despite the documented benefits, comparatively few studies dedicated their efforts to the role of vegetation in bioretention performance (Funai and Kupec, 2017). The few (Read et al., 2009; Read et al., 2008) that have, typically analyzed the effect of vegetation independently of the media. Table 2.1 provides an overview of a few studies that investigated the effects of media and plants simultaneously and the associated findings. To date, the majority of design specifications were provided on the media with the expectation that plants will cope with the media conditions and only recently some studies started evaluating media with the specific purpose of supporting plant growth without compromising the engineering functions (Funai and Kupec, 2017, 2018).

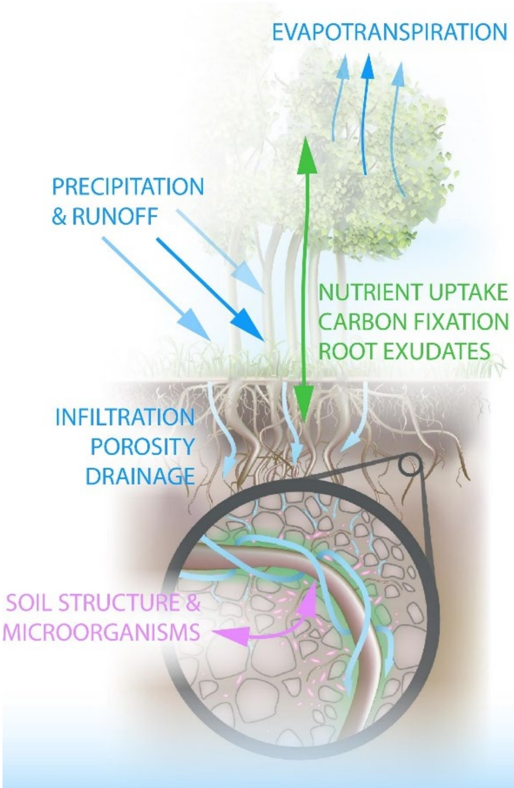


Figure 2.1. Biogeochemical interactions that could impact bioretention performance.

Table 2.1. Key characteristics and findings of the articles that investigated both media and plant effects.

Article	Experiment Duration	Establishment Period	Effect of media	Effect of vegetation
1- Henderson et al., 2007	<10 days	12 months	Sand or sandy-loam were the best media	Improves nutrient removal efficiency
2- Le Coustumer et al., 2007	12 months	N/A	Addition of vermiculite, mulch, and compost appear to improve hydraulic properties	Appears to improve hydraulic performance (but not statistically significant)
3- Bratieres et al., 2008	~12 months	6 months	Sandy loam is suitable as media; organic matter may lead to leaching	Selected species improve removal of nutrients
4- Lucas and Greenway, 2008	~12 months	3 years	Loam appeared to be more effective at nutrient removal than sand or gravel	Improves nutrient removal, and the extent exceeds anticipated plant uptake
5- Le Coustumer et al., 2012	72 weeks	N/A	Compost, vermiculite and perlite appeared to improve media conductivity	Only vegetation with thick roots appears to maintain hydraulic conductivity of media
6- Gautam and Greenway, 2014	N/A	~8 years	Loam appears to retain the most P, and media effects varies for N	Certain species retains more nutrients in their tissues and survives in various media
7- Liu et al., 2014b	~5 months	~ 5 months	Physical properties, nutrient and metal content influence treatment performance	Not as effective at treatment under some conditions or no difference
8- Glaister et al., 2014	12 months	~ 4 months	No difference in media type attributed to relatively short duration of the study	Improves nutrient removal
9- Turk et al., 2017	2 years	6 weeks	Not emphasized	No consistent trend in using native species vs cultivars; some plants improve treatment
10- Shrestha et al., 2018	2 years	2 years	Media additive treatment is the most effective at nutrient retention	Impact of vegetation appears irrelevant in comparison to media effects

Ultimately, a greater understanding of plant-media interactions will enable a more effective application of bioretention systems to the management of urban pollutants and hydrology. The intent of this review is to showcase the prominent role of the interaction of bioretention vegetation and media and how it impacts the fate of runoff and associated contaminants. Due to the high degree of complexity of the natural processes that govern bioretention performance, further research is needed to be able to characterize these systems and optimize future designs (Liu et al., 2014a).

2.2. Methodology

This paper encompasses a critical review and analysis of a variety of relevant literature sources, including peer-reviewed articles, books, design guidelines, government documents, and theses. The review process was conducted in several steps. First, a comprehensive search was done for relevant peer-reviewed articles using "bioretention" as a keyword and University of Calgary Library Database as a search engine, which covers a total of 1013 of online databases including Google Scholar, Web of Science, Scopus, BIOSIS Previews, and ScienceDirect. Approximately 300 articles were deemed relevant based on their title, the information presented in the abstract, and full-text availability. The articles were then reviewed in detail to gain an adequate appreciation of the existing state of knowledge of bioretention performance and the emphasis (or lack thereof) on plant-media interactions. Table 2.2 lists the 51 relevant articles that focused their efforts on the properties and optimization of media and vegetation.

Table 2.2. Articles that focused their efforts on media effects, plant effects, and a few papers that analyzed the impacts of both plants and media simultaneously.

Main focus (total # of articles)	Articles	
Media (30) Note: batch experiments were not included	Vegetation present (12)	Vegetation absent (18)
	(Brown et al., 2016) (Guo et al., 2016) (Tang and Li, 2016) (Hess et al., 2017) (Liu and Fassman-Beck, 2017) (Logsdon, 2017) (Wan et al., 2017) (Wang et al., 2017a) (Li et al., 2018) (Liu and Fassman-Beck, 2018) (Zhang et al., 2018) (Funai and Kupec, 2018)	(Kim et al., 2003) (Hsieh and Davis, 2005) (Hatt et al., 2007) (Stander and Borst, 2010) (Cho et al., 2011) (Good et al., 2012) (Paus et al., 2014) (Fassman-Beck et al., 2015) (Iqbal et al., 2015) (Peterson et al., 2015) (Adhikari et al., 2016) (Chahal et al., 2016) (Li et al., 2016) (Tian et al., 2016) (Jay et al., 2017) (Segismundo et al., 2017) (Kim et al., 2018) (Mei et al., 2018)
Vegetation (11)	(Read et al., 2008) (Read et al., 2009) (Zinger et al., 2013) (Chandrasena et al., 2014) (Payne et al., 2014a) (Houdeshel et al., 2015) (Nocco et al., 2016) (Rycewicz-Borecki et al., 2017) (Wang et al., 2017b) (Xia et al., 2017) (Morse et al., 2018)	
Media and vegetation (10)	(Henderson et al., 2007) (Le Coustumer et al., 2007) (Bratieres et al., 2008) (Lucas and Greenway, 2008) (Le Coustumer et al., 2012) (Gautam and Greenway, 2014) (Glaister et al., 2014) (Liu et al., 2014b) (Turk et al., 2017) (Shrestha et al., 2018)	

It can be seen from Table 2.2 that only 10 articles investigated the effects of media and plant properties simultaneously, and plant-media interactions were not explicitly investigated. Upon confirming that limited information on bioretention plant-media interaction was available, the search was expanded to using various combinations of keywords that included "plants", "vegetation", "media", "soil", and "interaction", which yielded a much broader collection of literature sources, some of which were no longer focused on bioretention systems, yet offered valuable information. The sources from other fields provided additional insight into the potential significance of plant-media interactions and how they might impact bioretention performance. It is important to point out that some of the materials, which offered relevant information on the interactions, did not contain information on plant-media interactions, but rather plant-soil interactions, which is why it is important to clarify how the definitions differ. To clarify, in this manuscript soil refers to natural soil, while media refers to the engineered media of bioretention systems and other LID practices. By definition, soil refers to the naturally occurring solid materials capable of supporting plant growth, whereas bioretention media refers to the engineered mix of solid materials designed to meet the various objectives set forth by the relevant practitioners. Once the review process was completed, this review paper was composed ins such a way as to categorize the relevant information, knowledge gaps, and the impacts of plant-media interactions based on the water quantity and quality considerations and the associated impacts on the performance. The hydrological aspects of the performance encompass the water quantity considerations and impact the water quality ones due to volumetric capture. For this reason, hydrological considerations are presented first, followed by water quality considerations.

2.3. Hydrological Performance

2.3.1. Overview

Most of the first studies conducted on the hydrological performance of bioretention systems showed that these systems were capable of significantly reducing the overall runoff volume and effectively capturing most of the runoff generated by small storm events (EPA, 2000). By the early 2000s, the research efforts were mainly focused on documenting the existence of hydrological performance and its variability and not necessarily the processes underlying the hydrological performance (Dietz, 2007). The variability in the hydrological performance of bioretention systems is still a relevant research topic today, as the performance is influenced by a multitude of contributing factors, such as design configuration, location, average annual precipitation, potential evapotranspiration, I/P ratio, presence of underdrain, depth of ponding, subsoil conditions and subsoil infiltration rate, as well as growing media composition (Li et al., 2019; Zhang and Chui, 2019).

One of the first attempts to quantify the hydrological performance of bioretention systems was done by Davis (2008). The study provided a simple approach to assessing bioretention performance using hydrologic parameters to characterize the pre- and post-development conditions and, in turn, to quantifying bioretention hydrological benefits. The parameters included rational method's runoff coefficient and Manning's roughness coefficient, which very broadly (at land use level) relate to the impacts of vegetation and vegetation-media interactions on the hydrologic performance, but the relationship was not explicitly emphasized at the time.

Subsequently, Davis et al. (2011) attempted to quantify the fundamental hydrological aspects of bioretention performance and to link the performance to design parameters. They introduced the concept of Bioretention Abstraction Volume (BAV), which was defined by the storage available in the media pore spaces and the depression bowl of a bioretention system and used to describe the commonality behind the observed event-based hydrological performance. To determine BAV for a bioretention system, one would need the knowledge of soil water retention parameters, such as porosity, field capacity, and wilting point, as well as the extent of root zone that would utilize the available moisture. Despite acknowledging that plant-related traits (i.e., the extent of root zone) would shape the hydrological functionality, the BAV approach mainly focused on the media characteristics.

By the mid2010s, the variation in the hydrological performance was attributed to the variation in the magnitude of runoff events as well as the magnitude of the infiltration and evapotranspiration (ET) (Ahiablame et al., 2012). Despite the attribution, there was an apparent gap in the knowledge of ET and percolation processes as they related to bioretention performance (Denich and Bradford, 2010). Concurrently, it was becoming apparent that continuous, rather than event-based, approach to modeling the water balance of bioretention systems was necessary to better represent reality. Some of the first continuous simulation tools designed specifically for bioretention systems, such as the City of Calgary Water Balance Spreadsheet, were sufficiently advanced to incorporate ET, yet were somewhat limited in quantifying it with accuracy (Calgary, 2011). Understanding plant-media interactions is critical in defining the processes of ET and percolation, while approaching media and plants separately is believed to lead to incomplete analysis of bioretention performance and potentially erroneous predictions.

Overall, several studies have nowadays presented evidence of bioretention systems as being effective at shifting the urban hydrologic condition towards a more natural state characterized by reduced runoff volumes, peak flows, and increased time of concentration. However, when it comes to the underlying mechanisms, the current knowledge is often one-sided, and the approach may be overly reductionist to understand a bioretention system in its entirety. Plant-media interactions have not been investigated by the researchers in the field, and further research of these interactions is needed in order to improve our holistic understanding and facilitate successful implementation of bioretention systems in the future. Figure 2.2 depicts the processes/mechanisms related to bioretention hydrological performance as would be perceived by the conventional approach and the more holistic approach, where the latter highlights the impacts of plant-media interactions. The following sections of the review delve deeper into the relevant aspects of hydrological performance and the associated impacts of plant-soil interactions.

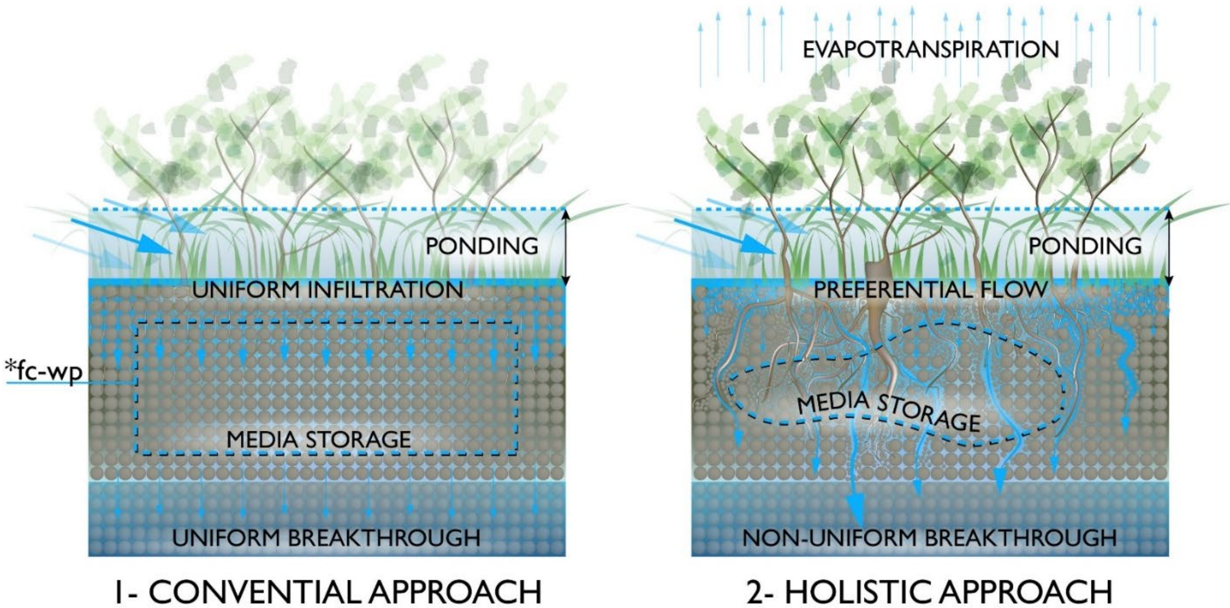


Figure 2.2. A comparison of the key hydrological processes that influence bioretention performance between (1) the conventional approach and (2) the more holistic approach that considers plant-media interactions (*fc -field capacity, wp -wilting point).

2.3.2. Media Porosity and Storage

Characterizing and optimizing media properties have dominated bioretention research, and the concept of BAV is a good example of that. Focusing on the media and ponding storage offers a tangible approach to designing bioretention systems (Lewellyn et al., 2018), but it only provides a snapshot of the system rather than addressing the continuous and evolving processes, which shape the interactions between the media and the vegetation and, ultimately, the performance.

There is no denying that media storage is primarily a function of the available pore space. The most common approach to designing the pore space (and the associated storage) is specifying the texture of the media. Using texture of the media to define storage assumes a degree of uniformity of particle sizes and the pore spaces in the media. There is a well-documented link between soil texture and associated porosity, as well as wilting point and field capacity (Brady and Weil, 2008). One could assume that knowing the media texture is sufficient to estimate the storage-related parameters and, consequently, the overall storage capacity of the media. However, the ultimate size and shape of the three-dimensional void space that is available for storage, as well as transport and reactivity, is defined by the soil structure, not texture. Soil and media structure is the outcome of multiple evolving processes and characteristics, of which texture is only one component. The importance of structure is highlighted by the reported differences in the properties of a structured soil upon disturbance, which causes destruction of the soil structure (Logsdon et al., 2013), and improved ability to predict soil retention and hydraulic properties upon the incorporation of structure into the process (Nguyen et al., 2015). Vegetation plays a key role in soil structure formation and development, primarily through root-related mechanisms, which has been shown in a study by (Daynes et al., 2013).

Vegetation is also a key contributor to replenishing media storage through ET, yet the extent is not well-defined or understood. Available water content, or the difference between the soil water content at field capacity and permanent wilting point, is conventionally considered as the soil water available for plant use (Dingman, 2008). However, some studies show that transpiration-related losses can also be significant at moisture contents greater than field capacity, which undermines the conventional notion of plant available water (Timlin and Ahuja, 2013). In addition, pore size is thought to play an important role in the availability of soil water to plants, and the presence of mesopores (0.2 - 60 um) is considered to be critical (Jim and Ng, 2018). Root zone extent is another factor that is critical in defining how media storage gets replenished, and it cannot be treated as a static parameter as root growth and distribution change in response to the available soil moisture. The root zone extends deeper into the soil profile when the soil moisture is limited and stays shallow when the moisture is abundant (Timlin and Ahuja, 2013).

There are additional media storage and porosity considerations that are impacted by dynamic and evolving plant-media interactions – clogging of the pores by the incoming sediment and creation of pores by the growth and decay of plant roots. Le Coustumer et al. (2007) showed that sediment accumulates in bioretention media over time and it clogs up the pores. Clogging of the media is likely the leading factor in determining the longevity of bioretention systems, and the inflow sediment concentration and particle size appear to have an impact on the rate of clogging (Kandra et al., 2014). Media clogging can be very rapid, as reported by Segismundo et al. (2017), who observed signs of clogging developing within hours in an unvegetated test column. Vegetation may play a key role in counteracting the impacts of clogging, primarily due to the turnover of roots and creation of macropores. Rapid root turnover, where substantial root mass is created and lost to decay within a relatively short time frame, could have the greatest impact on media porosity. For example, grasses are capable of growing up to six sets of roots to about 0.6 m of depth per growing season, which would create abundant macropores and could counteract clogging (Houdeshel et al., 2012). However, the current data on root-induced porosity and its role in prevention of bioretention media clogging are insufficient to support a practical shift in the design process.

To improve our understanding of the ways in which bioretention media storage and porosity affect hydrological performance, more research is needed to address the impacts of soil structure, dynamics of soil water availability and plant root growth, as well as the clogging and root turnover. Soil structure considerations, such as pore space arrangement, pore size distribution, and the role of plant roots in shaping the pore space need to be acknowledged and incorporated into bioretention system design in order to optimize the hydrological performance. Additional research is needed to understand and quantify the impacts of media moisture dynamics on root distribution, plant growth, and media storage capacity replenishment. When it comes to addressing the potential impacts of clogging, one needs to balance the knowledge of root turnover and its impact on the porosity to better predict the dynamic long-term performance of a bioretention system.

2.3.3. Infiltration and Conductivity

Conventionally, ignoring the role of compaction, infiltration-related considerations mainly focus on the texture of the media. Many articles state that media selection is key, and clay content needs to be minimized to maintain adequate infiltration (Liu et al., 2014a). The argument is based on the observation that fines in the media may result in lower infiltration rates and may exacerbate the negative impacts of the incoming sediment as they clog up the pores and result in diminished hydrologic performance. Instead, media with coarse soil texture (i.e., sand) are typically preferred to maximize effective porosity and minimize the negative impacts of clogging. However, coarsely textured media could be problematic due to poor water retention capacity and the associated negative impacts on plant survival (Funai and Kupec, 2018). Finely textured media would provide a better substrate for bioretention vegetation, but the perceived negative impacts on media conductivity render them undesirable (Liu et al., 2014b). The majority of vegetated runoff treatment systems call for at least 75 % sand with minimal fines (Funai and Kupec, 2017). A potential solution is a two-layer media with the surface soil layer promoting plant growth and the underlying layer having high sand content for greater filtration as it could offer multiple benefits when it comes to performance and plant survivability (Liu et al., 2014a).

Good et al. (2012) found that soil-based bioretention media were slower in infiltration than sand only or a mixture of sand and soil. Selbig and Balster (2010) found that for bioretention systems, the median infiltration rates of sand media were an order of magnitude greater than those of clay media. However, the study by Selbig and Balster (2010) also demonstrated that markedly different infiltration rates were observed between systems planted with turfgrass and prairie vegetation. Prairie vegetation not only caused greater infiltration rates in both sand and clay media, but also promoted adequate drainage and soil development as compared to turfgrass. Soil texture alone may not be an effective indicator of media conductivity (Fassman-Beck et al., 2015), potentially due to the higher order of structural organization of the pore spaces, which ultimately control conductivity. As mentioned above, vegetation plays a critical role in soil structure development and pore space organization. It has even been argued that living organisms may have a greater impact on infiltration than the intrinsic properties of soil itself (Funai and Kupec, 2017). Without vegetation and soil structure considerations, one may assume uniform infiltration into the uniformly ordered matrix of the media. In such a scenario, some retention would be expected based on the antecedent occupancy of the pore space, and the excess volume would result in uniform breakthrough at the bottom of the media. A more realistic scenario is one where media is impacted by the plants, and particularly the development of macropores and preferential flow, leading to non-uniform infiltration and potentially non-uniform breakthrough of poorly treated stormwater runoff. Therefore, the combined effect of plant and media can have a critical impact on the conductivity and the overall functionality of a bioretention system, and the use of soil texture parameters alone may be overly simplistic for reliable long-term performance predictions.

As aforementioned, vegetation is associated with macropore formation and, consequently, may promote enhanced infiltration and conductivity since roots create comparatively large, connected pathways in the growing media. Le Coustumer et al. (2012) showed that woody plants with thick roots appear to maintain the infiltration capacity of bioretention systems. Gonzalez-Merchan et al. (2014) supported the notion that vegetation might prevent surface clogging and enhance infiltration due to root action and macropore formation. Virahsawmy et al. (2014) reported similar results and argued that vegetated areas maintain infiltration even in the presence of sediment and hypothesized that this might be due to preferential flow path creation. A recent study conducted by Hart et al. (2017) investigated root-related infiltration changes in bioretention systems and concluded that there is a positive correlation between root morphology and infiltration rates as well as seasonal variability in infiltration associated with root traits. Unfortunately, the study did not address the impact of sediment accumulation in relation to root-induced infiltration changes.

Without plants, bioretention media is expected to be clogged by the influx of fines and be subject to the subsequent loss of conductive pore space and functionality (Subramaniam et al., 2018). EPA (2000) recommends replacing bioretention media every 5 to 10 years, based on the idea of clogging and deteriorating functionality of bioretention without taking the role of plant roots into consideration. If plants can counteract the deteriorating infiltration due to macropore creation over time, a much longer lifespan of bioretention systems can be expected. The notion that plant roots can create macropores and thus enhance infiltration in as short of time as 1 to 2 years has been thoroughly reviewed by Beven and Germann (1982, 2013), yet a working understanding and appreciation of the phenomena is still lacking. It is also unclear how to translate this understanding into knowledge about the actual performance of bioretention systems.

2.3.4. Evapotranspiration

Previous sections pointed to the importance of media storage and infiltration as the defining factors that shape the hydrological performance of bioretention systems. Traver and Ebrahimian (2017) pointed out that the use of traditional key performance parameters including ponding and media storage underestimated bioretention performance when it comes to the water balance aspects of it. Incorporating the effects of ET would be a next obvious step towards a more accurate representation of bioretention processes. However, the significance of the contribution of ET to the overall water balance remains controversial. More often than not ET is considered to make up less than 5 % of the overall water balance (Szota et al., 2018). However, there have been reports of significant ET losses in the past, such as a study by Li and Davis (2009), which reported that ET can account for up to 19% of stormwater runoff even when bioretention system is only 4.5% of its catchment. Nocco et al. (2016) published a more recent study where they showcased significant ET losses when using simulated runoff and sizing their systems at 17% of the contributing impervious catchment. They were able to demonstrate that ET losses can be as high as 82% of the overall water balance per simulated event for prairie vegetation and 52% for both turfgrass and shrub mesocosms.

When it comes to different vegetation, it is expected that larger woody species, such as shrubs and trees might provide substantial benefits to the bioretention water balance, as they offer large evaporating surface areas and consequently can have high ET rates. In contrast, Nocco et al. (2016) did not observe greater ET losses associated with larger woody vegetation as compared to herbaceous vegetation. Some studies even argue that trees have lower ET per unit area as compared to turfgrass in urban settings (Berland et al., 2017). To date, there is no clear consensus on whether woody vegetation, and especially trees, offer superior hydrological performance. In particular, the effects of trees on ET appear to be species-specific as demonstrated by Szota et al. (2018), who investigated 20 different tree species and their ET rates, which proved to be different, but in many cases comparable to herbaceous vegetation. A key limitation of the latter study was that the analysis was done on tree seedlings, not mature trees, which does not encompass the key benefit of the larger evaporating area.

It is not surprising to observe variation among different vegetation types and different species, as ET is dependent on several plant-specific parameters, such as root architecture, density, and internal tissue resistances to water transport (Moene and van Dam, 2014). However, media characteristics related to texture, structure and compaction, can also impact the ultimate root morphology. For example, soil penetration resistance is a soil (and media) characteristic that has been shown to significantly influence root growth and it is not only related to intrinsic soil properties, but also the soil moisture status (Colombi et al., 2018). The biggest issue with the media-vegetation interactions in general is the respective interconnectedness of the processes involved. Media conditions change as a consequence of physical and biological processes, which in turn triggers a response in the vegetation that could feedback to the media condition. An example is a halt in ET seen in plants in response to unfavourable growing conditions that could develop in the media, such as low moisture, insufficient oxygen, or presence of other environmental stressors. Bartens et al. (2009) showed that reduced drainage might decrease ET rates. Plants would wilt under poorly drained conditions because their intrinsic permeability is dependent on adequate cell respiration, which is compromised in the absence of oxygen typical of waterlogged soils. Soil type plays a role in the potential impacts of poor drainage, for example, clay soils are particularly susceptible to waterlogging.

In addition, a study by Hess et al. (2017) investigated the effects of different soil types and the inclusion of an internal water storage (IWS) layer on ET losses. Their results showed that the media with greater intrinsic water storage capacity as well as the inclusion of IWS both appeared to enhance ET rates and overall losses further supporting the notion of ET being highly dependent on the available soil moisture. Therefore, providing a saturation zone might be the most effective way of ensuring availability of soil moisture to maximize the hydrologic benefits of ET. Moreover, having a sub-surface reservoir is particularly beneficial in attenuating the fluctuations associated with moisture levels and soil hydraulic conductivity. Normally, soil water withdrawn by a plant in an unsaturated environment would decrease the soil hydraulic conductivity, which often creates the greatest resistance to the movement of water through the soil-plant-atmospheric continuum (Nobel, 2009).

Overall, more research is needed to characterize the performance of various types of vegetation, especially trees and other woody species as compared to herbaceous vegetation in the context of ET and its impact on bioretention performance. In addition, certain media characteristics, such as penetration resistance, could be critical in controlling root growth and availability of soil water to plans, yet there are no bioretention studies to date, which quantify this type of plant-media interaction. It is particularly relevant to dedicate research efforts to the areas where interactions are impacted by the soil moisture dynamics, as the interconnected nature of the interactions makes the processes particularly complex. Understanding how soil moisture status and other soil characteristics affect plant physiology and ET is beneficial to enable accurate characterization of bioretention hydrology and better predictions of performance in the future.

2.4. Water Quality

2.4.1. Overview

In the context of water quality, bioretention performance can be defined in terms of the reductions in pollutant concentrations and/or loadings, which are associated with pollutant concentration and the volumetric capture. The volumetric capture is dependent on the hydrological performance, which was discussed at length in the previous sections of this review. Consequently, the following sections will focus primarily on the processes and interactions between media and vegetation that could impact the pollutant concentrations, and especially nutrients, directly. The focus on nutrients is based on the widespread eutrophication concerns around excessive concentrations of nutrients in stormwater runoff that threaten receiving water bodies and pose significant challenges when it comes to removal. Nutrients are also essential to living organisms and the role of direct plant uptake as well as uptake by the associated microorganisms can have a significant impact on the overall performance of bioretention systems. Nowadays, several research studies have confirmed the role of vegetation and microorganisms on water and nutrient balance within bioretention systems (Zhang and Chui, 2019).

Plant-soil interactions play a critical role in water quality treatment as the soil controls the availability of nutrients and contaminants to plants due to its reactive nature (Caldwell et al., 2005), and plants change the soil physically and chemically over time (Ritz and Young, 2011). From the perspective of the media, certain properties, such as low phosphorus (P), low organic matter, and organic matter with high (greater than 20) carbon:nitrogen (C:N) ratio, e.g. derived from woody plant materials, are deemed beneficial for excess nutrient removal (McPhillips et al., 2018). In addition, there are multiple media amendments that have been tested in efforts to enhance nutrient (especially P) retention. The P retention has been believed to be mainly realized through adsorption and was shown to be improved by amending media with water treatment residuals (Lucas and Greenway, 2011), lime and alum sludge (Adhikari et al., 2016), fly ash (Kandel et al., 2017), and iron-enriched sand (Erickson et al., 2012). Unlike P, the role of the media on N removal is not as straightforward as P removal. Payne et al. (2014b) identified the need for a greater understanding of soil-plant interactions as well as microorganisms in N speciation and removal by bioretention systems. Nitrate and dissolved organic nitrogen, both of which are not retained well by the media (Li and Davis, 2014), are typically the dominating species of N. Nitrate removal is highly dependent on the inter-event period, when plant uptake, ET, and microbial mineralization can take place (Wang et al., 2018a).

Regarding the role of plants in the water quality performance of bioretention systems, a number of studies were conducted over the years. However, these studies have not led to a consensus yet. Davis et al. (2006) concluded that vegetation could play a significant role in nutrient removal through analyzing the fate of nutrient uptake in a bioretention mesocosm based on the observed nutrient loading and removal rates combined with knowledge of typical plant uptake rates. Henderson et al. (2007) showed that vegetated systems performed better at taking up nutrients across a variety of media textures, and that vegetation had a role in preventing nutrient leaching. Bratieres et al. (2008) observed that different combinations of soil and vegetation perform differently in removing nutrient and sediments. Lucas and Greenway (2008) demonstrated that vegetation improved nutrient removal through nutrient uptake, and pointed out that the uptake exceeded plant nutrient needs suggesting other mechanisms being involved for both P and N. Read et al. (2008) showed that only select plants had the ability to improve nutrient uptake of stormwater biofiltration systems. Read et al. (2009) further systematically investigated the linkage between plant traits and biofiltration performance and concluded that the length of the longest root, rooting depth, root length, and root mass were the most important plant parameters when analyzing nutrient uptake. Furthermore, a recent study by Muerdter et al. (2018) pointed out the lack of adequate characterization and understanding of the processes underlying the measurable benefits of vegetation to the functionality of bioretention systems. As a result, even though the role of vegetation was recognized over a decade ago, the quantitative consideration of its roles in practice is still somewhat lagging.

When attempting to describe the mechanisms of contaminant retention, the conventional approach has often characterized the sorption capacity of the media, which is commonly done in the absence of vegetation. The assumption is that there is a finite number of binding sites that are available for interaction and upon exceeding the capacity, breakthrough of the contaminant would take place. As was covered in previous sections, when taking the impact of vegetation into account, the microenvironment of the media where sorption takes place may be quite different from the conventional notion. The contaminants could be flowing along the preferential flow channels created by plant roots in the media, and there could be limited interaction between the contaminant and the bulk of the media. As a result, the contaminant could be primarily subject to the impact of the unique chemistry that develops within and immediately adjacent to root macropores and also be more prone to bypassing the media and resulting in breakthrough even when sorption sites are available. When a living root is present, an overall movement of water into the root due to transpiration could draw certain contaminants in. In addition, plant roots are known to secrete various compounds, called root exudates, which could impact the overall reactivity of the macropore and the available binding sites. Considering that macropores may carry the majority of the flow, the majority of the reactions may be very tightly linked to the specific biophysicochemical properties of root macropores. Figure 2.3 summarizes the key processes in the conventional approach and the holistic approach, which highlights the potential impacts of vegetation and the plant-media interactions on the unique nature of macropore reactivity and how it could impact treatment by bioretention systems. The following sections will describe the impact of plant-media interactions on water quality and treatment in greater detail.

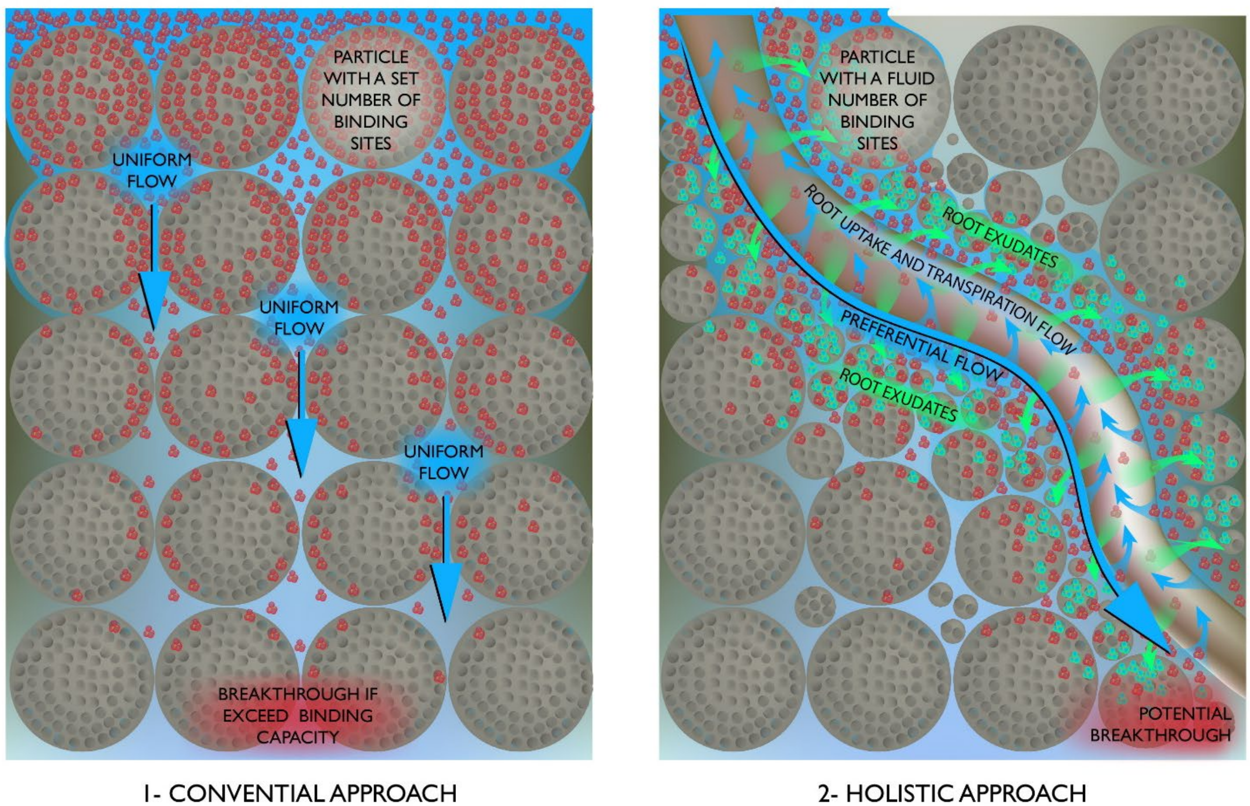


Figure 2.3 A comparison of the key water quality related processes that influence bioretention performance between (1) the conventional approach and (2) the more holistic approach that considers plant-media interactions.

2.4.2. Media Reactivity

Without a question, in the case of bioretention systems, the selection of the composition of the bioretention media is one of the most obvious tools for controlling water quality performance and ensuring that certain water quality targets are met. Although a bioretention medium is not exactly synonymous with soil, it carries much of the same functions. Soil is a complex medium, and it can "be considered as a chemical reactor linked to both plants and hydrology" (Franzle, 2010). Soil properties such as texture, structure, porosity, and reactivity are all highly relevant in defining the functionality of bioretention media in the context of water quality. The reactivity of soil is defined by both the reactive surface area and the functional groups at its surface (Essington, 2004).

Media selection is particularly important for some of the urban runoff contaminants that are thought to be removed solely by sorption processes. Adsorption is cited as the primary mechanism responsible for P retention in bioretention systems based on the existing body of knowledge (Li and Davis, 2016; Liu and Davis, 2014). Media of high concentrations of calcium (Ca), aluminum (Al), and/or iron (Fe) have shown the most promise in P removal (Logsdon, 2017). Some of the naturally occurring reactive minerals that are directly involved in phosphate sorption are boehmite, goethite, and ferrihydrite (Sparks, 2003). Depending on the origin of the materials used to create bioretention media, the reactive minerals might be present in large enough quantities to impact P retention. More commonly, bioretention media are amended with materials rich in Fe and Al to enhance its reactivity. For adsorption to take place, the P species must interact with the reactive species at the soil surface and displace the antecedent compound (Mei et al., 2012). Liu and Davis (2014) proposed a two-step mechanism where rapid (i.e., in the order of minutes) outer sphere adsorption of P takes place during a storm event, followed by a slow formation of more irreversible inner complexes between the events.

Both the outer sphere adsorption and the irreversible complex formation between P and the media are subject to interference by plant-based compounds. Root exudates including organic acids and chelating compounds might compete with P for complexation with the reactive metals in bioretention media. The exact composition and the extent of the release of root exudates depend on plant type and the conditions of the below- as well as above-ground environment that the plant is in. Limited data are available on how root exudates impact the soil water chemistry, and no data are available on such processes in the context of bioretention systems, yet the impacts could be significant. However, it is important to point out that the ligand exchange reactions of organic acids are often weaker than phosphate itself, which means that the concentration of exudates needs to be quite high to compete with phosphate (Guppy et al., 2005). In addition to direct competition, there are other mechanisms through which root exudates could impact media reactivity, as some exudates also promote solubilization of existing metal phosphates, such as Ca phosphate (Gregory and Nortcliff, 2013). Such plant-induced changes in media reactivity would result in increased nutrient availability and potential leaching, as well as altered sorption capacity.

Cumulative contaminant accumulation and media exhaustion are important considerations when the adsorption capacity and the history of exposure to the contaminant are the controlling factors. Jiang et al. (2017) are among the few researchers who have investigated the sorptive capacity of bioretention media. They estimated the life time of bioretention systems based on the annual retention and capacity consumption. A study by Johnson and Hunt (2016) showed that P accumulated in bioretention cells over time and might need to be removed to prevent build-up and potential impacts to the downstream environments due to leaching. However, Komlos and Traver (2012) reported substantial removal of phosphate in a 9-year old bioretention facility without any signs of diminished functionality. The observed superior long-term performance might be due to the soil-plant interaction effects, in particular the long-term solubilizing effects of plant exudates that would slowly regenerate the sorption capacity of the media. The impact of such interaction would have to be acknowledged when assessing the sorption capacity of the media, as one cannot predict the long-term performance of the system based on the chemical composition of the media alone.

Less impacted by the reactive minerals in the media, N removal, differing from P removal, is primarily thought to depend on the opportunities for microbial denitrification, which, in turn, depends on the presence of C sources and anaerobic conditions (Wan et al., 2018). A few different types of C were tested by Fowdar et al. (2015), with acetate resulting in removals of 48 mg N/L/day and hardwood resulting in 0.3 mg N/L/day. Similar to acetate, plant exudates are a readily available source of C and would result in comparatively high rates of denitrification. Denitrification is highly beneficial to bioretention performance as it allows excess N to be converted to N gas, which can then escape to the atmosphere. A biogeochemical assessment done by O'Reilly et al. (2012) showed that the loss of nitrate from a biofiltration system was primarily attributed to denitrification, as compared to direct plant uptake or microbial pathways.

An IWS layer is becoming a commonly recommended feature (CSA, 2018) to be incorporated into new bioretention systems to provide saturated anaerobic conditions and promote denitrification. Wang et al. (2018b) concluded that the addition or increase in depth of an IWS layer significantly improved nitrate and total N removal in bioretention column studies. However, denitrification was shown to also take place even in the absence of an IWS layer (Chen et al., 2013). Anaerobic microsites and available C are critical drivers of such phenomena. Norton et al. (2017) showed that about 23% of dissolved inorganic N species were subject to removal by denitrification in a bioretention system without an IWS. Tang and Li (2016) showed that the incorporation of a layer of low permeability into a bioretention column might be more effective at improving nitrogen removal than an internal storage layer, which raises additional questions around the optimal bioretention system design and calls for more supporting evidence of superior design configuration. Lynn et al. (2015) demonstrated that dissolved organic C accumulate in the pore spaces of media containing wood chips during the inter-event period, which then contributed to nitrate removal during the run-off event. Plants deposit as much as 50% of fixed C into their growing substrate and can create oxygen-deficient zones due to root respiration (Ritz and Young, 2011), which could promote the development of anaerobic microsites and the associated denitrification independently of an IWS layer.

Given the dependence of N removal on oxygenation and soil moisture, one would question whether environmental conditions ought to be considered as the key performance drivers. Waller et al. (2018) analyzed 23 different bioretention systems situated in a variety of climatological conditions and concluded that intrinsic bioretention design parameters had a greater impact on denitrification than the environment. Specifically, greater media C and inorganic N content were shown to have a role in promoting denitrification. In addition, the enhanced denitrification activity was found near the surface of the bioretention cells, despite a greater degree of saturation found near the bottom of the media, which can be explained by the abundant C input provided by the bioretention vegetation (Willard et al., 2017).

On the other hand, a recent study by Gold et al. (2019) challenged the notion of microbial mineralization and denitrification as the dominant process of N removal and argued that soil assimilation might play a greater role. Khorsha and Davis (2017) emphasized the importance of N removal mechanisms that are abiotic in nature, especially in the times when biological activity is restricted. There is some evidence that abiotic sorption of nitrate is possible by organic amendments, specifically activated C (Erickson et al., 2016). Harmayani and Faisal Anwar (2016) investigated adsorption of N species onto sawdust and found that sawdust particles are quite effective at capturing negatively charged forms of N, such as nitrate and nitrite. If organic amendments are capable of binding nitrate, plant detritus and turnover could play an important role in the dynamics of nitrate removal by sorption processes.

One of the biggest unanswered questions in the context of media reactivity is the impact of plant-produced compounds on the chemistry and reactivity of the media and the associated impacts on the performance of the system as a whole. The biophysicochemical nature of the impacts that plant exudates could have on the media and the role of the media properties in triggering the release of a particular host of exudates are unknown at this time. Having such knowledge could shed light on the long-term performance of bioretention systems. The performance parameters that are of particular relevance are long-term sorption capacity and reactivity of the media, as there is a potentially critical role in plant exudates controlling media regeneration.

2.4.3. Evapotranspiration and Soil Wetting and Drying

Section 2.4 of this review addressed the importance of ET in the hydrological performance of bioretention systems. The wetting and drying cycles as well as the duration of inter-event periods, which affect ET, also have a critical impact on the water quality performance of bioretention systems. Mangangka et al. (2015) showed that inter-event dry periods play an important role in nutrient capture and mobilization within bioretention systems. In addition, ET reduces the water content in the root vicinity and thus has a direct impact on the mass flow of nutrients into the root (Caldwell et al., 2005). Besides, ET also influences the development and duration of saturated conditions, which have important consequences in the retention and transformation of nutrients in a bioretention setting.

Soils with high availability of P that are near saturation have been shown to release P due to desorption (Clark and Pitt, 2009; Hunt et al., 2006b; Shrestha et al., 2018). Flooding leads to an increase in the available P in soil pore water due to several mechanisms, with a key one being the conversion of less soluble Fe_3^+-P complexes to more soluble Fe_2^+-P complexes (Rakshit et al., 2015). Interestingly, some studies indicated that the effect of flood-drain cycles might have a beneficial impact on P sorption and cause a more rapid binding of P when drained and subsequently exposed to a P-rich solution (Sah and Mikkelsen, 1986). On the contrary, soil drying can dramatically increase the amount of leachable P because of crystallization of minerals and soil structural changes (Li and Davis, 2016). Therefore, vegetation, which would decrease the duration and frequency of saturation through ET, would influence the solubilization of P in media and in turn affect the release of P from media.

As previously mentioned, N transformations in a bioretention setting are highly dependent on the wetting and drying cycles. The presence of saturated conditions directly influences denitrification and associated conversion of N species to N gas. In addition, antecedent dry days (ADD) or inter-event periods are also highly relevant to N transformations and removal within bioretention systems. Cho et al. (2011) showed that when supplied with an organic N and C source, bioretention columns contained less organic N when subject to longer ADDs, as organic N could be broken down to ammonia through the process of ammonification. Shrestha et al. (2018) stressed the importance of aerobic conditions in bioretention cells to promote ammonification. ET would drain the pore spaces and enable aerobic conditions and minimize saturation, and thus facilitate the associated N transformations.

Another potential step in N transformation is nitrification, in which ammonia can be converted to nitrate. Cho et al. (2011) showed that nitrate concentrations increased with increasing ADD, pointing to the occurrence of nitrification. Nitrification is also dependent on unsaturated and aerobic conditions, and thus would benefit from the consumption of excess moisture by ET.

Subramaniam et al. (2016) observed that wetting and drying cycles influenced the "first flush" of elution of nitrate from bioretention systems. They found that nitrate concentration in the initial portion of the effluent (samples collected immediately after effluent breakthrough) was dependent on the antecedent event and ADD. As a result, ET, which affects the soil moisture content during the inter-event period, would impact N speciation by controlling the degree of saturation and oxygen availability.

Plant transpiration is controlled by many factors and can have a major impact on the wetting and drying cycles, which in turn could create oxygen-poor and oxygen-rich conditions in the media. Many reactions that are relevant to bioretention performance are governed by the presence and/or absence of oxygen, water, and a form of carbon. The impact of plants on the water quality side of bioretention performance could be tightly linked to their transpiration, and more research is needed to better understand and quantify the potential impacts.

2.4.4. Soil Structure and macropores

When discussing media interactions and reactivity, one typically assumes that the entire matrix of the media is available for interactions. However, as mentioned in the previous sections, the soil structure and the connectivity of the media pore spaces ultimately determine the interface that provides the opportunity for the solutes to react with the media as runoff percolates through the media. Macropores are particularly relevant, as they can carry most of the percolating flow and induce short-circuiting of the media (Fassman-Beck et al., 2015). Tedoldi et al. (2016) showed that enhanced vertical transfer of contaminants is typically associated with macropore presence and that the physicochemical nature of macropores is different from that of the bulk media. The most obvious consequence of enhanced vertical transport is a reduced retention time, which is expected to reduce the effectiveness of water quality treatment by bioretention systems. However, Hatt et al. (2006) found that an increase in retention time did not appear to improve pollutant removals. Le Coustumer et al. (2009) also showed that an optimum relationship existed between the hydraulic conductivity of biofiltration media and the removal of nitrogen. These suggest that simply increasing the retention time alone is not a desirable measure for promoting treatment. Moreover, Ding et al. (2019) stated that macropore formation does not appear to have a deleterious effect on nutrient retention in a bioretention medium.

As for the development of a distinct chemistry around root macropores, it could be the result of the inability of roots to take up certain solutes at the rate of convective solute transport. Certain nutrients, such as Ca and magnesium, were shown to accumulate in the vicinity of roots due to the difference in rate of root uptake and convective solute transport (Moene and van Dam, 2014). Thus, vegetation is capable of creating uniquely reactive conduits within bioretention media, which could carry most of the flow and be the main interactive surface that is exposed to runoff contaminants. This puts the notion of a significant role of media properties into question as macropore hydrology and chemistry might be significantly different from the bulk media and ultimately govern the bioretention water quality performance. The formation of macropores and their impact on nutrient removal and/or leaching need further investigation in bioretention settings. In the formation of macropores in bioretention systems, the soil properties might also play a crucial role. Cohesive soils are more likely to form stable aggregates and develop discernible soil structure over time, which could lead to formation of a more stable network of macropores within these soils. Clay particles are more reactive, and their irregular shape and structure favours the formation of specific three-dimensional arrangements. When considering the general positive effects of fine particles in the media, studies showed the improved removals of pathogens (Wen et al., 2016), nutrients (Henderson et al., 2007), and heavy metals (Sapdhare et al., 2018). However, fines in the media may increase the risk of contributing turbidity to the bioretention outflow. Nevertheless, the export of fines from bioretention systems might be a short-term issue as Subramaniam and Mather (2016) observed significantly diminishing amounts following the first event. Considering the benefits and the drawbacks of fines in bioretention systems, it is common to see guidelines that recommend media mixed from sand and a small percentage of fines to achieve a balanced outcome. When it comes to soil structure development, organic matter could play a critical role. Complex organic compounds can bind mineral soil particles together to form organo-mineral three-dimensional complexes. Plants are the primary contributors of organic matter to an otherwise inert mineral soil, and this contribution is crucial in soil formation. Normally, soil evolution takes place within thousands or tens of thousands of years, yet plants may accelerate soil formation by dramatically increasing the soil C content within as short of time as 50 years (Gregory and Nortcliff, 2013). Interestingly, soil C may further enhance macroporosity as studies have shown that the addition of compost and grass coverage increased porosity several fold (Deurer et al., 2009).

Further research is needed to explore the unique reactivity of macropores and the extent to which it impacts the overall water quality performance of bioretention systems. There are multiple gaps in the current state of research and practice as very little is known about macropores in the context of bioretention systems. Some information is available on the impact of macropores on the hydraulic properties of the media, but essentially nothing is available on the impact on media chemistry and reactivity. Knowing that macropores could be carrying most of the flow, the potential impacts on the reactivity are likely to be significant and data are needed to be able to quantify the associated processes and eventually apply the knowledge to future designs and performance optimization.

2.4.5. Plant Uptake

Plant uptake is likely the most intuitive effect of plants on the removal of solutes from the incoming runoff. Chen et al. (2017) showed that plant uptake could be a significant contributor in removing pollutants (especially nutrients) from water and the contribution was species-specific. Plants, as any other living organisms, require nutrients for their growth and depend on a certain nutrient input per growing season. The essential nutrients are normally supplied by the soil that a plant is growing in. For example, a typical loam should contain sufficient nutrients to support adequate plant growth. However, in bioretention systems, the media may not supply enough nutrients if composed of coarsely-grained inert materials and thus the input from runoff would become critical to sustain vegetation growth.

N and P are key mineral nutrients that plants need for growth and that have the greatest deleterious effects on the downstream environments due to eutrophication. Plants contain N and P ranging between 1 to 6% and 0.05 to 0.5% in their biomass, respectively (Mitra, 2015). Consequently, the accumulation of plant biomass is one of the mechanisms, albeit not as significant as media, of capturing excess nutrients in a bioretention setting. Supporting this notion, Gautam and Greenway (2014) and Payne et al. (2018) argued that plants with higher growth rates, extensive root systems, and high plant biomass could remove more nutrients. Occasional harvesting of biomass is essential to the removal of excess nutrients, as without harvesting, accumulated nutrients return to the media through plant decomposition and litterfall (Jose and Gordon, 2008; Sun et al., 2017). However, there might be unintended consequences to the removal of plant material, as Herrman et al. (2012) showed that the disturbance and destruction of plant material in a soil mesocosm led to significant nutrient leaching and reduction in water retention. In the literature, the current knowledge on the uptake of N and P by plants is not consistent. In a study of co-optimizing the removal of N and P, Glaister et al. (2014) found that vegetation had a significant impact on the removal of both P and N, showcasing that plant uptake is a feasible pathway for nutrient sequestration. However, a study by Houdeshel et al. (2015) showed little difference in P removal but significant difference in N removal between vegetated and unvegetated bioretention mesocosms. Furthermore, Liu et al. (2014b) demonstrated that vegetation reduced the effectiveness of P removal in bioretention mesocosm studies with engineered media and short residence times (1 hr). An aspect of nutrient uptake that has been demonstrated in agricultural studies and not in bioretention is that nutrient availability in soil (or media) could impact water use efficiency of plants (Hatfield and Sauer, 2011), which would link water quality and hydrological performance parameters of bioretention systems.

Note that there is one more challenge that makes the assessment of N removal more difficult compared to that of P removal. Rycewicz-Borecki et al. (2017) showed that a nearly complete accounting of P mass balance could be performed by quantifying P uptake by plants, analyzing the relationships between nutrients applied, stored in soil and plant tissue, and the amount that left the system via exfiltrate, whereas the same approach was not applicable for N removal as about half of N was unaccounted for, potentially due to denitrification and loss of nitrogen gas to the atmosphere. Consequently, although the role of plant uptake in N removal has been investigated in different settings in the past years, it is not clear whether more N removal is simply associated with direct plant uptake, wetting-drying cycles, or other mechanisms (Dietz, 2016).

In particular for nitrate removal, there is also a lack of consensus on whether the process is primarily driven by microbial denitrification or plant assimilation. Plant uptake of nitrates was shown to correlate negatively with denitrification, presumably because less nitrate was available for denitrification to occur (Morse et al., 2018). The correlation was especially pronounced in the shallow (< 30 cm) zone of the soil, where the roots have the greatest density and activity. Payne et al. (2014a) investigated the fate of isotope-labelled nitrate in bioretention systems and found that the majority (over 90%) of nitrate was assimilated by plants. Stormwater runoff is generally characterized by having a low carbon-to-nitrogen ratio, which is thought to limit denitrification unless a carbon source is supplemented (Zinger et al., 2013). Some recent studies have pointed to the fact that root exudates might be sufficient to provide a continuous carbon source to enable adequate denitrification (Wang et al 2017). As a consequence, there is still a need to investigate both the direct and indirect roles of plants on nutrient removal for bioretention systems.

When evaluating the role of plants on nutrient removal, the other aspect that should be taken into consideration is the nutrient availability in bioretention media. The bioavailability of nutrients within a soil can be viewed as an equilibrium between nutrient release due to mineralization and nutrient capture due to sorption (Caldwell et al., 2005). Nutrient uptake by plants is dependent on the amount and availability of a nutrient in the soil and the rate at which it can be delivered to plant roots (Agren and Andersson, 2011). In addition, the plant uptake may play different roles under wet and dry conditions, as various correlations have been shown between plant traits and nutrient removal (Glaister et al., 2017) and, as discussed previously, wet and dry conditions can affect the availability of nutrients and their speciation. Seasonality is another highly important consideration, as high rates of uptake would take place during the peak of the growing season whereas there is essentially no uptake when plants go dormant (Lukac and Godbold, 2011).

In terms of the plant nutrient uptake, additional research is needed to reliably quantify the processes involved and estimate the role of the uptake in the overall mass balance. A key link between plant uptake and the overall performance of bioretention systems may lie in the relationships that exists between the uptake and wetting-drying cycles, which plants influence through ET. Plants are subject to flood and drought stress within a bioretention system, which triggers an intrinsic response from the plant on a molecular level in order to cope with the conditions of their environment. Plants are unique living organisms in that they are unable to physically move, which makes their intrinsic regulatory processes highly relevant to their survival. Very little data are available on how plants respond to the stressful conditions in the media, and no current studies show how it would impact bioretention performance. A greater understanding of the link between plant physiology and media conditions, such as nutrient availability and flooding, as well as drought conditions, would allow a better quantification of nutrient balance within bioretention systems and improved implementation in the future.

2.4.6. Microorganisms

This review is primarily focused on the interactions of media and vegetation, but one cannot underestimate the impact of microorganisms on shaping these interactions and bioretention performance in general. As an example, microorganisms have been known to provide beneficial impacts on nutrient retention. Multiple studies have focused their efforts on the impacts of microorganisms on N speciation, transformation, and retention by bioretention systems (as described in previous sections), yet much less is known about the impacts of microorganisms on P. Poor et al. (2018) showed that fungal growth might improve P retention in bioretention systems. Mycorrhizal fungi were shown to enhance P retention and/or reduce leaching of P from soils based on inoculation (Asghari et al., 2005) and bioretention mesocosm experiments (Poor et al., 2018). In agricultural settings, microbial-assisted uptake was proposed as a potential solution to manage P to mitigate the unintended consequence of soil pollution and/or downstream eutrophication due to fertilizing (Parmar and Singh, 2014).

An increasing number of studies, which analyzed bioretention and soil filtration systems from a microbiological perspective, suggest that there might be more complexity in some of the processes influencing pollutant removal than originally assumed. Microorganisms on their own have a unique role in the performance, but they also engage in numerous interactions with vegetation, which have critical impacts on nutrient cycles and thus water quality. It is well-known that a substantial amount of plant-based C is released from plant roots in the form of exudates and mucilage, which then provide a suitable source of energy for microbial growth (Moene and van Dam, 2014). However, microorganisms and plants are forced to compete for available nutrients as they share the same habitat. Although microorganisms could store a significant portion (i.e., up to 50% of soil P) of soil nutrients in their biomass, this pool of microbially-bound nutrients is subject to release upon changing conditions, such as in wetting and drying cycles, which is controlled by the vegetation (Parmar and Singh, 2014). Vegetation might then also benefit from the nutrients acquired and released by microorganisms. On the other hand, there is evidence that certain mycorrhizal fungi can increase soil weathering several fold, which would promote nutrient solubilisation and availability, but a clear cause-and-effect relationship has not yet been established (Bünemann et al., 2010). The notion is based on the observation that various bacteria and fungi produce organic acids and enzymes that lead to solubilization of phosphate. If such microbial solubilization impact is significant, its role in bioretention performance needs to be investigated.

The microbial composition is highly relevant to the functionality of the microbial community. Stormwater itself favours the development of a specific microbial community within vegetated stormwater practices (Endreny et al., 2012). Plants have a well-documented ability to shape their microbial community, as a number of studies has shown that vegetation has various ways of regulating their rhizosphere and the associated organisms (Bais and Sherrier, 2015). Deeb et al. (2018) argued that green infrastructure practices that are less than 10 years old could already develop substantial microbial biomass and activity, which is a very short term on the scale of soil formation. Mitchell Ayers and Kangas (2018) observed signs of soil development, which is the product of biologically-accelerated soil formation processes, in bioretention systems that are only a couple years old. A study by Fraser et al. (2018) demonstrated that bioretention media was colonized by pathogenic and denitrifying bacteria immediately after construction, and that there might be benefits in inoculating techniques to shape the microbial communities within bioretention systems. Winfrey et al. (2017) highlighted the need to explore mycorrhizal relationships in bioretention systems, supported by data indicating various mycorrhizal communities form within bioretention systems. Owing to the observed potential roles of microorganisms, it was recommended that bioretention systems be designed with a particular microorganism in mind, which could be achieved by choosing media and specific plants that promote the development of a particular rhizosphere, in order to enhance the removal of a target pollutant (Hong et al., 2018). However, this should be integrated with the selection of specific soil properties considering soil moisture regime and plant species, as soil and plant characteristics can favour the formation of a specific microbial community.

On the other hand, microorganisms have the ability to shape the soil structure, which has critical implications on soil conductivity and reactivity as discussed previously. Various soil-binding compounds released by microorganisms and fungal hyphae networks are critical contributors to the development of soil structure and its maintenance over time (Kubicek et al., 2007). Much effort has been made to investigate the role of microbial exudates and hyphae networks in stabilizing soil structure, yet in soils with high clay content, the shrink-swell properties of clay might diminish the stabilizing effects of microbial binding agents (Kubicek et al., 2007). Interestingly, fungal effects on soil aggregation are the strongest in sandy soils and minimal in clay soils (Kubicek et al., 2007). However, the activity of microorganisms is not the most significant in shaping the soil structure on a macroscale, as a larger role is played by the activity of roots and fauna, and a larger role yet is played by the wetting and drying cycles (Ritz and Young, 2011).

Microorganisms undoubtedly have a role in bioretention performance, as they shape a variety of natural processes, including soil weathering, nutrient and carbon cycling, and symbiotic relationships, which affect the water quality performance of bioretention systems. One of the biggest challenges is recognizing a set of bioretention parameters, which would facilitate the formation of stable microbial populations and consequently enhance a system's resilience and improve its performance. A study by Waldrop et al. (2017) investigated the relationship between soil properties, plant production, and organic matter on soil microbial composition and enzymatic activity across the contiguous United States, and found plant production and soil organic matter to be significant. Interestingly, soil mineral composition appeared to play a role from the perspective of its ability to form stable complexes with soil organic matter. A greater understanding of the interactions between the living components of bioretention systems and the mineral media is overdue as the functional implications of such interactions are important and many.

2.5. Conclusions

As aforementioned, the roles of vegetation, media, and microorganisms on water and nutrient balance within bioretention systems have been addressed to varying extent in the current literature. Multiple media optimization studies have shaped our understanding of the balance between adequate hydraulic properties, minimal leaching tendencies, and supporting plant growth. The fewer plant optimization studies have highlighted that selected plant species appear to enhance certain aspects of performance, especially when it comes to nutrient uptake and media conductivity. Nevertheless, our understanding of the overall impact of the living components on the performance and their interaction still has not benefited from adequate research efforts to date. To improve our understanding and subsequently the implementation of bioretention systems, a more adaptive and dynamic approach to bioretention design and performance assessment is needed.

A research direction worth pursuing is characterizing how the wetting and drying cycles influence nutrient speciation and retention. It is well-known that N balance is strongly dependent on the soil moisture; however, more data are needed to assess the respective contribution of multiple pathways of N transformation and the respective impact of ET on the overall performance. The same notion applies to P retention as well. Despite the emerging consensus that media composition dictates this aspect of the performance, there is a sensitivity to saturation that would undermine retention. Vegetation influences the media moisture content through ET, which would impact the degree of saturation and its consequences. In addition, a non-trivial amount of data suggests that there is a role for plant and microbial exudates in P retention and leaching, given the variety of chemicals that are secreted and their ability to interact with the reactive groups of the media.

Another aspect of bioretention performance that needs further qualitative and quantitative characterization is the functional balance between media pore clogging and macropore formation over time as it relates to media permeability. Being able to understand the parameters that enhance and reduce permeability and infiltration has direct implications on being able to optimize the hydrological performance. More importantly, the implications on the water quality improvements or lack thereof need to be characterized as there is a concern around reduced retention times and media by-pass associated with macropore formation.

The nature of microbe-plant interactions remains somewhat of a mystery, but progress has been made in other research fields, and the knowledge that relates to rhizosphere formation and its physical and chemical implications should be applied in the context of bioretention systems. There are numerous studies that show how certain types of vegetative covers promote soil formation, nutrient cycling, and microbial activity, but it is not known how these kinds of interaction impact bioretention performance. It would be highly beneficial to utilize the information on plant-microbe-soil interactions to ensure successful long-term operation of bioretention systems.

Overall, a more interdisciplinary approach is needed in order to capitalize on the breadth of functions that are offered by bioretention systems, especially when attempting to utilize these systems in challenging climactic conditions. For example, when precipitation is scarce, the overall impact of bioretention systems might be greater than in the contexts of abundant precipitation, but there is an added challenge of keeping the vegetation alive. Identifying more balanced solutions that recognize the importance of media, plants, and microorganisms will allow more effective applications of bioretention systems.

Chapter 3: The Hydrologic Performance of Bioretention Mesocosms – Impacts of Design Parameters and Their Temporal Evolution

3.1. Introduction

There has been an increasing demand for nature-based solutions to either supplement or replace conventional "grey" infrastructure. Low Impact Development (LID) advocates for a more natural, "green" approach in response to the negative hydrologic impacts associated with urbanization. The impacts are typically associated with increases in runoff flow rate, excess runoff volume, and impairment of runoff quality (LeFevre et al., 2015). Bioretention systems offer diverse benefits, such as a reduction of the peak runoff rate, attenuation of excess runoff volume, retention of various pollutants, as well as aesthetic and habitat benefits (Li and Davis, 2009). Their hydrologic function is often perceived as a key aspect of the overall performance and has been the focus of multiple investigations (e.g., Davis et al., 2011; Hathaway et al., 2014; Hatt et al., 2009; Li et al., 2019).

Peak flow management is attainable with conventional grey infrastructure, whereas the need for volumetric attenuation has created unique opportunities for LID, including bioretention systems. Despite the perceived benefits, annual runoff reduction varies widely depending on system size, media type, vegetation type, underdrain configuration, and underlying soils (Hathaway et al., 2014; Houdeshel et al., 2015; Liu and Fassman-Beck, 2016). There are multiple previous works that highlight substantial seasonal runoff volume reduction (Brown and Hunt, 2011; Davis, 2008; Hunt et al., 2006; Khan et al., 2012; Li et al., 2009). However, other studies argued that only minor hydrologic benefits are attributed to bioretention systems, specifically when it comes to controlling the runoff volume (Chin, 2016; Hatt et al., 2009).

As aforementioned, the apparent effectiveness of stormwater capture by bioretention systems depends on multiple factors, which can broadly be attributed to factors related to local climate or design configuration (Zhang and Guo, 2013). It also appears that discrepancies in runoff volume reduction can be caused by fundamental differences in the amount of runoff received, the amount of flow-through and percolation losses, and the inherent limitations in quantifying water balance in an unlined system. Adding complexity to the issue is the lack of consistency in the terminology of bioretention, rain gardens, and biofilters, which have been used interchangeably in the literature despite their functional and operational differences.

Furthermore, nature-based solutions, including bioretention systems, depend on complex biological, chemical, and physical interactions and the inherent intricacies of these interactions have not yet been fully established. Media and vegetation are among the most studied factors in bioretention design (Glaister et al., 2014; Henderson et al., 2007; Liu et al., 2014; Shrestha et al., 2018; Turk et al., 2017), yet data on media-vegetation interactions are lacking (Skorobogatov et al., 2020). To further complicate matters, nature-based systems change over time (Kratky et al., 2017), and the impacts of the changes are sparsely documented in the literature given that the duration of most studies is relatively short and reports are typically made on systems that may not have reached maturity. Lastly, it is notoriously challenging to make inferences about interactions in complex systems when different factors are studied in isolation (Soberg et al., 2020), which diminishes the value of such data in application to real systems. As a result, there is a need for investigating individual design parameters under varying conditions, as well as examining the interactions of the design parameters and the performance evolution of nature-based solutions.
Therefore, the focus of this paper is on investigating the hydrologic performance of 24 bioretention mesocosms that were monitored for four years, and to assess the impact of three bioretention

design parameters, namely media, vegetation, and hydrologic loading (as IP ratio) on stormwater capture. IP ratio is defined as the ratio of contributing impervious catchment area to the bioretention area (Calgary, 2016) and a greater IP ratio results in a greater hydrologic loading on a given system. The mesocosms were lined to prevent infiltration losses, allowing the analysis to focus on the runoff reduction associated with the bioretention system itself. Given the high degree of hydrologic variability that bioretention systems are typically exposed to (Hatt et al., 2007), this paper also investigates the effect of stormwater event magnitude on hydrologic performance and offers insight on how the associated impact compares to the impacts of the design parameters. The key questions on the hydrologic performance that this paper attempts to respond to are the following: (a) were there significant differences across the runoff events? (b) were there differences among the different mesocosm types based on design parameters? (c) did the differences change over time? and (d) how did they change over time?

3.2. Materials and Methods

3.2.1. Description of study site and mesocosms

A bioretention research site was constructed for this study in the Town of Okotoks (Alberta, Canada) in Fall 2016 / Spring 2017. Okotoks has a xeric temperate climate, with short warm summers and long cold winters. The average annual temperature is 4.6 °C and the average annual precipitation is 515 mm. The research site consists of 24 bioretention mesocosms that are lined, designed to receive no natural runoff, and drained by pumping through a perforated standpipe. All the mesocosms have the same configuration (Figure 3.1). There were three bioretention media; two of those, referred to as media 70 and media 40, were based on local LID guidelines (Calgary, 2016). The values refer to the targeted hydraulic conductivity in millimeters per hour. Both were made of different combinations of sand, sandy loam, and compost. The third one was a unique mix of clay loam and wood chips (referred to as CL). All media were installed at 60 cm depth, pre-mixed and supplied by a local company. The media parameters are summarized in Table 3.1. The drainage layer was made of three 10 cm deep layers of 40 mm washed drain rock, 10 mm washed gravel, and 3 mm washed sand. The mesocosms were planted with three different vegetation types including herbaceous, woody, and turfgrass (as control) plants. Plantings were done on a 20 cm grid and were identical in density and composition among the mesocosms of the same vegetation type. Details on plant species are provided in Table S1 (in Appendix). Lastly, the mesocosms were subject to two hydrologic loadings represented as IP ratios of 15 and 30. Overall, the setup of this experiment employed a partial factorial experimental design, considering three factors at two or three levels (Table S2, in Appendix). Each mesocosm was equipped with two TEROS-12 soil moisture sensors at 20 and 40 cm depth installed in 2018. Surface moisture (0 cm depth) was measured manually with a handheld adapter and TEROS-12 sensor in 2019. A weather station was installed on site to record the temperature, rainfall, wind speed, relative humidity, and solar radiation.

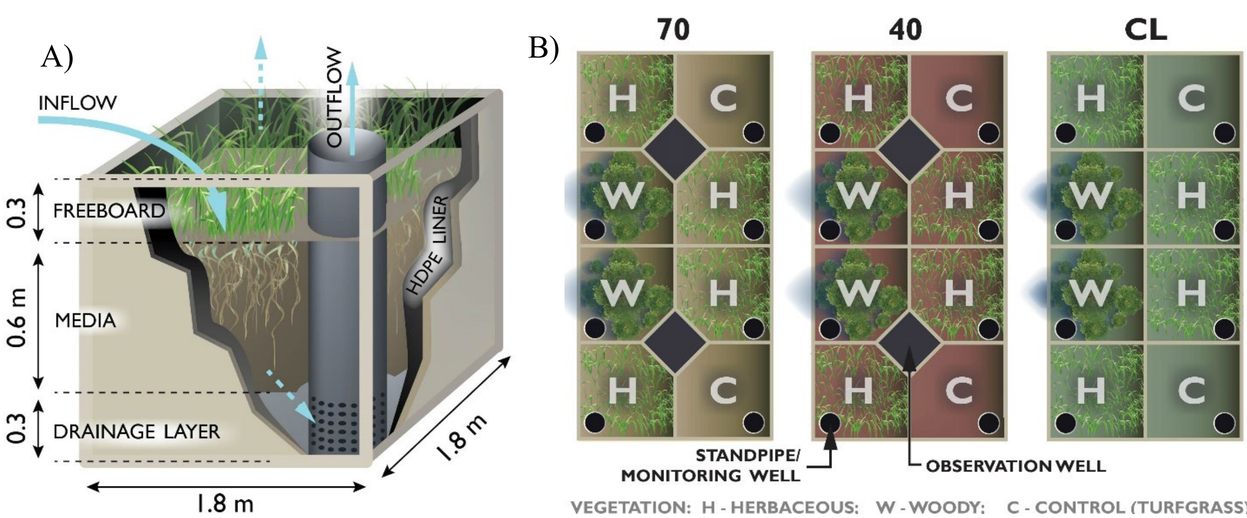


Figure 3.1. Bioretention mesocosm schematic – A) individual mesocosm and B) overall layout.

Table 3.1. Media characteristics.

Property	Media Type		
	Media 70 [a)]	Media 40 [a)]	CL
Organic Matter (w/w)	3.5 (5-10)	16.4 (15-20)	11.2 (8.7) [b)]
% Sand (0.05-2.00 mm)	74.6 (75-80)	73.7 (40-80)	41.6
% Silt (0.002-0.05 mm)	19.3 (10-15)	22.6 (10-25)	44.3
% Clay (<0.002 mm)	6.1 (3-10)	3.7 (0-20)	14.1

[a)] Values are calculated based on data from hydrometer test and laser light diffraction particle size distribution analyses, while values in brackets are targets from the local guidelines (City of Calgary, 2011).
[b)] The value of 11.2 was calculated based on % by volume of wood chips (using density of pine) that was used to create the media, whereas 8.7 was the value obtained through loss on ignition, where larger wood chips were not included.

3.2.2. Simulated storm events

The mesocosms were subjected to simulated runoff events during the growing season (May – October) of 2017-2020. The annual hydrologic loading, event magnitude, and inter-event period were taken into consideration in the study design, and they were determined by analyzing a 57-year (1960-2016) precipitation record. The typical application consisted of 24 events including twelve 5 mm events, five 10 mm events, four 15 mm events, and three 25 mm events, which reasonably approximates the hydrologic loading in the study region. In each simulated event, its magnitude of rainfall was reduced by 1 mm to account for depression storage. The events were spaced by approximately 5 days to be representative of local conditions. On average, every other event was one of the smallest (4 mm) magnitude. In 2017, the mesocosms were irrigated for the first two months to support plant establishment, followed by three preliminary simulated events of 15 mm each. Monthly breakdown of simulated events and simulated event schedule are presented in Tables S3 and S4, respectively (in Appendix).

The water used in the simulated events was sourced from a local stormwater pond and delivered to the site on the day of the event. Additional sediments (sourced from municipal street sweepings) were added to better represent the typical concentration of total suspended solids (400 mg/L) in the study region. The sediments were mixed with a small quantity (~ 5 L) of water and added as a slurry with each simulation. The water was applied into each mesocosm using garden hoses at 2 L/s flow rate. Free drainage was simulated by pumping the percolating water until gravity drainage ceased considerably. Once pumped, the volume of exfiltrate was recorded.

3.2.3. Field Capacity and Antecedent Media Storage Estimation

To quantify available storage, the field capacity (θ_{fc}) of the mesocosms was estimated through the saturation experiments. Each mesocosm was saturated from the bottom, analogous to the method of estimating the water holding capacity of soil cores (Margesin and Schinner, 2005). Mesocosms were then drained by gravity and pumped out for a minimum of 5 consecutive days following saturation. In the estimation, the recorded gravity drainage volume (V_{out}) was interpreted as the pore volume that did not contribute to retention. Furthermore, the maximum volumetric moisture content (θ_{max}) recorded by the soil moisture sensors at saturation was interpreted as the porosity. Thus, θ_{fc} was calculated by

$$\theta_{fc} = \theta_{max} - \theta_g$$

where θ_{max} is the average maximum soil moisture content (v/v%) measured at 20 and 40 cm depths of each mesocosm; and θ_g is the fraction representing water content of pores that drained by gravity and is calculated by

$$\theta_g = V_{out}/V_{media}$$

where V_{media} is the total volume of media within each mesocosm. The estimation of θ_{fc} was conducted three times over the four-year period. As the three measurements were not significantly different for each mesocosm, an average of the three measurements was used as to estimate field capacity. The estimated θ_{fc} was then applied to estimate antecedent media storage (S_{ac}) prior to a simulated event by

$$S_{ac} = \theta_{fc} - \theta_{ac}$$

where θ_{ac} is the antecedent soil moisture recorded prior to a simulated event. The temporal variation of soil moisture in a simulated event and the reading of antecedent soil moisture are presented in Figure S1.

3.2.4. Event-based Water Retention

To assess the hydrologic performance of the mesocosms, the water retention (both in terms of percent retention and the actual volume of water retained) was calculated for each mesocosm per event. In similar studies, an event is defined by the period within the 24 hours after runoff is received (Davis, 2008; Hatt et al., 2009; Li et al., 2009). In the present study, the duration of each event was defined as the period from the onset of a simulated event to the onset of the next simulated event. This provided a complete account of the water balance, as natural precipitation and/or additional drainage may take place beyond the 24 hours period. The percentage of water retention (PWR) and the volume of water retention (VWR) were calculated using the following equations for each event:

$$PWR = (1 - \frac{V_{out\_1} + V_{out\_2} + V_{out\_last}}{V_{in} + V_{ppt}}) * 100$$

$$VWR = \left(V_{in} + V_{ppt}\right) - (V_{out\_1} + V_{out\_2} + V_{out\_last})$$

where V_{in} is the volume of water applied into each mesocosm; V_{ppt} is the total volume of rainfall that fell onto each mesocosm during the duration of the event; V_{out_1} and V_{out_2} are the exfiltrate volume pumped on the first day of the event and the second day of the event, respectively; and V_{out_last} is the exfiltrate volume pumped on the day before the next simulated event.

3.2.5. Statistical Analysis

The statistical analysis was conducted at two levels, namely within individual events and between events. Within individual events, the impacts of the design parameters, i.e., media, vegetation, and IP ratio, on water retention were analyzed within each simulated event using analysis of variance (ANOVA). ANOVA is well suited to analyze factorial designs with two or three independent variables (Salkind, 2010; Weiss, 2005). The ANOVA analysis was considered valid when its associated assumptions on the normality and the homogeneity of variance were met. The normality assumption was tested using Kolmogorov-Smirnov (KS) and Shapiro-Wilk (SW) tests, whereas the homogeneity of variances was tested using Levene's test. Only in the case of instances when both normality and homogeneity assumptions were violated and/or the ANOVA model itself was not significant, were the events deemed unsuitable for the ANOVA analysis.

To further examine the hydrologic performance across events, as well as to connect the within-event and between-event performance, the linear mixed methods (LMM) were used. The repeated measures ANOVA and the LMM are commonly used for analyzing longitudinal data (Barton and Peat, 2014). A fundamental assumption of the repeated measures ANOVA is that within-subject effects/levels are uncorrelated (Locascio and Atri, 2011; West, 2009), which poses a problem when within-subject levels are related to time. This is especially relevant given that the analysis in the paper is focused on natural systems where growth, maturation, and seasonality are expected. In contrast, the LMM offers the most flexibility and allows to define the covariance structure, which does not depend on the sphericity assumption (Barton and Peat, 2014). Therefore, the LMM was adopted herein. In addition, pairwise comparisons were made using Bonferroni analysis to identify which subgroup means were significantly different from one another. Lastly, multiple linear regression analysis was conducted to analyze the impact of design and environmental factors on volumetric retention, where media and vegetation types were dummy-coded for the analysis. All statistical analyses were performed using IBM SPSS Statistics Version 25 at the significance level of 5% (unless otherwise specified).

3.3. Results and Discussion

3.3.1. Variability and Temporal Evolution of Water Retention

A total of 72 simulated events were conducted over the four years, and substantial inter-event variability in PWR was observed. Figure 3.2 reflects this variability across the events and years for all 24 mesocosms. The mean PWR across the dataset was 16.1%, which was lower than typical water retention reported for bioretention systems in the literature. For instance, Davis (2008), Hathaway et al. (2014) and Hunt et al. (2006) have reported water retention in a wide range of 27-86%. Other studies with lined systems (Hatt et al., 2009; Li et al., 2009) show lower water retentions (i.e., 19 – 33%) and point out the physical limitations to cumulative runoff capture associated with available media storage and evapotranspiration (ET). About 12% of the dataset for the PWR were below 0%, suggesting that the bioretention mesocosms were at times ineffective at stormwater capture. Negative PWR was associated with the smallest (4 mm) events. Similar findings have been reported in Davis (2008), where the outflow volumes occasionally exceeded the inflow volumes, and such negative retention was attributed to the presence of saturated media and overlapping events.

In addition, seasonality was also observed as generally less exfiltrate was collected in the middle of summer compared to the beginning and end of growing seasons. This was particularly apparent in 2019 and 2020, when vegetation became more mature. A peak in water retention was observed around mid-August, when vegetation was at its peak and daily evapotranspirative demand would be high. This corresponds well with the notion of higher average ET being observed during the warm summer months (Wadzuk et al., 2015).

According to the existing body of knowledge, the water retention of bioretention systems is dependent on media storage capacity, ponding water depth, losses to ET and exfiltration, media infiltration, as well as the rate, duration, and volume of stormwater input (Ahiablame et al., 2012; Davis, 2008; Kratky et al., 2017; Xia et al., 2017). In this experimental setup, the flow rate was kept constant, the ponding depth was fixed for all mesocosms, and there was no exfiltration since each mesocosm was lined. As such, key factors contributing to the variability in the water retention between events would be primarily attributed to variability associated with event magnitude, variability in media storage capacity, and variability in evapotranspirative losses. The following sections discuss the analysis of the impact of these three factors.

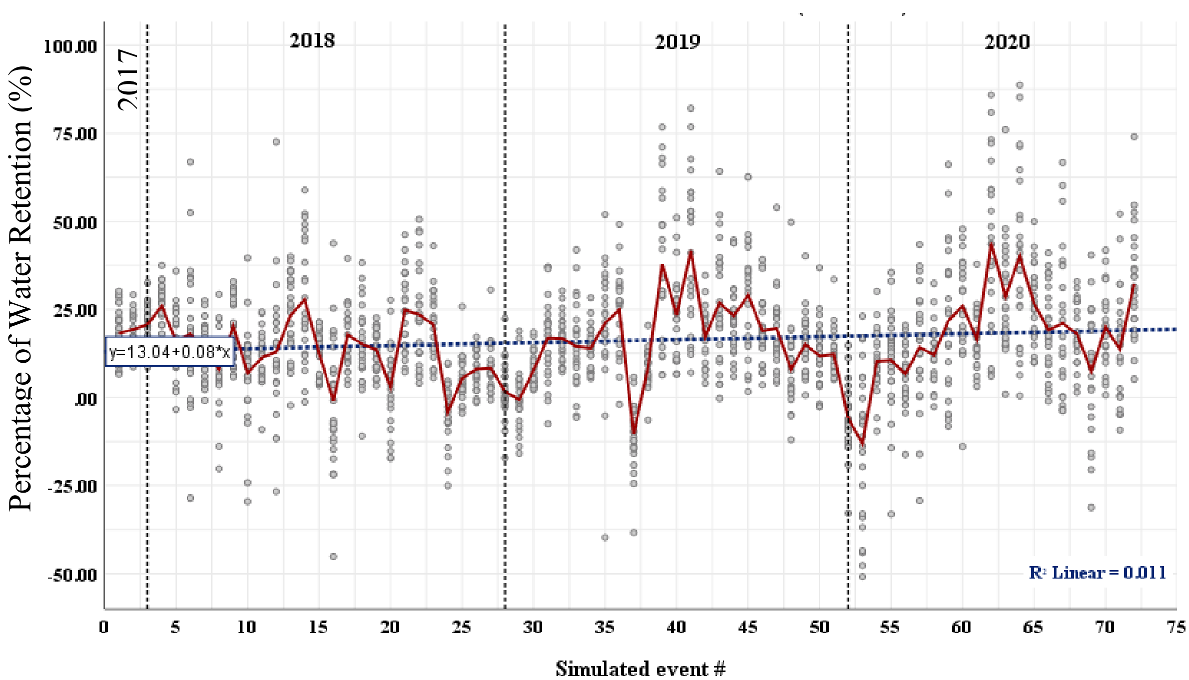


Figure 3.2. Event-based water retention (%) in the study period (2017-2020) (dots are individual values per mesocosm; red line indicates the mean values per event for all mesocosms; and the dotted blue line is the linear regression line on the event number).

3.3.2. Effect of Hydrologic Loading

Multiple linear regression was conducted to explore the potential dependence of VWR on the design (media and vegetation) and environmental variables. The variables included total volume applied/inflow (simulated runoff and direct rainfall), total volume pumped out (outflow volume), direct rainfall per event, antecedent moisture at various depths (0, 20, 40 cm), potential ET, and event date. Among these variables, 97% of the variance in the outflow volume was explained by the inflow volume. Strong linear relationships between the inflow volume and the outflow volume were also observed in other studies (e.g., Davis et al., 2011), especially for large storms when the finite media storage capacity had been exceeded. Note that in this study, the inflow volume was largely a function of the simulated event magnitude and the IP ratio.

Figure 3.3 shows the variations in the PWR and VWR by all 24 mesocosms among the different event magnitudes and IP ratios. Over the study period, there were 36 events of 4 mm, 13 events of 9 mm, 15 events of 14 mm, and 8 events of 24 mm magnitude applied to the mesocosms. Several studies (Davis, 2008; Shrestha et al., 2018) indicate that bioretention systems tend to have a greater PWR when exposed to smaller events, given that the retention capacity is limited (Kratky et al., 2017; Nissen et al., 2020). Such tendency was not prominent in this study, as the mean PWR values were 14.8, 18.3, 18.8, and 13.2% for simulated events of 4, 9, 14, and 24 mm magnitudes, respectively. Whereas the VWR appears to increase with increasing event magnitude as the mean VWR for the 4, 9, 14, and 24 mm events were 37, 100, 151, and 184 L, respectively. It is possible that the contact time of water with the media and consequently the utilization of pore spaces increased in large events, as there would be more opportunity for redistribution of water in the media with extended contact time (Dingman, 2008). Care must be taken when interpreting the impact of the runoff event magnitude as its effect could be somewhat confounded by the antecedent and temporal conditions (e.g., antecedent moisture, seasonality, vegetation maturity) associated with different events.

On the other hand, the effect of IP ratio was not confounded by environmental variability as it was varied within the same event, which provides a more straightforward outlook onto the hydrologic loading. As shown in Figure 3.3 for IP 15 and 30, it appears that the impact of IP ratio was consistent across the varying event magnitudes, where increased volume led to reduced retention. The means of the PWR were 10.2 % and 19.4% for IP 30 and IP 15, respectively. This corresponds to a nearly 2-fold decrease in the percent retention associated with a 2-fold increase in the inflow volume (i.e., twice the hypothetical catchment), which supports the notion of a finite retention capacity (Kratky et al., 2017). In addition, the VWR associated with the different IP ratios were similar given the same event magnitude, further highlighting the notion of finite retention capacity within the bioretention media.

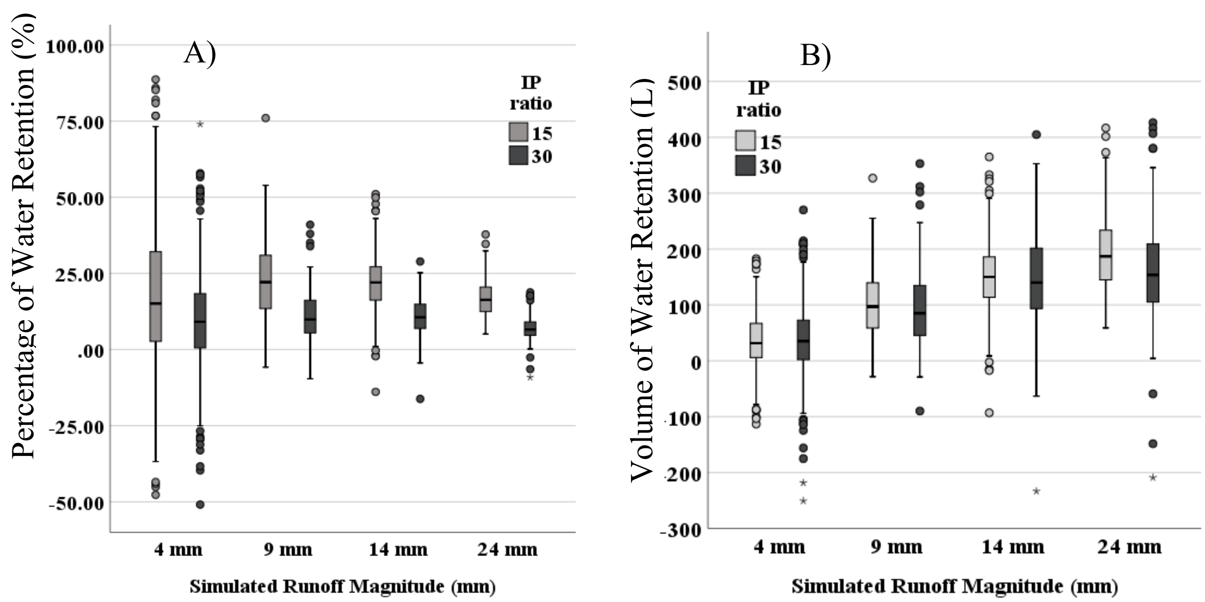


Figure 3.3. The relationship between simulated event magnitude and water retention – A) percentage of water retention, and B) volume of water retention (circles are outliers at 1.5 interquartile range (IQR), and stars are outliers at 3.0 IQR).

3.3.3. Media storage

Several studies point to the importance of antecedent moisture conditions in controlling the water retention, especially so for small events (Khan et al., 2012). In this work, the antecedent moisture was translated to the antecedent media storage using θ_{fc} measured through the saturation experiments. Figure 4 shows the relationship between the mean VWR per event and the antecedent media storage in 2019, which had an expanded set of antecedent moisture data including the surface (0 cm) measurements. As shown in Fig. 3.4, there was alignment between the variations of the antecedent media storage and the VWR per event. Of note is that the negative VWR corresponded with a negative value for the antecedent media storage. However, there was not a strong linear relationship between the antecedent media storage and VWR as only a moderate R^2 (0.26) was obtained from the linear regression analysis (Fig. 3.4B). This might be ascribed to the complexity of natural processes, which are often not linear, and other contributing factors. Additional investigation of moisture dynamics at different depths and their impacts on water retention is needed.

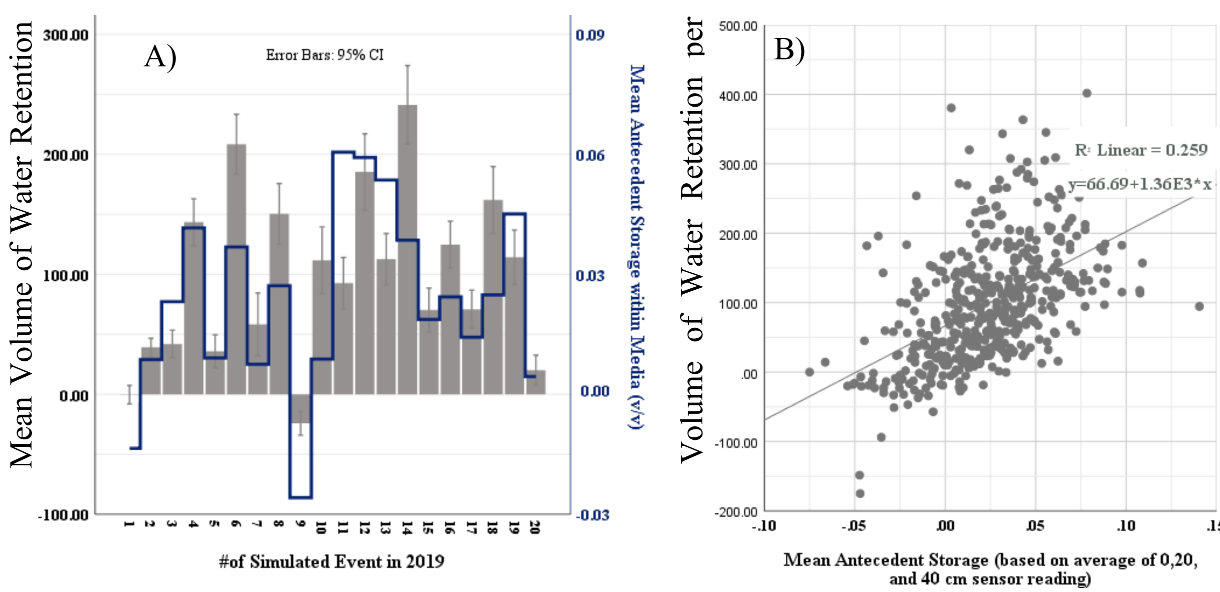


Figure 3.4. Relationship between volume retained per event and antecedent media storage – A) mean of 24 mesocosms per simulated event, and B) per simulated event per mesocosm.

3.3.4. Annual performance and evapotranspiration

The hydrologic performance of the mesocosms was also assessed at an annual scale (entire duration of the growing season/simulation period) to gain an appreciation of their overall performance. Table 2 shows a summary of the annual hydrologic parameters across the mesocosms, including the depths of direct rainfall, water applied (simulated runoff), and water retained as well as the average daily water retention (in depth) and the PWR for each season. Given the absence of exfiltration due to liner, the annual water retention effectively represents the amount of water lost by ET alone, as the change in storage can be assumed to be zero when analyzing the cumulative water balance (Brown and Hunt, 2011; Davis et al., 2011; Li et al., 2009).

It is important to point out that the seasonal water retention appears to be consistent with ET norms for the study area. In Alberta, the actual mean ET is about 364 mm, while the PET may be up to 902 mm per year (Government, 2013). The substantial discrepancy between actual ET and PET is due to soil moisture being the limiting factor for ET in this climate. The soil moisture was not a limiting factor with the regime that was simulated (semi-regular applications), which is why the water retention is closer to the PET than ET. The results shown in Table 3.2 point to the fact that, in a lined system, the annual PWR ultimately represents the relationship between the annual ET (which cannot exceed PET) and the amount of water applied; the latter being a function of the contributing catchment. The ET is limited by the climatic demand and plant physiology (Hess et al., 2017), which makes it a relatively constant parameter for a given location assuming mature vegetation. Thus, the footprint of a bioretention system could be determined based on the size of the catchment area and the desired target retention by quantifying seasonal runoff in relation to the typical PET. Exfiltration, which was not a part of this study, provides an additional avenue for water retention but one could argue, it is not, by itself, a parameter of a bioretention system.

Table 3.2. Summary of hydrologic parameters across the growing seasons – averaged across total mesocosm area.

Growing season	2017	2018	2019	2020
Direct rainfall (mm)	48	191	272	163
Water received (mm)	723	4729	4831	3876
Water retained (mm)	132	609	697	631
Number of days per season	45	129	137	118
Average daily water retention (mm/day)	2.9	4.7	5.1	5.3
Percentage of water retention	18.3%	12.9%	14.4%	16.3%

ET is frequently reported as a daily rate, and the results show that the average daily water retention increased with each year in the study period. The observed increase in the average daily water retention was presumably due to the establishment of the vegetation within the mesocosms and, in turn, the increased evapotranspirative water loss. This can be attributed to plant growth, maturation, and increases in aboveground biomass and surface area. The increase in the water retention due to evapotranspirative water loss is expected to plateau as plants reach their mature size. There was a substantial increase in daily retention between 2017 and 2018, which is related to abundant growth of herbaceous vegetation, which reached maturity in 2018. After all the vegetation matures, the variation of water retention could display a different behaviour, as it would be primarily dependent on the meteorological conditions, which were largely similar during this study.

3.3.5. Overall Effect of Media and Vegetation

To gain an overall assessment of the impacts of media and vegetation on water retention, the proportionate contribution of different mesocosm types to annual VWR was quantified. Table 3.3 shows the VWR in depth of the mesocosms of different media and vegetation types as compared to that of the average VWR of all mesocosms for each growing season in the study period. The results reveal that among the three media types, media 40 was the most effective at retaining water runoff, whereas CL was the least effective, particularly in the first three years of the study. Interestingly, the differences among the media types appeared to diminish over the years. Given the characteristics of the media (Table 3.1), media 40 had the greatest amount of organic matter by weight, which would have improved the water retention capacity (Fassman-Beck et al., 2015). In addition, when comparing the field capacity measured from the saturation experiments, media 40 had approximately 18% and 11% greater field capacity than media 70 and CL, respectively. Moreover, media 40 was also observed to support the most successful vegetation establishment, thus potentially promoting greater ET contribution.

Table 3.3. The seasonal water retention (mm) of mesocosms of different media and vegetation types and the average water retention across the 24 mesocosms.

Year	**2017**	**2018**	**2019**	**2020**
Average water retention (across mesocosms)	132	609	697	631
Media				
Media 70	149	706	720	699
Media 40	165	724	776	668
CL	85	406	600	529
Vegetation				
Herbaceous	144	575	672	602
Woody	127	629	747	699
Control (Turfgrass)	113	526	514	511

In terms of the vegetation, mesocosms containing woody species retained more simulated runoff than the rest in all years but 2017, which was the year of planting. The incremental increases in the water retention by the woody mesocosms was consistent with their observed incremental growth (i.e., each consecutive year had a higher average height than the year before). The control mesocosms consistently retained the least amount of water, which can be attributed to their minimal evapotranspirative capacity due to their controlled height (mowed to 10-15 cm to minimize evapotranspiration and represent turfgrass condition) and shallow root system, typical of Kentucky Bluegrass sod.

3.3.6. Event-specific effect of media, vegetation, and their interaction

To analyze the impacts of the design parameters including media, vegetation, and IP ratio (i.e., the IP ratio was included as part of within-event factors) as well as their interactions on the water retention for each event individually, factorial ANOVA was conducted. The results are summarized in relation to the year of the simulated events and are presented in Table 3.4. ANOVA assumptions were generally sustained, with a few minor violations, which were overlooked when only one parameter was violated at $p<.05$ for the purposes of this analysis given that ANOVA tolerates some level of assumption violation (Underwood, 1997). The data are presented in terms of the number of events within each year that had a significant effect with respect to each design parameter, and their interactions.

The results show that media had a strongly significant impact on the water retention in the beginning of the study period (2017), as indicated by all the events having a significant media impact on the water retention. However, its significance decreased dramatically over the years, with only about 20% of the events showing a significant impact of the media in 2019 (i.e., 5 out 24 events) and 2020 (i.e., 4 out of 20 events). The practical aspects of media selection involve adhering to tight specifications for media texture, organic matter, and hydraulic conductivity (City of Calgary, 2016; City of Portland, 2016; City of Seattle, 2017). This paper involved examining media with drastically different texture and organic matter content, yet the outcomes evolved to be comparable when it comes to water retention. The increasingly similar water retention among the different media types highlights the opportunity of achieving desired levels of service with less stringent tolerances with respect to media specification, which offer benefits in lowering production costs and material sourcing for media.

The impacts of both vegetation and IP ratio were significant across the years, which is consistent with the notion of water retention being primarily related to the antecedent moisture conditions (controlled largely by ET through vegetation) and the amount of inflow that the mesocosms were subject to (which is governed by the IP ratio). The percent of number of events with significant vegetation and IP ratio effects as compared to the total number of events did not increase consistently over the years, but no decrease was observed either.

Table 3.4. The number of events, in which the significant impacts of media, vegetation, and/or IP ratio on the percentage of water retention was identified using factorial ANOVA in each year.

Year	No. of events	Assumption violations [a)]			Model Violations [b)]	Sig Media	Sig Veg	Sig IP	Sig Interaction [c)]
		Normality		Homogeneity					
		KS	SW						
2017	3	0 (0)	0 (0)	1 (0)	0	3	2	n/a	0
2018	25	1 (0)	5 (2)	1 (0)	8	12	9	15	8
2019	24	2 (0)	5 (3)	3 (0)	4	5	16	18	7
2020	20	0 (0)	1 (0)	0 (0)	5	4	10	10	4
Total	72	3 (0)	11 (5)	5 (0)	17	24	37	43	19

[a)] The value shows any instances of violation of Kolmogorov-Smirnov (KS), Shapiro-Wilk (SW), or Levene's tests. The value in brackets shows the number of the more significant violations ($p<0.01$). Those events that had strongly significant deviations from either normality or homogeneity (or both) were excluded from the ANOVA analysis.
[b)] Instances where irrespective of assumptions, the ANOVA analysis showed the proposed media-vegetation-IP model as not being significant in explaining the variance (excluded from analysis).
[c)] If the same event had more than one type of interaction, it was only counted once for the purposes of this table.

Moreover, it appears that there was an overall decreasing trend in the significance of interactions of the design parameters over the years, as the number of events in which significant interactions were detected decreased over the years. More details on the types of interactions and their significance are presented in Table 3.5. The significance of interactions varied across the years, with media-vegetation interaction being the most consistent. The significance of media-vegetation interactions is supported by the existing body of knowledge around the interconnectedness of soil properties and plant growth. Numerous studies (Gerke and Kuchenbuch, 2007; Jotisankasa and Sirirattanachat, 2017; Leung et al., 2015; Yan and Zhang, 2015; Zhang, 2015) have investigated the complex interactions between plants and soils, and the impacts include (but are not limited to): modifications to soil-water characteristic curves, soil permeability function, soil water retention, modifications to soil structure, and impacts to the overall water balance (Skorobogatov et al., 2020). As such, it is pertinent to further quantify the media-vegetation interactions and the impacts thereof in a bioretention setting. Factorial analysis is uniquely suited for interaction analysis, and more factorial experiments are needed to shed light on the different types of interactions and their significance.

Table 3.5. The number of events, in which the significant impacts of interactions of design parameters on the volumetric percent retention was identified using factorial ANOVA in each year.

Year	No. of events	Significant Media x Veg	Significant Media x IP	Significant Veg x IP	Significant Media x Veg x IP
2017	3	0 (0)%	n/a	n/a	n/a
2018	25	5 (20%)	4 (16%)	2 (8%)	5 (20%)
2019	24	4 (17%)	4 (17%)	7 (29%)	5 (21%)
2020	20	3 (15%)	0 (0%)	1 (5%)	0 (0%)
Total	72	12 (17%)	8 (12%)	10 (14%)	10 (14%)

Pairwise comparisons were performed to identify how the design parameters compared to each other and to identify which specific factor was significantly different from the others. It was found that the mesocosms containing media 40 and 70 were, for most events, not significantly different from one another, but significantly different from the CL media mesocosms. The CL media was significantly lower in water retention as compared to the other two. The low water retention of the CL media mesocosms could be associated with its high infiltration rate (i.e., greater than the other two media) and, in turn, the short residence time, which has been observed when using large wood chips in bioretention media (Wan et al., 2018). Interestingly, the CL media has undergone the most change over the four years, as it retained significantly less runoff at the initial stages of the investigation but approached similar retention to the more conventional bioretention media towards the end of the study period. Given that the woodchips made up a significant fraction of the CL media, woodchip decomposition would likely cause the properties of the media to change, but such changes are challenging to quantify without destructive sampling. In wood chip bioreactors, decomposition and loss of wood is expected to average 50% at 3 to 5 years, with substantial losses projected over 8 years (Moorman et al., 2010). Long-term monitoring of CL media is required to understand the changes in structure and the associated performance impacts.

With respect to pairwise comparison analysis of different vegetation, the patterns shifted during the study period. In 2017, control mesocosms were significantly lower than herbaceous mesocosms in their water retention. In 2018, a mixed result was observed, with some instances of control mesocosms being significantly lower than that of the herbaceous and woody mesocosms, and some instances of the woody mesocosms having significantly greater water retention than the other two. In 2019 and 2020, woody mesocosms had significantly and consistently greater water retention, at times averaging several folds greater, than that of the other vegetation types. The willow shrubs in the woody mesocosms grew larger each year, which would increase their evapotranspirative capacity. In a natural setting, similar willow species can reach up to 10 m in height (van der Valk and Bliss, 1971), whereas the observed maximum height at the end of the study period was only about a third of that. Thus, the increase in the water retention of the woody mesocosms is expected to continue until the mature height is reached.

3.3.7. Seasonal and temporal effect of media, vegetation, and their interaction

Furthermore, the LMM analysis was conducted on the entire dataset (72 events) to confirm the significance of the media, vegetation, and IP ratio on the water retention, as well as on the progression of events of each year to infer whether there were significant differences among the design parameters and a change in their significance over time. The LMM analysis showed that the media, vegetation, IP ratio, and event order itself (represented as an ordinal value from 1 to 72) had a significant impact on the PWR. It also showed that the interactions between the media and the vegetation as well as between the vegetation and the IP ratio were significant.

When carrying out the LMM analysis for each year individually, a slightly different outcome emerged. In 2017, the only significant design parameter identified was the media type. In 2018, the media, vegetation, and IP ratio were all significant. In 2019, the media was no longer significant, while the vegetation and IP were highly significant, and the same outcome was observed in 2020. As a result, it appears that media selection might not be as relevant when it comes to the temporal evolution of the water retention by bioretention systems. The reality is such that the media porosity and intrinsic retention capacity might be dissimilar at the onset of bioretention lifetime, but natural processes (i.e., macropore formation, biofilm accumulation, root growth and decay, etc.) govern the evolution of available storage over time, while ET controls how much of that storage gets replenished irrespective of media type.

The results from LMM analysis (between events) appear to be generally consistent with the outcome of ANOVA analysis (within events) in that the media impacts lessened over time, whereas the vegetation and IP ratio were consistently significant. Based on the findings of this study, bioretention system design needs to take into account the temporal changes in these nature-based systems that lead to differences in the significance of the various design parameters between at the time of construction and at the time of their operation, once constructed. The results presented here apply to lined bioretention systems, but the notion of change over time applies to all bioretention systems, irrespective of the presence of a liner.

3.4. Conclusions

Bioretention systems, which are nature-based engineering solutions, pose unique design and implementation challenges as they are subject to complex interactions and change over time, which have not yet been characterized in a systematic manner. This paper focused on investigating the hydrologic performance of 24 lined bioretention mesocosms with respect to bioretention design parameters, namely media, vegetation, and hydrologic loading (as IP ratio), as well as their temporal evolution and the impacts thereof. The bioretention mesocosms were constructed and monitored under simulated events of varying magnitudes over multiple years in a field setting.

Overall, the results showed that the bioretention mesocosms provided hydrologic benefits with respect to water retention, but the extent of it appeared to be limited to the evapotranspirative demand in the absence of exfiltration. Thus, it may be that the true value of bioretention systems should not be dictated by hydrologic benefits (i.e., the water retention), as those may be limited, but by water quality benefits, as well as the ancillary benefits that are unique to nature-based solutions. The results also revealed that there was substantial variability in the water retention across the events, yet a strong linear relationship between the inflow and outflow volumes, confirming the notion of the limited storage capacity.

When comparing different media, the results showed that dissimilar media resulted in dissimilar water retention at the early stage of the investigation, but the differences appeared to diminish over the years. Moreover, differing from the effect of media, the effect of vegetation on water retention appeared to become more prominent over time, with larger woody vegetation retaining incrementally more stormwater runoff than herbaceous vegetation. These findings would suggest that for the design and implementation purposes, there is potential to achieve the desired level of service with less stringent tolerances with respect to media specification, and more consideration on the function of vegetation.

This paper offered an in-depth look at the core hydrologic benefit (i.e., water retention) of bioretention systems, yet future research on several aspects is recommended to better understand the underlying processes. The side-by-side comparisons of lined and unlined systems is desired to facilitate understanding of the proportionate roles of ET and subsoil infiltration in water retention. In addition, more insight is needed to understand the development or evolution of soil structure characteristics in bioretention media in order to better understand the long-term performance including the effects on storage capacity and subsequently water retention. Lastly, when it comes to complex interactions, there is a need to quantify their impacts and to establish practical implications of such findings in order to continue evolving the practice.

Chapter 4: Multi-year analyses of bioretention mesocosm performance – Effect of design factors over time on leaching of nutrients and organics.

4.1. Introduction

Excessive nutrients and organics in aquatic environments have been a global concern since the 1970s. Stormwater carries significant nutrient and organic loads, and the associated impacts are exacerbated by urbanization. In the past, stormwater pollutant load has been primarily attributed to the particulate materials and, as such, sediment removal dominated the water quality objectives (LeFevre et al., 2015). However, it is now understood that dissolved pollutants present substantial challenges and can be the leading cause of negative downstream impacts, such as eutrophication. Bioretention systems are becoming increasingly popular as a stormwater management practice capable of removing particulate and dissolved contaminants while offering multiple ancillary benefits.

Pollutants that are targeted by bioretention systems vary, but typically include sediment, nutrients, organics, metals, and pathogens. Sediment and particulate matter removal has been shown to be effective and consistent due to the straining effect of the media (LeFevre et al., 2015). Metal removal has been effective as well, with removal efficiencies over 80% frequently reported (Lange et al., 2020). Nutrient removal has been highly variable for both phosphorus and nitrogen (Li and Davis, 2014), and instances of bioretention systems acting as a source of nutrients have been reported on multiple occasions. Consequently, there is a need for a better understanding of the processes associated with nutrient removal and transformations within bioretention systems.

Phosphorus and nitrogen undergo different treatment processes, therefore different design adaptations may be necessary for targeted capture. Phosphorus in stormwater poses a particular risk to downstream environments as the limiting nutrient for biological productivity. Many bioretention studies have focused on total phosphorus (TP), but few have analyzed dissolved or reactive phosphorus (RP), which poses a greater environmental risk (LeFevre et al., 2015). Phosphorus retention is known to depend on hydrologic conditions, media, and vegetation (Roy-Poirier et al., 2010a). Specific to media composition is the phosphorus and organic matter content, which can contribute to RP leaching (LeFevre et al., 2015). Other factors, such as pH, redox condition, and resident time are also expected to impact RP removal (Liu et al., 2021b).

Whereas nitrogen comes in multiple chemical forms, which are subject to physical, chemical and biological transformations in bioretention systems. Dissolved organic nitrogen (DON) and nitrate (NO_3) dominate the available forms and are challenging to remove (Li and Davis, 2014). Nitrogen removal mechanisms include sedimentation, filtration, sorption, mineralization, and biological transformations (Li and Davis, 2014). Media selection impacts nitrogen retention through supporting biological transformations, presumably through the presence of organic carbon and localized anaerobic conditions (Hunt et al., 2012; Skorobogatov et al., 2020). Nitrogen transformation dynamics align with those of organic carbon due to carbon requirement of denitrification and competing oxygen demands of biological breakdown of organics and nitrification (Kavehei et al., 2021; Liu et al., 2021a). Vegetation selection also plays a role in nitrogen retention, either through direct uptake or by enhancing microbial processes (Read et al., 2008). Conversion of various nitrogen forms to nitrate and its poor retention appear to be the driving factor of the variability of nitrogen removal presented in the literature (Li and Davis, 2014). Therefore, understanding the dynamics of nitrate removal is key to understanding the performance.

Despite the growing body of literature dedicated to pollutant removal by bioretention systems, the substantial data variability and reports of leaching retain the need for ongoing systematic analyses of the effects of bioretention design factors and the associated water quality performance, especially as it relates to dissolved nutrient removal. A better understanding of the role of media properties in nutrient retention and leaching is needed, as existing data are limited (Jay et al., 2017). Impacts of vegetation on nutrient removal also lack data and understanding (Turk et al., 2017). In addition, hydrologic loading is a key factor, as it controls moisture and redox conditions, which have implications for phosphorus and nitrogen removal (Liu et al., 2021b; Norton et al., 2017). Additional complexity stems from the lack of field data and short-term, small-scale studies that do not yield useable results applicable to full-scale systems (Vijayaraghavan et al., 2021). There is a growing need to systematically investigate how various design factors, such as media, vegetation, and hydrologic conditions impact the water quality performance of bioretention systems and how such performance changes over time outside of the controlled laboratory environment.

The objective of this research is to determine the impact of soil media, vegetation and design considerations on leaching dynamics over a sustained period to determine critical factors and yield better designs for bioretention cells in the future. In this research, a multi-year analysis of bioretention mesocosms with different media, vegetation, and hydrologic loading was conducted with a focus on dissolved contaminant removal. Hydrologic loading was represented as the IP ratio, which refers to the ratio of contributing catchment area (I for impervious, assuming the entire catchment is impervious for simplicity) to the bioretention bed area (P for pervious) (Calgary, 2016). In addition to influencing the moisture and redox dynamics, the increased IP ratio is related to the impacts of increased rainfall and runoff associated with the effects of climate change. This study analyzed influent and effluent water quality parameters across multiple simulated events, for specific analytes including TP, RP, nitrate-nitrogen (NO_3-N), total nitrogen (TN), and total organic carbon (TOC). The setup of this experiment enabled not only the comparative analysis of the impacts of media, vegetation, and IP ratio but also the effects of interactions using factorial design principles and changes in performance over time.

4.2. Materials and Methods

4.2.1. Site description and design factors

The research was conducted at a field research facility, which was constructed in 2016 in the Town of Okotoks, Alberta, Canada. Okotoks has a xeric temperate climate, with short warm summers and long cold winters. The average annual temperature is 4.6 °C and the average annual precipitation is 515 mm. The facility contains a total of 24 mesocosms with three different types of media and three different types of vegetation (Figure 4.1). The experimental design of the mesocosms was done to enable factorial analysis of interactions. Each mesocosm is fully lined and contains 300 mm deep drainage layer at the bottom, which consists of 3 sublayers, namely, a 100 mm of coarse gravel at the base, followed by a 100 mm of pea gravel, and a 100 mm of coarse sand at the top. The drainage layer is overlaid by 600 mm of bioretention media. Above the media, there is 300 mm of freeboard, which blocks stormwater runoff from the surrounding areas during natural rain events into the mesocosms.

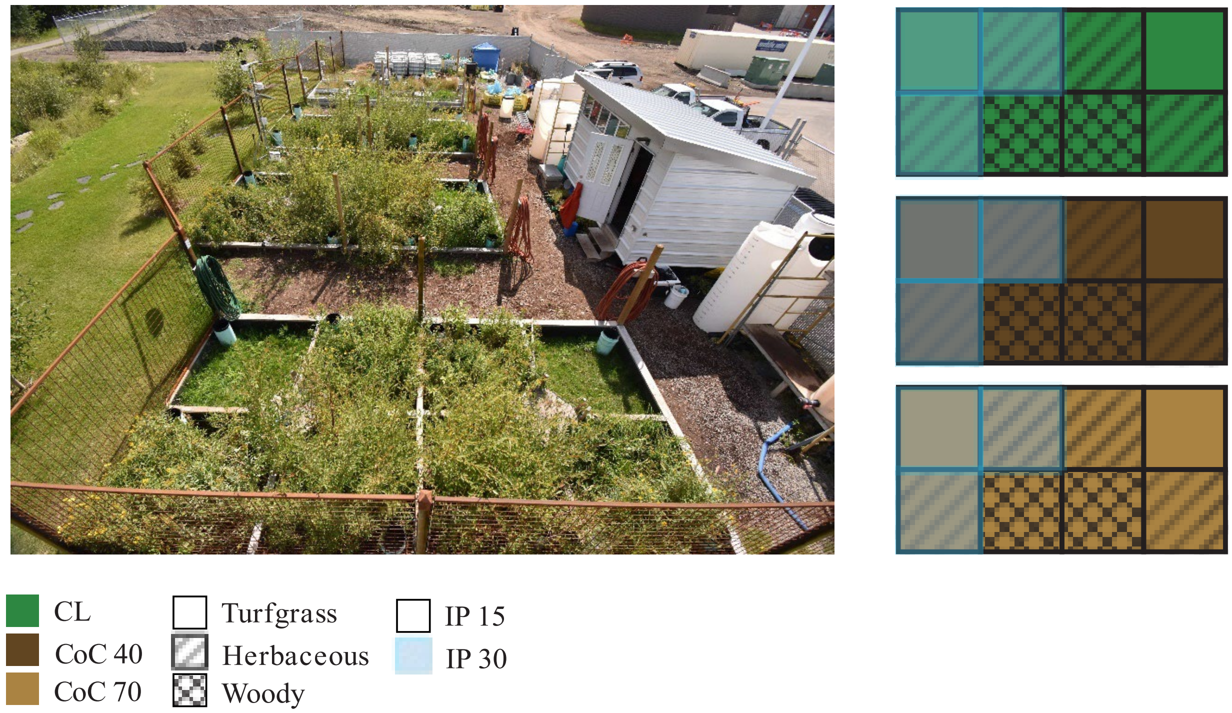


Figure 4.1. Bioretention mesocosms (photo in July of 2019) and schematic.

Among the three media types, two of them are based on the local guideline of the City of Calgary (CoC), namely CoC 70 and CoC 40 based on the 70 mm/hr and 40 mm/hr target infiltration rates (Calgary, 2016). The third media contains clay loam soil, which is abundant in the area and is typically not considered as suitable for bioretention systems due to the low permeability. As such, the clay loam soil was amended with 40% wood chips (by volume) in order to support adequate infiltration. The clay loam media mixed with wood chips is named as CL throughout this paper. Table 4.1 summarizes media characteristics. The mesocosms were planted in 2017 with three kinds of vegetation including turfgrass (as a control), herbaceous mix of native grasses and forbs, and woody mix of native shrubs. The cells were subjected to two hydrological loadings based on the target IP ratio of 15 and 30.

Table 4.1. Media characteristics.

		% Organic Matter (w/w)	Texture		
			% Sand (0.05-2.00 mm)	% Silt (0.002-0.05 mm)	% Clay (<0.002 mm)
Media Type	CoC 70*	3.5	74.6	19.3	6.1
	CoC 40	16.4	73.7	22.6	3.7
	CL	11.2 (8.7)**	41.6	44.3	14.1

*- Values are calculated based on data from hydrometer test and laser light diffraction particle size distribution analyses, values in brackets are targets from the local guidelines (City of Calgary, 2011).
**- the 11.2 value was calculated based on % by volume of wood chips (using density of pine) that was used to create the media, whereas 8.7 was the value obtained through loss on ignition but larger wood chips were not included

4.2.2. Simulated events and mesocosm monitoring.

The 24 mesocosms were monitored in a total of 72 simulated storm events, which were applied during May to October in the study period of 2017 through 2020. The simulated storm events were designed to represent the local hydrological regime as closely as possible while acknowledging practical limitations. Cumulative hydrologic loading, simulated event magnitude, and inter-event period were approximated based on a 57-year (1960-2016) record of historical precipitation of the closest major municipality, the City of Calgary. The simulated events were of 4 different magnitudes including 4 mm, 9 mm, 14 mm, and 24 mm. In each simulated event, water was sourced from a local stormwater pond, and mixed with street sweeping materials to mimic the typical concentration of sediments (400 mg/L) of stormwater runoff in the study region. The inflow was applied to the mesocosms at a constant rate of 2 L/s using garden hoses and submersible pumps.

For each simulated event, a water sample of effluent was collected from each mesocosm on the day of the simulated event, and the day after to collect additional exfiltrate, respectively. The composite sample was volumetrically weighted sample of effluent collected in these two days. The water samples were refrigerated and analyzed within 24-48 hours of collection at the Water and Wastewater Laboratory of the University of Calgary. The water quality analysis was conducted using Hach methods, namely Methods TNT835, 8190, and 8048 for NO_3-N, TP, and RP, respectively, while using Shimadzu TOC-L series analyzer with TNM-L unit for TOC and TN. Note that the water quality analytes were analyzed for the majority of events, but not all simulated events in 2018 and 2019. In addition, three water samples were collected from influent. As variations in the contaminant concentrations among the three water samples of influent were small, the average concentration of the three samples were used in the analysis.

In addition, soil moisture was continuously measured at two depths (20 and 40 cm deep from surface) using TEROS-12 for all mesocosms since 2018, while moisture at surface was manually measured prior to an event using a handheld device. In addition, in 2019, temperature (T), electrical conductivity (EC), pH, and dissolved oxygen (DO) of inflow and outflow were measured using a YSI multi-parameter sonde.

4.2.3. Data analysis and statistical analysis

In the literature, pollutant removal of bioretention systems is typically assessed by either concentration or mass load reduction. In this study, both were employed to better understand the extents of leaching. Elevated concentrations in outflow revealed leaching, while the load retention was used to confirm whether there was overall export of nutrients when taking water reduction into account. The percentage of load retention (PLR) was calculated by:

$$PLR = (1 - \frac{C_{out} * V_{out}}{C_{in} * V_{in}}) * 100$$

where C_{out} is the effluent contaminant concentration; V_{out} is the effluent volume; C_{in} is the influent contaminant concentration; and V_{in} is the water volume applied (not including natural fainfall) during the simulated event.

While the percentage load reduction provides an overarching analysis of nutrient release or retention, the effluent concentration provides insights into the underlying processes within the bioretention system that are unrelated to volumetric reduction (Gold et al., 2019; Li and Davis, 2014; McNett et al., 2011). Therefore, the analyses were conducted on the effluent concentration to investigate the temporal variability, impacts of design factors within each event, and impacts of design factors and time over the study period.

To assess the significance of the differences associated with the different design factors as well as correlations between parameters and time, linear mixed method (LMM), analysis of variance (ANOVA), and Pearson correlation methods were used. Of these, LMM, which has not been frequently applied in bioretention studies, is more flexible and a better theoretical fit for analysis of longitudinal data and repeated measures compared to ANOVA or simple regression analysis (Barton and Peat, 2014). The unique benefit of LMM is that it allows one to build structure into the analysis of longitudinal datasets, where the events are represented as repeated measurements and in turn the inter-event correlation is likely for each individual mesocosm. In LMM, first order autoregressive (AR1) covariance structure was used, which assumes greater correlation between adjacent events than those further apart. Moreover, random intercept and slope were incorporated into the model to allow for flexibility between individual mesocosms. Bonferroni method was used for pairwise comparison since it provides a conservative outcome (Duricki et al., 2016). Maximum Likelihood (ML) method was used as it reflects the fit of the model that accounts for both fixed and random parameters (Beaumont, 2012). The key disadvantage of LMM is its inability to analyze the magnitude of a particular effect, such as η-squared measure (Barton and Peat, 2014). Therefore, the magnitude of the effect was measured using ANOVA within each event individually. ANOVA was also used to analyze the interactions among the design factors, taking advantage of the factorial design of the experimental setup. Furthermore, Pearson correlation was used to identify correlations between continuous variables. All statistical analyses were performed using IBM SPSS Statistics Version 25 at the significance level of 5% (unless otherwise specified).

4.3. Results and Discussion

4.3.1. Contaminant leaching

Leaching was observed for all the constituents, which compromises the overarching water quality performance objective of pollutant retention of bioretention systems. Leaching was particularly apparent during the first few simulated events as the effluent concentrations were substantially higher than the influent concentrations for all the analytes. In 2017, the mean effluent concentrations were 2.9, 2.8, 17.4, 18.4, and 29.3-times higher than the mean inflow concentrations for RP, TP, NO_3-N, TN, and TOC, respectively. Other few studies have also reported instances of contaminant leaching, such as phosphorus (Brown et al., 2016; Chahal et al., 2016; Lucas and Greenway, 2011), nitrogen (Ding et al., 2022; Li and Davis, 2014; Wang et al., 2017b), and organic matter (Iqbal et al., 2015; Wan et al., 2017). As shown in Table 4.2, compared to the typical concentrations of International Best Management Practices (BMP) Database, the influent concentrations of RP, TP, TN, and TOC in this study were slightly low but the influent NO_3-N concentration was slightly high. Of note, the International BMP Database currently supports the notion of bioretention systems acting as a source, rather than a sink, for RP and TP, as well as NO_3-N.

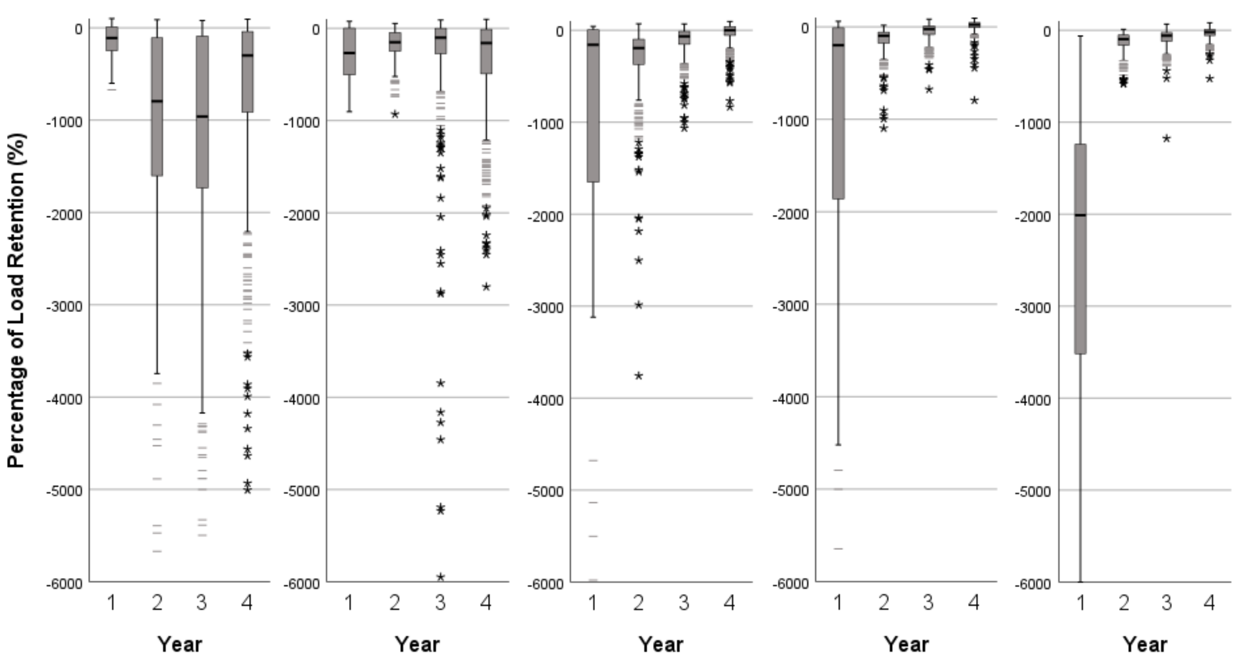
Table 4.2. Influent and effluent pollutant concentrations observed in this study as compared to typical concentrations.

Source	Concentration (mg/L)				
	RP	TP	NO_3-N	TN	TOC
Influent Median (this study)	0.017	0.098	0.504	1.061	10.543
Influent Median (BMP Database)*	0.030	0.190	0.360	1.260	15.820**
Effluent Median (BMP Database)*	0.270	0.240	0.441	0.96	N/A
Effluent Median (this study)	0.212	0.281	1.050	1.764	19.82

*Values are for bioretention only.
** Value from National Stormwater Quality Database to supplement the BMP Database.

Pollutant load reduction is viewed as the more comprehensive measure of water quality performance as compared to that of pollutant concentrations (Davis, 2007). Supporting this notion are specific reports of pollutant capture realized through pollutant load retention in the presence of elevated effluent concentrations (DeBusk and Wynn, 2011; Hunt et al., 2006a). This was not the case in the present study, as leaching was still prominent when analyzing pollutant load reduction as shown in Figure 4.2, which presents the PLR of the water quality analytes across the four years of the study. In addition, the temporal variation in the PLR was observed to be different among the pollutants. Leaching of phosphorus continued through the years without a measurable decline. For RP, the most leaching was observed during years 2 and 3; whereas for TP, the greatest leaching was in year 1, with a gradual decrease thereafter. A study by Hatt et al. (2009) demonstrated similar negative load reductions for TP (-398%) and RP (-1271%) when using media without specialized phosphorus-binding amendments. This contrasts with reports of over 90% load reductions in phosphorus observed in a few studies (Blecken et al., 2010; Ding et al., 2019), where the media composition supported effective removal through the presence of phosphorus-binding constituents.

Different from RP and TP, NO_3-N and TN had a dramatic initial flush, followed by moderate amounts of leaching, and even trending towards retention in the year 4. Similar initial flushing was observed in a study by (Chahal et al., 2016), in which the majority of NO_3-N flushed out with the first few events. Given the high mobility and poor retention of NO_3-N , its load retention in the literature has been primarily attributed to a reduction in water volume, not concentration (Li and Davis, 2014), but the effect of the water retention on the pollutant retention was not observed in this study. Similar to nitrogen analytes, TOC was released in dramatic quantities in the year 1 followed by a sharp decline in leaching in the year 2 and trending towards retention in the year 4. There are not many studies that have analyzed the leaching of organics, but it appears that soluble organics were present in the media and were easily mobilized following construction completion. Having confirmed that leaching was prominent when taking the water reduction into account (i.e., using the PLR), the remainder of the analysis was conducted on the effluent concentrations.



a) RP b) TP c) NO_3-N d) TN e) TOC

Figure 4.2. Percentage of load reduction of nutrients and organics across the years (- represent values outside the 1.5xIQR, and * represent values outside the 3xIQR).

4.3.2. Impact of design factors and time

The LMM analysis was conducted to understand how the different design factors impacted the pollutant concentrations and how these changed over time and across the different mesocosms. The LMM model included random slopes and intercepts for the various mesocosms. The random effects allowed individual mesocosms to follow a unique linear trajectory with time. The repeated measures or covariance component included both diagonal (variance of random errors) and rho (correlation of adjacent errors) parameters. The summary of LMM analysis, effect coefficients and their significance is provided in Table 4.3. To compare different media, vegetation, and IP ratio, CL, turfgrass (control), and IP ratio of 30 were used as the references, respectively.

Table 4.3. The impact of various design factors, time, and covariance on the effluent pollutant concentrations.

Factor	Water Quality Analytes (Effluent Concentration)				
	RP	TP	NO_3-N	TN	TOC
Fixed	Est.	Est.	Est.	Est.	Est.
Time[1]	-0.002	-0.008**	-0.009**	-0.023**	-0.271**
Media 70 (vs CL)	0.993**	0.921**	0.317**	0.480**	5.106**
Media 40 (vs CL)	0.967**	0.984**	0.863**	1.283**	14.628**
Veg. Herbaceous (vs Control)	-0.367**	-0.327**	-0.314**	-0.285*	1.164
Veg. Woody (vs Control)	-0.329*	-0.365**	-0.383**	-0.470**	0.809
IP Ratio 15 (vs 30)	-0.106	-0.090	0.253**	0.467**	5.190**
Random[2]	Est.	Est.	Est.	Est.	Est.
Intercept	0.033**	0.033*	0.005	0.016	3.462*
Slope	$2.2e^{-5}$**	$1.5e^{-5}$*	N/A	N/A	N/A
Repeated Measures	Est.	Est.	Est.	Est.	Est.
AR1 diagonal	0.078**	0.141**	0.495**	0.672**	51.854**
AR1 rho	0.314**	0.244**	0.443**	0.602**	0.485**

[1] Time expressed as continuous variable of event number;
[2] Wald Z test was used to estimate the significance of random effects;
* Significant at the 0.05 level;
** Significant at the 0.01 level.

As shown by the results for RP, there was no significant linear effect of time or IP ratio, but significant effects of media and vegetation. There was a positive fixed effect of .993 and .967 for media 70 and media 40, respectively, which means that on average the RP effluent concentration for these two media was significantly higher than that of CL. In other words, for the CL mesocosms, with every event, the effluent concentration decreased by 0.002, but this effect was not significantly different from zero. There was, however, a significant interaction between media type and time, with the slope increasing by 0.993 for the CoC 70 media (meaning the CoC 70 slope was 0.991). Thus, CL was significantly less prone to leaching than the typical bioretention media.

When it comes to vegetation, both herbaceous and woody mesocosms resulted in significantly lower RP effluent concentration than the turfgrass mesocosms. The interpretation of random effects offered limited value for the RP given no significant effect of time. For the repeated measures, significant ρ parameter indicated that adjacent errors indeed had a positive correlation, meaning that the results of individual events were sequentially correlated. For the TP, the most notable difference from the RP was a significant impact of time on the effluent concentration with a slight decreasing tendency (as demonstrated by the negative effect estimate). The remainder of the effect coefficients behaved quite similarly to that of the RP.

The NO_3-N effluent concentration also had a significant decreasing tendency with time based on the negative effect coefficient. The effects of media, vegetation, and IP ratio were all significant. Interestingly, CoC 40 and CoC 70 media were not as similar to each other as they were for phosphorus. The NO_3-N effect coefficient of CoC 40 was 2.7-times higher than that of CoC 70. Among the vegetation types, woody vegetation was found to correspond to the lowest effluent concentrations based on the effect coefficient. Between the IP ratios of 15 and 30, the NO_3-N effluent concentration was significantly higher for IP ratio of 15 than for IP ratio of 30. The effect of IP ratio points to a limited source scenario in which more water volume would yield a lower effluent concentration. Whereas random effects were not significant for NO_3-N, but the effects of repeated measures were. This applied both to variance of random errors and inter-event correlation. In addition, the effects of media, vegetation, and IP ratio on the TN effluent concentration were found to be similar to those on the NO_3-N effluent concentration. Namely, time had a stronger apparent effect, and wood vegetation had a more pronounced effect on reducing the NO_3-N effluent concentration than herbaceous vegetation.

Similar to nitrogen, the design factors and time were found to significantly affect the TOC effluent concentration, with a greater linear effect with time, and pronounced impacts of media and IP ratio. There was significantly more organics released by the CoC 40 mesocosms, wile a higher IP ratio led to significantly lowered effluent TOC concentrations. It is worth mentioning that there was no significant impact of vegetation and the estimate associated with repeated measures had an unusually high value (51.854), indicating substantial variance among the events.

4.3.3. Temporal evolution of effluent concentration.

The effluent concentrations of RP, NO_3-N and TOC in relation to different media, vegetation and IP ratio are shown in Figures 3-5, respectively, for all simulated events. The qualitative analyses focused on the temporal evolution of respective effluent concentrations, the variability and differences among mesocosm types. As shown in Figure 4.3, the effect of media on the RP concentration was apparent with the CL mesocosms having consistently lower effluent concentrations than the mesocosms with CoC 40 and CoC 70. Differences in the RP concentration between the turfgrass (control) and the other two vegetation types (i.e., woody and herbaceous vegetation) were apparent as well, especially the mesocosms planted with turfgrass had elevated effluent concentrations and pronounced variability. In addition, the discernible decreasing trend in the RP effluent concentration was present in the case of mesocosms with woody vegetation, which was particularly evident with the combination of high hydrologic loading (IP ratio of 30) and CoC 40/CoC 70 . Interestingly, bioretention vegetation is often presented as not having a significant effect on phosphorus retention (Dagenais et al., 2018), but the majority of previous studies rarely span a long enough period to observe a difference associated with plants maturing. This might be important as vegetation growth and the associated biomass accumulation have been linked to decreasing effluent concentrations by (Read et al., 2008). In this study, woody vegetation experienced the greatest growth over the years, which could explain the enhanced performance as compared to the other vegetation types.

As for the NO_3-N, the difference in its effluent concentration between the CL and CoC 40/CoC 70 was dramatic with the CoC 40/CoC 70 having effluent concentrations two orders of magnitude greater than those of the CL media, followed by subsequent reduction in dissimilarities among the three media types (Figure 4.4). Despite the significant effects of vegetation and IP ratio observed in the LMM analysis, the differences in the NO_3-N effluent concentration among different vegetation type and between two IP ratios were not as pronounced (Figure 4.4). The effluent concentrations for the IP 30 appeared to have a lower baseline, whereas the control vegetation appeared to result in greater effluent concentrations. Similar to the NO_3-N, the initial TOC leaching was dramatic for all three media types, which was distinct from NO_3-N leaching. The TOC effluent concentrations observed initially were comparable to that of untreated wastewater (Riffat and Husnain, 2022). The differences in the TOC effluent concentration among the media types were consistent across the years with distinct separation between the respective lines (Figure 4.5). The higher IP ratio resulted in lowered TOC effluent concentrations, suggesting the dilution effect.

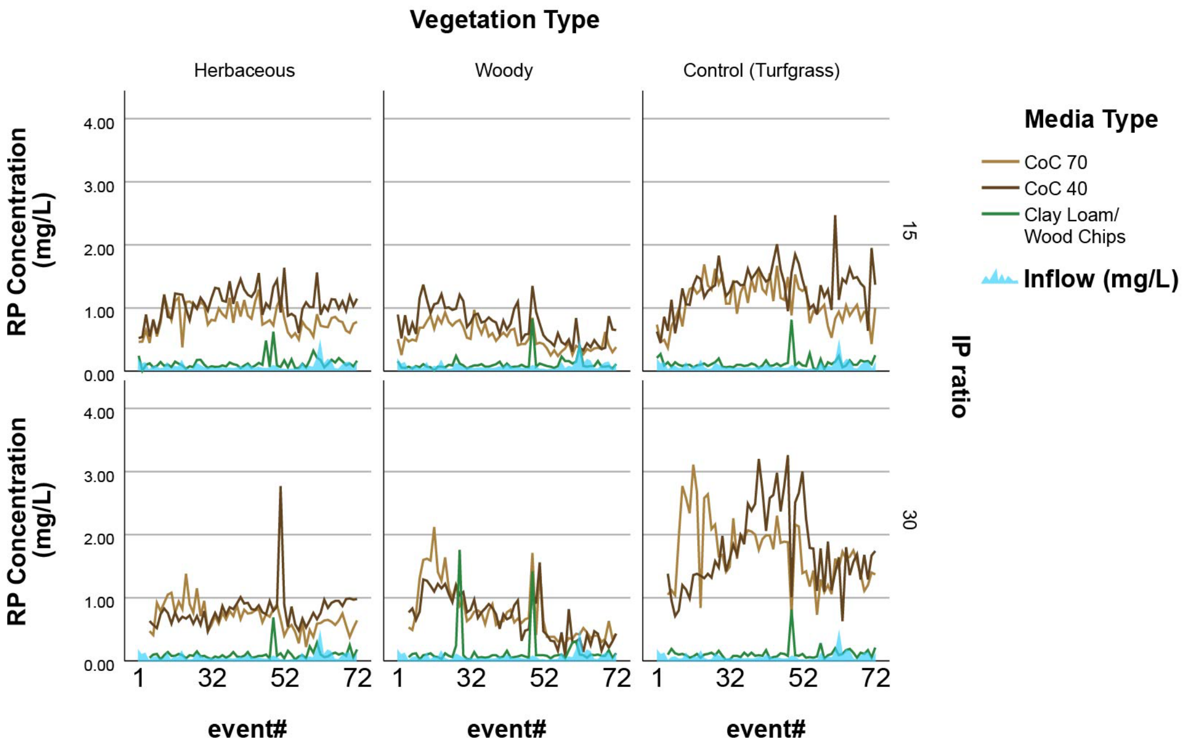


Figure 4.3. Reactive phosphorus leaching across the simulated events and design factors.

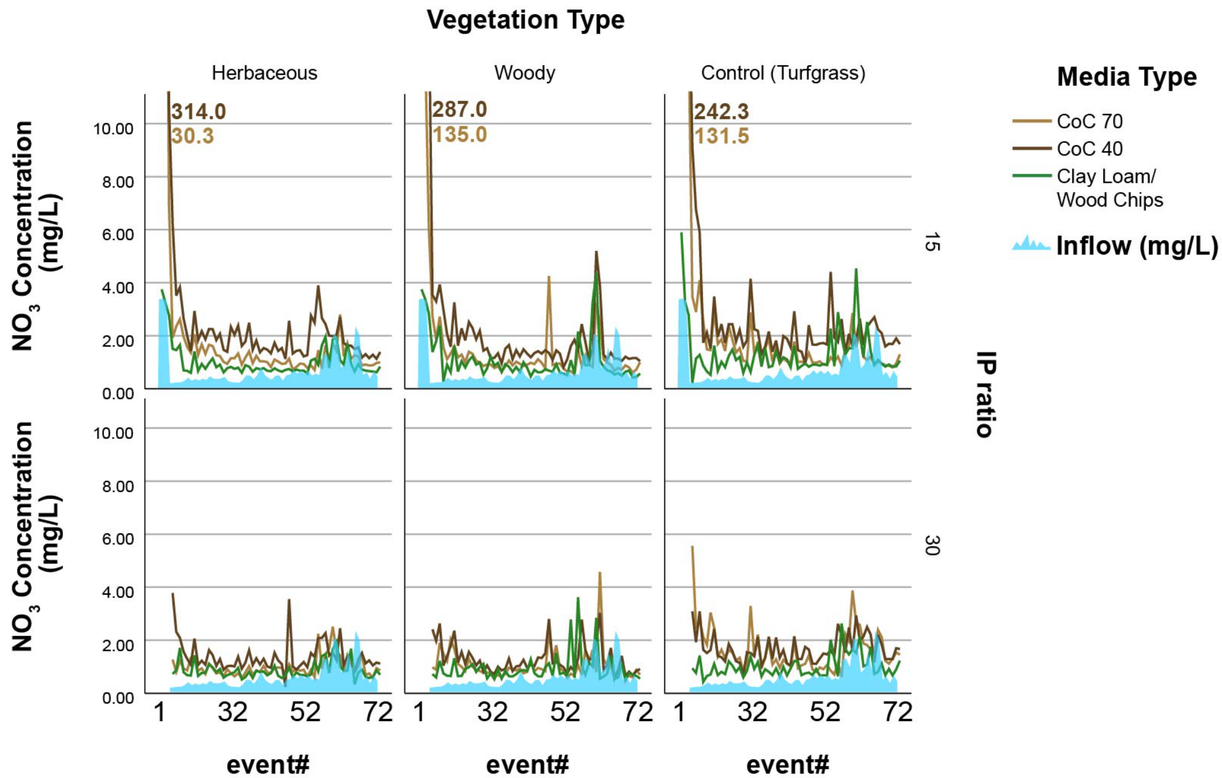


Figure 4.4. Nitrate leaching across the simulated events and design factors.

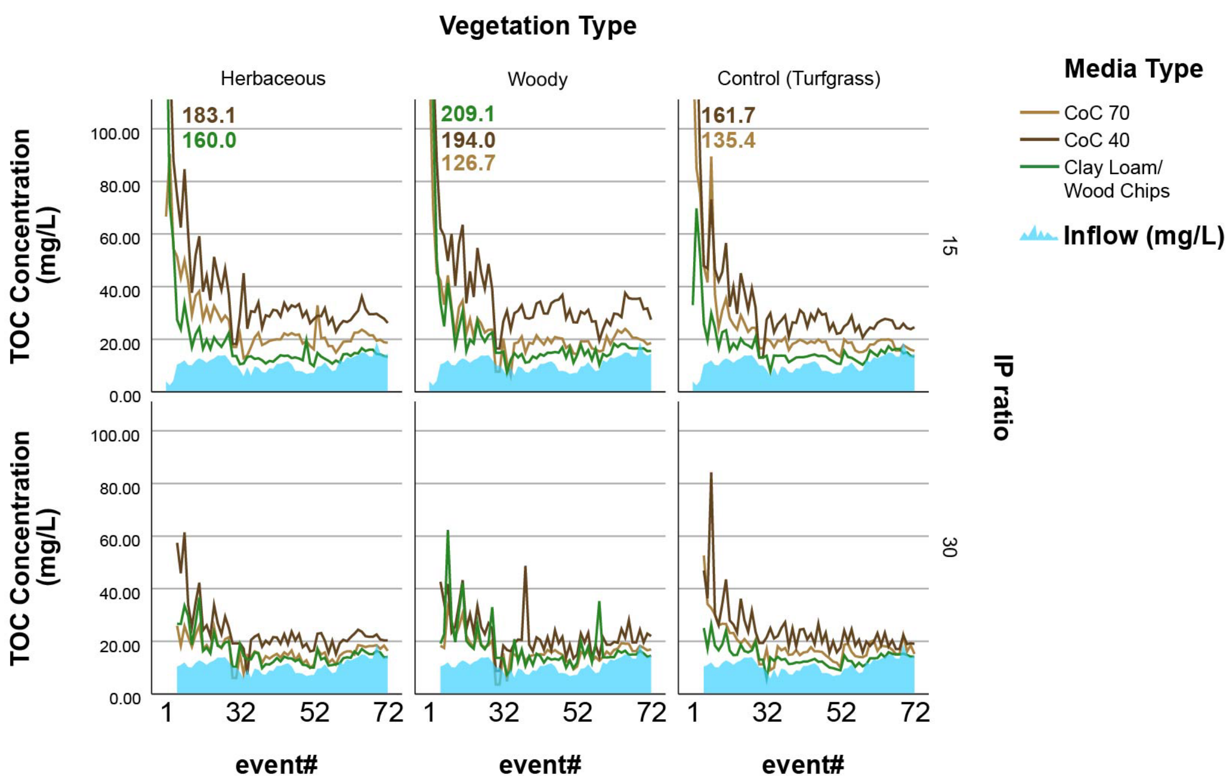


Figure 4.5. Total organic carbon leaching across the simulated events and design factors.

4.3.4. Impact of media nutrient content

Media had a significant impact on the analyte effluent concentrations based on the preceding analysis. Media composition is one of the key drivers for predicting leaching, especially for phosphorus. Specifically, the extractable media phosphorus content is often utilized as a predictor of phosphorus leaching (LeFevre et al., 2015). In addition, media with low organic matter content are recommended to avoid leaching of nitrogen and organic matter (Bratieres et al., 2008; Iqbal et al., 2015; Passeport et al., 2009). To shed light on the underlying media properties, extractable nutrient content was analyzed as part of this study for both phosphorus and nitrogen and the outcomes compared to mean effluent concentrations (Figure 4.6).

For the phosphorus content, the results showed that media of comparable phosphorus content can release different effluent concentrations (Figure 4.6). The extractable RP media contents followed approximately a 1:2:4 ratio for CL, CoC 70, and CoC 40 media, respectively. However, the effluent concentrations showed a 1:7:9 pattern, and the mean effluent concentrations of RP of CL mesocosms were only 1.5-fold greater than that of the influent, whereas the effluent concentration of the mesocosms with CoC 40 and CoC 70 was an order of magnitude greater than that of the influent. The extractable RP content was close to the allowed limits of 40 ppm for the bioretention design guidance standards (CSA, 2018), yet the effluent concentrations were in the hyper-eutrophic range of over 0.1 mg/L (CCME, 2004). Analyzing extractable phosphorus does not address the driving mechanism of phosphorus sorption, as it depends on the interaction with positively charged metal ions and their oxides within the media (Li and Davis, 2016). A better predictor of phosphorus leaching can be borrowed from the agricultural sector where the leaching metric incorporates extractable iron and aluminum content in addition to phosphorus (Jay et al., 2017).

Whereas the relationship between nitrogen content of the media and nitrogen effluent concentrations was more consistent. The extractable NO_3-N media content had a 1:3:6 ratio for the CL, CoC 70, and CoC 40, respectively, whereas effluent concentrations had a 1:3:8 ratio. The CL mesocosms effluent concentrations were about 1.3-times that of the influent. Given that nitrogen retention depends on biological transformations and several forms of nitrogen may be present at once, the analysis is incomplete without an understanding of speciation of nutrients in the effluent. Another issue of extractable nutrient analysis is only providing a snapshot in time, when there is considerable temporal variability in its effluent concentration.

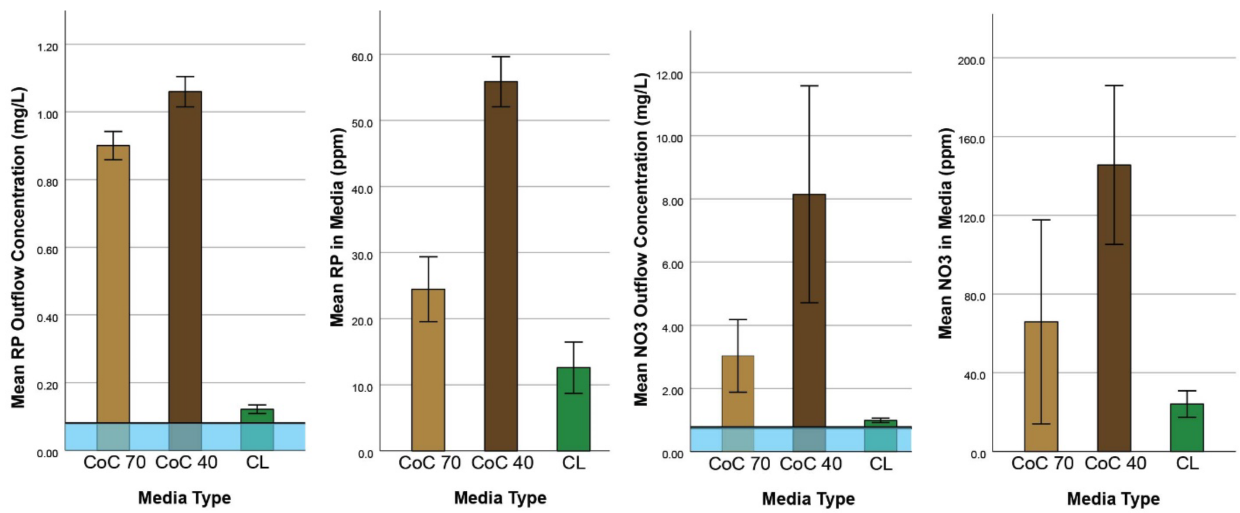


Figure 4.6. Mean nutrient concentrations in simulated runoff effluent and corresponding extractable media nutrient content, influent nutrient concentrations are shown as the blue baseline on the effluent graphs.

4.3.5. N and P Speciation

Bioretention effluent composition is known to vary as influenced by the design, hydrologic conditions, and time, especially with respect to nitrogen given its biochemical transformations. The media type had a significant effect on the effluent concentrations of NO_3-N and TN, and the associated speciation differences were analyzed to gain insight into the underlying processes. The dramatic nitrogen leaching observed in the first few events in the CoC 40 and CoC 70 was almost exclusively made up of NO_3-N, which accounted for 90% of the effluent TN for CoC 70 mesocosms and 99% of the effluent TN for CoC 40 mesocosms. The drastic release of NO_3-N in these two media types can be linked to their composition, where sand and compost were the key components. Compost in bioretention media can be the leading cause of NO_3-N leaching and other studies observed similar NO_3-N flushing from compost-amended bioretention media (Chahal et al., 2016; Hurley et al., 2017). In addition to the impact of compost, sandy media have been shown to promote nitrogen losses in agricultural systems (van Kessel et al., 2009).

After the initial flushing, the mesocosms with CoC 40 and CoC 70 continued to release NO_3-N, as the mean NO_3-N content of the effluent samples was 1.6, 1.4, and 1.2-times higher than the influent in year 2, 3, and 4, respectively. This could be attributed to organic nitrogen and ammonia transformations in the media between events, which would contribute additional NO_3-N to the effluent during events, as similar transformations have been demonstrated by (Wan et al., 2017). Moreover, sandy media encourage an aerobic environment and thus associated nitrogen transformations, which include conversion of organic nitrogen and ammonia to nitrate (Li and Davis, 2014).

In contrast to the CoC 40 and CoC 70, CL effluent speciation was generally similar to that of the influent. Wood chips in the CL media lend a unique quality with respect to nitrogen transformation as they can act as a source of carbon for denitrification, which converts NO_3-N to nitrogen gas (Liu et al., 2021a). Based on the consistent leaching of TOC in this study, there was no shortage of carbon (Figure 4.5). As such, a decrease in relative NO_3-N content was expected in the effluent, yet the NO_3-N portion of the TN was 1.2-times greater than that of the influent in years 2 and 3, and 1.6-times in year 4. This needs to be interpreted in conjunction with the changes in TN concentration, as in year 4, the TN effluent concentration of CL mesocosms was 1.6-times lower than the influent. It appears that the increase in relative proportion of NO_3-N was due to the capture of non-nitrate nitrogen by the CL media combined with no discernible denitrification. It is possible that the residence time was insufficient, or the conditions were not anaerobic enough for denitrification to have a measurable impact. Interestingly, neither vegetation nor IP ratio had an apparent impact on the speciation across the media types.

Similar to nitrogen, the forms of phosphorus play a role in the extents of leaching, with RP being significantly more mobile (Hatt et al., 2009). In addition, another study by (Hurley et al., 2017) found that compost in bioretention media may lead to continued breakdown and increasing concentrations of effluent RP over time. During this study period, the average TP effluent concentration was approximately 3-times higher than that of the influent. The average percent of RP relative to TP was 37% and 73% for influent and effluent concentrations, respectively, highlighting that RP was released from the mesocosms. There were no clear tendencies for increase or decrease in speciation across the years. However, there were notable differences among the media types, where CL had similar effluent composition to the influent (~30% RP), and CoC 40 and CoC 70 media were both characterized by elevated RP composition (~80% RP). The CL media had higher clay and silt content than the CoC 40 and CoC 70 media, and clay has been shown to increase retention of P and contribute to leaching reduction (Tahir and Marschner, 2017). The impact of vegetation or IP ratio on phosphorus speciation were not apparent.

4.3.6. The effect of ancillary water quality parameters and soil moisture

In the year 3 of the study, temperature (T), electrical conductivity (EC), pH, and dissolved oxygen (DO) of the influent and effluent were tested in addition to RP, TP, NO_3-N, TN, and TOC. These ancillary parameters can provide simplified inferences into the dissolved nutrient dynamics, namely the nutrient transformations and removal within the mesocosms. In addition, the effects of soil moisture were analyzed as well, as antecedent soil moisture is a key factor in the mechanisms of nutrient retention (Chen et al., 2021). Pearson correlation analysis was used to determine which of these variables are correlated with the effluent concentrations of RP, TP, NO_3-N, TN, and TOC (Table 4.4).

Table 4.4. A summary of correlation among effluent concentrations and the ancillary water quality and environmental parameters.

Environmental Parameter	WQ Parameter (Effluent Concentration)				
	RP	TP	NO_3-N	TN	TOC
Effluent temperature	0.017	0.124**	-0.097*	0.106*	0.091*
Effluent Dissolved oxygen	0.198**	0.145**	0.254**	0.084	0.125**
Effluent Electrical conductivity	-0.305**	-0.199**	-0.034	0.115**	0.218**
Effluent pH	0.135**	0.075	0.021	-0.102	-0.070
Antecedent Soil Moisture (0 cm)	-0.120*	-0.157**	-0.013	0.035	0.030
Antecedent Soil Moisture (20 cm)	0.147**	0.017	0.168**	0.221**	0.129**
Antecedent Soil Moisture (40 cm)	0.271**	0.154**	0.119**	0.152**	0.157**

* Correlation is significant at the 0.05 level
** Correlation is significant at the 0.01 level

The effluent concentrations of most analytes were significantly correlated with effluent temperature, dissolved oxygen, conductivity, and antecedent soil moisture below the surface. All analytes were significantly correlated with antecedent soil moisture at 40 cm depth, which indicates that a greater degree of saturation within the media prior to an event supported leaching during the event. This is consistent with findings of compost-amended bioretention media leaching under saturated conditions (Hurley et al., 2017). Leaching due to the greater degree of saturation could be interpreted as being linked to the development of anaerobic conditions, but it also appears that greater dissolved oxygen was positively correlated with greater effluent concentration for most analytes (except for TN). Based on these results, it appears that increased solubility of the analytes from the media into pore water may have been the cause of increased leaching. Out of all the analytes, only RP correlated with the effluent pH, suggesting that higher pH could lead to greater effluent concentrations. Effluent conductivity was correlated with TN and TOC concentrations, yet inversely related to the RP and TP effluent concentrations.

4.3.7. Within-event ANOVA analysis and interactions

As demonstrated previously, substantial inter-event variability, correlation, and changes with time were observed. The impacts of media, vegetation, and IP ratio, their interactions and effect size were further analyzed within each event individually using the ANOVA analysis. The results, namely the effect size and the number of significant events, are summarized by the analytes and years and are presented in Tables 4.5- 4.7. The effect sizes indicate the proportion of variance accounted for by each variable, allowing comparisons to be made on the effect strength, where values around 0.2 can be considered small, 0.5 medium, and 0.8 large (Strunk and Mwavita, 2020). For the RP, the results of the ANOVA analysis were consistent with those of the LMM, highlighting that media and vegetation had significant and consistent effects on the effluent concentration (Table 4.5). Both media and vegetation had a strong effect size, explaining the majority of variance in the RP effluent concentration. The IP ratio (i.e., the hydrologic loading) had a small effect size and diminishing number of significant events over the years. A unique finding of this analysis is that interactions were significant and appeared to be increasingly more significant each year. When looking specifically at the types of interactions, those between media and vegetation had the greatest effect size (74% of total variance explained) with increasing significance over the years. The results for TP (data not shown) were similar to those of the RP, with about a 15% reduction in the number of events with a significant vegetation effect and a 23% reduction in significant interactions.

Table 4.5. A summary of individual event analysis of RP effluent concentration using factorial ANOVA and three fixed factors of media, vegetation, and IP ratio. The data shows the effect size of the main effects and interactions as well as the number of events with a significant effect on the RP.

Parameter			Main Effects			Interactions			
			Media	Veg.	IP	Media x Veg	Media x IP	Veg x IP	Media x Veg x IP
Mean Effect Size (Partial Eta Squared)			0.94	0.80	0.25	0.74	0.40	0.54	0.53
Year	# of events	Model Violations *	Number of Significant Events						
1	3	0	3	0	n/a	0	n/a	n/a	n/a
2	16	0	16	13	6	5	8	5	3
3	22	1	21	19	5	14	3	13	8
4	20	0	20	20	0	16	3	5	2
Total	61	1	60	52	11	35	14	23	13

* Instances where irrespective of assumptions, the ANOVA analysis showed the proposed media-vegetation-IP model as not being significant in explaining the variance.

For the NO_3-N, only the media type had a strong effect on its effluent concentration, whereas vegetation, and IP ratio had a moderate effect size (Table 4.6). However, the significance of the media impact diminished over the years based on the number of events with significant effect. Reduction in the impact of IP ratio and interactions on the effluent concentration over the years were also observed. The interaction of media and IP ratio had the greatest number of significant events, but the strength of this interaction was comparable to that of media and vegetation. The results for TN (data not shown) were similar to those of the NO_3-N. There were about 20% more events with significant effects of IP ratio and interactions, and 30% less events with significant effect of vegetation. The overall decreasing trend in the significance of interactions was also observed, as very few interactions were observed in the year 4.

Table 4.6. A summary of individual event analysis of NO_3-N effluent concentration using factorial ANOVA and three fixed factors of media, vegetation, and IP ratio. The data shows the effect size of the main effects and interactions as well as the number of events with a significant effect on the NO_3-N.

Parameter			Main Effects			Interactions			
			Media	Veg.	IP	Media x Veg	Media x IP	Veg x IP	Media x Veg x IP
Mean Effect Size (Partial Eta Squared)			0.83	0.65	0.52	0.58	0.53	0.30	0.50
Year	# of events	Model Violations *	Number of Significant Events						
1	3	0	2	2	n/a	2	n/a	n/a	n/a
2	16	0	16	12	13	6	13	3	2
3	22	2	19	14	12	5	8	4	3
4	20	5	14	12	4	1	4	0	3
Total	61	7	51	40	29	14	25	7	8

* Instances where irrespective of assumptions, the ANOVA analysis showed the proposed media-vegetation-IP model as not being significant in explaining the variance.

For the organics, all the events in the year 1 were not suitable for the analysis, but in the subsequent years there was a consistent effect of the media, IP ratio, and their interaction (Table 4.7). Media type had the strongest effect on the leaching of TOC, and, based on the pairwise comparisons, the CoC 40 mesocosms were significantly different from the other two in the year 2, whereas all three media were significantly different from each other in the following years. The strongest interaction for the TOC effluent concentration was observed between media and IP ratio. Based on the temporal variation of the TOC concentration (Figure 5), the higher IP ratio brought the effluent TOC concentration of the CoC 40 and CoC 70 closer to that of the CL, which may explain the observed significance of this interaction. Consistent with the LMM analysis, vegetation did not have a pronounced impact on the release of organics, which is unexpected given that plants release organics from their roots and are thought to contribute to the removal of organic compounds in bioretention systems (Dagenais et al., 2018) . It is possible that due to substantial releases of TOC from the mesocosms, the plant effects were not easily detectable.

Table 4.7. A summary of individual event analysis of TOC effluent concentration using factorial ANOVA and three fixed factors of media, vegetation, and IP ratio. The data shows the effect size of the main effects and interactions as well as the number of events with a significant effect on the TOC.

Parameter			Main Effects			Interactions			
			Media	Veg.	IP	Media x Veg	Media x IP	Veg x IP	Media x Veg x IP
Mean Effect Size (Partial Eta Squared)			0.93	0.38	0.76	0.46	0.75	0.35	0.49
Year	# of events	Model Violations *	Number of Significant Events						
1	3	3	0	0	n/a	0	n/a	n/a	n/a
2	15	0	15	2	15	1	13	0	1
3	22	1	21	1	19	1	17	1	4
4	19	0	19	6	17	3	17	3	2
Total	59	4	55	9	51	5	47	4	7

* Instances where irrespective of assumptions, the ANOVA analysis showed the proposed media-vegetation-IP model as not being significant in explaining the variance.

4.4. Conclusions

Bioretention systems are designed to improve the water quality of stormwater runoff, yet this multi-year analysis showed that significant leaching of dissolved nutrients and organics will be the likely outcome when using conventional bioretention media. Leaching of nitrogen and organics had a decreasing trend over time, yet the initial effluent concentrations were comparable to that of untreated wastewater. In addition, phosphorus leaching was persistent across the years while the extractable phosphorus contents within the media were within the typical targets for bioretention systems. Consequently, it is paramount that bioretention system designs are amended to mitigate the leaching and potential downstream impacts.

Bioretention media had a significant impact on leaching of all the water quality analytes, primarily due to the differences between the more conventional bioretention media (i.e., CoC 40 and CoC 70) and the more unique CL media. The latter was especially beneficial in reducing phosphorus and organics leaching. Further research of the long-term impacts of wood chip decomposition are needed for a comprehensive assessment of the potential benefits and risks of a soil/wood chip bioretention media.

Vegetation had a significant effect on phosphorus leaching, with all three vegetation types presenting a different outcome where turfgrass was the least effective at the RP retention and woody vegetation was the most effective. Vegetation effects on nitrogen dynamics were less pronounced and largely insignificant for the leaching of organics, which was one of the unique findings of this study. Hydrologic loading had little effect on the leaching of phosphorus, meaning that greater volume of runoff did not cause a significant decrease in concentration. This could translate to a greater potential downstream threat with conventional bioretention systems in the face of increased intensity and magnitude of storm events under a changing climate. On the other hand, a dilution effect was observed with the increased hydrologic loading for the leaching of nitrogen species and organics.

Substantial variability and significant changes over time were observed for the different mesocosms, which underscores the need for long-term performance data on these nature-based systems. Given that the initial leaching may be unavoidable, targeted management strategies are required to support future implementation of bioretention systems, where the receiving water bodies are protected from the impacts of the initial nutrient flush.

Chapter 5: Bioretention System Infiltration: Temporal evolution and Impacts of Design Parameters

5.1. Introduction

Bioretention systems are becoming increasingly more common as the recommended source control practice for stormwater management within urban environments. These nature-based solutions offer unique hydrologic and water quality benefits that mitigate the negative impacts of urbanization. Many of these benefits depend on infiltration, which enables reductions in the overall volume of stormwater runoff and creates opportunities for runoff-media interactions to facilitate treatment. As such, infiltration capacity is critical for bioretention systems, especially for the long-term performance, as there are risks of diminishing infiltration due to clogging of bioretention media over time (Kandra et al., 2014).

Multiple bioretention studies attribute the loss of long-term functionality to sediment accumulation (Kandra et al., 2014; Le Coustumer et al., 2007; Segismundo et al., 2017; Subramaniam et al., 2018). Sediment accumulation may cause clogging due to the physical occlusion of the pores within bioretention media, which is often seen in conventional infiltration practices, such as sand and gravel filters. In addition to sediment accumulation, some studies attribute clogging to biological growth related to the development of biofilms (Kandra et al., 2014). Irrespective of the cause of clogging, multiple sources report declining infiltration capacity of bioretention systems over time and advise to factor an anticipated decline into the design (Gonzalez-Merchan et al., 2014; Khan et al., 2012; Le Coustumer et al., 2009). However, there is a key difference between conventional infiltration practices and bioretention systems, which stems from the biological activity unique to bioretention systems, specifically the soil structure formation associated with the vegetation and microbial processes (Le Coustumer et al., 2012). Often studies that focus on bioretention clogging are conducted in the laboratory setting and do not take natural processes such as the effect of plant roots, root turnover, and media perturbation into the account (Spraakman and Drake, 2021). Therefore, in order to ensure successful design and implementation of bioretention systems, a thorough understanding of the influence of the design parameters on the infiltration capacity and clogging is needed. This includes parameters such as the type of bioretention media, type of vegetation, and the anticipated hydrologic loading, which are typically dictated by the size of the system relative to the contributing catchment. Increased hydrologic loading would lead to the increased sediment accumulation and, thus, the risk of physical clogging of bioretention media.

The existing body of literature suggests that the type of media is one of the most important factors in controlling hydraulic performance of bioretention systems. Specifically, media texture and particle size distribution are thought to dictate hydraulic conductivity (Jiang et al., 2022). As the result, sandy media are typically preferred for permeability purposes (Jiang et al., 2019). Many bioretention design guidelines prioritize the reduction of clay and silt content as a way of ensuring adequate infiltration (CSA, 2018; Fassman-Beck et al., 2015). The downside of using sandy media for long-term permeability objectives is the reduced propensity for rhizosphere and soil structure formation in sandy soil as compared to finely textured and cohesive soil types (Funai and Kupec, 2017). The opportunities and benefits of finely textured media have been sporadically highlighted in the past, but the inability to overcome low permeability of finely textured mixes remained a barrier to practical implementation, creating a need for novel media designs.

Vegetation also plays a key role in the long-term maintenance of the infiltration capacity due to macropore formation and various associated processes. Plant-soil interactions play a critical role in bioretention performance through the impacts on media structure formation and enhancement of media pore space connectivity (Johnston et al., 2020; Skorobogatov et al., 2020). Very few studies have analyzed the relationship between vegetation and long-term infiltration capacity to date. A recent review on infiltration of bioretention systems calls for multi-season field investigations of infiltration and impacts of plant traits, as well as long-term changes in the associated performance (Techer and Berthier, 2023). This study utilizes the trait-based plant ecology approach to assess the impact of vegetation on the bioretention performance.

Despite the apparent significance of rhizosphere, there are very few bioretention studies that investigated the biological activity within these systems, and none have linked biological activity to infiltration capacity. Biological activity is difficult to define and it may be confounded by a variety of design and site-specific factors, as well as the changes that take place over time (Mitchell Ayers and Kangas, 2018). Plants roots have direct effects on soil respiration and production of CO_2, where specific root length defined as the ratio of root length to mass appears to play a significant role (Borden et al., 2021). As such, measuring the CO_2 production could provide insights into the rhizosphere-associated processes in bioretention media without the need for destructive testing methods and subsequently linkages to the impact on infiltration.

In the view of above, this research aims to bridge several gaps in the existing knowledge of infiltration of bioretention systems. The overarching goals were to analyze the infiltration of bioretention mesocosms configured with different designs, namely with different media, vegetation, and hydrologic loading, and to understand how infiltration changes over time. Among the three types of bioretention media, there were two conventional sand-based bioretention media and a unique mix of clay-loam and wood chips, which offers a novel alternative to the conventional sand-based bioretention media composition. Three vegetation types and two hydrologic loadings were investigated. Due to the factorial experimental setup, this research allowed to not only analyze the impacts of the main design parameters but also their respective interactions. In addition, soil respiration was also analyzed and compared to the infiltration capacity to shed light on potential linkages between infiltration and biological activity within bioretention media. This research was conducted in the field setting. The bioretention mesocosms were subject to external pressures of freeze-thaw and wetting/drying cycles, which is a close approximation of a full-scale bioretention implementation, but receiving runoff in a controlled manner.

5.2. Materials and Methods

5.2.1. Site description and experimental setup

This research was conducted at a field facility in the Town of Okotoks, Alberta, Canada, which was constructed for the purposes of this research in 2017. Okotoks has a xeric temperate climate, with short warm summers and long cold winters. The average annual temperature is 4.6 °C and the average annual precipitation is 515 mm. The facility has 24 bioretention mesocosms with three different media and three different vegetation types. Two media were based on local bioretention guidelines and had target infiltration rates of 70 and 40 mm/hr (Calgary, 2016), referred to as CoC 70 and CoC 40 in this paper. The third media was created from local clay-loam soil with the addition of 40% wood chips (by volume) (referred to as CL) to improve the media permeability. The media properties are summarized in Table 5.1. Media texture was analyzed using sieve analysis, hydrometer, and light diffraction methods (Mastersizer 2000, Malvern Instruments Ltd, UK.), while organic content was analysed by loss on ignition. Sediment was analyzed for particle size distribution as well.

Table 5.1. Media characteristics.

		% Organic Matter (w/w)	Texture		
			% Sand (0.05-2.00 mm)	% Silt (0.002-0.05 mm)	% Clay (<0.002 mm)
Media Type	CoC 70	3.5	74.6	19.3	6.1
	CoC 40	16.4	73.7	22.6	3.7
	CL	11.2 (8.7)*	41.6	44.3	14.1

* The value of 11.2 was calculated based on % by volume of wood chips (using density of pine) that was used to create the media, whereas 8.7 was the value obtained through loss on ignition, where larger wood chips were not included.

The three vegetation types included woody shrubs, herbaceous mix, and turfgrass (as control). The mesocosms were subject to two hydrologic loadings, namely IP ratios of 15 and 30. The IP ratio is defined as the ratio of contributing impervious catchment area to the bioretention basin area (Calgary, 2016). Among the bioretention mesocosms, 15 of them were exposed to the IP ratio of 15 and 9 mesocosms were exposed to the IP ratio of 30. Each cell had a TEROS-12 soil moisture sensor at 20 and 40 cm depths. Vegetation heights were measured to assess the increase in growth over time. Height was measured using a sward height technique for herbaceous vegetation and as the average of tallest tip measured individually for the woody shrubs.

5.2.2. Simulated Events and Field Monitoring

The mesocosm were monitored under simulated events. During the study period from 2017 to 2020, there were 72 runoff events simulated. The magnitude of events, inter-event period, and annual runoff volume were designed to represent average local hydrologic conditions. The runoff was simulated using water from a local stormwater pond that was delivered on the day of the event. The sediment concentration of the pond water was much lower than the typical sediment concentration of stormwater runoff in the study region (400 mg/L) due to sediment settling in the pond. To mimic the representative sediment concentration, additional sediment was added to each mesocosm by mixing a pre-measured quantity of dry sediments with a small (~5 L) volume of water and adding it in as a slurry during the simulated event. Street sweeping solids sourced from the Town of Okotoks were used as the additional sediments. The material was air-dried and sifted through a 2 mm sieve prior to use in the simulated events.

Simulated runoff was applied using garden hoses at a fixed rate of ~2 L/s, the volume applied varied with simulated runoff magnitude and IP ratio. Infiltration was measured by measuring the rate of decreasing water level across the area of each mesocosm, which is analogous to the measurement approach of single-ring infiltrometers (Dingman, 2008). The mesocosms were lined, so there was no lateral movement of water during the application of runoff. Infiltration was measured between 5 and 10 minutes of applying runoff to the surface, which is when the infiltration for most soils approaches a constant value (Dingman, 2008). In March of 2019, each mesocosm was analyzed for bulk density. Three samples were taken from each cell using stainless-steel 100 ml UMS sample rings and hammering adapters. Each sample was then dried and weighted to measure the bulk density. In this research, the bulk density was be used to reflect the bioretention media compaction (Yergeau and Obropta, 2013).

In addition, to link the infiltration to the biological activity within bioretention media, soil respiration of the mesocosms was measured and analyzed. All mesocosms were measured in September of 2018, while only nine mesocosms were selected for the measurement in September of 2019 due to inclement weather conditions. Soil gases were measured using Landtec GEM 5000 Plus combined with a custom-made perforated stainless-steel probe. The probe was made from a stainless-steel tube 10 mm in diameter, 250 mm long, with one end cut diagonally and then sealed off with epoxy. There were 5 rows of four 1 mm perforations spaced 5 mm apart. The probe was inserted into the media to a depth of 20 cm (measured to the centre row of perforations) in 5 locations within each mesocosm. The soil gas analysis included methane, carbon dioxide (CO_2), oxygen (O_2), carbon monoxide, and hydrogen sulfide.

5.2.3. Statistical analysis

Linear mixed method (LMM), analysis of variance (ANOVA), Linear Regression, and Kruskal-Wallis test were the main statistical tools used to evaluate the significance of the differences associated with the different design parameters as well as correlations of infiltration rate with design parameters and time. The LMM is uniquely suited to analyzing longitudinal datasets and has less restrictions than ANOVA (Barton and Peat, 2014). The LMM allows for correlation between events, which is likely to happen in environmental research. For the purposes of this research, first order autoregressive (AR1) covariance structure was applied, assuming greater degree of correlation between adjacent events than those further apart during the study period. Maximum Likelihood (ML) method was used to fit the LMM model as it incorporates both fixed and random parameters (Beaumont, 2012). Bonferroni method was used for pairwise comparisons among the design factors as it reduces the likelihood of false positives (Duricki et al., 2016).

However, the LMM does not estimate the strength of the effect of the independent variable(s) on the dependent variable (Barton and Peat, 2014). To overcome this limitation and analyze within-event effects, ANOVA was used. Another purpose of the use of ANOVA was to analyze the interactions among the design factors, taking full advantage of the factorial experimental design of the mesocosms. The Kruskal-Wallis method was used to compare different mesocosm types when ANOVA assumptions were violated. Log-transformation was applied in select analyses to correct for skewed distribution. The significance of the slope coefficients was analyzed using t-test statistic. All statistical analyses were performed using IBM SPSS Statistics Version 25 at the significance level of 5% (unless otherwise specified).

5.3. Results

5.3.1. Overall variation of infiltration rate

The temporal evolution of mean infiltration rate across the different mesocosms is shown in Figure 5.1A. The mean infiltration rate values were about an order of magnitude higher than the anticipated 40 to 70 mm/hr values suggested by the local guidelines (Calgary, 2016), and several fold higher than the 75-300 mm/hr range recommended by Canadian national standards for bioretention media with a specific goal of infiltration (CSA, 2018). Edge flow could have contributed to the increased infiltration rates due to the size of the mesocosms, but the present study used larger mesocosms than what has been used by others in the past. Moreover, there was an increasing trend across the years, where the mean infiltration was 286 mm/hr for the first event and 875 mm/hr for the last. This increasing trend bears important design implications, as it contradicts the conventionally expected decline in infiltration rates over time. This research was conducted under the exposure to variable environmental conditions, including variable wetting, drying, and freeze-thaw cycles. The latter may be of particular significance to increasing infiltration rates as others showed that consecutive freeze-thaw cycles increase the pore sizes and generate more pores within bioretention media (Ding et al., 2019).

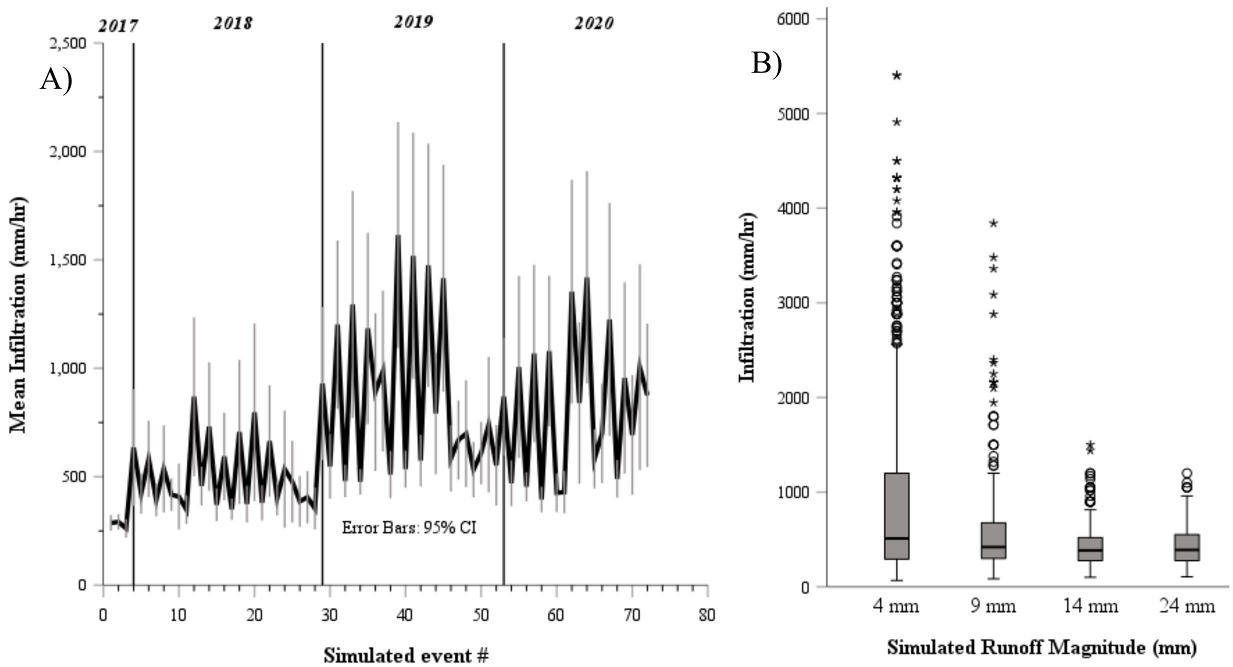


Figure 5.1. A) The temporal evolution of infiltration capacity over time (the simulated event number), solid black line indicating the mean infiltration across 24 mesocosms, bars representing 95% confidence intervals (CI); B) The relationship between infiltration and simulated event magnitude, whiskers representing the 95% CI, empty circles are for potential outliers outside the 1.5-times inter-quartile range (1.5xIQR), and stars for are potential extreme outliers outside the 3-times inter-quartile range (3xIQR).

Figure 5.1A also shows that there was substantial variability in the infiltration rates among the individual events. The experimental design may have contributed to this variability through varying simulated event magnitudes. The influence of different event magnitudes was analyzed to assess if there were significant differences in infiltration rates associated with the event magnitudes (Figure 5.1B). There was considerable difference in the range of infiltration rates for different event magnitudes with 4 mm events having the greatest range and highest values measured. It was evident that the distributions were skewed, so the boxplots are provided for illustrative purposes only. Due to significantly unequal variances as measured by Levene's test, a Kruskal-Wallis test was run to compare the median values, which were found to be significantly different. Median infiltration rates were equal to 510, 420, 384, and 390 mm/hr for 4, 9, 14, and 24 mm simulated event magnitudes, respectively. The 4 mm events had the shortest time between the application of runoff and infiltration rate measurement, which could mean that the measured values have not reached the near-static infiltration value, leading to a higher median value and greater degree of variability.

Aside from the experimental design, the variability in environmental conditions could have contributed to the variable infiltration rates. Antecedent media moisture content is the outcome of multiple environmental factors, including precipitation dynamics, media drainage, and evapotranspirative losses, making it a useful indicator to reflect on the observed variability. The moisture content measurements at 20 cm depth were grouped into 4 categories based on the data quartiles, namely dry (< 25%), medium dry (25-50%), medium wet (50-75%), and wet (> 75%). The log-transformed infiltration rates for the 4 moisture categories, presenting in Figure 5.2, were then compared. There were no dramatic differences in the median infiltration rates in relation to media moisture contents, and Kruskal-Wallis test confirmed no significant differences among the median values. As such, it appears that antecedent media moisture content had no consistent impact on the infiltration rates. Other studies observed increased infiltration capacity associated with drier media conditions, and attributed the increase to increased porosity and physical changes in the media properties (Hatt et al., 2007). Given the different composition of the media used in this study, there could be media-specific outcomes that are obscured when analyzing the mean infiltration rates. Following the same logic, analysis of vegetation-specific and IP-specific outcomes is needed to better understand the overall infiltration performance.

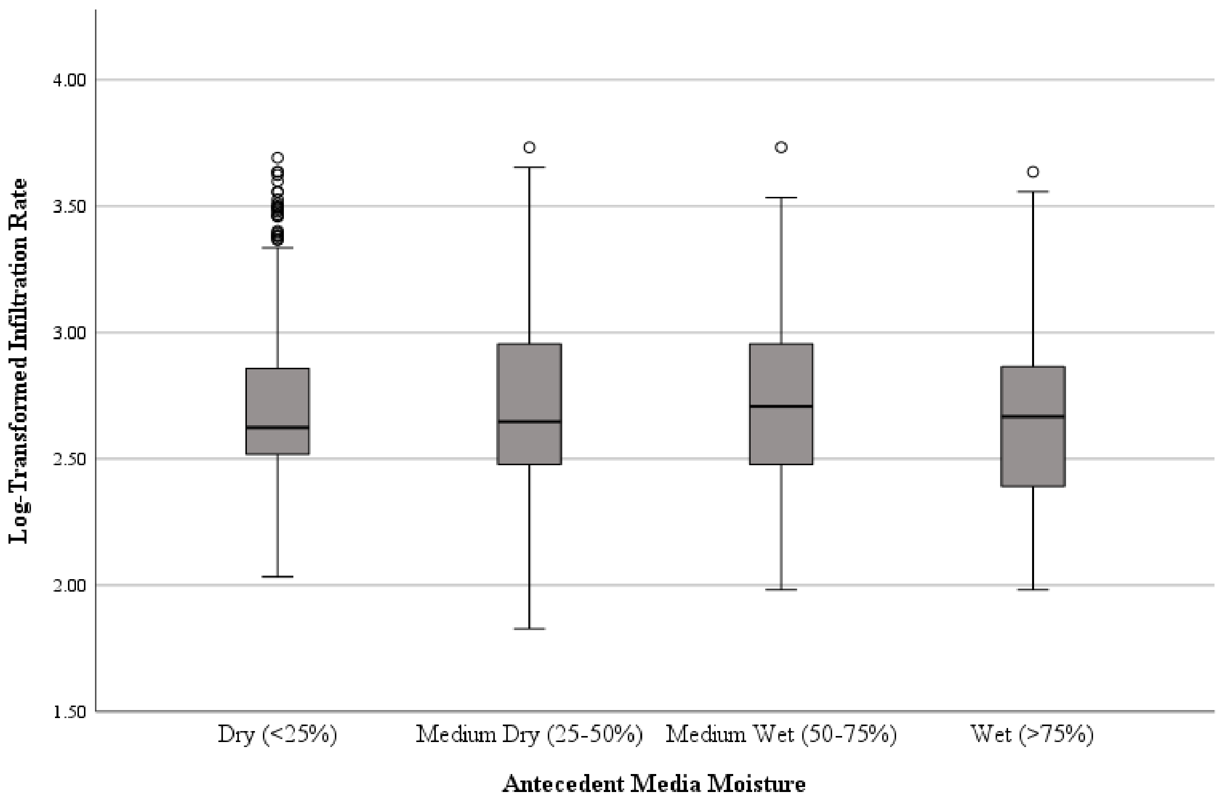


Figure 5.2. Log-transformed infiltration rate vs. antecedent media moisture conditions, whiskers represent the 95% CI, circles are potential outliers outside the 1.5xIQR.

5.3.2. Impact of design parameters and time

The LMM was used to analyze the effect of fixed design parameters and the change in infiltration rate over time. The LMM model treated media type, vegetation type, and IP Ratio as fixed factors, while allowing a random slope and intercept for each mesocosm to enable unique time-dependent linear trajectories for the different mesocosm types. The results are summarized in Table 5.2.

Table 5.2. The impact of the design parameters, time, and covariance on the bioretention infiltration.

Parameter	Estimate
Fixed	
Time[1]	6.814**
Media CoC 70 (vs CL)	-606.620**
Media CoC 40 (vs CL)	-458.518**
Veg. Herbaceous (vs Control)	222.518**
Veg.Woody (vs Control)	78.949
IP Ratio 15 (vs 30)	10.063
Random[2]	
Intercept	221.602
Slope	48.622**
Repeated Measures	
AR1 diagonal	288355.853**
AR1 rho	-.286**

[1] Time expressed as continuous variable of event#;
[2] Wald Z test was used to estimate the significance of random effects;
* Significant at the 0.05 level;
** Significant at the 0.01 level.

Based on the LMM analysis outcome, there was a significant positive effect of time on the infiltration rate, which was in alignment with the increasing trends discussed prior. This provides further support to the notion of vegetated systems being able to withstand sediment accumulation and maintain infiltration capacity following construction. Data from a 4-year time period may not be sufficient to reflect on the ultimate infiltration performance, but it is sufficient to detect a decline in infiltration due to clogging. Others suggest that a 3-year monitoring period is long enough to detect clogging in filtration-based systems as significant declines in hydraulic conductivity are typically observed after 4 years (William et al., 2019). Given that the duration of this study exceeded the 3-year mark, the data suggest that clogging from normal operation may not be a critical mode of failure for future bioretention designs.

This finding holds particular significance as the sediment concentration used in this study was higher than the 150-300 mg/L range used in the seminal bioretention clogging studies (Le

Coustumer et al., 2007; Le Coustumer et al., 2012). The increase in infiltration over time itself is not an isolated finding, as others have demonstrated stabilization and even increases in hydraulic conductivity in bioretention systems as well (Barrett et al., 2013). Currently, the adoption of increasing infiltration capacity into the bioretention design and practice is limited by the reports of hydraulic failure that are widespread in the industry. However, the reported failures are often related to poor construction practices, poor vegetation survival, and excessive compaction. Moreover, the notion of hydraulic failure due to clogging should not be associated with performance failure as nature-based systems are uniquely suited to adapt their performance and change over time (Natarajan and Davis, 2015).

5.3.3. Impact of media type

In addition to the significant effect of time, the LMM analysis showed that the media type had a significant effect on the infiltration rate as well. Based on the results, both CoC media had negative parameter estimates as compared to the CL media indicating significantly lower infiltration rates associated with the former. The results align with the mean infiltration rates for the entire dataset, which were 287, 479, and 1086 mm/hr for CoC 70, CoC 40, and CL media respectively. Notably CoC media were sand-based, whereas CL was clay-loam based, which contradicts the conventional notion of using textural classification as the main design parameter controlling infiltration capacity. The caveat in interpreting this finding as potentially undermining the role of media texture is the influence of coarse wood chips in the CL media, which drastically modified its physical properties.

Prior to the mesocosm construction, optimization of the CL media composition was done in a laboratory setting and a nearly exponential increase in hydraulic conductivity was observed with increasing wood chip content (Figure 5.3). The infiltration rates observed in the field conditions were even higher than the hydraulic conductivity values measured in the preliminary analysis. Hatt et al. (2007) suggested that clay particles and organic matter tend to increase infiltration capacity following periods of dry weather due to shrinking. The effect of antecedent moisture on the log-transformed infiltration rates of the CL media mesocosms was compared as per Figure 5.4, where the wet conditions appeared to reduce the infiltration rate. The significance of this difference was confirmed by a Kruskal-Wallis test. When comparing these results to the effects of the antecedent moisture averaged across the media types (Figure 5.2), it appears that the CL media is significantly more susceptible to the wetting and drying cycles, given the reduced infiltration. However, even the reduced infiltration rates associated with the wetter conditions remain high (672 mm/hr median) for the CL media mesocosms. Consequently, the CL media offers a potential alternative to sand-based bioretention media mixes, which expands the choice of suitable materials and aids in widespread implementation.

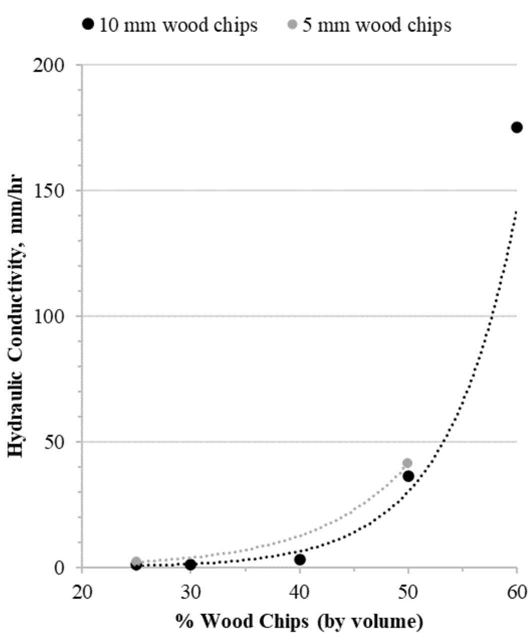


Figure 5.3. Hydraulic conductivity of CL media as the function of wood chip content, dotted lines presenting the exponential trendlines.

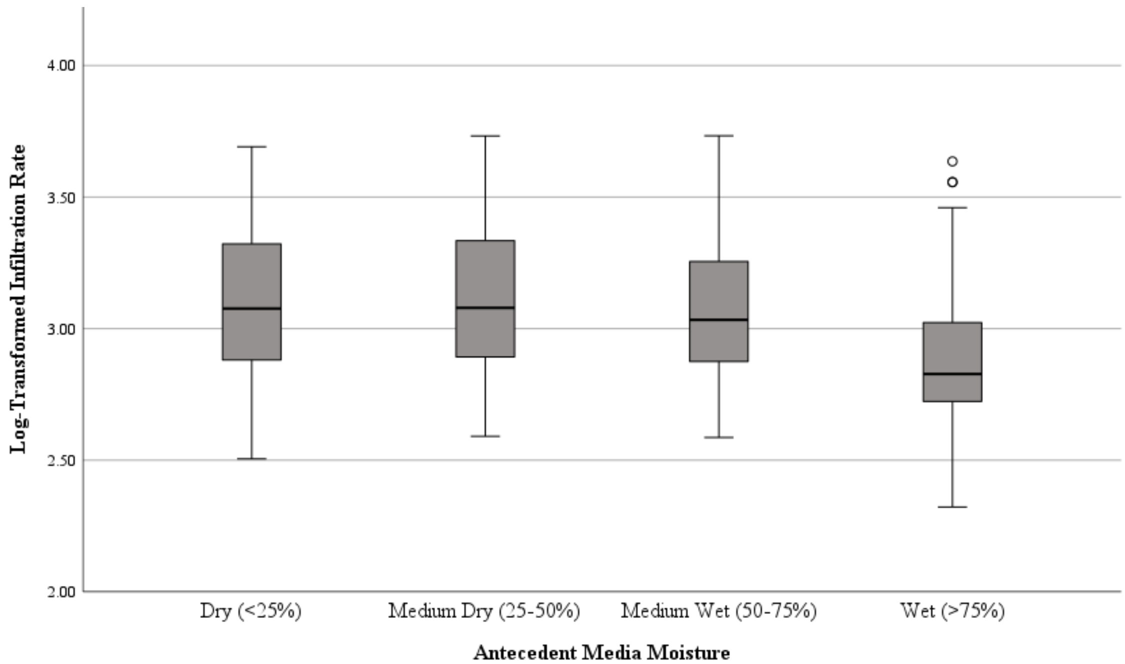


Figure 5.4. Infiltration rate vs. antecedent media moisture for the CL media, whiskers whiskers represent the 95% CI, circles are potential outliers outside the 1.5xIQR.

5.3.4. Impact of vegetation type

The infiltration rate was also significantly impacted by the type of vegetation, with herbaceous vegetation having a significantly higher LMM parameter estimate than the turfgrass control, indicating higher infiltration rates associated with the herbaceous vegetation (Table 5.2). Pairwise comparison of all three vegetation types revealed that the herbaceous mesocosms also had significantly higher infiltration rates than the woody mesocosms. The mean infiltration rates were 886, 529, and 509 mm/hr for herbaceous, woody, and control vegetation mesocosms, respectively. This finding underscores the importance of vegetation selection for bioretention systems, yet it appears to deviate from the current state of research with respect to the type of vegetation associated with the greatest impact on infiltration.

There is a growing body of literature highlighting the positive impact of vegetation on infiltration, with the strength of the impact generally decreasing with the decreasing vegetation size. The strongest impact is associated with large woody species (trees), followed by small woody species (shrubs), tall herbaceous, and lastly small herbaceous plants (Techer and Berthier, 2023). Vegetation height was significantly different among the different mesocosms in this study with the control mesocosms having the shortest and the woody mesocosms having the tallest vegetation, suggesting that woody species should be associated with the highest infiltration rate if other factors are held constant. However, previous research also highlighted the role of thick-rooted plants in maintaining and enhancing infiltration capacity (Barrett et al., 2013; Le Coustumer et al., 2009). Based on the field observations, a particular plant type is thought to be responsible for the enhanced infiltration associated with the herbaceous mesocosms. Awned Sedge (*Carex atheroides*) displayed profuse growth and aggressive spreading behaviour in all the herbaceous cells, and its thick (up to 10 mm) roots were observed in abundance. Woody species used in this research generally have thicker roots but will take longer to reach mature size. It is possible that higher infiltration rates may be attained by woody mesocosms over a longer time period.

5.3.5. Impact of IP Ratio

Different from other design parameters, the IP ratio was not detected to have significant impact on infiltration rate, which indicates that applying double the volume of runoff and double the sediment loading curiously did not cause a significant decrease in the infiltration rates. However, the mean infiltration rates across the dataset were 779 and 566 mm/hr for IP 15 and 30, respectively. Even though the lower mean infiltration rate associated with mesocosms of the IP ratio of 30 was not significantly different from those of the IP of 15, it raises a potential concern over long-term implications of the increased sediment loading.

Understanding the particle size distribution of the incoming sediment in relation to the media helps to interpret the impacts of sediment loading, as physical clogging would only occur if the sediment was introducing smaller particles than those that make up the bioretention media. Figure 5.5 shows the particle size distribution of the sediment and the bioretention media used in this experiment, and the sediment consisted of mainly coarse particles, as the sizes of majority of particles were within the range of 0.3 to 2.3 mm. Coarse sediment particles are less likely to block the pores in the bioretention media (Le Coustumer et al., 2009), which may partially explain the absence of the significant effect of the IP ratio on the infiltration rate.

In addition to the increased sediment loading, the higher IP ratio could lead to increased compaction of the media due to increased hydraulic loading (Le Coustumer et al., 2012). The impacts of the hydraulic loading-induced compaction are typically visible during the initial stages of operation of bioretention systems (Kratky et al., 2017). Such impacts would manifest in changes in the bulk density of bioretention media. The bulk density measured in March of 2019 are presented in Figure 5.6. As shown in the figure, higher IP did not cause an increase in the bulk density, whereas in fact the median of the infiltration rate associated with the IP ratio of 30 was lower than that associated with the IP ratio of 15. This result further supports the absence of the significant effect of the IP ratio on the infiltration rate.

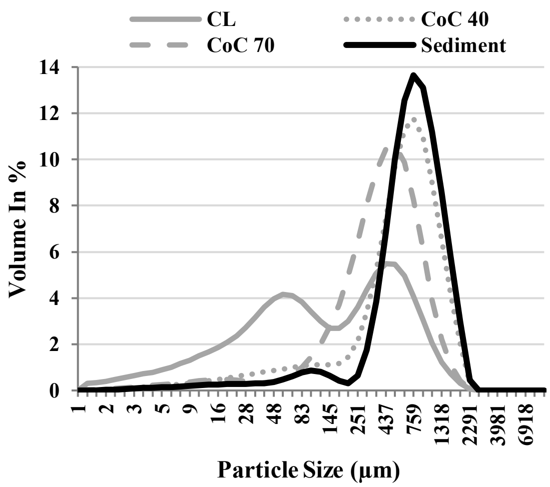


Figure 5.5. Particle size distribution of the street sweepings material used to simulate the typical sediment concentration of stormwater runoff and the three bioretention media (sample size of 3).

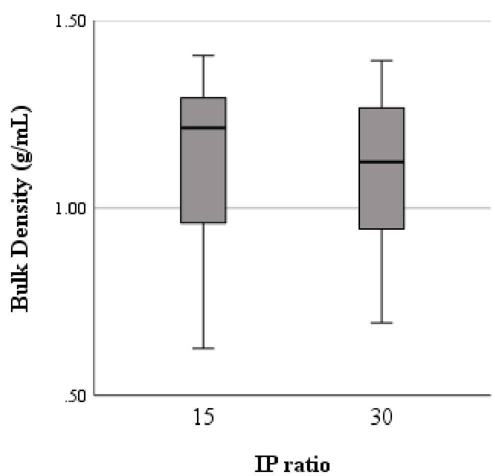


Figure 5.6. Bulk density vs. IP ratio. Black line inside the boxes represents the median and whiskers show 95% confidence intervals.

5.3.6. Inter-Mesocosm Infiltration

To gain a better understanding of the impacts of the design parameters including the media type, the vegetation type and the IP ratio on the infiltration rate, the temporal variability of the infiltration specific to the design parameters are shown in Figure 5.7. It appears that the infiltration rates tended to increase with the simulated event number and there were differences in the change of infiltration rates based on the media, vegetation, and IP ratios. More specifically, there was a consistent difference in the slopes of regression lines associated with the different IP ratios, namely, mesocosms of the IP ratio of 15 had a greater positive slope than those of the IP ratio of 30, suggesting that the mesocosms of the IP ratio of 30 were subject to a lesser increase in infiltration rate over time. The detailed description of the associated coefficients is provided in Table S5 (in Appendix). Among the three types of media, the CL media had the greatest variability in its infiltration response, but the mesocosms of the IP ratio of 30 still had a lower slope as compared with the mesocosms with the IP ratio of 15, although the difference was not significant for the CL mesocosms with woody vegetation. There was one combination of design factors, namely, IP ratio of 30, CoC 70, and turfgrass vegetation, that resulted in a negative slope or decreasing infiltration over time, albeit the relationship was not statistically significant. This outcome aligned with the field observations of increasingly extended inundation times during the simulated events. Turfgrass may be the least effective at maintaining infiltration capacity due to its shallow and thin roots. The CoC 70 media may also be more prone to clogging due to its high sand and low organic content, making it less likely to develop beneficial soil structure.

Based on the temporal variation in the infiltration rate associated with the IP ratio, increased sediment loading could pose a long-term risk to infiltration as irrespective of the media and vegetation types, a higher IP ratio was always found to result in a slower increase or even a decrease in the infiltration rate over the study period. Therefore, from the design perspective, the IP ratio of 15 may be a better recommendation given the successful performance across the mesocosm types as compared to the IP 30. If the IP ratio of 30 was used in the design, the pre-treatment is recommended to reduce the sediment loading to bioretention systems.

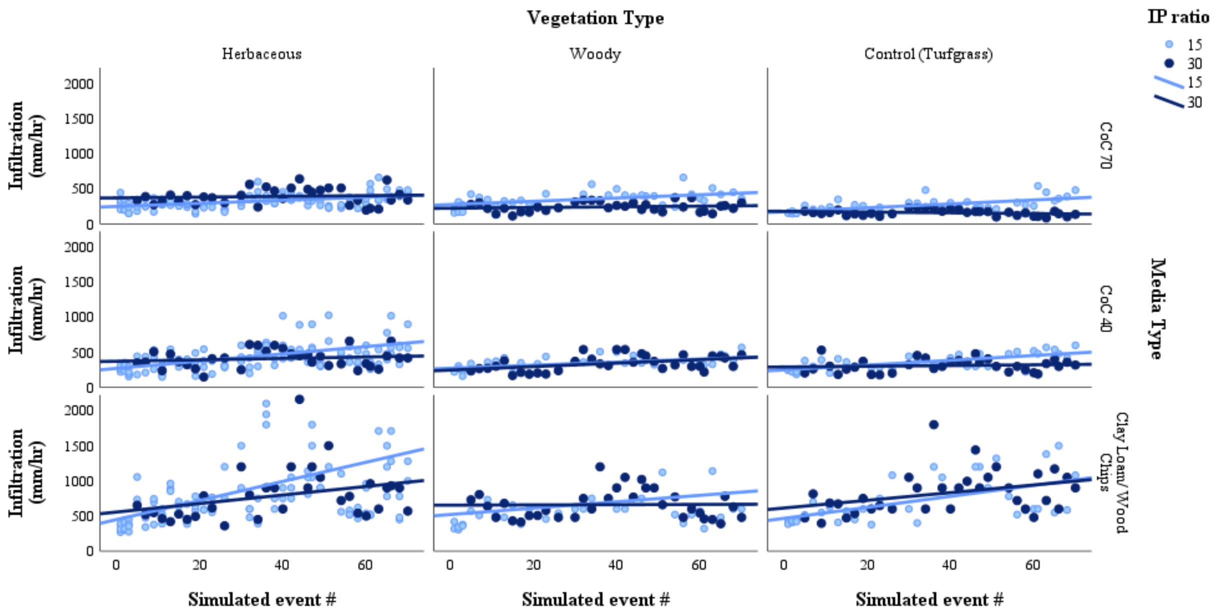


Figure 5.7. Temporal variation (along with the simulated event number) of the infiltration rates across design parameters. The solid lines are the linear regression lines.

Given that bioretention systems are living systems, apart from individual design parameters, the complex interactions between the design parameters would also affect the infiltration rate. To further analyze the impact of media, vegetation, and IP ratio as well as their interactions on the infiltration rate within each event, the factorial ANOVA analysis was employed. Table 5.3 shows the summary of the analysis results. The effect sizes indicate the proportion of variance of the infiltration rate that can be explained by the variance in each of the design variables and their interactions. Effect sizes of 0.2 are small, 0.5 are medium, and 0.8 are large (Strunk and Mwavita, 2020). Table 5.3 confirms the medium to large impacts of the individual design parameters, and also reveals the medium to large impacts of the interactions of the design parameters.

A significant impact of media on the infiltration rate was detected over 90% of all the events during the study period (66 out of 72 events). Based on the associated effect size, media type could explain about 89% of the variance in the infiltration rates. A significant effect of vegetation on the infiltration rate was found in about 50% of all events, and in particular there was a drop in significance in 2020 (Year 4) as the significant impact was identified in 30% of events. Overall, the vegetation type could explain about 59% of the variance of infiltration rate. Among the three design parameters, the IP ratio was found to have less significant impact on the infiltration rate, as its impact was identified in fewer events (29% of events). Whereas, the impact of the IP ratio appeared to increase, as the number events in which its significant impact was detected increased in 2020. These results along with the temporal variations of infiltration rate with the IP ratios (discussed previously) might call the considerations of potential risks of clogging and the need for continued long-term monitoring.

The significance of interaction effects varied across the types of interactions and years of the study period, but there was an overall decreasing significance of interactions over the years. Interestingly, the media-vegetation interaction had the highest effect size (0.48) among all the interactions, but it was the media-IP interaction which had the greatest number of significant events across the years. These results showcase the significance of design factor interactions on the bioretention performance. Further research is deemed required to understand the practical implications of such interactions, as their impacts are complex in nature.

Table 5.3. A summary of individual event analysis of infiltration using factorial ANOVA and three fixed factors of media, vegetation, and IP ratio. The data shows the effect size of the main effects and interactions as well as the number of events with a significant effect on the infiltration.

Parameter			Main Effects			Interactions			
			Media	Veg.	IP	Media x Veg	Media x IP	Veg x IP	Media x Veg x IP
Mean Effect Size (Partial Eta Squared)			0.89	0.59	0.33	0.48	0.40	0.31	0.45
Year	# of events	Model Violations*	Number of Significant Events						
1	3	0	3	0	n/a	1	n/a	n/a	n/a
2	25	1	24	14	6	1	8	5	5
3	24	0	24	16	5	5	7	3	4
4	20	5	15	6	10	2	4	2	1
Total	72	6	66	36	21	9	19	10	10

* Instances where irrespective of assumptions, the ANOVA analysis showed the proposed media-vegetation-IP model as not being significant in explaining the variance.

5.3.7. Association of infiltration rate with biological activity

As demonstrated previously, for most design combinations (vegetation type, media type, and IP ratio) the infiltrate rates did not decrease over the study period. This might imply that the clogging effect of sediments could be counteracted by biological activity in media and consequently soil structure formation. Given the complexity of interactions of the design parameters and processes associated with biological systems, it is challenging to estimate biological activity and its impact. This research employed a soil respiration method in an attempt to shed light on the differences in the biological processes associated with the various mesocosms and to make connections to the observed infiltration performance. Among the gases measured from the mesocosms, only CO_2 and O_2 had non-zero readings. Given that CO_2 can be correlated with root growth and microbial processes, it provides insights into the belowground processes within different mesocosms types. Therefore, CO_2 contents were used as the proxy of the biological activity herein.

Figure 5.8 shows the measured CO_2 content of the subsurface gases in both 2018 and 2019 across the different mesocosm types. It is worth mentioning that the Kruskal-Wallis test did not detect the significant difference in the medians of the measured CO_2 contents between 2018 and 2019. Whereas significant differences in CO_2 content were identified among different media types and among different vegetation types. Among the three types of media, the CL media had the highest CO_2 content, while the CoC 70 had the lowest CO_2 content. Having wood chips as part of the CL media provides a source of organic carbon, which could boost biological activity within the media. In addition, vegetation had a significant impact on the CO_2 content as well with control vegetation mesocosms having the highest CO_2 content and herbaceous mesocosms having the lowest CO_2 content. The differences in the CO_2 gas content among the media types align with the differences in the infiltration rates among the media types but the same was not observed for the effects of vegetation. The result that herbaceous vegetation had the lowest CO_2 content appeared to not support the notion of using CO_2 as a metric of biological activity. However, respiration is not as impacted by root diameter as it is by the specific root length (Borden et al., 2021), and root diameter is of greater relevance to the considerations of long-term infiltration capacity.

Reth et al. (2005) argued that there is a positive correlation between soil CO_2 efflux and root mass, but care should be taken when interpreting the results as soil CO_2 fluxes are quite sensitive to temperature and soil moisture. Figure 5.9 shows the CO_2 content as well as the media moisture content and media temperature measured on the days of CO_2 measurement. There were weak but significant relationships of the CO_2 content with the media temperature and moisture content, which might explain the differences in the measured CO_2 content among the different mesocosms. Among the mesocosms, the CL mesocosms had the highest moisture, but not the highest temperature when CO_2 content was measured. The turfgrass mesocosms, which were found to have the highest CO_2 content, had the same moisture content as woody mesocosms and the same temperature as herbaceous mesocosms. Consequently, the lack of a clear connection between the CO_2 content and the associated moisture and temperature points to a more complex underlying mechanism, which collectively could reflect the biological activity within the mesocosms. A more comprehensive analysis of temporal variability in media respiration is desired to shed light on the biological dynamics of bioretention systems and their impact on the infiltration capacity and consequently overall performance.

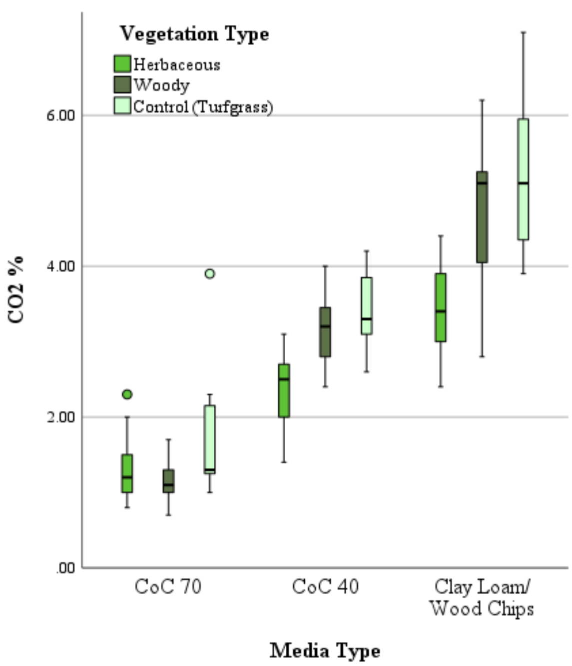


Figure 5.8. Percent of CO_2 as measured in the top 20 cm of bioretention media, error bars are 95% CI, circles are potential outliers outside the 1.5xIQR.

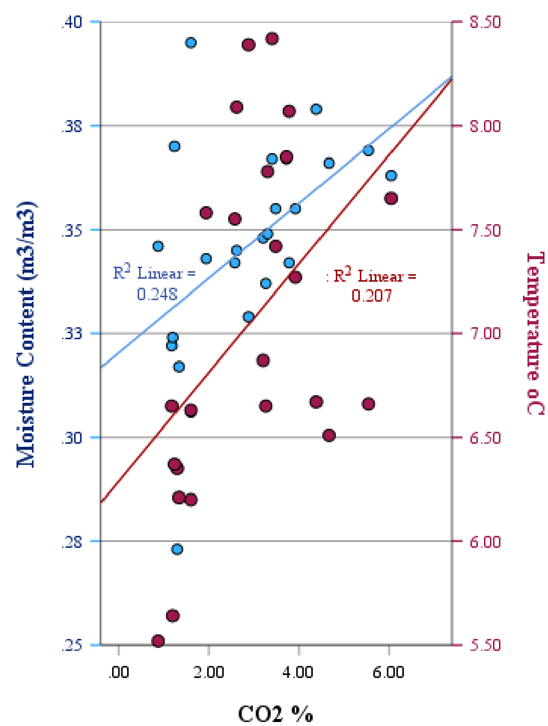


Figure 5.9. Percent of CO_2 in the soil gases as related to the media temperature and media moisture content.

5.4. Conclusions

This research examined the variation of infiltration rate and investigated the impacts of design parameters (including media, vegetation, IP ratio) and their interactions on infiltration rate of bioretention mesocosms using data collected in four years. Over the study period, irrespective of the mesocosm types, infiltration was observed to be not static as there was substantial variability in the infiltration rates. In particular, there was an overall increasing trend in the infiltration rates over time, which is the opposite of the conventional expectation of diminishing infiltration rate due to bioretention media clogging.

Among the design parameters, media and vegetation were demonstrated to have significant impacts on infiltration rates. Among the three types of media investigated, the CL media (mixed with wood chips) had the highest infiltration rates. This result might be of particular interest as the CL media would possibly offer unique benefits, such as the benefits of clay and silt associated with the structure formation and unique treatment opportunities. This finding highlights the need for an alternative approach to bioretention media specifications, especially as they relate to the specifics of texture and a limit on clay and silt content. However, a key outstanding consideration is the fate of wood chips within the CL media and the ultimate media structure and hydraulic capacity once the majority of wood chips disintegrate. Among the three types of vegetation investigated, herbaceous vegetation appeared to offer the greatest benefit in increasing and maintaining the infiltration rates, while turfgrass vegetation appeared to be the least effective at counter-acting the impacts of sediment accumulation and consequently media clogging. The duration of this study might not sufficient to observe the impacts of woody species at maturity, which may create additional benefits over a longer period. Overall, a vigorous and varied vegetation mix would offer the greatest functional benefit to maintaining the hydraulic capacity over time. Although the accelerated hydrologic loading did not cause a significant impact on the infiltration rates, there was some evidence of potential risk for diminishing infiltration associated with the impacts over a longer term. The sediments used in the study was largely coarse textured, which might pose a lower clogging risk with respect to physical occlusion of media pore spaces. The particle size distribution of inflow sediments can largely vary depending on catchment characteristics; thus, a more thorough analysis of the implications is needed. Similarly, the particle size distribution of inflow sediments may dictate the design of bioretention systems.

The ability to maintain infiltration rate is critical to the design and implementation of bioretention systems. Media texture has been the key consideration when considering the infiltration rate in the bioretention system design. The observed temporal evolution of infiltration rates as well as significant impacts of the design parameters (including their interactions) argue the inadequacy of the consideration of media texture only. Although this paper did not successfully link the variation of the infiltration rate to the biological activity and subsurface processes from the "living" aspect of the bioretention mesocosms, further research on in-depth analysis of the variability in respiration and the impact of environmental factors on the respiration is recommended.

Chapter 6: Conclusions and Recommendations

6.1. General Conclusions

This dissertation aimed to advance the understanding of the roles of media, vegetation, and hydrological loading on the hydrologic and water quality performance of bioretention systems. The results demonstrated a high degree of variability in the performance that were associated with the design parameters and naturally occurring environmental conditions. The results demonstrated the change in bioretention performance over time, which affirms the challenge of the design and implementation engineering living systems, such as bioretention systems. This research made the following major contributions, which are summarized for each chapter.

Chapter 2 provided a critical review of bioretention research and showcased the existing gaps in understanding with respect to media-vegetation interactions and changes in performance over time. This chapter highlights that bioretention systems should be considered as living systems as their performance depends on complex biological, chemical, and physical interactions which evolve over time. This chapter also provides a comprehensive assessment of the critical studies that not only shaped the existing body of bioretention knowledge, but also served as foundation for design standards and guidelines. A critical caveat of the existing knowledge is limited understanding of long-term processes and changes in bioretention performance over time. Generally, bioretention media is viewed as the most important design parameter that controls various aspects of the performance. However, multiple sources and emerging data challenge the importance of media given the role of biological processes, development of soil structure, and anticipated changes within bioretention systems over time.

Chapter 3 focused on investigating the hydrologic performance of the bioretention mesocosms with respect to bioretention design parameters, namely media, vegetation, and hydrologic loading (as IP ratio), as well as their temporal evolution and the impacts thereof. Overall, the results showed that the bioretention mesocosms provided limited hydrologic benefits with respect to water retention, where the storage capacity of bioretention systems was limited when subsurface exfiltration is eliminated from the water balance and retention becomes associated with the evapotranspiration demand. Thus, it may be that the true value of bioretention systems (especially for the cases when groundwater recharge is negligible) should not be dictated by hydrologic benefits (i.e., the water retention), but by water quality benefits, as well as the ancillary benefits that are unique to nature-based solutions. From the hydrological perspective, the results showed that bioretention mesocosms with dissimilar media had dissimilar water retention at the early stage of the investigation, but the differences appeared to diminish over the years. Moreover, differing from the effect of media, the effect of vegetation on water retention appeared to become more prominent over time, with larger woody vegetation retaining incrementally more stormwater runoff than herbaceous vegetation. These findings would suggest that for the design and implementation purposes, there is potential to achieve the desired level of service with less stringent tolerances with respect to media specification, and more consideration on the function of vegetation. The effect of IP ratio underscored the limited storage capacity of the mesocosms, as similar volumes were retained with low and high IP ratios, and the percent retention decreased proportionately to the increase in simulated runoff volume applied with the high IP ratio condition. As for the interactions, the greatest number of significant interactions was associated with media and vegetation, which aligns with the notion that hydrological performance of bioretention systems is impacted by both media and vegetation.

Chapter 4 highlighted significant leaching of dissolved nutrients and organics, which would be the likely outcome when using conventional bioretention media. This notion raises concerns over widespread implementation of such media given the associated risks to the receiving aquatic environments. Leaching of P was of particular concern as it did not decrease substantially over the years and the effluent concentrations could trigger eutrophic conditions downstream. In addition, the extractable P contents within the media were within the typical target range for bioretention systems. Consequently, it is paramount that bioretention system designs are amended to mitigate the leaching and potential downstream impacts. This chapter also highlighted the potential benefits of a novel media, composed of clay-loam and wood chips, which had the least leaching of the three media. Further research of the long-term impacts of wood chip decomposition are needed for a comprehensive assessment of the potential benefits and risks of a soil/wood chip bioretention media. This chapter also showed that vegetation had a significant effect on P leaching, especially with respect to woody vegetation. Vegetation effects on N dynamics were less pronounced and largely insignificant for the leaching of organics, which was one of the unique findings of this study. Substantial variability and significant changes in the removal of nutrients and organics over time were observed for the different mesocosms, which underscores further need for long-term performance data on these nature-based systems. Greater IP ratio introduces a dilution effect for nitrogen species and organics, but not phosphorus species, where additional volume of runoff appeared to extract additional phosphorus. As for the interactions, media x IP were the more significant for nitrogen and organics, whereas media x vegetation interactions were the more significant for phosphorus. Given that the initial leaching may be unavoidable, targeted management strategies are required to support future implementation of bioretention systems, where the receiving water bodies are protected from the impacts of the initial nutrient flush.

Chapter 5 examined the substantial variability in the infiltration rates across the simulated events and over the years. Most importantly, there was an overall increasing trend in the infiltration rates over time, which is the opposite of the conventional expectation of diminishing infiltration rate due to bioretention media clogging. In addition, the CL media had the highest infiltration rates, which means that the CL media offers unique potential for areas where sand materials may be limited and drought resiliency is prioritized. As per the previous chapters, the CL media offers unique benefits, such as the benefits of clay and silt associated with unique treatment opportunities, reduced leaching, and the general tendency for better soil structure formation. Among the three types of vegetation investigated, herbaceous vegetation appeared to offer the greatest benefit in increasing and maintaining the infiltration rates, which is aligned with the existing knowledge of thicker roots driving the long-term infiltration capacity as vigorous development of thick roots was observed in these mesocosms. The duration of this study might not sufficient to observe the impacts of woody species at maturity, which may create additional benefits over a longer period. Although the accelerated hydrologic loading did not cause a significant impact on the infiltration rates, there was some evidence of potential risk for diminishing infiltration associated with the impacts over a longer term. The sediments used in the study were largely coarse textured, which might pose a lower clogging risk with respect to physical occlusion of media pore spaces. The ability to maintain infiltration rate is critical to the design and implementation of bioretention systems. Media texture has been the key consideration when considering the infiltration rate in the bioretention system design. The observed temporal evolution of infiltration rates as well as significant impacts of the design parameters (including their interactions) argue the inadequacy of the consideration of media texture only. Although this chapter did not successfully link the variation of the infiltration rate to the biological activity and subsurface processes from the "living" aspect of the bioretention mesocosms, further research on in-depth analysis of the variability in respiration and the impact of environmental factors on the respiration is recommended.

6.2. Novel contributions

This dissertation enhanced the understanding of bioretention performance from hydrological and water quality performances perspectives and provided the much-needed insights into the long-term changes in bioretention performance. The findings of this research would be directly applicable to bioretention design and consequently promoting implementation of this nature-based solution. The specific novel contributions of this work include:

1) Highlighting the need for understanding and investigating media-vegetation interactions.
2) Revealing the changes in bioretention performance over time, especially as it relates to the role of bioretention media and vegetation, where the significance of media effects generally diminishes over time while the significance of vegetation effects increases over time.
3) Demonstrating the limited storage capacity of bioretention systems when subsurface exfiltration is eliminated from the water balance and providing an association with the evapotranspiration demand.
4) Showcasing the extensive leaching associated with conventional bioretention media and analysis of the associated parameters.
5) Investigating the temporal evolution of bioretention infiltration capacity and the associated influence of the design factors.
6) Developing an approach for analyzing temporal evolution of bioretention performance and design factor interactions using a combination of LMM and ANOVA methods.

7) Characterizing a novel bioretention media, which offers unique opportunities for widespread implementation of bioretention systems.

6.3. Limitations of this research

The findings in this research can apply to most bioretention systems, yet there were several key limitations that may influence the implications of the research findings. Given that this research was done on mesocosm systems, there will likely be some differences between the performance observed with the mesocosms and full-scale bioretention systems.

One of the most relevant limitations associated with the scale of the testing systems would be the susceptibility to preferential flow along the perimeter of the mesocosm cells, which could influence the infiltration rate, hydraulic retention rate, and associated outcomes. All feasible efforts were taken during the construction of the bioretention mesocosms to minimize the impacts of preferential edge flow, such as placement and compaction of bioretention media in lifts, yet the mesocosms may still have been susceptible to some preferential flow impacts.

Another potential limitation of this research was the lack of exposure to an extended period of drought, which may be experienced by full-scale bioretention systems. Extended periods of dry weather could have implications for vegetation growth, infiltration processes, soil structure, and water quality performance. A related limitation stems from the inability to control the effect of direct precipitation on the water balance in this research as the mesocosms were not enclosed with a canopy. Direct precipitation added variability to the dataset, which was accounted for but could not be controlled. Nevertheless, the simulated event regime was sufficiently robust to yield valuable insights into the performance of bioretention systems provided that the limitations are taken into account when considering widespread applicability of the results.

6.4. Recommendations for future research

In addition to the novel contributions of this research, this work identified the need for future research directions to better understand and predict functionality of bioretention performance. These include:

1) Further long-term studies with the focus on soil structure formation and the influence of root architecture and characteristics on bioretention performance. Destructive methods are recommended to shed light on subsurface processes and their relationships to bioretention performance.
2) A need to define the core bioretention functionality with respect to its hydrological benefits when decoupled from the subsurface exfiltration, given the limited retention observed in this study. In order to further support the water balance accounting, studies that focus on surface-subsurface interactions of full-scale bioretention systems are needed. In addition, side-by-side comparisons of lined and unlined systems are desired to facilitate understanding of the proportionate roles of ET and subsoil infiltration in water retention. When it comes to complex interactions, there is a need to quantify their impacts and to establish practical implications of such findings in order to continue evolving the practice.
3) Further research to develop strategies for leaching management, which may include media amendments and specialized bioretention designs as well as treatment train approach, i.e. re-use of bioretention effluent for irrigation purposes as a way of capturing excess nutrients and organics.
4) Qualitative and quantitative characterization of the functional balance between media pore clogging and macropore formation over time as it relates to media permeability. Being able to understand the parameters that enhance and reduce permeability and infiltration has

direct implications on being able to optimize the hydrological performance. More importantly, the implications on the water quality improvements or lack thereof need to be characterized as there is a concern around reduced retention times and media by-pass associated with macropore formation.

5) Media specification modifications recommended based on the results of this research given the diminishing significance of media selection for a variety of functional considerations. In addition, there is a need for performance metrics for alternative bioretention media, which may vary depending on whether the primary objectives are hydrological or treatment-focused.

Overall, a more interdisciplinary approach is needed in order to capitalize on the breadth of functions that are offered by bioretention systems, especially when attempting to utilize these systems in challenging climactic conditions. For example, when precipitation is scarce, the overall impact of bioretention systems might be greater than in the contexts of abundant precipitation, but there is an added challenge of keeping the vegetation alive. Identifying more balanced solutions that recognize the importance of media, plants, and their interactions will allow for a more effective application of bioretention systems.

References

Adhikari, R.A., Bal Krishna, K.C., Sarukkalige, R., 2016. Evaluation of phosphorus adsorption capacity of various filter materials from aqueous solution. Adsorpt. Sci. Technol. 34, 320-330.

Agren, G.I., Andersson, F.O., 2011. Plant production, Terrestrial Ecosystem Ecology, pp. 88-123.

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2012. Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. Water Air Soil Pollut. 223, 4253-4273.

Asghari, H.R., Chittleborough, D.J., Smith, F.A., Smith, S.E., 2005. Influence of arbuscular mycorrhizal (AM) symbiosis on phosphorus leaching through soil cores. Plant Soil. 275, 181-193.

Bais, H., Sherrier, J., 2015. Plant microbe interactions, Web.

Barrett, M.E., Limouzin, M., Lawler, D.F. 2013. Effects of Media and Plant Selection on Biofiltration Performance. Journal of Environmental Engineering 139, 462-470.

Bartens, J., Day, S.D., Harris, J.R., Wynn, T.M., Dove, J.E., 2009. Transpiration and root development of urban trees in structural soil stormwater reservoirs. Environ. Manage. 44, 646-657.

Barton, B., Peat, J. 2014. Medical Statistics : A Guide to SPSS, Data Analysis and Critical Appraisal. John Wiley & Sons, Incorporated, Somerset, UNITED KINGDOM.

Beaumont, R. 2012. Analysing repeated measures with Linear Mixed Models.

Berland, A., Shiflett, S.A., Shuster, W.D., Garmestani, A.S., Goddard, H.C., Herrmann, D.L., Hopton, M.E., 2017. The role of trees in urban stormwater management. Landsc. Urban Plan. 162, 167-177.

Beven, K., Germann, P., 1982. Macropores and Water Flow in Soils. Water Resour. Res. 18, 1311-1325.

Beven, K., Germann, P., 2013. Macropores and water flow in soils revisited. Water Resour. Res. 49, 3071-3092.

Blecken, G.-T., Zinger, Y., Deletić, A., Fletcher, T.D., Hedström, A., Viklander, M. 2010. Laboratory study on stormwater biofiltration: Nutrient and sediment removal in cold temperatures. Journal of Hydrology 394, 507-514.

Borden, K.A., Mafa-Attoye, T.G., Dunfield, K.E., Thevathasan, N.V., Gordon, A.M., Isaac, M.E. 2021. Root Functional Trait and Soil Microbial Coordination: Implications for Soil Respiration in Riparian Agroecosystems. Front Plant Sci 12, 681113.

Brady, N.C., Weil, R.R., 2008. The Nature and Properties of Soils. Pearson Education Inc., Upper Saddle River, New Jersey.

Bratieres, K., Fletcher, T.D., Deletic, A., Zinger, Y., 2008. Nutrient and sediment removal by stormwater biofilters: a large-scale design optimisation study. Water Res. 42, 3930-3940.

Brown, R.A., Hunt, W.F. 2011. Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. Journal of Irrigation and Drainage Engineering 137, 132-143.

Brown, S., Corfman, A., Mendrey, K., Kurtz, K., Grothkopp, F., 2016. Stormwater Bioretention Systems: Testing the Phosphorus Saturation Index and Compost Feedstocks as Predictive Tools for System Performance. J. Environ. Qual. 45, 98-106.

Bünemann, E., Frossard, E., Oberson, A., 2010. Phosphorus in action: Biological processes in soil phosphorus cycling. Soil Biology Series 26, Springer, New York.
Beaumont, R. (2012) Analysing repeated measures with Linear Mixed Models.

Caldwell, M.M., Heldmaier, G., Jackson, R.B., Lange, O.L., Mooney, H.A., Schulze, E.D., Sommer, U., 2005. Nutrient Acquisition by Plants - An Ecological Perspective. Springer Science+Business Media, Berlin, Germany.

Calgary, 2011. Water Balance Spreadsheet for the City of Calgary (WBSCC) User Manual, Calgary, Alberta.

Calgary 2016. Low Impact Development Guidelines Module 2 - Bioretention and Bioswales.

CCME, (2004) Canadian water quality guidelines for the protection of aquatic life: Phosphorus: Canadian Guidance Framework for the Management of Freshwater Systems., Canadian environmental quality guidelines. Canadian Council of Ministers of the Environment, Winnipeg.

City of Portland, (2016) City of Portland Stormwater Management Manual. Retrieved from City of Portland.

City of Seattle, (2017) Stormwater Manual. Retrieved from City of Seattle.

Chahal, M.K., Shi, Z., Flury, M., 2016. Nutrient leaching and copper speciation in compost-amended bioretention systems. Sci. Total Environ. 556, 302-309.

Chandrasena, G.I., Pham, T., Payne, E.G., Deletic, A., McCarthy, D.T., 2014. E.coli removal in laboratory scale stormwater biofilters: Influence of vegetation and submerged zone. J. Hydrol. 519, 814-822.

Chen, C., Zhao, T., Liu, R., Luo, L., 2017. Performance of five plant species in removal of nitrogen and phosphorus from an experimental phytoremediation system in the Ningxia irrigation area. Environ. Monit. Assess. 189, 497.

Chen, X., Peltier, E., Sturm, B.S., Young, C.B., 2013. Nitrogen removal and nitrifying and denitrifying bacteria quantification in a stormwater bioretention system. Water. Res. 47, 1691-1700.

Chen, Y., Chen, R., Liu, Z., Yu, X., Zheng, S., Yuan, S. 2021. Nitrogen process in stormwater bioretention: the impact of alternate drying and rewetting on nitrogen migration and transformation. Environ Sci Pollut Res Int 28, 43803-43814.

Chin, D.A. (2016) Designing Bioretention Areas for Stormwater Management. Environmental Processes 4, 1-13.

Cho, K.W., Yoon, M.H., Song, K.G., Ahn, K.H., 2011. The effects of antecedent dry days on the nitrogen removal in layered soil infiltration systems for storm run-off control. Environ. Technol. 32, 747-755.

Clark, S.E., Pitt, R., 2009. Storm-water filter media pollutant retention under aerobic versus anaerobic conditions. J. Environ. Eng. 135, 367-371.

Colombi, T., Torres, L.C., Walter, A., Keller, T., 2018. Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth - A vicious circle. Sci. Total Environ. 626, 1026-1035.

CSA, 2018. W200-18 Design of bioretention systems, Codes & Standards.

Dagenais, D., Brisson, J., Fletcher, T.D. 2018. The role of plants in bioretention systems; does the science underpin current guidance? Ecological Engineering 120, 532-545.

Davis, A.P. 2007. Field Performance of Bioretention: Water Quality. Environmental Engineering Science 24, 1048-1064.

Davis, A.P., 2008. Field performance of bioretention: Hydrology impacts. J. Hydrol. Eng. 13, 90-95.

Davis, A.P., Shokouhian, M., Sharma, H., Minami, C., 2006. Water quality improvement through bioretention media: Nitrogen and phosphorus removal. Water Environ. Res. 78, 284-293.

Davis, A.P., Traver, R.G., Hunt, W.F., Lee, R., Brown, R.A., Olszewski, J.M., 2011. Hydrologic performance of bioretention storm-water control measures. J. Hydrol. Eng. 17, 604-614.

Daynes, C.N., Field, D.J., Saleeba, J.A., Cole, M.A., McGee, P.A., 2013. Development and stabilisation of soil structure via interactions between organic matter, arbuscular mycorrhizal fungi and plant roots. Soil Biol. Biochem. 57, 683-694.

DeBusk, K.M., Wynn, T.M., 2011. Storm-Water bioretention for runoff quality and quantity mitigation. J. Environ. Eng. 137, 800-808.

Deeb, M., Groffman, P.M., Joyner, J.L., Lozefski, G., Paltseva, A., Lin, B., Mania, K., Cao, D.L., McLaughlin, J., Muth, T., Prithiviraj, B., Kerwin, J., Cheng, Z., 2018. Soil and microbial properties of green infrastructure stormwater management systems. Ecol. Eng. 125, 68-75.

Denich, C., Bradford, A., 2010. Estimation of evapotranspiration from bioretention areas using weighing lysimeters. J. Hydrol. Eng. 15, 522-530.

Deurer, M., Grinev, D., Young, I., Clothier, B.E., Muller, K., 2009. The impact of soil carbon management on soil macropore structure: a comparison of two apple orchard systems in New Zealand. Eur. J. Soil Sci. 60, 945-955.

Dietz, M.E., 2007. Low impact development practices: A review of current research and recommendations for future directions. Water Air Soil Pollut. 186, 351-363.

Dietz, M.E., 2016. Modified bioretention for enhanced nitrogen removal from agricultural runoff. J. Environ. Eng. 142(12), 06016007.

Ding, B., Rezanezhad, F., Gharedaghloo, B., Van Cappellen, P., Passeport, E., 2019. Bioretention cells under cold climate conditions: Effects of freezing and thawing on water infiltration, soil structure, and nutrient removal. Sci. Total Environ. 649, 749-759.

Ding, W., Qin, H., Yu, S., Yu, S.-L. (2022) The overall and phased nitrogen leaching from a field bioretention during rainfall runoff events. Ecological Engineering 179.

Dingman, S.L., 2008. Physical Hydrology, 2 ed. Waveland Press, Inc., Long Grove, IL, USA.

Duricki, D.A., Soleman, S., Moon, L.D. (2016) Analysis of longitudinal data from animals with missing values using SPSS. Nat Protoc 11, 1112-1129.

Eckart, K., McPhee, Z., Bolisetti, T. (2017) Performance and implementation of low impact development - A review. Sci Total Environ 607-608, 413-432.

Endreny, T., Burke, D.J., Burchhardt, K.M., Fabian, M.W., Kretzer, A.M., 2012. Bioretention column study of bacteria community response to salt-enriched artificial stormwater. J. Environ. Qual. 41, 1951-1959.

EPA, U.S. 2000. Low impact development (LID) a literature review. United States Environmental Protection Agency EPA-841-B-00-005, 1-35.

Erickson, A.J., Gulliver, J.S., Arnold, W.A., Brekke, C., Bredal, M., 2016. Abiotic Capture of Stormwater Nitrates with Granular Activated Carbon. Environ. Eng. Sci. 33, 354-363.

Erickson, A.J., Gulliver, J.S., Weiss, P.T., 2012. Capturing phosphates with iron enhanced sand filtration. Water Res. 46, 3032-3042.

Essington, M.E., 2004. Soil and water chemistry: An integrative approach. CRC Press, Boca Raton, Florida, USA.

Fassman-Beck, E., Wang, S., Simcock, R., Liu, R., 2015. Assessing the Effects of Bioretention's Engineered Media Composition and Compaction on Hydraulic Conductivity and Water Holding Capacity. J. Sustainable Water Built Environ. 1(4), 04015003.

Fowdar, H.S., Hatt, B.E., Breen, P., Cook, P.L., Deletic, A., 2015. Evaluation of sustainable electron donors for nitrate removal in different water media. Water Res. 85, 487-496.

Franzle, S., 2010. Chemical elements in plant and soil: Parameters controlling essentiality. Springer Science+Business Media, Zittau, Germany.

Fraser, A., Zhang, Y., Sakowski, E., Preheim, S., 2018. Dynamics and functional potential of stormwater microorganisms colonizing sand filters. Water 10, 1065.

Funai, J.T., Kupec, P., 2017. Exploring planting and filter media in stormwater bioremediating landscapes: A review. Water Air Soil Pollut. 228, 340.

Funai, J.T., Kupec, P., 2018. Evaluation of three soil blends to improve ornamental plant performance and maintain engineering metrics in bioremediating rain gardens. Water Air Soil Pollut. 230, 3.

Gautam, D.N., Greenway, M., 2014. Nutrient accumulation in five plant species grown in bioretention systems dosed with wastewater. Australas. J. Environ. Manag. 21, 453-462.

Gerke, H.H., Kuchenbuch, R.O. 2007. Root Effects on Soil Water and Hydraulic Properties. Biologia 62, 557-561.

Glaister, B.J., Fletcher, T.D., Cook, P.L., Hatt, B.E., 2014. Co-optimisation of phosphorus and nitrogen removal in stormwater biofilters: the role of filter media, vegetation and saturated zone. Water Sci. Technol. 69, 1961-1969.

Glaister, B.J., Fletcher, T.D., Cook, P.L.M., Hatt, B.E., 2017. Interactions between design, plant growth and the treatment performance of stormwater biofilters. Ecol. Eng. 105, 21-31.

Gobat, J.-M., Aragno, M., Matthey, W. 2004. The Living Soil. Science Publishers, Inc., Enfield, New Hampshire, USA.

Gold, A.C., Thompson, S.P., Piehler, M.F., 2019. Nitrogen cycling processes within stormwater control measures: A review and call for research. Water Res. 149, 578-587.

Gonzalez-Merchan, C., Barraud, S., Bedell, J.P., 2014. Influence of spontaneous vegetation in stormwater infiltration system clogging. Environ. Sci. Pollut. Res. Int. 21, 5419-5426.

Good, J.F., O'Sullivan, A.D., Wicke, D., Cochrane, T.A., 2012. Contaminant removal and hydraulic conductivity of laboratory rain garden systems for stormwater treatment. Water Sci. Technol. 65, 2154-2161.

Government of Alberta, 2013. Evaporation and Evapotranspiration in Alberta, in: Development, A.E.a.S.R. (Ed.). Alberta Environment and Sustainable Resource Development, Edmonton, p. 283.

Gregory, P.J., Nortcliff, S., 2013. Soil conditions and plant growth. Wiley-Blackwell, Hoboken, NJ, USA.

Guo, C., Li, J., Li, H., Liang, Z., 2016. Soil nitrogen speciation and the relationship with microbial biomass carbon in bioretention tanks. Water Air Soil Pollut. 227, 474.

Guppy, C.N., Menzies, N.W., Moody, P.W., Blamey, F.P.C., 2005. Competitive sorption reactions between phosphorus and organic matter in soil: a review. Soil Res. 43(2), 189-202.

Harmayani, K.D., Faisal Anwar, A.H., 2016. Adsorption kinetics and equilibrium study of nitrogen species onto radiata pine (Pinus radiata) sawdust. Water Sci. Technol. 74, 402-415.

Hart, T., Yeakley, J.A., Latimer, S., Maser, J., Rosenstiel, T., 2017. Root-enhanced infiltration in stormwater bioretention facilities in Portland, Oregon. Environmental Sciences and Resources Portland State University Portland, Oregon, USA, p. 143.

Hatfield, J.L., Sauer, T.J., 2011. Soil management - Buiding a stable base for agriculture. American Society of Agronomy , Madison, WI, USA.

Hathaway, J.M., Brown, R.A., Fu, J.S., Hunt, W.F. 2014. Bioretention Function under Climate Change Scenarios in North Carolina, USA. Journal of Hydrology 519, 503-511.

Hatt, B.E., Fletcher, T.D., Deletic, A., 2007. Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes. Water Sci. Technol. 56, 11-19.

Hatt, B.E., Fletcher, T.D., Deletic, A. 2009. Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. Journal of Hydrology 365, 310-321.

Hatt, B.E., Siriwardene, N., Deletic, A., Fletcher, T.D., 2006. Filter media for stormwater treatment and recycling: the influence of hydraulic properties of flow on pollutant removal. Water Sci. Technol. 54, 263-271.

Henderson, C., Greenway, M., Phillips, I., 2007. Removal of dissolved nitrogen, phosphorus and carbon from stormwater by biofiltration mesocosms. Water Sci. Technol. 55, 183-191.

Herrman, K.S., Scott, D.T., Lenters, J.D., Istanbulluoglu, E., 2012. Nutrient loss following phragmites australis removal in controlled soil mesocosms. Water Air Soil Pollut. 223, 3333-3344.
Hess, A., Wadzuk, B., Welker, A., 2017. Evapotranspiration in rain gardens using weighing lysimeters. J. Irrig. Drain. Eng. 143, 04017004.

Hess, A., Wadzuk, B., Welker, A. 2017. Evapotranspiration in Rain Gardens Using Weighing Lysimeters. Journal of Irrigation and Drainage Engineering 143.

Hoaglin, D.C., Iglewicz, B. 1987. Fine-Tuning Some Resistant Rules for Outlier Labeling. Journal of the American Statistical Association 82, 1147-1149.

Hong, J., Geronimo, F.K., Choi, H., Kim, L.H., 2018. Impacts of nonpoint source pollutants on microbial community in rain gardens. Chemosphere 209, 20-27.

Houdeshel, C.D., Hultine, K.R., Johnson, N.C., Pomeroy, C.A., 2015. Evaluation of three vegetation treatments in bioretention gardens in a semi-arid climate. Landscape Urban Plan. 135, 62-72.

Houdeshel, C.D., Pomeroy, C.A., Hultine, K.R., 2012. Bioretention design for xeric climates based on ecological principles. J. Am. Water Resour. As. 48, 1178-1190.

Hsieh, C.-H., Davis, A.P., 2005. Evaluation and optimization of bioretention media for treatment of urban storm water runoff. J. Environ. Eng, 131, 1521-1531.

Hunt, W.F., Davis, A.P., Traver, R.G. 2012. Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design. Journal of Environmental Engineering 138, 698-707.

Hunt, W.F., Jarrett, A.R., Smith, J.T., Sharkey, L.J., 2006a. Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. J. Irrig. Drain. Eng. 132, 600-608.

Hunt, W.F., Jarrett, A.R., Smith, J.T., Sharkey, L.J. 2006b. Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. Journal of Irrigation and Drainage Engineering 132, 600-608.

Hurley, S., Shrestha, P., Cording, A. 2017. Nutrient Leaching from Compost: Implications for Bioretention and Other Green Stormwater Infrastructure. Journal of Sustainable Water in the Built Environment 3.

Iqbal, H., Garcia-Perez, M., Flury, M., 2015. Effect of biochar on leaching of organic carbon, nitrogen, and phosphorus from compost in bioretention systems. Sci. Total Environ. 521-522, 37-45.

Jay, J.G., Brown, S.L., Kurtz, K., Grothkopp, F., 2017. Predictors of phosphorus leaching from bioretention soil media. J. Environ. Qual. 46, 1098-1105.

Jiang, C., Li, J., Hu, Y., Yao, Y., Li, H. 2022. Construction of water-soil-plant system for rainfall vertical connection in the concept of sponge city: A review. Journal of Hydrology 605.

Jiang, C., Li, J., Li, H., Li, Y. 2019. An improved approach to design bioretention system media. Ecological Engineering 136, 125-133.

Jiang, C., Li, J., Li, H., Li, Y., Chen, L., 2017. Field performance of bioretention systems for runoff quantity regulation and pollutant removal. Water Air Soil Pollut. 228, 468.

Jim, C.Y., Ng, Y.Y., 2018. Porosity of roadside soil as indicator of edaphic quality for tree planting. Ecol. Eng. 120, 364-374.

Johnson, J.P., Hunt, W.F., 2016. Evaluating the spatial distribution of pollutants and associated maintenance requirements in an 11 year-old bioretention cell in urban Charlotte, NC. J. Environ. Manage. 184, 363-370.

Johnston, M.R., Balster, N.J., Thompson, A.M. 2020. Vegetation Alters Soil Water Drainage and Retention of Replicate Rain Gardens. Water 12.

Jose, S., Gordon, A., 2008. Towards agroforestry design: An ecological approach. Springer Science+Business Media, Dordrecht, Netherlands.

Jotisankasa, A., Sirirattanachat, T. 2017. Effects of grass roots on soil-water retention curve and permeability function. Canadian Geotechnical Journal 54, 1612-1622.

Kandel, S., Vogel, J., Penn, C., Brown, G., 2017. Phosphorus retention by fly ash amended filter media in aged bioretention cells. Water 9, 746.

Kandra, H., McCarthy, D., Deletic, A., 2014. Assessment of the Impact of Stormwater Characteristics on Clogging in Stormwater Filters. Water Resour. Manage. 29, 1031-1048.

Kavehei, E., Shahrabi Farahani, B., Jenkins, G.A., Lemckert, C., Adame, M.F. 2021. Soil nitrogen accumulation, denitrification potential, and carbon source tracing in bioretention basins. Water Res 188, 116511.

Khan, U.T., Valeo, C., Chu, A., van Duin, B. 2012. Bioretention cell efficacy in cold climates: Part 1 — hydrologic performance. Canadian Journal of Civil Engineering 39, 1210-1221.

Khorsha, G., Davis, A.P., 2017. Characterizing clinoptilolite zeolite and hydroaluminosilicate aggregates for ammonium removal from stormwater runoff. J. Environ. Eng. 143(2), 04016082.

Kim, H., Choi, J.-W., Kim, T.-H., Park, J.-S., An, B., 2018. Effect of TSS removal from stormwater by mixed media column on T-N, T-P, and organic material removal. Water 10, 1069.

Kim, H., Seagren, E.A., Davis, A.P., 2003. Engineered bioretention for removal of nitrate from stormwater runoff. Water Environ. Res. 75, 355-367.

Komlos, J., Traver, R.G., 2012. Long-term orthophosphate removal in a field-scale storm-water bioinfiltration rain garden. J. Environ. Eng. 138, 991-998.

Kratky, H., Li, Z., Chen, Y., Wang, C., Li, X., Yu, T. 2017. A critical literature review of bioretention research for stormwater management in cold climate and future research recommendations. Frontiers of Environmental Science & Engineering 11.

Kubicek, C.P., Druzhinina, I.S., Esser, K., 2007. Environmental and microbial relationships. Springer Science+Business Media, Berlin Heidelberg.

Lange, K., Osterlund, H., Viklander, M., Blecken, G.T. 2020. Metal speciation in stormwater bioretention: Removal of particulate, colloidal and truly dissolved metals. Sci Total Environ 724, 138121.

Le Coustumer, S., Fletcher, T.D., Deletic, A., Barraud, S., 2007. Hydraulic performance of biofilters for stormwater management: first lessons from both laboratory and field studies. Water Sci. Technol. 56, 93-100.

Le Coustumer, S., Fletcher, T.D., Deletic, A., Barraud, S., Lewis, J.F., 2009. Hydraulic performance of biofilter systems for stormwater management: Influences of design and operation. J. Hydrol. 376, 16-23.

Le Coustumer, S., Fletcher, T.D., Deletic, A., Barraud, S., Poelsma, P., 2012. The influence of design parameters on clogging of stormwater biofilters: a large-scale column study. Water Res. 46, 6743-6752.

LeFevre, G.H., Paus, K.H., Natarajan, P., Gulliver, J.S., Novak, P.J., Hozalski, R.M. (2015) Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. Journal of Environmental Engineering 141.

Leung, A.K., Garg, A., Ng, C.W.W. 2015. Effects of Plant Roots on Soil-Water Retention and Induced Suction in Vegetated Soil. Engineering Geology 193, 183-197.

Lewellyn, C., Wadzuk, B., Smith, V., Traver, R.G., Vacca, K., 2018. Mitigating risk and increasing resilience through adaptive green infrastructure. ProQuest Dissertations and Theses.

Li, C., Peng, C., Chiang, P.-C., Cai, Y., Wang, X., Yang, Z. 2019. Mechanisms and applications of green infrastructure practices for stormwater control: A review. Journal of Hydrology 568, 626-637.

Li, H., Davis, A.P., 2009. Water quality improvement through reductions of pollutant loads using bioretention. J. Environ. Eng. 135, 567-576.

Li, H., Sharkey, L.J., Hunt, W.F., Davis, A.P. 2009. Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland. Journal of Hydrologic Engineering 14, 407-415.

Li, J., Davis, A.P., 2016. A unified look at phosphorus treatment using bioretention. Water Res. 90, 141-155.

Li, J., Jiang, C., Lei, T., Li, Y., 2016. Experimental study and simulation of water quality purification of urban surface runoff using non-vegetated bioswales. Ecol. Eng. 95, 706-713.

Li, J., Li, L., Dong, W., Li, H., 2018. Purification effects of amended bioretention columns on phosphorus in urban rainfall runoff. Water Sci. Technol. 78, 1937-1945.

Li, L., Davis, A.P., 2014. Urban stormwater runoff nitrogen composition and fate in bioretention systems. Environ. Sci. Technol. 48, 3403-3410.

Liu, J., Davis, A.P., 2014. Phosphorus speciation and treatment using enhanced phosphorus removal bioretention. Environ. Sci. Technol. 48, 607-614.

Liu, J., Sample, D., Bell, C., Guan, Y., 2014a. Review and research needs of bioretention used for the treatment of urban stormwater. Water 6, 1069-1099.

Liu, J., Sample, D.J., Owen, J.S., Li, J., Evanylo, G., 2014b. Assessment of selected bioretention blends for nutrient retention using mesocosm experiments. J. Environ. Qual. 43, 1754-1763.

Liu, L., Wang, F., Xu, S., Sun, W., Wang, Y., Ji, M. 2021a. Woodchips bioretention column for stormwater treatment: Nitrogen removal performance, carbon source and microbial community analysis. Chemosphere 285, 131519.

Liu, R., Fassman-Beck, E., 2017. Hydrologic response of engineered media in living roofs and bioretention to large rainfalls: experiments and modeling. Hydrol. Process. 31, 556-572.

Liu, R., Fassman-Beck, E., 2018. Pore Structure and Unsaturated Hydraulic Conductivity of Engineered Media for Living Roofs and Bioretention Based on Water Retention Data. J. Hydrol. Eng. 23, 04017065.

Liu, Y., Engel, B.A., Flanagan, D.C., Gitau, M.W., McMillan, S.K., Chaubey, I., 2017. A review on effectiveness of best management practices in improving hydrology and water quality: Needs and opportunities. Sci. Total Environ. 601-602, 580-593.

Liu, Y., Goor, J., Robinson, C.E. 2021b. Behaviour of soluble reactive phosphorus within field-scale bioretention systems. Journal of Hydrology 601.

Logsdon, S., 2017. Nutrient leaching when soil is part of plant growth media. Water 9, 501.

Logsdon, S., Berli, M., Horn, R., 2013. Quantifying and modeling soil structure dynamics. Soil Science Society of America, Inc., Madison, WI, USA.

Locascio, J.J., Atri, A. (2011) An Overview of Longitudinal Data Analysis Methods for Neurological Research. Dementia and Geriatric Cognitive Disorders Extra 1.1, 330-357.

Lucas, W.C., Greenway, M., 2008. Nutrient retention in vegetated and nonvegetated bioretention mesocosms. J. Irrig. Drain. Eng. 134, 613-623.

Lucas, W.C., Greenway, M., 2011. Phosphorus retention by bioretention mesocosms using media formulated for phosphorus sorption: Response to accelerated loads. J. Irrig. Drain. Eng. 137, 144-153.

Lucke, T., Dierkes, C., Boogaard, F., 2017. Investigation into the long-term stormwater pollution removal efficiency of bioretention systems. Water Sci. Technol. 76, 2133-2139.

Lukac, M., Godbold, D.L., 2011. Soil ecology in northern forests. Cambridge University Press, Cambridge, UK.

Lynn, T.J., Yeh, D.H., Ergas, S.J., 2015. Performance of denitrifying stormwater biofilters under intermittent conditions. Environ. Eng. Sci. 32, 796-805.

Mangangka, I.R., Liu, A., Egodawatta, P., Goonetilleke, A., 2015. Performance characterisation of a stormwater treatment bioretention basin. J. Environ. Manage. 150, 173-178.

Margesin, R., Schinner, F. 2005. Manual of Soil Analysis: Monitoring and Assessing Soil Bioremediation. Springer.

McNett, J.K., Hunt, W.F., Davis, A.P. 2011. Influent Pollutant Concentrations as Predictors of Effluent Pollutant Concentrations for Mid-Atlantic Bioretention. Journal of Environmental Engineering 137, 790-799.

McPhillips, L., Goodale, C., Walter, M.T., 2018. Nutrient leaching and greenhouse gas emissions in grassed detention and bioretention stormwater basins. J. Sustainable Water Built Environ. 4(1), 04017014.

Mei, Y., Gao, L., Zhou, H., Wei, K.H., Cui, N.Q., Chang, C.C., 2018. Ranking media for multi-pollutant removal efficiency in bioretention. Water Sci. Technol. 77, 2023-2035.

Mei, Y., Yang, X.-H., Guo, Y.-N., He, J., Jiang, R., Li, Y.-Q., Li, J.-Q., 2012. Thermodynamic and kinetics studies of the adsorption of phosphorus by bioretention media. Therm. Sci. 16, 1506-1509.

Meyers, L.S., Gamst, G.C., Guarino, A.J. 2013. Performing Data Analysis Using IBM SPSS. John Wiley & Sons, Incorporated, ProQuest Ebook Central, Web.

Mitchell Ayers, E., Kangas, P., 2018. Soil layer development and biota in bioretention. Water 10, 1587.

Mitra, G.N., 2015. Regulation of nutrient uptake by plants: A biochemical and molecular approach. Springer Science+Business Media, New Delhi, India.

Moene, A.F., van Dam, J.C., 2014. Transport in the atmosphere-vegetation-soil continuum. Cambridge University Press, New York, NY, USA.

Moorman, T.B., Parkin, T.B., Kaspar, T.C., Jaynes, D.B. 2010. Denitrification Activity, Wood loss, and N2O Emissions over 9 Years from A Wood Chip Bioreactor. Ecological Engineering 36, 1567-1574.

Morse, N., Payne, E., Henry, R., Hatt, B., Chandrasena, G., Shapleigh, J., Cook, P., Coutts, S., Hathaway, J., Walter, M.T., McCarthy, D., 2018. Plant-microbe interactions drive denitrification rates, dissolved nitrogen removal, and the abundance of denitrification genes in stormwater control measures. Environ. Sci. Technol. 52, 9320-9329.

Muerdter, C.P., Wong, C.K., LeFevre, G.H., 2018. Emerging investigator series: the role of vegetation in bioretention for stormwater treatment in the built environment: pollutant removal, hydrologic function, and ancillary benefits. Environ. Sci.: Water Res.Technol. 4, 592-612.

Natarajan, P., Davis, A.P. 2015. Hydrologic Performance of a Transitioned Infiltration Basin Managing Highway Runoff. Journal of Sustainable Water in the Built Environment 1.

Nguyen, P.M., De Pue, J., Le, K.V., Cornelis, W., 2015. Impact of regression methods on improved effects of soil structure on soil water retention estimates. J. Hydrol. 525, 598-606.

Nissen, K.A., Borst, M., Fassman-Beck, E. 2020. Bioretention Planter Performance Measured by Lag and Capture. Hydrological Processes 34, 5176-5184.

Nobel, P.S., 2009. Physicochemical and environmental plant physiology. Academic Press Elsevier, Oxford, UK.

Nobel, P.S. (2009) Physicochemical and Environmental Plant Physiology. Academic Press Elsevier, Oxford, UK.

Nocco, M.A., Rouse, S.E., Balster, N.J., 2016. Vegetation type alters water and nitrogen budgets in a controlled, replicated experiment on residential-sized rain gardens planted with prairie, shrub, and turfgrass. Urban Ecosyst. 19, 1665-1691.

Norton, R.A., Harrison, J.A., Kent Keller, C., Moffett, K.B., 2017. Effects of storm size and frequency on nitrogen retention, denitrification, and N2O production in bioretention swale mesocosms. Biogeochemistry 134, 353-370.

O'Reilly, A.M., Wanielista, M.P., Chang, N.B., Xuan, Z., Harris, W.G., 2012. Nutrient removal using biosorption activated media: preliminary biogeochemical assessment of an innovative stormwater infiltration basin. Sci. Total Environ. 432, 227-242.

Parmar, N., Singh, A., 2014. Geomicrobiology and biogeochemistry. Springer Science+Business Media.

Passeport, E., Hunt, W.F., Line, D.E., Smith, R.A., Brown, R.A. 2009. Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution. Journal of Irrigation and Drainage Engineering 135, 505-510.

Paus, K.H., Morgan, J., Gulliver, J.S., Hozalski, R.M., 2014. Effects of bioretention media compost volume fraction on toxic metals removal, hydraulic conductivity, and phosphorous release. J. Environ. Eng. 140(10), 04014033.

Payne, E.G., Pham, T., Cook, P.L., Fletcher, T.D., Hatt, B.E., Deletic, A., 2014a. Biofilter design for effective nitrogen removal from stormwater - influence of plant species, inflow hydrology and use of a saturated zone. Water Sci. Technol. 69, 1312-1319.

Payne, E.G.I., Fletcher, T.D., Cook, P.L.M., Deletic, A., Hatt, B.E., 2014b. Processes and drivers of nitrogen removal in stormwater biofiltration. Crit. Rev. Environ. Sci. Technol. 44, 796-846.

Payne, E.G.I., Pham, T., Deletic, A., Hatt, B.E., Cook, P.L.M., Fletcher, T.D., 2018. Which species? A decision-support tool to guide plant selection in stormwater biofilters. Adv. Water Resour. 113, 86-99.

Peterson, I.J., Igielski, S., Davis, A.P., 2015. Enhanced denitrification in bioretention using woodchips as an organic carbon source. J. Sustain. Water Built Environ. 1(4), 04015004.

Poor, C., Balmes, C., Freudenthaler, M., Martinez, A., 2018. Role of mycelium in bioretention systems: Evaluation of nutrient and metal retention in mycorrhizae-inoculated mesocosms. J. Environ. Eng. 144(6), 04018034.

Rakshit, A., Singh, H.B., Sen, A., 2015. Nutrient use efficiency from basics to advances. Springer Science+Business Media, New Delhi, India.

Read, J., Fletcher, T.D., Wevill, T., Deletic, A., 2009. Plant traits that enhance pollutant removal from stormwater in biofiltration systems. Int. J. Phytoremediat. 12, 34-53.

Read, J., Wevill, T., Fletcher, T., Deletic, A., 2008. Variation among plant species in pollutant removal from stormwater in biofiltration systems. Water Res. 42, 893-902.

Reth, S., Reichstein, M., Falge, E. 2005. The effect of soil water content, soil temperature, soil pH-value and the root mass on soil CO2 efflux – A modified model. Plant and Soil 268, 21-33.

Riffat, R., Husnain, T. 2022. Fundamentals of Wastewater Treatment and Engineering. CRC Press, Milton.

Ritz, K., Young, I., 2011. The architecture and biology of soils - Life in inner space. CAB International, Cambridge, MA, USA.

Roy-Poirier, A., Champagne, P., Filion, Y. 2010a. Bioretention processes for phosphorus pollution control. Environmental Reviews 18, 159-173.

Roy-Poirier, A., Champagne, P., Filion, Y., 2010b. Review of bioretention system research and design: Past, present, and future. J. Environ. Eng. 136, 878-889.

Rycewicz-Borecki, M., McLean, J.E., Dupont, R.R., 2017. Nitrogen and phosphorus mass balance, retention and uptake in six plant species grown in stormwater bioretention microcosms. Ecol. Eng. 99, 409-416.

Sah, R.N., Mikkelsen, D.S., 1986. Effects of temperature and prior flooding on intensity and sorption of phosphorus in soil. Plant Soil 95, 163-171.

Salkind, N.J. 2010. Encyclopedia of Research Design. Thousand Oaks: SAGE Publications. Web.

Sapdhare, H., Myers, B., Beecham, S., Brien, C., 2018. Performance of a kerb side inlet to irrigate street trees and to improve road runoff water quality: a comparison of four media types. Environ. Sci. Pollut. Res. Int. doi: 10.1007/s11356-018-3083-y.

Segismundo, E., Kim, L.-H., Jeong, S.-M., Lee, B.-S., 2017. A laboratory study on the filtration and clogging of the sand-bottom ash mixture for stormwater infiltration filtermedia. Water 9, 32.

Selbig, W.R., Balster, N.J., 2010.Evaluation of turf-grass and prairie-vegetated rain gardens in a clay and sand soil, Madison, Wisconsin, Water Years 2004–08. City of Madison and Wisconsin Department of Natural Resources, U.S. Geological Survey, Reston, Virginia.

Shrestha, P., Hurley, S.E., Wemple, B.C., 2018. Effects of different soil media, vegetation, and hydrologic treatments on nutrient and sediment removal in roadside bioretention systems. Ecol. Eng. 112, 116-131.

Skorobogatov, A., He, J., Chu, A., Valeo, C., van Duin, B. 2020. The impact of media, plants and their interactions on bioretention performance: A review. Sci Total Environ 715, 136918.

Soberg, L.C., Al-Rubaei, A.M., Viklander, M., Blecken, G.T. 2020. Phosphorus and TSS Removal by Stormwater Bioretention: Effects of Temperature, Salt, and a Submerged Zone and Their Interactions. Water, Air, and Soil Pollution 231, 270.

Sparks, D.L., 2003.Environmental soil chemistry. Academic Press, San Diego, CA, USA.

Spraakman, S., Drake, J.A.P. 2021. Hydrologic and soil properties of mature bioretention cells in Ontario, Canada. Water Sci Technol 84, 3541-3560.

Stander, E.K., Borst, M., 2010. Hydraulic test of a bioretention media carbon amendment. J. Hydrol. Eng. 15, 531-536.

Strunk, K.K., Mwavita, M. 2020. Design and analysis in educational research ANOVA designs in SPSS®. Routledge, Milton.

Subramaniam, D., Mather, P., Russell, S., Rajapakse, J., 2016. Dynamics of nitrate-nitrogen removal in experimental stormwater biofilters under intermittent wetting and drying. J. Environ. Eng. 142(3), 04015090.

Subramaniam, D.N., Logeswaran, T., Tharshikka, V., Nilakshan, B., 2018. Dynamics of clay particles in non-vegetated stormwater biofilters. Water Air Soil Pollut. 229, 302.

Subramaniam, D.N., Mather, P.B., 2016. Preliminary stabilisation of stormwater biofilters and loss of filter material. Water Sci. Technol. 74, 787-795.

Sun, Y., Zhang, D., Wang, Z.-W., 2017. The potential of using biological nitrogen removal technique for stormwater treatment. Ecol. Eng. 106, 482-495.

Szota, C., McCarthy, M.J., Sanders, G.J., Farrell, C., Fletcher, T.D., Arndt, S.K., Livesley, S.J., 2018. Tree water-use strategies to improve stormwater retention performance of biofiltration systems. Water Res. 144, 285-295.

Tahir, S., Marschner, P. 2017. Clay Addition to Sandy Soil Reduces Nutrient Leaching—Effect of Clay Concentration and Ped Size. Communications in Soil Science and Plant Analysis 48, 1813-1821.

Tang, N.-y., Li, T., 2016. Nitrogen removal by three types of bioretention columns under wetting and drying regimes. J. Cent. South Univ. 23, 324-332.

Techer, D., Berthier, E. 2023. Supporting evidences for vegetation-enhanced stormwater infiltration in bioretention systems: a comprehensive review. Environ Sci Pollut Res Int.

Tedoldi, D., Chebbo, G., Pierlot, D., Kovacs, Y., Gromaire, M.C., 2016. Impact of runoff infiltration on contaminant accumulation and transport in the soil/filter media of sustainable urban drainage systems: A literature review. Sci. Total Environ. 569-570, 904-926.

Tian, J., Miller, V., Chiu, P.C., Maresca, J.A., Guo, M., Imhoff, P.T., 2016. Nutrient release and ammonium sorption by poultry litter and wood biochars in stormwater treatment. Sci. Total Environ. 553, 596-606.

Timlin, D., Ahuja, L.R., 2013. Enhancing understanding and quantification of soil-root growth interactions. American Society of Agronomy, Inc., Madison, WI, USA.

Traver, R.G., Ebrahimian, A., 2017. Dynamic design of green stormwater infrastructure. Front. Environ. Sci. Eng. 11(4), 15.

Trowsdale, S.A., Simcock, R., 2011. Urban stormwater treatment using bioretention. J. Hydrol. 397, 167-174.

Turk, R.P., Kraus, H.T., Hunt, W.F., Carmen, N.B., Bilderback, T.E., 2017. Nutrient sequestration by vegetation in bioretention cells receiving high nutrient loads. J. Environ. Eng. 143(2), 06016009.

Underwood, A.J. 1997. Experiments in Ecology. Cambridge University Press, Cambridge, UK.

van Kessel, C., Clough, T., van Groenigen, J.W. 2009. Dissolved organic nitrogen: an overlooked pathway of nitrogen loss from agricultural systems? J Environ Qual 38, 393-401.

van der Valk, A.G., Bliss, L.C. 1971. Hydrarch Succession and Net Primary Production of Oxbow Lakes in Central Alberta. Canadian Journal of Botany 49, 1177-1199.

Vijayaraghavan, K., Biswal, B.K., Adam, M.G., Soh, S.H., Tsen-Tieng, D.L., Davis, A.P., Chew, S.H., Tan, P.Y., Babovic, V., Balasubramanian, R. 2021. Bioretention systems for stormwater management: recent advances and future prospects. Journal of Environmental Management 292, 112766.

Virahsawmy, H.K., Stewardson, M.J., Vietz, G., Fletcher, T.D., 2014. Factors that affect the hydraulic performance of raingardens: implications for design and maintenance. Water Sci. Technol. 69, 982-988.

Wadzuk, B.M., Hickman, J.M., Traver, R.G. 2015. Understanding the Role of Evapotranspiration in Bioretention: Mesocosm Study. Journal of Sustainable Water in the Built Environment 1, 04014002.

Waldrop, M.P., Holloway, J.M., Smith, D.B., Goldhaber, M.B., Drenovsky, R.E., Scow, K.M., Dick, R., Howard, D., Wylie, B., Grace, J.B., 2017. The interacting roles of climate, soils, and plant production on soil microbial communities at a continental scale. Ecology 98, 1957-1967.

Waller, L.J., Evanylo, G.K., Krometis, L.H., Strickland, M.S., Wynn-Thompson, T., Badgley, B.D., 2018. Engineered and environmental controls of microbial denitrification in established bioretention cells. Environ. Sci. Technol. 52, 5358-5366.

Wan, Z., Li, T., Liu, Y., 2018. Effective nitrogen removal during different periods of a field-scale bioretention system. Environ. Sci. Pollut. Res. Int. 25, 17855-17861.

Wan, Z., Li, T., Shi, Z., 2017. A layered bioretention system for inhibiting nitrate and organic matters leaching. Ecol. Eng. 107, 233-238.

Wang, C., Wang, F., Qin, H., Zeng, X., Li, X., Yu, S.-L., 2018a. Effect of saturated zone on nitrogen removal processes in stormwater bioretention systems. Water 10(2), 162.

Wang, J., Zhao, Y., Yang, L., Tu, N., Xi, G., Fang, X., 2017a. Removal of heavy metals from urban stormwater runoff using bioretention media mix. Water 9(11), 854.

Wang, M., Zhang, D., Li, Y., Hou, Q., Yu, Y., Qi, J., Fu, W., Dong, J., Cheng, Y., 2018b. Effect of a submerged zone and carbon source on nutrient and metal removal for stormwater by bioretention cells. Water 10, 1629.

Wang, S., Lin, X., Yu, H., Wang, Z., Xia, H., An, J., Fan, G., 2017b. Nitrogen removal from urban stormwater runoff by stepped bioretention systems. Ecol. Eng. 106, 340-348.

Weiss, D.J. 2005. Analysis of Variance and Functional Measurement: A Practical Guide. Oxford University Press, Incorporated.

Wen, J., Li, J.-s., Li, Y.-F., 2016. Wetting patterns and bacterial distributions in different soils from a surface point source applying effluents with varying Escherichia coli concentrations. J. Integr. Agric. 15, 1625-1637.

West, B.T. 2009. Analyzing Longitudinal Data With the Linear Mixed Models Procedure in SPSS. Evaluation & ther Health Professions 32, 207-228.

Willard, L.L., Wynn-Thompson, T., Krometis, L.H., Neher, T.P., Badgley, B.D., 2017. Does it pay to be mature? Evaluation of bioretention cell performance seven years postconstruction. J. Environ. Eng. 143(9), 04017041.

William, R., Gardoni, P., Stillwell, A.S. 2019. Reliability-Based Approach to Investigating Long-Term Clogging in Green Stormwater Infrastructure. Journal of Sustainable Water in the Built Environment 5.

Winfrey, B.K., Hatt, B.E., Ambrose, R.F., 2017. Arbuscular mycorrhizal fungi in Australian stormwater biofilters. Ecol. Eng. 102, 483-489.

Xia, J., Wang, H., Stanford, R.L., Pan, G., Yu, S.L., 2017. Hydrologic and water quality performance of a laboratory scale bioretention unit. Frontiers Environ. Sci. Eng. 12(1), 14.

Yan, W.M., Zhang, G. 2015. Soil-Water Characteristics of Compacted Sandy and Cemented Soils with and without Vegetation. Canadian Geotechnical Journal 52, 1331-1344.

Yergeau, S.E., Obropta, C.C. 2013. Preliminary Field Evaluation of Soil Compaction in Rain Gardens. Journal of Environmental Engineering 139, 1233-1236.

Zhang, K., Chui, T.F.M., 2019. Linking hydrological and bioecological benefits of green infrastructures across spatial scales - A literature review. Sci. Total Environ. 646, 1219-1231.

Zhang, B., Li, J., Li, Y., Li, H., 2018. Adsorption characteristics of several bioretention-modified fillers for phosphorus. Water 10(7), 831.

Zhang, S., Guo, Y. 2013. Stormwater Capture Efficiency of Bioretention Systems. Water Resources Management 28, 149-168.

Zinger, Y., Blecken, G.-T., Fletcher, T.D., Viklander, M., Deletić, A., 2013. Optimising nitrogen removal in existing stormwater biofilters: Benefits and tradeoffs of a retrofitted saturated zone. Ecol. Eng. 51, 75-82.

Appendix

Table S1. Plant species.

Vegetation type	Original # of plants and species	
Control	64 Kentucky Bluegrass – *Poa pratensis*	
Herbaceous	64 plants in total, 32 grasses and 32 forbs, 8 different species of each	
	Grasses: Foothills fescue – *Festuca campestris* Green Needle Grass – *Nassella viridula* Tufted Hairgrass – *Deschampsia cespitosa* June Grass – *Koeleria macrantha* Fowl Manna Grass – *Glyceria striata* Fowl Bluegrass – *Poa palustris* Awned Sedge – *Carex atherodes* Rough Hair Grass – *Agrostis scabra*	**Forbs:** Blue Flax – *Linum lewisii* Showy Milkweed – *Asclepias speciosa* Purple Coneflower – *Echinacea purpurea* Missouri Goldenrod – *Solidago missouri* Smooth Aster – *Aster laevis* Black-eyed Susan – *Rudbeckia hirta* Tall Sunflower – *Helianthus giganteus* Meadow blazingstar – *Liatris ligulis*
Woody	11 plants in total 6 Dwarf Birch – *Betula nana* 4 Yellow Willow – *Salix lutea* 1 River Birch – *Betula occidentalis*	

Table S2. Experimental Design Details.

Factor	Levels	Description
Media	1	CoC 70 Media
	2	CoC 40 Media
	3	CL Media
Vegetation	1	Turfgrass
	2	Herbaceous
	3	Woody
IP	1	15
	2	30

The mesocosm set-up was analyzed as a partial factorial experimental design with three factors – media, vegetation, and IP ratio. Media and vegetation each had three levels, and IP ratio had two levels. The setup was partially replicated, where the combination of IP15 and herbaceous vegetation was replicated three times for each media type.

Table S3. Monthly precipitation of the historical median year and the simulated program.

Monthly precipitation (mm)	May	Jun	Jul	Aug	Sep	Oct	Total
Median year*	54	89	71	49	46	16	325
2017**		~7	~7	14	28		56
2018		49	69	59	35	8	220
2019	13	59	50	55	40	4	221
2020***		31	46	55	40	8	180

*Median year values are shown for precipitation, not runoff (i.e., no correction for depression storage).
**2017 was an establishment year, which included a mix of irrigation and simulated runoff events.
***2020 – data collection was impacted by COVID-19 restrictions. The start of the monitoring program was delayed till mid-June.

Table S4. Detailed Simulated Event Schedule.

Event #	Year	Date	Magnitude (mm)
1	2017	22-Aug	14
2		06-Sep	14
3		29-Sep	14
4	2018	01-Jun	4
5		05-Jun	9
6		10-Jun	4
7		15-Jun	14
8		20-Jun	4
9		28-Jun	14
10		03-Jul	4
11		08-Jul	24
12		13-Jul	4
13		18-Jul	9
14		23-Jul	4
15		27-Jul	24
16		01-Aug	4
17		07-Aug	14
18		10-Aug	4
19		15-Aug	24
20		20-Aug	4
21		28-Aug	9
22		04-Sep	4
23		11-Sep	14
24		16-Sep	4
25		21-Sep	4
26		25-Sep	9
27		01-Oct	4
28		05-Oct	4
29	2019	22-May	4
30		27-May	9
31		01-Jun	4
32		05-Jun	14
33		10-Jun	4
34		15-Jun	24
35		25-Jun	4
36		30-Jun	9
37		05-Jul	4
38		10-Jul	24
39		20-Jul	4
40		25-Jul	14
41		30-Jul	4
42		04-Aug	24

43		14-Aug	4
44		19-Aug	9
45		24-Aug	4
46		29-Aug	14
47		08-Sep	9
48		13-Sep	4
49		18-Sep	14
50		23-Sep	4
51		28-Sep	9
52		03-Oct	4
53	2020	15-Jun	4
54		20-Jun	9
55		25-Jun	4
56		30-Jun	14
57		05-Jul	4
58		10-Jul	24
59		20-Jul	4
60		30-Jul	14
61		04-Aug	24
62		14-Aug	4
63		19-Aug	9
64		24-Aug	4
65		29-Aug	14
66		08-Sep	9
67		13-Sep	4
68		18-Sep	14
69		23-Sep	4
70		28-Sep	9
71		03-Oct	4
72		08-Oct	4

The events were not selected based on climatic parameters, rather they were run on a typical 5-day interval (with occasional 10-day intervals), which was based on the average inter-event duration typical for the City of Calgary in the months of May to October.

Table S5. Infiltration rate linear regression statistics.

Media Type	Vegetation Type	IP ratio	Unstandardized Beta Coefficients	Standardized Beta Coefficients	t	Sig.
CoC 70	Herbaceous	15	2.624	.476	7.981	<.001
		30	**1.363**	**.225**	**1.887**	**.063**
	Woody	15	2.534	.483	4.710	<.001
		30	1.290	.319	2.753	.008
	Control (Turfgrass)	15	3.140	.606	6.508	<.001
		30	**-.207**	**-.095**	**-.785**	**.435**
CoC 40	Herbaceous	15	11.211	.303	4.691	<.001
		30	**1.850**	**.127**	**1.051**	**.297**
	Woody	15	3.544	.423	3.993	<.001
		30	2.766	.482	4.506	<.001
	Control (Turfgrass)	15	5.928	.452	4.325	<.001
		30	**.604**	**.087**	**.714**	**.478**
Clay Loam/ Wood Chips	Herbaceous	15	20.253	.362	5.720	<.001
		30	11.106	.255	2.160	.034
	Woody	**15**	**5.303**	**.200**	**1.747**	**.085**
		30	**2.800**	**.105**	**.860**	**.393**
	Control (Turfgrass)	15	10.005	.474	4.605	<.001
		30	9.340	.409	3.668	<.001

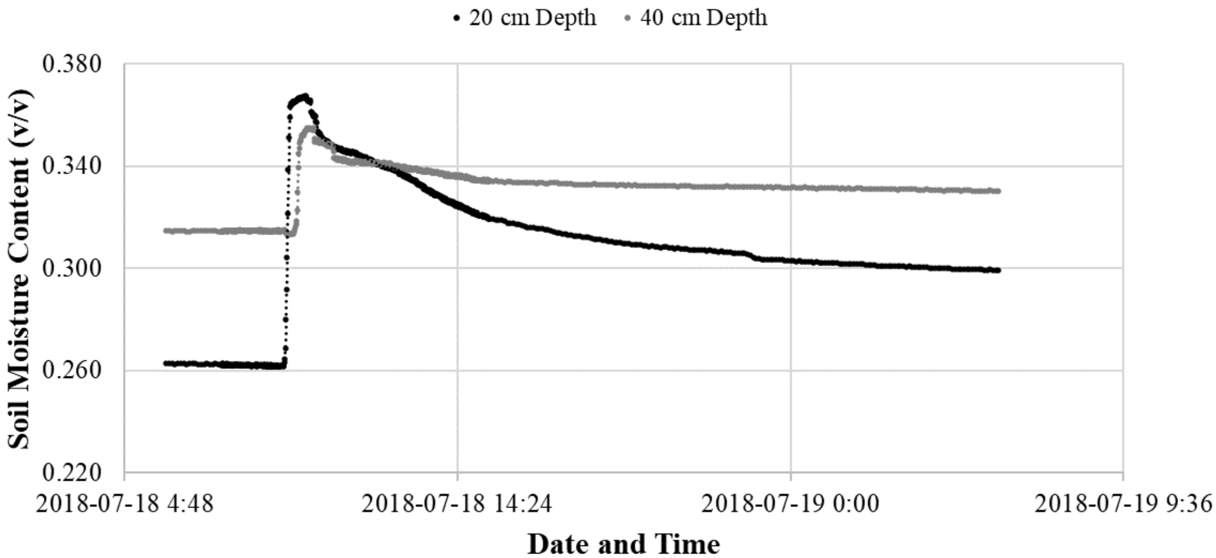


Figure S1. Typical Soil Moisture Curves during the first 24-hours of an event at 20 cm and 40 cm depths of Cell 7 of 70 CoC media. The value prior to the steep increase in soil moisture was used as "antecedent soil moisture" value.