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Stormwater Management Performance of Green Roofs

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STORMWATER MANAGEMENT PERFORMANCE OF GREEN ROOFS

(Thesis format: Integrated Article)

by

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Graduate Program in Civil and Environmental Engineering

A thesis submitted in partial fulfillment
of the requirements for the degree of
Masters of Engineering Science

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Abstract

Green roofs are becoming popular in North America as they are effective tools for managing stormwater runoff in urban areas. A greater understanding of how green roofs perform with respect to fundamental stormwater management processes, such as stormwater retention and peak flow attenuation, is required. This study investigated the impact that differing climates have on the retention performance of three green roofs in London, Calgary, and Halifax. It was found that Calgary (67%) has significantly better retention performance than both London (48%) and Halifax (34%). However, London retained the greatest volume of stormwater (758 mm), followed by Halifax (517 mm) and then Calgary (474 mm).

Additional monitoring of the hydrologic response for a fourth green roof in London Ontario was conducted to identify and measure the fundamental processes of peak attenuation on a green roof. It was determined that field capacity is a quantifiable point after which peak attenuation performance significantly decreases. Before field capacity peak attenuation is governed by capillary storage (72%) and routing (7%). After field capacity, gravity storage provides peak attenuation (22%) and drainage routing plays a larger role (11%). A predictive model was developed using Richards equation to simulate the outflow hydrographs of a green roof. Model results show that there is no significant difference from observed data for the performance metrics (i.e. water storage, drainage, and peak flow rate).

Green roofs perform very well as stormwater management tools by providing considerable retention and attenuation of stormwater. Additional benefits provided by green roofs (e.g. improved energy consumption, improved runoff quality, reduced air pollution, improved aesthetics etc…) makes this tool a desirable option for low impact development.

Keywords

Co-Authorship Statement

The candidate conducted field monitoring; collected, interpreted and analyzed experimental data under the supervision of Denis M. O'Carroll, Clare Robinson, and Christopher Smart. The candidate wrote the manuscript draft of the following chapters:

Chapter 3: Retention Performance of Green Roofs in Three Different Climate Regions

By Andrew Sims, Denis O'Carroll, Clare Robinson, Christopher Smart, James Voogt, Brandon Powers

Contributions:

Andrew Sims: Collected and interpreted experimental data, and wrote the draft of the paper.

Denis M. O'Carroll: Initiated research topic, developed methodology, supervised data interpretation and reviewed draft chapter

Clare Robinson: Initiated research topic, developed methodology, supervised data interpretation and reviewed draft chapter

Christopher Smart: Initiated research topic, developed methodology, assisted with experimental setup, and supervised data interpretation

James Voogt: Initiated research topic and developed methodology

Brandon Powers: Organized and sorted experimental data

Chapter 4: Quantification and Prediction of Peak Flowrate Attenuation Mechanisms on Green Roofs

By Andrew Sims, Denis O'Carroll, Christopher Smart, Clare Robinson

Contributions:

Andrew Sims: Collected and interpreted experimental data, developed model, and wrote the draft of the paper.

Denis M. O'Carroll: Initiated research topic, developed methodology, supervised data interpretation and reviewed draft chapter

Clare Robinson: Initiated research topic, developed methodology, supervised data interpretation and reviewed draft chapter

Christopher Smart: Initiated research topic, developed methodology, assisted with experimental setup, and supervised data interpretation

Acknowledgments

Thank you to my supervisor Denis O'Carroll for your kind advice, patience, and mentorship. It was a pleasure to work and learn from you over the past two years. I would also like to thank my Co-Supervisor Clare Robinson for guiding me through my Masters Degree. I truly appreciate all of the work that the both of you contributed, as principal investigators for the green roof project, to assist me with completing this thesis.

I also wish to express my deepest gratitude to Chris Smart for teaching me, I imagine, only a small fraction of your seemingly endless knowledge. You always encouraged discussion on data analysis or instrumentation and I truly believe I learned many skills I will use for the rest of my life. Thank you to Jamie Voogt as well for all the guidance you have provided over years of working together.

A special thanks to all members of the green roof team; Dr. Maja Staniec, Dimuth Kurulula, Patrick Breach, Maria Sia, Ginevra Perelli, Luke Gebert, and Jeremy Lundholm. Each one of you helped me along the way in one-way or another.

Thank you to the RESTORE group for making the past two years some of the most enjoyable years of my life. I will always cherish the friendships and memories made.

Lastly, I would like to thank my parents, Terri Paul and Stephen Sims, and my girlfriend Anna Kornmuller for their continual love and support.

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List of Abbreviations, Symbols, and Nomenclature

LID – Low impact development

SWM – Stormwater management

CMLP – Claudette MacKay-Lassonde Pavillion

ET – Evapotranspiration

ADWP – Antecedent dry weather period

CSO – Combined sewer overflow

IDF – Intensity duration frequency curve

θ – Soil moisture content ($m^3 \cdot m^{-3}$)

θ_r – Residual water content ($m^3 \cdot m^{-3}$)

θ_s – Saturated water content ($m^3 \cdot m^{-3}$)

F_c – Field capacity

T_c – Time of concentration (min)

ADC – Analog to digital converter counts

α – EC5 fitting parameter

ϕ – Porosity ($m^3 \cdot m^{-3}$)

$P_{drainage}$ – Peak drainage flow rate (mm/min)

P_{rain} – Peak rain flow rate (mm/min)

$S_{gravity}$ – Gravity storage (mm)

S_{peak} – Storage at peak flow rate (mm)

$S_{F.C.}$ – Storage at field capacity (mm)

t_{delay} – Time delay (min)

$tp_{drainage}$ – Time of peak drainage (min)

$tp_{rainfall}$ – Time of peak rainfall (min)

S_e – Effective saturation

H_p – Pressure head (m)

K_s – Saturated hydraulic conductivity (m/s)

k_r – Relative permeability

α, n, m – Van Genuchten soil parameters

Chapter 1

1   Introduction

1.1   Background

1.1.1   Value of Stormwater Management

Increased urbanization will have a direct impact on the local hydrologic cycle. By adding impervious surfaces, an increase in surface runoff, reduced infiltration, and reduced evapotranspiration (ET) is expected (Berndtsson 2010). Ideally, the impact of development on the water balance is accounted for during the design stage through proper implementation of stormwater management (SWM) measures. If the effects of urbanization are not appropriately managed, channel geomorphology and aquatic ecology will degrade, stream base flow will decrease, water quality will diminish, and flooding frequency will increase (Voyde 2011).

The effects of increased stormwater runoff are inherently related to one another through various cause and effect relationships. For example, impervious surface cover increases stormwater volume and flow rate, which results in an increased frequency of flooding (Dhalla and Zimmer 2010) causing changes in stream channel geomorphology. The channel cross section will expand through erosion to compensate for more stormwater runoff. This destroys riparian buffer zones and decreases stream depth during dry periods (P'ng, Henry et al. 2003). The erosion will increase sediment loads in the water and alter stream bed composition, ultimately impacting the aquatic ecology that depends on the stream ecosystem. By mitigating impacts of stormwater runoff at the source and reducing runoff volume and peak flow rates, the impacts on receiving water bodies can be reduced (P'ng, Henry et al. 2003).

The water quality of a watershed is also compromised by stormwater runoff. Impervious surfaces act as a first flush mechanism for pollutants to accumulate and then rapidly enter the receiving waterways. Urban stormwater can have higher levels of suspended solids, bacteria, heavy metals, oil and grease (Dhalla and Zimmer 2010). Thermal pollution

through heat conduction as runoff moves over hot pavement can also be problematic (P'ng, Henry et al. 2003). Data has increasingly become public with regards to the serious issue of combined sewer overflows (CSOs). Combined sewer networks convey both stormwater and sanitary sewage. During precipitation events the water treatment facilities cannot treat the large volumes of water and as a result, directly discharge the untreated stormwater and sewage mixture (containing bacteria, viruses, oxygen depleting substances, nutrients, suspended solids and more) into receiving bodies of water (MacDonald, Podolsky et al. 2009). Reports have shown that the Great Lakes basin received 92 billion litres of sewage/stormwater from CSOs in 2006 (MacDonald, Podolsky et al. 2009).

Stormwater management systems need to be improved to account for the changes in the hydrologic cycle that results from urbanization. By designing a stormwater management system that mimics the predevelopment stormwater runoff, the negative impacts of stormwater can be mitigated. In areas that have already been developed without sufficient stormwater management systems, retrofitting to reduce the runoff can be difficult. However, 40-50% of impervious surface cover in urban areas is unused roof space (Mentens, Raes et al. 2006). Rooftops are generally vacant areas that are not required for any essential building operations, yet remain impervious and contribute to stormwater runoff. The implementation of a stormwater control as a retrofit on vacant roofs could significantly reduce the impervious surface cover and help eliminate stormwater generation at the source. The use of low impact development (LID) tools like green roofs can provide pervious surface cover to mimic predevelopment landscapes on unused roof space.

1.1.2   Design Criteria of SWM Techniques

The goals of SWM design, as outlined by the Ontario Ministry of the Environment (P'ng, Henry et al. 2003), is typically to preserve groundwater, prevent geomorphic changes in waterways, prevent flooding risks, protect water quality, and maintain aquatic life. SWM techniques are designed to maximize stormwater reduction and provide flow rate control. SWM controls can include lot level/conveyance (e.g. green roofs, permeable pavement,

filter strips) or end-of-pipe (e.g. wet pond, dry pond, infiltration basins) treatment techniques. The idea of managing stormwater as close to the source area as possible and using various lot level techniques is often referred to as low impact development (LID) controls (Dhalla and Zimmer 2010). The aim of LIDs include: treating stormwater as close to the source as possible, decreasing impervious area, and implementing systems that have multiple functions (i.e. attenuating peak flow rates, storage of precipitation, delay of stormwater generation, infiltration, filtration, enhancing aesthetics, improve ecology) (Dhalla and Zimmer 2010). In most cases, an LID will be the first step of a treatment train, where multiple SWM tools are used to fully manage the runoff (P'ng, Henry et al. 2003). Green roofs are becoming a more commonly implemented LID control. The effectiveness of green roof's as a stormwater LID control depends mainly on its ability to retain runoff (e.g. Hutchinson, Abrams et al. 2003), attenuate peak flow rates (e.g. Stovin, Vesuviano et al. 2012), while providing energy benefits and ecological benefits (e.g. Liu and Minor 2005; Speak, Rothwell et al. 2014). To effectively implement green roofs as LIDs, an in depth understanding of how they retain and attenuate stormwater is necessary. Development of accurate predictive models is essential to help the stormwater engineers effectively design and incorporate green roofs as a component of a large scale urban SWM system. In the following chapters an analysis of green roof performance with respect to SWM will be considered.

1.1.3 Green Roof Legislation

The advantages of green roofs have been recognized by the municipality of Toronto, who recently introduced a regulation that requires the construction of green roofs for stormwater management purposes (City of Toronto 2012). As of January 30th, 2010, every building or building addition constructed that has 6 or more stories with a gross floor area of greater than 2,000 m^2 must include a green roof. The size of the required green roof is dependent on the gross floor area of the building. Table 1.1 indicates the specific green roof coverage required.

Table 1. 1: Toronto green roof sized required by municipal legislation

Gross floor area	Size of required green roof
2,000 — 4,999 m^2	20%
5,000 — 9,999 m^2	30%
10,000 — 14,999 m^2	40%
15,000 — 19,999 m^2	50%
20,000 m^2 or greater	60%

For any Industrial building constructed after April 29, 2012, a green roof must be built with the minimum of either 2000 m^2 or 10% of available roof space.

The implementation of green roof legislation is occurring all over the North America (e.g. Montreal, Vancouver, Chicago, Portland) and the world (e.g. Switzerland, Germany, France, Singapore) (Lawlor, Currie et al. 2006). This demonstrates that policy makers are recognizing the importance of urban stormwater management. Green roof research is required to optimize design and thoroughly assess the fundamentals of green roof performance.

1.2   Research Objectives

The objective of this research is to evaluate the effectiveness of green roofs as stormwater management tools. A total of four green roof sites located in Calgary (1), Halifax (1), and London (2), are subject to continuous monitoring to quantify the water balance. The specific goals within the research include:

1. Monitoring green roofs in Calgary, London, and Halifax to assess the impact that varying climates have on retention performance. This will provide insight on the ideal areas to focus green roof installation efforts, as well as quantify the benefits that green roofs can provide in different conditions.
2. Assess the ability of green roofs to attenuate and delay stormwater. Quantify the impact that field capacity, capillary storage, gravity storage, and routing have on peak attenuation.
3. Use modelling techniques to simulate green roof outflow hydrographs. Use field data or measurements for all model parameters to develop a predictive model.

1.3   Thesis Outline

This thesis is written in "Integrated Article Format". A brief description of each chapter is presented below.

Chapter 1 provides an introduction to the importance of stormwater management and the role that green roofs have as an LID control. It also outlines the objectives of the study.

Chapter 2 provides a summary of the current state of green roof knowledge, including the various design components that are used on green roofs and the benefits that green roofs provide. Recent research focusing on the ability of green roofs to retain and attenuate stormwater through monitoring and modelling is presented.

Chapter 3 presents the results of continuous monitoring of green roof sites in London, Calgary, and Halifax. The impact that different climates have on stormwater retention performance of green roof set ups is assessed.

Chapter 4 identifies and subsequently quantifies the fundamental processes that lead to stormwater attenuation and delay on a green roof in London Ontario. A predictive model is developed using fundamental unsaturated flow equations to simulate single event green roof drainage hydrographs.

Chapter 5 outlines the conclusions that can be made from the research and some general recommendations for future research.

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Chapter 2

2 Literature Review

Green roofs are used as stormwater management tools and LID controls to retain runoff, attenuate peak flows, delay peak flows, and delay runoff generation. These are widely accepted indicators of stormwater management effectiveness (Dhalla and Zimmer 2010). The literature available related to green roofs is extensive, ranging from life cycle analysis, to energy budgets, ecological assessments, hydrologic assessments and more. The focus of this thesis will be on the hydrologic benefits of green roofs; as such, the literature review will stress the current knowledge of green roof stormwater management. The literature will be summarized in four distinct sections:

    i.   Summary of green roof design and history.

    ii.   Stormwater retention.

    iii.   Peak flow rate attenuation and delay of stormwater.

    iv.   Green roof modelling techniques.

2.1 Introduction to Green Roofs

2.1.1 Green Roof History

Historical references to green roofs include the Hanging Gardens of Babylon and the ancient Ziggurats of Mesopotamia where green roofs were used to provide shade (Berardi, GhaffarianHoseini et al. 2014). Later green roofs in the Roman Empire functioned as 'rooftop gardens' for growing food and facilitating social interaction. The Villa of Mysteries in Pompeii (Figure 2.1) was discovered to have a green roof that was used for social activities as well as insulation and extending roof life (Berardi, GhaffarianHoseini et al. 2014). In more recent history, vegetated/sod roofs, similar to today's green roofs, were used in Scandinavia. The sod roof technique was then introduced in North America by Scandinavian immigrants. In the late 1800's in New York City rooftop gardens were created for theatre and entertainment, providing the origins for structures like Madison Square Gardens (Shimmin 2012).

Figure 2. 1: Villa of Mysteries in Pompeii, Italy (Shimmin 2012)

In 1975 the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL), a garden, landscape and sports field construction organization, was established and produced guidelines and principles for vegetated roofs. The 2002 volume is commonly applied in North America for design purposes (FLL 2002). The FLL guidelines are regarded as the global standard for vegetated roofs (Voyde 2011). Germany is leading the world with regards to area covered by green roofs, with about 14% of all flat roofs being green roofs (13.5 km^2) (Stovin 2010). The benefits are becoming widely recognized and many areas are making progress with regards to implementing this urban design tool, or creating policies for green roofs.

2.1.2   Green Roof Design

There are various design considerations for green roofs, one of which is the decision to install either an extensive, intensive, or semi-intensive vegetated roof. Site conditions such as annual precipitation, sun exposure, periods of drought, frost or snow and building structure (additional load, slope of roof, wind), in addition to owner preferences, are used to determine whether an intensive or extensive roof should be installed (FLL 2002). The main difference between an extensive and intensive green roof is the depth of media used. Generally, a vegetated roof with over 150 mm of substrate is considered an intensive roof (Berndtsson 2010). Intensive roofs have >150 mm substrate layers, providing a much wider range of plant options. Extensive green roofs have media depth

of less than 150 mm and are designed to be very low maintenance, while preserving full vegetative cover. Extensive green roofs are desirable for retrofits because of the reduced structural load. Plant selection for an extensive vegetated roof usually consists of mosses, grasses, herbaceous plants, or succulents (FLL 2002).

The three common setups for green roofs include modular systems, pre-cultivated systems, or complete systems. The pre-cultivated system consists of pre-grown vegetated mats that can then be rolled out on the roof (Dhalla and Zimmer 2010). A complete system is the traditional installation technique, where the green roof is installed in its component layers (Figure 2.2) and then the plants are sowed or inserted as plugs. A modular system uses a collection of pre-planted trays to assemble the green roof.
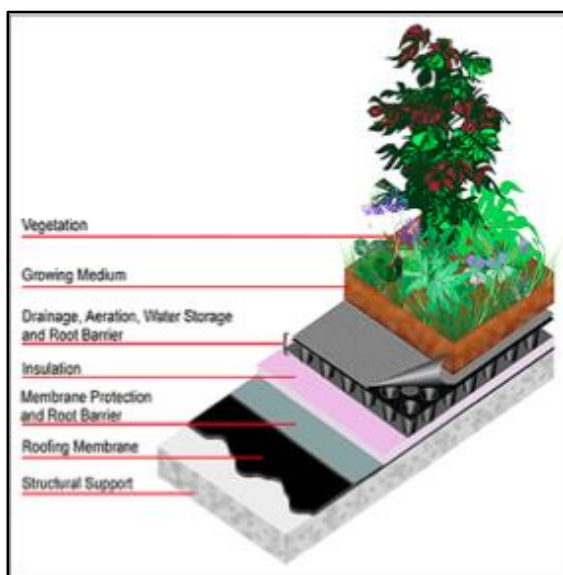
Figure 2. 2: Layers of a conventional green roof (Dhalla and Zimmer 2010)

Each layer of the conventional green roof system (Figure 2.2) has an important function.

- Vegetation Layer: The vegetation will reduce wind erosion, provide shading for the substrate, and reduce the temperature during daylight hours in the warm season (Dhalla and Zimmer 2010; Voyde 2011). Transpiration restores water storage capacity to the media, and the canopy can provide interception storage. Plant selection in most cases should be restricted to native varieties of grasses or sedums (Snodgrass 2014).

- Growing Media**:** An engineered substrate generally consisting of sand, gravel, crushed rock and some organics. It is designed to meet FLL guidelines for saturated hydraulic conductivity, pH, organic content, nutrients, and grain size distribution. The substrates main purpose is to store excess rainfall and support plant life (FLL 2002; Voyde 2011).

- Drainage Layer: A synthetic mat or a layer of porous media that permits conveyance of excess precipitation to outlets and roof drains.

- Water Proofing Membrane: The first layer directly above the conventional surface. Insulation should be placed above or below the water proofing membrane, as well as a root barrier to stop root invasion (Dhalla and Zimmer 2010; Voyde 2011)

New modular systems are being implemented that combine some of the layers together. The LiveRoof modular system (Figure 2.3) sits directly on the water proofing membrane and has the drainage layer incorporated into the module structure (LiveRoof 2014). Each type of green roof system will require a different level of initial maintenance depending on whether the plants were pre-cultivated, planted as plugs, or sowed as seeds. After the vegetation is established, some modest continual maintenance, such as weeding, is encouraged to maintain green roof consistency.
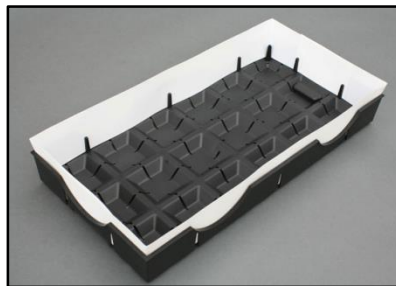
Figure 2. 3: LiveRoof green roof module (Liveroof 2014)

2.1.3   Green Roof Benefits

Green roofs are commonly used for stormwater mitigation. However, there are numerous other benefits that green roofs provide. These include:

- Improved runoff water quality: It has been found that green roofs can neutralize the acidity of rainfall (Teemusk and Mander 2007; Berndtsson 2010). Additionally, runoff from an extensive green roof can reduce lead by 99%, Zinc by 96%, Cadmium by 92%, and copper by 97% (Steusloff 1998). This reduction in heavy metals is largely a result of total pollutant load reduction due to retention rather than an effective filtration process. The nutrient concentration in the effluent will depend on fertilization methods.

- Reduce energy consumption: Green roofs can provide energy savings, especially in poorly insulated buildings. In warm climates, the green roof will cool the building by shading the roof, preventing direct solar radiation and adding extra insulation. The green roof also stabilizes daily temperature fluctuations (Berardi, GhaffarianHoseini et al. 2014). A study found that green roof surface temperatures in Toronto only fluctuated by $6\,°C$, while the bare roof had $45\,°C$ fluctuations (Liu and Baskaran 2003). Green roof vegetation uses about 60% the incoming solar radiation for photosynthesis and the green roof has an albedo of 0.7-0.8 resulting in less available energy to heat the media (Weng, Lu et al. 2004).

- Reduce air pollution: Green roofs act to replace vegetation removed due to urbanization. Green roofs have the potential to remove NOx, SO_2 and particulate matter (Speak, Rothwell et al. 2014). In Singapore, a study measured SO_2 before and after installation a green roof, and found a 37% decrease in SO_2 concentrations (Yok and Sia 2005). Modeling has found that 109 Ha of green roofs would remove 7.87 tons of pollutants from the air (Currie and Bass 2008). Additionally, the air pollution from manufacturing of materials for the green roof is offset within 13 years of green roof operation (Bianchini and Hewage 2012).

- Reduce acoustics and noise: Vegetation and soil can reduce noise in urban settings. The media depth directly relates to noise reduction; as the depth is increased, improved noise reduction is experienced (Yang, Kang et al. 2012).

- Ecological preservation: Green roofs can augment fruit and vegetable production (Dunnett and Kingsbury 2008) as well as provide habitats for small creatures and insects (MacIvor and Lundholm 2011). Species including bees, killdeer, Canadian

geese, caterpillars, grasshoppers, spiders, and beetles have been seen on London, ON green roofs.

- Decrease urban heat island effect: Green roofs have a higher albedo than black roofs and have, on average, ambient air temperatures above the roof that are 1.5-2 ℃ cooler (Susca, Gaffin et al. 2011). Green roofs also have increased latent energy production, providing greater evaporative cooling compared to a bare roof where sensible energy fluxes that heat ambient air dominate.
- Increase roof life: Green roof can increase the life of a 10-20 year water proofing layer to 50 years (Niu, Clark et al. 2010).

2.2   Green Roof Stormwater Retention

When rain falls on an impervious surface, stormwater runoff is generated. Replacing impervious surfaces with permeable surfaces can reduce stormwater runoff and downstream impacts. Green roofs act as permeable surfaces that instead of infiltrating into the ground, provide storage (i.e. retention) of stormwater. Retention refers to the amount of rainfall that is stored in the green roof substrate. The rainfall is stored in the media by soil capillary forces and will then evaporate over time, which in turn regenerates storage capacity to capture subsequent precipitation. Retention, often presented as a percentage, can be calculated as;

$$Retention\ (\%) = \frac{Rainfall\ (mm) - Runoff\ (mm)}{Rainfall\ (mm)} \cdot 100 \qquad\qquad 1$$

Various factors can influence the retention performance of green roofs, including study characteristics (e.g. study duration and instrumentation) and green roof design components (e.g. roof slope, depth, vegetation, age). Literature detailing retention performance and the influence these design components will be presented.

2.2.1   Cumulative Retention (Annual and Seasonal)

Long-term assessments (i.e. full year measurements) of cumulative retention can provide a realistic indicator of the expected performance of a green roof over its lifetime. Annual

retention performance values will moderate the variation in performance that may occur due to seasonal changes and the unpredictable nature of rain events. Annual cumulative retention is a simple metric that can be valuable for policy and design guidelines.

Various studies have presented long term cumulative retention values for green roofs. The reported retention values range from 27-81% as reported by Mentens, Raes et al. (2006).

Table 2. 1: Summary of cumulative green roof retention values from recent studies

Study	Cumulative Retention (%)	Location	Duration Months(events)	Roof Type and Depth (mm)
Moran, Hunt et al. (2005)	63	North Carolina USA	18 (67)	Full - 70
Mentens, Raes et al. (2006)	27-81	Germany	12 – 48	Full - 20-150
Voyde, Fassman et al. (2010)	66	Auckland NZ	12 (91)	Full - 50-70
Carpenter and Kaluvakolanu (2011)	68.25	Michigan USA	6 (21)	Full - 101.6
Stovin, Vesuviano et al. (2012)	50.2	Sheffield UK	29 (468)	Test Bed - 80
Stovin, Vesuviano et al. (2012)	30	Sheffield UK	29 (21)	Test Bed - 80
Fassman-Beck, Voyde et al. (2013)	56	Auckland NZ	28 (396)	Full - 50-70
Fassman-Beck, Voyde et al. (2013)	39	Auckland NZ	14 (166)	Full - 100
Fassman-Beck, Voyde et al. (2013)	53	Auckland NZ	14 (166)	Full - 150
Fassman-Beck, Voyde et al. (2013)	57	Auckland NZ	8 (79)	Full - 100
Bengtsson, Grahn et al. (2005)	46.3	Sweden	18	Test Bed - 30
Gregoire and Clausen (2011)	51.4	Connecticut USA	12 (97)	Full - 102
VanWoert, Rowe et al. (2005)	60.6	Michigan USA	14 (83)	Test Bed - 25
Hutchinson, Abrams et al. (2003)	69	Oregon USA	12	Full - 120
Liu and Minor (2005)	57	Toronto Canada	20	Full - 100
Carter and Rasmussen (2006)	62.5	Georgia USA	12 (31)	Test Bed - 76.2

It is extremely difficult to generate meaningful conclusions from this collection of long term retention results since each green roof has different media depths, vegetation, slopes, duration and study location. For example, the study published by Mentens, Raes et al. (2006) is a compilation of 18 German papers detailing green roof performance. Within this study, the media depths of extensive roofs range from 30 mm to 140 mm, resulting in a range of reported cumulative retention values of 27-81%. Given the results from Mentens, Raes et al. (2006), providing a consistent green roof setup and study structure with which to compare long-term retention trends could provide valuable

information on factors that have never been considered, such as the influence of green roof location (i.e. climate) on retention.

The study duration is very important in climates with major seasonal fluctuations. Some research has considered the impact of seasonal weather changes on green roof retention performance (Carter and Rasmussen 2006; Mentens, Raes et al. 2006; Berghage, Beattie et al. 2009; Stovin, Vesuviano et al. 2012). Each study found that there was increased retention during summer months when compared with winter months, since warmer months provide more evapotranspiration which would replenish storage capacity at a greater rate. Alternatively, studies by Voyde, Fassman et al. (2010), Fassman-Beck, Voyde et al. (2013), and Speak, Rothwell et al. (2013) have found minimal effect of seasonal differences. Fassman-Beck, Voyde et al. (2013) does point out that this is likely due to the fact that Auckland, New Zealand's climate has very little seasonal fluctuation. These contrasting results identify a substantial hole in green roof literature. Various studies have considered green roof retention, but each study has varying design characteristics and study locations. This makes it difficult to formulate broad empirical conclusions about green roof retention performance as stormwater management (SWM) tools. The different responses in green roof literature with respect to seasonal retention performance is attributed to climate, however, no studies have ever been carried out to assess the effect of climate on green roof retention. Additional green roof research must be conducted to effectively assess the impacts of climate on green roof performance.

2.2.2 Event Based Retention and the Effect of Rainfall Characteristics

An alternative to the cumulative retention of a green roof over long periods is to consider each specific rain event that occurred during the study period. Event based retention is often reported as the average or median retention for a collection of individual events. This can be a valuable way to assess green roof performance if the sample size of individual storm events is large enough. Various papers have researched green roof

trends with respect to these individual rainfall characteristics with occasionally conflicting results.

Average event retention values found within the literature vary from 34% to 80.2%.

Table 2. 2: Summary of average event retention values from recent studies

Study	Event Retention (%)	Location	Duration - Months (Events)	Roof Type and Depth (mm)
Getter, Rowe et al. (2007)	80.2	Michigan USA	13 (62)	Test Bed - 130
Carter and Rasmussen (2006)	78	Georgia USA	12 (31)	Test Bed - 76.2
Voyde, Fassman et al. (2010)	78	Auckland NZ	12 (91)	Full - 50-70
DeNardo, Jarrett et al. (2005)	45	Pennsylvania USA	2	Test Bed - 30
Fassman-Beck, Voyde et al. (2013)	76	Auckland NZ	28 (396)	Full - 50-70
Fassman-Beck, Voyde et al. (2013)	56	Auckland NZ	14 (166)	Full - 100
Fassman-Beck, Voyde et al. (2013)	66	Auckland NZ	14 (166)	Full - 150
Fassman-Beck, Voyde et al. (2013)	72	Auckland NZ	8 (79)	Full - 100
VanWoert, Rowe et al. (2005)	82.8	Michigan USA	8	Test Bed - 25
Stovin (2010)	34	Sheffield UK	4 (11)	Test Bed - 80
Stovin, Vesuviano et al. (2012)	70	Sheffield UK	27 (468)	Test Bed - 80
Stovin, Vesuviano et al. (2012)	43	Sheffield UK	27 (21)	Test Bed - 80
Volder and Dvorak (2014)	78	Texas USA	6 (15)	Test Bed - 114

There is substantial variability between studies, as seen in Table 2.2. This could be a result of varying green roof designs, but is also a result of grouping all event sizes into one statistic. Getter, Rowe et al. (2007) assessed the impact of storm event size by organizing events into three different event size categories, light (i.e. <2mm), medium (i.e. 2-10mm) and heavy (i.e. >10mm). The average event retention within each grouping was calculated and it was observed that the light, medium and heavy storms retained 94.2%, 89.5%, and 63.3% of precipitation respectively. These values are similar to some studies by VanWoert, Rowe et al. (2005), Carter and Rasmussen (2006), and Carpenter and Kaluvakolanu (2011). The trend of decreasing retention with increasing event size is consistent throughout the majority of studies. The single exception is made by Speak, Rothwell et al. (2013) and in this case the light and medium sized events had about the same retention. A summary of some of the event size retention trends can be seen in Table 2.3.

Table 2. 3: Summary of retention results as defined by various size categories

Study	Category	Sizes (mm)	Events (#)	Retention (%)
Carter and Rasmussen (2006)	Small	<25.4	21	88
	Medium	25.4-76.2	8	54
	Large	>76.2	2	48
(Carpenter and Kaluvakolanu 2011)	Small	<12.7	10	98.6
	Medium	12.7-25.4	8	90.24
	Large	>25.4	3	52.7
(Getter, Rowe et al. 2007)	Light	<2	16	94.2
	Medium	2-10	24	89.5
	Heavy	>10	22	63.3
(VanWoert, Rowe et al. 2005)	Light	<2	26	96.5
	Medium	2-6	30	82.9
	Heavy	>6	27	52.4
(Speak, Rothwell et al. 2013)	Small	<2	45	77
	Medium	2-10	99	79
	Large	>10	34	50

There has been very limited research carried out on the response of green roofs to large events that exceed a 1 or 2 year return period. This is reasonable, since these events inherently occur on an infrequent basis. Determining the performance of green roofs during large return period events is important to compare green roofs to other stormwater management tools. Some studies have captured the occasional large event that exceeds 45+ mm of precipitation (Carter and Rasmussen 2006; Stovin, Vesuviano et al. 2012; Speak, Rothwell et al. 2014; Volder and Dvorak 2014), but Stovin, Vesuviano et al. (2012) is the only study to conduct a thorough analysis of large-scale events. Stovin, Vesuviano et al. (2012) monitored 21 useable events that exceed the size criteria of 1-year return period. The site used a 3m x 1m green roof test bed with a substrate depth of 80 mm. The monitored data was collected over a 29-month period in Sheffield, England. The average event retention was found to be 30% for these 21 significant events. However, 17 of the 21 events were only between 1 and 2-year return period. The sample size of storms greater then a 2-year return period only consisted of 4 events, a 2-year, 3-year, 5-year, and 16-year storm. There is undoubtedly still very important research that needs to be conducted on significant sized storm events, with a larger data set of appropriate events. Further analysis of significant events of sizes greater than 2-year events is required for the comparison of green roofs to traditional stormwater management techniques, which often use 2-year return period storms in design guidelines (Dhalla and Zimmer 2010).

The effect of storm intensity on retention was investigated by Villarreal and Bengtsson (2005) through the use of artificial storms. They found that constant intensity events retained 20-29%, whereas varying intensity events retained 34-52%. The idea that rainfall intensity impacts retention has been considered in other literature (Moran, Hunt et al. 2005; Berndtsson 2010; Voyde, Fassman et al. 2010; Fassman-Beck, Voyde et al. 2013; Speak, Rothwell et al. 2013), but there is still no clear resolution to this claim. For the most part it seems that there is no statistically significant correlation between rainfall intensity and retention (Stovin, Vesuviano et al. 2012; Fassman-Beck, Voyde et al. 2013; Speak, Rothwell et al. 2013). Another storm event characteristic that has been linked to retention is antecedent dry weather period (ADWP). ADWP is the duration of the dry period preceding a storm event. A longer ADWP would provide more time for evaporation of water from the substrate and provide more storage capacity. Many studies agree that ADWP certainly has some impact on the performance of a green roof (Getter, Rowe et al. 2007; Berndtsson 2010; Voyde, Fassman et al. 2010; Stovin, Vesuviano et al. 2012; Fassman-Beck, Voyde et al. 2013). However, no statistical significance has been shown between ADWP and retention. It is likely due to inherent inconsistencies of the ADWP definition. For example, it is possible to have a very small ADWP where the preceding rain event was only 0.5 mm. This would result in a small ADWP implying a small availability of storage capacity when in fact the substrate could still retain a large amount of rainfall (Stovin, Vesuviano et al. 2012). The ADWP for a given green roof has a strong link to the climate patterns for the study location of study. By conducting further research on the effects of green roof location and climate region on retention, some more definitive conclusions regarding the influence ADWP could be possible.

2.2.3   Effect of Green Roof Design Characteristics on Retention

There are various aspects of a green roof design that can be altered from site to site. When retrofitting a building with a green roof, some sites will be able to support a greater substrate depth, while some rooftops will have more severe slopes than others. Varying the planting scheme may also impact the green roof performance. Assessing the various

design components of green roofs and how they affect retention can lead to optimization of a site-specific design.

The slope of a green roof influences the retention performance. The FLL (2002) design guidelines state, "as the gradient increases, so does the rate at which water runs off the roof". These guidelines also strongly recommend that no green roof be constructed with a slope of over 45°. Various studies conducted on the effect of green roof slopes (Liesecke 1998; Schade 2000; VanWoert, Rowe et al. 2005; Villarreal and Bengtsson 2005; Getter, Rowe et al. 2007) have found mixed results. Studies that conducted the analysis of sloped retention with the green roofs initially at field capacity found no effect of changing slope on retention (Liesecke 1998; Schade 2000; Villarreal and Bengtsson 2005). Meanwhile, research that was conducted with various antecedent conditions found that the retention actually increases as the slope decreases (VanWoert, Rowe et al. 2005; Getter, Rowe et al. 2007).

The load bearing capacity of the roof often limits the depth of media used on green roofs. Varying the depth of the media should theoretically impact the retention capability of a green roof since the available pore space for water storage is being altered. Mentens, Raes et al. (2006) found that the amount of retention on any given roof is directly related to the depth of substrate. Various others also found a trend of increasing retention capabilities with increasing depth of substrate (VanWoert, Rowe et al. 2005; Nardini, Andri et al. 2012; Carson, Marasco et al. 2013).

The selection of plants used on a green roof will impact the vegetation coverage, root uptake, root pathways in the media, storage of water in plant tissue, transpiration, interception, and shading of media, and as a result the evaporation rate. Research conducted by Nagase and Dunnett (2012) assessed 4 forb, 4 grass, and 4 sedum species in monocultures, as well as 4 and 12 species mixtures. The study found that grasses were most effective for retention of water, followed by forbs and sedum. Generally, the plants with taller heights, larger root biomass increased retention (Nagase and Dunnett 2012). It was also found that during different irrigation treatments the mat-forming sedum retained the most water in the substrate, implying that increasing plant canopy coverage reduced

evaporation from the substrate, in turn resulting in less available storage during precipitation events (Wolf and Lundholm 2008). Whereas, Volder and Dvorak (2014) hypothesized that broadleaved plants would provide increased transpiration and interception, resulting in greater storage capacity. Research by Nardini, Andri et al. (2012) found that there was no significant difference between herbaceous and shrub retention. It is commonly agreed that vegetated media retains more water than bare media (VanWoert, Rowe et al. 2005; Nardini, Andri et al. 2012; Volder and Dvorak 2014). The method with which the vegetation is planted can have some minor effects on retention as well. Prefabricated mats will have greater plant coverage in the first few years of implementation then planting plugs or shoots (Emilsson and Rolf 2005).

The age of a green roof can alter its effectiveness through changes in the plant maturity as well as substrate composition. An aged green roof can experience physical and chemical changes over time through loss of fine soil particles, loss of dissolvable substances, and changes in organic matter and soil porosity (Berndtsson 2010). Getter, Rowe et al. (2007) conducted an analysis of green roof substrate after 5 years of use and found that organic matter content and pore space doubled in that time period from 2% to 4% and 41% to 82% respectively, and water holding capacity increased from 17% to 67%. Perelli (2014) noted that green roof media aged 5 years had decreased amount of fines (i.e. grain size of less than 150 μm) after sieve analysis. Perelli (2014) deconstructed an aged in-situ green roof module and found that the soil at the top of the aged module had half of the fines as new substrate, while the bottom layer of aged soil had 5-10% less fines then the new soil. These findings imply a downward transport of fines though the substrate over time and out through drainage (Perelli 2014).

As seen from the literature outlined above, there are many well-established notions about how green roofs retain stormwater and the factors that affect retention. However, there is a prominent hole in the research with respect to the influence of green roof location. The impact that the site climate has on a green roof performance needs to be considered to fully understand the capability of green roofs as an LID tool. Many studies have been conducted in a variety of locations (ie., United States, Italy, England, Germany, Canada, New Zealand, South Korea etc.) but each of these studies have completely different green

roof design factors including substrate type, depth, slope, age and plant type. Each of these factors are shown to have quantifiable influence on retention performance in the previous section. This makes any direct comparison between green roof retention studies challenging.

2.3   Stormwater Attenuation and Delay Using Green Roofs

2.3.1   Peak Flow Rate Attenuation

Peak flow rate attenuation is an important concept in stormwater engineering design. The term attenuation generally refers to a reduction in intensity of a flux due to transport through a medium. This concept can be applied to green roofs to assess how rainfall peak flows compare to the drainage peak flows. Ideally, any urban development will preserve stormwater peak flow rates at the predevelopment peak flow rate for events ranging from 2-100 year return periods (P'ng, Henry et al. 2003).

Many studies have reported on peak flow rate attenuation from green roofs (Hutchinson, Abrams et al. 2003; Bengtsson 2005; Carter and Rasmussen 2006; Villarreal 2007; Uhl and Schiedt 2008; Berghage, Beattie et al. 2009; Voyde, Fassman et al. 2010; Carpenter and Kaluvakolanu 2011; Stovin, Vesuviano et al. 2012; Fassman-Beck, Voyde et al. 2013). Bengtsson (2005) conducted a thorough analysis of peak flow rate reductions using a 3 cm depth green roof with both artificial and real events. The study determined that a rain event of 0.5-year return period corresponded to the runoff of a 0.1-year event. Peak flow rate attenuation is calculated in literature as the percent difference between the largest rainfall peak and the largest drainage peak during and event. Reported peak flow attenuation ranges from 57% (Moran, Hunt et al. 2005; Stovin 2010) up to 93% (Fassman-Beck, Voyde et al. 2013). Alternatively, Villarreal (2007) conducted some artificial rain experiments where there was actually an increase in runoff flow rate compared to rainfall of 5%; this was ascribed to potential overland flow. Since all of the current literature uses the same definition of attenuation, where only the event peak rainfall and event peak drainage are considered, there is a limited understanding of attenuation. No research has ever quantified the attenuation of various peaks within a storm or quantified the different mechanisms that could influence flow rate attenuation.

Comparison of peak flow rate reductions from different studies is difficult. The averaging time interval (generally 5, 10, or 15 min) used to compute flow rates could differ between studies and alter the peak rainfall intensity magnitude. This was confirmed though a statistical study by Bengtsson (2005). Additionally, there are various examples of studies using either rainfall (Hutchinson, Abrams et al. 2003) or a control roof (Carpenter and Kaluvakolanu 2011) to measure attenuation. Measuring attenuation relative to a control roof will provide conservative results.

Generally the attenuation is defined by comparing the largest rainfall peak to the largest drainage peak over the entire duration of the event (Hutchinson, Abrams et al. 2003; Carter and Rasmussen 2006; Carpenter and Kaluvakolanu 2011; Stovin, Vesuviano et al. 2012). However, naturally occurring rain events have variable rain intensities and green roofs provide an initial level of storage. Therefore, the peak rainfall and the peak drainage could be completely unrelated peaks occurring hours apart. To provide an effective analysis of peak flow rates, the multiple peaks within a storm should be considered and correlated with the subsequent peaks occurring in the runoff.

The dominant factors that affect peak flow rate have not yet been determined with any reasonable measure of confidence. Uhl and Schiedt (2008) found that depth, slope, and layers of green roof did not affect attenuation, while Berghage, Beattie et al. (2009) proposes that seasonal rain pattern and ADWP are the key determinants. Hilten, Lawrence et al. (2008) used HYDRUS simulations and proposed that rain event size is the most important factor. Bengtsson (2005) determined that neither slope nor roof length significantly influenced the runoff, meaning that the vertical infiltration process dominates the rain-runoff relationship. There is no definite answer yet to the question of what is the key factor leading to attenuation. Literature has yet to consider the potential impact that soil characteristics can have on attenuation. Some literature has discussed the concept of field capacity as it relates to the retention of stormwater (Bengtsson 2005; DeNardo, Jarrett et al. 2005; Hilten, Lawrence et al. 2008), but the impact that field capacity has on green roof attenuation has never been empirically studied. Field capacity has various definitions in literature but is generally defined as the point where drainage through the soil falls below a defined value (Twarakavi, Sakai et al. 2009; Assouline and

Or 2014). With respect to green roofs, field capacity is the amount of water that can be completely retained by the media, due to soil capillary forces exceeding the force of gravity (She and Pang 2010). There is an opportunity to directly identify and quantify the effect that field capacity and the forces influencing field capacity have on green roof peak flow attenuation. This could provide valuable insight into the role that green roof media has on attenuation and allow for performance optimization of green roof media.

2.3.2   Stormwater Runoff Delay and Duration

Stormwater delay is an important aspect of managing runoff from impervious areas, and is a concept closely linked with retention and peak flow rate attenuation. By providing delay in the peak of the runoff hydrograph, delay in the time to initiation of runoff, and an increase in runoff duration it is expected that both stream channel erosion (P'ng, Henry et al. 2003) and combined sewer overflows is reduced. This will lead to further benefits resulting from reducing pollutant load into waterways (Dhalla and Zimmer 2010; Voyde 2011; Li and Babcock 2014). Previously in stormwater engineering, the concept that has been used in relation to runoff delay and travel times is referred to as time of concentration (Tc) (Hutchinson, Abrams et al. 2003). Tc is the time it takes for runoff flow from the hydraulically furthest point in a catchment to the outlet. Bengtsson (2005) conducted trials to quantify the Tc for a study roof and found that for a 0.4 mm/min intensity Tc was 16–20 min, and for 1.0 mm/min was 12–13 min. A similar concept of rooftop stormwater routing, the process of attenuating and delaying the flow of runoff travelling from the generation point to the roof outlet, can be considered for green roofs. This concept of rooftop routing will occur, both on green roofs (with drainage) and conventional roofs (with generated stormwater).

Analysis of peak flow rate delays has been considered in some previous studies (Bengtsson 2005; DeNardo, Jarrett et al. 2005; Getter, Rowe et al. 2007; Villarreal 2007; Carpenter and Kaluvakolanu 2011; Stovin, Vesuviano et al. 2012). DeNardo, Jarrett et al. (2005) found that there was a delay in peak flow rates of 2 hours on average. This finding was similar to Carpenter and Kaluvakolanu (2011) who found the peak delay for a green roof was an average of 2.16 hours. Alternatively, some studies have found smaller values for peak delays. Carter and Rasmussen (2006) found that 57% of storms were delayed

between 0-10 minutes, with only the largest delay approaching 2 hours. Villarreal (2007) found the delay in the peak flows was generally about 1 minute when analysis of artificial rain events was conducted. Conflicting results is likely a problem inherent in the definition of peak delay with respect to green roofs. Similar to peak flow attenuation, peak delay is generally calculated as the time between when the peak rain intensity and the peak runoff intensity occur. Since there is a storage element of green roofs that retains stormwater, situations where the peak rain intensity isn't actually related to the peak drainage intensity can occur. This completely undermines the concept of peak delay for many storm events (Stovin, Vesuviano et al. 2012). Some studies present another method of time delay by calculating time delay between the centroid of the rain and runoff hydrographs (Carpenter and Kaluvakolanu 2011; Stovin, Vesuviano et al. 2012). This provides an estimate of when the majority of runoff occurred relative to rainfall. Stovin, Vesuviano et al. (2012) used the centroid method and found that the delay was generally around 1 hour. However, this method still has issues, as using the centroid delay method the investigation of individual peaks during a storm is not possible. An in depth analysis of storm events that accounts for each respective peak within an event should be done to find true peak to peak delay times.

The peak time delay that a green roof provides has not been identified with consistency, due to the variable definitions for time delay. By looking closely at each event and determining the delay between the rainfall and drainage for each respective peak within a storm, much more detailed analysis and understanding of time delay would be possible.

2.4   Green Roof Hydrologic Modelling

Modeling the hydrologic response of green roofs is an important part of understanding how they function, and effectively designing and implementing them. Accurate models will allow for better prediction of green roof performance and therefore improved design and placement of green roofs. Papers focusing on modelling the hydrology of green roofs have mostly come out in recent years. Green roof hydrologic models currently vary from models at large watershed scales (Mentens, Raes et al. 2006; Carter and Jackson 2007) to single roof scale. The various types of models include analytical and physical models (Villarreal and Bengtsson 2005; Stovin, Poe et al. 2013; Zhang and Guo 2013), empirical

models (Mentens, Raes et al. 2006; Carson, Marasco et al. 2013; Fassman-Beck, Voyde et al. 2013), and numerical models (Hilten, Lawrence et al. 2008; Palla, Gnecco et al. 2009; She and Pang 2010; Metselaar 2012). Some of the models are event based and only work on the scale of one event, while some are capable of long-term simulations. The various modelling attempts generally conceptualize green roofs as either water balance reservoirs or porous media. The current state of green roof hydrologic modelling will be detailed in the following sections.

2.4.1   Empirical Models

Empirical green roof models use observed data or data from an experiment to estimate a parameter (i.e. retention). Empirical green roof models can be valuable (if they work), since they are extremely easy to apply and are based off of long term green roof trends, rather than just a few calibration events like some numerical models (Carson, Marasco et al. 2013).

Mentens, Raes et al. (2006) used retention data from 18 different green roof publications to produce regression equations for green roofs, gravel roofs and bare roofs that only require yearly precipitation data to produce a runoff estimate. It was found that linear relationships correlating rainfall to runoff could be applied to gravel roofs and bare roofs (R^2=0.99 & R^2 =0.99), while the green roof relationship was a second order polynomial function (R^2 = 0.78). However, this particular empirical model can only estimate annual runoff and is only applicable for areas with annual precipitation ranges of 554-1347mm. Both Carson, Marasco et al. (2013) and Fassman-Beck, Voyde et al. (2013) published findings supporting very similar empirical models based on Mentens, Raes et al.'s (2006) polynomial relationship. Both separately found, using rain and runoff data from individual rain events, that there is a strong quadratic relationship between precipitation and runoff for green roofs. Carson, Marasco et al. (2013) achieved correlations of R^2 = 0.98 R^2 = 0.98 and R^2 = 0.91 for the three green roofs monitored. Meanwhile Fassman-Beck, Voyde et al. (2013) achieved a correlation of R^2 = 0.81 for a data set that included event data from four separate green roofs.

2.4.2   Analytical and Physical Models

Analytical and conceptual models for green roofs generally attempt to estimate retention by representing different green roof processes and functions through mathematical techniques. For example, Carbone, Garofalo et al. (2014) made a conceptual water balance model to predict green roof behavior. It had 3 main components, a superficial layer modelled as an aquifer, a substrate layer to model the infiltration using Green and Ampt theory, and a storage/routing layer using the kinematic wave approach. The model showed reasonable correlation with constant intensity rain events, but consistently overestimated runoff volumes. Kasmin, Stovin et al. (2010) published another water balance model which consisted of a moisture storage component and a transient storage component, which was modelled using storage routing. Two fitting parameters were used to calibrate the model against monitored rain events. The Thornthwaite calculation was used for evapotranspiration, yielding a good fit between modelled and monitored data. Vesuviano and Stovin (2013) also improved on the Kasmin, Stovin et al. (2010) and Stovin, Vesuviano et al.'s (2012) conceptual model by adding a delay parameter and trying to link the model to physical drainage characteristics of a green roof. They tested 20 different types of drainage layers and related these physical set up changes to the model parameters. The calibrated parameters were dependent on roof slope and drainage layer type and the simulations yielded high correlation (R^2 = 0.9889). Villarreal and Bengtsson (2005) took a slightly different approach to the modelling of green roofs by using rain event data and linear programming to estimate a unit hydrograph for their green roof. This 1 mm (of effective precipitation) unit hydrograph can be used to simulate the runoff hydrograph from any rain input. Other conceptual models using reservoir and routing models were also published by Berthier, Ramier et al. (2011) and Jarrett and Berghage (2008).

Zhang and Guo (2013) recently published an analytical model to evaluate the hydrologic response of green roofs, using a few simplifying assumptions to mathematically describe hydraulic and hydrologic processes. In the analytical model, the derived probability distribution theory is used to obtain closed form expressions, and then the results are validated against numerical simulations and monitored data. Both the correlation to

numerical simulations in SWMM and monitored data showed a reasonable level of accuracy. However, important parameters such as ET rates were assumed from pan evaporation rates to simplify calculations. There are numerous conceptual models that each uses a unique set of functions to attempt to characterize green roof behavior. In general, most of these models show reasonable correlations with monitored data. Some areas to improve in the future could be to validate the models against long term data sets and data sets from different climates to see how the models translate to different environmental conditions. The use of calibration in all of these models indicates that there is still a lack of a predictive modelling tool for green roofs.

2.4.3 Numerical Models

Common numerical models used to simulate green roof performance include EPA SWMM, SWMS-2d, and HYDRUS. These models can simulate computationally difficult processes like the flow through variably saturated soil, convection, dispersion and routing.

Burszta-Adamiak and Mrowiec (2013) used the LID control module of SWMM, which is based off a water balance approach (i.e. calculating infiltration and storage) (Li and Babcock 2014), to try and model the green roof response. Although the LID module of SWMM allowed various relevant green roof parameters to be entered, very poor correlation between the simulated and monitored runoff suggests that SWMM has limited capabilities to model green roof runoff hydrographs. She and Pang (2010) also utilized SWMM, but only for its capabilities in runoff routing. Other components of the model included an infiltration simulation (using Green & Ampt written in FORTRAN) and an ET simulation. The infiltration component was designed so that no drainage is produced until field capacity is reached, and after this point free drainage was allowed. This differs from classical infiltration models (e.g. Green & Ampt), which require the soil to be saturated before drainage occurs. Calibration of the model was conducted with two monitored events, and the validation results show absolute error of about 10% when compared to a 2-month observation period.

Hilten, Lawrence et al. (2008) used HYDRUS, a numerical model to simulate flow and transport in porous media, to model green roof hydrology. HYDRUS solves Richards equation and can be coupled with either the Brooks & Corey relationship or the Van Genuchten capillary pressure/saturation relationship (Van Genuchten 1980). HYDRUS requires a number of inputs including water retention curve data (capillary pressure/saturation), fluid and soil matrix parameters, and meteorological data. Hilten, Lawrence et al. (2008) simulated the green roof assuming the media was 100% sand and with a constant initial condition of 10% volumetric water content. Field capacity, residual water capacity, and wilting point values were measured as 11%, 3%, and 8% respectively as volumetric water content for green roof media vegetated with various sedum species. The model was validated using observed data, and the model was used to simulate the response to design storms. Linear regression of the observed to modelled runoff produced an R^2 of 0.918 and a slope of 1.14, but errors of up to 19 mm of runoff were found. This model was effective at establishing the potential of Richards equation to simulate green roofs, but it did not provide accurate predictive power. Palla, Gnecco et al. (2009) created a similar numerical model based off of Richards equation using SWMS-2D. The domain was 2D and compared the results to field data from a green roof (350 mm depth) in Genoa Italy. Palla, Gnecco et al. (2009) calibrated and validated the model with observed data from 8 storm events (i.e. 4 calibration events and 4 validation events) monitored on a green roof in Italy. The hydraulic conductivity, residual water content, and saturated water content parameters were calibrated to find the best model fit for runoff volume, peak flow, and hydrograph centroid of each calibration event. The model simulated retention to within a 15% error with satisfactory peak delays, but underestimated peak flow rates. Palla, Gnecco et al. (2009) suggests improvement could be made by physically measuring the water retention curves for the substrate, instead of using estimation based off of literature values. Palla, Gnecco et al. (2009) and Hilten, Lawrence et al. (2008) both prove the potential of modelling the green roof as a porous media and using the Richards equation. However, both of these models assume and calibrate very important parameters. To create an accurate predictive model for green roof stormwater performance, all required parameters should be measured in the field or through lab tests.

2.5   Soil Physics

2.5.1   Unsaturated Soils and Retention Models

Green roof substrate is, in most cases, an engineered medium optimized to provide storage and fast infiltration rates to reduce any chance of ponding. In situ conditions of green roof substrate also encourage evaporation, transpiration, and quickly conveyed drainage. Due to a combination of these factors, green roofs rarely, if ever, reach saturated conditions. It is expected for almost all cases, that green roof media acts as an unsaturated system. The retention characteristics and unsaturated flow within a substrate must be considered to accurately reproduce or estimate green roof performance through modelling.

To describe water flow in unsaturated or variably saturated soils, the Richards equation has been used for decades. The Richards equation is a partial differential equation resulting from the combination of the Darcy-Buckingham equation and a continuity requirement. The Richards equation used to calculate vertical flow of water as a function of soil moisture is seen below (Richards 1931).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta) \cdot \left(\frac{\partial H_p}{\partial z} + 1\right)\right] \qquad\qquad 2$$

Where t is the time, z is the depth, and K is the hydraulic conductivity. The Richards equation is directly dependent on both the volumetric water content (θ) and the capillary pressure head (Hp). These two parameters have a complex relationship that changes drastically as soil properties vary (grain size distribution, soil composition, hydraulic conductivity, etc…) (Gerhard 2014). The soil moisture content and capillary pressure relationship for a soil is derived through laboratory scale tests. An example of a characteristic soil water retention curve can be seen in Figure 2.4 below (Molnar 2009), where S_{wr} represents the residual water saturation.
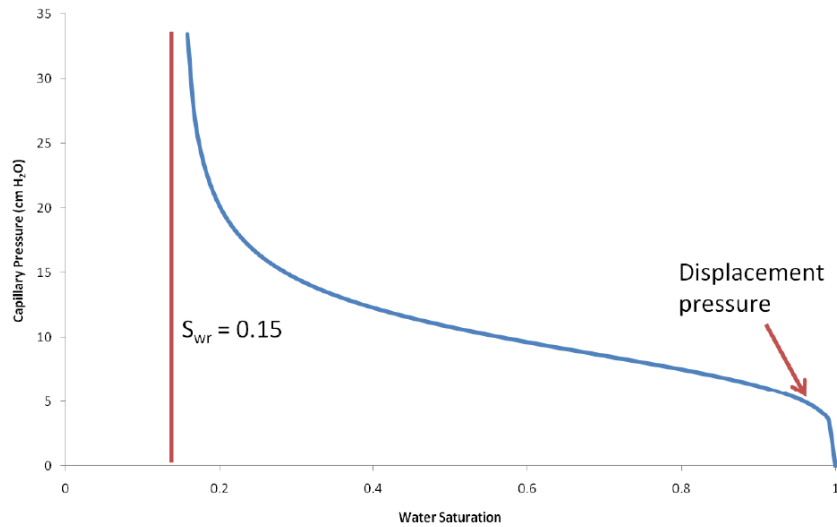
Figure 2. 4: Example of a characteristic capillary pressure-saturation curve (Molnar 2009)

Laboratory tests conducted by Perelli 2014 determined the soil water retention curve for growing media engineered by LiveRoof green roofs. A soil column was studied using pressure transducers and soil moisture probes to establish the imbibition and drainage curves for the substrate. As an example, some of the drainage curves that were derived can be seen in Figure 2.5 below from (Perelli 2014), where P_c is the capillary pressure and S_w is the water saturation.
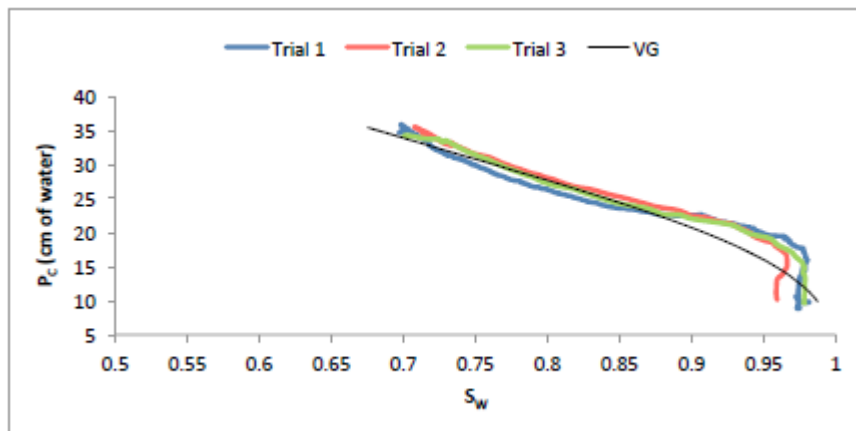
Figure 2. 5: Capillary pressure-saturation curves derived from lab experiment on green roof media (Perelli 2014)

There are two main functions used to empirically describe these soil water retention curves, one was derived by Brooks and Corey (1964) and the second was presented by

Van Genuchten (1980). The Brooks and Corey equation tends to work best for soils that have narrow pore size distribution, while the Van Genuchten generally only fails to accurately represent the soil water retention curve for strongly bimodal pore size distributions (Van Genuchten, Leij et al. 1991). The Van Genuchten relationship is;

$$S_e = \frac{1}{[1+(\alpha \cdot H_p)^n]^m} \qquad 3$$

$$\text{Where } m = 1 - \frac{1}{n} \quad \& \quad S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad \text{4a \& 4b}$$

Where α (1/m), n (-) and m are all empirical constants used to adjust the shape of the soil water retention curve, θ_r is the residual water content, θ_S is the saturated water content, Hp is capillary pressure head, and Se is effective saturation. α is related to the entry pressure of the substrate and n is an indicator of the pore size distribution (Van Genuchten, Leij et al. 1991).

The Van Genuchten relationship is also commonly coupled with the Mualem (1976) relative permeability hydraulic conductivity model. This is important to consider, since in an unsaturated medium, the hydraulic conductivity is a function of the moisture content (Equation 1). So to have an accurate idea of the processes occurring in unsaturated media, the functions for soil water retention and hydraulic conductivity are coupled. This provides a value for hydraulic conductivity that is dependent on the saturation of soils referred to as relative permeability. When coupled with the Van Genuchten model it can be calculated as (Van Genuchten 1980):

$$K(S_e) = K_s S_e{}^l \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \qquad 5$$

Using these relationships and the derived soil water retention curves for green roof media, analysis of the green roofs stormwater performance during precipitation events could be analyzed through analytical or numerical modelling. This is an avenue that has not been researched adequately yet, but has direct implications on how green roof hydrology is understood. Some models have been proposed that assume or calibrate soil parameters, but by measuring all of the required parameters, a predictive model could be developed.

2.6 Summary

An analysis of green roof current research demonstrates substantial evidence suggesting that green roof design factors such as media depth, roof slope, roof age, plant selection, and study period all significantly affect stormwater retention performance. This is reinforced by the fact that there is a wide range in reported retention values from various studies that all have varying green roof design components. One important factor that has not been addressed in literature yet is the impact that green roof location and climate region has on the retention performance. Whether it is even reasonable to compare green roof performance in different climates is not known. By controlling all the design factors for green roofs in different climates, the retention performance of green roofs in changing climates could be assessed for the first time.

There is limited knowledge of how green roofs actually provide peak flow attenuation, yet it is one of the most important functions that a green roof provides. The peak attenuation benefits of green roofs have been reported in various studies. However, the antiquated definition of peak attenuation may be hampering the understanding of the fundamental green roof processes that attenuate stormwater. Concepts such as field capacity, drainage routing, gravity storage, and capillary storage have been briefly mentioned in some studies (Bengtsson 2005; DeNardo, Jarrett et al. 2005; Hilten, Lawrence et al. 2008; Speak, Rothwell et al. 2013), but no research has yet isolated the response and quantified the individual impact of these processes.

There is a wide range of green roof models that have been published in literature, including empirical, physical, and numerical models. Unsaturated soil theory has potential for modelling green roof stormwater response, however, all of the current models either calibrate or assumed important model parameters (Hilten, Lawrence et al. 2008; Palla, Gnecco et al. 2009). There is an opportunity to develop a numerical model, based on the Richards equation, which would require no calibrations and act as a predictive tool for green roof outflow hydrographs. An accurate predictive green roof model would have major implications for progressing the design of green roofs to as stormwater management LID controls.

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Chapter 3

3 Retention Performance of Green Roofs in Three Different Climate Regions

3.1 Introduction

Urban rooftops generally constitute 40-50% of all urban impervious surface area (Mentens, Raes et al. 2006). Therefore retrofitting the rooftop areas provides considerable opportunity to mitigate the effects of stormwater runoff. Excessive urban stormwater can contribute to pollution of streams, rivers and lakes, as well as channel erosion, flooding and infrastructure damage (P'ng, Henry et al. 2003).

Green roofs provide retention of stormwater by storing water in the growth media and to a lesser extent in the vegetation canopy. Water is held in the soil pore space by capillary forces until it is transpired through the vegetation or evaporated to the atmosphere. Evapotranspiration (ET) restores soil pore space and the green roofs ability to retain stormwater. However, green roof growth media is only able to retain a finite amount of precipitation. Once the storage capacity of the green roof growth media is full, runoff or drainage will occur. Quantifying the ability of a green roof to retain stormwater is essential to guide the implementation of this technology as a low impact development (LID) control.

Green roof studies have been conducted all over the world from Europe (e.g. Italy (Palla, Gnecco et al. 2009), UK (Stovin, Vesuviano et al. 2012), and Sweden (Bengtsson, Grahn et al. 2005)) to North America (e.g. Texas (Volder and Dvorak 2014), Portland (Hutchinson, Abrams et al. 2003), and New York (Carson, Marasco et al. 2013)) and Asia/Oceania (e.g. New Zealand (Voyde, Fassman et al. 2010) and South Korea (Lee, Moon et al. 2013)). More importantly, due to the increasing recognition of the stormwater management benefits, green roofs are being installed more frequently all around the world. Literature focusing on stormwater retention has evaluated the impact of growth media depth (VanWoert, Rowe et al. 2005; Nardini, Andri et al. 2012), roof slope (VanWoert, Rowe et al. 2005), vegetation type (Wolf and Lundholm 2008; Nagase and

Dunnett 2012), and age (Berndtsson 2010; Perelli 2014). Most studies consider real rain events, although some literature focuses on artificial (i.e. man-made) rain events (Villarreal and Bengtsson 2005; Buccola and Spolek 2011). Despite the increase in global application of green roofs as a stormwater management tool, the influence of climate on retention performance and applicability of results from one location to another is uncertain. Comparison of results from literature is difficult as they typically have differing green roof design components (e.g. media depth and slope) and study duration (e.g. one season or on an annual basis) in addition to study location. This is evident in the variability seen in reported performance.

Reported retention performance in the literature varies. For example Mentens, Raes et al. (2006) reported annual retention values ranging from 27-81%, when compiling results from 18 different studies. Similarly Gregoire and Clausen (2011) reported retention between 34 - 69% based on 13 recent extensive green roof studies. Retention differences may, in part, be due to climatic differences in the study areas. For example Stovin, Vesuviano et al. (2012) found 50% annual retention in Sheffield, England, and Fassman-Beck, Voyde et al. (2013) reported 39% retention for a green roof in Auckland, New Zealand. Alternatively, Hutchinson, Abrams et al. (2003) and Carpenter and Kaluvakolanu (2011) reported improved retention of 69% and 68% in Portland, Oregon and Southfield, Michigan, respectively. Although retention performance differences may be due to climate, it is not possible to isolate and evaluate the effects of climate from the current literature due to the differing green roof design parameters and durations of these studies.

Stormwater green roof retention studies in the literature range in duration from 2 months (DeNardo, Jarrett et al. 2005) to greater than 18 months (Moran, Hunt et al. 2005; Stovin, Vesuviano et al. 2012; Fassman-Beck, Voyde et al. 2013). Study duration is important for the reported retention performance, as the degree to which ET replenishes storage capacity between storms is a function of season (i.e. ET rates are typically greater in summer when compared to late fall). Additionally, longer duration studies are more likely to represent historical climate normal, whereas a larger return period event observed in a short study may skew data. For example, with 4 months of monitoring data Stovin (2010)

obtained retention of 34%, while after continued monitoring for a total of 29 months Stovin, Vesuviano et al. (2012) reported an updated retention of 50%. Similarly, Voyde, Fassman et al. (2010) found a retention of 66% over 12 months of monitoring in Auckland New Zealand while Fassman-Beck, Voyde et al. (2013) reported a long term retention of 56% over 28 months of monitoring the same site, increasing the sample size from 91 to 396 events. It is important to consider multiple seasons (i.e. spring through fall) to provide a representative event sample size; once this is accomplished, analysis of the annual and event based retention performance of green roofs is reasonable.

In general, literature studies report greater percentage retention for smaller size events, as less ET is required prior to the event to generate sufficient storage capacity in the green roof growth media. For example, the study of VanWoert, Rowe et al. (2005), conducted in Lansing, Michigan over 430 days, quantified retention for 83 rainfall events using green roof platforms (0.67m x 2.44m) of varying depths. They found 97% retention for light events (i.e. <2mm), 83% for medium events (i.e. 2-6mm) and 52% for heavy events (i.e. >6mm); similar trends were also found by Getter, Rowe et al. (2007), Fassman-Beck, Voyde et al. (2013), Carter and Rasmussen (2006), and Carpenter and Kaluvakolanu (2011). However, each study grouped event size differently and found varying amounts of retention. Carpenter and Kaluvakolanu (2011) studied a green roof in Southfield Michigan (100mm depth), in close proximity to VanWoert, Rowe et al. (2005), and found 98.6% retention for small events (i.e. <12.6mm), 90.2% retention for medium events (i.e. 12.7-25.4mm) and 52.7% retention for large events (i.e. >25.4mm). Carpenter and Kaluvakolanu (2011) had a study period of 6 months and observed 21 storms, only 3 of which were in the large size category. The influence of study durations and green roof design parameters are evident in the disparity between the results of VanWoert, Rowe et al. (2005) and Carpenter and Kaluvakolanu (2011) considering the different storm size classifications adopted. Additionally, Speak, Rothwell et al. (2013) conducted a similar analysis on an intensive 170mm deep green roof in Manchester UK. They found higher average event retention for medium events (i.e. 2-10 mm) than for small events (i.e. <2 mm), a result that is unique in green roof literature. Studies in close proximity have varying results due to different durations and design components, and studies in different

climates yield varying results as well. To effectively evaluate the impact of climate on retention the same green roof design is needed as well as similar study duration.

In addition to quantification of retention for different storm sizes, there is a particular need to understand retention for significant events with large return periods. It is these events that generally overwhelm stormwater management systems and result in flooding. Stovin, Vesuviano et al. (2012) quantified retention performance for 'significant' events (i.e. greater than 1-year return period in their case). They used a 3m x 1m x 0.08m green roof test bed in Sheffield, England, over a 29-month period to measure 21 significant events and reported a total retention of 30% for the significant events. Other groups have quantified retention for very large rainfall events (i.e. >45 mm) and reported retention ranging from 0 to 60% (Carter and Rasmussen 2006; Carpenter and Kaluvakolanu 2011; Stovin, Vesuviano et al. 2012; Speak, Rothwell et al. 2013). With the large range of results reported, additional information on green roof performance under significant rainfall events is required.

There is a need to quantify the response from similar green roofs in different climate regions to isolate and evaluate the impact of climate on retention performance. As such, this study assesses the retention response of three green roofs in distinctively different climates. The green roof design was replicated at each site (i.e. depth, vegetation, age) with identical instrumentation and monitoring periods. The retention performance of the green roofs in different climates is compared based on event size retention and annual retention. The factors controlling retention performance as well as the climates under which green roofs provide optimal performance are considered. Finally, large design storms (i.e. storms greater than 2-year return period, used for SWM design) are assessed to provide insight on the benefits of green roofs compared to traditional stormwater management tools.

3.2   Materials and Methods

3.2.1   Site Description

Three experimental green roofs were installed in July 2012 in London Ontario, Calgary Alberta, and Halifax Nova Scotia. The site and climate characteristics are shown in Table

3.1 and layouts are shown in Figure 3.1. The green roof installed in London, Ontario is on Talbot College at Western University. The Calgary, Alberta green roof was placed on the Earth Sciences building at the University of Calgary. Lastly, the Halifax, Nova Scotia green was installed on an office building in a business park. All of the climate normal data in Table 3.1 is based on data from 1981-2010 (Environment Canada, 2015). The plant hardiness rating shown in Table 3.1 is used by Agriculture Canada to evaluate where vegetation is most likely to survive, based on average climatic conditions from 1961-1990. In this scale 0 is the harshest conditions and 8 is the mildest conditions for plant life (Agriculture Canada, 2015).

Table 3. 1: Site and climate characteristics of the three green roofs

	London Ontario	*Calgary Alberta*	*Halifax Nova Scotia*
Underlying roof type	Conventional asphalt	Gravel ballast	White roof
Latitude, Longitude	43.007613, -81.270607	51.079991, -114.129280	44.696163, -63.581223
Roof area (m^2)	65	52	55
Yearly rainfall (Environment Canada, 2015)	845.9 mm	326.4 mm	1,196.1 mm
Max/min monthly average temperature (Environment Canada, 2015)	20.8 ℃ and -5.5 ℃	16.5 ℃ and -7.1 ℃	19.1 ℃ and -4.1 ℃
Climate region (Statistics Canada, 1998)	Great Lakes/St. Lawrence (warm summers, cool winters)	Prairie (extreme temperatures)	Atlantic Canada/Maritime (warm winters, cool summers)
Plant hardiness rating (Agriculture Canada, 2015)	5b - 6a	3a	6a

Figure 3. 1: Experimental green roofs in a) London Ontario b) Halifax Nova Scotia and c) Calgary Alberta

These green roofs are extensive modular LiveRoof setups (LiveRoof 2014) consisting of 0.3m x 0.3m modules with 150 mm growth media depth. The green roof arrays have an elevated central section (0.2 m high) to enable instrumentation to be placed under the vegetated modules. All of the hydrologic measurements are taken from individual modules on the elevated portion of the array. Modules surrounding the central elevated section are sloped at 12 degrees. As the green roof arrays are modular installations, there is no drainage layer or filter membrane used and the drainage flow paths are built into the module. The green roof modules that are the subject of this study were on the elevated portion of the array and were planted with *Sedum spurium* 'John Creech'. The modules had complete vegetation coverage throughout the monitoring period. The growth media mixture, provided by LiveRoof, is the same at all three sites and consists of fine and coarse haydite, crushed dolostone, bark, peat moss, and some fertilizer. The properties of the growth media were quantified in soil tests conducted at Pennsylvania State University (LiveRoof 2008) as well as at Western University (Perelli 2014). Analysis of the green roof growth media indicates that it meets FLL guidelines (FLL 2002).

3.2.2   Instrumentation

The experimental green roofs were monitored from September 2012 until November 2014, encompassing more than two full monitoring seasons. A full monitoring season generally ranged from March to November and was selected to avoid snow accumulation at each site. Most of the season in 2012 was required for green roof construction and set up of instrumentation. Rainfall was measured using Texas Electronic TE525WS-L tipping bucket rain gauges. Each site had one or more rain gauges that were embedded in the array and collected rain at the same height as the vegetation canopy, and one external rain gauge that measured rainfall directly adjacent to the array. The tipping buckets tip volume ranged from 0.09mm/tip to 0.14 mm/tip depending on the calibration of each specific rain gauge.

Drainage from 2-4 replicate single green roof modules at each site was also measured continuously using tipping buckets. Drainage units installed beneath single modules funneled runoff from the bottom of the module directly into a tipping bucket. The

drainage units have slightly improved resolution, ranging from 0.04 mm/tip to 0.06 mm/tip depending on the instrument calibration.

Water storage and evapotranspiration was monitored continuously on 2-4 replicate single module weighing lysimeters. These lysimeters used an Interface SPI-25 load cell to provide continuous high-resolution module weights. Lysimeter data was also used to estimate drainage volumes. The lysimeter design was similar to the design detailed in Grimmond, Isard et al. (1992).

3.2.3   Data Collection and Analysis

Data was collected at each site using Campbell Scientific data loggers (CR3000) logging at 1-minute intervals. Over the period monitored from September 2012 - November 2014, 160, 86, and 98 rain events were recorded at London, Calgary and Halifax respectively. A rain event was defined as a period of precipitation followed by 6 consecutive hours of no precipitation (VanWoert, Rowe et al. 2005; Getter, Rowe et al. 2007; Voyde, Fassman et al. 2010; Stovin, Poe et al. 2013). Any rainfall that resulted in more than a one tip of the rain gauges was considered an event. This definition ensures that an observed event could not be the result of residual rainfall left stagnant in a bucket from previous events. Critical instrumentation malfunctions were experienced at the Halifax and Calgary sites during the 2012 season and at the Halifax site from 13 March– 9 May 2013 and 12 March– 22 May 2014 decreasing the number of rainfall events captured at these sites.

The volumetric retention of stormwater is reported as the depth of water (mm) stored over an arbitrary time period. Retention is also reported as the percentage of rainfall stored:

$$Retention\ (\%) = \frac{Rainfall\ (mm) - Runoff\ (mm)}{Rainfall\ (mm)} \cdot 100 \qquad\qquad 6$$

3.3   Results and Discussion

3.3.1   Monitored Cumulative Retention

Green roof stormwater retention performance was quantified in London Ontario for two complete monitoring seasons in 2013 and 2014 and for 2 months in 2012 (Figure 3.2a).

Stormwater retention is the difference between cumulative rainfall and drainage. The drainage measured by the lysimeter and tipping buckets have small discrepancies probably due to heterogeneities in the modules. The cumulative stormwater retention performance for 2012, 2013, and 2014, based on the averaged tipping bucket and lysimeter drainage data, was 41.1%, 47.1%, and 50.7% respectively. The total recorded rainfall was 1,720 mm and the drainage was 892.5 mm (48.1% retention). This long-term retention is consistent with previous studies (Mentens, Raes et al. 2006; Gregoire and Clausen 2011). Liu and Minor (2005) measured an annual retention of 57% from a 100 mm depth green roof in Toronto Ontario and VanWoert, Rowe et al. (2005) measured a retention of 60.6% over a year in Lansing Michigan. Both of these sites are expected to have similar climates to London as they have relatively close proximity (i.e. less than 300 km distance). The high retention found by VanWoert, Rowe et al. (2005) may be due to use of a retention mat and rainfall over the study period being substantially less than the climate normal for the area (NCDC 2015).

In 2013 and 2014 between mid-May and early September there were extended periods with minimal runoff (i.e. slightly over 200 mm of rainfall but only about 50 mm of runoff) (Figure 3.2a). This is attributed to large ET rates during the hot summer months generating available water storage in the growth media. Precipitation over the 2013 and 2014 monitoring periods was relatively evenly distributed (Figure 3.2a) consistent with climate normals for London Ontario (Appendix Figure A1). Evenly distributed precipitation is advantageous for retention as it provides time for ET and thus storage capacity to be recovered between rainfall events. Given that the rainfall over the monitoring period is consistent with the regional climate normals, it is reasonable to expect about 47-50% retention in London over extended periods of time.

Calgary received only 388.8 mm of rain over the 2013 monitoring period, with an average of 151.3 mm of drainage, resulting in 61.1% retention (Figure 3.2b). In the 2014 monitoring period there was 314.9 mm of rainfall and 78.1 mm of drainage, resulting in 75.2% retention. This retention is substantially higher than London, Ontario. The total retention in Calgary of 67% is at the upper range of that previously reported but very similar to the findings of Hutchinson, Abrams et al. (2003) and Carpenter and

Kaluvakolanu (2011). Carpenter and Kaluvakolanu (2011) measured 68 % retention in Southfield Michigan with 100 mm media depth from 21 events over 6 months. 340 mm of rainfall occurred over their study period which is considerably less than the climate normal for Detroit Michigan (NCDC 2015), but comparable to the rainfall amounts in Calgary. Hutchinson, Abrams et al. (2003) studied annual retention from a 76 mm green roof in Portland Oregon, which historically receives >900 mm of rainfall per year (NCDC 2015). Hutchinson, Abrams et al. (2003) recorded annual retention of 69% with more than 1000 mm of rainfall. This is a unique result in literature, and is the only North American study to report >65% retention at a location with high rainfall amounts.

As expected from the climate normal (Appendix Figure A2), Calgary received less precipitation than the sites in London and Halifax. This provides longer drying periods in Calgary and subsequently a greater amount of storage available for retention. In 2013 and 2014 there were prolonged periods of no drainage with intermittent large drainage events. For example, in 2014 there was minimal drainage over the entire monitoring period except for two large events on June 18th (45 mm rainfall) and September 8th (49.3 mm rainfall), which resulted in a total of 66.9 mm of drainage. For the remainder of the period, 220.45 mm of rainfall (46 events) only produced 16.3 mm of drainage. Similarly in 2013 there were three large rainfall events on May 23rd, May 31st, and June 19th, which resulted in 132.5 mm drainage while the remainder of the events (35 events) only produced 18.8 mm of drainage.

Halifax experienced two very different monitoring seasons with respect to rainfall amounts, with 1164.8 mm of rainfall in 2013 (59 events) compared with 446.5 mm in 2014 (39 events) (Figure 3.2c). From a historical perspective, the 2013 precipitation exceeded the expected precipitation of 822 mm and the 2014 precipitation was below the historical average of 552 mm for the respective monitoring periods (Appendix Figure A3). In 2013 the annual retention for the green roof was 27.7 %, while in 2014 the retention increased to 43.4 %. These results indicate that reduced rainfall amounts improve annual retention and implies a connection to site climate normals. The total retention for Halifax was 33.5%, which is substantially less than London and Calgary. Some literature does report retention values similar to Halifax. For example, Mentens,

Raes et al. (2006) suggests annual retention can be as small as 27%, and Stovin (2010) observed retention of 34% in Sheffield England with 80 mm media depth green roof, however, they only considered 11 events over 4 months.

The Halifax green roof retention in 2014 is interesting because only 446.2 mm of rainfall occurred over 158 days, well below the historical average. However, there was limited cumulative retention (43.4%). The drainage response in Halifax over the 2014 monitoring period (Figure 3.2c) differs substantially from the response in Calgary (Figure 3.2b), which has similar total rainfall but almost no drainage except for a few major storms. This shows that, while amount of rainfall greatly impacts retention performance, climate factors (e.g. temperature, relative humidity, and wet hours) that affect ET rates also have considerable impact on green roof retention. Sites with high precipitation coupled with high ET rates are likely to have the highest retention performance. This is further investigated by comparing the volumetric retention of the three sites.

While the green roof in Calgary had the highest percent retention, when the total volume of retained water over the 2013-2014 monitoring seasons is considered, London had the best volumetric retention, retaining a total of 757.9 mm of rainfall (i.e. an average of 53 mm/month). Halifax retained 516.6 mm (i.e. an average of 43 mm/month) and Calgary only retained 474.3 mm (i.e. an average of 41 mm/month). The roof in London had good volumetric retention due to the moderate climate, receiving considerable rainfall while also having adequate ET rates. Storing and evaporating a larger volume of water will also result in increased evaporative cooling, benefiting the urban climate and building cooling loads (Sailor 2008). The low rainfall due to Calgary's dry climate limited the volumetric retention performance. It is interesting to note that while annual percent retention was substantially greater for the roof in Calgary, due to Halifax's maritime climate and high rainfall, the green roof in Halifax had higher volumetric retention, both overall and on a monthly basis. The fact that the green roof in London retained the greatest volume of rainfall shows that the retention performance of green roofs are not only affected by rainfall amounts but also by ET rates, both of which are climate dependent.
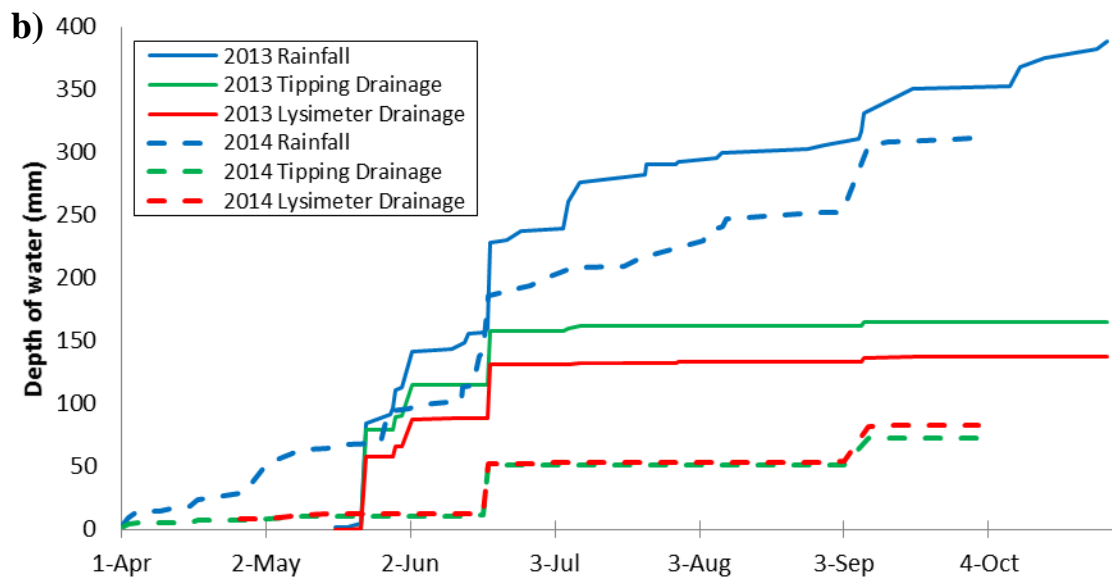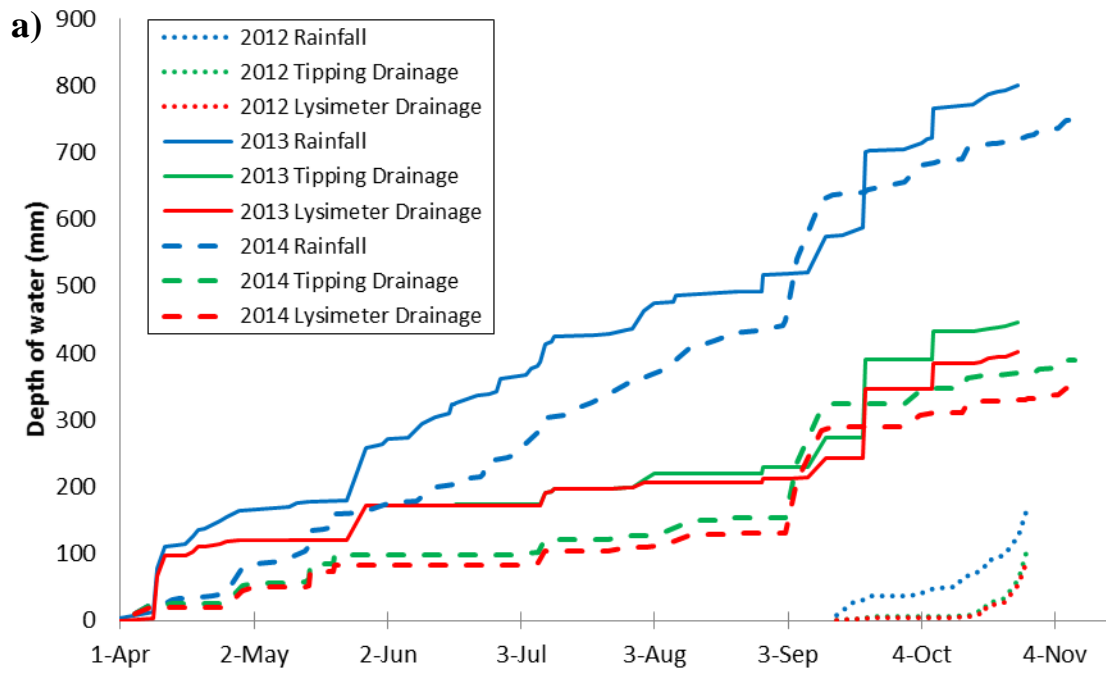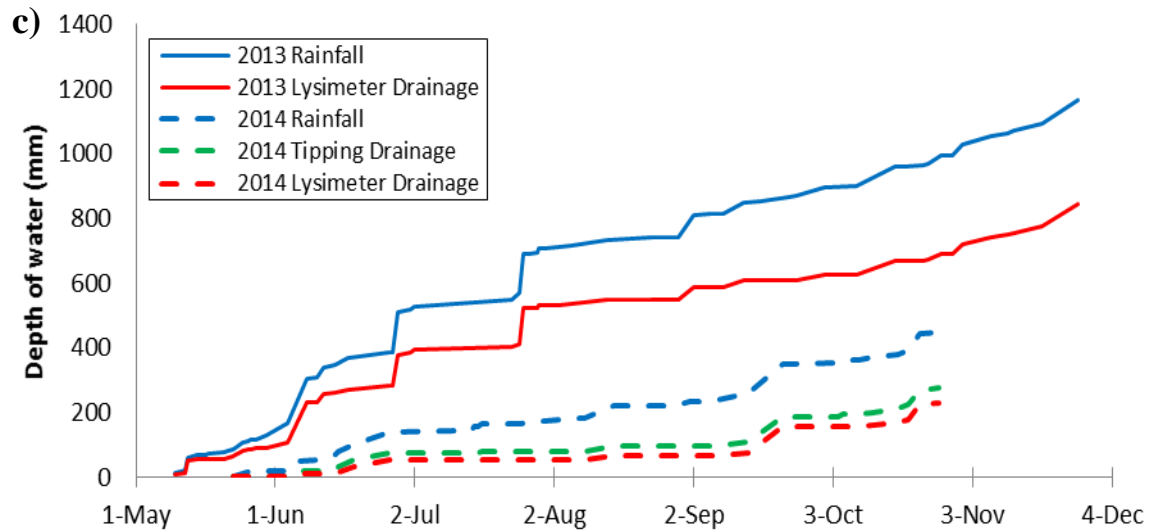
Figure 3. 2: Cumulative retention in a) London Ontario b) Calgary Alberta and C) Halifax Nova Scotia over the 2012-2014 monitoring seasons. The rain gauge (blue), lysimeter drainage (red) and the tipping bucket drainage (green) are shown.

The extent to which green roofs decrease stormwater drainage was analyzed using cumulative exceedance plots (Figure 3.3). These graphs are generated by ranking all rainfall and drainage events by size, then calculating the cumulative frequency of the respective event size occurring, based on its rank. The cumulative probability shows the percentage of events that will have rainfall or drainage depths of less than the corresponding water depth on the x-axis. For example, 90% of all drainage events are less than 14.4 mm, 2.9 mm, and 22.9 mm for London, Calgary and Halifax, respectively, indicating large differences in retention performance for each site. Comparatively, the 90th percentile rainfall events are 26.6 mm, 22.2 mm, and 37.1 mm for London, Calgary and Halifax, respectively. Figure 3.3 shows the cumulative exceedance plots for London (160 events), Calgary (86 events), and Halifax (98 events) over the 2013-2014 monitoring seasons. An important note to consider in Figures 3.3 is that Halifax, London, and Calgary, completely retain 15.2%, 33.6% and 66.7% of all rain events, respectively. Retaining such a high percent of storms will have considerable benefits for reducing the environmental damage of stormwater runoff on receiving water bodies.
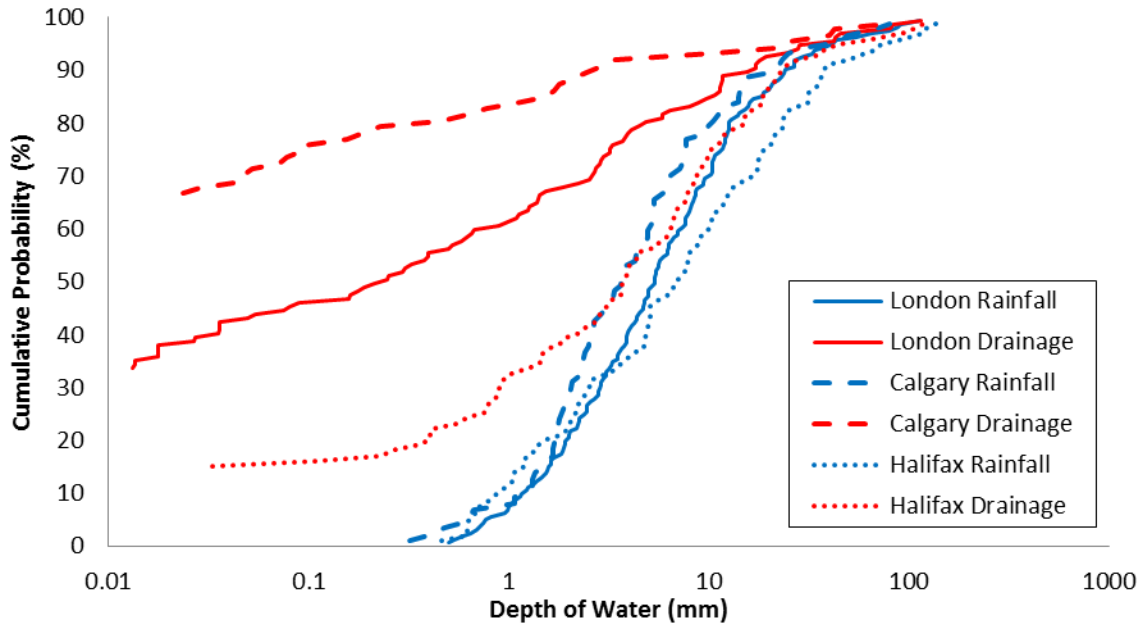
Figure 3. 3: Cumulative exceedance curves for London, Calgary and Halifax

Using the Kolmogorov-Smirnov (K-S) statistical tests it was found that there was a significant difference between rainfall and drainage for all α tested (up to $\alpha=0.001$) for both London and Calgary. K-S statistical tests on the Halifax data showed that there is a significant difference between rainfall and drainage for α up to 0.05. For α values smaller than 0.05 there was no statistically significant difference between the two frequency curves. The fact that both London and Calgary have a significant amount of retention for all α values, while Halifax only shows significant retention up to an α of 0.05 implies that Halifax is less efficient at retaining rainfall. Further K-S tests show that rainfall frequency curves for London and Calgary, as well as London and Halifax ($\alpha = 0.1$) were not statistically different. However, there were significant differences between the drainage curves for London, Calgary, and Halifax ($\alpha = 0.001$). Given this, it can be said that Halifax has significantly worse retention than London and also that London has significantly worse retention than Calgary. Cumulative exceedance plots for each individual site can be seen in Appendix Figure A4.

3.3.2   Monitored Average Event Retention

Previous studies evaluate green roof retention performance based on rainfall event size (VanWoert, Rowe et al. 2005; Getter, Rowe et al. 2007; Carpenter and Kaluvakolanu 2011). Similar to Getter, Rowe et al. (2007) and VanWoert, Rowe et al. (2005), storms were grouped into three size categories: small (<3mm), medium (3-15mm), and large (>15mm). These size categories provide a roughly even distribution of events in each category, creating comparable sample sizes. Between the three sites, 344 events were recorded, of which 121, 156, and 67 were classified as small, medium, and large (Table 3.2 and Figure 3.4).
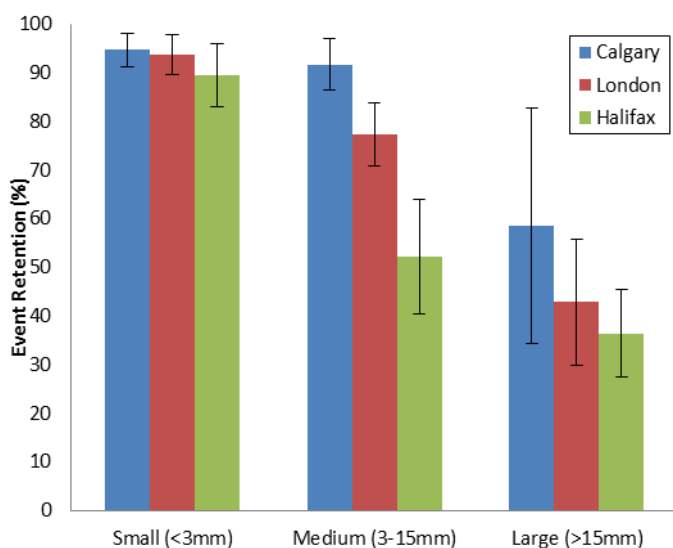
Figure 3. 4: Average event retention for all sites (error bars indicate 95% confidence interval)

Table 3. 2: Average event retentions

London, Ontario		
Events	Event Size	Retention (%)
51	Small (<3 mm)	93.76
81	Medium (3-15 mm)	77.24
28	Large (>15 mm)	42.81
160	All events	76.48
Calgary, Alberta		
38	Small (<3 mm)	94.65
39	Medium (3-15 mm)	91.74
9	Large (>15 mm)	58.54
86	All events	89.55
Halifax, Nova Scotia		
32	Small (<3 mm)	89.59
36	Medium (3-15 mm)	52.18
30	Large (>15 mm)	36.42
98	All events	59.56

A decrease in event stormwater retention as storm size increases (Figure 3.4) is consistent with prior studies (VanWoert, Rowe et al. (2005), Getter, Rowe et al. (2007), Fassman-Beck, Voyde et al. (2013), Carpenter and Kaluvakolanu (2011), and Carter and Rasmussen (2006)). Calgary has the highest average retention in each size category, while Halifax has the lowest. This is in agreement with the annual retention trends discussed earlier. The only size category in which the three sites have significantly different event retentions is for medium size events (i.e. 3-15 mm). As expected, the smallest storm size category (i.e. < 3 mm) is not significantly different across the three

sites since the ET rate and time required to replenish storage volume is relatively small and feasible at each site. The large storms also do not show a significant difference in performance. This could be due to the limited storage available in the growth media meaning that a certain amount of drainage will occur during large events, regardless of site location. Analysis of the medium event response indicates that the significant difference in retention performance can be attributed to the soil moisture conditions at the start of each event. The average medium storm sizes at each site were relatively consistent for Calgary (7.1mm), London (7.3mm), and Halifax (7.7mm). However, the average initial moisture condition at each site, reported as available storage, was 7.3 mm, 5.9 mm, and 4.5mm for Calgary, London and Halifax, respectively. Linear regression of the initial moisture conditions with respect to the average event retention yields a slope of 0.08 and an R^2 of 0.96 (Appendix Figure A5). Every additional mm of storage available at the start of an event results in a 12.5% increase in the average event retention. The storage available and retention is therefore directly impacted by the preceding drying conditions and ET rates, and thus the diverse climates of the three sites.

The large difference in total event retention performance across the three sites may partially be attributed to Calgary receiving 9 large events while London and Halifax experienced 28 and 30 large events. Some literature has suggested that antecedent dry weather period (ADWP) has a large impact on event retention (Getter, Rowe et al. 2007; Voyde, Fassman et al. 2010). This was not the case at the three sites monitored here. The average ADWP was 2.7 days, 3.3 days and 3.6 days for London, Halifax and Calgary, respectively, while the average event retention was 77%, 60%, and 90% (Table 3.2). There is no clear trend with respect to ADWP, likely due to the inherent problems with the definition (i.e. a 0.5 mm event would not affect storage much but would reset the ADWP). Initial moisture conditions (i.e. determined by ET conditions preceding event) combined with rain event sizes are much more powerful indicators of event retention. Therefore, understanding the climate where green roofs are installed is essential to design optimization. It can aid in decisions such as selection of media depth, as well as provide information on areas where the greatest reduction of stormwater runoff will be experienced and assist stormwater engineers with projected performance.

The response of the three sites to 'significant' events (i.e. >2-year storm) was also compared. Over the monitoring periods London and Halifax had six significant events, and Calgary had three. The average event retentions for the significant events were 16.4%, 21.1%, and 15.3% for London, Calgary, and Halifax respectively. These values are slightly better than the event retention of 11.8% calculated from data of Stovin, Vesuviano et al. (2012), which had 4 significant events greater than the 2-year return period. Comparison of significant event green roof performance at sites with different climates should be done with caution as design IDF curves are different for each location. Nonetheless, design storms (i.e. ≥2-year storm) are a useful metric commonly used by stormwater managers and engineers to design stormwater infrastructure.

For a more impartial comparison of very large events, without the influence of regional IDF curve variability, green roof performance for all events larger than 45 mm were analyzed and compared with available literature data (Appendix Figure A6 and Table A1). Stovin, Vesuviano et al. (2012) reported three events >45mm, while Carter and Rasmussen (2006) had six, and Carpenter and Kaluvakolanu (2011) and Speak, Rothwell et al. (2013) each had one. During the monitoring periods, Calgary had four events >45mm while Halifax had nine, and London had six. Carter and Rasmussen (2006) reported extremely high average event retention of 49.1%, retaining as much as 41.7 mm of water (from an 84.3 mm rainfall) with a 75mm depth green roof. Achieving this much retention for large events at any of our three monitoring sites is unlikely, considering that the maximum event storage observed over all rain events was 26.5 mm, 27.6 mm, and 31.6 mm in London, Calgary and Halifax respectively. The average event retention for events >45mm was 28.6% in Calgary, 17.7% in Halifax, and 16.4% in London. These values are much higher than the calculated average event retention of 6% in Stovin, Vesuviano et al. (2012). Carpenter and Kaluvakolanu (2011) retained 35.4% (26.4 of 74.7 mm) and Speak, Rothwell et al. (2013) retained 39.4% (22.1 of 56.1 mm) for each of their events. Speak, Rothwell et al. (2013) monitored a 170 mm intensive roof, which could account for the high retention. Whereas Carpenter and Kaluvakolanu (2011) experienced an uncharacteristically dry year for rainfall in Michigan, as noted earlier when comparing their findings to the retention response observed in Calgary. In fact the maximum retention of 26.4 mm experienced by Carpenter and Kaluvakolanu (2011) is

similar to that of Calgary (27.6 mm) and London (26.5 mm). Appendix Figure A6 shows that Carter and Rasmussen (2006) repeatedly have the highest retention, while Stovin, Vesuviano et al. (2012) has very low retention. It is clear that for very large events the retention is greatly influenced by the limited storage available in growing media relative to the large total rainfall amount. Therefore the variation in retention values from site to site will be reduced for very large events but still directly impacted by the available storage, and as a result, the climate influences.

3.4   Summary and Conclusions

It is difficult to compare the retention performance from various green roofs of conducted in different climates. However understanding the impact of climate on retention ultimately helps identify climate regions where the benefits of green roofs for stormwater management are highest. Calculation of retention performance at three green roof sites in Calgary, London and Halifax found that cumulative retention was greatest in Calgary (67%) and lowest in Halifax (33.5%). This is attributed to less total rainfall in Calgary as well as longer drying periods resulting in more available storage to retain water. On a total volume basis, however, London retained the greatest overall volume of water because it is located in a moderate temperate climate, providing adequate dry periods for ET as well as considerable rainfall, rather than coastal (Halifax) or semi-arid (Calgary) climates.

Consistent with prior studies, on an event basis, small events (<3mm) were retained much more efficiently then medium (3-15mm) and large events (>15mm). There was a statistically significant difference in the performance of the three sites for medium sized events. Correlation between the initial moisture contents (i.e. available storage) and the event retention ($R^2 = 0.96$) indicates that the retention performance of a green roof is significantly impacted by the climate (i.e. temperature, relative humidity, net radiation) and precipitation normals. Evaluating the retention for design storms are particularly important since these storms impact the design of stormwater infrastructure, however the regional differences in the definition of the size of a 2-year return period storm can bias

the retention. Maximum observed storage at the three sites ranged from 26.5 mm to 31.6 mm, which clearly defines the upper limit of storage that can be obtained for significant events.

Ultimately it can be concluded that drier climates receiving less rainfall will retain a much higher percentage of rainfall in comparison to wet climates. However, this should not discount the service that green roofs can provide in wet climates to reduce the total volume of runoff and help mitigate against the impacts of rain events of all sizes. A green roof in a moderate climate, where there is considerable rainfall as well as extended drying periods, can deliver substantial benefits in the form of high average percent retention as well as large reduction in runoff volumes. Green roofs provide high retention of stormwater for small events in all climates, but the impact of climate is a significant factor when considering medium sized events. The maximum storage available in green roofs limits the extent to which very large events can be retained.

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Chapter 4

4 Quantification and Prediction of Peak Flowrate Attenuation Mechanisms on Green Roofs

4.1 Introduction

Impervious surfaces in urban areas increase stormwater drainage with subsequent stress on municipal infrastructure and downstream environments (e.g. channel erosion and increased flooding). Green roofs are a low impact development (LID) tool that can mitigate excessive stormwater drainage and its impacts (Dhalla and Zimmer 2010). They are generally comprised of a waterproofing membrane, a drainage layer, followed by growing media and vegetation layers. In addition to retaining stormwater and thus reducing the volume of stormwater (Chapter 3), green roofs can attenuate and also delay peak stormwater flow rates (P'ng, Henry et al. 2003; Dhalla and Zimmer 2010). Reduced flow velocities decrease downstream environmental damage, while peak run off delay reduces the total peak sewer flowrates by allowing runoff from impervious surfaces to move through stormwater infrastructure before green roof runoff. The stormwater management benefits that green roofs provide are now acknowledged by a number of large cities. For instance, the City of Toronto requires a green roof on any newly constructed building with over 2000m^2 of floor area (City of Toronto 2012). With the increasing installation of green roofs, detailed knowledge of how they attenuate and delay peak flow rates is essential to optimize their performance as a stormwater management tool.

When precipitation falls on a green roof, rain is held in the media through capillary storage until field capacity is reached, at which point drainage occurs. Figure 4.1 illustrates the water storage and drainage response of a green roof during two typical rain events. Field capacity is defined in a variety of ways in the soil literature but is generally considered the point at which soil water flux out of the rooting zone becomes negligible for deep soil profiles (Twarakavi, Sakai et al. 2009; Assouline and Or 2014). As it relates to green roofs, here we consider field capacity to be the point at which capillary pressure can no longer permanently store water in the growing media. The concept of field

capacity is indicated in Figure 4.1. The interception of the horizontal and vertical dashed lines indicates the storage capacity and time at which there is no more capillary storage available and field capacity is reached. In Figure 4.1a there are three clear rainfall peaks. The first two peaks are almost completely attenuated (i.e. very little or no drainage from single green roof modules or from the full green roof), but once field capacity is reached the peak attenuation response (i.e. extent to which peak outflow decreases relative to peak inflow) changes considerably. While the concept of field capacity has received some attention in green roof experimental monitoring (Bengtsson 2005; Villarreal and Bengtsson 2005; Villarreal 2007) and modelling (Hilten, Lawrence et al. 2008; She and Pang 2010) studies, field capacity has generally only been considered as a factor influencing retention. The effect of field capacity on peak attenuation and delay is not well understood.

Figure 4.1a also illustrates the concept of gravity storage. The term gravity storage is used to describe water that is briefly stored in the media, but freely drains out over time due to the force of gravity overcoming the soil capillary pressure. As shown in Figure 4.1a, gravity storage occurs once field capacity is reached and provides some temporary storage of water. The effects of gravity storage are not well quantified for green roofs. Bengtsson (2005) examined gravity storage using artificial rainfall experiments conducted by saturating one 4 x 1.25 m green roof plot and letting it drain to field capacity. They found gravity storage varied with rain intensity; 1 mm/min rain resulted in almost 8 mm of gravity storage, compared with only 4 mm of gravity storage when the rain intensity was reduced to 0.4 mm/min. In these experiments Bengtsson (2005) did not directly measure gravity storage but it was inferred from the experimental rainfall and measured drainage rates. Due to the potential impact of gravity storage on the hydrologic performance of green roofs, there is a need to quantify the effects of gravity storage for real rainfall events.

Numerous studies have investigated green roof hydrologic performance (e.g. Berndtsson 2010; Berardi, GhaffarianHoseini et al. 2014). The volumetric retention of stormwater (i.e. the difference in area under the rainfall curve and drainage curve in Figure 4.1) has been found to range from 27 - 81% for extensive green roofs (Mentens, Raes et al. 2006).

While many studies have quantified stormwater retention, there is limited fundamental understanding of the mechanisms affecting the attenuation and delay of peak stormwater drainage from green roofs. Voyde, Fassman et al. (2010) reported an event average peak flow rate attenuation of 93% from a 250 m^2 green roof with 70 mm media depth in Auckland New Zealand. Attenuation values for 91 individual storm events were determined by comparing the peak rainfall for the entire event to the peak drainage over the entire event. Peak attenuation values were also quantified for 11 events by Stovin (2010) using green roof test plots with an 80 mm media depth (3m x 1m) in Sheffield England. Using the same attenuation definition as Voyde, Fassman et al. (2010), they reported average event peak flow rate attenuation of 57%. Carpenter and Kaluvakolanu (2011), also using the same definition, reported an event average peak flow rate attenuation of 89% from monitoring three full scale green roofs with 100 mm media depth in Michigan over a period of 6 months. The method these prior studies used to calculate attenuation does not consider the various individual peaks within a storm event. As shown in Figure 4.1 rainfall intensity varies within individual storm events causing distinct identifiable rainfall and green roof drainage peaks. Each of these distinct rainfall peaks has different peak attenuation response. As illustrated in Figure 4.1b, the peak drainage flow rate may not be related to the peak rainfall. The traditional approach of calculating attenuation is only representative if the largest rainfall peak occurred after field capacity had been reached, or field capacity was never reached during the storm. The definition of peak attenuation used in prior literature simplifies the process thereby limiting detailed understanding of green roof attenuation. To better understand the mechanisms by which green roofs attenuate peak flows it is necessary to consider the specific rainfall and drainage peaks rather than only the event peaks.

The method by which peak flow delay is typically quantified masks underlying processes similar to peak attenuation as outlined above. Some studies quantify peak delay as the time difference between the largest rainfall and drainage peaks during an event. DeNardo, Jarrett et al. (2005) reported a time delay on average of roughly 2 hours using this definition. Calculating time delays using this approach neglects the multiple peaks within an event and can relate two completely separate peaks – this can considerably increase the time delay (Figure 4.1b). Alternatively, other researchers calculate time delay as the

time difference between the rainfall and drainage hydrograph centroid. Carpenter and Kaluvakolanu (2011) and Stovin, Vesuviano et al. (2012) reported peak delay times of 2.16 hours and 1 hour respectively, using this definition. The centroid calculation method is not able to assess trends for the individual peaks within a single rain event. As illustrated in Figure 4.1, the delay of peak flow rates may change depending on when the individual peak occurs during a rain event (i.e. before or after field capacity). There is opportunity to assess the drainage delay associated with individual peaks within a storm event, and investigate how concepts such as field capacity impact the peak delay performance of green roofs.

Another factor that affects peak attenuation and delay is drainage routing. Routing, the flow of water as it moves to the roof outlet drain, occurs on green roofs as well as conventional roofs. The effect of routing on green roofs has received limited attention in green roof literature. Only Bengtsson (2005) has quantified drainage routing times, finding that they ranged from 12 – 20 min depending on the artificial rain intensity for their experimental set up. The effect that drainage routing has on peak attenuation and delay of drainage in field conditions is yet to be quantified.
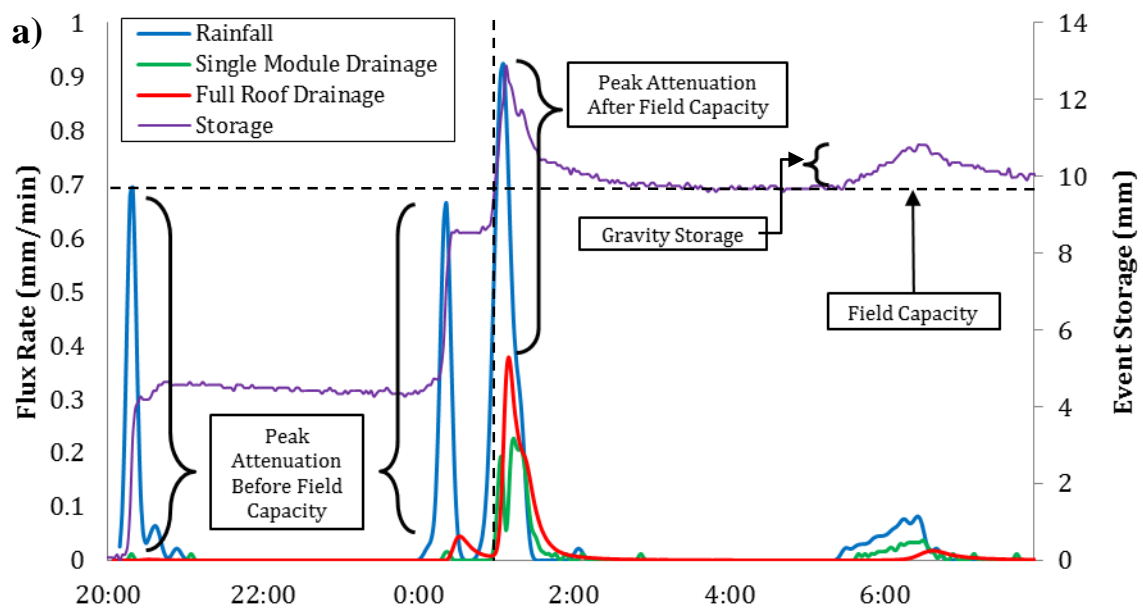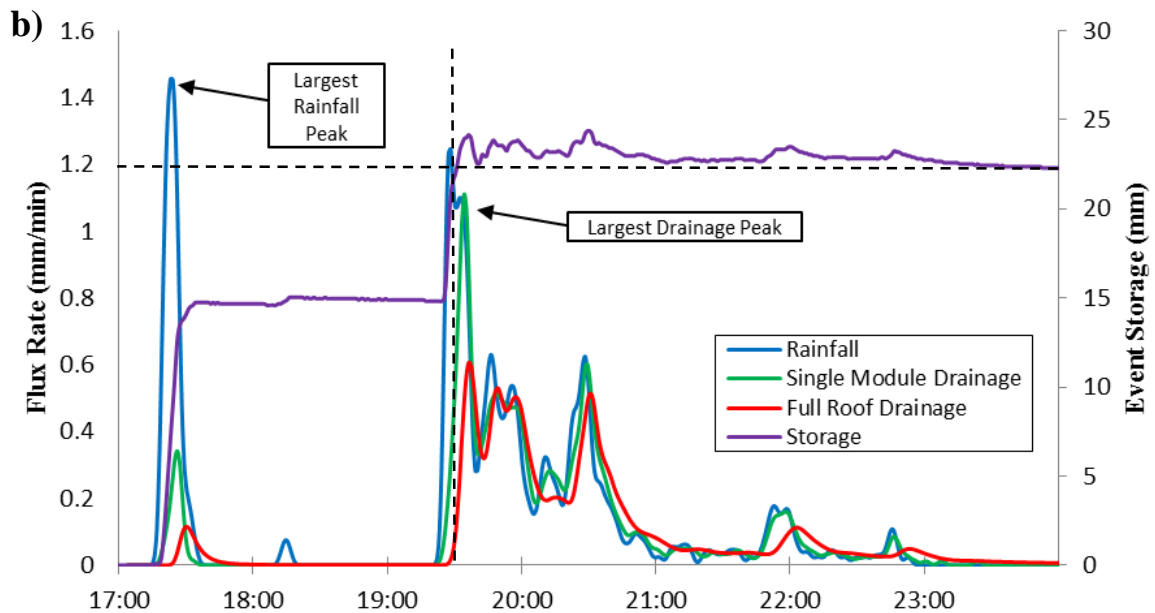
Figure 4. 1: Typical event hydrographs a) May 20th 2014 (18 mm rain event) and b) September 11th 2013 (56 mm rain event)

Simulation of green roof hydrologic performance is required to guide the design of green roofs. Various modeling approaches have been used to simulate green roof stormwater performance, including empirical models (Mentens, Raes et al. 2006; Carson, Marasco et al. 2013; Fassman-Beck, Voyde et al. 2013) and physical/conceptual models (Villarreal 2007; Kasmin, Stovin et al. 2010; Zhang and Guo 2013; Carbone, Garofalo et al. 2014). Some studies have developed variably-saturated porous media flow models based on the Richards equation to simulate outflow hydrograph and peak attenuation in response to storm events (Hilten, Lawrence et al. 2008; Palla, Gnecco et al. 2009). Hilten, Lawrence et al. (2008) developed a model using the Richards equation based Hydrus-1D that was validated against data collected for a 37 m^2, 100 mm deep green roof at the University of Georgia. They measured field capacity and wilting point in the laboratory but for other hydraulic parameters (e.g. hydraulic conductivity) they assumed the media properties were identical to that of sand. Once validated the model was used to simulate the drainage response to design storms. Linear regression of the observed to modelled drainage produced an R^2 of 0.918 but a slope of 1.14 and errors of up to 19 mm of

drainage. Palla, Gnecco et al. (2009) also developed a model based on the Richards equation using SWMS-2D. This study simulated water flow through a 2D domain and compared the results to field data from a green roof in Genoa Italy. Model parameters (e.g. residual and saturated moisture content, hydraulic conductivity, and the Van Genuchten soil parameters (α and n)) were calibrated by minimizing the difference between observed and simulated green roof retention, peak flow rate, and hydrograph centroid data for 4 storm events. The model simulated retention to within a 15% error, with satisfactory peak delays, but underestimated peak flow rates. These studies illustrate the ability of variably saturated porous media models to simulate stormwater drainage from green roofs; however, in both cases important soil parameters were assumed or calibrated. Predicting green roof hydrologic performance using Richard's equation requires model validation based on independently measured parameters.

This study aims to quantify the different mechanisms that affect the ability of green roofs to attenuate and delay stormwater flows including capillary storage, gravity storage, and routing. Field data was collected on a green roof array installed in London, ON from July 28th – November 11th 2013 and April 11th – October 21st 2014. Stormwater attenuation is quantified by analyzing individual peaks within storm events rather than the traditional approach of comparing total event peak rainfall and drainage. This provides important insight into the mechanisms that affect peak attenuation and delay. The field data is then used to validate a predictive model based on the Richards equation. This model, based only on independently measured parameters, is a valuable tool that may be used evaluate green roof stormwater performance and optimize design.

4.2   Materials and Methodology

4.2.1   Site Description

The green roof site monitored in this study is located on the Claudette MacKay-Lassonde Pavilion (CMLP), a LEED Gold building, at Western University in London, Ontario. London has a moderate climate with cool winters and warm summers. The average annual precipitation is 1011.5 mm, of which 845.9 mm is rainfall (Environment Canada, 2015).

The CMLP green roof is an extensive modular system supplied by LiveRoof (0.3m x 0.3m and 0.6m x 0.3m modules), with a media depth of 100 mm. The green roof design includes a waterproof membrane over a conventional rooftop with modules arranged on top of this membrane. The drainage layer is built into the base of the modules (see ridges in Figure 4.2a). The CMLP site has a permanent green roof, installed in 2009, that covers roughly 200 m^2 (Figure 4.2b), as well as a separate highly instrumented green roof array (Figure 4.2c). The permanent green roof has full plant coverage with sedum varieties that include *Sedum kamtschaticum*, *Sedum album*, *Sedum sexangulare*, and *Sedum spurium*. The instrumented array (Figure 4.2c) that was used for detailed quantification of the hydrologic response was separated from the permanent green roof by about 3 meters. The instrumented array was approximately 4 x 3m. Half of this array was unvegetated (bare media) and the other half was vegetated with the same sedum mixture as the permanent roof. Unlike the permanent green roof, the instrumented array was elevated 10 cm above the waterproof membrane and underlain by insulation to facilitate installation of instruments. Green roof growth media, provided by LiveRoof, is a heterogeneous engineered media mainly consisting of organic matter (bark), haydite, dolostone, peat moss and fertilizer. Detailed analysis of both the thermal and hydrologic properties of the media is provided by Perelli (2014).
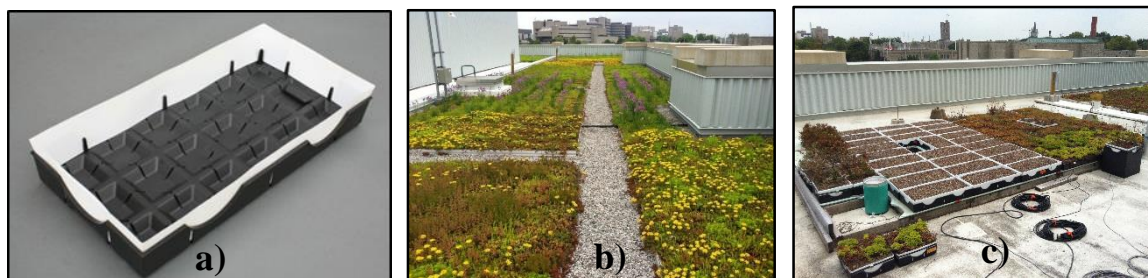
Figure 4. 2: a) LiveRoof module structure (Liveroof 2014) b) Permanent 200m^2 green roof on CMLP roof c) Highly instrumented green roof array

Instruments were used to quantify the water balance at the green roof site from July 28th – November 11th 2013 and April 11th – October 21st 2014. Two tipping bucket rain gauges calibrated separately for high (Hoskin Scientific) and low (Campbell Scientific

TE525MM) intensity rainfall events measured precipitation at 1-minute intervals. Data from these rain gauges were supplemented with 5 Hoskin Scientific metric rain gauges that were checked daily.

Drainage was monitored using three measurement devices. Two devices measured drainage from individual 0.3m x 0.3m modules, eliminating the effects of routing (Figure 4.3a). One of the single module drainage devices used a tipping bucket placed directly underneath the module to measure drainage. The other single module drainage device used a load cell to continuously weigh water draining from the module – this is referred to as an accumulating drainage gauge. The third device was a weir system that measured drainage from a 98m^2 catchment area and accounts for the effects of routing. The weir device receives drainage directly from two roof drains within the permanent green roof. The height of water in the weir was monitored with a Honeywell FP200 pressure transducer (Figure 4.3b).

Figure 4. 3: a) Single module drainage units b) Full roof catchment weir

Water storage and evapotranspiration from the green roof was monitored using two mini-lysimeter devices installed under the instrumented green roof array. These devices used a sensitive load cell (Interface SPI Load Cell with 25-lbf capacity) mounted in an aluminum plate structure placed underneath two vegetated modules (0.3 m x 0.3 m). Additionally, two Decagon EC-5 soil moisture probes were used to quantify volumetric

water content at a depth of 50 mm (i.e. mid-media depth). The EC-5 probes were calibrated using the two point Sakaki method outlined in Sakaki, Limsuwat et al. (2008):

$$\theta = \frac{ADC^\alpha - ADC_{dry}^{\ \alpha}}{ADC_{sat}^{\ \alpha} - ADC_{dry}^{\ \alpha}} \Phi \qquad\qquad 7$$

Where α=2.5 and is specific to the EC-5. The *ADC$_{sat}$* and *ADC$_{dry}$* is the mV response multiplied by a factor of 1.3661 for saturated and dry soil conditions (also specific to the EC-5), and ϕ is the porosity. This method was also used in the characterization of the green roof media by Perelli (2014). More detailed information on the calibration of each piece of equipment is provided in Appendix B.

4.2.2   Data Collection and Analysis

All instruments collected data at 1-minute intervals using one Campbell Scientific CR10 and two CR10x data loggers. A rain event was defined as any precipitation that resulted in more than one tip of a tipping bucket rain gauge. This two tip minimum threshold was used to ensure that a single tip was not considered a rain event in case there was residual water in the tipping bucket from a previous rain event. The end of a rain event was defined by 6 hours of no precipitation (VanWoert, Rowe et al. 2005; Getter, Rowe et al. 2007; Stovin 2010; Voyde, Fassman et al. 2010). When drainage was still occurring more than 6 hours after a rain event and rainfall occurred again, the two events were merged.

Green roof hydrologic performance was evaluated by quantifying rainfall and drainage depth, duration, event intensity, peak flow intensities, and peak flow delay, as well as gravity and capillary storage. Previous studies have only considered attenuation by comparing largest peak rainfall rate and largest peak runoff rate (VanWoert, Rowe et al. 2005; Speak, Rothwell et al. 2013). In this study distinct rainfall peaks within individual rain events were compared to the corresponding drainage peak to determine peak attenuation and delay.

Peak flow rate attenuation is calculated as a percent flow reduction:

$$Attenuation\ (\%) = \frac{P_{rain} - P_{drainage}}{P_{rain}} \cdot 100 \qquad\qquad 8$$

Gravity storage is calculated by:

$$S_{gravity} = S_{peak} - S_{F.C}$$ 9

Time delay is calculated by:

$$t_{delay} = tp_{drainage} - tp_{rainfall}$$ 10

Where P_{rain} and $P_{drainage}$ are the peak rainfall (mm/min) and peak drainage values (mm/min). $S_{gravity}$, S_{peak} and $S_{F.C.}$ are gravity storage (mm), peak storage during an event (mm) and storage at field capacity (mm). t_{delay}, $tp_{drainage}$, and $tp_{rainfall}$ are the peak time delay (min), time of drainage peak (min) and time of rainfall peak (min).

4.2.3   Numerical Model

Richards (1931) equation, coupled with the Van Genuchten-Mualem (Van Genuchten 1980) capillary pressure-saturation model, was used to simulate water storage and drainage from the green roof in response to rain events. The system of governing equations is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta) \cdot \left(\frac{\partial H_p}{\partial z} + 1\right)\right]$$ 11a

with,

$$S_e = \begin{cases} \frac{1}{\left[1+(\alpha \cdot H_p)^n\right]^m} & H_p < 0 \\ 1 & H_p \geq 0 \end{cases}$$ 11b

$$k_r = \begin{cases} S_e^{\,l}\,[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m]^2 & H_p < 0 \\ 1 & H_p \geq 0 \end{cases}$$ 11c

$$\theta = \begin{cases} \theta_r + S_e(\theta_s - \theta_r) & H_p < 0 \\ \theta_s & H_p \geq 0 \end{cases}$$ 11d

Where θ is the volumetric water content ($m^3 \cdot m^{-3}$), θ_s is the saturated water content ($m^3 \cdot m^{-3}$), θ_r is the residual water content ($m^3 \cdot m^{-3}$), $K(\theta)$ is the hydraulic conductivity (m/s), H_p is the pressure head (m), S_e is effective saturation and k_r is the relative permeability. α (1/m), n, and m (1-1/n) are Van Genuchten parameters defined by the soil water retention curve (SWRC). A lab measured SWRC was used in this model to relate the water content to the capillary forces of the growing media. The subsurface flow module in COMSOL multiphysics was used to solve Richards equation (COMSOL 2013). COMSOL has been used previously to simulate similar hydrological processes (e.g. Chui and Freyberg 2009). A 1D model domain was used with a 100 mm depth and a mesh element size of 1 mm. Individual rain events were simulated using a time varying flux boundary condition on the inlet (top) boundary to represent rainfall. The flux across this boundary was defined by 1-minute resolution precipitation data. The bottom outlet boundary was specified as a free drainage boundary with drainage allowed to occur when water saturation exceeded field capacity. A similar approach was adopted by She and Pang (2010):

$$Drainage = \begin{cases} 0 & S_e < F_c \\ k_r \cdot K_s & S_e \geq F_c \end{cases} \qquad\qquad 12$$

Where K_S is the saturated hydraulic conductivity (m/s) and F_c is field capacity. The field capacity for the simulations was based on measured soil moisture data from the green roof from April - November 2014 (Figure 4.4). The field capacity was determined to be 0.215 volumetric water content during the wet periods (i.e. April - May and September - November), and 0.193 during the drier period (i.e. May - September). These values were determined by considering all events with drainage and identifying the moisture content when capillary storage was full and substantial drainage started. The higher field capacity during the wet periods is attributed to higher moisture contents providing the stored water adequate time to diffuse into internal pores of the media. Alternatively during the dry season, these internal pores will dry out over extended drying periods, resulting in a lower field capacity. Figure 4.4 was also used to justify the residual water content value, which was determined from extrapolation of the volumetric water content at the end of extended drying periods.

The initial soil moisture for each simulation was based on measured soil moisture at the start of each event. The initial moisture distribution was assumed to be uniform with depth. The model used a 1-minute time step, consistent with available observed data. Simulations were run until drainage through the lower boundary ceased. The soil water retention curve used to model the green roof media was determined from laboratory measurements and fitted with Van Genuchten parameters (Perelli 2014) (Table 4.1).
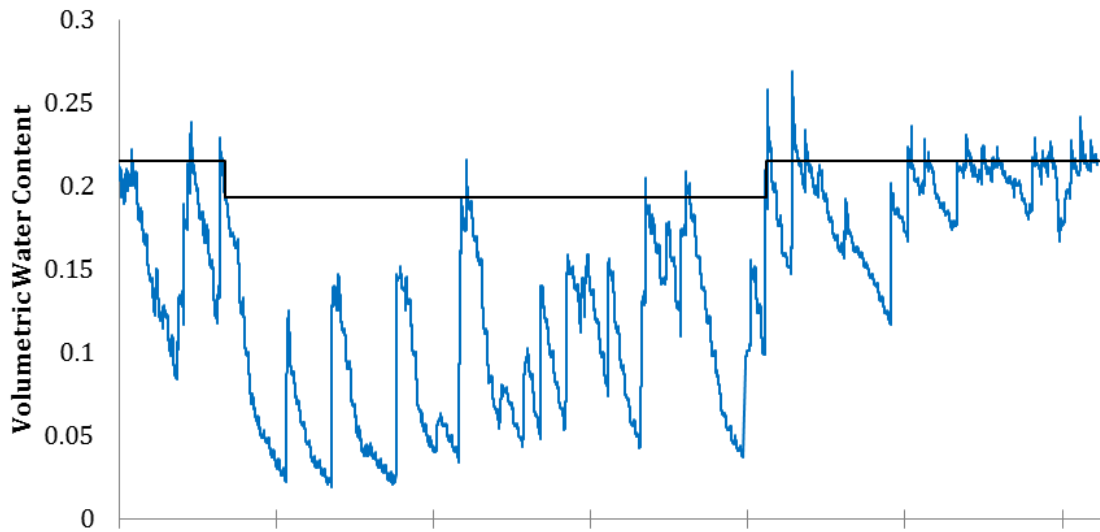
Figure 4. 4: Water content of the CMLP green roof over the 2014 season (black lines indicate the field capacity water content for the wet and dry periods)

Table 4. 1: Summary of model parameters

| Parameter	Unit	Variable	Value	Source
Gravity	m/s^2	g	9.81	-
Saturated hydraulic conductivity	m/s	K_S	0.000168	(Perelli 2014)
Saturated moisture content	-	θ_s	0.45	(Perelli 2014)
Residual moisture content	-	θ_r	0.01	Observed data
Fluid density	Kg/m^3	ρ	1000	-
Fluid compressibility	1/Pa	X_p	4.4×10^{-10}	(Furman, Hinnell et al. 2012)
Matrix compressibility	1/Pa	X_f	10^{-8}	(Furman, Hinnell et al. 2012)
Alpha parameter	1/m	α	28	(Perelli 2014)
n parameter	-	n	3	(Perelli 2014)
Pore connectivity parameter	-	l	0.5	(Van Genuchten, Leij et al. 1991)
Initial pressure	m	H_{p0}	Event variant	Observed data
Inflow boundary flux	m/s	-	Time variant	Observed data

All parameter values used to solve the unsaturated flow equations were determined from field data, laboratory tests, or literature (Table 4.1). This eliminated the need for model calibration. As such, the model can be used as a predictive tool rather than a validation of the suitability of Richards equation for simulation of hydrologic processes in green roofs.

4.3   Results and Discussion

4.3.1   Measured Attenuation and Delay in Stormwater Drainage

Ninety-eight distinct rainfall events were captured over the measurement periods of July 28th – November 11th 2013 and April 11th – October 21st 2014. Event rainfall and drainage intensities during the study period are shown in Figure 4.5. The London Intensity-Duration-Frequency (IDF) curves based on 50 years of historical rain data are also presented for comparison (Environment Canada 2015). Six of the events were equivalent to or greater than a 2-year storm, with one event approaching a 100-year storm. The characteristics of the drainage events (shown in red) are distinctly different than the rainfall characteristics. Nearly half of the rain events produced no drainage, as indicated by the greater number of rainfall events shown in Figure 4.5. Most of the longer duration rain events produced drainage and, as expected, the drainage was of longer duration (shift right) and lower intensity (shift down) compared to the rainfall. For instance, for rain events that produced drainage, the average rain duration and intensity are 10.70 hours and 2.84 mm/hr respectively, compared to 18.54 hours and 0.46 mm/hr respectively, for the average drainage duration and intensity. The six large events that have over a 2-year return period have average rainfall duration and intensity of 20.0 hours and 4.20 mm/hr, while the average drainage duration and intensity for these events are 34.6 hours and 1.62 mm/hr. Drainage intensity for the largest rainfall event (50-100 year return period) decreased to about a 10-year storm. These results highlight the overall stormwater management benefits that green roofs provide in increasing the duration and decreasing intensity of events, specifically for large return period events. This analysis however only considers event averages. To more closely evaluate the ability of green

roofs to attenuate peak flow rates, a detailed attenuation analysis of each of the 50 events that produced drainage event was conducted.
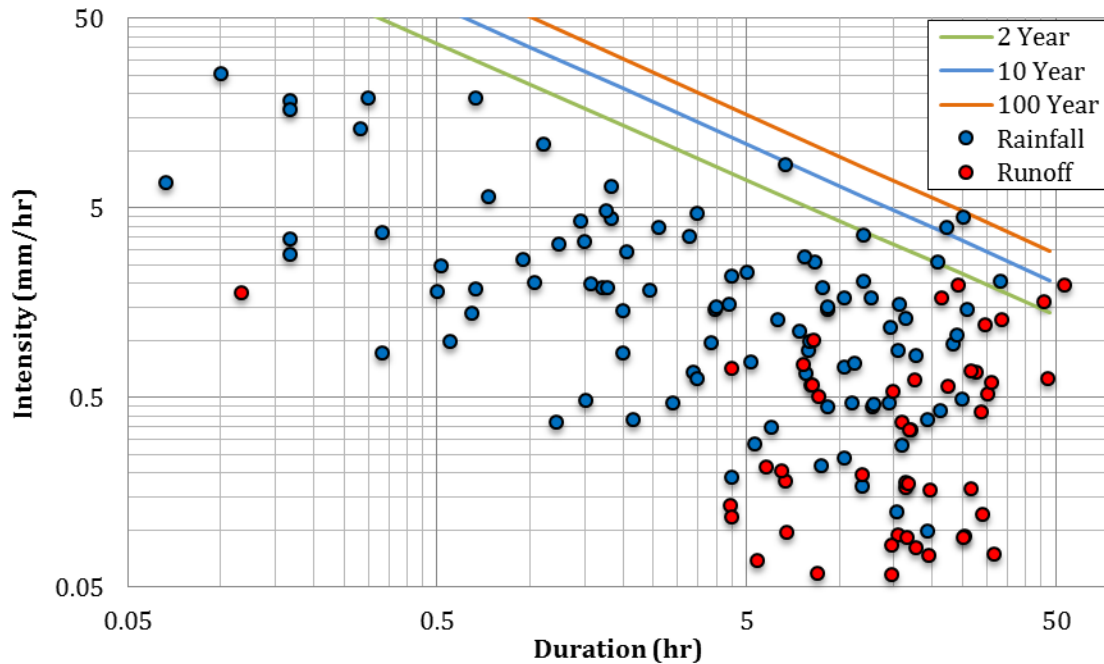
Figure 4. 5: London region IDF curves with CMLP rain and drainage events

There were 121 clear rainfall peaks within the 50 events that had drainage. 66 of these peaks occurred before the green roof achieved field capacity and 55 peaks occurred after field capacity. Table 4.2 provides an overview of the averaged peak flow rate attenuation and delay results.

Table 4. 2: CMLP green roof attenuation and delay (uncertainty indicated by 95% confidence interval)

| 2013-2014 Rain Events		
	Attenuation (%)	*Peak Delay (min)*
All Peaks (n=121)	58 ± 3.9	12.8
Before Field Capacity (n=66)	*Attenuation (%)*	*Peak Delay (min)*
Single Module Drainage	77 ± 6.1	12.6
Full Roof Drainage	88 ± 3.8	23.8
After Field Capacity (n=55)	*Attenuation (%)*	*Peak Delay (min)*
Single Module Drainage	29 ± 5.0	4.1
Full Roof Drainage	47 ± 5.5	10.9

The average attenuation of all peaks is 58%. This is similar to Moran, Hunt et al. (2005) and Stovin (2010) who found peak flow rate attenuation of 57%, but dissimilar to the findings of Voyde, Fassman et al. (2010) (93%) and Carpenter and Kaluvakolanu (2011) (89%). These previous studies used event peak flows to calculate the attenuation as well as included events with no drainage in the attenuation statistics. This would result in larger peak attenuation values and explain why Voyde, Fassman et al. (2010) and Carpenter and Kaluvakolanu (2011) found attenuation values much higher than those presented here. The comparatively low values reported in both Moran, Hunt et al. (2005) and Stovin (2010) may be partially explained from the small sample sizes of their studies (13 and 11 events respectively).

The average time delay between rainfall and drainage peaks is 12.8 min. If a rainfall peak occurred but there was no drainage, the peak was omitted from time delay averages. The measured time delay differs from DeNardo, Jarrett et al. (2005) who found peak delays of about 2 hours as well as Villarreal (2007) who found peak delays of 1 min, both using the event peak rainfall and event peak drainage time difference. The results of Carter and Rasmussen (2006) are most similar to this study, where 57% of storms were found to have delays ranging from 0-10 min also using the event peak rainfall and drainage values. Quantifying averaged attenuation and delay using event peaks however does not provide insight into the processes that control green roof attenuation and delay. Peak attenuation and delay are a function of specific storage mechanisms occurring (i.e. capillary and gravity storage, and routing), as well as the media moisture content when the rainfall peak occurred (i.e. greater or lower than field capacity). Comparison of single module drainage to the drainage response for the full roof (i.e. using the weir) also enables quantification of the various processes influencing attenuation.

The influence of field capacity on flow attenuation was assessed by comparing drainage versus rainfall rate before and after field capacity. Results shown in Figure 4.6 indicate substantial flow rate attenuation with all data falling below the 1:1 lines which represent zero flow attenuation. Before field capacity, the regression slopes indicate 72% peak attenuation due to capillary storage, for the single module drainage, and 79% attenuation for full roof drainage, due to capillary storage and routing (Figure 4.6a). It is noted that

R^2 values indicate considerable scatter about the trend lines since field capacity has not been achieved. These attenuation values differ slightly to those reported in Table 4.2, since trendlines represent the best fit of drainage versus rainfall intensities whereas Table 4.2 reports the arithmetic average of all attenuation values from drainage events. The average attenuation presented in Table 4.2 before field capacity was 77% for single module, and 88% for full roof drainage. The difference between the single module and full roof drainage values is due to routing. The routing of the drainage increased peak attenuation by 11% and increased peak delay by 11.2 min (Table 4.2). When we consider Figure 4.6a, routing increased attenuation by 7%.

After field capacity has been achieved the regression line slopes are larger (i.e. less attenuation) and correlations are improved (i.e. $R^2 > 0.93$, Figure 4.6b). The impact of drainage routing also becomes more important in flow attenuation. The full roof drainage measurements suggest attenuation of 33%, compared with 22% for single module drainage (Figure 4.6b). As such, the effect of routing increases the attenuation performance by a factor of 1.5x. This observation is also confirmed from data presented in Table 4.2. After field capacity, comparison of the average single module attenuation (29%) and the full roof attenuation (47%) showed that routing improved peak attenuation by 18% and increased the peak delay by 6.8 min. Based on Table 4.2 routing accounts for only 13% of the total attenuation before field capacity, whereas after field capacity, routing accounts for 38% of the total attenuation, providing almost a 3x increase in impact on the attenuation response. This means that routing has a greater contribution to peak attenuation after field capacity.
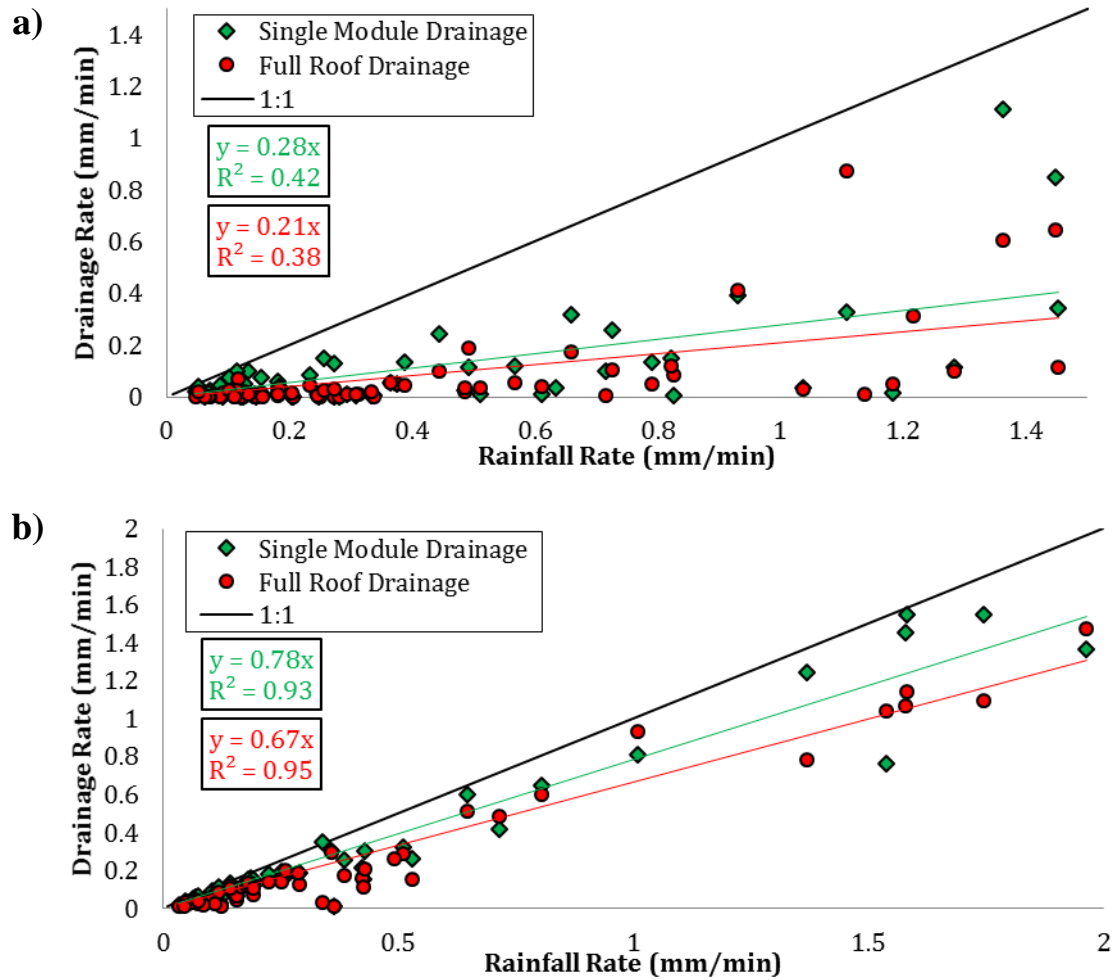
Figure 4. 6: Comparison of peak rainfall and drainage rates a) before field capacity and b) after field capacity

To statistically assess the influence of field capacity on the peak rainfall and drainage, intensities data from the rain gauge, single module, and full roof drainage were plotted as cumulative probability distributions before and after field capacity (Figures 4.7a and 4.7b). These plots were made by ranking the monitored peak intensities by size and calculating the cumulative probability that is associated with each intensity based upon the rank. The cumulative probability value represents the percentage of monitored peaks equal to or less than the corresponding flow rate on the *x*-axis.
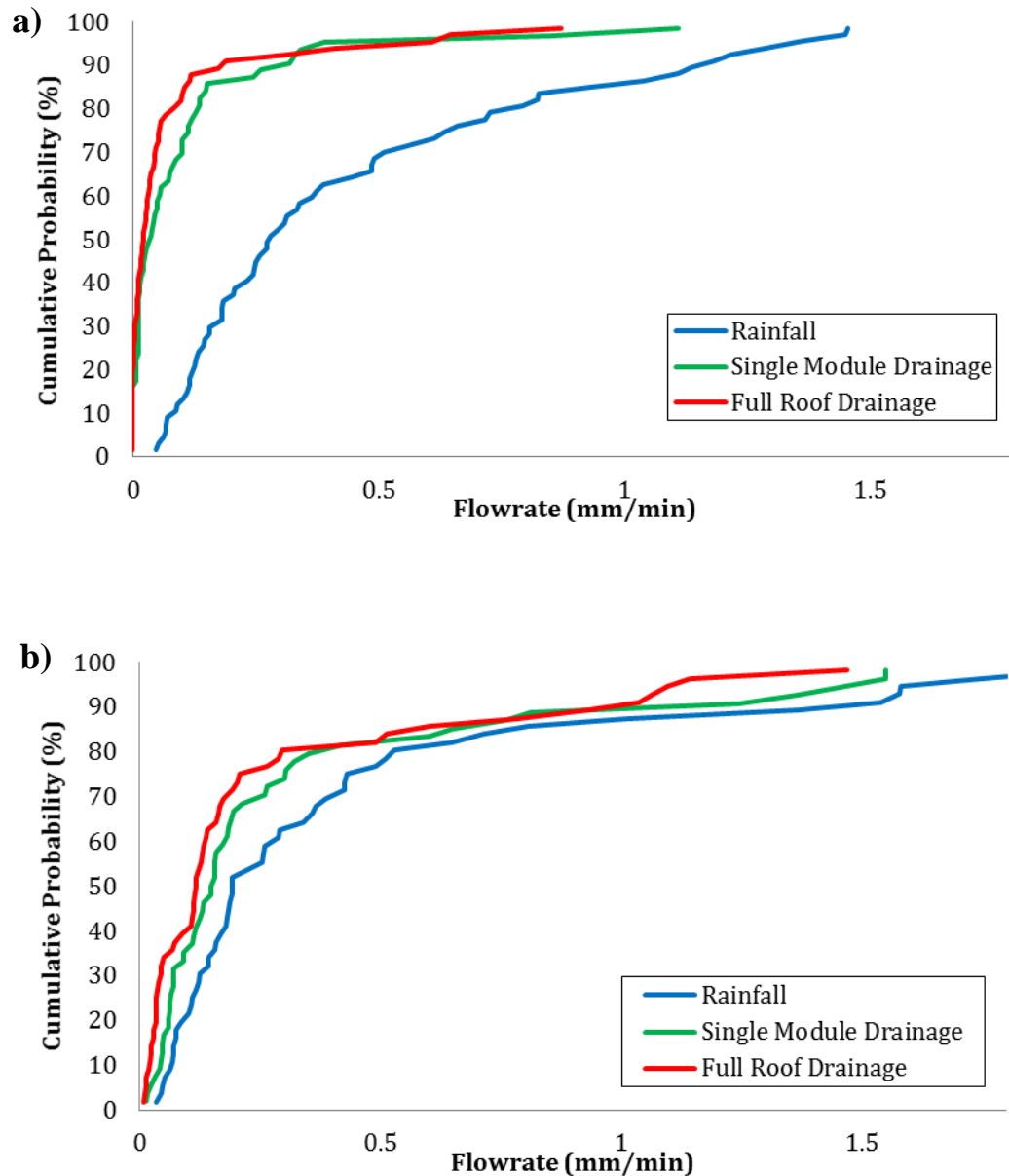
Figure 4. 7: a) Cumulative probability plots for CMLP green roof before and b) after field capacity

The Kolmogorov-Smirnov non parametric test was used to determine significance. Using Figures 4.7a and 4.7b it was determined that rainfall before and after field capacity were statistically equivalent ($\alpha > 0.1$), meaning valid statistical comparisons can be made between the drainage distribution functions and rainfall before and after field capacity. The Kolmogorov-Smirnov tests indicate there were significant differences between the single module drainage intensities before and after field capacity ($\alpha < 0.001$), and

between full roof drainage intensities before and after field capacity ($\alpha < 0.001$). These tests suggest that attenuation performance of a green roof significantly decreases after the media reaches field capacity. Therefore, the point at which the green roof media reaches field capacity indicates a quantifiable point where attenuation performance of a green roof significantly decreases.

Attenuation is significantly greater before field capacity due to capillary storage. After field capacity is reached total attenuation significantly decreases, increasing the relative influence of routing on peak attenuation. After field capacity is reached some attenuation is also attributed to gravity storage in the media. This is illustrated by the single module drainage data shown in Figure 4.6b. Bengtsson (2005) noted the presence of gravity storage after field capacity was reached for artificial rain experiments, however, the gravity storage values were not directly quantified but inferred from the rainfall and drainage rates. Here, the gravity storage was directly measured, and determined for each individual peak after field capacity (Figure 4.8).
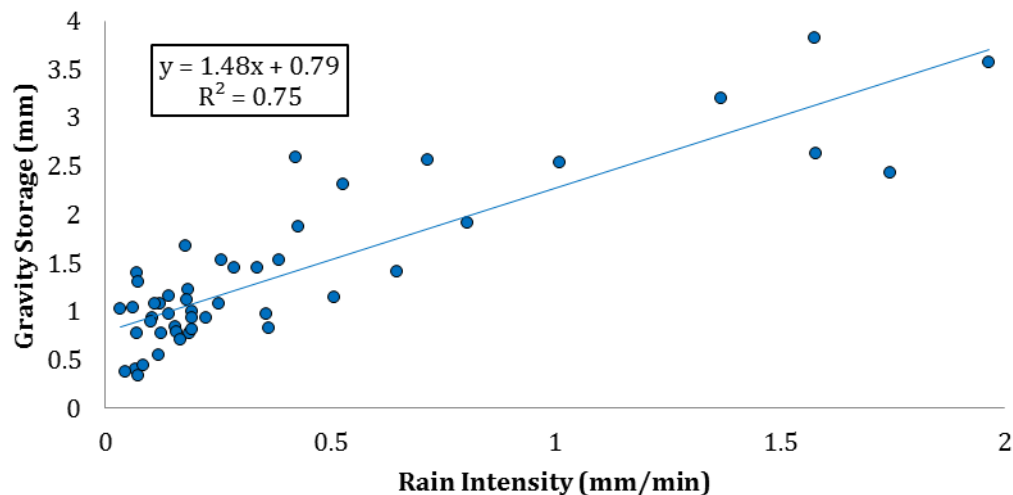

Figure 4. 8: Relationship between gravity storage and peak rainfall intensity

Consistent with the Bengtsson (2005), gravity storage was found to increase as rain intensity increases. The Spearman correlation for non-parametric data shows a good positive correlation (0.735) between rain intensity and gravity storage. This indicates that gravity storage is dynamic, temporarily storing more water during greater intensity peaks.

4.3.2   Comparison of Measured and Simulated Peak Attenuation

The green roof drainage response to 33 separate events (i.e. number drainage events that occurred in 2014 after the accumulating drainage unit was installed) was simulated using Richards equation in COMSOL multiphysics to assess the predictive capabilities of the numerical model. As the model is 1D and does not account for routing effects, only single module drainage measurements were compared to the model predictions. The measured and simulated outflow hydrographs for three representative rain events are shown in Figure 4.9. These simulated events highlight the various characteristics of the hydrograph, including time to initiation of drainage, storage, peak flow rate attenuation and delay. The simulated results match well with the measured green roof drainage. The simulated initiation of drainage shown in Figure 4.9b is slightly delayed relative to the measured data. This discrepancy is attributed to uncertainty in the EC-5 soil moisture data obtained at mid-depth only and used as the initial soil moisture in the model domain. However, after drainage commenced the simulated and measured outflow hydrographs are almost identical. Figure 4.9a and 4.9c both show increased model accuracy with respect to the initiation of drainage. The simulated peak flow rates, delays, and drainage volumes visually correspond well to the measured data.

Quantitative metrics for comparing the simulated and measured results for the events shown in Figure 4.9 are provided in Table 4.3. Three quantitative metrics were selected to statistically assess the ability the model to predict observed field data: volume of water retained in the green roof (capillary storage), volume of water drained from the green roof, and peak flow rates (Figure 4.10). These metrics were selected rather than using a standard error calculation such as RMSE which would show bias between events (i.e. exaggerates error for longer events with larger flow rates).
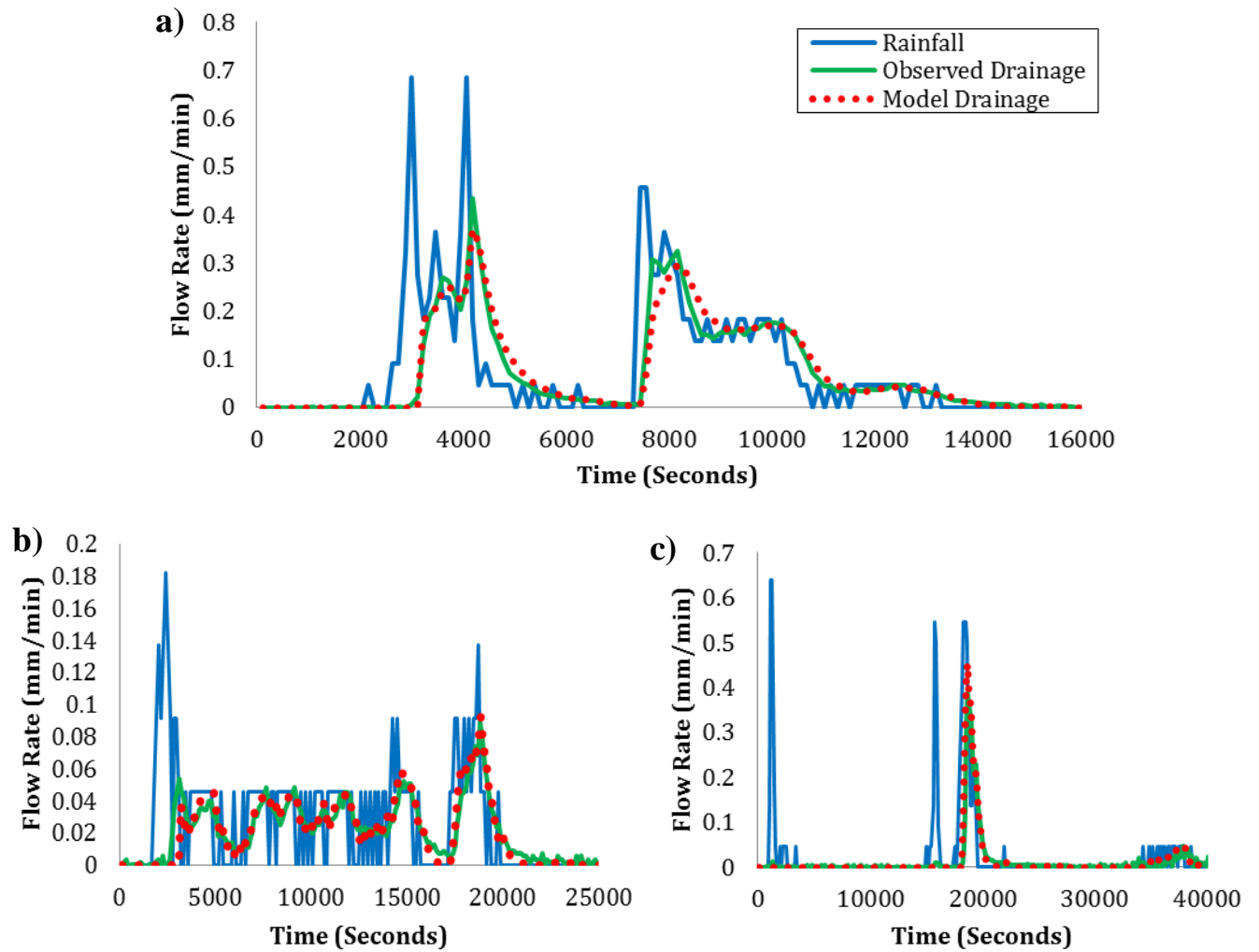
Figure 4. 9: a) July 8th, 2014 rain event (21.5 mm) b) April 30th 2014 rain event (11.5mm) c) May 20th 2014 rain event (17.5mm)

Table 4. 3: Model details for rain events

Event	Rainfall (mm)	Measured Drainage (mm)	Simulated Drainage (mm)	Measured Storage (mm)	Simulated Storage (mm)	Drainage RMSE
April 30th	11.55	9.15	9.06	2.4	2.49	0.013
May 20th	17.42	8.28	9.30	9.14	8.12	0.11
July 8th	21.44	19.62	20.74	1.82	0.7	0.066

A comparison of the simulated and measured capillary storage and drainage are shown in Figures 4.10a and 4.10b, respectively. Simulated drainage is calculated as the cumulative flux through the bottom outflow boundary over the event. The relationship between the simulated and measured capillary storage yields a slope of 0.96 and an R^2 of 0.93, implying a high degree of correlation. The Spearman coefficient (ρ) was calculated to be 0.892, indicating a strong positive correlation. The Mann-Whitney U test showed that

there is no statistically significant difference between the model and observed storage values (P=0.705). Despite no significant difference between the model and observed data, there is still some scatter about the 1:1 line. This is likely due to uncertainty with the initial moisture conditions or the model assumption of no evaporation during the rain event. The same statistical analysis was conducted for drainage predictions with results suggesting an even greater correlation between simulated and measured drainage. The slope of the linear trendline is 1.025 with an R^2 of 0.99. The Spearman coefficient for the modelled and observed drainage is 0.964. The Mann-Whitney U test showed that there is no statistically significant difference between the model and observed drainage values (P=0.682). The simulated and measured drainage likely correlate better than the storage values as drainage is directly affected by the amount of rainfall for each event (i.e. an error of 2 mm in simulated capillary storage will have minimal effect on the cumulative drainage amount for large rain events).

The correlation between the individual simulated and measured peak flow are not as strong as the other two metrics (Figure 4.10c). The slope of the trendline is 0.905 implying a small but consistent underestimation of peak flow rates. The trendline is influenced by a few large peak flow rates that were underestimated (i.e. far right data point in Figure 4.10c). The slight underestimation of some peaks may be a result of uncertain initial moisture conditions that could affect the relative permeability model during the peak, causing a slightly smaller simulated peak flow rate. Palla, Gnecco et al. (2009) also found peak flow rates to be underestimated in their model. The R^2 value for the trendline was 0.95 and the Spearman coefficient is 0.815. The Mann-Whitney U test showed that there is no statistically significant difference between the simulated and observed peak flows (P=0.352). The discrepancy in peak flow rates for some events (e.g. data points that lie on the *x*-axis showing no simulated drainage) is attributed again to uncertainty in the initial moisture conditions. The initial condition measurement could be improved in future studies by having duplicate soil moisture measurements in different modules and at different depths to account for heterogeneity in the green roof media.
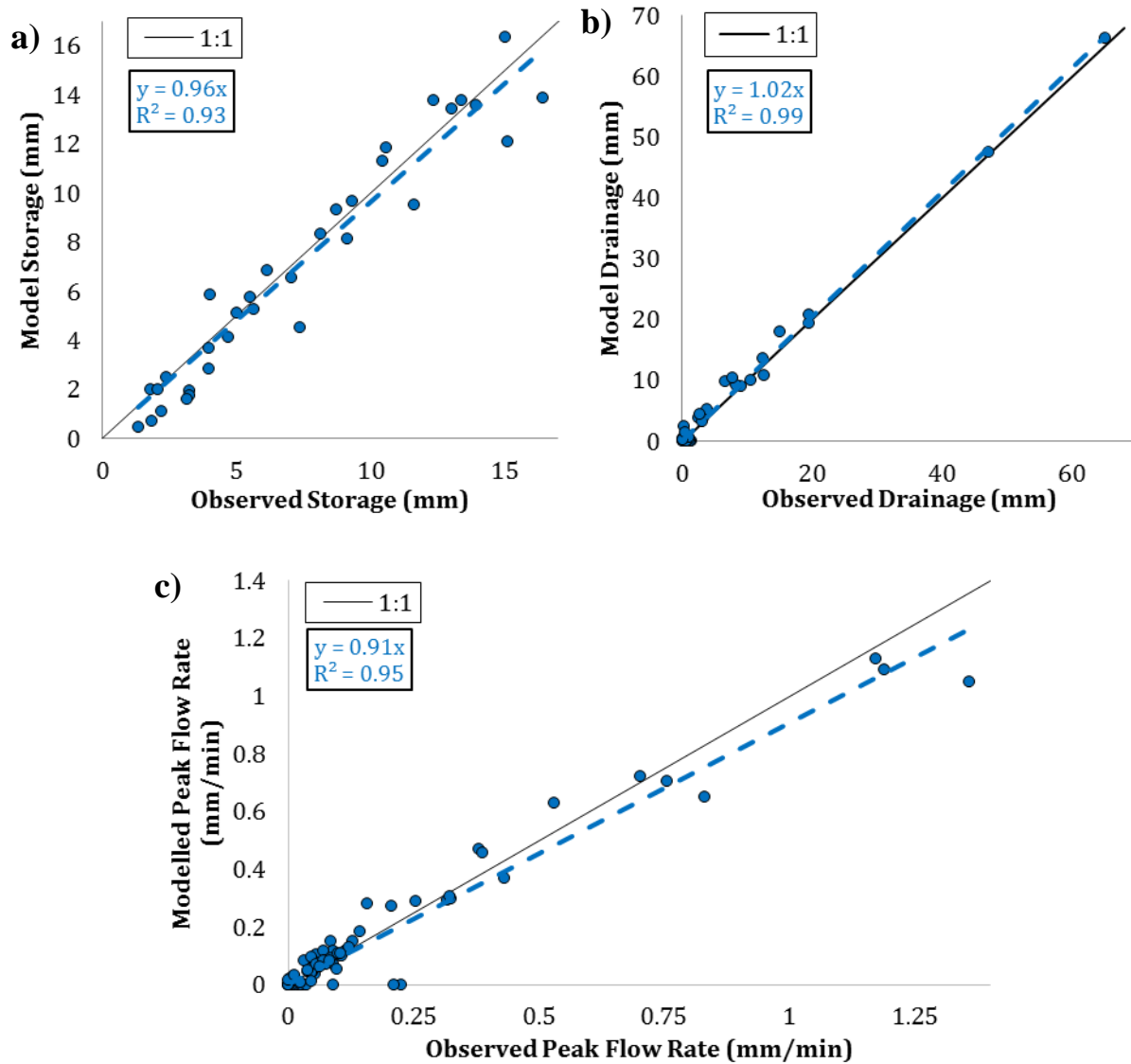
Figure 4. 10: a) Model versus observed storage b) model versus observed drainage c) model versus observed individual peak flow rates

Simulated outflow hydrographs show that the numerical model was able to predict outflow hydrographs from a green roof media without any parameter calibration. While other studies have shown that Richards equation can provide good model results (Hilten, Lawrence et al. 2008; Palla, Gnecco et al. 2009) these studies calibrated model parameters using rain event data (Palla, Gnecco et al. 2009) and estimated growth media parameters (i.e. Hilten, Lawrence et al. 2008; Palla, Gnecco et al. 2009). The model presented here could be applied to estimate the retention of different green roof designs

including the effects of varying media composition and depth. It may also be applied as a design tool for stormwater engineers to predict the impact of green roofs on outflow hydrographs. The limitation of this model is that it requires initial soil moisture conditions and soil parameters. To address some of the limitations, the model could be coupled with an evapotranspiration model to enable for long-term simulations, and thus soil moisture dynamics to be calculated between rain events. Additionally, it is recommended that further work incorporate a routing model. As shown by the field data, incorporation of this attenuation mechanism is particularly important once field capacity is reached. This may be achieved by combining the existing model with a program such as EPASWMM.

4.4 Summary

The average attenuation from 98 events in London Ontario from 2013-2014 was calculated to be 58%. This average attenuation however does not quantify the underlying processes governing peak flow rate attenuation. Detailed analysis of individual rain and drainage peaks within rain events showed that before field capacity, capillary storage processes account for the largest component of peak flowrate attenuation (72%) and routing has a minor effect (7%). However, after field capacity drainage routing becomes considerably more important (11%), and peak flow attenuation also occurs through gravity storage (22%). When the green roof media reaches field capacity, this represents a statistically significant point at which attenuation efficiency decreases. After field capacity capillary storage is no longer available and drainage is only attenuated by gravity storage and routing.

The green roof drainage response was simulated using a Richards equation based model. Palla, Gnecco et al. (2009) and Hilten, Lawrence et al. (2008) previously modelled green roofs using the Richards equation but used calibration events. The model used here is a predictive tool that used laboratory derived relationships and field data. Without calibration of any parameters, the model provided very good predictions of observed data. All performance metrics (i.e. water storage, event drainage, and peak flow rates) suggest a high degree of correlation between the model and observed values. Statistical

analysis shows no significant difference between the model and observed performance metrics.

Green roofs have been empirically proven to provide substantial attenuation of peak flow rates. Understanding the fundamental process of green roof attenuation can help guide green roof design in the future. The development of an accurate predictive tool for green roofs will assist stormwater engineers in effective implementation of green roofs as an LID.

4.5 References

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Chapter 5

5   Summary and Recommendations

5.1   Summary and Conclusions

This thesis investigated the capability of green roofs, an emerging LID tool, to attenuate and retain stormwater. Two separate studies were conducted, the first study considered three similarly designed green roof sites in London, Calgary, and Halifax and monitored during 2012-2014. The complete water balance was monitored and analyzed at each of these sites to assess the impact of differing climate on green roof retention performance. The second study focused on the degree to which a green roof can attenuate peak flow rates, and the major processes occurring in the green roof that lead to peak attenuation. The study considered a green roof in London Ontario that was established in 2009 and monitored over two years (2013-2014). Important processes such as capillary storage, gravity storage, drainage routing, and field capacity were continuously monitored to provide insight to the attenuation of stormwater. A model was developed using Richards equation and empirically derived values to act a predictive tool for modelling green roof outflows without any need for calibration.

The first study aimed to assess the impact of climate on retention performance of green roofs. It was found that the Calgary green roof (67% retention) performed significantly better than both London (48%) and Halifax (34%) with respect to percent retention. However, London performed the best with respect to total volume reduction of stormwater. London stored a total of 757.9 mm of rainfall (53 mm/month), while Halifax stored 516.6 mm (43 mm/month) and Calgary only stored 474.3 mm (41 mm/month). This is because London received a large amount of rainfall but also had sufficient ET rates to regenerate capillary storage in the media. On an event basis, Calgary retained 67% of all storms while London and Halifax only retained 34% and 15% of all storms. The average event retention for Calgary (n=86), London (n=160), and Halifax (n=98) was 90%, 77% and 60% respectively. Small storms (<3mm) were retained much better than medium (3-15mm) and large (>15mm) storms at each site. However, the three sites

only showed a significant difference in performance for retention of medium sized events. The medium event retention is highly correlated to the soil moisture prior to a rain event, and therefore, the ET characteristics and precipitation normals of the climate. Small events were very effectively retained in all of the green roof sites. Due to the size of the rainfall and the limited storage of the green roof media, only a small portion of large events can be retained, even in optimal conditions.

Climate clearly has a significant impact on the performance of green roof retention. Annual and event retention is much greater in areas with less rainfall and increased ability to provide ET. The effect of climate is most evident on retaining medium sized events. The most beneficial overall application of green roofs may be found in moderate climates where precipitation is common and drying periods are frequent, providing both a large reduction in volume of stormwater and high average retention rates.

The second study concluded that green roofs result in substantial improvements in runoff management during rain events by decreasing the average event intensity and increasing total event duration. The average rain event intensity and duration was 2.84 mm/hr and 10.7 hours, while the average drainage event intensity and duration was 0.46 mm/hr and 18.54 hours. The averaged peak attenuation from all drainage events was 58% (n = 121 peaks) and the average peak delay was 12.8 minutes. It was determined that field capacity is a statistically significant point where attenuation performance decreases dramatically. Kolmogorov-Smirnov tests show that the peak drainage attenuation for both single and full roof drainage units before field capacity is significantly higher than after field capacity. Before field capacity is reached, capillary storage is the main mechanism attenuating peak flows leading to 72% attenuation. Routing has a relatively minor effect, providing a further 7% attenuation in addition to the effects of capillary storage. Alternatively, after field capacity gravity storage attenuates peak flows by 22% and routing attenuated peaks by 11%. Since the attenuation performance decreases significantly after field capacity, the proportional impact that routing contributes to attenuation is increased substantially. It was found that gravity storage increases linearly with rain intensity, indicating that it is a dynamic mechanism that can adapt to higher

rainfall intensities. The quantification of each respective aspect of peak attenuation will guide development of green roof design to increase attenuation performance.

The predictive model based upon unsaturated soil theory accurately predicts outflow hydrographs. Three performance metrics were used to determine model correlation to observed data; volume of stored water, volume of drainage, and peak flow rate intensities. It was found that there was no statistically significant difference between the model and the observed data for any of these performance metrics. Even though the modelled response did slightly underestimate peak flow rates, this predictive model has significant potential to be used as an engineering tool when designing green roofs for stormwater management.

The research presented in this thesis considers the stormwater response of green roofs to better understand their capability as an LID tool. Two aspects of green roof performance were closely studied (i.e. effect of changing climates on retention and the processes that influence attenuation) that had not been adequately addressed in literature. Empirical data shows that green roofs can effectively retain and attenuate stormwater. In addition to the numerous other benefits that green roofs provide (e.g. improved energy consumption, improved runoff quality, reduced air pollution, improved aesthetics, mitigation of urban heat island effect, and providing habitats etc…), implementation of this tool in urban areas will provide relief to stressed stormwater management systems. The reduction and attenuation of stormwater runoff provided by green roofs can have directly positive impacts on the environment in areas using combined sewer networks, such as London Ontario. Implementation of green roofs to reduce impervious surface cover and manage stormwater is strongly encouraged in all appropriate urban areas.

## 5.2   Recommendations for Future Work

The first study presented in this thesis focuses on the retention capabilities of green roofs in three different climates. The analysis only considered the water balance data that was collected. However, coupling the retention analysis with an analysis of the radiation and energy balance data would provide more useful information. Assessing the energy and radiation data and evaluating the evapotranspiration trends at each site, could support the investigation of climatological impact on the overall performance of green roofs. Additionally, it would be interesting to consider duplicate roofs in each individual climate region to provide replicate data and assess whether microclimate differences have an impact on retention performance.

The second study considered the processes that lead to peak attenuation on green roofs as well as developed a model to accurately reproduce the outflow hydrographs from the green roof. For enhanced analysis of the attenuation mechanisms, monitoring the runoff from an impervious control roof could be beneficial. Comparisons of routing attenuation could be made between green roof and impervious roof. There is also an opportunity to improve the function of the proposed predictive model. This model could be coupled with a standard routing model to provide a better estimate of the drainage rates that are affecting municipal infrastructure. If a routing model was combined with the Richards equation model, comparisons to the monitored data for each of the major attenuation process could be conducted (capillary storage, gravity storage and routing). To progress the model further, the implementation of a valid evapotranspiration model could lead to an entirely continuous predictive model which would have significant implications on the design of green roofs.

Further study on the characteristics of the green roof media could also provide valuable information. Detailed continuous soil moisture records at various media depths and locations could improve insight into how the heterogeneous green roof media behaves over the course of the year, and how the complex mixture of grain types effect retention.
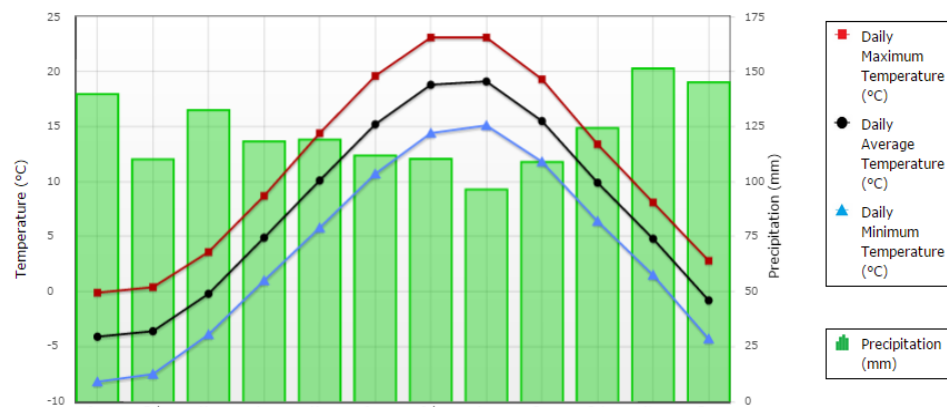
Appendices

Appendix A: Supporting documentation for Chapter 3
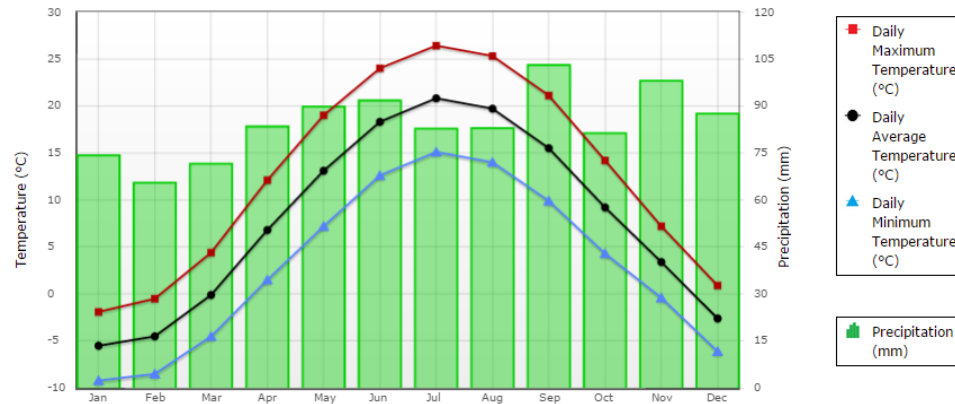
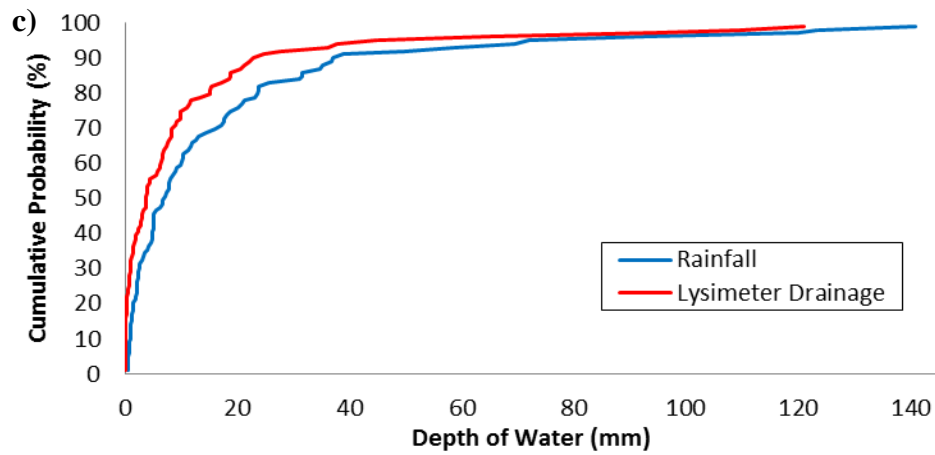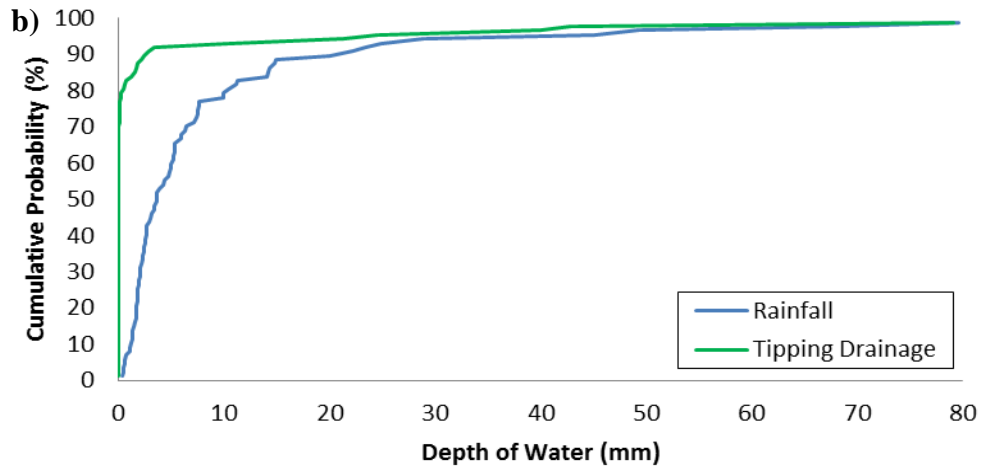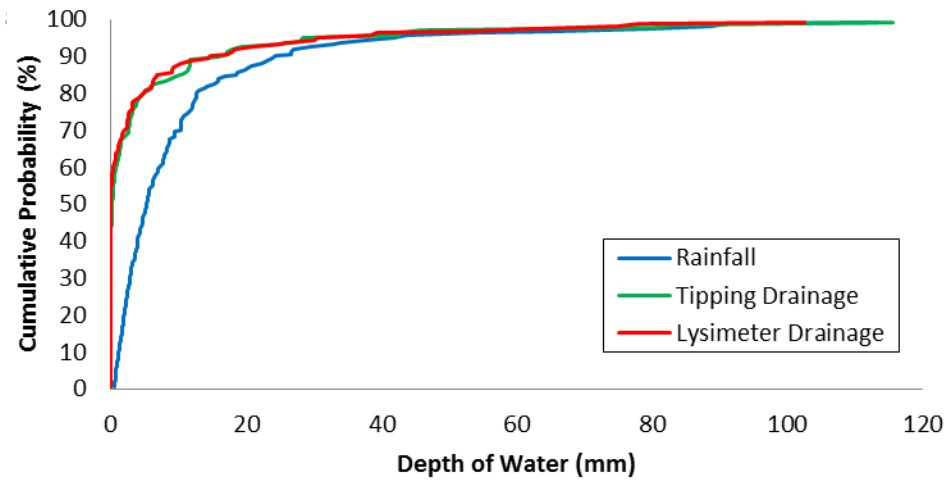**Figure A 1: London Ontario climate normal (Environment Canada, 2015)**
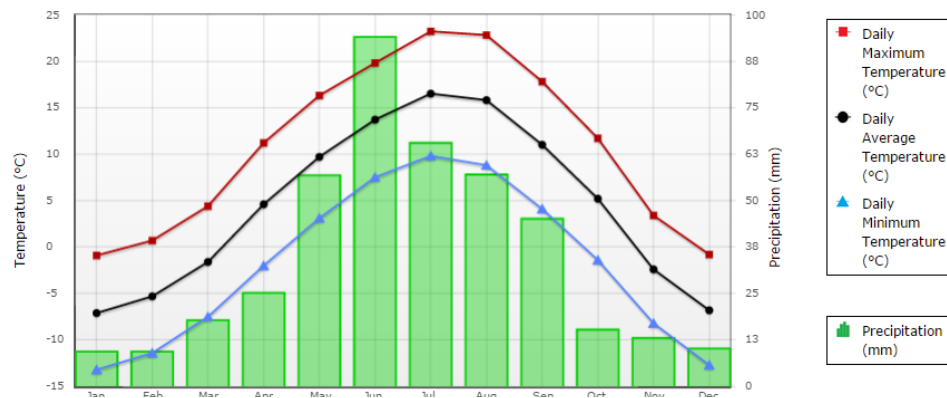
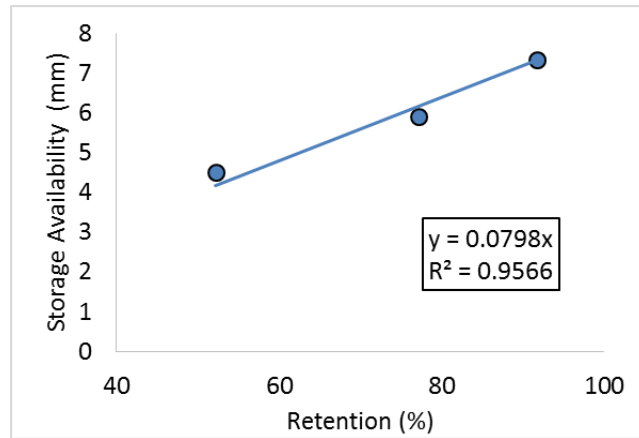**Figure A 2: Calgary Alberta climate normal (Environment Canada, 2015)**

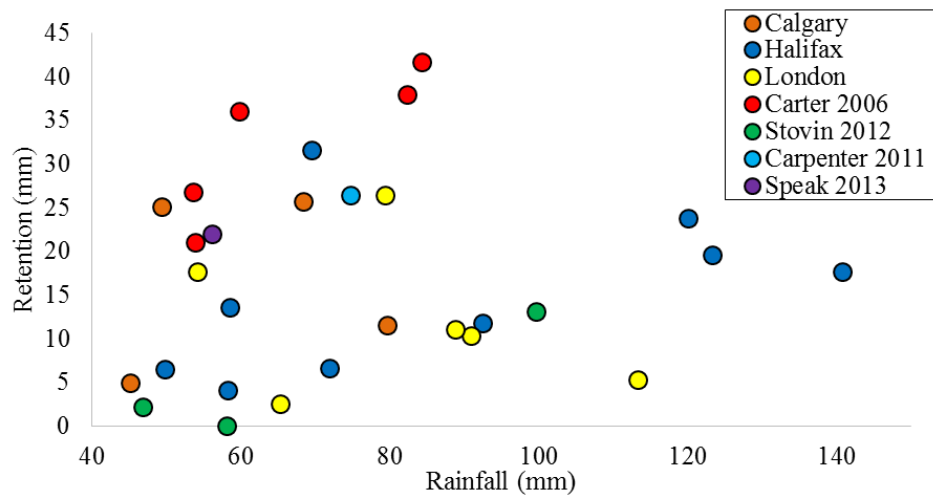**Figure A 3: Halifax Nova Scotia climate normal (Environment Canada, 2015)**

Figure A 4: Cumulative exceedance plot for a) London b) Calgary and c) Halifax

Figure A 5: Correlation of initial storage conditions to average event retention

Figure A 6: Retention scatter plot of monitored and literature events that exceed 45 mm of rainfall

Table A 1: Events from monitoring and literature of events greater than 45mm of rainfall

Rain Events > 45mm				
Source	Rain (mm)	Drainage (mm)	Retention (mm)	Retention (%)
Carpenter 2011	74.68	48.26	26.42	35.38
Stovin 2012	99.60	86.48	13.12	13.17
	58.00	57.96	0.04	0.07
	46.80	44.53	2.27	4.85
Speak 2013	56.08	34.01	22.07	39.35
Carter 2006	53.80	32.70	21.10	39.22
	59.70	23.60	36.10	60.47
	53.60	26.80	26.80	50.00
	82.30	44.30	38.00	46.17
	84.30	42.60	41.70	49.47
Calgary	79.66	68.07	11.58	14.54
	68.38	42.61	25.77	37.68
	45.10	40.05	5.05	11.19
	49.31	24.11	25.20	51.11
Halifax	58.16	54.04	4.13	7.10
	140.79	123.06	17.74	12.60
	123.34	103.73	19.61	15.90
	120.10	96.26	23.84	19.85
	58.41	44.74	13.67	23.41
	92.47	80.68	11.79	12.75
	69.49	37.85	31.64	45.53
	71.93	65.22	6.71	9.33
	49.75	43.19	6.56	13.19
London	65.20	62.59	2.61	4.00
	79.35	52.83	26.52	33.42
	54.13	36.48	17.64	32.60
	113.21	107.86	5.34	4.72
	90.89	80.51	10.37	11.41
	88.77	77.70	11.08	12.48

**Appendix B: Supporting information on CMLP instrument calibrations**

Tipping Buckets

The tipping bucket instrument operates using a magnetic switch closure system, where a magnet attached to the tipping mechanism actuates a switch as the bucket tips. The switch closure is counted on the data logger as a pulse of voltage and will register one tip. The tipping buckets were individually calibrated using a volumetric pipette to ensure that both buckets of the instrument tip at the same volume. The calibration volumes for the three CMLP tipping buckets are seen below.

Table B 1: Tipping bucket calibration values

Instrument	Tip Volume	Water Depth
Hoskin Rain Gage	9 mL/tip	0.275 mm/tip
Campbell Scientific	4.3 mL/tip	0.091 mm/tip
Drainage Unit	4.5 mL/tip	0.05 mm/tip

The Campbell Scientific rain gage (Figure B1a) was calibrated for smaller tipping volumes to allow for better resolution of small rain events, while the Hoskin rain gage (Figure B1b) was calibrated to perform better for large events. Calibrations were performed twice at the beginning of the monitoring season, once in a lab setting and again in the field. Calibrations were done a third time before the instrument was removed at the end of the monitoring season.


a) b)
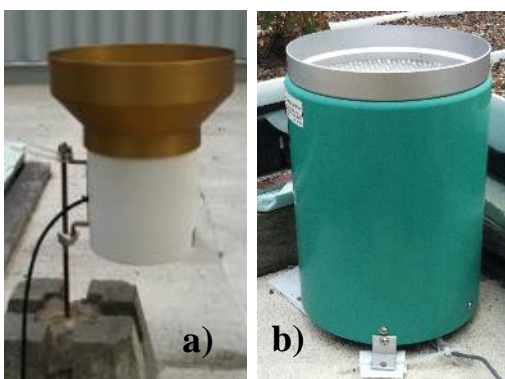
Figure B 1: a) Campbell scientific tipping bucket b) Hoskin scientific tipping bucket

Lysimeters

Lysimeters are frequently used in various environmental applications to obtain point measurement of evaporation. A lysimeter uses a sensitive load cell to provide data and works on the principle of a strain gage, where the resistance of a wire per unit area will increase if it is under tension forces and decrease under compression. The load cells that were used throughout the monitoring are Interface SPI Load Cells with 25 lbf capacity.

Calibrations had to be undertaken on the load cells to allow for conversion of the mV readings into a mass. Multiple calibrations were completed in both the lab and the field. The calibrations are a simple process of adding a known series of weights to the lysimeters and monitoring load cell response. The results of these calibrations for one lysimeter can be seen in Figure B2.
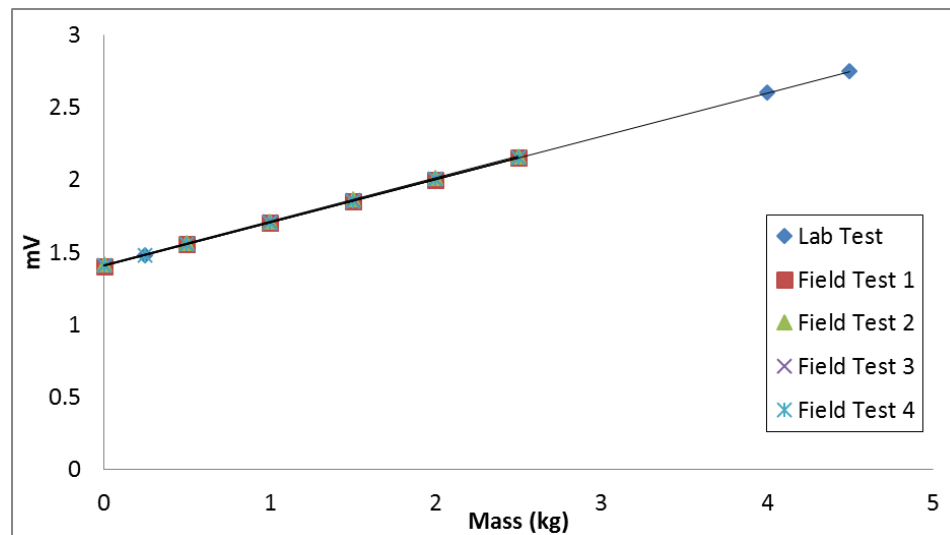
Figure B 2: 2014 calibrations for one of the lysimeters used on CMLP

The reproducibility (precision) of the lysimeter under various loads and in various environments is excellent. Both the line slope and y-intercept are consistent from test to test, providing reliable mV to mass conversions.

Soil Moisture Probes

The Decagon EC-5 soil moisture probe is a two prong instrument that measures the dielectric constant of the media using excitation voltages. The specific probe used can be seen in Figure B3.

**Figure B 3: Decagon EC-5 soil moisture probe**

The Decagon EC-5 probes were calibrated using the two point Sakaki method outlined in Sakaki, Limsuwat et al. (2008):

$$\theta = \frac{ADC^{\alpha} - ADC_{dry}{}^{\alpha}}{ADC_{sat}{}^{\alpha} - ADC_{dry}{}^{\alpha}} \Phi \qquad\qquad 13$$

Where $\alpha = 2.5$, *ADC* is the mV response multiplied by a factor of 1.3661, θ is the volumetric water content, and Φ is the media porosity. This method was used in the characterization of the green roof media by Perelli (2014). Perelli (2014) found through comprehensive testing of eight EC-5 soil moisture probes that dry EC-5 values in the green roof media ranged from 288 mV to 338 mV and saturated values ranged from 603 mV to 678 mV. The dry calibration point for the CMLP EC-5 data was extrapolated to be 290 mV and the saturated calibration point was chosen as 605mV to maintain a consistent range with Perelli (2014) measurements.

Weir

The weir measures the runoff from a 98 m² catchment on the CMLP green roof. The water is routed one floor below the green roof to a weir pictured in Figure B4a.
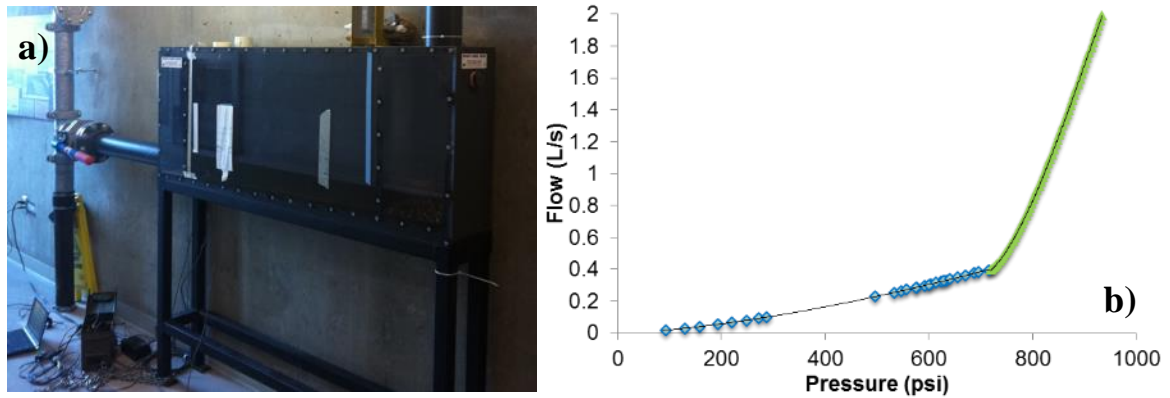
Figure B 4: a) Weir installed in the CMLP building b) calibration curve for the weir

The weir is calibrated using a calibration curve from a Honeywell pressure transducer, placed at the bottom of the holding tank. The measured pressure is directly related to the depth of water, and therefore, the flow of water through the weir plate. The weir plate is a double notch rectangular shape, hence the two distinct curves seen in Figure B4b. The lower calibration curve was determined by pump testing at a number of flow rates, and the second curve was determined from weir plate theoretical calculations. A future recommendation to improve the weir response would be to install a V-notch weir to allow for one continuous calibration curve, or to obtain a very large pump to reach sufficient flow rates to calibrate the second rectangular notch.

Curriculum Vitae

Name:	Andrew Sims
Post-secondary Education and Degrees:	University of Guelph Guelph, Ontario, Canada 2009-2013 B.Eng.
Honours and Awards:	R.M. Quigley Award 2014
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