Green Roof Water Retention: Reduction of Stormwater Runoff in the District of Columbia

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at George Mason University

by

Erik Steven Hovland
Bachelor of Science
Old Dominion University, 2013

Director: Paul Houser, Professor
Department of Geographic and Cartographic Sciences

Spring Semester 2015
George Mason University
Fairfax, VA

DEDICATION

This is dedicated to my loving grandfather, Lyle Hovland, who taught me much wisdom and love.

ACKNOWLEDGEMENTS

First and foremost I would like to thank God and all the family, friends, and supporters he has provided. My family has supported me since day one and I could not be more grateful. Drs. Houser, Rice, and Fuhrman were of invaluable help. Thank you for your time and consideration as a Master's Candidate.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

Benefit-Cost Ratio .... BCR
Best Management Practice.. BMP
Comprehensive Development Plan..CDP
Green Area Ratio .... GAR
Harmful Algae Blooms... HAB
Leadership in Energy & Environmental Design... LEED
Light Detection and Ranging .... LIDAR
Non-Point Source.. NPS
Rational Curve Number .... RCN
Royal National Institute for the Blind...RNIB
The District of Columbia .... D.C.
Ultraviolet ....UV
Unit Area Reduction Factor ....UARF
United Kingdom...UK
Urban Green Space .... UGS
Waste Water Treatment Plant .... WWTP

ABSTRACT

GREEN ROOF WATER RETENTION: REDUCTION OF STORMWATER RUNOFF IN THE DISTRICT OF COLUMBIA

Erik Steven Hovland, M.S.

George Mason University, 2015

Thesis Director: Dr. Paul Houser

Green, vegetated, or living roofs can be defined as a roof that is partially or fully covered with a live plant material. Green roofs have gained momentum in cities over the past decade, as builders and city leaders have recognized their advantages over traditional roofing materials in terms of ecological functions, energy efficiency, and storm water management. This study evaluates the stormwater mitigation potential of green roofs in the District of Columbia. Using LIDAR data, coupled with masking and filtering techniques, roof area and slope will be calculated. Using the Mini-Model, provided by Limno-Tech Inc. and Casey Trees, three scenarios will be assessed where 20%, 50%, and 80% of the green roof potential will be achieved, and the consequential storm water management effect will be analyzed.

INTRODUCTION

Recently, an increased demand for environmentally friendly products, companies, and urban planning has been illustrated worldwide. Green products reduce negative impacts on the environment and human health. Environmentally friendly products incorporate the use of recycled materials, manufacturing processes that require less energy, and a reduction in energy consumption. This shift in societal interests is creating a viable market for sustainable living.

1.1 Overview

The global population is rapidly increasing, causing urban areas to become more concentrated. The higher volume of people demands the expansion of cities, creating more city infrastructure, which inherently generates more impervious surfaces. Impervious surfaces are any materials such as roads, sidewalks, and rooftops that prohibit the infiltration of water into the soil. Studies show that large amounts of impervious surfaces lead to stream degradation, thus causing pollution, erosion, and disruption of the natural water cycle (Arnold Jr and Gibbons 1996; Berndtsson 2010; Brabec, Schulte, and Richards 2002; Carson et al. 2013). Impervious surfaces create tributaries that are unhealthy for both humans and wildlife, and are an issue that city planners and dwellers need to address.

To reduce the environmental damage of city infrastructure, best management practices (BMPs) were initiated in the 1970's with the United States Clean Water Act. Retention ponds, vegetative swales, riparian buffers, and porous paving materials all serve as BMPs through their ability to reduce pollution and decrease the rate at which water enters the surrounding streams and rivers. Unfortunately BMPs require open space, which is limited in established urban areas. In addition to scarcity, real estate is a premium that comes at a high cost in cities. Most urban architectural designs aim to optimize space by building up, implementing sky lobbies and creating retail availability at the ground level. Open green space is not space efficient and thus difficult to retain in growing, over populated cities. City planners need to retire the traditional understanding of open green space to evolve with the urban setting, and optimize functionality by installing green roofs.

Rooftops are one of the few settings in an urban environment with wasted space. As stated above, open space is valuable in developed cities and unused space needs to be harnessed. Green roofs address the issue of space and are becoming more popular in the United States. In 1999, mayor Richard Daley, Jr. initiated the green roof movement in Chicago by installing a green roof on City Hall (Taylor 2007). This action helped establish 5.5 million square feet of green roof on 500 buildings in America's windy city (NRDC 2011). Chicago is currently leading the United States in green roof coverage, encouraging other major cities to join the green movement.

Over the past decade, developers and city leaders have recognized green roofs advantages over conventional roofing materials in terms of ecological functions, energy efficiency, and storm water management. The benefits associated with green roofs are extensive: improved air quality by absorbing pollutants and reducing dust and smog, abating noise levels, lowering air and surface temperatures resulting in a suppression of the urban heat island effect, reducing stormwater runoff, decreasing water pollution, and improving the quality of life by providing natural habitats for both humans and wildlife (Berndtsson 2010; Milburn et al. 2010; Gregoire and Clausen 2011; Morgan, Celik, and Retzlaff 2012; Tian and Jim 2012; Lee et al. 2013; Neema and Ohgai 2013; Vijayaraghavan and Raja 2014). Green roofs benefit the immediate city and the Earth globally as they sequester ozone gases, such as carbon, and produce oxygen. Green roofs provide an alternative solution to creating urban green space (UGS) in settings where space is valuable and limited.

Many studies and have demonstrated that green roofs are highly variable. Variables such as climate, dynamics of precipitation, moisture content, depth, field capacity, plant cover, and physical changes over time each affect the green roofs performance. Pilot scale studies consist of a model green roof in an elevated test box with a small watershed area, less than 12 m^2 (Carson et al. 2013). Pilot scale studies have the ability to be controlled, and have multiple testing units that allow observations to be made with respect to which conditions have the greatest performance. These analyses have created significant data that has produced a range of runoff reduction values. However, it is uncertain how accurately they can be translated to full-scale green roof performance.

Full-scale green roofs, constructed on buildings, provide the most representative and accurate data. However, climatic changes require these studies to span at least a year, and the results are specific to the climate zone or areas with similar weather patterns. Rainfall characteristics including intensity, duration, and frequency are critical factors in the runoff retention performance and can make comparing the results of green roofs in the same climate difficult.

Modeling green roofs stormwater management performance also has it challenges, however it permits the use of long-term weather records. This increases the chances of capturing the variance in climatic conditions and provides better insight as to how green roofs perform. Accounting for all the variables at play is difficult, which creates limitations to modeling as well. Regardless, every study has indicated green roofs out perform the traditional roofs, its just a matter of by how much and is it worth it.

1.2 Study Goal

The purpose of this research is to assess the stormwater mitigation properties of green roofs in the District of Columbia using a roof slope analysis to delineate 20%, 50%, and 80% roof cover potentials. For each scenario the green roof water retention capacity and its influence on the stormwater runoff will be estimated. The findings of this report is aimed to increase the District of Columbia city leaders understanding of green roof benefits and its ability to manage stormwater runoff.

1.3 Study Objectives

- Determine roof slope and area for buildings in the District of Columbia.
- Compare applied models that simulate green roof stormwater response.
- Assess the dynamic response of stormwater runoff at 20%, 50%, and 80% cover.
- Develop a report to present to the District of Columbia.

1.4 Organization

This thesis is organized into five sections: Introduction, Literature Review, Methods, Results, and Conclusion. The literature review discusses the relationship between city infrastructure and stream degradation. Best management practices, specifically green roofs, will be discussed in detail regarding the composition, benefits, and water retention capabilities that have been observed. Methods provide a comprehensive outline of the analysis and calculations performed to identify green roof potential in the District of Columbia and its impact on stormwater runoff. The outcomes of each scenario will be compared and reported in the results. The conclusion identifies the inverse relationship between green roofs and stormwater runoff.

LITERATURE REVIEW

The literature review consists of three major sections. An introduction to the natural and urban hydrology, and the role they play in producing stormwater runoff. The best management practices currently being implemented to reduce stormwater effects on the natural habitat, primarily green roofs and their composition, benefits, and water management capabilities. Lastly, a review of current studies and the methods of calculating green roof water retention and their results.

2.1 Hydrology

The hydrologic cycle is a well-balanced system that efficiently manages water through the processes of interception, depression storage, infiltration, runoff, evaporation and transpiration. This is a perpetual progression that transports water from the oceans, to the atmosphere, to the land, and back to the sea, with many intermediate subcycles (Warren. Viessman 1989). In a natural setting, vegetation and pervious surfaces absorb and retain water. Interception, the first contact precipitation has with the ground, is where the water wets and adheres to ground objects such as tree canopies and grasses, Figure 1 (Warren. Viessman 1989; J Marsalek 2008). The retained water present on the leaves becomes evaporated and returned to the atmosphere.

Figure 1. An example of interception.

Depression storage is the second phase in the natural water cycle, consisting of water that is retained in small depressions and catchment surfaces. This water remains in place until it becomes evaporated or infiltrates the surface. In a forest and open field setting, as much as 15 mm of water can be evaporated through depression storage (J Marsalek 2008). The evaporation process helps reduce the amount of water saturating the ground and or becoming runoff.

The next phase in the natural water cycle is infiltration. Infiltration is when water on the surface begins to percolate down into the soil, replenishing shallow aquifers and moving water in underground systems to where it eventually intercepts a larger water source (Warren. Viessman 1989; J Marsalek 2008). There are many paths water can take underground, some last days and others last many years. A portion of water will not infiltrate the ground and become surface runoff. This water flows downhill, over the surface, to a defined waterway such as a stream (Warren. Viessman 1989). There is a direct relationship between runoff and urbanization.

Evaporation is the process in which water in a liquid state is transformed into a gas and returned into the atmosphere. Transpiration is the vaporization of water from the plants leaves, which entered through the root system (Overton and Meadows 2013). The two processes are often combined and referred to as evapotranspiration. During the natural water cycle, evapotranspiration plays a large role in removing water.

2.2 Urban Hydrology

Urban areas characterized by a high plot ratio, dense site coverage, impervious surface, mixed land use, close juxtaposition of different land uses, efficient public transit system, and highly fragmented urban green space (Burgess 2000; Ganesan, Lau, and others 2000; Zaman, Lau, and Mei 2000; Tian and Jim 2012) are continually growing in space and density. The density of cities demands the removal of vegetation, formation of impervious surfaces, and compaction of soils. Impervious surfaces have been utilized as one indicator to define the intensity of the urban environment (Espey, Morgan, and Masch 1966; Stankowski 1972). This increased stress creates a significant impact on the surrounding microclimate and natural water cycle, which alters the hydrological sequence, producing the urban water cycle.

Open green space is removed to accommodate the development pressures of urban areas. Space is a premium and profit is the objective, unfortunately open green space is not effective for either. The reduction in vegetation interception and evapotranspiration causes a decrease in air humidity, an increase in air temperature, and an influx of water in the urban hydrologic cycle (Berndtsson 2010). The mean annual actual evapotranspiration calculated using data from 1971-2000 estimated 61-90 cm of water is returned to the atmosphere in the humid subtropical region of the United States, Figure 2. Decreased evapotranspiration in the urban water cycle results in a larger volume of water needing to be managed.

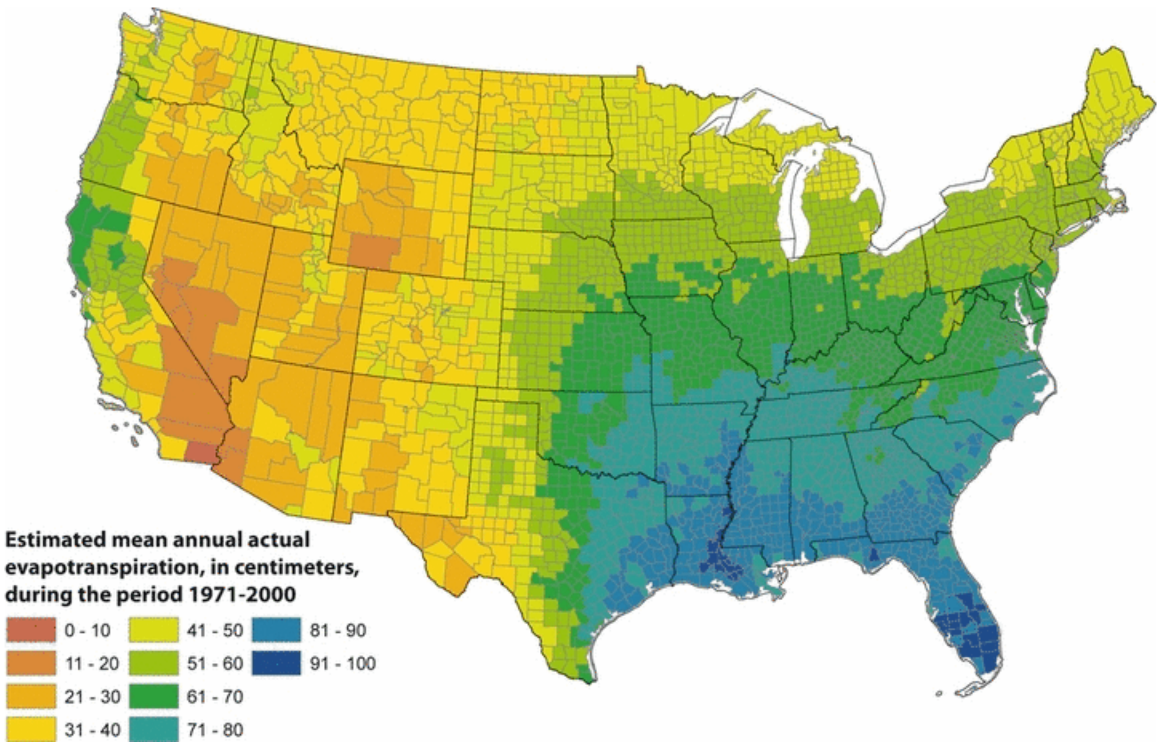

Figure 2. Map of Estimated Mean Actual Evapotranspiration (ET) for the conterminous U.S. for the period of 1971-2000 (Sanford and Selnick 2013).

Urban infrastructure has two primary impervious surfaces, pavement and roofs. Approximately 35 to 90 percent of urban groundcover is pavement (Liptan 2003), and roofs comprise an average of 40 to 50 percent of the total area (Dunnett and Kingsbury 2003). Arnold and Gibbons identify a direct relationship between urbanization and hydrologic changes. With the expansion of impervious surfaces, the velocity and volume of surface runoff increases (Arnold and Gibbons 1996). Impermeable ground cover reduces the amount of shallow infiltration, deep infiltration, and evapotranspiration, resulting in augmented runoff, as illustrated below in Figure 3.

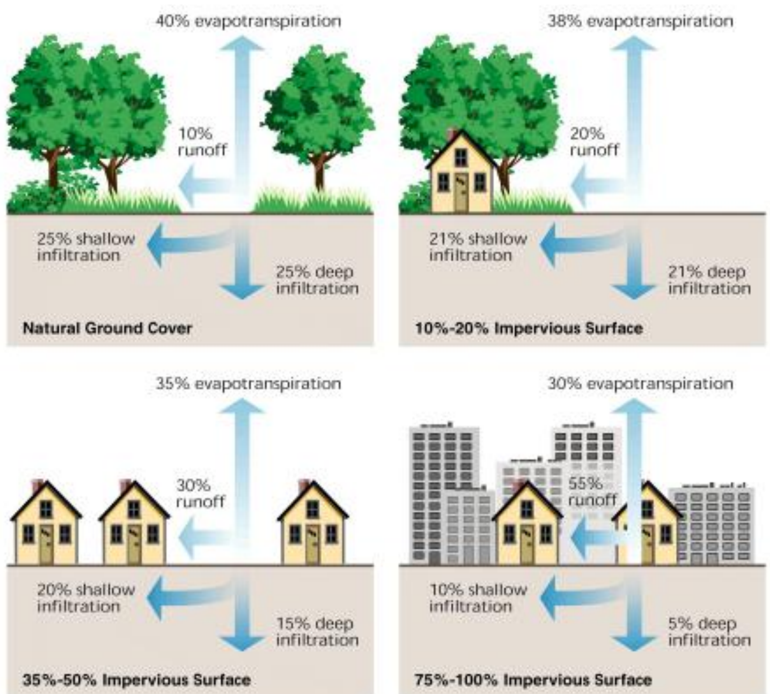

Figure 3. The direct relationship between impervious surface and runoff (FISRWG 1998).

Impervious surfaces require the compaction of soil to prevent structural damage, sinking, and settling. This enhances the impermeable characteristics of urban ground cover, making it more difficult for water to infiltrate the ground. This further impacts the hydrologic cycle and ground water recharge.


Figure 4. An example of urban depression storage.

In the urban water cycle depression storage is still present where roofs and impervious surfaces hold water due to slumps and cavities, Figure 4 (Berghage et al. 2008). Limited open green space, impervious surfaces, and the compaction of soils diminish the canopy interception, infiltration, and ground water recharge. Excess depletion of water resources in subsurface aquifers and greater surface water flow, referred to as stormwater, are resultants of the urban hydrologic cycle.

2.3 Stormwater

Impervious surfaces require the removal and redirection of water. Traditionally, the goal of this process was to remove water as quickly and effectively as possible (Arnold Jr and Gibbons 1996). Water removal ensures the safety of drivers and the health of the residents by preventing flooding and standing water. “Once off the road and out of sight, stormwater has been largely out of mind – downstream consequences be damned (or dammed)" (Arnold Jr and Gibbons 1996). In recent years, it has come to light that stormwater has adverse effects on waterways, wildlife, and their habitat.

Arnold and Gibbons state that there is a direct relationship between impervious coverage and stream health (1996). Increased impervious surfaces result in higher stream degradation, Figure 5.

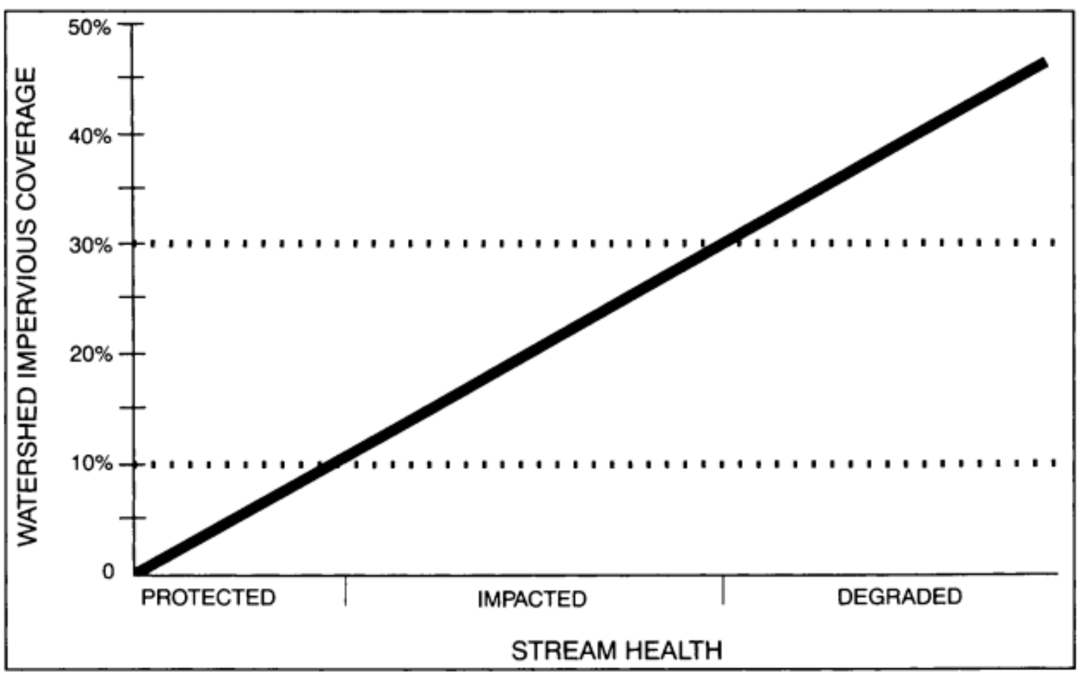

Figure 5. Direct relationship between impervious surface and stream health (Arnold Jr and Gibbons 1996).

Streams become impacted when impervious cover represents 10% of the local area, and degraded when coverage is greater than or equal to 30%.

In an urban environment, stormwater is transported through impervious drainage systems, such as pipes and gutters. The efficient removal of stormwater causes water to quickly build velocity and volume, entering the streams with a large rush of water, causing an intensification in peak discharges (R. W. Carter 1961; Anderson and County 1970; Leopold 1968; Tourbier 1981; Arnold Jr and Gibbons 1996). The higher velocities of stormwater increase suspension capabilities, transporting greater amounts of pollutants. This hydrologic disturbance generates a wave of ecological complications.

2.3.1 Sources and Pollutants

Two primary types of stormwater pollutants exist; point source and non-point source (NPS). Point source pollutants can be directly linked to one source, or facility. This enables the identification of the source, and has helped decrease this category of pollutants. In a study of the Long Island Sound, the major source of pollutants was determined to originate from sewage treatment plants, a point source pollutant (Long Island Sound Study 1994). However, an estimated 47% of pathogenic contamination was derived from urban runoff, a NPS pollutant (Long Island Sound Study 1994). NPS pollutants such as, pathogens, erosion, nutrients, and toxic contaminants are more difficult to isolate, and among one of the leading causes of pollution in United States waterways.

The largest point source and NPS pollutant contributors, inputting pathogens, sediment, and nutrients into stormwater, are combined sewer overflows (CSOs) and agricultural practices, respectively. Human waste and manure are a source of bacteria and viruses that can be pathogenic, leading to outbreaks in disease (NOAA 2008; Carson et al. 2013). Pathogenic contamination can cause water to be off-limits and prohibit the consumption of raw shellfish, as it can be a health hazard causing intestinal illness (Arnold Jr and Gibbons 1996; NOAA 2008). The District of Columbia Water and Sewer

Authority caution the public to avoid contact with the Potomac River for 72 hours after heavy rains due to CSOs. It is estimated that an average of 2.5 billion gallons of CSOs enter the Potomac, Anacostia, and Rock Creek each year (DC Water 2004; Lisle 2014). The ultra large crude oil tanker, the largest operating cargo vessel in the world, carries 84 million gallons of oil, Figure 6 (Hamilton 2014). It would take more than 29 tankers to equal the amount of CSOs that enter the Chesapeake Bay each year from the District of Columbia sewershed.

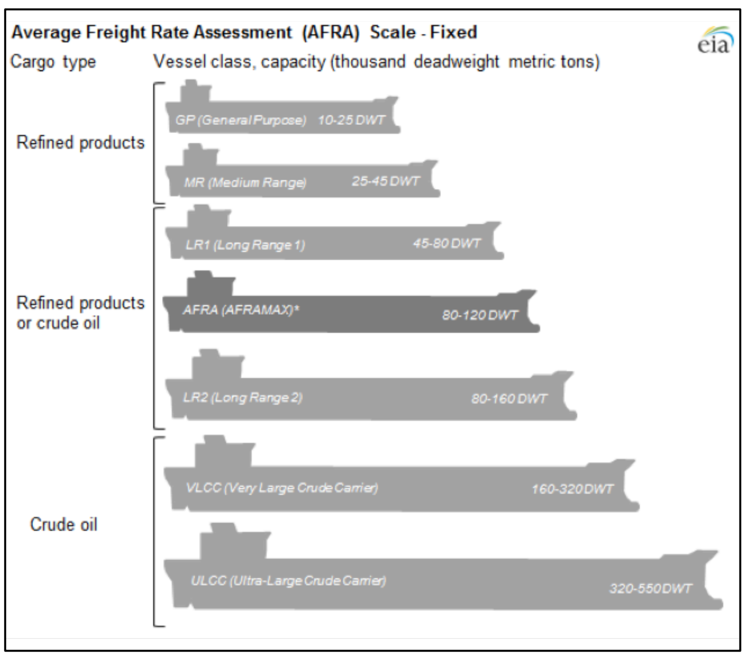

Figure 6. Oil tanker size comparisons. Ultra Large Crude Carrier, ULCC, being at the bottom (EIA).

Erosion and particulates in runoff cause the waters in the tributary to become murky and loaded with suspended sediment. This decreases the clarity and penetration of light, reducing the depth at which vegetation is able to grow. More than half of the

Chesapeake Bay's eelgrass has died since the early 1970's (Pelton and Goldsborough 2008). The depletion of this natural habitat puts wildlife such as hatchlings and immature crustaceans like the blue crab, a staple in the Maryland and Virginia seafood market, at risk. Figure 7 depicts roads covered in excess sand and salt from the winter season.

Figure 7. Remnant sand and salt from the winter season.

Excess amounts of nutrients cause harmful algae blooms (HABs) that have the potential to create anoxic zones. Anoxic zones are produced by the consumption of oxygen as HABs break down and decay. Roughly 75,000 metric tons of clams and worms are destroyed each year by anoxic zones, enough food to support 30 million crabs or half of the commercial crab harvest (Pelton and Goldsborough 2008). Some HABs are comprised of toxic cyanobacteria, also known as blue-green algae, that is capable of producing cyanotoxins (Carey et al. 2013). Cyanotoxins are harmful if ingested, potentially killing humans, animals, and threatening potable water (Dortch et al. 2008;

Bigham, Hoyer, and Canfield Jr 2009; Gilinsky et al. 2009; Carey et al. 2013). In the mid 1970's the harmful effects of stormwater removal became noticeable, and new strategies were put in place to help reduce its influence on the local streams and ecological habitats.

2.3.2 Best Management Practices

With the establishment of the Clean Water Act in 1972, multiple strategies for reducing the pollution of the surrounding urban tributaries emerged. Over time the colloquial term became best management practices (BMPs). The key to BMPs accomplishing the removal of pollutants is allowing runoff to sit before reentering the hydrologic cycle (Horner et al. 1997). Infiltration basins, swales, rain gardens, and green roofs are a few examples of BMPs.

In some areas BMPs have become a mandatory requirement for new construction projects. The District of Columbia, in the 2013 Stormwater Rule, set a 1.2-inch stormwater retention standard for land-disturbing development projects (DDOE 2014). The Green Area Ratio (GAR) sets minimum requirements for vegetative cover, and the Green Building Act of 2006 requires all non-residential District public buildings to be LEED certified (DDOE 2014). Many of these requirements are met with the implementation of BMPs. BMPs are most effective in a network, but in urban areas, the space required for implementing BMPs is not available. Rather than deconstruct a building to install a BMP, the unused space on rooftops can easily be converted into green roofs.

2.4 Green Roofs

Green, vegetated, or living roofs can be defined as a roof that is partially or fully covered with a live plant material. Green roofs, due to their benefits and aesthetic appeal, have grown in popularity over the past couple of years, but are not a new concept. The early examples of green roofs are the hanging gardens in Babylon, rooftop trees in Rome, and sod roofs on the longhouses of the Vikings (Stewart; Magill et al. 2011). The components of green roofs have evolved over time. Lightweight materials make retrofitting green roofs feasible and more common. Green roofs are appearing in many United States cities and have attracted much interest because of the economic and ecologic potential.

2.4.1 Green Roof Design

Green roofs are broken into two categories: extensive and intensive, based on the depth of the soil medium. Extensive green roofs typically consist of a depth of less than 150 mm, which supports drought resistant vegetation such as sedum and grass (Kosareo and Ries 2007; Carson et al. 2013; Speak et al. 2013; Vijayaraghavan and Raja 2014). This roof system is utilitarian and intended for its storm water mitigation and other various benefits. Intensive green roofs are greater than 150 mm supporting a larger root system, which include woody plants such as trees and shrubs (Rowe 2011; Carson et al. 2013; Vijayaraghavan and Raja 2014). Intensive green roofs are interactive, consisting of walkways and outdoor seating for enjoyment purposes. Although intensive green roofs are more stimulating, extensive green roofs are more cost effective and require less structural support, making them more widespread and studied. The remainder of the study will focus solely on extensive roofs.

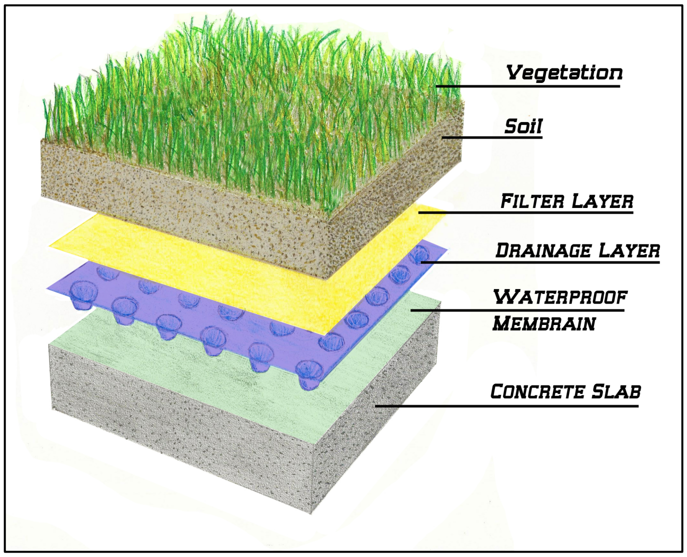

Figure 8. Layers of a green roof system (Sustainability 2015).

2.4.2.1 Vegetation

Harsh growing conditions limit the vegetation compatible with green roofs. The vegetation on extensive green roofs consists of hardy drought tolerant plants such as sedums and grasses. Many studies have assessed the value of vegetation on green roofs and found they increase runoff retention, cool the roofs surface, and decrease soil erosion (Steusloff 1998; Oberndorfer et al. 2007; Wolf and Lundholm 2008; Nigel Dunnett et al. 2008). Morgan et al. (2012) states that, 20-25% of vegetative cover is required to increase the stormwater retention capabilities beyond the capacity of the growing media. VanWoert et al. (2005) observed that vegetated roofs retained 60.6% of overall rainfall, whereas media only roofs retained 50.4%. Vegetation, as a living organism, has an extensive root system that absorbs water, transferring it into the plant where it is stored, consumed or transpired. It is this fundamental process that enables vegetation to increase stormwater retention.

A porous substrate, that provides ample air flow, is required to promote deep root growth in the media (Buist and Friedrich 2008). A deep root system locks the soil in place, preventing erosion, and enables the plant to sustain itself during periods of extreme temperatures (Buist and Friedrich 2008). Vegetation also protects the media surface from rain damage and compaction (Nigel Dunnett et al. 2008). Compacted soil is less pervious and requires additional wetting to restructure the surface (Nigel Dunnett et al. 2008). A compacted surface has the potential to create surface flow, causing erosion and a reduction in green roof performance.

2.4.2.2 Growing Media

Growing media is a mixture of lightweight aggregates such as sand, gravel, lava, perlite, vermiculite, crushed brick and concrete (Nigel Dunnett 2004; Buist and Friedrich 2008). These materials have pore spaces that lighten the load, requiring less structural support, and trap nutrients and water (Buist and Friedrich 2008). It is advised that organics be kept at a minimum, less than 20%, as they break down and become washed out over time (Buist and Friedrich 2008). Fine organic particles can clog filter fabric, impeding proper drainage.

Not all organics are problematic. Organics with crystalline structures, such as certain bark-based products, will behave much like sand as they break down, and organics with strand characteristics retain their structure (Buist and Friedrich 2008). Organics hold water through particle swelling which is more effective than void filling (Buist and Friedrich 2008). Particle swelling increases the performance of green roofs, making organics a valuable asset.

It is important that green roofs have a well-aerated and porous media. Sedums require that the substrate is not so fine that moisture is unable to be removed (Buist and Friedrich 2008). Excessive water in the soil media can cause root rot and vegetation to be lost during the wet season. Storage is measured by the field capacity, also referred to as water retention capacity (DeNardo et al. 2005; Berndtsson 2010). This provides estimates of the percentage of stormwater green roofs are capable of retaining.

The growing media depth of extensive green roofs ranges from 50-150 mm. A study performed by Morgan et al. indicates that the 100 mm substrate was most effective in retaining storm water and producing adequate plant growth (2012). A 100 mm substrate compared to 150 mm, reduces the weight and cost of a green roof.

2.4.2.3 Filter Layer

The filter layer is positioned between the growing media and the drainage layer. It is responsible for preventing fine particles from being lost from the media (Buist and Friedrich 2008; Hathaway, Hunt, and Jennings 2008). This keeps the drainage layer free of debris that could hinder the movement of water and improves the quality of runoff from the green roof by removing sediment. The filter fabric is susceptible to clogging if there is an accumulation of fine organic matter.

2.4.2.4 Drainage Layer

The drainage layer is composed of a lightweight gravel or highly porous mat. Drainage mats are specially designed with wells for water storage during dry weather, and keep drainage pathways open to allow removal of surplus water (Stewart). Having clear drainage channels reduces the risks of the green roof flooding, which could cause roof damage or plant loss (Miller 2003). Excess water surrounding the plant roots for an extended period of time can be equally as fatal as a prolonged drought.

2.4.2.5 Moisture and Root Barrier

The waterproofing membrane and root barrier is placed at the bottom of the green roof system to prevent water and vegetation from damaging the underlying roof structure. This membrane is composed of synthetic materials such as ethylene propylene diene monomer (EPDM), polyvinyl chloride (PVC) or butyl rubber (Nigel Dunnett 2004). Unlike a conventional roof, UV rays are unable to weather the waterproof membrane because it is situated at the bottom of the green roof layer stack. This reduces expanding, contracting, and the drying out of the waterproofing material. The unweathered synthetic materials form a strong barrier that enhance the longevity of the roof and reduce the risks of future leaks, mold, and root damage.

2.4.3 Benefits

There are many benefits associated with green roofs such as the sequestering of atmosphere pollutants, improving air and water quality, abating noise pollution, reduced building energy consumption, providing habitat, lowering air temperatures lessening the urban heat island effect, reducing stormwater runoff volumes, and improving the quality of life (Nigel Dunnett 2004; Berndtsson 2010; Aitkenhead-Peterson et al. 2011; Morgan, Celik, and Retzlaff 2012; Bates, Sadler, and Mackay 2013; Neema and Ohgai 2013; Carey et al. 2013; Vijayaraghavan and Raja 2014). In this section, the benefits of green roofs will be broken into three broad categories: ecological, energy reduction, and stormwater.

2.4.3.1 Ecological

Vegetation naturally acts as a pollutant filter, as well as produces oxygen. Plants intercept particulate matter with their leaves and absorb gaseous pollutants such as CO_2, NO, and NO_2 through stomates, pores on the leaves and stems (Baker and Brooks 1989; Bealey et al. 2007). Nearly half of the people in the United States live in counties with unhealthy levels of ozone or particulate pollution (ALA 2014). A 2000 m^2 green roof is able to remove 4000 kg of particulate annually, while an automobile releases 0.1 kg of particulate matter annually (Johnston and Newton 2004; Rowe 2011). Thus, one square meter of green vegetation can offset the annual particulate matter produced by 20 vehicles.

Vegetation in combination with soil media absorbs sound waves, reducing echoing and excess sound frequencies (Rowe 2011). Conventional roofs have hard surfaces, which can exacerbate sound by reverberation. Van Renterghem and Botteldooren observed a reduction of up to 10 dB for an extensive green roof (2008). This is a significant reduction considering the OSHA daily permissible noise level exposure states that 90 dB is acceptable for eight hours a day, but 100 dB is only acceptable for two hours (OSHA 2015). Reducing noise levels in urban areas would help prevent hearing impairment, sleep disturbance, and other related health problems.

Increased green space also improves the quality of life for humans and wildlife. Intensive green roofs provide pleasant areas for recreational activities and social gatherings. Extensive green roofs, though not habitable by humans, aid quality of life by providing aesthetically attractive roofs and visual relief. Green spaces reduce mental fatigue and provide enhanced life functioning, relaxation, and restoration (Hartig, Mang, and Evans 1991; Kuo 2001). Wildlife such as insects and birds has also developed communities on green roofs, providing local habitat conservation.

2.4.3.2 Energy Reduction

Urban infrastructure such as, concrete roofs, asphalt, and conventional roofing, have low albedo values and high thermal conductivities, leading to the absorption and storage of heat (Hutchison and Taylor 1983; Wolf and Lundholm 2008; Milburn et al. 2010). Conventional roofs allow solar radiation to penetrate the roof membrane, which causes the interior temperature to rise (Milburn et al. 2010). Roughly 90% of the total incident solar radiation is absorbed or reradiated (Hutchison and Taylor 1983). Warmer household temperatures require additional cooling, which results in greater energy usages and costs. The urban heat island effect has sprouted from this phenomenon, resulting in increased city temperatures compared to the surrounding rural area, by as much as 45°F (7°C) (Oke 2002; Lazzarin, Castellotti, and Busato 2005). The urban heat island effect has become an issue in many cities, which can lead to health hazards and illnesses.

Green roofs have become a major strategy for reducing building energy consumption and the urban heat island effect. Vegetation has a lower surface albedo and acts as a barrier that reduces the amount of solar radiation able to penetrate the roof (Oberndorfer et al. 2007). This creates more constant indoor temperatures and a reduction in energy costs (Mendler and Odell 2000; Fang 2008). In Figure 9, green roofs insulative properties are illustrated, as their temperature remains constant and the white surface, cool roof, temperature fluctuates drastically.

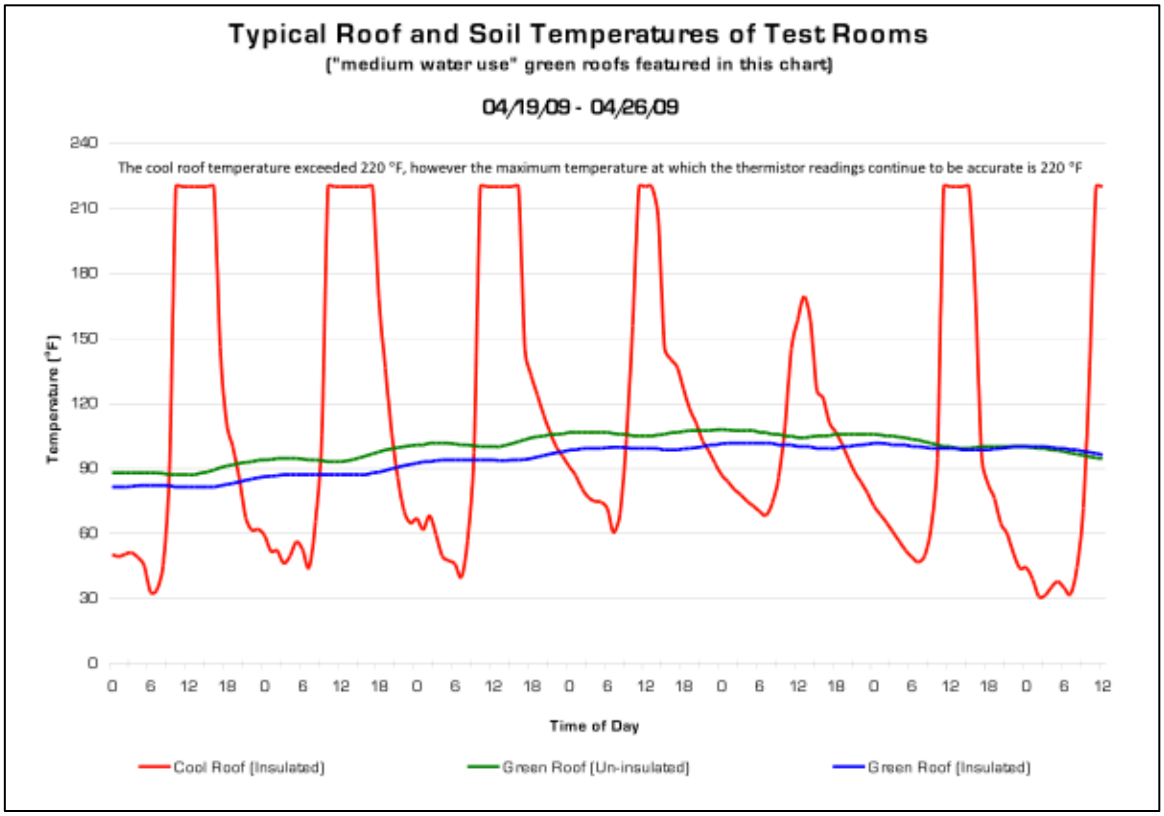

Figure 9. Soil temperatures of green roofs (Blue and Green) compared to standard white surface cool roof (Red) exterior temperature (Milburn et al. 2010).

Not only does the green roof insulate, but the vegetation also has many natural cooling attributes. Regular biological functions such as photosynthesis, respiration, transpiration, evaporation, and shade reduce surface temperature and latent heat transfer (Niachou et al. 2001; Tan et al. 2003; T. L. Carter and Rasmussen 2006). These processes cool the layer of air present on the roof and are referred to as microclimatic cooling. With a network of green roofs established, area wide evapotranspiration rates would increase and result in lower air temperatures, decreasing the urban heat island effect.

2.4.3.2 Stormwater

As mentioned above, in Sources and Pollutants, stormwater degrades local waterways through the input of anthropogenic pollutants. Impervious coverage is rampant in cities, causing small rainfall events to generate large volumes of water and flashy, elevated stormflow (T. L. Carter and Rasmussen 2006). Green roofs absorptive characteristic allows them to attenuate and delay runoff, whereas conventional roofs are the first slopes of many that lead to elevated stormflow. Depending on the storm severity, a portion of the detained water will drain after it has passed through the green roof, creating a lag between peak runoff and runoff from green roofs (Berndtsson 2010). The remaining water will evaporate or be consumed by vegetation. "It is the evaporated and transpired water that explains the observed runoff volume reduction from green roofs" (Berndtsson 2010). The reduction in stormwater runoff decreases the strain on sewer systems and treatment plants, making it more feasible to treat stormwater before reverting to CSOs. This helps prevent pollution in the local tributaries and lessens the effects of urban infrastructure.

2.4.4 Hydrology of Extensive Green Roofs

The initial stages of the hydrologic water cycle on a green roof are similar to that of natural vegetation. Precipitation first comes in contact with the canopy, where a portion of the water will be intercepted, stored on the plant, and later evaporated. The remaining water will infiltrate the growing media where it will remain as field capacity, or exit as stormwater runoff.

Green roofs are specially engineered to have a high hydraulic conductivity to ensure that the infiltration rate exceeds the precipitation rate to minimize the risks of overland flow (Miller 2003; Villarreal and Bengtsson 2005; Bengtsson 2005; Martin 2008). Surface flow across the green roof can cause erosion and loss of growing media. A reduction in growing media reduces green roof performance, exposes plant roots making them susceptible to the harsh environment, requires maintenance, and creates additional costs.

As precipitation infiltrates the green roof, the field capacity of the growing media decreases. Field capacity refers to the maximum water absorption potential of a green roof, and is greatest when the growing media is dry. Excess water will begin to drain from the roof when field capacity is reached (Hilten, Lawrence, and Tollner 2008). The surplus water is referred to as runoff, and is a common variable used to identify a green roofs ability to manage stormwater. Figure 10 displays a model-based approach of defining precipitations path through a green roof.

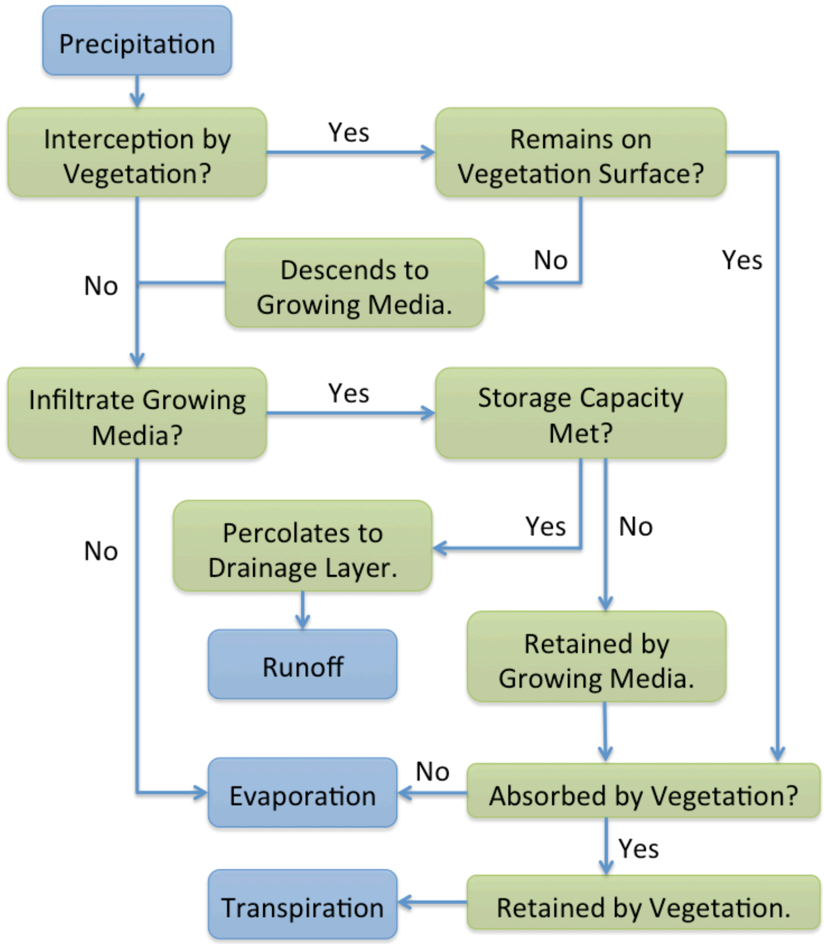

Figure 10. The hydrologic movement of a green roof.

2.5 Modeling the Green Roof Stormwater Response

Many studies have been conducted on green roofs ability to retain stormwater runoff. Extensive green roofs have demonstrated a broad spectrum of runoff reductions from 27-81% of annual precipitation (Mentens, Raes, and Hermy 2006; Berndtsson 2010). The variations in runoff reduction are due to an assortment of variables such as antecedent moisture conditions, vegetative cover, rainfall intensity, soil hydraulic properties, precipitation distribution, climate, slope, and evapotranspiration rates (Hilten, Lawrence, and Tollner 2008; Berndtsson 2010). The variable characteristics of green roofs make it difficult to directly compare green roof studies. As the number of green roof stormwater retention studies propagates, and new green roofs are installed and monitored, more conclusive references emerge.

2.5.1 Green Roof Performance

Green roof performance is typically reported in terms of runoff reduction, or the amount of water retained. Retention is defined as the difference between depth of precipitation and depth of runoff (DeNardo et al. 2005). Evapotranspiration, field capacity, and plant consumption are the main attributes of a green roof that reduce the volume of runoff (Berndtsson 2010; Roehr and Kong 2010). Values for runoff reduction varies between studies, but is usually between 45-65%, Table 1.

Table 1. Average green roof runoff retention values. Rows highlighted in green are studies located in the same climate zone as the District of Columbia.

Study Period (Months)	Total Rainfall(mm)	Retention (mm)	Retention (%)	Growing Media depth (mm)	Location	Study
12	1600	752	47	100	New York, NY	Carson et al. 2013
18	1245	622	50	100	St. Louis, MO	Morgan et al., 2013
13	1307	667	51	102	Storrs, CT	Gregoire & Clausen 2011
11	683	360	53	100	State College, PA	Berghage et al. 2009
14	1400	756	54	100	St. Louis, MO	Morgan et al., 2013
3	314	173	55	100	Raleigh, NC	Moran, 2004
12	1600	976	61	100	New York, NY	Carson et al. 2013
18	1514	961	63	75	Goldsboro, NC	Moran, 2004
14	1270	450	64	75	Goldsboro, NC	Hathaway et al. 2008
6	350	125	64	100	Kinston, NC	Hathaway et al. 2008
13	1079	842	78	76.2	Athens, GA	Carter and Rasmussen 2006

A green roof study, sponsored by the EPA and carried out by Berghage et al. in 2009, used six identical test buildings: three with green roofs, two with asphalt rolled roofing, and one with unplanted green roof media. Weather data was recorded every five minutes and runoff readings were recorded after each storm event from January 2005 to November 2005. Over the 11-month period, 111 storm events took place resulting in 35.5 inches (902 mm) of precipitation. Runoff data was collected for 26.9 inches (683 mm) of precipitation (Berghage et al. 2009). Of the recorded precipitation the mean value for green roof runoff was 12.7 inches (323 mm) whereas the asphalt roof runoff mean value was 23.1 inches (587 mm) (Berghage et al. 2009). The green roofs retained 53% of the water, whereas the asphalt roof retained only 14% due to depression storage (Berghage et al. 2009). This is a percentage point increase of 39%, and subsequently a runoff reduction of 10.4 inches. In every study, where green roofs and traditional roofs have been compared, green roofs have out performed the traditional roofs in reducing stormwater runoff volumes.

2.5.2 Curve Number Method

In the absence of a physical green roof and time to monitor its reduction in runoff, alternate methods with equivalent accuracy are needed to quantify green roof performance. The runoff curve number (RCN) method was developed in 1954 by the U.S. Soil Conservation Service (SCS) and quickly became established in hydrologic practice (Ponce and Hawkins 1996). The RCN method was originally an infiltration loss model for agricultural fields, but has been modified by the hydrologic community to estimate peak runoff rates and volume

$$Q = \frac{[CN(P+2)-200]^2}{CN[CN(P-8)+800]} \tag{1}$$

where, Q is runoff in inches, P is total rainfall, CN is curve number, subject to $P >$ (200/CN) – 2; and $Q = 0$ otherwise (Ponce and Hawkins 1996). The principal component of the RCN method is the curve number (CN), which is determined by the water transmission rate of the soil and the cover type present in the area (Roehr and Kong 2010). The CN is a coefficient that estimates the extent of which total precipitation is reduced by infiltration, interception, evaporation, evapotranspiration, and surface storage (Ponce and Hawkins 1996). These aspects are referred to as abstractions. An impervious surface has a high CN of 98, whereas pervious areas such as meadows have a CN of 30 (USDA 1986). The RCN method has proven effective for calculating runoff from impervious surfaces. It is used widely by engineers and watershed managers, and is recommended in many watershed manuals, such as the District of Columbia *Stormwater Management Guidebook* (Roehr and Kong 2010; DDOE 2013). However, a CN for green roofs is not listed in many of the guidebooks and runoff curve number tables.

Several studies have sought to determine a CN that represents green roof hydrological characteristics. Carter and Rasmussen (2006) using 31 storm events developed a rainfall-runoff relationship that estimated a CN of 86 for green roofs. Getter et al. (2007) went a step further and derived curve numbers for multiple slopes. Curve numbers of 84, 87, 89, and 90 were assigned for roof slopes of 2%, 7%, 15%, and 25% respectively (Getter, Rowe, and Andresen 2007). However, a single curve number cannot represent all types of green roofs, as soil depth, growing media, and plant selection would influence runoff (Roehr and Kong 2010). The RCN method is unable to account for the multitude of variables that are present in green roofs.

2.5.3 Rational Method

The rational method is another runoff calculation that is popular among engineers. This method is used to estimate design discharge and predict peak flow runoff for given rain intensities (Moran, Hunt, and Smith 2005; Mobilia, Longobardi, and Sartor 2014). The formula is

$$Q = CIA \tag{2}$$

where, Q is design discharge, C is runoff coefficient, I is design rainfall intensity, and A is watershed drainage area (Mobilia, Longobardi, and Sartor 2014). For impervious roofs the runoff coefficient is generally 0.9-0.95 (Moran, Hunt, and Smith 2005; Lee et al. 2013; Mobilia, Longobardi, and Sartor 2014). Runoff coefficients derived from physical green roof studies averaged between 0.5-0.55 (Moran, Hunt, and Smith 2005; T. Carter and Jackson 2007; Gregoire and Clausen 2011; Lee et al. 2013). Lee et al. (2013) investigated the dynamics of green roofs catchment efficiency, or runoff coefficient, using simulated rain events with various durations and intensities. It was determined that green roofs, due to their variation in storage capacity, were unable to be given a single runoff coefficient (Lee et al., 2013). The variable nature of the green roofs storage requires a chart to illustrate the runoff coefficient fluctuation between 0 and 0.91, as seen in Figure 11 (Lee et al., 2013).

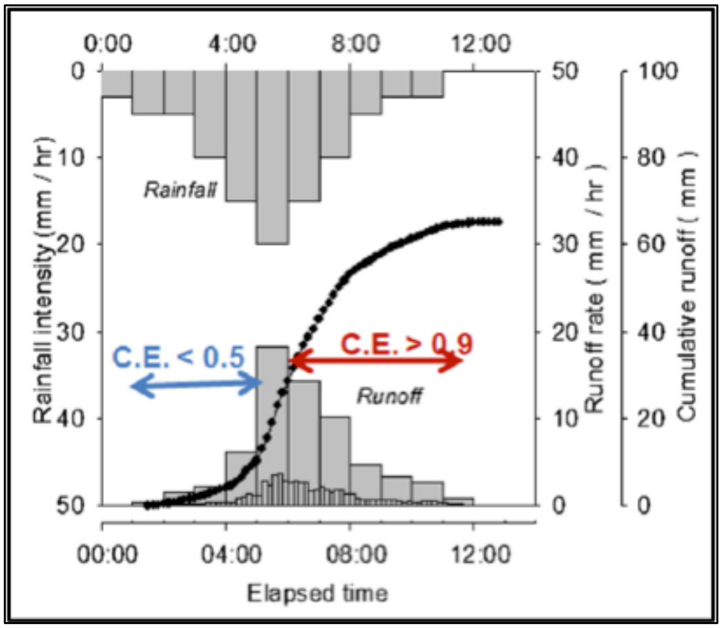

Figure 11. Green roof catchment efficiency as it reaches storage capacity (Lee et al. 2013).

As precipitation fills the storage capacity of the growing media, the catchment efficiency value rapidly increases to that of an impervious surface. When the green roof growing media looses its ability to retain water, the water is discharged at the same rate of runoff from an impervious roof. The storage capacity of the green roof enables the peak discharge from the roof to be delayed, Figure 12. Moran, Hunt, and Smith (2005) recorded a peak runoff delay of four hours from when the rainfall began and when runoff was observed from the green roof. Peak flow reductions of 51% were observed for rain events larger than 38 mm (1.5 in.), and delays were observed in 90% of rain events (Moran, Hunt, and Smith 2005). DeNardo et al. (2005) showed that green roofs reduce average rainfall peak intensities from 4.3 mm/h to an average of 2.4 mm/h. The offset in the total peak discharges reduces the volume and strain on sewer systems and stormwater management facilities, making it more feasible to process the incoming stormwater.

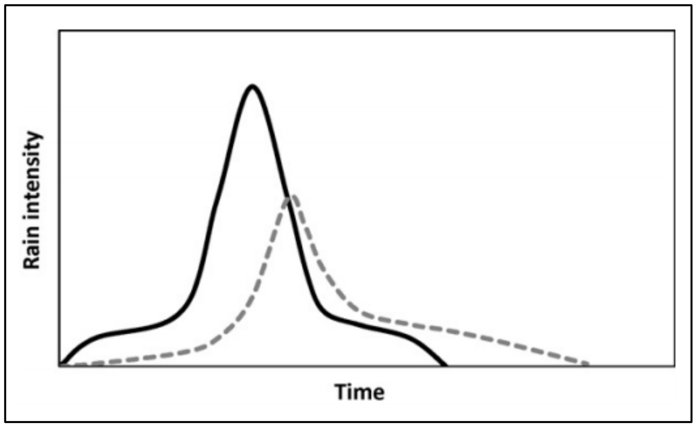

Figure 12. Example runoff from a green roof (dashed) compared to a rain event (black) (Berndtsson 2010).

Runoff continues to flow from the roof after the rain event has ceased. A portion of water, corresponding to the storage capacity, will remain in the growing media and eventually become evaporated, consumed, or transpired (Berndtsson 2010). As mentioned above, this is the water that explains the observed volume reduction in runoff from green roofs. The rational method is able to calculate peak discharge reductions, but is unable to account for long-term evaporation, transpiration, and water usage from the vegetation and growing media that determines the annual performance of green roofs.

2.5.4 Soil Water Balance

Research has proven successful in using the soil water balance to determine the volume of annual runoff reductions attributed by green roofs. Generally, once precipitation is present in the growing media, it enters and leaves the green roof system in one of two ways, evapotranspiration and runoff (Hilten, Lawrence, and Tollner 2008). The soil water balance equation is capable of measuring the moisture fluctuations in soil as the growing media is saturated by rain events and dehydrated by evaporation. The soil water balance equation is

$$I - ET + P - RO - DP + CR \pm \Delta SF \pm \Delta SW = 0 \quad (3)$$

where, I is irrigation, ET is evapotranspiration, P is precipitation, RO is surface runoff, DP is deep percolation, CR is capillary rise, ΔSF is change subsurface flow, and ΔSW is change in soil water content (Hilten, Lawrence, and Tollner 2008). Several simplifications can be made in the soil water balance equation when it is applied to green roofs.

When appropriate plant species and growing media are selected, most green roofs will not require supplemental irrigation, except for temporary irrigation during prolonged periods of drought or initial establishment (DDOE 2013). If irrigation is installed, it is suggested to use reclaimed water captured by rain barrels to continue the reduction of stormwater and promote sustainability (Buist and Friedrich 2008; DDOE 2013). However, because in most cases irrigation is temporarily applied, it can be assumed that irrigation has a negligible influence on runoff.

Green roofs are engineered to have sufficient drainage to keep vegetation healthy and to prevent surface flow. This permits the removal of RO, surface runoff, from the soil water balance equation. Capillary rise is also non-existent on green roofs as it requires a water table, and subsurface flow is considered zero due to the soil column containment (Hilten, Lawrence, and Tollner 2008). Lastly deep percolation is considered to be the flow through the drainage layer that exits the green roof, and is renamed as runoff

(Hilten, Lawrence, and Tollner 2008). With the remaining variables, the equation can be rewritten as

$$R = P - ET \pm \Delta SW \quad (4)$$

where R is runoff, P is precipitation, ET is evapotranspiration, and ΔSW is change in storage (Deutsch et al. 2005; Deutsch et al. 2007; Hilten, Lawrence, and Tollner 2008; Roehr and Kong 2010). According to the soil water balance equation, green roof runoff can be defined as the sum of precipitation minus evapotranspiration plus or minus water retained in the growing media and vegetation.

In a study by Deutsch et al. (2007), the soil water balance equation was used as the base of the Mike Urban hydrologic and hydraulic model. The Mike Urban model has been peer reviewed and successfully applied by the District of Columbia Water and Sewer Authority (WASA) in the development of an EPA-approved Long Term Control Plan (LTCP) for the Combined Sewer System (CSS) (Deutsch et al. 2007). This model incorporates the sewer system layout and represents runoff as a kinematic wave that behaves like flow in an open channel (Deutsch et al. 2007). The runoff volume is determined by the quantity of precipitation, size and characteristics of the sewershed, and various hydrologic loss mechanisms (Deutsch et al. 2007).

When determining green roof ready areas, Deutsch et al. made several assumptions. First, it was assumed that 25% of the rooftop was required for HVAC, access, and maintenance. Secondly, they chose 40% of the total buildings to be the intensive scenario, and 20% of this area would be the moderate scenario. This equates to 53% and 20% of the green roof ready area being utilized for the intensive and moderate circumstances respectively. China stipulates that green areas should exceed 50% to provide significant ecological and environmental benefits, but are limited to 80% coverage due to facility and infrastructure needs (Tian and Jim 2012).

Table 2. Green Roof Assumptions (Deutsch et al. 2007).

Roof Size	Total Roof Area, square feet (sf)	Green Roof-Ready Area (= 75% of roof area)	Number of Buildings	Type of Building	Implementation Considerations	Intensive Greening %	Intensive Greening Green Roof-Ready Area, sf	Moderate Greening % (20% of Intensive Scenario)	Moderate Greening Green Roof Area, sf
<1,000 ft	57,423,950	43,067,963	98,748	Most small rowhomes, garages, sheds	These homes may choose to implement less expensive/ easier LID such as rain barrels. Homes may also be historical and/or less structurally capable of supporting a green roof. Many owners to target.	10%	4,306,796	2%	861,359
1,000ft - 2,000ft	62,224,642	46,666,982	46,126	Larger rowhomes	Generally flat roofs, but potential structural issues. Many owners to target.	30%	14,000,544	6%	2,800,109
2,000ft - 5,000ft	33,295,571	24,971,678	11,447	Single family homes, large rowhomes	Many of these buildings are single family homes, which may have sloped roofs, structural issues.	50%	12,485,839	10%	2,497,168
>5,000ft	106,469,278	79,851,959	5,509	Large commercial, institutional or government buildings	Generally no structural issues. There may be some historical issues and sloped roofs.	90%	71,866,763	18%	14,373,353
Total	**259,413,441**	**194,560,081**	**161,830**	**-**	**-**	**53% of Green roof ready area (or 40% total building area)**	**102,659,943**	**20% of Green roof ready area (or 10.5% of total building area)**	**20,531,989**

All green roofs were assumed to be extensive green roofs with a growing media of 3-4 inches (75-100 mm) (Deutsch et al. 2007). Storage was derived from peer-reviewed literature, and assumed to be one inch for a three to four inch media (Deutsch et al. 2007). In the absence of GIS data to identify protected buildings, structural capacity, and roof slope, it was assumed that in the intensive scenario 90% of buildings greater than 5,000 sq. ft. and 100% of buildings less than 5,000 sq. ft. could support a green roof

(Deutsch et al. 2007). For the moderate greening scenario, 20% of the potential intensive greening roof area was calculated.

The study concluded that with the implementation of green roofs, stormwater runoff volume for an average year was reduced from 16,423 MG to 15,495 MG for the intensive greening scenario, Table 3 (Deutsch et al. 2007). This is a citywide runoff reduction of 928 MG (5.7%), and a reduction of 877 MG of stormwater discharged into the three rivers (Deutsch et al. 2007). The moderate greening scenario illustrated a total runoff reduction of 187 MG (1.1%), and a 184 MG reduction in discharged stormwater (Deutsch et al. 2007). A hydrograph, Figure 13, illustrates the peak runoff responses reductions associated with green roofs and trees.

Table 3. D.C. runoff reduction volumes with the implementation of green roofs (Deutsch et al. 2007).

Sewershed	Baseline Runoff	Moderate Greening Scenario Runoff (MG)	Moderate Greening Scenario Runoff Volume Reduction (MG)	Moderate Greening Scenario Runoff Reduction (%)	Intensive Greening Scenario Runoff (MG)	Intensive Greening Scenario Runoff Volume Reduction (MG)	Intensive Greening Scenario Runoff Reduction (%)
Total CSS	7,668	7,569	99	1.3%	7,182	486	6.3%
Anacostia CSS	4,219	4,168	51	1.2%	3,971	248	5.9%
Potomac CSS	1,013	994	18	1.8%	922	91	9.0%
Rock Creek CSS	2,437	2,406	30	1.2%	2,289	148	6.1%
Total MS4	8,755	8,667	88	1.0%	8,313	442	5.0%
Anacostia MS4	3,719	3,684	35	0.9%	3,545	174	4.7%
Potomac MS4	3,177	3,141	36	1.1%	3,000	177	5.6%
Rock Creek MS4	1,860	1,841	19	1.0%	1,768	92	4.9%
TOTAL	16,423	16,236	187	1.1%	15,495	928	5.7%

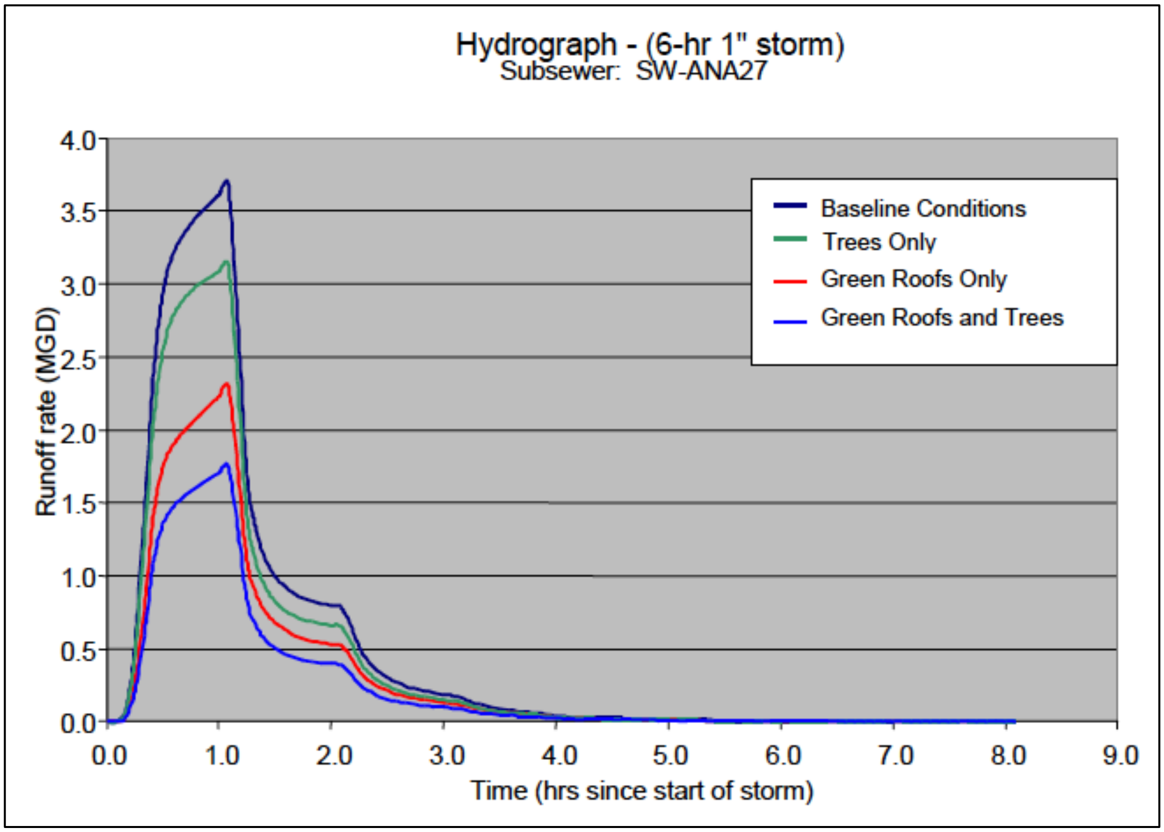

Figure 13. Peak runoff responses for the Anacostia Sewershed (6 hr, 1” design storm) (Deutsch et al. 2007).

2.5.5 Calculating Green Roof Extent

To accurately define potential green roof cover, the roof area and slope need to be calculated. Area is significant as it determines the amount of runoff volume generated by roofs, and it shapes the total impact green roofs will have on the city hydrologic cycle. Roughly 15% of the area that makes up the District of Columbia is roof cover. Considering that a majority of roof space is unoccupied, this is a significant amount of unutilized space, 259 million sq. ft. of impervious surface to be exact (Deutsch et al. 2007). Impervious coverage is often the most feasible and cost-effective method of addressing water pollution (Arnold Jr and Gibbons 1996). With the unused roof space, the property is free and the only cost required is the installation fee.

Slope is one criterion that impacts the possibility of a traditional roof to be converted into a green roof. The major problem associated with slope is slippage (Nigel Dunnett 2004). The percent slope in which a green roof can be installed is confined due to the friction coefficient between the two slickest materials in the green roof profile, for example membrane-membrane interfaces (Nigel Dunnett 2004). Dunnett and Kingsbury (2004) state that the upper limit of a standard green roof system is 17% (9.5°) slope and the upper limit of a modified green roof system, by the use of horizontal strapping, laths, battens, or grids, is 58% (30°) slope. A roof slope beyond 58% orients granular materials at the critical angle of repose (Nigel Dunnett 2004). Additionally, green roofs with slopes above the 17% margin have an estimated cost increase of 30% per sq. ft. (Long 2015). Using slope as a restriction for potential green roof coverage, roofs can be screened for eligibility.

In a study by Kassner et al. (2008), a methodology for calculating roof slope was produced in order to assess the solar potential of roofs. A digital surface model (DSM) point cloud, generated with LIDAR, provided accurate x, y, z data pertaining to the vegetation and objects, such as buildings, on the Earths surface. Using building footprints, Kassner et al. (2008) masked the DSM point cloud to isolate the points associated with the structures. The masked LIDAR points were then filtered by establishing a threshold of three meters above the interpolated surface height, further eliminating points unrelated to the roof structure (Kassner et al. 2008). A raster interpolation of the remaining points provided detail height information enabling the classification of roofs into two categories flat (<10°) and sloped (10°-60°) roofs (Kassner et al. 2008).

Nguyen et al. (2012) demonstrated a similar approach to determining roof area when using LIDAR to assess rooftop solar photovoltaic deployment potential. LIDAR data was transformed into a grid by applying a Triangulated Irregular Network (TIN), which was then used to generate a DSM (Nguyen et al. 2012). Using the building footprints, a buffer region of ±0.5 m was established for each roof to eliminate the noise occurring along the break lines (Nguyen et al. 2012). Nguyen et al. (2012) used a threshold value of 2.5 m above the bare earth elevation to filter out the non-roof objects. A number of data cleaning steps were performed to eradicate trees and noise from the building data. A point cloud statistical analysis was then carried out to differentiate flat roofs from sloped roofs (Nguyen et al. 2012). With the use of building footprints, the LIDAR data of interest was extracted and analyzed. The methodologies of Kassner et al. (2008) and Nguyen et al. (2012) can be translated to delineate the prospective area available for green roofs.

2.5.6 Estimating Green Roof Cost

The initial cost of green roof installations is greater than a traditional roof. In a study by Peck and Kuhn (2003) extensive green roof installation costs were assessed to be $23-$46 per sq. ft. when the design and administrative fees are included. To provide sufficient loading capacity, structural upgrades are often required. The cost for building modifications is difficult to predetermine, as the amount will vary depending on the site condition. Gregory Long, President and Founder of Capitol Greenroofs, LLC, stated that all buildings require a structural engineering report, but most concrete and steel buildings are capable of supporting a 4” extensive green roof system (Long 2015). Newly constructed buildings can be designed with additional load bearing capacities meeting green roof requirements.

Benefits and incentive programs associated with green roofs can compensate the additional cost. Green roofs act as an additional insulation layer for the buildings, decreasing the amount of heat and cool air lost in the winter and summer months. Milburn et al. (2010) in a study on building temperatures in Las Vegas, NV, observed that green roof surfaces were typically 80°F, whereas the white and black control roofs consistently exceeded 220°F. The decrease in cooling required during the summer months has been modeled to reduce a buildings energy usage by as much as 25% (Bass and Baskaran 2001). The multiple layers in the green roof system also protect the waterproofing membrane from weathering. Reduced weathering increases the lifespan of the roof by as much as 90 years (Brenneisen 2006). The annual reduction in building electricity costs and increased lifetime of the roof condenses the price difference between green roofs and conventional roofs.

Local governments in urban areas have begun to implement rebate programs for many BMPs such as green roofs, rain barrels, solar panels, and increased property vegetation. RiverSmart Rooftops is a green roof program in the District of Columbia that offers base funding of $10-$15 per sq. ft. of green roof installed in target watersheds (DDOE 2014). The program also offers a discount of up to 55% off the DDOE

Stormwater Fee charged on a property owners sewer and water utility bill (DDOE 2014). The District of Columbia also hosts a Stormwater Retention Credit (SRC) Trading Program. This is a market-based program, where property owners can accrue and sell SRCs by installing green infrastructure that has the capacity to retain stormwater (DDOE 2014). One SRC is equal to one gallon of retention for one year. SRCs are mainly purchased by regulated development sites to supplement their requirements for retaining stormwater runoff (DDOE 2014). By participating in the stormwater management programs provided by the local governments green roofs become more affordable.

METHODS AND MATERIALS

The District of Columbia was selected due to its influential location and an increased interest in the implementation of green roofs to mitigate stormwater runoff. D.C. is situated at the conjunction of two major rivers, the Potomac and Anacostia, which feed into the Chesapeake Bay, the largest estuary in the United States. This unique ecosystem provides critical habitat for a wide variety of wildlife and is host to a major industry of commercial fishing (EPA 2014).

The District on average discharges 2.5 billion gallons of CSO's into the adjacent tributaries each year (DC Water 2004). CSO's from the Districts sewer system can be caused by as little as 0.1 inches of rainfall. A 1 inch rainfall event causes roughly half of the 60 combined sewer outfalls to overflow (DC Water 2004). For an average year, there are 75 rain events larger than 0.1 inches and 12 events greater than 1 inch (NOAA 2015). The conditions of the surrounding rivers do not only affect wildlife, but also recreational activities. In 2014, the swim portion of the Nation's Triathlon had to be canceled due to the unsanitary conditions in the Potomac River (WTOP 2014).

The Clean Rivers Project is a $2.6 billion program designed to reduce CSOs and protect the public from harmful substances contained in wastewater (Lisle 2014). The first phase of the project is underway and involves constructing a massive underground tunnel system to hold stormwater until the waster water management plant is able to process it. Currently the tunnels are able to hold 38 MG of stormwater, when the tunnel system is completed in 2032, the maximum capacity will be 157 MG (DC Water 2015b). As green infrastructure has become more popular in U.S. cities, D.C. has begun to revise its original plan to include BMP's. The Rock Creek tunnel has been eliminated and $90 million has been allotted for green infrastructure (DC Water 2015a).

The District of Columbia is located in the humid subtropical climate, which is characterized by high temperatures and evenly distributed precipitation (Encyclopedia Britannica 2015). Washington, D.C. covers 61.4 square miles of land, and has a population of 658,893 residents and a surrounding metropolitan area consisting of 5.4 million (Census 2014). 15% of the total area is represented by impervious roof coverage.

3.1 Study Period

To determine the annual runoff reduction calculations were based on conditions that characterize an average year. Deutsch et al. (2005) performed a review on 50 years of rainfall data from the Ronald Reagan National Airport weather station. The most representative year was determined to be 1990, which had an annual maximum temperature, minimum temperature, and rainfall of 69.2°F, 50.7°F, and 40.84" (1037 mm) respectively, Table 4 (NOAA 2015).

Table 4. Climatological Summary 1990 (NOAA 2015).

04/06/2015

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Annual Climatological Summary
(1990)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801
www.ncdc.noaa.gov

Station: **WASHINGTON REAGAN NATIONAL AIRPORT, VA US**

COOP:448906
Elev: 10 ft. Lat: 38.848° N Lon: 77.034° W

Date	Temperature (F)													
Elem->	MMXT	MMNT	MNTM	DPNT	HTDD	CLDD	EMXT		EMNT		DT90	DX32	DT32	DT00
Month	Mean Max.	Mean Min.	Mean	Depart. from Normal	Heating Degree Days	Cooling Degree Days	Highest	High Date	Lowest	Low Date	Number Of Days: Max >=90	Max <=32	Min <=32	Min <=0
1	52.3	34.8	43.6	8.4	656	0	69	18	26	14	0	0	14	0
2	55.1	35.3	45.2	7.7	550	0	73	14	14	26	0	2	10	0
3	60.1	40.3	50.2	4.4	481	30	89	12	22	07	0	0	8	0
4	67.3	46.3	56.8	0.1	285	46	93	27	31	08	2	0	2	0
5	73.1	55.4	64.3	-1.7	64	50	85	17	48	23	0	0	0	0
6	84.8	65.1	75.0	0.5	4	309	97	29	50	05	5	0	0	0
7	87.9	70.8	79.4	0.5	0	451	100	05	63	13	14	0	0	0
8	84.2	68.8	76.5	-1.1	0	364	93	28	62	21	7	0	0	0
9	78.1	61.1	69.6	-1.5	38	183	93	07	46	18	2	0	0	0
10	72.5	53.0	62.8	3.5	153	88	86	10	35	27	0	0	0	0
11	62.4	41.6	52.0	3.3	381	0	79	03	29	19	0	0	1	0
12	53.1	35.9	44.5	5.6	630	0	71	23	20	25	0	0	10	0
Annual	69.2*	50.7*	60.0	2.5	3242*	1521	100	Jul	14	Feb	30*	2*	45*	0*

Date	Precipitation (inches)									
Elem->	TPCP	DPNP	EMXP		TSNW	MXSD		DP01	DP05	DP10
Month	Total	Depart. from Normal	Greatest Observed: Day	Date	Snow, Sleet: Total Fall	Max Depth	Max Date	Number Of Days: >=.10	>=.50	>=1.0
1	2.95	0.19	0.92	25	0.2	0T	31	6	4	0
2	1.30	-1.32	0.46	10	0.0T	0T	28	3	0	0
3	2.57	-0.89	1.34	17	2.4	0		6	1	1
4	4.09	1.16	1.00	29	0.2	0T	30	10	4	1
5	5.20	1.72	1.38	29	0.0	0		10	4	2
6	3.14	-0.21	2.19	09	0.0	0		5	1	1
7	3.78	-0.10	1.22	14	0.0T	0T	31	6	3	1
8	6.74	2.34	1.93	09	0.0	0		8	6	3
9	0.87	-2.35	0.42	16	0.0	0		3	0	0
10	3.30	0.40	1.67	18	0.0	0		5	2	2
11	2.17	-0.65	1.77	10	0.0	0		3	1	1
12	4.73	1.55	0.74	03	3.0	3	28	10	4	0
Annual	40.84	1.84	2.19*	Jun*	5.8*	3*	Dec*	75*	30*	12*

Notes

(blank) Data element not reported or missing.
\+ Occurred on one or more previous dates during the month. The date in the Date field is the last day of occurrence. Used through December 1983 only.
A Accumulated amount. This value is a total that may include data from a previous month or months or year (for annual value).
B Adjusted total. Monthly value totals based on proportional available data across the entire month.
E An estimated monthly or annual total.
X Monthly means or totals based on incomplete time series. 1 to 9 days are missing. Annual means or totals include one or more months which had 1 to 9 days that were missing.
T Trace of precipitation, snowfall, or snowdepth. The precipitation data value will equal zero.
Elem Element types are included to provide cross-reference for users of the NCDC CDO system.
Station Station is identified by: COOP ID, Station Name, State
S Precipitation amount is continuing to be accumulated. Total will be included in a subsequent monthly or yearly value. Example: Days 1-20 had 1.35 inches of precipitation, then a period of accumulation began. The element TPCP would then be 00135S and the total accumulated amount value appears in a subsequent monthly value.
* Annual value missing; summary value computed from available month values.

3.2 Data Collection

Accurate roof area estimation is required to assess green roofs ability to reduce storm water runoff. The District of Columbia Geographic Information Systems (DCGIS) is a program that provides a wealth of GIS information to the general public to improve the quality and lower the cost of services provided by the District of Columbia Government. Light detection and ranging (LIDAR) will be the primary source of data collection when generating a detailed roof model. Additional sources of information that will assist in building extraction are building footprints and aerial imagery.

LIDAR data collected by Science Applications and International Corporation (SAIC) in 2008 was employed for building height information. LIDAR is a laser system that uses principles that are similar to radar. Elevation is determined by calculating the difference between the time of the initial pulse (t_0) and the time at which the pulse returns (t_1). Laser pulses emitted by a LIDAR system reflect off of objects such as ground surface, vegetation, and buildings returning x, y, z information about a single point. With LIDAR systems capable of emitting 400,000 pulses per second, the point cloud generated is very large.

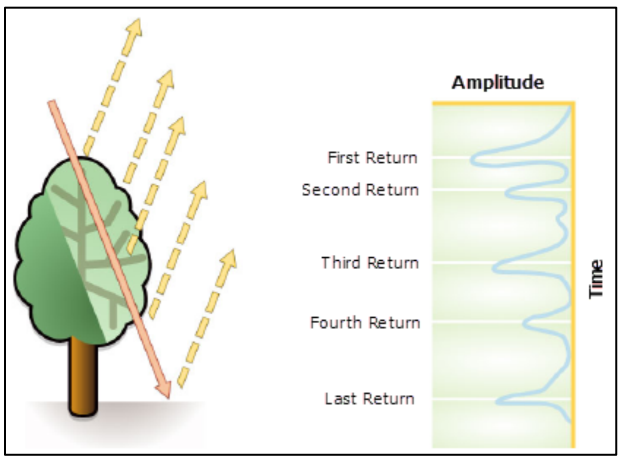

Figure 14. LIDAR pulse returns (ESRI 2015).

The first return LIDAR data was provided in a raster DSM format and had a 1 m resolution, with a horizontal and vertical accuracy of 0.5 m and 1 m respectively. The National Geospatial-Intelligence Agency (NGA) reported that based on 45 control points, the average error between the bare earth LIDAR coverage for Washington, D.C. and the control was 0.004 m with a root mean square error (RMSE) of 0.107 (2008). The vertical accuracy was tested using 7 control points and had an average error of 0.034 m and a root mean square error (RMSE) of 0.095 m (NGA 2008). The Leica Systems ALS50 II scanner was flown at a height of 4,000 feet and speed of 126 KIAS (NGA 2008). The scanners field of view, swath width, and nominal ground distance were 40°, 887.6 ft., and 3 ft. respectively (NGA 2008). Nine flights and 259 flight lines, between October 31, 2008 and December 23, 2008, were flown to collect LIDAR data for the entirety of D.C.

The 2013 orthoimagery data was used to provide ground reference. This data was generated by the District of Columbia in November 2013 during leaf off conditions. Multispectral digital imagery was used to create natural color digital orthophotography with a 16 cm pixel resolution (DCGIS 2013). The final orthoimage was produced in Maryland State Plane coordinates NAD 83 meters and has a horizontal accuracy of 1 ft. RMSE (DCGIS 2013).

Building footprints were also collected from DCGIS. The dataset contains polygons representing planimetric buildings originally captured in 1999, but updated in 2005, 2008, and 2010 (DCGIS 2013). The building footprint is delineated around the roof line and captures all buildings in D.C. over 100 sq. ft. (DCGIS 2013). The polygons are labeled as Buildings, Memorials, and Voids, which are atriums and open space between buildings. Lastly, weather and design storm data for 1990 was collected from NOAA's national climatic center.

3.3 Slope Analysis

The slope analysis was performed in accordance to the flow diagram portrayed in Figure 15. The District of Columbia building footprints were used to mask the LIDAR DSM. The analysis mask limits processing to the features that fall within the designated area, and assigns all locations outside the area as NoData (ESRI 2015). Before masking the DSM, the polygons pertaining to Memorials and Voids were removed as it was assumed memorials were protected buildings and voids were open green space. An internal buffer of 0.5 m was applied to remove unwanted ground points that can cause interference along building breaklines. Most green roofs do not cover the full roof extent, as footpaths are put in place to assist with maintenance. Thus, the internal buffer will make for safer estimations in the conclusion.

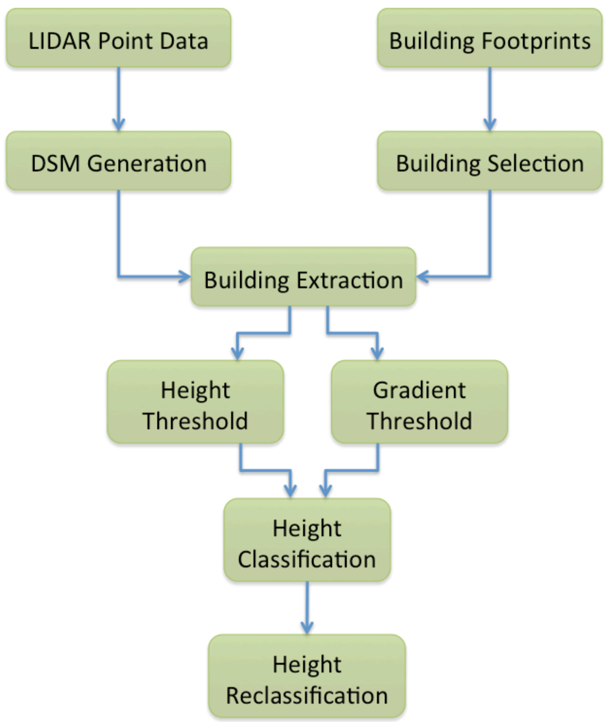

Figure 15. Roof slope analysis flow diagram.

The masked LIDAR cells contain the elevation data associated with D.C. roofs and buildings. To further eradicate potential unwanted points representing the ground level around the buildings, a threshold is established. The District of Columbia defines a habitable room as having a ceiling height of at least 7 ft. (DCR 1955). With the addition of facility needs, insulation, and roof materials it is assumed that the minimum threshold for a one-story building is 2.5 m. Using Extract by Attribute, all values greater than or equal to 2.5 m were selected and used for analysis.

The 3D Analyst Slope tool was applied to the filtered points to determine the percent rise for each roof surface. 17% and 58% are the thresholds for green roofs as defined by the coefficient of friction and angle of repose (Nigel Dunnett 2004). Using Dunnett and Kingsbury's values, roof classification can be defined as standard (≤17%) and modified (≤58%). Green roofs can be installed on surfaces up to 58% (30°) if special soil barriers such as horizontal strapping, laths, battens, and grids are installed to prevent slipping and erosion (Nigel Dunnett 2004). As mentioned above, the additional requirements of modified green roofs increases the price by 30%. Standard green roofs can be recognized as the first phase of greening as they are more cost efficient and effective, whereas modified green roofs would be the second phase of greening. By reclassifying the raster, a pixel count is produced for each class. A pixel is equal to one square meter when using LIDAR with 1 m resolution. The count of the pixels provides the area of each class and the total area when summed in meters squared. With the proposed areas of green roofs, the Mini-Model created for the District of Columbia can be employed.

3.4 Runoff Analysis

As the Mike Urban Model is a proprietary model that is rather expensive and time-consuming to run, a simplified model, for planning purposes, was developed and named the Mini-Model (Deutsch et al. 2007). The Mini-Model uses unit area reduction factors (UARFs) to assess the reduction of runoff for a given area with the implementation of green roofs (Deutsch et al. 2007). A hypothetical 100-acre flat impervious surface was used as the base line conditions and assessed in the Mike Urban Model (Deutsch et al. 2007). The 100-acre surface was then covered in green roofs and calculated with the same hydrologic assumptions assigned to green roofs in the original Mike Urban Model (Deutsch et al. 2007). The UARF is then calculated using the following equation

$$UARF_{greenroof}(MG/YR/acre) = \left(\frac{Baseline\ Runoff\ (MG/YR) - Green\ Infrastructure\ Runoff\ (MG/YR)}{100\ (acres)}\right) \quad (5)$$

The results were then tested and compared with the results from the Mike Urban Model and calibrated to achieve the best possible match between the two Models (Deutsch et al. 2007). On the sewershed level, the median difference in results is less than 0.002 million gallons per year (MGY), with a maximum difference of 1.4 MGY (Deutsch et al. 2007).

Four parameters are required to run the Mini-Model: existing roof area, existing green roof area, future green roof area, and annual baseline runoff volume in the catchment area. Existing green roof cover is considered to be zero because the Mike Urban Model is calibrated with actual flow data where green roofs influence is justified (Deutsch et al. 2007). Using Deutsch et al. (2007) values from the Mike Urban Model, the accuracy of the Mini-Model was reevaluated.

When calculating runoff reductions for the slope analysis, the baseline for the District of Columbia’s annual runoff volume remained the same, 16,423 MG. However, as the reason for Deutsch et al. (2007) choosing the 40% threshold was unclear, an alternate methodology was used to facilitate a more accurate consideration of green roof area. As mention above, Tian and Jim (2012), state that new towns in China consist of roughly 20% green space. Most cities in Mainland China specify that green areas should exceed 50% to provide significant ecological and environmental benefits (Tian and Jim, 2012). After excluding footpaths and facility needs the upper limit of green areas for roofs and podiums was determined to be 80% (Tian and Jim, 2012). For both the standard and modified classes, potential green roof cover is evaluated at the 20%, 50%, and 80% limits. The maximum potential green roof area was reduced by 20% to account for the facility and access needs. 20% and 50% coverage were then calculated from the adjusted area. Using figures provided by Peck and Kuhn (2003), an estimate total cost for green roofs was calculated, Table 5.

Table 5. Extensive green roof costs estimates (costs assume an existing building with sufficient loading capacity. The larger the green roof, the cheaper the cost on a square foot basis.) (Peck and Kuhn 2003).

	Component	Cost	Notes & Variables
a)	Design & Specifications	5% - 10% of total roofing project cost.	The number and type of consultants required depends on the size and complexity of the project.
b)	Project Administration & Site Review	2.5% - 5% of total roofing project cost.	The number and type of consultants required depends on the size and complexity of the project.
c)	Re-roofing with root-repelling membrane	$100.00 - $160.00 per sm. ($10.00 - $15.00 per sf.)	Cost factors include type of existing roofing to be removed, type of new roofing system to be installed, ease of roof access, and nature of flashing required.
d)	Green Roof System (curbing, drainage layer, filter cloth, and growing medium).	$55.00 - $110.00 per sm. ($5.00 - $10.00 per sf.)	Cost factors include type and depth of growing medium, type of curbing, and size of project.
e)	Plants	$11.00 - $32.00 per sm. ($1.00 - $3.00 per sf.)	Cost factors include time of year, type of plant, and size of plant - seed, plug, or pot.
f)	Installation / Labour	$32.00 - $86.00 per sm ($3.00 - $8.00 per sf.)	Cost factors include equipment rental to move materials to and on the roof (rental of a crane could cost as much as $4,000.00 per day), size of project, complexity of design, and planting techniques used.
g)	Maintenance	$13.00 - $21.00 per sm ($1.25 - $2.00 per sf) for the first 2 years only.	Costs factors include size of project, timing of installation, irrigation system, and size and type of plants used.
h)	Irrigation System	$21.00 - $43.00 per sm. ($2.00 - $4.00 per sf).	*Optional, since the roof could be watered by hand. Cost factors include type of system used.

RESULTS

The building footprints outlined 161,484 structures with the memorials and voids removed. Based on the District of Columbia's 61.4 sq. mi. land cover, roof surface accounted for 15.5% of the total area with a 265,436,256 sq. ft. coverage. The internal buffer reduced the total roof area by roughly 39 million sq ft. A total of 77,893,626 sq. ft. was estimated for the standard green roof approach (0-17% slopes), and 126,041,480 sq. ft. represented the modified approach (0-58% slopes). The Mike Urban Model determined that D.C. produces 16,423 MG of runoff annually without the presence of green roofs. With the implementation of green roofs, stormwater runoff can be reduced by 141 MG-1140MG depending on the coverage level attained.

4.1 Roof Extraction

Several locations picked at random were used to assess the accuracy of the slope calculation using the LIDAR data. The building footprints and slope estimation correlated extremely well. Some tree interference took place and can be seen in Figure 17. Total roof area estimation was comparable to Deutsch et al. (2007) roof estimate.

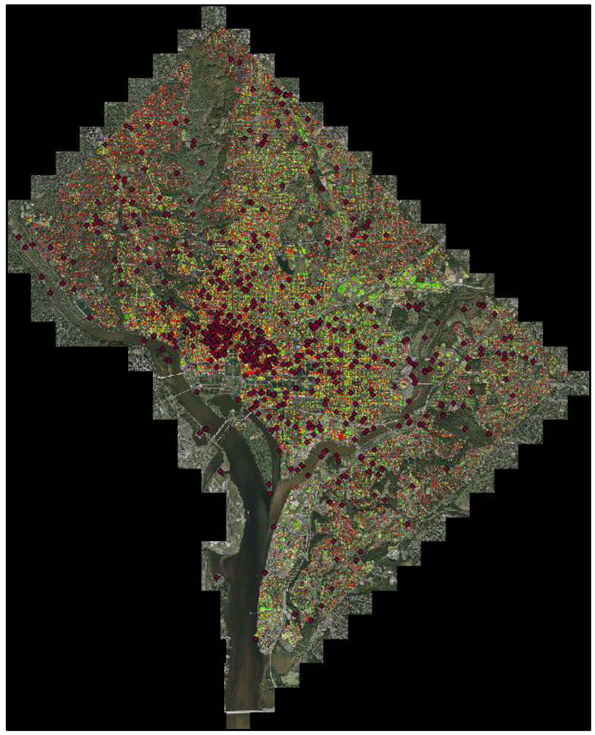

Figure 16. Orthoimage of D.C. at full extent with roof slope (green/red) and existing green roofs (maroon).

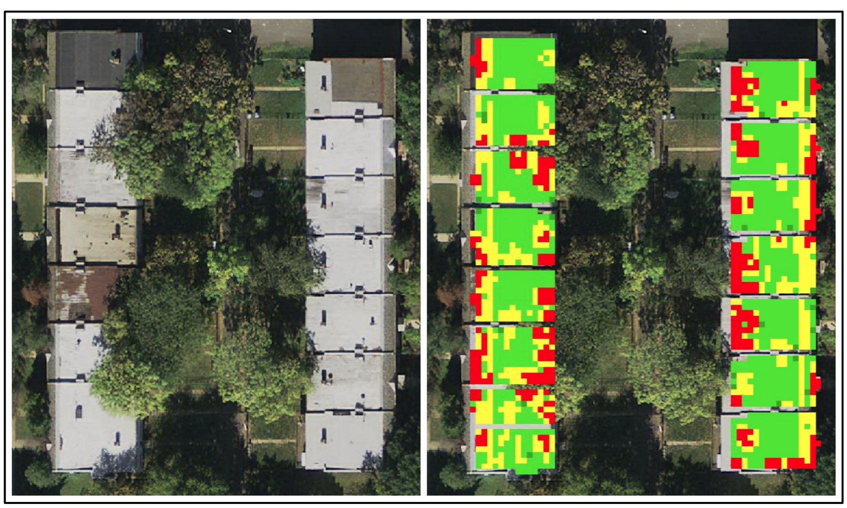

Figure 17. Tree interference along row homes.

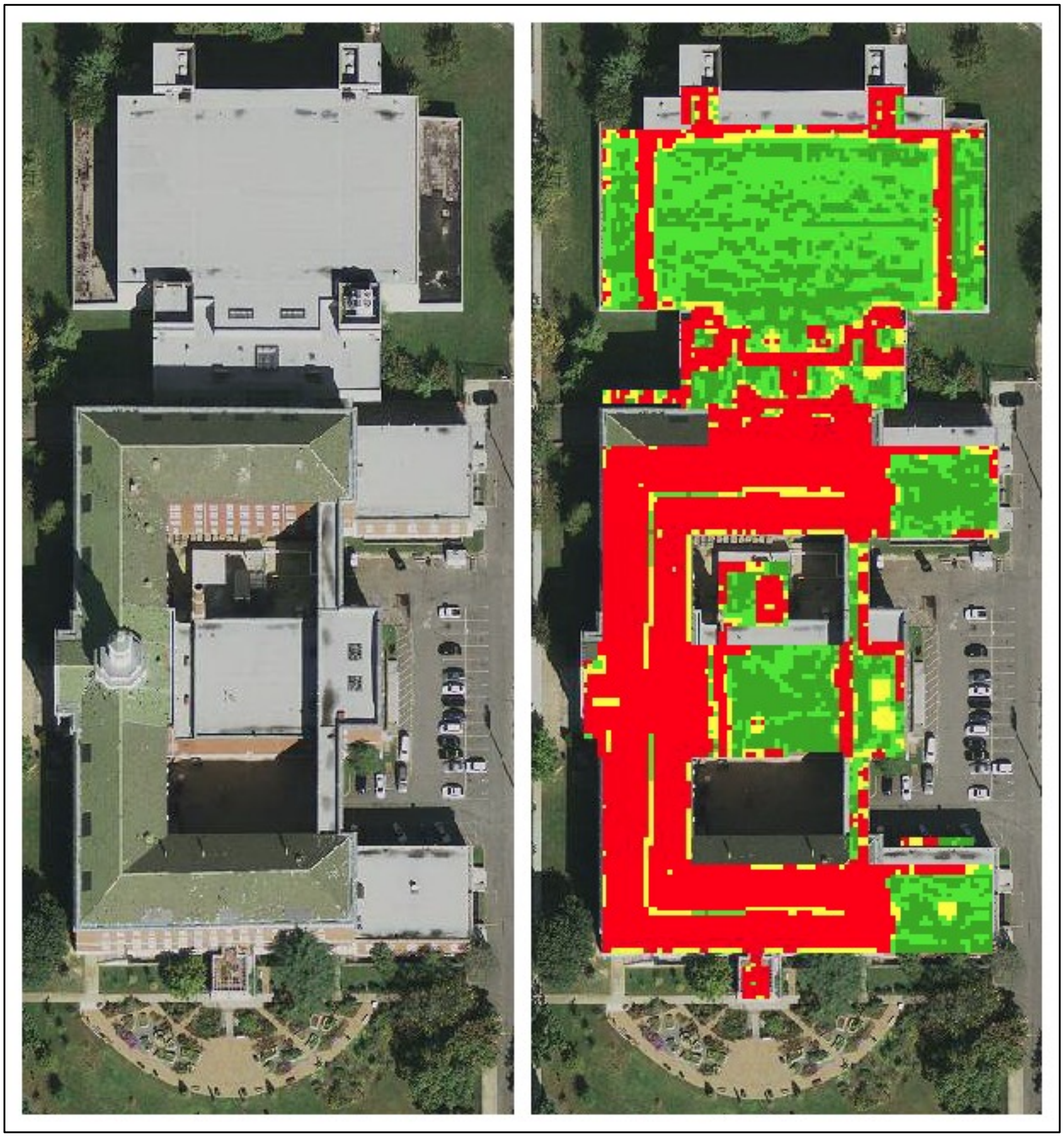

Figure 18. Mixed pitched and flat roof areas.

Figure 19. Example of the orthoimage (top), LIDAR (middle), and slope (bottom).

Figure 20. Intricacy of building voids. Orthoimage (top), LIDAR (middle), and slope (bottom).

4.1 Slope Analysis

When the Mike Urban Model and the Mini-Model were compared using values from Deutsch et al. (2007), a difference of -3 MG and +1 MG was calculated for the moderate and intensive scenarios respectively, Table 6. The difference between the two models is most likely attributed to a rounding error, as the percent's for potential green roof cover and reduction in runoff are the same.

Table 6. Mike Urban Model and Mini-Model Comparison.

	Slope (%)	Potential Green Roof Area (sq ft)	Total Runoff w/o GR (MG)	Model	Cover	Potential GR Cover	Runoff Reduction	Total Runoff w/ GR (MG)	Reduction (MG)	Difference (MG)
Mike Urban Model	N/A	194,560,080	16,423	Moderate	20,351,989	10.5%	1.10%	16,236	187	
				Intensive	102,659,943	52.8%	5.70%	15,495	928	
Mini-Model	N/A	194,560,081	16,423	Moderate	20,351,989	10.5%	1.10%	16,239	184	-3
				Intensive	102,659,943	52.8%	5.70%	15,494	929	1

The estimated green roof ready area defined by Deutsch et al. (2007) was 35% higher than the potential green roof area defined by the slope analysis. Tian and Jim (2012) proposed that 20%, 50%, and 80% were sensible estimates of potential green roof cover. The slope analysis considered these potential coverage's and produced a lower estimate of potential green roof areas and runoff reduction than Deutsch et al. (2007), as seen in Table 7. Tables 8 and 9 estimate the total cost of green roofs without structural upgrades using values from Peck and Kuhn (2003).

Table 7. Runoff reductions for the Mike Urban Model and Slope Analysis.

	% Slope	Total Area (sq ft)	Potential Green Roof Area (sq ft)	Total Runoff w/o GR (MG)	Potential GR Cover	Cover (sq ft)	Total Area Cover	Runoff Reduction	Total Runoff w/ GR (MG)	Reduction (MG)
Mike Urban Model	N/A	259,413,441	194,560,080	16,423	20%	20,351,989	7.8%	1.1%	16,236	187
					53%	102,659,943	39.6%	5.7%	15,495	928
Standard	0-17	265,436,256	77,893,626	16,423	20%	15,578,725	5.9%	0.9%	16,282	141
					50%	38,946,813	14.7%	2.1%	16,071	352
					80%	77,893,626	29.3%	4.3%	15,718	705
Modified	0-58	265,436,256	126,041,480	16,423	20%	25,208,296	11.9%	1.4%	16,195	228
					50%	63,020,740	23.7%	3.5%	15,853	570
					80%	126,041,480	47.5%	6.9%	15,283	1,140

Table 8. Low estimates for standard and modified greening cost, without structural upgrades.

		Standard - Low			Modified - Low		
Component	Cost	20%	50%	80%	20%	50%	80%
Design	5%	$13,086,129	$32,715,323	$65,430,646	$30,483,485	$76,208,713	$152,417,427
Administrative	2.5%	$6,543,065	$16,357,661	$32,715,323	$15,241,743	$38,104,357	$76,208,713
Re-Roofing (sq ft)	$10	$124,629,801	$311,574,502	$623,149,005	$290,318,908	$725,797,269	$1,451,594,539
Green Roof System (sq ft)	$5	$62,314,901	$155,787,251	$311,574,502	$145,159,454	$362,898,635	$725,797,269
Plants (sq ft)	$1	$12,462,980	$31,157,450	$62,314,900	$29,031,891	$72,579,727	$145,159,454
Installation (sq ft)	$3	$37,388,940	$93,472,351	$186,944,701	$87,095,672	$217,739,181	$435,478,362
Maintenance (first 2 years) (sq ft)	$2	$24,925,960	$62,314,900	$124,629,801	$58,063,782	$145,159,454	$290,318,908
Total Cost		$281,351,776	$703,379,439	$1,406,758,878	$655,394,934	$1,638,487,335	$3,276,974,671

Table 9. High estimates for standard and modified greening cost, without structural upgrades.

		Standard - High			Modified - High		
Component	Cost	20%	50%	80%	20%	50%	80%
Design	10%	$49,851,920	$124,629,801	$249,259,602	$116,127,563	$290,318,908	$580,637,815
Administrative	5%	$24,925,960	$62,314,900	$124,629,801	$58,063,782	$145,159,454	$290,318,908
Re-Roofing (sq ft)	$15	$186,944,702	$467,361,754	$934,723,507	$435,478,362	$1,088,695,904	$2,177,391,808
Green Roof System (sq ft)	$10	$124,629,801	$311,574,502	$623,149,005	$290,318,908	$725,797,269	$1,451,594,539
Plants (sq ft)	$3	$37,388,940	$93,472,351	$186,944,701	$87,095,672	$217,739,181	$435,478,362
Installation (sq ft)	$8	$99,703,841	$249,259,602	$498,519,204	$232,255,126	$580,637,815	$1,161,275,631
Maintenance (first 2 years) (sq ft)	$4	$49,851,920	$124,629,801	$249,259,602	$116,127,563	$290,318,908	$580,637,815
Total Cost		$573,297,085	$1,433,242,711	$2,866,485,422	$1,335,466,975	$3,338,667,439	$6,677,334,877

DISCUSSION

By applying an inner buffer of 0.5 meters, the total roof area was reduced by 14.6%. However, the buffer analysis caused the total area for the standard approach to increase by 2.9% (252,373 sq. ft.). The increase in surface area could be attributed to a reduction in interference along structural breaklines, Figure 21. The slope tool calculates the maximum rate of change between adjacent cells, using a 3x3 cell neighborhood (ESRI 2015). If a range of elevations is present in the cell neighborhood such as the ground, building edge, and roof plane, slope estimations can be inaccurate and cause a decrease in surface area. For the modified approach, a total area loss of 0.5% (68,930 sq. ft.) was calculated. The reduction in the area for the 17-58% slopes could be due to an overestimation of the margin required to eliminate breakline interference.

Figure 21. Building edges that could potentially cause interference in slope estimation (JW Roofing 2011).

The Mike Urban Model was unable to assess the buildings present in the District of Columbia due to a lack of GIS data. This required assumptions to be made in order to define an area that could be retrofitted with green roofs. With a robust analysis of the sewershed, total runoff volume, and climatic data, it is unfortunate that the speculation of ready green roof area leaves the results vulnerable to inaccuracies. Although slope is not the only factor that determines green roof suitability, it does provide context in the assessment of green roof coverage.

Slope and structural information are the main qualifying factors for green roof placement. Using slope, an accurate assessment of potential green roof area was quantified. The maximum area that can be greened is 126,041,480, roughly 68.5 million sq. ft. less than predicted by Deutsch et al. (2007). An onsite structural analysis is required for each green roof and structural upgrades vary on a case-by-case basis.

The 20% and 50% values in the slope analysis are most comparable to the moderate and intensive scenarios outlined in the Mike Urban Model. The moderate and intensive cases have 23% and 62% reduction in area respectively for the standard green roof potential. This indicates that Deutsch et al. (2007) overestimated the reduction in stormwater runoff by 46 MG and 576. The standard scenario, however still reduces the citywide storm water runoff by 141 MG and 352 MG for the 20% and 50% green scenarios respectively. This scenario is a safe estimation of the roofs that would be greened, as they do not require additional stabilization measures. For the modified condition, a 38% decrease in area is seen for the intensive greening, but an increase of 19% is observed for the moderate greening. This is a decrease of 358 MG and an increase of 41 MG respectively.

The 20% standard green roof coverage is considered to be the achievable scenario. At this level, runoff would be reduced by 141 MG, comparable to the entire tunnel storage system (157 MG). Using cost estimates for extensive green roof construction, the low and high appraisal for the standard 20% scenario is $281 and $573 million respectively. To put things into perspective, the Northeast Boundary Tunnel Project (NEBT) is estimated at more than $500 million dollars with a stormwater storage capacity of 33 MG (DC Water 2015b). Implementing the 20% standard green roof system has a projected cost of $4 million per MG reduction, prior to structural assessment and modifications. The tunnel system cost $15 million per MG retained. This leaves an $11 million dollar margin of error for structural upgrades. Although these figures are estimates, from a planning perspective it provides reference when determining the benefit-cost ratio (BCR).

Building alterations create discontinuities between the data. Deutsch et al. (2007) used data from 2006-2007, the LIDAR data was produced in 2008, and the building footprints were last updated in 2010. This difference between the files could cause a loss or in increase in potential green roof area, though, a majority of the buildings have remained the same. Tree interference reduced the total potential green roof area, but was considered to be negligible due to the low number of buildings that had tree canopies impeding the roof space. The current volume of stormwater runoff is most likely greater than the amount calculated by Deutsch et al. (2007). The slope analysis calculated roughly six million sq. ft. of additional total roof area than Deutsch et al. (2007). The District of Columbia has grown in size, creating more impervious surface and roofs to generate stormwater.

CONCLUSION

Green roofs have been proven as an excellent BMP for reducing stormwater runoff, particularity for small rain events. The design of a green roof is a significant factor in its success and performance. It has been demonstrated that a 100 mm growing media depth, with sufficient aeration and drainage is desired for an extensive green roof system. Non-native sedums are the most common species of green roof vegetation as they are drought-resistant and very low maintenance. The retention capabilities of the field capacity and vegetative storage permit the process of evapotranspiration. This process is the reason for the reduction in total stormwater runoff.

After review of the green roof runoff calculation methods, it was determined that the soil water balance is optimal for capturing climatic conditions and soil moisture fluctuations. Roof slope is an effective qualification for determining potential green roof area. An applicable method of discerning slope is through the use of LIDAR DSMs and building footprints. The slope analysis is an excellent method for evaluating green roof potential for a large area. This method is recommended for city planners when generating a comprehensive development plan, CDP.

Retrofitting the existing buildings in the District of Columbia can substantially reduce the peak flow and volume of water requiring processing from the WWTP. Estimated reductions ranging from 141-1,140 MG were observed for the incrementing scenarios. As of January 2015, the District of Columbia reports that 2,365,480 sq. ft. of green roofs have been installed in the city (DDOE 2015), equivalent to 15% of the 20% standard scenario. Although it is unlikely the 80% modified scenario will be achieved, it does illustrate that there is an inverse relationship between the green roof area and the reduction in stormwater runoff.

With the implementation of green roofs, the reduction in runoff can be achieved at a cost effective price when compared to the construction of stormwater storage tunnels. Green roofs benefits exceed stormwater reductions by improving air quality, abating noise levels, reducing air and surface temperatures, suppressing the urban heat island effect, decreasing water pollution, and improving the quality of life by providing natural habitats for both humans and wildlife. The associated benefits reinforce green roofs superiority over stormwater storage tunnels and the need to employ them as active BMPs for urban areas.

REFERENCES

Aitkenhead-Peterson, Jacqueline A., Bruce D. Dvorak, Astrid Volder, and Nina C. Stanley. 2011. "Chemistry of Growth Medium and Leachate from Green Roof Systems in South-Central Texas." *Urban Ecosystems* 14 (1): 17–33.

ALA. 2014. "'State of the Air' – Half of U.S. Live with Unhealthy Air." *American Lung Association*. http://www.lung.org/about-us/our-impact/top-stories/state-of-the-air-2014-top-story.html.

Anderson, Daniel G., and Fairfax County. 1970. *Effects of Urban Development on Floods in Northern Virginia*. US Government Printing Office. http://pubs.usgs.gov/wsp/2001c/report.pdf.

Arnold Jr, Chester L., and C. James Gibbons. 1996. "Impervious Surface Coverage: The Emergence of a Key Environmental Indicator." *Journal of the American Planning Association* 62 (2): 243–58.

Baker, A. J. M., and RR1989 Brooks. 1989. "Terrestrial Higher Plants Which Hyperaccumulate Metallic Elements. A Review of Their Distribution, Ecology and Phytochemistry." *Biorecovery.* 1 (2): 81–126.

Bass, Brad, and Bas Baskaran. 2001. *Evaluating Rooftop and Vertical Gardens as an Adaptation Strategy for Urban Areas*. Environment Canada, Adaptation and Impacts Research Group.

Bates, Adam J., Jon P. Sadler, and Rae Mackay. 2013. "Vegetation Development over Four Years on Two Green Roofs in the UK." *Urban Forestry & Urban Greening* 12 (1): 98–108.

Bengtsson, Lars. 2005. "Peak Flows from Thin Sedum-Moss Roof." *Nordic Hydrology* 36: 269–80.

Berghage, Robert D., David Beattie, Albert R. Jarrett, Christine Thuring, Farzaneh Razaei, and Thomas P. O'Connor. 2008. *Green Roof for Stormwater Runoff Control*.

Berghage, Robert D., David Beattie, Albert R. Jarrett, Christine Thuring, Farzaneh Razaei, and Thomas P. O'Connor. 2009. "Green Roofs for Stormwater Runoff Control."

Berndtsson, Justyna Czemiel. 2010. "Green Roof Performance towards Management of Runoff Water Quantity and Quality: A Review." *Ecological Engineering* 36 (4): 351–60.

Bigham, D. L., M. V. Hoyer, and D. E. Canfield Jr. 2009. "Survey of Toxic Algal (microcystin) Distribution in Florida Lakes." *Lake and Reservoir Management* 25 (3): 264–75.

Brabec, Elizabeth, Stacey Schulte, and Paul L. Richards. 2002. "Impervious Surfaces and Water Quality: A Review of Current Literature and Its Implications for Watershed Planning." *Journal of Planning Literature* 16 (4): 499–514.

Brenneisen, Stephan. 2006. "Space for Urban Wildlife: Designing Green Roofs as Habitats in Switzerland." *Urban Habitats* 4 (1): 27–36.

Buist, R., and C. Friedrich. 2008. "The Organic Question." *Living Architecture Monitor* 10 (1): 16–21.

Burgess, Rod. 2000. "The Compact City Debate: A Global Perspective." *Compact Cities: Sustainable Urban Forms for Developing Countries*, 9–24.

Carey, Richard O., George J. Hochmuth, Christopher J. Martinez, Treavor H. Boyer, Michael D. Dukes, Gurpal S. Toor, and John L. Cisar. 2013. "Evaluating Nutrient Impacts in Urban Watersheds: Challenges and Research Opportunities." *Environmental Pollution* 173 (February): 138–49. doi:10.1016/j.envpol.2012.10.004.

Carson, T. B., D. E. Marasco, P. J. Culligan, and W. R. McGillis. 2013. "Hydrological Performance of Extensive Green Roofs in New York City: Observations and Multi-Year Modeling of Three Full-Scale Systems." *Environmental Research Letters* 8 (2): 024036. doi:10.1088/1748-9326/8/2/024036.

Carter, R. W. 1961. "Magnitude and Frequency of Floods in Suburban Areas."

Carter, Timothy, and C. Rhett Jackson. 2007. "Vegetated Roofs for Stormwater Management at Multiple Spatial Scales." *Landscape and Urban Planning* 80 (1): 84–94.

Carter, Timothy L., and Todd C. Rasmussen. 2006. *Hydrologic Behavior of Vegetated Roofs*. Wiley Online Library. http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2006.tb05299.x/abstract.

Census, United States Census Bureau. 2014. *Annual Estimates of the Residential Population*. http://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml.

DCGIS. 2013. "Ortho2013 and BldgPly." http://opendata.dc.gov/.

DCR, The District of Columbia Register. 1955. "The Housing Regulations of the District of Columbia." http://www.dcregs.dc.gov/Gateway/RuleHome.aspx?RuleNumber=14-405.

DC Water, District of Columbia Water and Sewer Authority. 2004. *CSO Overflow Predictions for Average Year*. C2. http://www.dcwater.com/wastewater_collection/css/CSO%20Overflow%20Predictions%20%20for%20Average%20Year.pdf.

DC Water, District of Columbia Water and Sewer Authority. 2015a. *DC Water Proposes Modifying Long Term Control Plan for Green Infrastructure*. http://www.dcwater.com/education/green.cfm.

DC Water, District of Columbia Water and Sewer Authority. 2015b. *Tunnel Storage Capacity*. http://www.dcwater.com/workzones/projects/pdfs/Tunnel_Capacity_Document.pdf.

DDOE, District Department of the Environment. 2013. "Stormwater Management Guidebook." http://ddoe.dc.gov/node/610622.

DDOE, District Department of the Environment. 2014. *2014 MS4 Annual Report*. Government of the District of Columbia. http://ddoe.dc.gov/sites/default/files/dc/sites/ddoe/publication/attachments/2014%20Annual%20Report%20Final.pdf.

DDOE, District Department of the Environment. 2015. "Inventory of Green Roofs." http://green.dc.gov/publication/inventory-green-roofs.

DeNardo, J. C., A. R. Jarrett, H. B. Manbeck, D. J. Beattie, and R. D. Berghage. 2005. "Stormwater Mitigation and Surface Temperature Reduction by Green Roofs." *Transactions of the ASAE* 48 (4): 1491–96.

Deutsch, B., H. Whitlow, M. Sullivan, and A. Savineau. 2005. "Re-Greening Washington, DC: A Green Roof Vision Based on Environmental Benefits for Air Quality and Storm Water Management." In *Proc. of 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Washington, DC*, 4–6.

Deutsch, B., H. Whitlow, M. Sullivan, A. Savineau, and B. Busiek. 2007. “The Green Build-out Model: Quantifying the Stormwater Management Benefits of Trees and Green Roofs in Washington, DC.” *CaseyTrees and Limnotech, Washington, DC*.

Dortch, Q., D. Anderson, D. Ayres, and P. Glibert. 2008. *Harmful Algal Bloom Research, Development, Demonstration and Technology Transfer: A National Workshop Report. Woods Hole Oceanographic Institute, Woods Hole, MA*. Woods Hole, MA.

Dunnett, Nigel. 2004. *Planting Green Roofs and Living Walls*. Portland, Or: Timber Press.

Dunnett, Nigel, Ayako Nagase, Rosemary Booth, and Philip Grime. 2008. “Influence of Vegetation Composition on Runoff in Two Simulated Green Roof Experiments.” *Urban Ecosystems* 11 (4): 385–98.

Dunnett, N, and N Kingsbury. 2003. “Up on the Roof: Green Roofs.” *Landscape Design*, no. 321: 35–38.

EIA, U.S. Energy Information Administration. n.d. *Vessel Class, Capacity*. U.S. Energy Information Administration, London Tanker Brokers’ Panel.

Encyclopedia Britannica. 2015. “Humid Subtropical Climate.” http://www.britannica.com/EBchecked/topic/276218/humid-subtropical-climate.

EPA, Environmental Protection Agency. 2014. *Chesapeake Bay*. http://www.epa.gov/oaqps001/gr8water/xbrochure/chesapea.html.

Espey, William Howard, Carl W. Morgan, and Frank D. Masch. 1966. *A Study of Some Effects of Urbanization on Storm Runoff from a Small Watershed*. Texas University at Austin, Center for Research in Water Resources.

ESRI. 2015. “ArcGIS Resources.” http://resources.arcgis.com/en/help/main/10.1/index.html#//015w00000041000000.

Fang, Chih-Fang. 2008. “Evaluating the Thermal Reduction Effect of Plant Layers on Rooftops.” *Energy and Buildings* 40 (6): 1048–52.

FISRWG, Federal Interagency Stream Resoration Working. 1998. “Stream Corridor Restoration: Principles, Processes, and Practices.” http://scholarworks.umass.edu/fishpassage_reports/111/.

Ganesan, S., S. S. Y. Lau, and others. 2000. “Urban Challenges in Hong Kong: Future Directions for Design.” *Urban Design International* 5 (1): 3–12.

Getter, Kristin L., D. Bradley Rowe, and Jeffrey A. Andresen. 2007. “Quantifying the Effect of Slope on Extensive Green Roof Stormwater Retention.” *Ecological Engineering* 31 (4): 225–31. doi:10.1016/j.ecoleng.2007.06.004.

Gilinsky, Ellen, M. G. Baker, J. M. Capacasa, and Ephraim S. King. 2009. “An Urgent Call to Action–Report of the State-EPA Nutrient Innovations Task Group.” *US Environmental Protection Agency*.

Gregoire, Bruce G., and John C. Clausen. 2011. “Effect of a Modular Extensive Green Roof on Stormwater Runoff and Water Quality.” *Ecological Engineering* 37 (6): 963–69.

Hamilton, T. Mason. 2014. “Oil Tanker Sizes Range from General Purpose to Ultra-Large Crude Carriers on AFRA Scale.” *Today in Energy - EIA*, September 16. http://www.eia.gov/todayinenergy/detail.cfm?id=17991.

Hartig, Terry, Marlis Mang, and Gary W. Evans. 1991. “Restorative Effects of Natural Environment Experiences.” *Environment and Behavior* 23 (1): 3–26.

Hathaway, Amy Moran, William F. Hunt, and Gregory D. Jennings. 2008. “A Field Study of Green Roof Hydrologic and Water Quality Performance.” *Trans. ASABE* 51 (1): 37–44.

Hilten, Roger Norris, Thomas Mark Lawrence, and Earnest William Tollner. 2008. “Modeling Stormwater Runoff from Green Roofs with HYDRUS-1D.” *Journal of Hydrology* 358 (3): 288–93.

Horner, Richard R., Derek B. Booth, Amanda Azous, and Christopher W. May. 1997. “Watershed Determinants of Ecosystem Functioning.” In *Effects of Watershed Development and Management on Aquatic Ecosystems*, 251–74. ASCE. http://cedb.asce.org/cgi/WWWdisplay.cgi?9701313.

Hutchison, Boyd A., and Fred G. Taylor. 1983. “Energy Conservation Mechanisms and Potentials of Landscape Design to Ameliorate Building Microclimates.” *Landscape Journal* 2 (1): 19–39. doi:10.3368/lj.2.1.19.

J Marsalek. 2008. *Urban Water Cycle Processes and Interactions*. Urban Water Series ; v. 2. Paris, France: UNESCO Pub; Leiden, The Netherlands.

Johnston, Jacklyn, and John Newton. 2004. “Building Green: A Guide to Using Plants on Roofs.” *Walls and Pavements, Greater London Authority, London*, 121.

JW Roofing. 2011. *Pool House Roof*. http://www.jwroof.com/Residential_Roofing_Miami_Beach.html.

Kassner, R., W. Koppe, T. Schüttenberg, and G. Bareth. 2008. "Analysis of the Solar Potential of Roofs by Using Official Lidar Data." In *Proceedings of the International Society for Photogrammetry, Remote Sensing and Spatial Information Sciences,(ISPRS Congress)*, 399–404. http://www.emmy-humboldt.09y11.de/PDF_Dateien/SE_3_Kassner_Bereth_2008.pdf.

Kosareo, Lisa, and Robert Ries. 2007. "Comparative Environmental Life Cycle Assessment of Green Roofs." *Building and Environment* 42 (7): 2606–13. doi:10.1016/j.buildenv.2006.06.019.

Kuo, Frances E. 2001. "Coping with Poverty Impacts of Environment and Attention in the Inner City." *Environment and Behavior* 33 (1): 5–34.

Lazzarin, Renato M., Francesco Castellotti, and Filippo Busato. 2005. "Experimental Measurements and Numerical Modelling of a Green Roof." *Energy and Buildings* 37 (12): 1260–67.

Lee, J. Y., H. J. Moon, T. I. Kim, H. W. Kim, and M. Y. Han. 2013. "Quantitative Analysis on the Urban Flood Mitigation Effect by the Extensive Green Roof System." *Environmental Pollution* 181 (October): 257–61. doi:10.1016/j.envpol.2013.06.039.

Leopold, Luna Bergere. 1968. *Hydrology for Urban Land Planning: A Guidebook on the Hydrologic Effects of Urban Land Use*. US Government Printing Office.

Liptan, Tom. 2003. "Planning, Zoning and Financial Incentives for Ecoroofs in Portland, Oregon." *Greening Rooftops for Sustainable Communities*, 113–20.

Lisle, John. 2014. "Sewage Clean up near Capital Crescent Trail." *District of Columbia Water and Sewer Authority - News*, May 1. http://www.dcwater.com/site_archive/news/press_release651.cfm.

Long, Gregory. 2015. Interviewed by Erik Hovland. Capitol Greenroofs.

Long Island Sound Study. 1994. *The Comprehensive Conservation and Management Plan for Long Island Sound*. Stamford, CT: Long Island Sound Office of the Environmental Protection Agency.

Magill, John D., Karen Midden, John Groninger, and Matthew Therrell. 2011. "A History and Definition of Green Roof Technology with Recommendations for Future Research."

Martin, Bruce Keith. 2008. "The Dynamic Stormwater Response of a Green Roof." The University of Guelph. http://atrium.lib.uoguelph.ca/xmlui/handle/10214/1905.

Mendler, Sandra, and William Odell. 2000. *The HOK Guidebook to Sustainable Design*. John Wiley & Sons. http://www.bcin.ca/Interface/openbcin.cgi?submit=submit&Chinkey=231903.

Mentens, Jeroen, Dirk Raes, and Martin Hermy. 2006. "Green Roofs as a Tool for Solving the Rainwater Runoff Problem in the Urbanized 21st Century?" *Landscape and Urban Planning* 77 (3): 217–26. doi:10.1016/j.landurbplan.2005.02.010.

Milburn, Lee-Anne S., Alfredo Fernández-González, Travis Jones, Fidel Solano, and Elvira Martínez-Wong. 2010. "Wasted Space: Altering Building Temperatures by Greening Barren Rooftops in the Desert Southwest." In *Landscape Legacy: Landscape Architecture and Planning Between Art and Science*.

Miller, Charlie. 2003. "Moisture Management in Green Roofs." In *Proceedings of the 1st Greening Rooftops for Sustainable Communities Conference*, 1:177–82.

Mobilia, Mirka, Antonia Longobardi, and Joachim F Sartor. 2014. "Impact of Green Roofs on Stormwater Runoff Coefficients in a Mediterranean Urban Environment." http://www.wseas.us/e-library/conferences/2014/Florence/USCUDAR/USCUDAR-13.pdf.

Moran, Amy, Bill Hunt, and Jonathan Smith. 2005. "Hydrologic and Water Quality Performance from Greenroofs in Goldsboro and Raleigh, North Carolina." In *Third Annual Greening Rooftops for Sustainable Communities Conference, Awards and Trade Show*, 4–6.

Morgan, Susan, Serdar Celik, and William Retzlaff. 2012. "Green Roof Storm-Water Runoff Quantity and Quality." *Journal of Environmental Engineering* 139 (4): 471–78.

Neema, Meher Nigar, and Akira Ohgai. 2013. "Multitype Green-Space Modeling for Urban Planning Using GA and GIS." *Environment and Planning B: Planning and Design* 40 (3): 447–73. doi:10.1068/b38003.

NGA, National Geospatial-Intelligence Agency. 2008. "First Return 2008 Metadata."

Nguyen, Ha T., Joshua M. Pearce, Rob Harrap, and Gerald Barber. 2012. "The Application of LiDAR to Assessment of Rooftop Solar Photovoltaic Deployment Potential in a Municipal District Unit." *Sensors* 12 (4): 4534–58.

Niachou, A., K. Papakonstantinou, M. Santamouris, A. Tsangrassoulis, and G. Mihalakakou. 2001. "Analysis of the Green Roof Thermal Properties and Investigation of Its Energy Performance." *Energy and Buildings* 33 (7): 719–29.

NOAA, US Department of Commerce. 2008. "NOAA's National Ocean Service Education: Nonpoint Source Pollution." March 25. http://oceanservice.noaa.gov/education/kits/pollution/013bacteria.html.

NOAA, US Department of Commerce. 2015. *National Cimatic Data Center - 1990 Daily Averages*. http://www.ncdc.noaa.gov/cdo-web/.

NRDC. 2011. *A Case Study of How Green Infrastructure Is Helping Manage Urban Stormwater Challenges*. National Resources Defense Council. http://www.nrdc.org/water/stormwater/files/RooftopstoRivers_Chicago.pdf.

Oberndorfer, Erica, Jeremy T. Lundholm, Brad Bass, Reid Coffman, Hitesh Doshi, Nigel Dunnett, Stuart Gaffin, Manfred Kohler, Karen Liu, and D. Bradley Rowe. 2007. "Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services." *BioScience* 57 (10): 823–33. doi:10.1641/B571005.

Oke, Timothy R. 2002. *Boundary Layer Climates*. Routledge.

OSHA, Occupational Safety and Health Administration. 2015. "Occupational Noise Exposure." United States Department of Labor. https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10625.

Overton, Donald E., and Michael E. Meadows. 2013. *Stormwater Modeling*. Elsevier.

Peck, Steven W., and Monica Kuhn. 2003. *Design Guidelines for Green Roofs*. Ontario Association of Architects.

Pelton, Tom, and Bill Goldsborough. 2008. *Bad Water and the Decline of Blue Crabs in the Chesapeake Bay*. Chesapeake Bay Foundation. https://www.conservationgateway.org/Documents/CBF-BadWatersReport.pdf.

Ponce, Victor M., and Richard H. Hawkins. 1996. "Runoff Curve Number: Has It Reached Maturity?" *Journal of Hydrologic Engineering* 1 (1): 11–19.

Roehr, Daniel, and Yuewei Kong. 2010. "Runoff Reduction Effects of Green Roofs in Vancouver, BC, Kelowna, BC, and Shanghai, P.R. China." *Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques* 35 (1): 53–68. doi:10.4296/cwrj3501053.

Rowe, D. Bradley. 2011. "Green Roofs as a Means of Pollution Abatement." *Environmental Pollution*, Selected papers from the conference Urban Environmental Pollution: Overcoming Obstacles to Sustainability and Quality of Life (UEP2010), 20-23 June 2010, Boston, USA, 159 (8–9): 2100–2110. doi:10.1016/j.envpol.2010.10.029.

Sanford, Ward E., and David L. Selnick. 2013. "Estimation of Evapotranspiration Across the Conterminous United States Using a Regression With Climate and Land-Cover Data1." *JAWRA Journal of the American Water Resources Association* 49 (1): 217–30. doi:10.1111/jawr.12010.

Speak, A. F., J. J. Rothwell, S. J. Lindley, and C. L. Smith. 2013. "Rainwater Runoff Retention on an Aged Intensive Green Roof." *Science of The Total Environment* 461: 28–38.

Stankowski, Stephen J. 1972. "Population Density as an Indirect Indicator of Urban and Suburban Land-Surface Modifications." *US Geological Survey Professional Paper* 800: 219–24.

Steusloff, Sabine. 1998. "Input and Output of Airborne Aggressive Substances on Green Roofs in Karlsruhe." In *Urban Ecology*, 144–48. Springer. http://link.springer.com/chapter/10.1007/978-3-642-88583-9_24.

Stewart, Curtis. 2015. "Thinking Above the Box: Green Roof History and Systems." Accessed April 4. https://extension.tennessee.edu/publications/Documents/W293-A.pdf.

Sustainability. 2015. *Detail of the Layers of a Green Roof.* http://www.museumofthecity.org/green-roofs-in-cities/.

Tan, Puay Yok, Nyuk Hien Wong, Yu Chen, Chui Leng Ong, and Angelia Sia. 2003. "Thermal Benefits of Rooftop Gardens in Singapore." In *Proceedings Greening Rooftops for Sustainable Communities Conference, Chicago, Illinois*.

Taylor, David A. 2007. "Growing Green Roofs, City by City." *Environmental Health Perspectives* 115 (6): A306.

Tian, Yuhong, and C. Y. Jim. 2012. "Development Potential of Sky Gardens in the Compact City of Hong Kong." *Urban Forestry & Urban Greening* 11 (3): 223–33. doi:10.1016/j.ufug.2012.03.003.

Tourbier, J. Toby. 1981. *Water Resources Protection Technology: A Handbook of Measures to Protect Water Resources in Land Development*. Washington, D.C: Urban Land Institute.

USDA, United States Department of Agriculture. 1986. "Urban Hydrology for Small Watersheds TR-55." http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf.

Van Renterghem, T., and D. Botteldooren. 2008. "Numerical Evaluation of Sound Propagating over Green Roofs." *Journal of Sound and Vibration* 317 (3–5): 781–99. doi:10.1016/j.jsv.2008.03.025.

VanWoert, Nicholaus D., D. Bradley Rowe, Jeffrey A. Andresen, Clayton L. Rugh, and et al. 2005. "Green Roof Stormwater Retention: Effects of Roof Surface, Slope, and Media Depth." *Journal of Environmental Quality* 34 (3): 1036–44.

Vijayaraghavan, K., and Franklin D. Raja. 2014. "Design and Development of Green Roof Substrate to Improve Runoff Water Quality: Plant Growth Experiments and Adsorption." *Water Research* 63: 94–101.

Villarreal, Edgar L., and Lars Bengtsson. 2005. "Response of a Sedum Green-Roof to Individual Rain Events." *Ecological Engineering* 25 (1): 1–7.

Warren. Viessman. 1989. *Introduction to Hydrology.* 3rd ed. / Warren Viessman, Jr., Gary L. Lewis, John W. Knapp.. New York: Harper & Row, HarperCollins Pub.

Wolf, Derek, and Jeremy T. Lundholm. 2008. "Water Uptake in Green Roof Microcosms: Effects of Plant Species and Water Availability." *Ecological Engineering* 33 (2): 179–86. doi:10.1016/j.ecoleng.2008.02.008.

WTOP, Washington's Top News. 2014. "Nation's Triathlon to Cause Road Closures Sunday; Swim Canceled," September 5. http://wtop.com/news/2014/09/nations-triathlon-to-cause-road-closures-sunday-swim-canceled/.

Zaman, QMM-u, S. S. Y. Lau, and S. O. Mei. 2000. "The Compact City of Hong Kong: A Sustainable Module for Asia." *Compact Cities: Sustainable Urban Forms for Developing Countries. Spon Press, London*, 255–68.

BIOGRAPHY

Erik Steven Hovland graduated from Saints Peter and Paul High School, in 2008. He received his Bachelor of Science from Old Dominion University in 2013. He is currently an employee as part of the Fairfax County Economic, Demographic, and Statistical Research team. In 2015, he received a Master of Science in Geographic and Cartographic Sciences from George Mason University.