GREEN ROOFS AS AN URBAN STORMWATER BEST MANAGEMENT PRACTICE FOR WATER QUANTITY AND QUALITY IN FLORIDA AND VIRGINIA

By

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To my parents, husband and Simran

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Abstract of Dissertation Presented to the Graduate School
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GREEN ROOFS AS AN URBAN STORMWATER BEST MANAGEMENT PRACTICE FOR WATER QUANTITY AND QUALITY IN FLORIDA AND VIRGINIA

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Green roofs are well known as an urban stormwater volume Best Management Practice (BMP) in northern climates, but information regarding water quality benefits/impacts and optimal plant-growing media combinations for green roofs in the sub-tropics is lacking. The objectives of this study were to: 1) determine the optimal plant-growing medium combination for water and nutrient retention and 2) characterize green roofs' capability to reduce stormwater volume and peak runoff and 3) determine whether green roofs behave similarly (as a sink or source) for nutrients and metals, in Florida and Virginia. Objectives were tested via i) a green roof bin study in Florida and ii) paired green roof studies in Florida and Virginia.

The results of the green roof bin study showed that growing medium type affected water retention and nutrient leaching more than plant type. Water retention ranged from a low of 24% for Building Logics (B) medium with no vegetation to a maximum of 83% for UCF (U) growing medium with perennials. Differences among media were attributed to physical characteristics of the media: pore-size distribution and OM content. Plants increased water retention by 7-10% above bare medium, with perennials having the greatest, and succulents having the least effect.

TP and TN loads for the establishment period (initial 6-weeks) ranged from 110 mg P m^{-2} (U-perennials) to 1800 mg P m^{-2} for (H-succulents or bare medium); and from 190 mg N m^{-2} (U-runners) to 1800 mg N m^{-2} (H-succulents) . The majority (60-90%) of the nutrient load leached out in the establishment period of the 24-week study period.

Green roofs monitored in Virginia and Florida behaved similarly for water retention and peak reduction. In both Florida and Virginia, small rain events (< 0.254 cm), had significantly ($p<0.05$) higher mean retention (79% and 98%, Florida and Virginia respectively) than large rain events (26% retention and 72%, Florida and Virginia, respectively). Green roofs significantly ($p<0.05$) reduced the peak runoff in both Florida (94% for small and 60% for large events) and Virginia (100% for small and 79% for large events). Green roofs behaved similarly for nutrients (sources for phosphorus, sinks for $N\text{-}NO_3$, and buffered pH) and differently for metals. Al and Fe levels were significantly higher ($p<0.05$) in green roof (GR) runoff than conventional roof (CR) runoff in Florida; while Pb was significantly lower ($p<0.05$) in Virginia GR runoff. In conclusion, this study found that green roofs in the subtropics are better suited as a stormwater volume control BMP, than a nutrient control BMP.

CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

Introduction

Green roofs have been in use in Europe for approximately 40 years as a stormwater best management practice, while in the United States they are just becoming recognized as a new way to reduce stormwater at the source. The effectiveness of extensive green roofs to reduce stormwater quantity and treat it for water quality has been studied primarily in cool temperate climates such as Sweden, Germany, Michigan, Ontario, Oregon, and Pennsylvania (Berndtsson et al., 2006; Van Woert et al., 2005; Liptan and Strecker, 2003; and DeNardo et al, 2003.). Energy savings gained by using green roofs has been explored in warmer climates such as the Mediterranean and the tropics (Theodosiou, 2003; and Wong, 2003), but currently little information is available regarding plant hardiness, optimal substrate depth and type for subtropical regions such as Florida (Hardin, 2006).

The subtropics present a unique situation for green roofs, because of higher precipitation rates and potential evaporation rates, higher temperatures, occasional hurricanes, and even the occasional winter frost. This unique climate also attracts humans, making Florida one of the fastest growing states in the United States. As urban areas become more densely populated, space for stormwater BMPs becomes limited, making green roofs a good option as an alternative BMP (Moran, 2003; Liptan and Strecker, 2003). Green roofs take advantage of already existing rooftop space to reduce the source of urban stormwater by detaining and evaporating the rainwater.

Green roofs also have the potential to reduce urban stormwater pollution by adsorbing particles from wet and dry atmospheric deposition. Green roof water quality depends on the soil thickness, medium, vegetation and drainage system in place (Berndtsson et al., 2006); green roofs have been cited both as a sink and as a source for nitrogen, phosphorus and metals. German researchers (Steuslof, 1998 in Berndtsson et al., 2006) found that green roofs mitigate for elevated levels of metals and nutrients largely based on their ability to detain the water, while Swedish studies (Berndtsson et al., 2006) found that nitrogen is released from roofs.

Currently there are few studies regarding the performance of green roofs as an urban stormwater BMP to mitigate water quality in Florida (Hardin et al., 2006), and limited information exists for the south-Atlantic region of the United States in general (Florida, Georgia, North Carolina, South Carolina, Virginia, West Virginia, Maryland, Washington, D.C. and Delaware) (Moran et al., 2005, De Nardo et al., 2005; and Carter et al., 2005). (Note: The mid-Atlantic states traditionally refer to New York, Pennsylvania, New Jersey, and usually Delaware and Maryland, Virginia are part of the south-Atlantic region and technically lies within the northern extent of the Cfa Koppen system of climate classification) (Pickett et al., 2000).

Rooftops as a Source of Urban Stormwater

Urban areas contribute large amounts of stormwater runoff and pollutants due to impervious surfaces. In a highly urbanized city setting in the USA, typically 72% of the land area is impervious (Schueler, 2001); 40% being comprised of rooftops (Urbonas, 2001; and Liptan, 2003) and 60% consisting of "car habitat".

Rooftop runoff poses a greater threat to water quantity in urban watersheds than rural watersheds. This is because the runoff enters receiving water bodies more rapidly in urban areas than in rural settings due to the greater connectivity of roofs to gutters and sewers. The presence of pavement impedes infiltration to groundwater, increasing the proportion of water going to surface overland flow and increasing the velocity of the runoff. When surfaces are paved, vegetation that originally provided interception and evapotranspiration is removed, and natural depressions in the landscape, which normally detain 50% of the runoff, are eliminated (Dunne and Leopold, 1978). The volume and rate at which the runoff is delivered to the receiving water body is greatly increased (Andoh, 1997), resulting in a reduction of the hydrologic response time and greater recurrence of floods.

Rooftops contribute to stormwater pollution via two mechanisms, one is through the release of constituents from the roofing materials used—such as zinc, copper, polyaromatic hydrocarbons (PAHs), cadmium or lead (Clark, 2001) and secondly from atmospheric deposition—for example nitrogen, phosphorus and even pesticides (Moran, 2003 and Dietz, et al., 2005). Researchers in Michigan looking for sources of stormwater contaminants found rooftops to be the largest source of dissolved metals, while parking lots contributed the PAHs (Clark, 2001).

Green roofs reduce contamination from rooftops by reducing the amount of water leaving the roof (De Nardo, 2003; Van Woert, 2005; Liptan, 2003; and Villareal, 2004) and by plant uptake and transformations of N and P deposited atmospherically or added by fertilization (Berndtsonn, et al., 2006).

Green Roof Design: Intensive, Extensive and Florida

Green roofs are generally categorized into two types: intensive green roofs and extensive green roofs. Intensive roofs are capable of sustaining plants such as shrubs and small trees 1 m to 5 m in height, requiring soil depths of 0.4 m and upward and must sustain a higher load bearing and may require more irrigation and fertilization (Moran, 2003).

Extensive green roofs generally consist of a regular roof covered with an asphalt coating (the bituminous layer), overlain by a protective root barrier layer (copper wire may be woven through this layer or root resistant polyester can be used to prevent root penetration). Overlying the root barrier layer is the moisture retention mat or fabric which holds the excess precipitation that percolates through the growth medium and drainage layer. The moisture retention fabric is often 0.75 cm thick and may have an eggshell carton type filter above it that also has retention capabilities. Above these layers is the growing medium.

Growing media for green roofs vary, but are characteristically light in weight, low in organic matter, and preferably consist of local materials (Emilsson, 2005). The vegetation on extensive roofs needs to be both inundation and drought-tolerant, as well as tolerant to heat and cold. In temperate climates (Sweden, Germany, Michigan, Pennsylvania and Virginia) extensive roofs are often planted with a variety of sedums (*Sedum album, S. reflexum, S. sexangulare, S. spurium, S. album, S. kamtschaticaum*, and *S. pulchellum*) or may include *Delosperma spp. (D. aberdeenense, D. basuticum, D. cooperi, D. nubigenum)* (Snodgrass and Snodgrass, 2006; Berndstonn et al., 2006; Van Woert et al., 2005; DeNardo et al. 2005; and Moran, 2003).

Extensive green roofs require little maintenance. They have shallow soil substrate depths usually between 5 cm to 15 cm and are often planted with native vegetation that can survive on precipitation alone, therefore they usually can survive without irrigation or fertilization. Vegetation heights are low, ranging from 5 cm to 8 cm (Moran, 2003). Extensive green roofs in Florida have been more successful in deeper substrates than those typically used in cool climates, likely due to higher evapotranspiration rates in the subtropics (personal communication Martin Wanielista and Mike Hardin, 2006).

Stormwater Best Management Practices (BMPs)

Stormwater BMPs can be structural and non-structural. Non-structural BMPs mimic nature and include techniques such as marking-off areas for conservation before building, keeping imperviousness and car habitat to a minimum and diminishing the footprint of buildings on the landscape. Green roofs help reduce the footprint of a building—by placing the accompanying stormwater BMP on the roof —and help replace a small portion of the original vegetation that once existed in the building's place.

Structural BMPs are man-made works that contribute to detaining flow of stormwater and treating the stormwater for water quality. They can be small distributed structures, such as vegetated swales, bioretention areas or rain gardens, or mini-wetlands distributed through out the watershed that promote infiltration. Rainwater is evapotranspired and/or reused at the source by disconnecting impervious surfaces from stormwater conveyance systems and by creating absorbent surfaces (Graham, 2004).

Source control BMPs may include improved site design of new buildings and housing complexes, that include marking off and setting aside natural areas, reducing impervious areas and footprints of the buildings and roads, re-infiltrating rooftop runoff on-site, or collecting it in rain barrels or cisterns for later re-use, and minimizing runoff from roofs and pavements via green roofs and pervious pavement (Graham, 2004). Green roofs are both a source control as well as a structural control for stormwater.

Green Roofs' Role in Stormwater Retention and Detention in the Hydrologic Cycle

Green roofs retain and detain water from rainfall events and assist in evaporation. High rates of evapotranspiration from a vegetated roof can reduce the annual runoff to less than half the amount of incoming precipitation (Berndtsson, 2006). Rainfall detention is defined as water temporarily detained after a rainfall event to be later released it at a later time; and retention as the fraction of rainfall that is retained on the roof that eventually is evaporated from the growing medium or transpired by the plants. For example, De Nardo (2003) found that green roofs played an important role in attenuating the peak runoff by detaining the water for a period of time. She found that green roofs reduced total runoff over a whole year by 40%.

Villareal et al. (2004) in Sweden, tested the role of green roofs as one link in a chain of connected BMPs. The green roofs were retrofit on to municipal buildings and its stormwater runoff entered a chain of BMPs that included open channels, inner courtyard detention ponds and miniature treatment wetlands in an urbanized setting. By simulating runoff for different sized storms, Villareal et al. (2004) found that in the absence of green roofs, peak flows and the total inflow volumes to the last BMP in the series of BMPs increased significantly for the same storm event return periods. The authors concluded that to be able to offer the same level of retention and attenuation without green roofs, the pond complex would have to be significantly larger (Villareal et al. 2004). They also found that green roofs played a more important role in mitigating small storms, while the stormwater pond had a greater relative importance in large storms.

Nutrients and Metals

In a second study in Sweden, Berndtsson et al. (2006) examined green roof runoff quality from green roofs over bicycle parks in Malmo, Sweden and green roofs covering a school in Augustenborg, Sweden. They found that the green roof on the school acted as a sink for nitrogen, reducing TN by 58%, but behaved as a source for phosphorus and potassium. They also found that the green roof's role as a sink or source varied either due to age, parent materials or input levels with regards to metals in runoff. The newer green roof covering the bicycle parks in Malmo acted as a sink for lead, while the older green roof on top of the school in Augustenborg behaved as a source for lead. These results corroborated those of a German study on vegetated roof research plots at the Technical University of Berlin, where green roof plots were capable of acting as a sink when input levels were elevated (the green roof plots retained 95%, 88%, 80% and 68% of the loads of Pb, Cd, NO_3 and PO_4 over a 3-year period), however when input levels were low, then the green roof acted as a source (Kohler et al., 2002 in Berndtsson et al., 2006).

Green Roofs in Florida

Green roofs in the subtropics are purported to need 15 cm (6 in) of soil to sustain the currently recommended native plant for green roofs in central Florida (Wanielista and Hardin,

2005) and plants native to Florida or those that are naturalized to the Florida climate were hypothesized to be the plants that would be best suited to surviving on a green roof in Central Florida with the least amount of maintenance necessary (limited irrigation and no fertilization). The list of plants below was originally created by the curator of the arboretum at UCF, Martin Quigley, and shows mainly native or plants adapted to the Florida climate that were considered for use in the first extensive green roof in Central Florida created at UCF; the first six plants were eventually chosen for UCF's green roof in 2006 and those plants successfully survived hot summers and cool winters with minimal irrigation (Hardin and Wanielista, 2006).

Lonicera sempervirens (Coral Honeysuckle)
Gaillardia pulchella (Firewheel Daisy)
Myricanthes fragrans (Simpson's Stoppers)
Muhlenbergia capillaries (Muhly Grass)
Helianthus debilis (Beach or Dune Daisy)
Salvia coccinea (Tropical Sage)
Monarda punctata (Spotted Beebalm)
Hamelia patens (Firebush)
Erythrina herbacea (Coral Bean)
Mimosa strigillosa (Powderpuff)
Solidago spp (Goldenrod)
Hypericum hypericoides (St. Andrew's Cross)
Oenothera laciniata (Cutleaf Primrose)
Scoparia dulcis (Sweet Broom)
Phyla nodiflora (Carpet Flower)
Scutellaria integrifolia (Rough Scullcap)

Justification

Green roofs have potential in the sub-tropics to be a mechanism to reduce stormwater runoff at the source, attenuate the peak runoff rates and increase the lag time to peak of concentration in urban areas. Due to Florida's unique climatic conditions, such as intense heat, drought, intense and frequent rains, its green roofs will depend on plants that need a deeper substrate than temperate green roofs (Wong et al., 2003). Deeper substrate requires roofs to have a higher structural load bearing capacity, resulting in increased costs. A growing medium that is light-weight and has water retention capabilities that favor green roof plant health with minimum irrigation and fertilization could make the use of green roofs feasible in Florida at reduced costs. Another potential obstacle with green roofs in the subtropics is that heat tolerant plants occasionally die during an unusual frost, as was the case in experimental roofs in Mexico (pers. comm.. Green Roof Conference, 2004.) More published articles and controlled studies with replicates or field studies with paired roofs are needed in the sub-tropics to determine which plant types and respective growing media types would yield the most viable green roof for Florida cost effectively. Additionally quantitative data regarding the effects of green roofs on urban stormwater hydrology and water quality are needed to determine what would be the benefits or drawbacks of using green roofs as an urban stormwater BMP in north Central Florida or northern Virginia.

Data in the literature regarding the effect of green roofs on water quality is contradictory and inconsistent. More research is needed with continuous flow measurements of precipitation events in the field with a paired roof study between a conventional roof and green roof of the same size in subtropical climates. Results could help suggest whether or not green roofs improve water quality by reducing the total volume of outflow; or whether green roofs have the capacity to actually treat the water passing through the growing medium and root zones of the plants; or whether green roofs will act as a nutrient and metal source in this climate.

Data generated from this study regarding water quality and quantity, optimal growing medium type and plant type will be available for economic projections by land-use managers as to the monetary value of green roofs as a BMP in an urban area. Stormwater managers can use this data to answer questions such as: How much BMP credit should be allocated for green roofs for water quantity and/or water quality? This research on green roofs aims to conduct experiments which will generate results that will help address the following questions regarding water quantity for Florida and Virginia: 1) What role do green roofs play in reducing stormwater runoff? 2) What role do green roofs play in increasing the lag time of stormwater runoff entering its receiving water body? 3) What amount of coverage of green roofs is necessary to achieve a significant reduction in stormwater volume entering a receiving water body?

For water quality, the research aims to address these questions: 1) Do green roofs act as a source or sink for N and P? 2) How do green roofs behave differently at two extremes of the same climatic zone, with regards to being a sink or source for N and P? 3) What amount of green roof coverage would be necessary in an urban watershed before a water quality change could be measured in the receiving water body?

For Florida only, this research aims to answer the following questions: 1) Which plants can withstand the extreme drought conditions, heavy rains and high temperatures as well as occasional frost typical of the Florida sub-tropical zone the best, with the least amount of irrigation?

Research Goals

The goals of the research are to:

1. Determine the optimal plant-growing medium combination for Florida out of three growing media used in Florida and three plant types.
2. Characterize the effect of green roofs on urban stormwater hydrology for Florida and Virginia.
3. Characterize the effect of green roofs on the water quality of runoff for Florida and Virginia.

Hypotheses and Research Objectives

The hypotheses specific to green roof growing media and plant types are:

H1: Successful green roof plants in the sub-tropics (defined as those plants that can survive drought, high heat and intense rain without irrigation after establishment) will consist of a mixture of (structural) plant types different than those used in cool temperate climates, because of the differences in climatic conditions between the two climates.

H2: Plant type will have a greater affect than growing medium type on water retention and nutrient retention in the green roof system, especially in the sub-tropics, because of the role of plants in nutrient and water uptake during rapid plant growth and the ability of the plants to evapotranspire water out of the green roof system.

H3: The highest rates of nutrient leaching will occur during the establishment period of a green roof as compared to later in the green roof's life, because the growing medium at this time acts as a nutrient source with little influence of plants.

H4: An optimal plant-growing medium combination exists for the sub-tropics that will minimize irrigation requirements and minimize nutrient leaching in green roofs.

H5: The overall benefit of green roofs for water retention, peak runoff attenuation and increases in lag time to peak runoff will be less in green roofs in Florida than in Virginia, because of higher peak precipitation rates, greater total volume of rain events, and greater recurrence of convective storms in a humid subtropical climate (Florida) than in a transitional humid subtropical/continental climate (Virginia).

H6: Green roofs' influence on water quality in stormwater runoff will be similar in both in Virginia and Florida and will act as a sink for nitrogen and source for phosphorus and sediment, and may be either a sink or source for metals, when compared to conventional roofs.

Objectives specific to green roof growing media and plant types for Florida and regarding water quantity and quality in both Florida and Virginia are:

1. Quantify the effect of growing medium type and plant type on storm water retention capacity in Florida and determine whether growing medium type or plant type plays a more significant role in water retention.

2. Quantify the amount of nutrient (TSS, TN [TKN+ NO_3], TP) leaching from green roof bins with different types of growing media and plants and a) determine which plant growing medium combination has the least amount of leaching (greatest amount of nutrient retention) and b) whether plant or growing media type is most influential in nutrient leaching in the subtropics.

3. Quantify the amount of nutrient leaching during the establishment period and after the establishment period, determine whether there is a trend of decreasing leaching over time.

4. Observe the plant health of three different plant types growing in different growing media types and determine whether any plant-growing medium combination can survive without irrigation or fertilization after the establishment period and if so, which plant-combination has the best plant health without irrigation or fertilization.

5. Quantify the amount of stormwater retention, peak runoff attenuation, and increase in lag time to peak, if any, due to the presence of the green roof in both Florida and Virginia and compare these rates.

6. Measure water quality—concentration and load of nutrients (NO3/NO2, PO4, TDS, TSS) and metals (Cd, Zn, Al, Fe, Cu)— in green roof and conventional roof runoff in Florida and Virginia to determine whether the green roofs are acting as a sink or source for N, P and metals, and whether they are behaving the same way (as a sink or source) for the same parameters in both regions (Florida and Virginia).

Study Approach

The hypotheses were tested through a three part study consisting of: a) a controlled green roof bin experiment in Florida, b) a green roof monitoring study in Florida, and c) a paired green roof study in Virginia. The controlled green roof bin study was used to test the first three hypotheses and objectives, which are those related to: 1) determining the affect of growing medium versus plant type on water retention and nutrient retention and identifying successful plants in the sub-tropics; 2) quantifying the rates of nutrient leaching during the establishment period of a green roof and determining any trends or differences over time in the beginning of the green roof's life; and 3) identifying the optimal growing medium-plant type combination for extensive green roofs in north central Florida (that will minimize irrigation requirements and minimize nutrient leaching in green roofs). Specifically, the controlled green roof bin study was carried out using three commercial growing media types and several plants previously suggested for green roofs in Florida during a 6-week establishment period with regular irrigation, followed by 6 months of no-irrigation, to determine which plant types can potentially survive heat, drought, frost and inundation without irrigation after becoming "established" (defined as 6-weeks) during the peak growing season.

The paired green roof/conventional roof study in Virginia and the green roof monitoring in Florida provided data to meet Objectives 5 and 6, which were to 1) characterize the effect of green roofs on urban stormwater hydrology and 2) characterize the effects of green roofs on water quality, for Florida and Virginia. Specifically, this was accomplished in Virginia by monitoring the volume of runoff from both a green roof and conventional roof of the same age and size in Merrifield, Virginia continuously between 2005 and 2008. In Florida, the Charles R. Perry Construction Yard Green Roof was monitored continuously for stormwater runoff quantity throughout 2007 and 2008. The hydrology data was used to characterize the water detention and retention capabilities of these two green roofs. The water quality objective was met for these roofs by sampling runoff from discrete storms over a 2-year period and analyzing the runoff for nutrients and metals and comparing total loads from each roof type.

Dissertation Format

The dissertation is written as a series of chapters on the individual studies in a manuscript format. Chapter 2 presents the results of the hydrologic component of the optimal plant-growing medium combination study for north Central Florida. The hydrologic component of the study characterizes the water release curves/water retention capacity of the various soil-plant combinations which was measured by weighing individual bins regularly and measuring filtrate throughout the study period. The hydrologic component also describes the evapotranspiration rates of the various plant types. Chapter 3 contains the results of the optimal plant-growing media combination study with regards to nutrient retention and focused on characterizing the nutrient levels in leachate of the various soil-plant combinations primarily during the "establishment phase" of the green roof, defined here as the initial six (6) weeks of watering and growing of the plants, beginning in mid-summer, followed by additional samples taken at 12, 18 and 24 weeks. Leachate was analyzed for TSS, TP and TN in samples taken directly after controlled irrigation events collected at weeks 1, 6, 12, 18, 24 and 52 as well as in composite samples representing 6 week periods of time up to 6 months. Based on the results of this study, a conceptual model was created to predict the runoff quantity and quality from the Florida and Virginia green roofs that were studied in situ for the paired roof study.

Chapter 4 contains the results of the green roof monitoring study in Florida, and the paired green roof study in Virginia, as well as a comparison of the two roof systems in the two extremes of the sub-tropical climate. Chapter 5, the conclusion chapter, focuses on the policy implications and the implications of load data and coverage models for Florida and Virginia and a prototype of green roof policies for Florida and Virginia and contains the overall conclusions regarding the management of green roofs in Virginia and north Central Florida as a stormwater BMP for water quantity and quality.

CHAPTER 2
HYDROLOGIC DYNAMICS OF GREEN ROOF PLANT-GROWING MEDIUM COMBINATIONS FOR NORTH CENTRAL FLORIDA

Introduction

Due to the variability of the subtropical climate—uneven distribution of rain, high ET in windy months, occasional frost and drought—extensive green roofs in Florida have been hypothesized to function better at depths of (>15 cm) of growing media, as compared to their temperate climate counterparts, which are typically designed with 5 cm – 10 cm of growing medium (Mike Hardin and Martin Wanielista personal communication, 2006). The deeper medium is thought to provide a greater water storage capacity, therefore buffering the variability in water demand and supply of water for plants on Florida green roofs.

In general, green roofs are designed to retain and detain water from rainfall events and assist in evapotranspiring the water. Evapotranspiration rates from a vegetated roof can reduce the annual runoff to less than half the precipitation (Berndtsson, 2006). Retention is defined as the fraction of rainfall that either evaporates from the growing medium, or transpires out of the plants, or remains on the roof stored as (non-plant available) soil moisture. Detention is defined as the water temporarily stored in the growing medium's pore space that eventually is released as runoff over a longer period of time. Retention and detention processes of green roofs reduce the peak volume entering the stormwater system, increase the lag time to peak concentration and influences baseflow over a longer period of time (Bengtsson et al., 2005; Zimmer et al., 1997; DeNardo et al., 2004).

Physical Characteristics of Growing Media

Important physical characteristics of growing media which can directly or indirectly affect water retention include: bulk density, grain-size distribution, sorting, packing arrangement, organic matter content, texture and mineralogy. For example bulk density is important for green roofs because it determines the overall mass that will be added to a roof and can reflect the amount of compaction. Compaction influences infiltration rate which influences the ability of the green roof to act as a water storage device. Organic matter and mineralogy are important because it influences both the pore size distribution and intra-aggregate pore space, which can affect moisture content (Brady and Weil, 2002).

Content of growing media can vary vastly with the region, the ingredients chosen and intention of the roof. In Germany, where green roofs have been used extensively for over 40 years, standards are in place regarding the proportion of aggregates to other particle size classes, % organic matter, type, maximum carbonate content and other regulations with regards to slope, substrate contents, bulk density and compactibility. The US has few standards for green roof growing media at this time, ASTM E2396-05, 2398-05 and 2397-05.

Currently, many of the green roof media used in the US have been patterned after growing media characteristics of those used and tested in Germany, a cool oceanic temperate climate, which are largely carbonate-free aggregates in the 0.95 cm (3/8 in.) range, with few finer particles and low in organic matter (1-3%). I hypothesize that the sub-tropics have a growing media that is optimal for this climate (maximizing plant available water between storms, but able to create enough void pore space so as to be useful in stormwater detention) and may have characteristics that differ from a growing media that is optimal in a cool temperate climate. Examples of growing media from various parts of the world include materials varying from crushed roof tiles to volcanic pumice for the inorganic aggregate sized portion of the mix and from sphagnum peat moss to chicken manure for the organic portions of the growing media (Table 2-1).

Green roof systems have other layers that influence water retention, such as drainage layers. Drainage layers vary in their form and water retention characteristics, ranging from small cups to large with holes at the top of the cup for drainage, to an absorbent plastic mesh layer, to an aggregate layer with perforated PVC running through the aggregate for drainage. The details of these layers vary as well, such as the size of cups and density of holes for drainage in the corrugated plastic drainage layers type and the mesh thickness and absorbency varies for the plastic mesh layer and aggregate layers can vary in thickness and amount of piping available to carry the water to the downspout, all these factors further influence the water retention capacity of a green roof and the amount of water available to plants. This study characterizes the water retention properties of exclusively the growing media, (and does not incorporate the water retention effects of the under layers).

Table 2-1. Examples of variability of growing media constituents and physical properties among locations.

Location	Constituents	Source	Physical Properties
Sweden	43% crushed ceramic roof tiles (8-12 mm) 37% sand 10% organics 5% clay 5% crushed limestone (8-12 mm)	Villareal et al. (2004) Emilsson (2008)	BD= 1.48 g cm^{-3} Porosity 43.34% Organic Content=1.6%
Pennsylvania	60% hydrolite 12.5% sphagnum peat moss 12.5% coir 15% perlite	DeNardo et al. (2003)	Saturated wt 4.9 kg m^{-3} (porosity 55%, field capacity 11%, K_{sat} 0.12 to 0.2 mm s^{-1})
Michigan	40% heat expanded slate 40% USGA sand, 10% Michigan Peat 5% dolomite 3.33% composted yard waste 1.67% composted poultry manure	Van Woert et al. (2005)	Capillary pore space 20%, non-capillary pore space 21.4% Bulk density 1.3 kg m^{-3}

In situ, each growing medium is underlain by a different material—the Building Logics growing medium in Virginia has a corrugated plastic cup underlayer that contains absorbent gel packs in the bottom of the cups. American Hydrotech's system on the Charles R. Perry Construction Yard also uses a corrugated cup under layer which has a higher density of smaller cups than Building Logics and no gel packs; and UCF's mix a top the Student Union at UCF in Orlando was underlain with aggregate and perforated PVC piping. The aim of this study was not to analyze the whole green roof system, but isolate the role of the media in retention. For this reason, when the media were tested in the mesocosms, Floradrain drainage layer was employed in a reverse position, with the drainage holes that are normally situated at the top of the cups positioned on the bottom to readily transport percolate water away. This study does not promote any brand over another; each company whose proprietary mixes were used, have several growing media types for different situations. The growing media tested here, were chosen based on the fact that two were actually used in Florida—Hydrotech's Litetop® on the Charles R. Perry Construction Yard, and UCF's Black and Gold ™ was used on the Student Union Building at UCF in Central Florida, and Building Logics's mix was chosen because it was used on the Yorktowne Square Condominium green roof that is monitored and described in Chapter 4, and because Building Logics intends to use their mix in Florida and would like to adapt it to the subtropical climate.

Role of Plants in Retention and Detention of Stormwater

In addition to growing media, plants are also an integral component of green roofs. Plants are important in a green roof system because of aesthetics, cooling via transpiration, shading and creating a monolithic layer by holding the substrate in place with its root system (Cantor, 2008). In terms of green roofs as a stormwater management practice—the main function of plants is their ability to reduce media moisture content via transpiration and increase interstitial pore space available for water storage. This is important because the amount of storage available for the next storm event depends on how much water was released via transpiration rate of the plants after drainage stops.

After a storm, the available storage volume in the growing media depends on the percent of available volume of void pores. Before the next storm, the growing media plant system must release the water either via the plants or due to physical characteristics of the soil, to create new available pore space in the green roof media. Further, to serve as a stormwater control for the local climate, ideally the cycle of filling the pore spaces and voiding the pore spaces would match up to the periodicity and volume of the storms in the region.

Additionally, since green roofs are defined as being “living roofs”, the plants must remain viable during the lifetime of the roof. To sustain plant life on a roof, either enough plant available water must remain in the soil betweens storms for plants to survive or irrigation must be added. Plant available water is defined as the difference between field capacity and wilting point (Brady and Weil, 2002).

Role of Plant–Growing Media System in Stormwater Control

Zimmer and Geiger (1997) simulated and tested small beds of green roofs by applying rainfall via sprinklers at intensities ranging from 5 cm hr^{-1} (2 in hr^{-1}) to 18 cm hr^{-1} (11 in hr^{-1}). They found that for intensities up to 18.5 cm hr^{-1} (7.3 in hr^{-1}) the green roofs showed positive retention effects (Zimmer and Geiger, 1997). De Nardo et al. (2003) also found that green roofs played an important role in attenuating the peak runoff by detaining the water for a period of time. She found that green roofs reduced total runoff over a whole year by 40% in the mid-Atlantic region.

Swedish scientists tested the role of green roofs as one BMP in a chain of connected BMPs. The green roofs in the study were retrofit at municipal buildings and runoff from these buildings then entered a chain of BMPs that included open channels, inner courtyard ponds and miniature wetlands in an urbanized setting. The hydrological performance of the new stormwater system was assessed by "modeling the individual BMP elements using the unit hydrograph and design storm concepts to provide synthetic inflow hydrographs" (Villareal et al., 2004). Simulations for the area that contained the green roof were run with and without the green roofs as part of the chain of BMPs (the green roofs covered 31% of a 4600 m^2 area that drained to an elongated pond located between the building and the parking lot).

They found that the BMPs significantly reduced peak flow because they were very effective in retaining and detaining stormwater volumes. Their presence delayed the storm peaks in the unit hydrograph as well as lowered the peak flow. The upstream BMPs in the study, which included the green roofs, retained 50% of the stormwater produced by the ½-yr rain event, 37% for the 2-yr, 30% for the 5-yr and 21% for the 10-yr design storm. Their green roofs played a more important role in mitigating small storms, while the stormwater pond had a greater relative importance in large storms.

Given that different plants have different transpiration rates and soils have different water retention capabilities and evaporation rates, I hypothesize that an optimal growing media-plant combination exists for each regional climate and that by varying medium composition, depth and plant selection it should be possible to construct a green roof with little or no supplemental irrigation after the establishment period for north central Florida. The "optimal" plant-growing medium combination in a green roof for stormwater management in north central Florida should have high water retention capacity and medium re-release characteristics.

Objectives

The objective of this study was to determine which plant-growing media combination at a 15 cm depth is optimal for water retention during storm events and re-release before the next storm, while maintaining healthy plants. Three (3) plant groupings and three (3) commercially available growing medium types were tested and compared to each other and to several controls over a period of 6 months in a mesoscale field experiment. The determination of “optimal” plant-soil combination for a stormwater BMP was based on 1) plant viability and plant growth, 2) nutrient retention/release, and 3) water retention/release. This chapter deals exclusively with the water retention/release portion of the study.

The specific objectives of the hydrological component of the study were to:

1. Determine water retention during a six (6) week plant establishment period with irrigation.
2. Quantify and compare the water retention of the experimental green roof bins after establishment with no irrigation over a longer period of time (6 months).
3. Determine an overall water balance for plant-growing media combinations, meaning determine amount of water leached, taken up by plants and growing medium after irrigation, and back-calculate ET rates based on water loss for each plant-growing medium combination, based on these values.
4. Characterize the water release characteristics of the plant-growing media combinations and how they change over time.

Hypotheses

The null hypotheses related to the hydrologic study on the establishment period of the green roof (first six weeks of growth) and the 6 month study for a shallow north central Florida green roof (15 cm deep) were:

H1o: There are no significant differences in water retention among growing media types, plant types or any of the 9 growing media-plant combinations and/or bare media.

H2o: There are no significant differences in evapotranspiration rates among the 3 plant types, 3 growing-media types or any of the 9 growing media-plant combinations and/or bare media.

H3o: There are no significant differences in water retention within plant-growing media combinations over time.

Materials and Methods

Study Area

The climate of north central Florida is humid with an average annual rainfall of 1300 mm (NOAA, 2007). Rainfall distribution is uneven throughout the year and characterized by a relatively short "wet" season and relatively long "dry" season with variable beginning and end dates (Butson, 1958). For Gainesville, the average beginning date of the rainy season based on a 25-year record (1931-1955) is June 15th and the end date is September 5th (Butson, 1958). During this period over 50% of the annual precipitation occurs. Rain events in the rainy season are due to convective storms (NOAA, 2007; Brown, 1981; Irmak et al., 2002).

The mean monthly precipitation average between June and September is 178 mm and the mean monthly temperature for these months range from 18 to 35°C. The winter mean monthly precipitation average is 80 mm and mean monthly temperature ranging from 4°C to a maximum 22°C (NOAA, 2007; Brown, 1981; Irmak et al., 2002). Periods of drought can occur within the rainy part of the year and during the winter months there is also regular frost and occasional hard freeze events. The peak values of evaporation in north-central Florida occur in May when daily incoming solar radiation are at a maximum of 7 mm day^{-1} and are lower in June, July and August because of cloud cover associated with the summer rainy period. Minimum daily evaporation rates occur in December and January at a rate of 2 mm day^{-1} (Irmak et al, 2002).

Experimental Design

The hypotheses for hydrologic dynamics were tested using 40 different mesocosms. The mesocosms were set up in a 3 x 4 factorial design with each treatment replicated 3 times, plus 2 filter fabric controls and 2 empty bin controls. The mesocosms were set-up outdoors on the UF campus, 60 cm above the ground. The ground consisted of white gravel that was devoid of vegetation. The study had two hydrologic phases, an establishment period where irrigation and rain occurred and a post-establishment phase where only rainfall occurred (and no irrigation was administered). Soil moisture release curves were evaluated at the beginning and end of the establishment phase and several times during the post-establishment phase to determine how moisture retention and the water release characteristics changed over time in the mesocosms.

Three different soil growing media, Building Logics®, Hydrotech's LiteTop® and Black and Gold® were tested in 39—30.5 cm by 45.7 cm containers, and planted with three different plant types (Perennials, Succulents and Runners), shown in Figure 2-1. Three replicates of each plant type were planted in each growing medium. Controls for the growing medium consisted of three containers of medium without plants for each growing medium. Overall controls consisted of two containers containing only the corrugated material and filter fabric that underlain the growing medium in all container types, as well as two empty containers-devoid of plants, growing medium or underlayers.

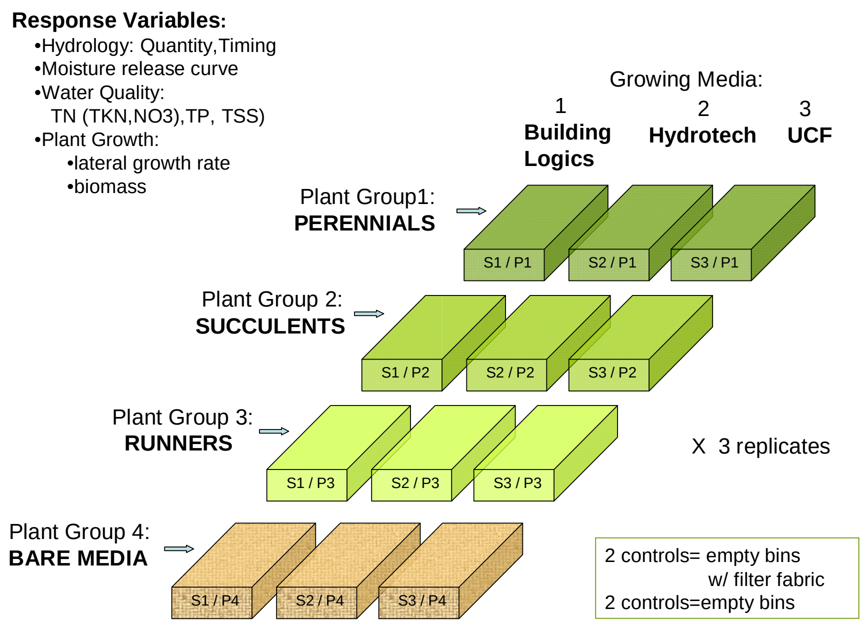


Figure 2-1. Complete Randomized Block Design of 3 growing media versus 3 plant types (and bare media) with 3 replicates and 2 filter fabric controls and 2 empty bin controls (not depicted.)

The green roof mesocosm bins were situated side by side in a randomized block design. Five large wooden frames were built to hold 8 green roof bins side by side. The frames were constructed out of two 3 m long (3 m x 10 cm x 10 cm) landscape beams set parallel to each other on top of two cinder blocks located at both ends of the beam. The beams were placed into two beam holders sawed out of wood, created to hold the beams parallel to each other in such a manner that the top surface of the beam had a slope of 1:12. The bins rested on top of the beams 60 cm above the ground at a slope of 1:12, mimicking the slope of the green roof on top of both the Charles R. Perry Construction Yard and Yorktowne Square Condominiums. The cinder blocks were leveled before the beams were placed on top of them. (Figure 2-2).

Filtrate generated by the bins after rain events and irrigation flowed passively into lidded buckets that were placed on the ground underneath each of the 40 bins. The volume of filtrate was measured weekly for the initial six weeks after planting and then every six weeks between weeks 6 and 24. Additionally, the volume of filtrate was collected and measured directly after a 1.27 cm controlled irrigation test administered on weeks 1, 6, 12, 18 and 24. Water samples of the filtrate from the 40 green roof bins were collected weekly for six weeks and then once every six weeks up to 24 weeks. Sampling times and methods are described in detail the section 'Sampling Protocol'.

Experimental Set-Up

All bins were packed with equal volumes of growing media between July 4th and July 23rd, 2007 and packed following ASTM standards for green roofs used by American Hydrotech, which is based on German FLL standards for the installation of green roofs in Germany. The bins were filled with 17.8 cm (7 inches) of loosely packed growing medium then compacted to 15.2 cm (6 inches) of depth using a 4.5 kg (10 lb) weight which was dropped on to the surface of the bins from a height of 30 cm (1 ft) with 20 blows per surface area of the bin (Figure 2-2).

After packing, the bins were covered with heavy plastic to keep rain and moisture out of the growing media until planting. All bins were planted on 7/22/07 and were moistened pre-planting and then immediately irrigated after planting for 32 minutes, the equivalent of 2.54 cm (1 inch) of irrigation. All bins were irrigated uniformly using a mister nozzle at a flow rate of (280 mL min^{-1}). Bins were irrigated regularly for 1.27 cm (0.5 inch) over 16 minutes following the irrigation regime shown in Appendix A.

During the establishment period, defined as the first six weeks of plant growth, all filtrate resulting from both irrigation and rain was funneled into an 18.9 L (5 gallon) bucket through a tube attached to a hole drilled in the bottom of the bin. The buckets were opaque white with opaque lids and were placed directly under the bins to provide shading to reduce algal growth. Before the study began, the buckets were scrubbed with soapy water, rinsed, then acid washed and triple rinsed. Additionally, the buckets were scrubbed weekly the first six weeks and thereafter were scrubbed every six weeks until the study was completed at the end of week 24. The water that funneled into the buckets from the bins remained in the buckets for up to one week at a time during the establishment phase of the study. After the initial 6 week establishment period ended, the filtrate would remain in the bucket for 6 weeks of time, and was sampled from on weeks 6, 12, 18, and 24.

Water samples from the bins were considered to be composite samples representative of the time period during which the filtrate accumulated. Samples taken weekly during the first 6 weeks (weeks 1, 2, 3, 4, 5 and 6), represented leachate resulting from both rainfall and irrigation. While for weeks 12, 18 and 24, the composite samples represented leachate generated from rainfall over 6 weeks time with no irrigation. Bins were irrigated only during the first 6 weeks of the study.

To create the water release curves for the three growing media, and the three plant types and their combinations, the volume of filtrate collected directly after a controlled 1.27 cm irrigation event was measured at 20 minutes, 60 minutes, 2 hours, 6 hours, 12 hours and 24 hours after irrigation. The buckets were scrubbed immediately before the controlled irrigation experiment and kept directly under the bins at all times during this portion of the experiment. Water collected during the water release characterization experiment was measured for volume using a 500 mL and 100 mL graduated cylinder.

Figure 2-2. Photo of the 40 bins in a complete randomized block design. Succulents (*Sedum acre*, *Delosperma cooperii* and *Portulaca grandiflora*) are shown planted in UCF's Black and Gold® in the forefront, next to it are succulents planted in Hydrotech's LiteTop® mix, followed by perennials (*Helianthus debilis*, *Coreopsis lanceolata* and *Gaillardia pulchella*) in UCF's growing media.

Growing media

The three growing media selected for this study have been used in Florida or will be used in Florida in the near future. The first growing medium was UCF's Black and Gold® growing medium (referred to as U in this chapter) which was engineered by UCF/STE and used in

Orlando at UCF. The second medium, Building Logics® growing medium (referred to as B in this chapter), will be used in Florida in the near future and was utilized on the green roof at Yorktowne Square Condominiums in Merrifield, Virginia. The third medium, Hydrotech's Hydrolite® growing medium (referred to as H in this chapter), is manufactured by American Hydrotech, Inc., a Chicago based green roofing company, which installed the green roof atop the Charles R. Perry Construction Yard in Gainesville, Florida. American Hydrotech's LiteTop® Intensive growing media meets the German FLL Standards for the Guidelines for Planning, Performance, and Maintenance of Vegetated Rooftops. Hydrotech's LiteTop® Intensive growing medium consists of 45-70% LiteTop Lightweight aggregate (0.15 cm to 0.95 cm [1/16"- 3/8"] aggregate), 0-30% Coarse to Medium Sand, 0-30% Perlite, Sphagnum, or Other Lightweight Soil Additive and 5-30% Approved Compost and Nutrient additives "as needed"; Hydrotech adjusts their performance specification values in accordance to the availability of local materials and special project conditions related to plant selection and/or environmental conditions. Appendix B contains the Specifications of LiteTop® Intensive growing media and the General Description and LiteTop Components. Table 2-2 shows the range of density and saturated water and air content, OM content of Hydrotech's LiteTop® Intensive growing medium.

Table 2-2. Physical properties and organic matter content of Hydrotech's LiteTop ® growing medium from Hydrotech's specifications sheet.

Property	
Dry bulk density	0.6-1.1 g/cm3
Saturated bulk density	1.0-1.5 g/cm3
Saturated water capacity	>40%
Saturated air content	>10%
Organic matter content (mass %)	6-12%

Bins packed with UCF's growing media contained 12.7 cm of an expanded clay mix—which by volume, was 60% expanded clay, 15% peat moss, 15% perlite and 10% vermiculite and was underlain by 2.54 cm of Black and Gold™ "pollution control layer" consisting of 40% tire crumb from recycled automobile tires, 20% expanded clay, 15% peat moss, 15% perlite and 10% vermiculite. Building Logics growing medium consists of 90% Stalite (Rotary Kiln Expanded Lightweight Aggregate) and 10% mulch (See Appendix C for the specifications of Stalite).

Analysis of physical properties of the growing media

As the reported values of physical and chemical properties for each growing media based on their specification sheets had wide ranges for bulk density, organic matter and particle sizes, soil samples taken before and after the study was completed were analyzed for BD, OM, particle size distribution, porosity, as well as chemical properties (pH, TP and TN reported in Chapter 3). Each growing medium was sampled before the study began and sampled again at the end of the study. Soil cores (40 cm long x 10.2 cm dia.) were taken from the bulk mixes before packing the bins and subsamples were taken from the cores, air dried, ball milled. After the study was completed, all 40 bins were placed in a green house to air dry for 8 weeks and were weighed weekly. When the mass of the bin no longer changed for three consecutive weeks, the bins were stirred to homogenize the soil and (15 cm long x 10.2 cm dia.) cores were taken from the bins and used for organic matter content (OM) analysis and for grain-size distribution analysis and porosity measurements.

OM was measured through loss on ignition (LOI) in a muffle furnace—1 g of ball milled air dried soil was oven dried for 24 hours at 105°C, reweighed, then baked in the muffle furnace at 250°C for 30 minutes and then the temperature was raised to 550°C for 2 hours. The samples were reweighed after cooling in a desiccator. The loss on ignition values from the muffle furnace method were compared to LOI values using a Thermogravimetric Analyzer (951 TGA) by DuPont, Thermal Analyzer Analytical Instruments Division. The graphs of loss on ignition from the 951 TGA were analyzed using the TA.PC for Windows Acquisition Program, Version 3.2 by Instrument Specialists, Inc.

The air dried soils samples were sieved using four USA Standard Testing Sieves which meet ASTM E-11 specifications. Approximately 100 g of air dried soil was weighed out in triplicate from the soil core taken from before the study began as well as the soil samples from the three replicate bins of bare media for each growing medium type. The soil was sieved using Sieve #10 (2 mm), Sieve #18 (1 mm), Sieve #35 (500 um) and Sieve #60 (250 um) and shaken on a Ro-Tap® Testing Sieve Shaker Model B by CE Tyler for 5 minutes.

Bulk density for each bin was calculated based on the volume (23,000 cm^3) of soil packed into the bin and the mass of the soil after 8 weeks of air drying in the green house. Particle density was measured by water displacement. Porosity was calculated as 1-BD/PD, where BD is bulk density and PD is particle density.

Plant types

The three plant groups were selected based on several factors: a) assumed position along an evapotranspirative scale, b) nativeness, and c) growth and reproductive mechanisms. The three plant groups tested are categorized as follows: 1) Native Florida Dune habitat plants, 2) Succulent plants, and 3) Runner type plants, (Figure 2-3).

Native Florida dune habitat plants: selected for this study were *Helianthus debilis*, *Coreopsis lanceolata* and *Gaillardia grandiflora* (Figure 2-4). They consist of clump-forming upright perennials that reseed themselves, which make them useful in laterally covering a green roof over a period of time (several seasons). They are considered to have medium to low ET rates as compared to other flowering ornamentals in the Florida landscape. They are known to survive periods of drought and heat in dune habitats and several species of these genera evolved in this climate.

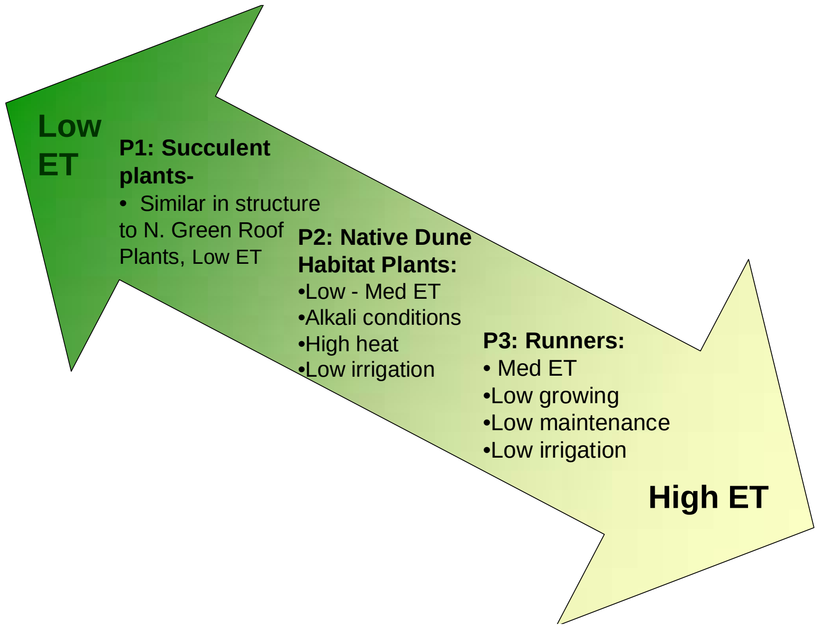


Figure 2-3. Rubric of plant groups in relation to an assumed ET gradient.

The structure and function of these plants is that they are medium low growing self-seeding Asteraceae, that spread by both vegetative growth and reseeding and rebound after high temperature and drought. They have low irrigation requirements, have high heat tolerance, like alkali conditions and are adapted to the native climate--thin medium sized leaves that wilt easily under low water conditions, however are resilient.

Helianthus debilis Nutt. is one of 62 species of *Helianthus* that exist world-wide, *Helianthus* are facultative upland plants and are planted most commonly by placing the root mass 1.27 cm to 2.54 cm below the surface; this was the method of planting was used for both the bins and the Charles R. Perry Construction Yard roof. Adequate water up to 6 months is recommended by the USDA for *Helianthus debilis* after which point irrigation is not needed. In our study, the plants were irrigated for only 6 weeks.

Gaillardia pulchella (one of 13 spp. of *Gaillardia*), commonly know as “Firewheel Daisy” or “Blanket Flower,” is planted in a similar manner to *Helianthus* and reseeds itself by dropping seeds on a well-drained firm soil. *Coreopsis lanceolata* is a clump-forming perennial herb with short rhizomes. *Coreopsis* prefer full sun in well-drained soil and are naturally found in dry infertile sites, making them ideal of Florida roof tops. *Coreopsis* require a firm seed-bed for establishment. Having a thick layer of plant residue on the surface interferes with seed germination. Seed germination occurs by fall and during the winter plants remain low growing rosettes. Lanceleaf can tolerate regular mowing in summer and fall and one fall mowing is recommended (USDA/NRCS 2009).

Figure 2-4. Photos of *Gaillardia grandiflora* 'Goblin', *Coreopsis lanceolata* and *Helianthus debilis* Nutt. (photos by P.J. Alexander and K.Hill.)

Succulent plants: were selected for this study because of their well-known performance on northern green roofs during drought, heavy rain and cool temperatures (DeNardo, 2004; Van Woert, 2006). Three species selected for this study were Sedum acre, Delosperma cooperii and Portulaca grandiflora (Figure 2-5) and were purchased from a local nursery, Grandiflora in Alachua, FL. The species and varieties used were adapted to the Florida climate. The succulents have low ET rates, because, Sedums and Delosperma use Crassulacean Acid Metabolism (CAM) to reduce moisture loss during drought. While Portulaca grandiflora, while a succulent C4 dicot, it also can exhibit acid metabolism similar to CAM plants in certain environments (Ku et al., 1981).

The way succulents generally reduce moisture loss, is by having thick leaves with a low area-to-volume ratio and sunken stomata and thick cuticles. The CAM metabolism in allows the plants to close their stomata during the day, open them by night and absorb low amounts of CO_2

in the night, which the plant transforms into malic acid and store in their vacuoles, to use as an energy source in the day time (Keeley and Rundel, 2003). Therefore succulents with CAM metabolism, release very little water through their stomata, additionally they can store water in vacuoles, making them resistant to drought and heat. Succulent plants are chosen for cool climate green roofs, based on their rapid lateral coverage, low moisture and low fertilization requirements (because CAM plants are very efficient in using nitrogen), and ability to grow in a thin soil substrate (5 cm to 10 cm). While *Sedums* and *Delosperma* are known to tolerate freezing temperatures, snow coverage and droughts, Purslane can tolerate heat and drought for short periods as well as periodic inundated conditions (http://plants.usda.gov).

Figure 2-5. Photo of *Sedum acre* (photo S. Lang 2007), *Delosperma cooperi* and *Portulaca grandiflora* Hook.

Runner type plants: include those plants which are suggested by IFAS at UF based on decades of study to be Floridian alternatives to turf because of their low maintenance—no mowing, little fertilizing. For example, many varieties of perennial peanut (*Arachis spp.*) have been tested by IFAS at UF as an alternative to lawn that require less irrigation and fertilizer than a normal lawn. *Arachis glabrata* (Figure 2-7), while non-native, has adapted well to the Florida climate; it is native to South America between latitudes of 13°S and 28°S, is found naturally in climates with 1200 to 1600 mm yr^{-1} of rain, however it is extremely drought tolerant and can survive once established on 600-700 mm yr^{-1} rain with a 5 month wet season and also can tolerate wet conditions and flooding on occasion, such as a climate with 4000 mm yr^{-1}. *Arachis glabrata* can grow laterally at a rate of 2 m per year with no competition and with other plants present grows at a rate of 5 cm – 20 cm a year. In one year the plant can fully fill in an area where it is planted at a rate of 1 rhizome per 0.5 m with adequate water. However, generally it takes 2-3 years to fully establish. As a nitrogen fixer, N fertilization rates are low, and the plant is usually propogated by rhizome versus plantlets or seed, growing one woody tap root and spreading laterally (French et al., 2006 and Freire et al. 2000).

The two other runners that grow well in Florida under low moisture conditions are *Mimosa strigillosa* and *Phyla nodiflora* and are native to the region (Figure 2-6). An adaptation to the sub-tropical climate that both plants possess is the ability to become dormant under high heat. They are able to survive on little irrigation and have the ability to reseed themselves. The structure and function of this plant group is to spread primarily through lateral vegetative growth and place energy into creating a deep woody root system first, for which reason the plant has the capacity to grow back if it dies back from a frost or drought. Mimosa and Perennial peanut have the ability to close their leaves to reduce the amount of ET during hot periods.

Figure 2-6. *Arachis glabrata* (Perennial Peanut) photo by Roka 2004, *Mimosa strigillosa* (Sunshine mimosa) and *Phyla nodiflora*.

Irrigation regime and rainfall

The irrigation regime during the establishment period consisted of watering daily the first week and then 3 times a week in subsequent weeks until week 6 at which time the irrigation was discontinued (Appendix A). This irrigation regimen is the same as the irrigation regime used on the Charles R. Perry Construction Yard (CRP) green roof, so that comparisons can later be made between runoff data from Hydrotech bins in this study with runoff from Hydrotech LiteTop® mix used on the CRP green roof. A green roof study on optimal irrigation for Central Florida green roofs at UCF 2006 found that 1.27 cm (½”) or irrigation twice a week was superior to “overwatering” defined as 2.54 cm (1”) twice a week (Hardin, 2006).

Rainfall

Rainfall for the site was measured using the University of Florida station W4DFU located at N 29° 38’22” (29.639°) and W 82° 20’43” (-82.345°) at an elevation of 42.5 m (140 ft), using Peet Bros Ultimeter 2000. The 30-yr average rainfall pattern for Gainesville, FL from NOAA (2007) was used for comparisons of rainfall from the study period. Rainfall measured during the different time periods is shown in reported in the Results and Discussion section of this chapter.

Sampling Regime

Composite water sampling

Weekly composite samples of drainage water were taken on Mondays on Weeks 1, 2, 3, 4, 5, and 6 and Weeks 12, 18, and 24. Samples were composite over time, meaning that all drainage from individual rain events and separate irrigation events from the week were passively collected through a tube and funneled into a bucket for each bin. The stage height of the water was measured in the bucket before sampling and multiplied by the cross-sectional area of the bucket to determine the volume of drainage water for the time period. The volume of drainage water was used in the calculation of water retained by the growing media-plant system. Water retained was defined as that water which did not exit the system as filtrate at any point. The volume of water retained was assumed to be either stored in the growing media, or taken up by plants and/or evapotranspired out of the bins by the plants. The amount of retention was determined by subtracting the filtrate from the quantity of water in and dividing this by the volume of water applied to the system via rain or irrigation: Vol. Water Retained = (Vol. $Water_{IN}$ – Vol. Filtrate)/Vol. $Water_{IN}$. The source of water and sampling dates are shown in Table 2-3.

Table 2-3. Composite water sampling dates and sources of water IN.

Week	Sampling Date	Time Period of Composite Sample	Source of $Water_{IN}$	Parameters Measured
Week 1	7/30/2007	1 week	Rain/Irrigation	Volume
Week 2	8/5/2007	1 week	Rain/Irrigation	Volume
Week 3	8/13/2007	1 week	Rain/Irrigation	Volume
Week 4	8/20/2007	1 week	Rain/Irrigation	Volume
Week 5	8/27/2007	1 week	Rain/Irrigation	Volume
Week 6	9/3/2007	1 week	Rain/Irrigation	Volume
Week 12	10/14/2008	6 weeks	Rain	Volume
Week 18	11/30/2007	6 weeks	Rain	Volume
Week 24	1/17/2008	6 weeks	Rain	Volume

Water release characterizations (lysimetric sampling)

Water release curves for the different media types and growing medium-plant combinations were determined via a lysimeter experiment. The lysimeter experiment consisted of weighing the bins, both before and after irrigating the bins with a 1.27 cm (½”) of water, at different intervals up to 72 hours (Table 2-4) every 6 weeks. Bins were weighed the morning of the first day of the experiment using a CPWplus Parcel Scale (Adam Equipment Company 2005), with a maximum capacity of 75 kg and readability to the 0.01 kg. The error in readings of 0.01 kg represents 10 cubic centimeters of water or 0.06 mm of precipitation or ET across the surface of the bin. The bins were irrigated with 1.27 cm (½”) of water directly after the initial weighing, and then reweighed at 1 hour post-irrigation, 6 hours post-irrigation, 12 hours post-irrigation, 24 hours post-irrigation, 36 hours post-irrigation, 48 hours post-irrigation, 60 hours post-irrigation and 72 hours post-irrigation. Filtrate was collected from the bins at 20 minutes, 1 hour and 6 hours after irrigating and 12 hours post-irrigation, (and 24 hours after irrigation in the event that water was still seeping out 24 hours after irrigation). A recipient was kept under all bins at all time periods to collect filtrate at any time period.

The objective of the lysimeter experiment was to create water release curves for the three different growing media and for the different plant types in response to controlled irrigation events over 72 hour periods at different points of the study period. The results of the experiment also reveal how water content changes in the green roof bins over 6 months in response to differences in the climate during different periods of the year.

Water inputs were determined in two ways. One, by pre-calculating the value of expected irrigation volume based on the duration of irrigation in minutes multiplied by the flow rate of the individual nozzles and secondly, by verifying this value by summing the volume of filtrate collected directed after irrigation with the increase in mass of the bin after irrigation. The flow rate of the nozzles was determined before the bins were planted during an initial irrigation test—where empty buckets were placed directly under the nozzles for 1 hour; the flow rate was 280 mL min^{-1}. The nozzle flow rates were measured periodically during intermittent calibration tests throughout the study period by placing a small plastic bottle under the nozzle and irrigating for 5 minutes and then measuring the volume of water emitted.

Water retention at times 1 hour, 6 hours, 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and 72 hours post-irrigation were calculated as the change in the mass of the bins minus leachate volume divided by $water_{IN}$. For example to calculate water retention at Time = 6 hours post-irrigation:

Water Retention $_{Time\ 6\ hr}$ = (ΔMass of Bin $_{0hr\ to\ 6hr}$ - Mass of filtrate $_{0\ to\ 6hr}$)/ Water$_{IN}$

Where ΔMass of Bin $_{0\ hr\ to\ 6\ hr}$ = (Mass of bin $_{6\ hours}$ - Mass of bin $_{Time\ 0}$)

Evapotranspiration rates were determined based on the change in mass of the bins over 12 hour periods of the 72 lysimeter experiment when no leaching occurred, no rain occurred and solar radiation was optimum (sunny versus overcast days), for example between hours 36 and 48 and/or hours 60 to 72, which correspond to 7am to 7pm of days two and three of the experiment:

ET$_{Time\ 48\ to\ 60\ hours}$ = Mass of Bin $_{60\ hr}$ – Mass of Bin $_{48\ hours}$

The lysimeter experiments were planned for every sixth week, if rain was forecast for the experiment days, the experiment was postponed by several days until sunny weather was forecast.

Table 2-4. Water Release Curves (Lysimeter Experiment) Sampling

Week	Sampling Dates	Parameters Sampled	Leachate Source
Week 1-UCF	7/26/07-7/29/07	Bin mass/leachate volume at 0hr, 1hr, 6hr, 12hr, 24hr, 36hr, 48hr, 60hr, 72hr	1.27 cm irrigation event (16 min)
Week 1-H	7/30/07-8/2/07	Bin mass/leachate volume at 0hr, 1hr, 6hr, 12hr, 24hr, 36hr, 48hr, 60hr, 72hr	1.27 cm irrigation event (16 min)
Week 1-BL	8/5/07-8/8/07	Bin mass/leachate volume at 0hr, 1hr, 6hr, 12hr, 24hr, 36hr, 48hr, 60hr, 72hr	1.27 cm irrigation event (16 min)
Week 6	9/5/07-9/8/07	Bin mass/leachate volume at 0hr, 1hr, 6hr, 12hr, 24hr, 36hr, 48hr, 60hr, 72hr	1.27 cm irrigation event (16 min)
Week 12	10/17/07-10/20/07	Bin mass/leachate volume at 0hr, 1hr, 6hr, 12hr, 24hr, 36hr, 48hr, 60hr, 72hr	1.27 cm irrigation event (16 min)
Week 18	12/5/07-12/8/07	Bin mass/volume at 0hr, 1hr, 6hr, 12hr, 24hr, 36hr, 48hr, 60hr, 72hr	1.27 cm irrigation event (16 min)
Week 24	2/3/08-2/5/08	Bin mass/volume at 0hr, 1hr, 6hr, 12hr, 24hr, 36hr, 48hr, 60hr, 72hr	1.27 cm irrigation event (16 min)
Week 60	9/8/2008--Bare Media	Bin mass/volume at 0hr, 1hr, 6hr, 12hr, 24hr, 36hr, 48hr, 60hr, 72hr	2.54 cm irrigation event (32 min)

Criteria for Evaluating Growing Media for North Central Florida Green Roofs for Stormwater BMPs

The criteria by which the growing media are being evaluated in their selection as a growing medium for use on a green roof as a stormwater BMP in N. Central Florida are:

- Ability to support plant life
- Water Retention/Evaporation Rate
- Nutrient Release

The growing media were evaluated for their ability to support plants during establishment with irrigation and after the establishment period without irrigation, to test their potential to survive in a low maintenance setting. This chapter deals exclusively with the influence of growing media; plants; and plant-growing media combinations on water retention and water release characteristics in a green roof system.

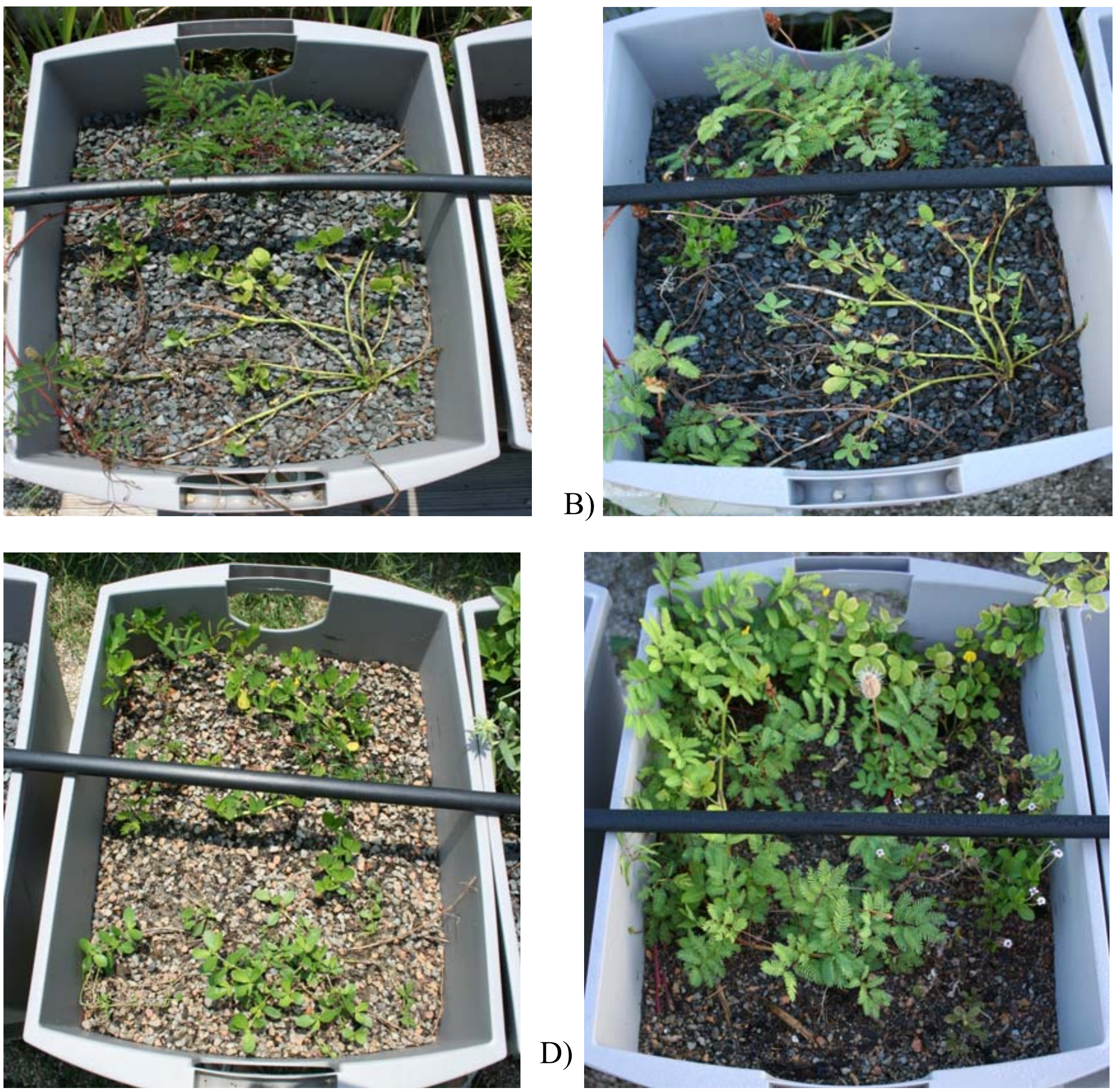
Criteria for Evaluating Plant Selection for North Central Florida Green Roofs for Stormwater BMPs

The 3 selections of plant mixes with different ET rates were evaluated for usefulness as plants for green roofs as a BMP for north central Florida on the basis of: a) survivability in FL climate on a green roof (low substrate, low water), b) growth rate and lateral coverage rate (time it takes to reach 60% coverage), c) water efficiency—water usage and evapotranspiration rates.

Plant health was assessed several times during the first six weeks and then regularly every six weeks. Plant health was measured by examining the plant, noting the succulence, rigor, greenness, condition of leaves, presence/absence of insects and diseases, and yellowing. A healthy thriving plant was given a 5 on a scale of 1-5. Thriving was defined as having green leaves fully intact (no holes, crumbling or yellowing), blooms when in season, noticeable biomass growth (evaluated with photos taken from the same distance every sampling period).

A plant in "good health" (Figure 2-7 B) but with little increase in biomass or less turgor was given a 4 on a scale of 1-5. Plants that were not affected by disease or had no yellowing on leaves, but had not grown much since the previous evaluation, were rated as having "fair health," and given a 3 (Figure 2-7 C). A plant in "poor health"—defined as presence of insects or partial yellowing of leaves was given a 2; a plant that was beginning to wither, but still alive was given a 1; and dead plants received a 0. The rating system was tested by three different people independently using photos and the same numbers were given to 39 of the 40 plants.

Lateral growth of the plant was determined by measuring percent coverage based on taking a photo from 1 m directly above the plant and analyzing the coverage on computer. Ideally, a healthy bin would end up with 33% coverage by each of the three species present and a plant health of 5 (thriving).



A) B) C) D)

Figure 2-8. Photos on the left shows plants after 2 weeks of growth compared to 5 weeks of growth; photos above (A and B) show runners planted in U, while photos below (C and D) show them in B growing medium.

The Plant Health Index (PHI) incorporated both the % coverage and plant health and was scaled to 1-100. A bin covered equally by species (33% coverage by each) and a plant health rating of 5 would receive a 35, therefore graphs demonstrating the PHI are shown on a scale of 1-35.

Statistical Analyses

Water retention was calculated by subtracting the volume of water that drained out from the volume of water in and dividing it by the total volumeIN, which was the total mm of rain and irrigation. Irrigation depth was calculated based on minutes of actual irrigation during the time period multiplied by the mean flow rate of the mister nozzle heads (280 mL/min +/- 10 mL).

Differences in water retention data among growing media types, then among plant types irrespective of growing media type, then and finally between time periods was analyzed using mixed models in GLIMMIX (in SAS 9.2 by SAS Institute). Differences were considered significant at the $p \leq 0.05$ level. Tukey's HSD tests were used to detect significant differences in water retention among plant types within each growing media type and time period.

Two types of water retention/release curves were created from the lysimeter experiment data. One curve showing water content in the bins calculated on a dry mass basis and a second graph showing the percent retention of $water_{IN}$ (which was normally 1.27 cm) during the lysimeter experiment. The water content was determined by subtracting out the dry mass of the bin and the dry biomass of the plants from the mass of the bin taken at a given time period, for example at Time = 12 weeks, the equation for this would be:

$$\theta_{kg} = \text{Mass of Bin}_{\text{12 weeks}} - \text{Dry Mass of Bin} - \text{Dry Biomass}$$

The percent of water applied retained was calculated for each time step that the mass of the bins was recorded between 0 and 72 hours and was plotted against time. To compare the characteristics of water retention and water release between growing media types and growing medium-plant combinations, the slope was calculated for the uptake side (initial water retention between time 0 and time 1 hr) and the slope on the release side, between time 1 hr and time 72 hr. The decrease in water in the growing medium between time 1 hr and 12 hr is attributed to plant uptake/evapotranspiration and drainage, while water loss after drainage stops is attributed solely to plant uptake/evapotranspiration. At some point the water release curve decreases below the original water content, at this point the water loss is attributed to the effect of the plant in the growing medium versus the medium alone.

Results I—Water Retention

Characterization of rainfall and irrigation

The six week establishment period of the green roof bins began on July 23, 2007 and ended September 3, 2007, total rain and irrigation per 6-week time period is shown in Figure 2-8. During this time period the bins were irrigated regularly following the irrigation regime in Appendix A. Rainfall occurred on 21 different days during the 43 day establishment period, and on 22 of the days there was no rain. Precipitation events ranged from 0.25 mm to 72 mm of rain per day. The total amount of rainfall for this period was 286 mm, which represents 20% of the mean annual precipitation for Gainesville, FL (NOAA 2007).

The distribution of the rainfall was uneven. The number of dry days between storms ranged from 1 day to 9 days. The number of consecutive days in a row with rain ranged from 1 to 5 days. Rainfall per day ranged from a minimum of 0.25 mm to a maximum of 72 mm. The 4 days with the highest amount of precipitation (72 mm, 61 mm, 38 mm and 24 mm) accounted for 70% of the total rainfall for the whole period, while the other 17 days of rain (80% of the rainy days) accounted for 30% of the total rainfall. This pattern of 20 - 30% of the days of rain accounting for 70 - 80% of the rainfall for a whole year is seen in many parts of the US and world (e.g. Boston, Seattle, Florida), for which reason Low Impact Development techniques and urban stormwater BMPs usually focus on capturing the small events (< 2.54 cm) as these represent the majority of precipitation events in a year (France 2002, Urbonas et al. 2002). The average pan evaporation rates for May, June, July, August and September are 132 mm mo-1 (Irmak 2002).

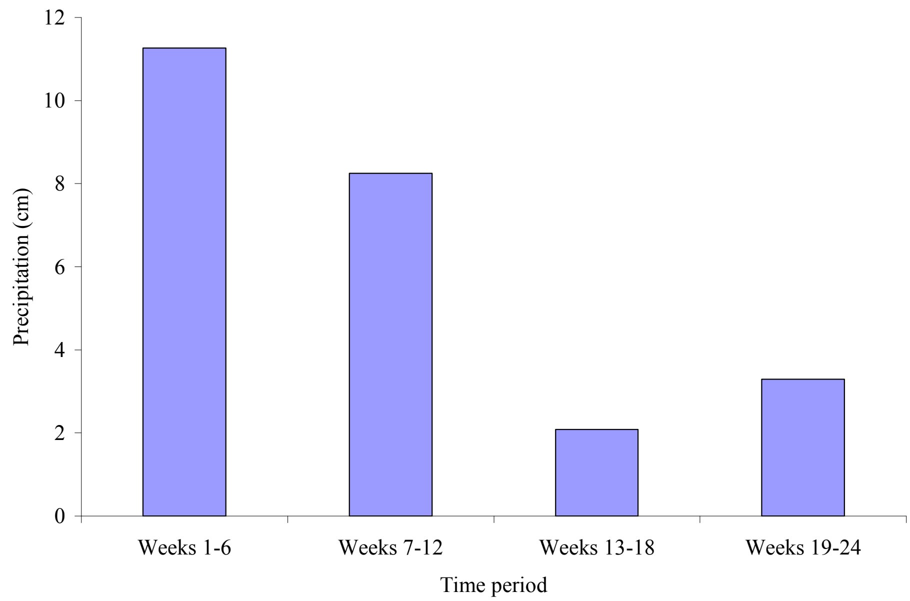


Figure 2-8. Precipitation/irrigation for the four different 6-week time periods (7/23/07 - 1/18/08).

Water retention

Water retention in the individual bins ranged from a minimum of 14% to a maximum of 96% (Figure 2-9) for the various 6-week time periods over the 6 month study period. When comparing mean water retention among growing media types, irrespective of time periods or plant type, Building Logics growing medium had significantly lower overall mean water retention (32% ± 1.4%) than Hydrotech's LiteTop® Intensive and UCF's Black and Gold™ (47% ± 1.4% and 52% ± 1.4%) growing media respectively (Figure 2-10) (at an $\alpha = 0.05$, $p < 0.0001$ level, using a generalized linear mixed model GLIMMIX in SAS 9.2).

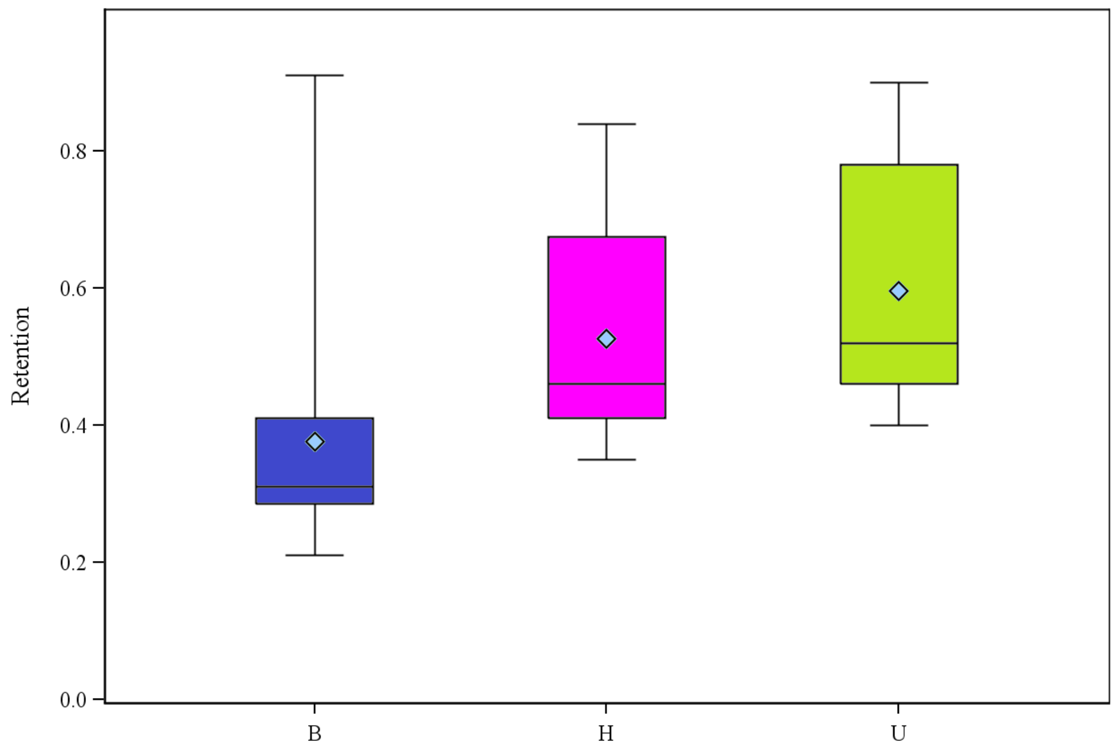


Figure 2-9. Box plot distribution of water retention for Building Logics (B), Hydrotech (H), and UCF (U) growing media for all weeks combined and all plant types included (box indicates the interquartile range, horizontal line indicates median and diamond shows mean and whiskers the range).

The water retention data for each bin for three time periods (Weeks 1-6, Weeks 13-18 and Weeks 19-24) were entered into PROC GLIMMIX in SAS 9.2 and analyzed in a generalized linear mixed model using an AR(1) structure subject to bin (model parameters are in Appendix D), with water retention as the response variable and growing media and plant types and time as factors (see Table 2-5). (Note that the time period for Weeks 7-12 was not used because overflow occurred in the buckets during that time period.) There was a significant effect of growing media, plant type and time on water retention, however there were no significant interactive effects on water retention due to growing media-plant type ($p = 0.3967$) (Table 2-5).

Table 2-5. Results of the type III tests of fixed effects for the PROC GLIMMIX model for water retention data for all bins over 24 weeks.

Effect	Num	Den	F	Pr>F
G_media	2	24	118.7	<.0001
P_type	3	24	12.9	<.0001
G_media*P_type	6	24	1.09	0.3967
Week	1	70	518.02	<.0001
Week*week	1	70	497.42	<.0001

Since the effect of time on water retention was significant, two-way ANOVA analyses of growing media and plant type were carried out for each six week period separately using PROC GLM in SAS 9.2. Table 2-6 shows the p-values of these processes and how the p-values of growing media and plant type and growing medium-plant combination change over time.

Table 2-6. P-values for 2-way ANOVAs of water retention by growing media and plant type and growing media-plant type interactions for three 6-week periods (analyses performed in PROC GLM in SAS 9.2; model fit, F-values shown in Appendix D).

	1-6 weeks	13-18 weeks	19-24 weeks
Growing media	<.0001	<.0001	<.0001
Plant type	<.0001	.7951	0.0016
G*P combination	0.0385	.0003	0.1607

The water retention values among growing media types were significantly different from each other in all time periods ($p < 0.0001$, using PROC GLM to perform ANOVAs by time period at an $\alpha = 0.05$ level), Table 2-6. Mean water retention values by growing medium type are shown for each 6 week period in Table 2-7. The basic pattern of Building Logics having less retention and Hydrotech and UCF having comparable retention rates was exhibited over all time periods (Table 2-7). The percent of retention in the different media fluctuated over time. These fluctuations are attributed to changes in the actual inputs of water from rain and irrigation, as there was a weak negative correlation between the amount of water input and the amount of water retention (Pearson Correlation coefficient of -0.41, with $p < 0.0001$, $n = 108$), the same pattern was seen in Moran (2005). For example, in time periods with lower rainfall, such as weeks 13-18 where only 20 mm fell, proportionally more water was retained (57% retention for B), than in a time period with less rain, such as weeks 19-24 (with 38 mm of rainfall), where only 28% was retained for B, even though the absolute amounts of water retained in the two time periods was the same.

Table 2-7. Mean water retention (%) and standard error for each growing media type for each time period (results of a generalized linear mixed model in GLIMMIX, SAS 9.2. Levels not connected by a letter denote significant differences at a $p < 0.005$ level, within time periods.

	Weeks 1-6 Mean ± SE		Weeks 13-18 Mean ± SE		Weeks 19-24 Mean ± SE	
B	27.8 ± 1.3%	a	57 ± 1.3%	a	28.2 ± 1.3%	a
H	42.7 ± 1.3%	b	71.9 ± 1.3%	b	43.1 ± 1.3%	b
U	49.7 ± 1.3%	c	78.9 ± 1.3%	c	50.1 ± 1.3%	c

Effect of plant type on water retention irrespective of growing medium type

The presence of plants augmented water retention, irrespective of growing media type, significantly ($p < 0.005$) in all three time periods (Table 2-8). Bins containing bare media showed significantly lower water retention than bins containing vegetation, irrespective of growing media type ($p < 0.001$, $\alpha = 0.05$, GLIMMIX in SAS 9.2).

Table 2-8. Mean water retention (%) by plant type (irrespective of growing medium type) for each time period; results of a generalized linear mixed model in GLIMMIX, SAS 9.2. Levels not connected by the same letter within a time period, denote significant differences within that time period only at the $p<0.005$ level, among plant types. (Weeks 7-12 overflowed).

Plant Type	Weeks 1-6 Mean ± SE		Weeks 13-18 Mean ± SE		Weeks 19-24 Mean ± SE	
m	33 ± 1.4%	a	63.1 ± 1.4 %	a	34.3± 1.4 %	a
p	43.2 ± 1.4%	b	72.5± 1.4 %	b	43.6± 1.4 %	b
r	42.7 ± 1.4%	b	71.9± 1.4 %	b	43.0± 1.4 %	b
s	40.5 ± 1.4 %	b	69.7± 1.4 %	b	40.9± 1.4 %	b

Interactive effects of plant-growing medium combinations on water retention over time

Tukey’s test, a more conservative method to detect significant differences among means, was implemented to determine the interactive effects of plant type-growing media type on water retention within each time step (Figure 2-10). Differences between plant-growing media combinations were determined using the mean of each of the 12 plant-growing medium combinations and a pooled variance, resulting in lower type I error (less probability of the test detecting a significant difference, when in actuality there is not). This section analyzes the data in a way that shows the least amount of significant differences of any other analyses used and discusses how plant-growing media combinations affected water retention over time. In this section, "significant difference" refers to a difference between means of two growing medium-plant combinations that is significantly greater than a predicted value determined by Tukey's test at a $p < 0.05$ level. Abbreviations used are U for UCF, B for Building Logics, H for Hydrotech and p for perennial, r for runners, s for succulents and m for bare media and these letters are used in combinations (for example Hp or Br or Us) to represent the individual growing medium-plant combinations. The results in this section all refer to Figure 2-10.

In weeks 1-6: UCF bins planted with perennials had significantly higher retention (Tukey's test between means, $p< 0.05$), than any other growing media-plant combination (Figure 2-10); and Bm (Building Logics bare growing media) had the lowest retention among all plant-growing media combinations. In weeks 1-6, perennials also had a positive effect on retention in B and H media, with significantly higher water retention ($p <0.05$, Tukey's test) than those bins containing bare media. However no significant differences in retention were found among the three plant types (perennials, runners and succulents) in B or H growing medium (Figure 2-10).

Nor was retention in bins planted with runners or succulents significantly different from bins containing bare media in either B or U (Figure 2-10), only in H growing media did bins planted with runners have significantly higher retention than those with bare media. Bp was not significantly different from H and U bins planted with succulents or left bare, but had significantly less retention that H and U bins planted with perennials or runners.

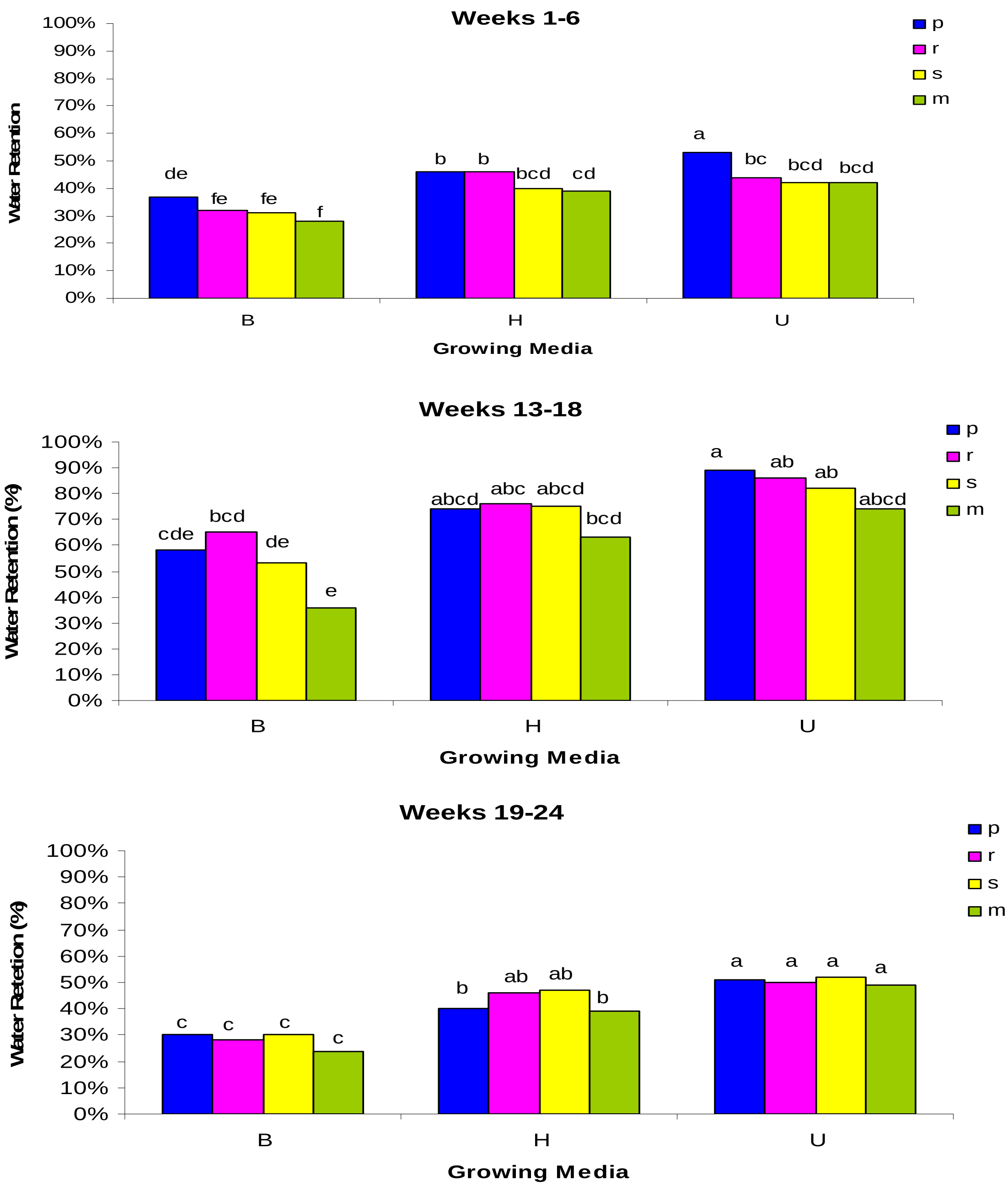


Figure 2-10. Differences in water retention among growing medium-plant type combinations for three of the 6-week time periods. Levels not connected by the same letter signify significant differences in retention based on Tukey's test at an $\alpha = 0.05$ level using PROC GLM in SAS 9.2.

In weeks 13-18: Perennials planted in U growing medium again had the highest retention value of all plant-growing media combinations and Bm had the lowest retention values. However in this time period, Up was only significantly higher ($p < 0.05$, Tukey's test) than Hm (bare media in Hydrotech) and all B bins; Up was not significantly higher than other plant types in U growing media, nor bare U medium. Among bins containing B medium, Br had the highest retention in this time step (versus those planted with perennials as seen in the previous time step). Br was significantly higher than B bare media, but not significantly different from the other plant types within B. By weeks 13-18 differences in retention among all plant-growing media combinations was lessening, in fact, retention exhibited by Br was not significantly different from any H bins, nor from U bins planted with runners or succulents or left bare, Br was only significantly lower than Up.

In weeks 19-24: U bins again had the highest retention values and B bins had the lowest, but there were no longer any significant differences in retention among plant types and/or with bare media within any of the growing media types (Figure 2-10). Retention of B bins was significantly less than that of H bins or U bins. There were few significant differences in retention between H bins and U bins. H bins planted with runners or succulents were not significantly different from any of the U bins; only retention in H bins planted with perennials or left bare were significantly lower than all types of U bins.

Effect of plant type on water retention within growing media --all time periods combined

The results of PROC GLM within each growing media type, when all time periods were combined, showed that perennials had a positive effect on retention. Within Building Logics growing media, bins planted with perennials exhibited significantly higher retention rates (38% ± 2% over all time periods combined) as compared bare media (27.5 %) ($p = 0.0003$), as well as compared to runners (32% ± 2%) and succulents (32% ± 1.9%) to a lesser degree ($p = 0.029$ and p = 0.031, respectively). Table 2-9 shows the significant differences in retention among plant types within Building Logics growing media for all time periods.

Table 2-9. Results of PROC GLM comparing effect of plant type on retention within each growing medium for all time periods combined. Levels not connected by the same letter (within a growing medium type) are not significantly different.

Plant Type	Sig. Diff.		B (Mean ± SE)
p	a		38% ± 2%
r		b	32% ± 2%
s		b	32% ± 2%
m		b	28% ± 2%
Plant Type			H (Mean± SE)
p	a	b	50% ± 2.8%
r	a		52% ± 2.8%
s	a	b	46% ± 2.8%
m		b	42% ± 2.8%
Plant Type			U (Mean ± SE)
p	a		60% ± 3%
r	a	b	51% ± 3%
s		b	49% ± 3%
m		b	47% ± 3%

Within Hydrotech growing media, bins planted with perennials (50% ± 2.8%) or runners (52% ± 2.8%) had significantly more retention for all time periods combined than bare media (42% ± 2%) to a $p < 0.05$ level. There were no significant differences in retention among runners, succulents and perennials within Hydrotech growing media.

Within UCF's Black and Gold growing media type, bins planted with perennials exhibited significantly higher water retention rates than either succulents or bare media. Bins planted with runners in this media type only had significantly higher retention rates than bare media ($p < 0.05$). UCF bins planted with perennials had the highest mean retention over all time periods combined (60% ± 3.3%), followed by U bins planted with runners (51% ± 3.3%), then succulents (49% ± 3%) and lastly bare media (47% ± 3%).

The analysis of water retention for all time periods combined shows that bins planted with perennials had significantly higher water retention than those planted with runners, succulents and bare media in B medium (Table 2-9); perennials had significantly higher water retention than those planted with succulents and bare media in H medium; and perennials only had significantly higher water retention than bare media in U medium.

Effect of plant type on water retention irrespective of growing medium type

The overall mean retention of bare growing media, irrespective of type of media, was 43%, the extra retention of the green roof bin attributed to plant type, irrespective of growing media is shown in Figure 2-11. Perennials, on average for all time periods combined, increased water retention by 9.6 ± 0.5% above having just bare media. Runners increased water retention by 9.1 ± 0.5% and succulents increased water retention on average by 6.9 ± 0.5%.

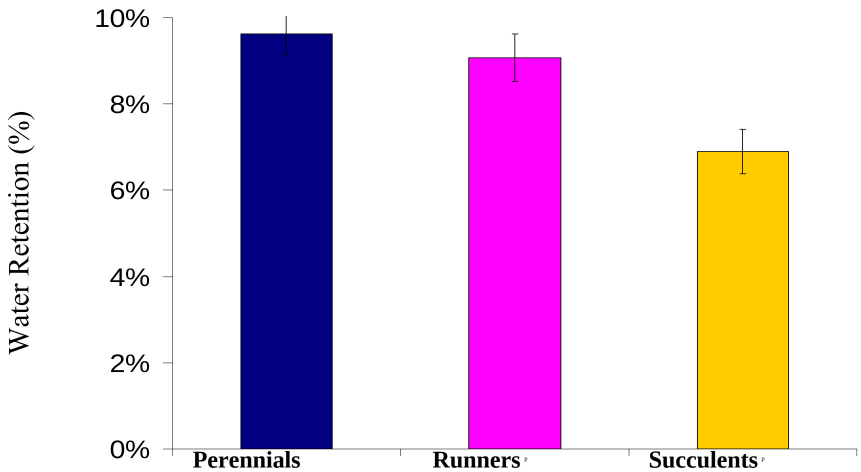


Figure 2-11. Amount of increase of water retention by plant-growing medium type attributed solely to plant type, irrespective of g-m type or time period.

Results II-Water Release Curves

Changes in Mass and Water Content over the Six Month Study Period

The three different growing media followed similar general patterns of changes in absolute mass and water content in the green roof bins irrespective of growing media type (Figure 2-12 and 2-13). In general, water content decreased sharply during the summer months (July-beginning of October) when ET was respectively higher than the rest of the study period; and water content increased over the winter months (between October and February), when ET was lower. The increase in water content in the cooler season are attributed to changes in ET, a decrease in plant growth and increase in plant senescence (Figure 2-13).

Viewing water content and mass together (Figures 2-12 and 2-13), one can see that while U and H have the similar water content levels at all time periods ($p < 0.05$ t-test SAS 9.2), the absolute mass of the media is significantly different at each time period, except 9/5/07, with U being significantly lighter ($p< 0.05$, t-test, SAS 9.2) than H. The importance of the absolute mass of the medium from a green roof design standpoint, relates to the cost implications involved in the building design with respect to the implied increased load bearing capacity of the roof for a heavier medium.

UCF's Black and Gold medium and Hydrotech's Lite Top mix showed more overall fluctuation in water content over the study period than Building Logics, ranging from 0.17 - 0.33 for H and 0.21 - 0.35 for U, while water content in B fluctuated less (0.12 - 0.18), had a narrower range of values, and lower mean water content at all time periods irrespective of plant types (Figure 2-12). The fluctuation in the mass of bins is attributed to changes in: a) water uptake in plants, as well as, b) biomass growth and c) water storage in the porous medium of the green roof system over different periods of the year.

Effect of Plant Type on Water Content by Growing Media Type over Six Months

Figures 2-14, 2-15 and 2-16, show the changes in water content within each growing medium due to plant types; water content was isolated by subtracting out the mass of the dry biomass mass of the bin as well as the dry mass of the soil. Between weeks 1 and 6, the difference in water content between plant types within a growing media type increased (Figure 2-14, 15 and 16).

For example, by Week 6, the water content of bins planted with perennial plants were significantly lower than those planted with succulents or contained bare media, in all growing media types, due to a successive loss in soil moisture, caused by the higher rate of ET of the plant type.

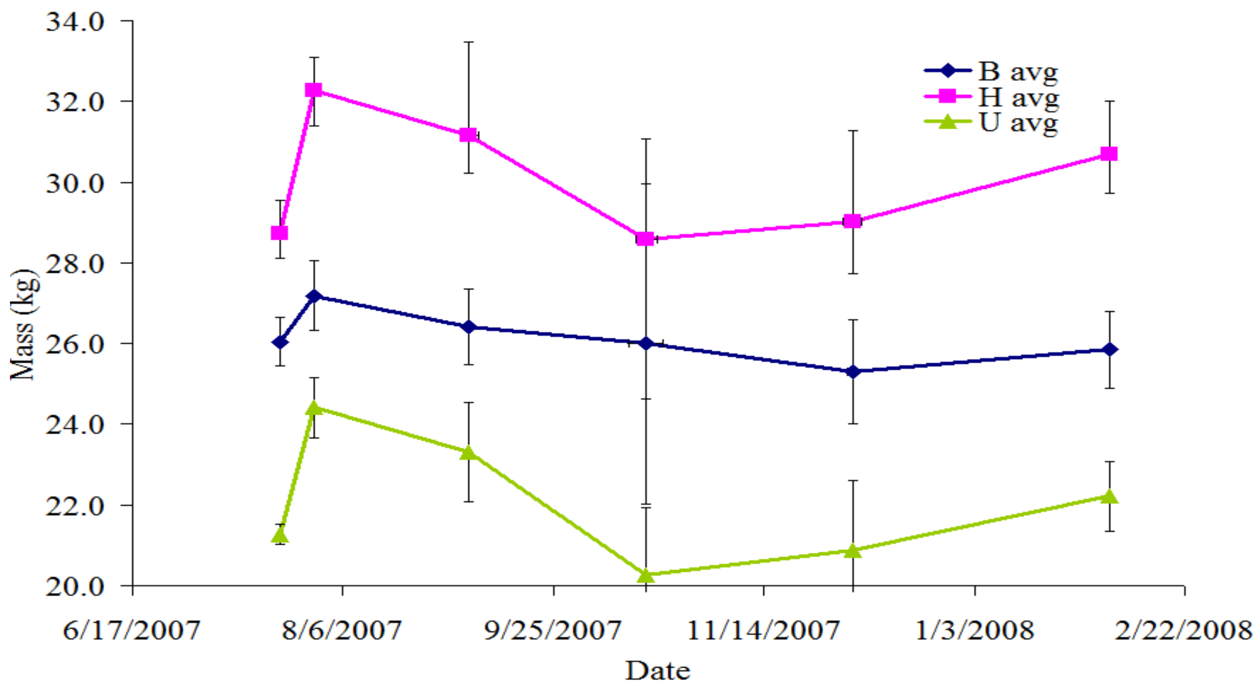


Figure 2-12. Mean change in mass of bins for Hydrotech (upper line), Building Logics (middle line) and UCF (lower line) over 6 month study period.

Plant growth for all plant types at week 6 was characterized by 20-30% coverage by individual species in both plant types and no senescence had occurred. In H growing media, the water content of bins planted with runners was also significantly lower than those planted with succulents or bare media (Figure 2-15).

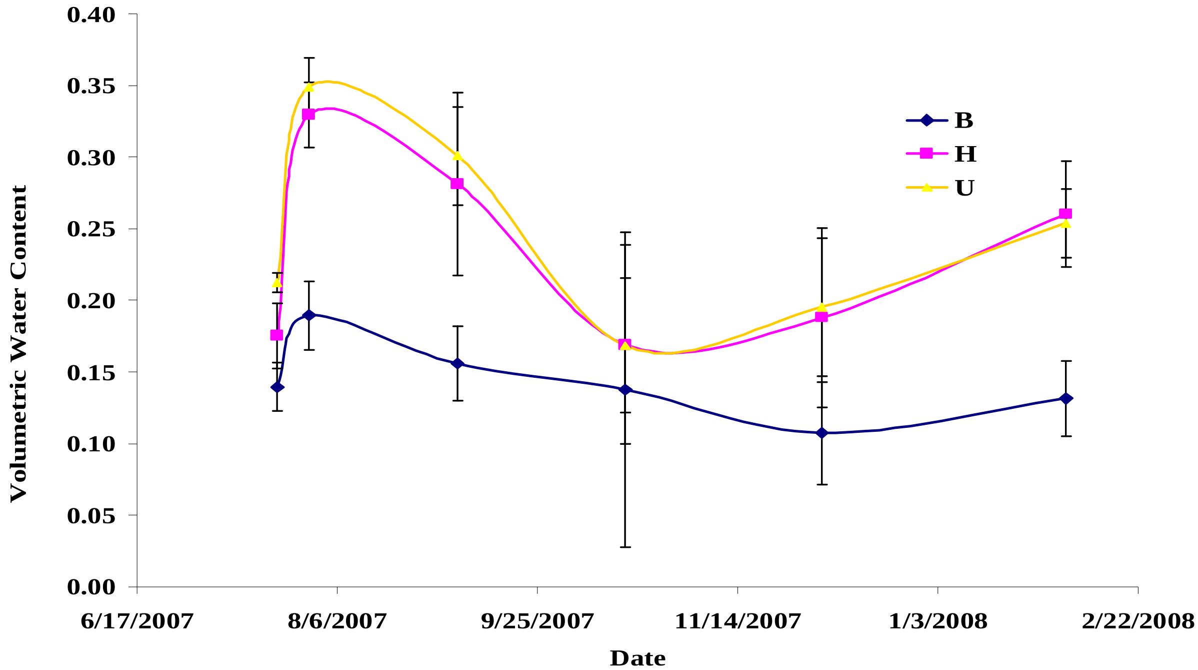


Figure 2-13. Mean change in volumetric water content in bins containing Building Logics (B), Hydrotech (H), and UCF (U) growing media over 6 months. Comparing this water content graph in Figure 2-12, of absolute mass of the bins, one can see that despite an average 8 kg difference in mass per bin between U and H bins, the water content at each point in time is similar between U and H.

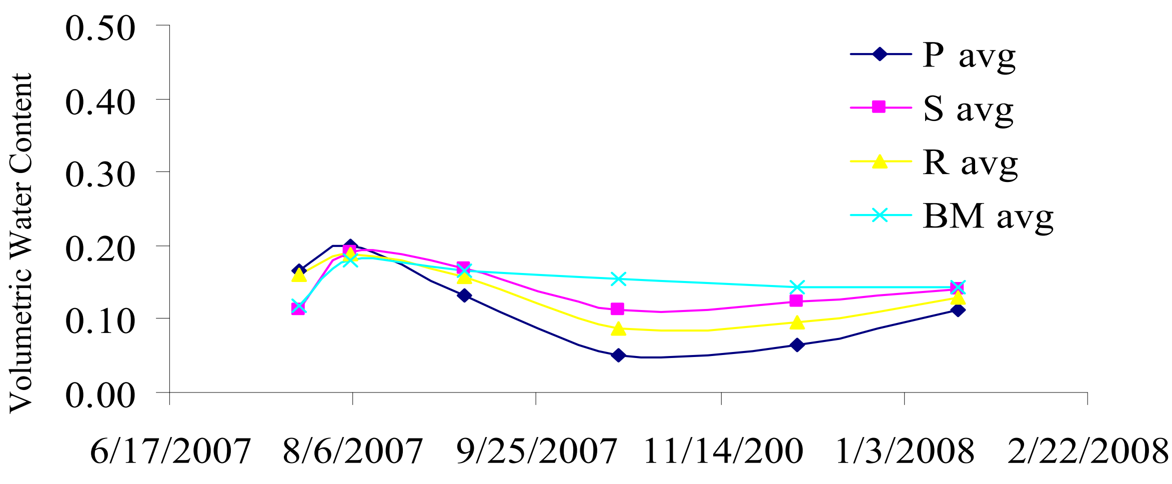


Figure 2-14. Effect of plant type on water content in Building Logics' growing medium over six months.

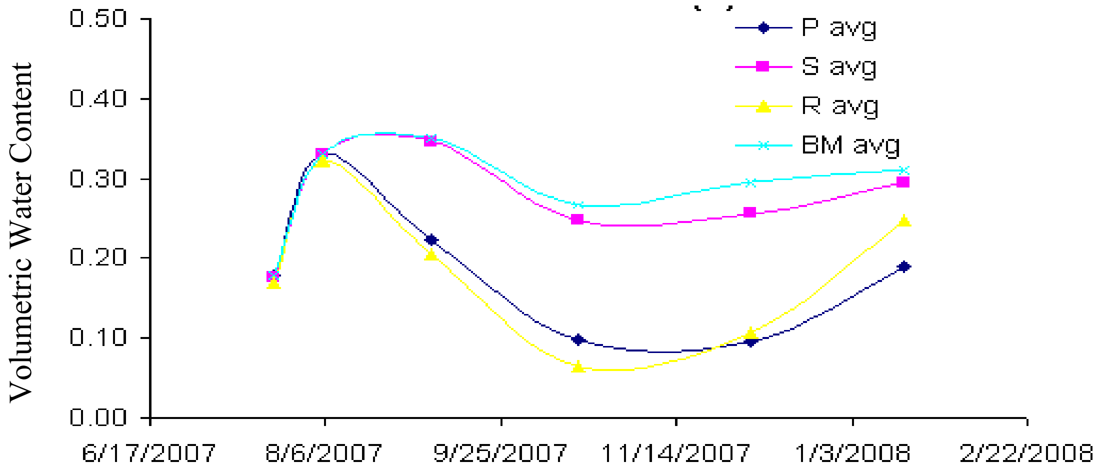


Figure 2-15. Effect of plant type on water content in Hydrotech's growing medium over 6 months.

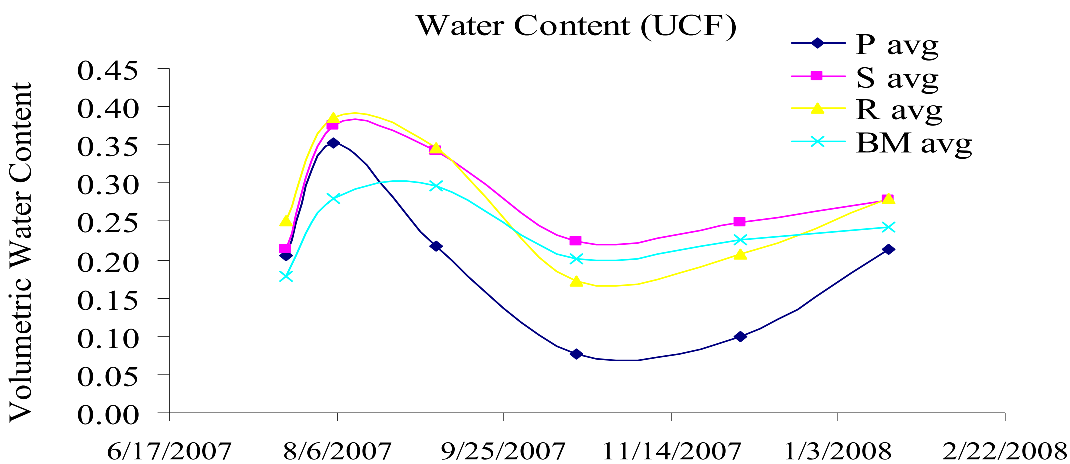


Figure 2-16. Effect of plant type on water content in UCF's Black and Gold growing medium.

Effect of Growing Media Type on Water Uptake and Release Directly after Irrigation

Water uptake and release was measured via the lysimetric method. Water content and % retention directly after irrigation with 1.27 cm was measured by weighing the bins before, 1 hr , 6 hrs, 12 hrs, 24 hrs, 36 hrs, 48 hrs and 72 hours after irrigation. The results were 12 water content graphs for each of the growing medium-plant combinations (Appendix E) and 12 graphs of change in % water retention over time (Appendix E). The water content graphs for the growing media in Week 6, the end of the establishment period, are shown below in Figure 2-17, as an example of water content curves for the other time periods, which are in Appendix E.

Water contents curves highlighting the effect of plant type on growing medium type, are shown later in the "Effect of plant type on water uptake and release" section of this chapter, in Figures 2-20, 21 and 22. To visually better compare the absolute differences in water uptake and release among the growing media types and plant types within the growing media types, the amount of change in water content per time step was plotted against time. In this manner, the change in water content for each growing medium, can be viewed superimposed and normalizes the initial water content of the plant-growing medium combination for the start of each lysimeter experiment (Figure 2-18). The process of normalizing the data by plotting amount of change in volumetric water content against time (number of hours post-irrigation) made it possible to visually compare the effect of plants on change in water content over time within growing medium types, as well, (shown later in Figures 4-23, 24, and 25.) To numerically compare differences in rates among the various plant-growing medium combinations, the amount of change of water content per time step was then divided by the hours in the time step to yield the rate of uptake in change in water content per hour after irrigation, and the rate of release was calculated as the change in volumetric water content per hour for the descending limb of the water content curves.

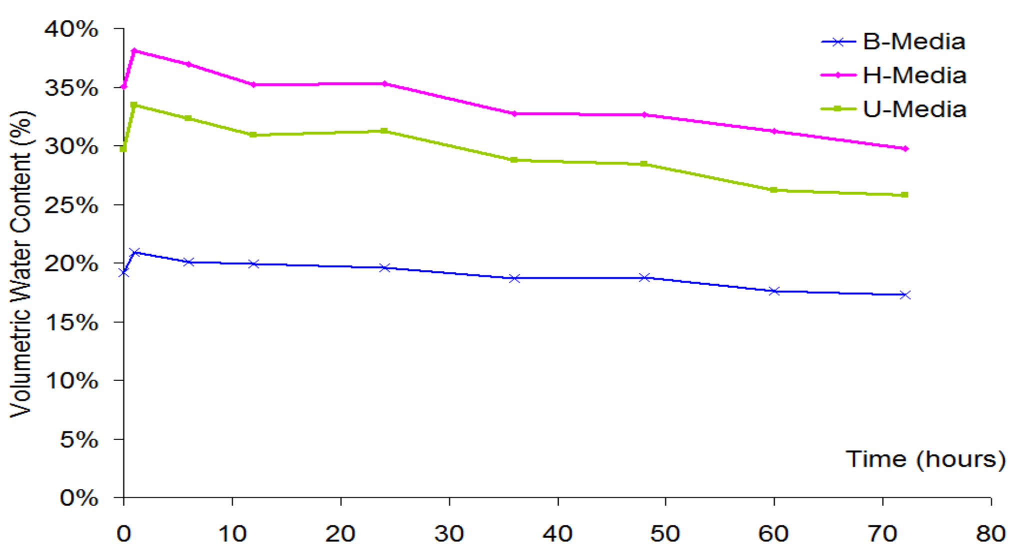


Figure 2-17. Water content curves for the three growing media (B, H, U) over 72 hours post irrigation at the end of Week 6.

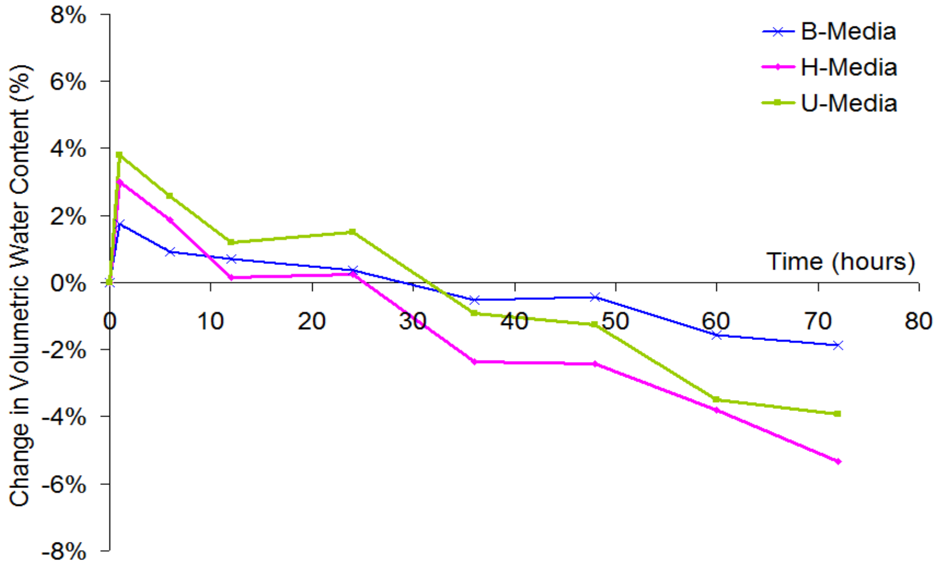


Figure 2-18. Comparison of change in volumetric water content over 72 hours among three growing media types (B, H, U) with no vegetation in response to 1.27 cm (½") irrigation during week 6 of the study (9/5/07-9/8/07).

The same analytical process was used to calculate the water uptake and release rates for all the other weeks as well (Weeks 12, 18 and 24) for all plant-growing medium combinations. The mean water uptake and release rates for the growing media are reported in a table in Appendix G, and shown below in Figure 2-18. (Uptake and release rates for the plant-growing media combinations for the different weeks are also reported in Appendix G, and discussed in the "plant effect" section of the chapter). The uptake and release rates were analyzed in a generalized mixed linear model in SAS to identify whether there were significant differences in water uptake among the growing media and among all plant-growing medium combinations, within time periods(in Appendix G).

The water content in the bins containing UCF's growing medium increased most quickly after irrigation and also decreased the most quickly as the bins dried out for 72 hours after irrigation, in four of the five time periods (Figure 2-22 and 2-25—Week 6, and Appendix E—

Weeks 12, 18 and 24). The rate of uptake of water in the first hour after irrigation was significantly greater in UCF growing medium than in Hydrotech or Building Logics growing medium in Weeks 12, 18 and 24 (Appendix G). In week 6 there were no significant differences between U and H. Hydrotech growing medium also had a quicker rate of uptake than BL in every time period (Figure 2-19).

The differences in water retention among the growing media are attributed to the differences in pore size distribution and organic matter content among the media, with media with finer pores and greater OM content taking up more water after irrigation at a greater rate, also noted in Getter (2007) in Wolf and Lundholm (2006). Wolf and Lundholm (2006) noticed in their study of water uptake by different plant forms under varying watering regimes, that the plants (under the driest regime) had greater uptake of water than the controls. They assumed that both the planted and unplanted pots had been taking up the same amount of water after irrigation, as they would weigh their plants after it reached field capacity (drainage stopped). They were surprised that planted microcosms lost more water than unplanted ones and stated that

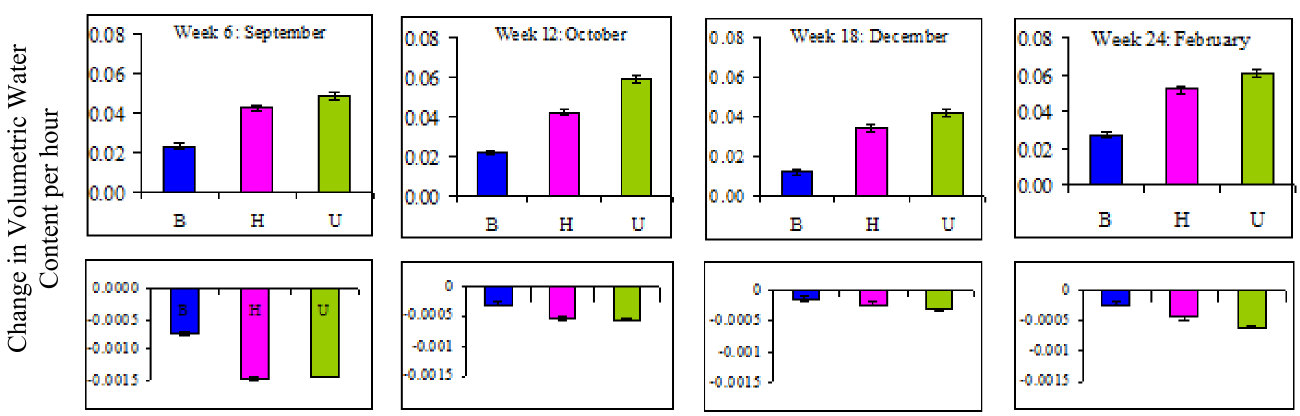


Figure 2-19. Top row shows rate of water uptake as increase of % of volumetric water content per hour for Weeks 6, 12, 18 and 24 (September 5-8, October 18-20, December 5-8 and February 2-4). Bottom row shows the rate of water release from the mesocosms as % volumetric water content per hour on the y-axis. The x-axis indicates growing medium type.

their finding “may indicate that planted microcosms actually retained more water immediately after watering.” In my study, I found that the planted mesocosms in the beginning of the study (Week 6) did indeed retain more water than unplanted ones directly after watering (Figures 2-20, 21 and 22). Furthermore, variability in the amount of water uptake between plant types, seemed to be influenced by the plant physiology, water content at the time of watering, and season. I propose that one reason the uptake of water was greater in planted mesocosms relates to increases in organic matter content due to belowground growth of plants and changes in porosity due to the increased OM content in the medium (Getter et al, 2007; Wolf and Lundholm, 2008).

The initial water content of the soil at the time of irrigation played a role in the water uptake rate, regardless of the season. For example, the water content was similar in two different seasons (Week 6-late summer and Week 24-early spring), with a value of approximately 0.20, the respective rates of water uptake for the same mesocosms (UCF and H planted with Perennials) were also similar for those weeks. Additionally, the water uptake rate was greater when the water content started out at this level (0.20) then when the soil was very dry. Such as in weeks 12 and 18, where the water content in the growing media was about half that (0.1) for both UCF and H for perennial plants, but the water uptake rate was significantly lower. It may seem intuitive that when the soil is the most dry (has the lowest water content, it would absorb the most amount of water most quickly), however this was not the case in this study. The reduced uptake of water seen in October and December may be due to reduced plant health or growth or season. For example, late summer plants and early spring, the plant-combinations are taking up water and utilizing it, while in late October and early December, the plants are starting to use less water and are not putting any of the water into biomass production and unhealthy plants are not able to remove as much water through transpiration as viable late summer plants, or new spring growth plants.

Effect of Plant Type on Water Uptake/Release Characteristics

The effect of plant type on the water retention and water release characteristics of the growing medium was most obvious in week six (Figures 2-20, 21 and 22), where it was evident that bins planted with perennials and runners were uptaking water a quicker rate than those planted with succulents or were left bare. Furthermore, the accumulated potential water loss grew over time, creating a wider spread between the water release curves of bins planted with perennials at the end of the study than in the beginning. Consecutively over time, the perennial bin dried out more, so at the beginning of each lysimeter experiment the water content of the bin was less than the previous time.

The greatest amount of retention and overall re-release of water over time is visible in the bins planted with perennials and runners. Leaching occurred up to 12 hours in both soils, after which all decreases in mass are attributed to evaporation, and transpiration. Bins planted with succulents and bare media had similar retention and release patterns in both growing media types. No significant differences in amount retained or total amount released was detected between succulents and bare media (Table in Appendix G).

Perennials growing in UCF's Black and Gold took up water the quickest after irrigation, as well as released the most amount of water within 72 hours post-irrigation (Figure 2-26).The increased uptake of water in the Up plant-growing medium combination was attributed to the physiology of perennial plants with their high quantity of medium fine roots (see photo in Figure 2-35) relative to the two other plant types tested in this study (runners and succulents) (Figure 2-35), coupled with their inability to close the stomata as in the case of succulents or fold their leaves closed such as leguminous runners are able to do, to prevent water loss, that makes them ideal for a finer grain size distribution growing medium with a higher water retention capacity. Paradoxically, the perennials ability to both take up water more quickly and release it more quickly and even release water to a water content lower than the content measured at the beginning of the 72 hr lysimeter experiment, resulted in a greater soil moisture deficiency over time. The sequential lowering of the water content of the soil containing perennials (as well as runners), irrespective of the soil type, widened the gap between the water content levels in the soils growing perennials and runners as compared to those with succulents and bare media (Appendix E), over time as the growing season advanced and then lessened as the growing season ended.

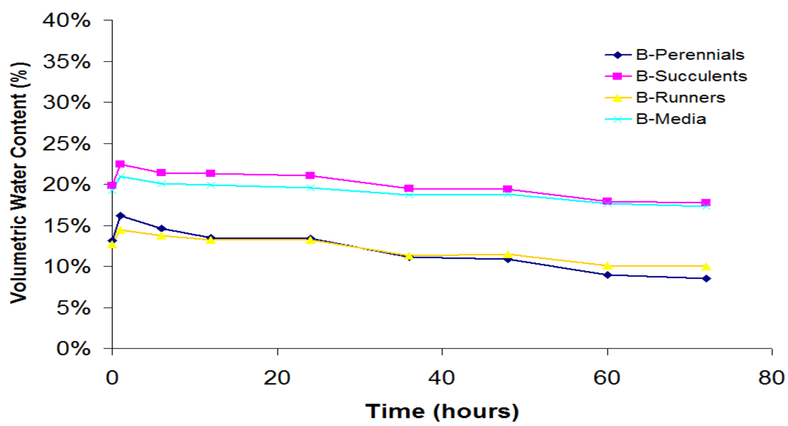


Figure 2-20. Volumetric Water Content (%) over 72 hours for 3 plant types and bare medium (p, s, r, m) within Building Logics growing medium for Week 6.

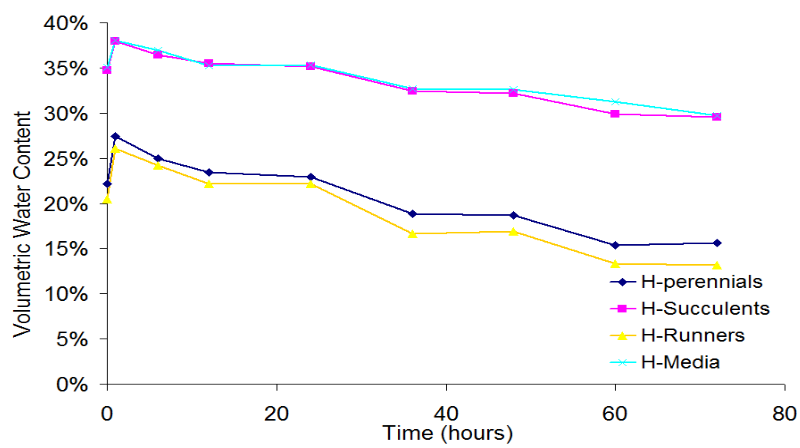


Figure 2-21. Change in Volumetric Water Content (%) over 72 hours for 3 plant types and bare medium (p, s, r, m) within Hydrotech growing medium for Week 6.

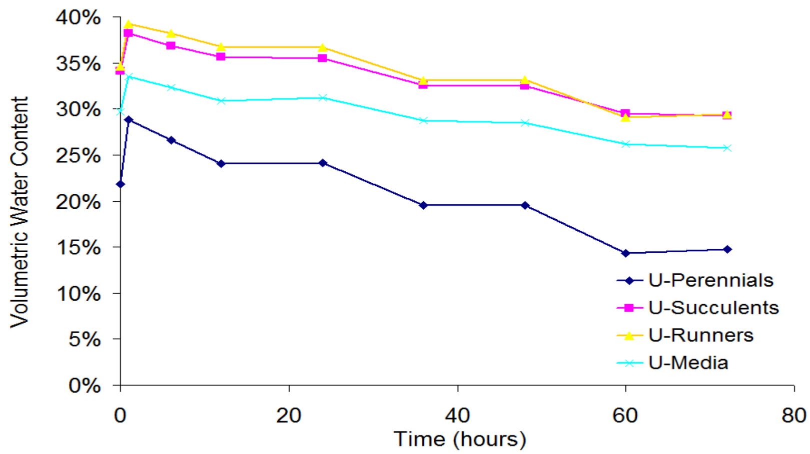


Figure 2-22. Volumetric Water Content (%) over 72 hours for 3 plant types and bare medium (p, s, r, m) within UCF growing medium for Week 6.

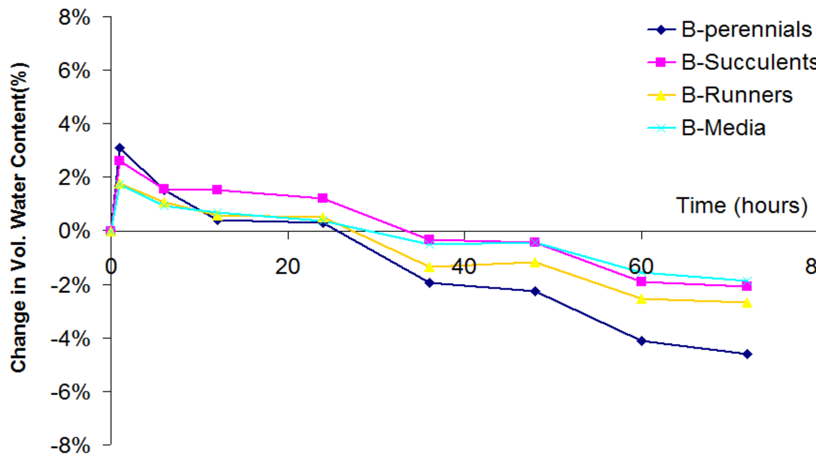


Figure 2-23. Change in Volumetric Water Content (%) over 72 hours for 3 plant types and bare medium (p, perennials; s, succulents; r, runners; and m, bare media) within Building Logics growing medium for Week 6.

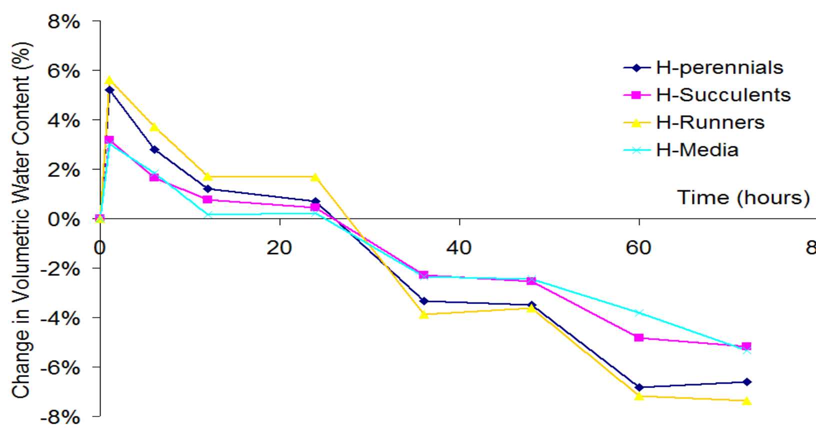


Figure 2-24. Change in Volumetric Water Content (%) over 72 hours for 3 plant types and bare medium (p, s, r, and m) within Hydrotech growing medium for Week 6.

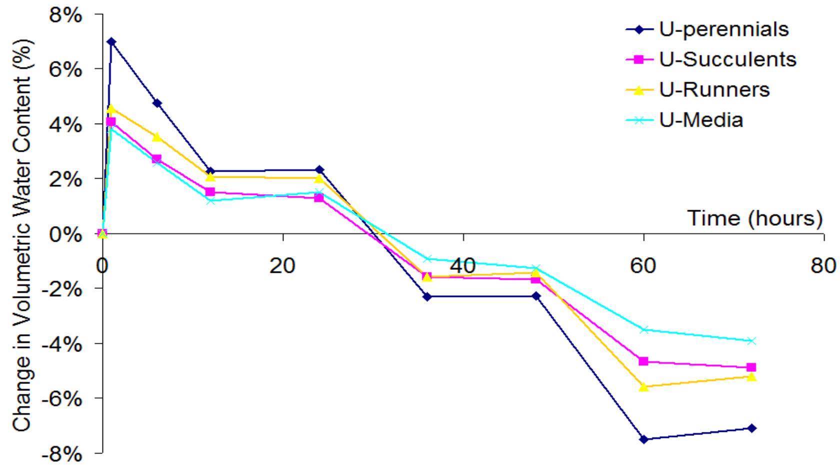


Figure 2-25. Change in Volumetric Water Content (%) over 72 hours for 3 plant types and bare medium (p, s, r, and m) within UCF growing medium for Week 6.

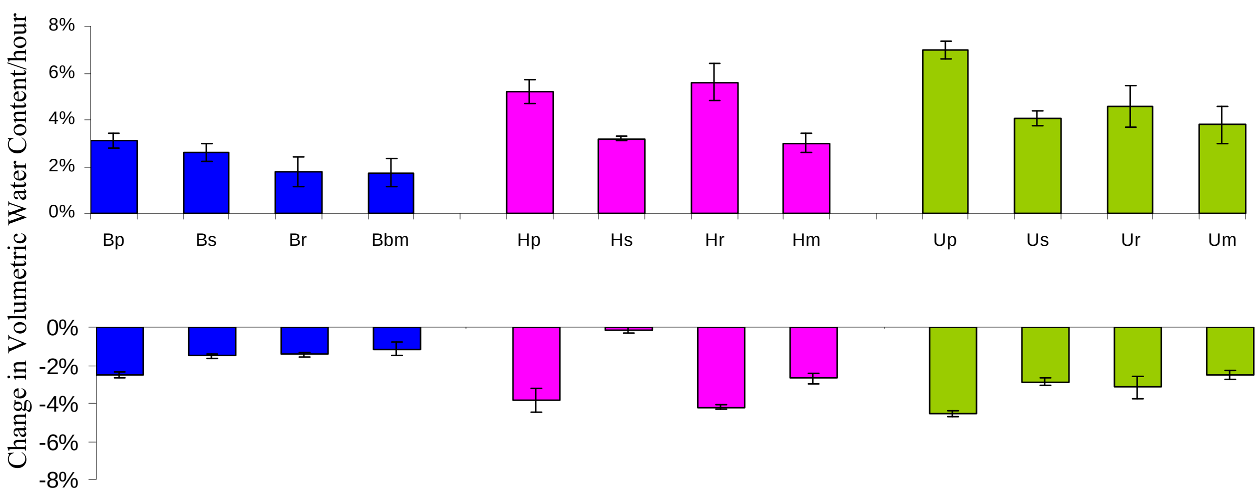


Figure 2-26. Mean rates of uptake and release (change in volumetric water content per hour) for each plant-growing medium combinations for lysimetric sampling week 6. Error bars show standard deviation. Mean rates of uptake and release for other weeks are in Appendix G. (B, Building Logics; H, Hydrotech; U, UCF; p, perennial; s, succulent; r, runner; and m, bare media.)

The difference in water content between plants containing perennials and those containing succulents or bare media was greatest in the Late Summer/Early Fall (weeks 12 and 18). The water content in these plant types was the least different at the beginning of the study, immediately after pre-moistening soils and planting them; and at the end of the study in the dry/winter season, characterized by low ET, and the presence of some dead plants. While the rapid uptake and release of water from perennials can be seen as advantageous to opening pore space up for water storage before the occurrence of a subsequent storm, this lowered water content in the soils growing the perennials (irrespective of plant type) jeopardizes the plants health by creating water stress on the plant due to the high accumulated potential water loss that plant-soil combination is experiencing and makes the plant susceptible to diseases—whether insects, root rot or other disease, that in optimum health would be less. For example, 2 weeks after irrigation ended (Week 8) the perennial plants had an infestation of insects, while other plant types did not. Perennial peanut suffered yellowing—which could have been due to a) low iron, b) high pH, c) improper inocculation of the soil with Rhizobium due to dislodging all soil from the roots during transplanting of the plant and a resultant N-deficiency in the plant (USDA-NRCS, 2009; Sartain personal communication, 2007).

Bins planted with succulents or no vegetation had the highest and least fluctuating amount of water content over the six month study period. Within the Building Logics growing medium type, there were no significant differences in water content planted with succulents as compared to those with no vegetation at any point in time during the study period. Nor were there any significant differences in water content between bins planted with runners and perennials within the Building Logics growing media (Figure 2-20). There were however significant differences in water content between both the perennials when compared to succulents or bare media and significant differences between runners and succulents or bare media at the end of the 6 week establishment period, and week 12 and week 18, but not week 24 (Appendix E). These differences were attributed to the greater capacity of runners and perennials to transpire than succulents. Durham et al. (2006) also noticed a higher water content in microcosms containing the succulent plant Sedum acre as well, and attributed it in part to a shading effect of thick-even coverage of Sedum acre, reducing the amount of evaporation from the soil itself by reducing the surface temperature of the soil (in Wolf and Lundholm, 2008.)

Growing media without plants had a higher water content because water stored in the lower part of the soil profile had no mechanism by which to leave the soil profile after leaching stopped other, than through evaporation and evaporation is controlled by pore size and continuity of the pores. This phenomenon of higher soil moisture in areas without vegetation has been well documented in watershed studies conducted in the Coweeta Watershed in North Carolina where whole catchments were deforested in order to increase soil moisture and baseflow to streams (Douglass and Swank, 1972). Media with smaller pores are able to evaporate over a longer period of time, because of the connectivity of the pores, however at some point the smaller pores hold on to the residual water more tightly, making this water unavailable to plants. The higher saturated water content and lower residual water content levels in finer soils yields a larger range of plant available water than that of a coarse soil (Brady and Weil, 2002), as was seen in the case of the coarser Building Logics growing medium—which had a lower water content in every season and smaller increases in water content during the 72 hour lysimeter experiments.

The differences in the steepness of the slope reflect the effect of plant type due to differences in ET rate among plant types, and uptake of water as these two factors control changes in water storage within the same media type. Perennials have the steepest slope or fastest decrease in mass over time The mass in all bins decrease sharply (have the steepest slope) between weeks 6 and 12 (September 5 and October 14), which corresponds to the time period directly after the six week establishment period when irrigation was suspended, immediately after which there were 9 consecutive days without precipitation. The distribution of the rain in time is an important factor in designing the irrigation regime for a green roof. The rainfall pattern for the second six weeks (Sept 5 to Oct 14, 2007), highlights how the distribution of the rain, not the total volume can be important, often more so than the total volume in deciding plant health or mortality. For example the total rain for this period was 60% above the 30 year average, yet the distribution of the rain in time, having nine days without rain consecutively be followed by six days for rain that contained 80% of the total rain of October, underscores the need to deal with uneven distribution of rain in time and the need for a either cistern or a soil moisture sensor to regulate irrigation on a green roof.

The UCF soil had the most change in soil moisture over the study period and was the least affected by plant type—i.e. had the lower variability of change in soil moisture among succulents, runners and bare media than Hydrotech. Also bins planted with succulents and runners had a higher water content than those containing bare media, which is similar to what was noticed in Wolf and Lundholm (2008) and Durham et al. (2006), where they attributed the higher water content of planted bins as compared to bare media to the surface cooling effect of the shading from vegetation and therefore reduced evaporation rates from the soil itself. In the UCF medium, the water content of bins planted with perennials was significantly less than any other plant type in Week 6 and always lower than succulents and bare media in all subsequent weeks as well.

The general trend of a steeply decreasing mass during the summer period and a sharp rise in mass that correlates to the period of year when ET rates decline (Irmak, 2002) was seen in all bins. The increase in mass during the cooler part of the year is attributed to an increase in soil moisture due to both the death of plants during the cool part of the year and the reduction of ET due to seasonal changes. Figures 2-27, 28 and 29 show how plant health changed by species over time. The absence of certain plant species starting in Weeks 13-18, corresponds to the increase of soil moisture and change in seasons to a cooler time of year shown in Figures 2-14, 15 and 16. The death/decline of the perennials at week 18, absence of one species of succulents (Portulaca) and the decline of runners by week 18, coupled with the season (declining ET due to lower relative humidity, less solar radiation and lower temperatures) may explain the stabilization of the mass and increase in mass due to increasing soil moisture for those dates coinciding with early winter (Week 18) and the subsequent rise in soil moisture throughout late winter/early spring (Week 24).

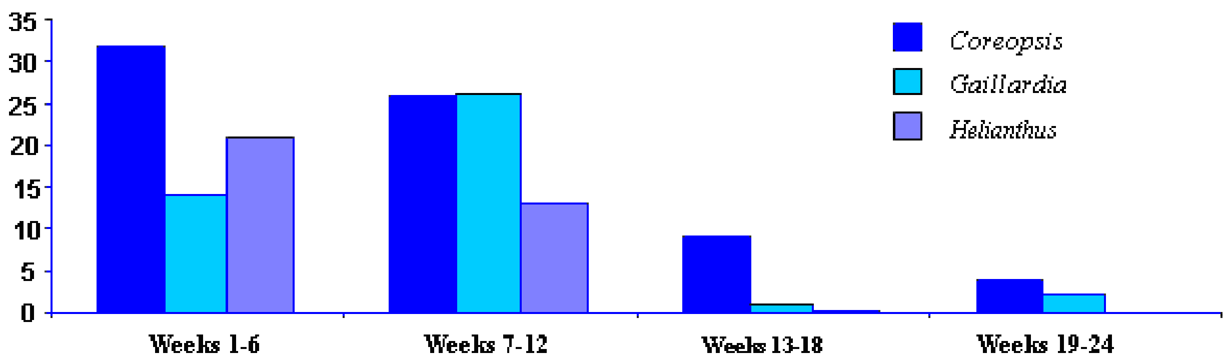


Figure 2-27. Plant Health Index (PHI) for perennial plants (*Coreopsis lanceolata,Gaillardia pulchella and Helianthus debilis*). PHI combines % coverage by species with plant health (1-5); PHI of 35= 33% coverage of bin and maximum (5) plant health).

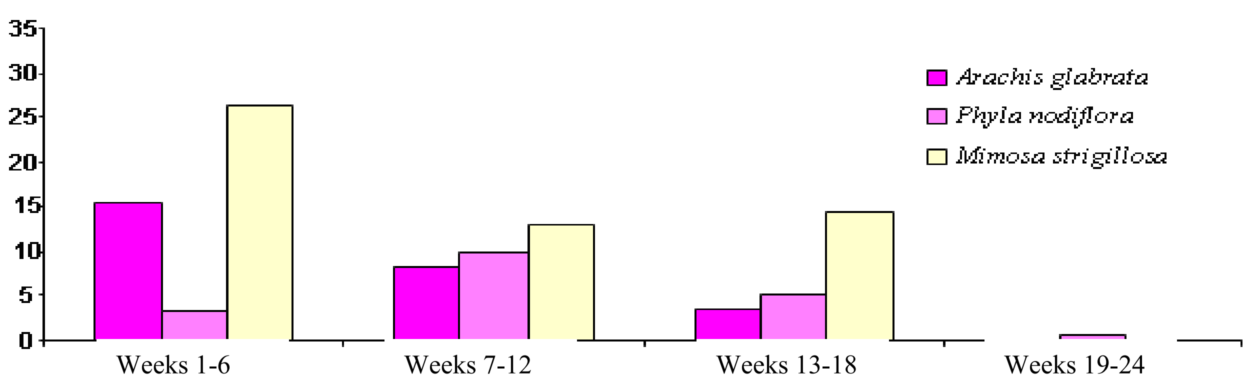


Figure 2-28. Plant health index (PHI) of Runner Type species (*Arachis glabrata, Phyla nodiflora and Mimosa strigillosa*); PHI combines % coverage by species with plant health (1-5); PHI of 35= 33% coverage of bin and maximum (5) plant health).

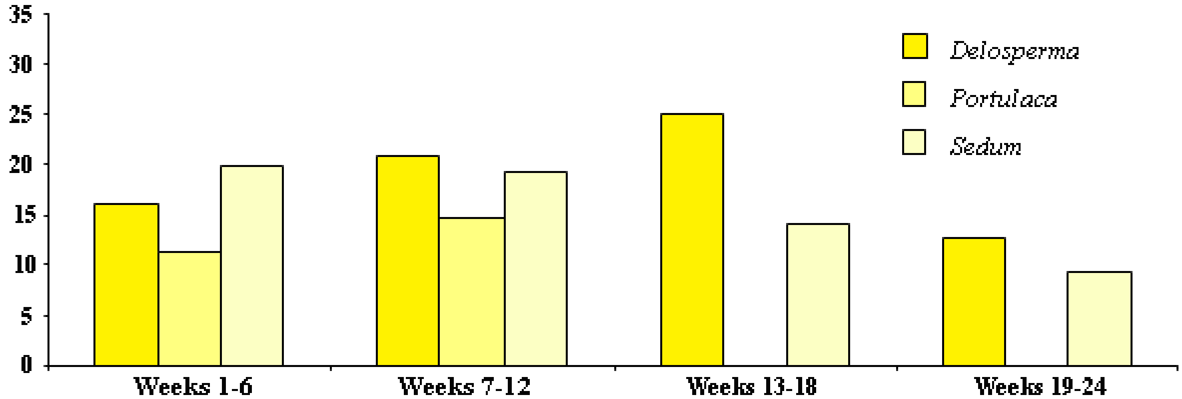


Figure 2-29. Plant health index (PHI) of succulent type plants (*Delosperma cooperii, Portulaca grandiflora, Sedum acre*); PHI combines % coverage by species with plant health (1-5); PHI of 35= 33% coverage of bin and maximum (5) plant health).

It is hypothesized that the physiology of perennials root system in conjunction with the leaf structure may have allowed for more water uptake, as well as ET when planted in a finer soil with greater pore connectivity and smaller pore sizes, such as in H and UCF. Growing-media with pore size distributions that have a more even gradation usually have more fine pores. Additionally growing media with higher OM content usually have more micropores and higher water content as a result. Therefore finer pores with good connectivity between pores, organic matter content or actual mineralogy may be affecting why there was less difference in water retention between plant types within UCF's growing medium.

The lessening capacity of bins originally planted with perennials to retain water over time, may be attributed to the fact that most perennials died either from disease after suffering from drought in September, or from frost in late December/early January. Succulents however did not die from the drought or frost; while, some species of runners, such as Perennial Peanut were dead by late fall.

Evapotranspiration Rates

Evapotranspiration rates measured during the lysimeter experiment at the end of the establishment period, Week 6 (Table in Appendix H) are within the range of mean daily ET rates calculated for September for the Gainesville region using the FAO56-PM method based on Kpan values in Irmak 2002. In Hydrotech and UCF's growing media, the ET rates for bins planted with perennials and runners are higher than those planted with succulents (Appendix H). In all growing media, bins containing plants had higher ET rates than those without plants, except for Hydrotech being planted with succulents. Evaporation rates reported for Building Logics are lower than in the other porous media. This may be due to larger texture not being able to evaporate out the water, and less water being retained initially to be evapotranspired out. Large pores in a coarse layer are not be able to support capillary movement up from smaller pores of a finer layer (Brady and Weil, 2002). As shown in Figure 2-30, the grain size distribution of Building Logics' media is comprised of 90% gravel size particles in the beginning of the study.

As expected, as the growing season ended and winter started, ET rates decreased for all growing medium-plant combinations (Appendix H). This was attributed to decrease in plant health, increase in plant senescence (shown in Figures 2-27, 28 and 29), as well as less hours of sunlight, cooler temperatures and lower PET rates associated with the change of seasons.

Discussion

Effect of Physical Characteristics of the Growing Media on Water Retention, Uptake and Release

The differences in water retention among growing media was attributed to differences in pore-size distributions and organic matter content between the media, rather than the total porosity and total void space available for storage in the various media. For example, Building Logics growing medium had a porosity similar to that of Hydrotech (of approximately 34%), but a different particle size distribution (Figure 2-30). Therefore the pore size distribution, which is a function of grain size distribution and porosity, of these two media, Hydrotech and Building Logics, were dissimilar as well. Hydrotech's grain size distribution had a lower percentage of gravel sized particles and higher percentage of very coarse, coarse and medium and fine sand particles than Building Logics (Figure 2-30).

Building Logics growing medium consists of 90% Stalite™ (rotary kiln expanded shale) and 10% compost. Stalite ™ contains 90% gravel sized particles of expanded shale with a porosity of 43% and 10% coarse sand sized particles of expanded shale (Stalite Specification sheets 2007—Appendix C). As a result, B's particle size distribution is comprised of 90% gravel size (>2 mm) particles and has a total of 1.6% OM with the majority (85%) of the OM residing in the top particle size fraction (the >2 mm) (Appendix I) In contrast Hydrotech has 28.6 % gravel sized particles (and 71.4% sand sized particles); it has 4.4% ± 0.6% OM content and the majority (76%) of the organic matter is in the smaller particle sizes < 2 mm (Appendix I). Having more organic matter in the smaller size fractions can positively influence aggregate formation and hence water retention (Thomas 2006). Therefore, despite the similarity in porosity, bins containing Building Logics growing medium consistently had the lowest water content available to plants irrespective of the time of year, as evidenced by the water retention curves (Appendix F) and water content curves in Figure 2-23 in the Water Release Characteristics section of this Chapter.

Futhermore, even in growing media which had more similar grain size distributions to begin with, such as that of Hydrotech and UCF (Figure 2-30), it is likely that the greater amount of organic matter (Figure 2-31) in U growing medium positively influenced water retention. According to Brady and Weil (2002), the available water holding capacity of two well-drained mineral soils that are similar in every way but organic matter (OM) content, even with a difference as low as 2% OM, will find that the water holding capacity is higher in the one with more OM, due to direct and indirect factors.

A direct factor of OM that positively influences water retention includes the OM's very high water-holding capacity, which exceeds that of mineral soil of an equal volume (whether at field capacity or wilting point) (Brady and Weil, 2002). Indirect factors include OM's ability to increase plant available water by stabilizing soil structure and increasing total pore space, both through increasing the volume of individual pores and the amount of pores (Brady and Weil, 2002). Higher OM content therefore results in an increase in water filtration and water-holding capacity along with an increase in the amount of water held at the wilting coefficient.

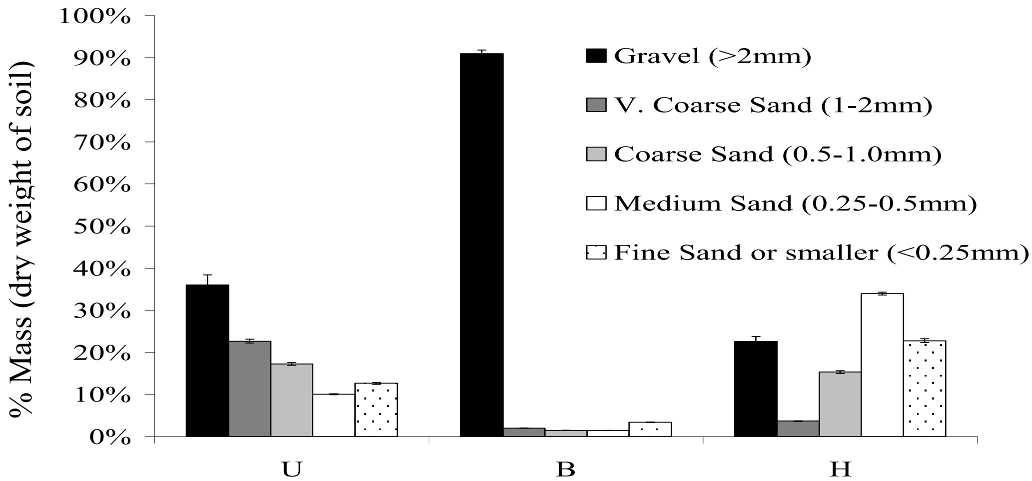


Figure 2-30. Grain size distribution of the three growing medium before planting.

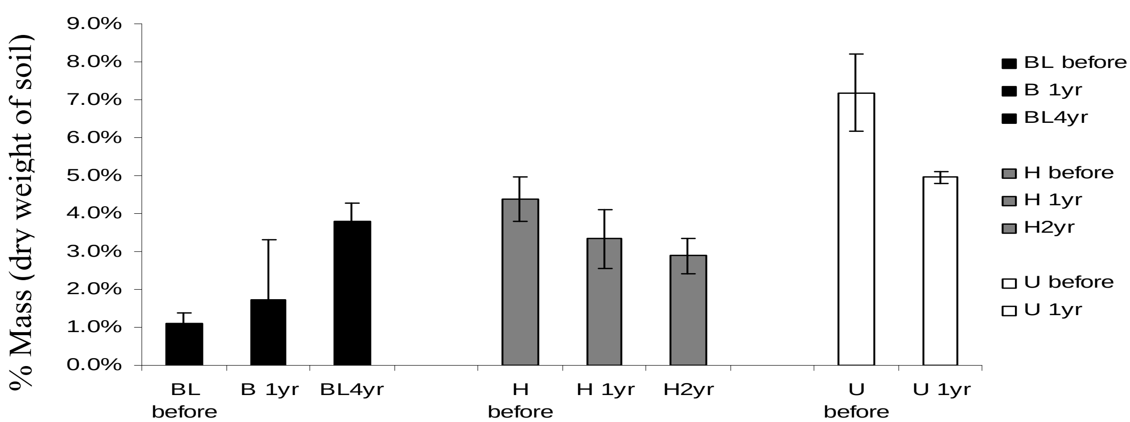


Figure 2-31. Organic matter by percent mass determined by Loss on Ignition for all three media before and after 1 year; and for H medium, after 2 years in situ on the CRP green roof in FL and for B medium, after 4 years on the YSC green roof in Virginia.

The particle size distribution for U growing medium, of an even gradation of particles from gravel to fines (Figure 2-30) combined with elevated OM content (6.5% ± 0.8%) as compared to other growing media, indicates that U growing medium likely has more finer pores in the soil than B and H and may have more micropores within the organic matter, which have a stronger affinity to hold water. While Building Logics growing medium may also have micropores within the intraggregate pores of the heat expanded shale, the vapor pressure differences at the edge of the gravel pieces and higher affinity of water to be held by the micropores within the gravel, may be immobilizing water present inside the Stalite, and keeping that water unavailable to plants.

The large amount of energy needed to overcome the vapor pressure differences inside and outside the porous gravel pieces for water uptake or release to occur, may explain why the rates of water uptake and water release are significantly lower in B growing medium than in the other media ($p = 0.05$); and why the water content of B does not shift much throughout the six month study period. From one point of view, less variability in water content throughout the year could be beneficial in a green roof setting if a homeostatic condition of water is positive for the plant type's health, neither much water is lost during the drying out process, nor gained during the wetting process. However since the AET rates of plants planted in Building Logics appear to be half that of the AET rates of the same plants in other soils at the end of the establishment period, such as UCF's growing medium ($ET_{perennials}$ = 6.0 mm day^{-1} in UCF and $ET_{perennial}$ = 3.1 mm day^{-1} in BL), the water in the soil appears not to be plant available and plants with higher transpiration rates will be stressed in this growing media as compared to one with finer pore sizes and more organic matter.

Succulents, however, which have naturally adapted in xeric climates and are able to close their stomata throughout the day and store water in their vacuoles to later use this moisture during periods of drought (Keeley and Rundel, 2003), do not seem to be deterred from growth by the lesser water content apparent in B growing medium. Succulents are ideal for this growing medium—which is why they were chosen initially during 40 years of development of green roofs after being observed to naturally colonize gravel roofs in Germany. A loosely packed gravel soil with low water retention actually mimics the natural setting in which succulents are found—rocky, porous and well-drained or dry landscapes. Adding organic matter or a substance with finer pores to Building Logics growing medium for use in the subtropics, especially as a growing medium for native Floridian plants, could increase the water holding capacity of Building Logics growing medium significantly and support Florida plant life more easily.

Effect of Plant Type on the Physical Characteristics of the Growing Media

Plant type affected the physical characteristics of the growing media such as bulk density and porosity over six months' growth. Table 2-10 shows the initial bulk densities of the various growing media at the time of packing (before plants were added) and Figure 2-32, shows the final average bulk densities (BD) of the different growing medium-plant combinations at the end of the study period. The bulk density of the medium changed by varying degrees over 6 months of growth depending on the type of plant present. These changes in BD and porosity are likely due to the formation of aggregates as OM was broken down from larger particles to finer particles, and as organic matter was incorporated into the growing medium after the senescence of finer root hairs (or via organic acids exuded by the roots). The stabilization of soil through the creation of aggregates and resulting increase in pore sizes and pore volume and decreased BD is well described by Brady and Weil (2002), Mosaddeghi et al. (2000) and Thomas et al. (1996). The greatest increases in porosity and decreases in BD were seen in bins planted with runners, which had the finest root hairs of the three plant types, and next in perennials, which had the greatest quantity of medium sized roots. For example, the bulk density of UCF's bare media at the end of the study was 0.74 ± 0.01 g cm^{-3}, while the bin planted with runners the BD was 0.69 ± 0.01 g cm^{-3}, this same trend of decreasing BD and increasing porosity was noticed in bins planted with runners in Building Logics' growing medium (BD of 1.01±0.01 g cm^{-3} in bare medium at the end of the study and BD 0.96 ± 0.01 g cm^{-3} for bins with runners). BD and porosity did not vary significantly between those bins planted with succulents or left bare over the study period.

Table 2-10. Bulk density and porosity of the three growing media before the study 7/3/08.

Growing Medium	BD (g/cm3)	SD	Porosity	SD
U	0.71	0.01	0.41	0.01
H	1.07	0.02	0.31	0.01
B	0.99	0.02	0.31	0.01

It is likely that organic matter below ground increased more significantly for runner and perennial plants than succulents, based on the physiology of their root systems (see Figure 2-33 and 34). The runners utilized generally had one tap root with finer root hairs emanating from the main root. Perennials, such as *Coreopsis lanceolata* had a large quantity of medium roots emanating from one point below the surface (Figure 2-35), while succulents had a smoother engorged root, as in the case of *Delosperma cooperii*, with relatively few root hairs (Figure 2-34). According to Bernard et al. (2003) , 60-70% of plant carbon entering the soil from plant residue is derived from the root system and includes soluble (amino acids, organic acids, carbohydrates) and insoluble (sloughed off cells, etc.) material. The soluble carbon originating from the incorporation of plant residue below the surface—such as polysaccharides and organic acids facilitate the formation of aggregates (Tisdall and Oades, 2006), which enhances water retention.

Bins planted with runners in UCF and Building Logics showed a decrease in BD and increase in porosity that is likely due to additions of OM in the finer particle sizes. The hypothesis that there was an increase in aggregates is supported by evidence of an increase of particles in the >2mm size fraction that did not break apart after shaking during the sieving test in soils collected after 1yr in the bins and 2 yrs in situ on the CRP green roof.

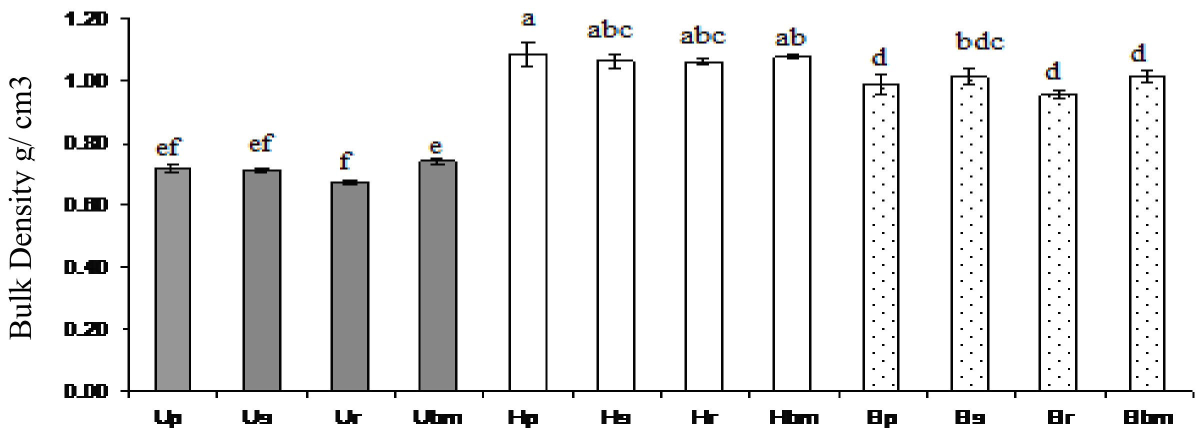


Figure 2-32. Bulk density of each growing medium-plant type combination after the study period ended 11/8/08.

Figure I-1 in Appendix I shows how the top size fraction (>2 mm) increased in H and U growing media, while in B growing medium, the top size fraction decreased over time. In the case of B medium, it began with 90% gravel sized (>2 mm) particles which contained the majority of the OM present in the medium, in the form of mulch. Over time the proportion of OM in this top fraction decreased, likely due to the OM in the large size classes breaking down into smaller particles, increasing the proportion of finer OM in the smaller particle size ranges. The increase in finer particles of OM from senescing root material in B may have increased the likelihood of aggregate formation. Before the study began, over 85% of the OM for BL was located in the top particle-size fraction; after 1-year, only half of the organic matter was located in the top size fraction (the other half of the OM being distributed among the lower size fractions (<2 mm)); and by year 4, the majority of organic matter in B growing medium was found in the smallest size fractions (Appendix I). Total OM content increased over time in B growing medium, increasing from 1.1% ± 0.1% from before the study to 3.5 % after 1 yr and to 3.65 % after 4 yrs in situ on a green roof (YSC in VA). In contrast, the OM content decreased in H and UCF. This trend of increasing OM in a highly mineral medium was seen in Emilsson (2006), as well as the trend of a growing medium with high OM content decreasing initially due to oxidation and then over time building back up again. When below ground plant residue enters the soil, initially two-thirds of the plant residue decomposes in one year (Cresser et al., 1995 in Bernard et al., 2003), followed by a slower steady breakdown of OM. In the case of growing media—often there is peat moss and compost present to begin with. The 3-fold increase in OM in B growing medium after 4 years of being planted with *Sedums spp*. on the YSC green roof (Figure 2-31) was attributed to the incorporation of senesced plant material from the root system. The increase in OM in the B medium in situ suggests that an originally low OM mix is not only adequate for succulents, but that water retention may increase with time on such a green roof, as OM increases time. Furthermore, the presence of OM, and increase in aggregate formation due to exudation of organic acids during the decomposition of added plant residue (Bernard et al., 2003), may result in greater retention of heavy metals on a green roof.

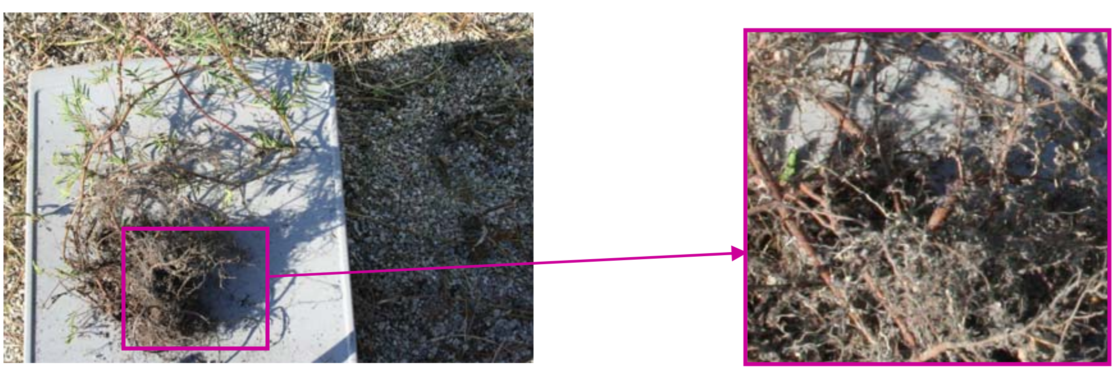


Figure 2-33. Photographs showing the root morphology of a runner type plants, *Mimosa strigillosa.*

Figure 2-34. Photographs showing the root morphology of a succulent, *Delosperma cooperii* .

Figure 2-35. Photographs showing the root morphology of a perennial type plant, *Coreopsis lanceolata.*

Figure 2-36. Photographs of the root systems of a self-recruited plant after bins were abandoned, Tropical Crab Grass.

Conclusions

When designing a green roof for stormwater reduction control in Florida, the most important design factor influencing retention is the initial selection of growing medium type. This decision, when interested in greatest water retention, should be made based on the pore size-distribution of the media, presence of organic matter or constituents such as perlite and vermiculite and total porosity. In this study, retention rates were comparable to those found in studies in both temperate climates (DeNardo, 2005) and in the subtropics eg. Texas (Timm and Rasmussen, 2008). The retention rates ranged from a low of 24% for Building Logics medium with no vegetation to a maximum of 83% for UCF growing medium planted with perennial plants. Within each growing media type--retention ranged from 24-53% BL, 30-72% H and 31-

85% for the four different 6-week study periods, depending on the plant types present and amount of rainfall in the individual 6-week study period.

Plants were the next most important factor influencing water retention rates on the selected plant-growing media combinations used in this study. Evapotranspiration rates at the end of the 6-week establishment period, ranged from 1.5 mm day^{-1} for Building Logics-unvegetated medium to a maximum of 3.6 mm day^{-1} for UCF bins planted with perennials. There was a significant difference in the amount of water released by transpiration versus that of just evaporation within a growing media. Having plants present in the northern Florida climate definitely increased the amount of void pores available for water storage from the subsequent storm—retention increased by 7-10% (above bare medium alone) due to plants. It was however noticed that the plant type most capable of transpiring the greatest amount of water, the perennials, also suffered the most from heat stress during droughts and were consequently more susceptible to plant diseases and succumbed more easily to death than succulents.

The succulents, while surviving the largest range of climatic variation during the study and exhibitin best overall plant health, contributed less to increasing retention of water directly after storms. Bins containing succulents did have the highest residual (non-plant available) water content in the medium it was planted in (irrespective of media type) and healthiest overall plants during the entire study.

In terms of the water release curves, water content was generally the lowest and water retention directly after irrigating was the lowest in Building Logics growing medium and highest in UCF's Black and Gold mix. As stated earlier, the ability of the perennials to evapotranspire out more water over the same period of time as the other plants resulted in a larger differential between the water content over time in those bins containing perennials and those containing no vegetation or succulents. Essentially, the water content in those bins planted with perennials and runners became successively less, to the point that the plants themselves (which were responsible for transpiring the water out) were in greater peril of suffering from plant diseases.

It is recommended that for a roof with no irrigation in the north central Florida climate succulents be used, however in a situation where irrigation can be used, then it is recommended that a mix of succulents, perennials and runners be used together as each plant structure has a different adaptation which may make them compatible to be planted together. Wolf and Lundholm (2008) also found that planting species with different morphologies together can maximize the plants' different capabilities of utilizing water at different moisture levels along a moisture gradient, increasing the amount of total transpiration, total soil moisture utilization and maximimizing the clearing of pore spaces before a subsequent storm.

Furthermore, it is suggested that subtropical grasses be tested in vegetated rooftops in Florida, especially those turf grasses such as Bahia, Sunstar and tropical crabgrass, which thrive on low water inputs.

Perennials in this study appeared to best suited for finer grained, higher porosity soils, such as UCF and Hydrotech's growing media and needed more water than was being applied for proper plant health (eventhough a recommended irrigation level that worked else where was being implemented). Succulents, a hearty plant type in all three media, were the best suited plants for B growing medium. If Building Logics would like to make a mix for FL that will support native vegetation, the addition of finer particles, organic matter (composed of finer particles) or an additive such as WTR (wastewater treatment residuals), could vastly increase the water retention capabilities for this climate and may improve plant growth of other forms than just succulents. Hydrotech may consider adding more OM and/or reducing the medium-sand portion of its mix, e.g. reducing the quantity of USGA sand that comprises the medium-sand portion to a different ingredient with greater water holding capacity. There is a need to study change in OM over time in roofs in situ. This study briefly analyzed some changes in OM content and changes in particle size-distribution over time after being in-situ on a green roof for 2 years and 4 years (H on the CRP roof and B on the YSC roof, respectively), but a systematic study of OM changing over time would be useful, as a trend has been noticed cursorily in other studies, but a well thought out study has not been carried out with regards to natural accumulation of OM over time (versus noting a reduction in OM due to decomposition and oxidation over a short period, which has been noticed over 1 year studies, such as in Emilsson and Rolf (2005). A mix that starts with high OM seems to oxidize and decrease at first; while a mix that is very mineral with gravel size OM, like in the case of B medium, appears to degrade into finer OM particles, increasing the water content and retention capacity of the medium and building up the overall OM content over time corollary to plant senescence.

In the case of a green roof that is situated out of sight, well inoculated Perennial Peanut in a lower pH medium and *Phyla nodiflora* may have the potential to perform well with little to no irrigation. A mix of *Mimosa strigilosa* and Perennial Peanut grown intermingled with tropical crab grass, may also have the potential to fill a roof quickly, create a monolithic layer with the formation of a large quantity of fine root hairs, based on the fact that tropical crabgrass colonized the abandoned bins in the hottest, driest part of the season, during a time period with no irrigation and survived for one year without irrigation. Further study is needed to corroborate or disprove this theory. Tropical crab grass seemed to accumulate the most amount of fine root hairs the quickest, upon visual inspection at the time of deconstructing the bins and investigating which plants survived without irrigation a year after planting. The *Sedum* and *Delosperma* were noted to grow back from below-ground biomass the following spring after the study, as did the *Coreopsis* and in some cases the *Gaillardia*. *Helianthus* did not grow back as frequently or healthily as *Coreopsis* or *Gaillardia*, in this study. While the *Sedums* and *Delosperma* did not do much to reduce stormwater runoff through increased water retention directly after irrigation, the green roof bins planted with those two species did stay alive as a whole over one year with and without irrigation and did shade the soil, possibly increasing the amount of water content in the soil, due to less evaporation of moisture, similar to Getter (2007). Less ET due to plant shading has the potential of allowing more moisture to be present for another plant type when grown in combination with other plants, a possible benefit of growing a continuum of plant forms in conjunction with each other to utilize the soil moisture at all points in the water gradient, as noted by Wolf and Lundholm (2008).

In summary, the first hypothesis that there would be no significant differences in water retention among growing media was rejected and the alternate hypothesis that growing medium type does significantly effect water retention after irrigation or rainfall, was accepted. Infact, it was found that growing medium type was the single most important factor governing retention and water uptake and plants were secondary. The second hypothesis that there would be no significant differences in water retention among plant types was also rejected and the alternate hypothesis that plant type does affect water retention was accepted. The perennial plant type increased water retention more than any other plant type in all media. The analysis of water retention for all time periods combined shows that bins planted with perennials had significantly higher water retention than those planted with runners, succulents and bare media in B medium; perennials had significantly higher water retention than those planted with succulents and bare media in H medium; and perennials had significantly higher water retention than bare media in U medium, but not other plant types.

The third hypothesis that there would be no significant differences in water retention among the 12 plant-growing medium combinations was also rejected, and the alternative hypotheses was accepted that there were significant differences among plant-growing medium combinations, with Up having the highest retention rate and water uptake/rerelease rates and Bs, Br, Bm, having the lowest.

The fourth hypothesis that there would be no significant differences in ET rates among growing medium types, plant types or any combination was rejected, as well as the hypothesis that there were no significant differences in retention over time was rejected. It was found that, % water retention fluctuated mainly in relation to water input, which varied over time, as well as varied with respect to changes in the season and related changes in the plants morphology and the ET rates. There was however no specific decreasing or increasing trend of retention or water uptake and release over time, it was most highly associated with changes in the season and rainfall patterns.

CHAPTER 3
NUTRIENT DYNAMICS OF PLANT-GROWING MEDIUM COMBINATIONS FOR NORTH CENTRAL FLORIDA

Introduction

While green roofs have been proven to provide stormwater quantity benefits (Denardo et al., 2005; Van Woert, 2006; Berghage, 2007), their role in influencing water quality has been questionable—sometimes being cited to improve water quality (Berghage, 2007; and Berndtsson, 2006) and other times shown to increase nutrient concentrations in runoff (Van Setter et al., 2006; Berndtsonn, 2006). Berghage et al. (2008) summarizes the current consensus of green roof researchers, that: “Nutrient load of a green roof is to a large extent determined by the organic component of the medium and the fertilization practice” and goes on to say that “it is clearly necessary to maintain sufficient nutrient content in the green roof to support the plant community, however it is not clear what deficient, sufficient or excessive nutrient content is, or what test should be used to evaluate nutrient content.”

Certainly, an integral component of the green roof is plants; and for plants to remain viable they depend on water and the availability of nutrients. Nutrients are present in the medium depending on the mineralogy of the growing-medium, or they must be added to support plant life. Ideally, for a green roof to function as a stormwater quality BMP, it will contain sufficient nutrient levels to support healthy plant life, but little or no excess that will enter stormwater through leaching.

“Excess” nutrients are being defined here, as those leaching out of the growing media and not being taken up by plants. Most hydrologic and water quality studies related to green roofs begin after the green roof has already been established, this time period ranges from several weeks to several months depending on the study (Van Woert, 2006; Berndtsson, 2005). Therefore, most green roof water quality studies do not account for the load of nutrients leaving the roof before the study even begins, when the roof is initially becoming established, which is the period that has the highest nutrient load leaving the roof and entering stormwater (Emilsson et al., 2007). This study characterized the load of nutrients exiting the roof during this time period. In the case of Florida, the establishment period was defined as 6 weeks, this time period was chosen based on crop-nutrient studies in Florida for plants with similar life-cycles and phenology as the green roof plants being tested here (IFAS, 2009 and personal communication Sartain, 2007).

This study characterized the nutrient release from three different growing media being used or with intended use in Florida, vegetated by three different plant types, which provides data for modeling the expected nutrient levels in leachate from a green roof in a sub-tropical climatic setting (similar to N. Central Florida), for these growing media types at 15 cm of depth.

As stated in Chapter 2, to qualify as an effective urban stormwater BMP in the subtropics, it is hypothesized that a green roof must have high water retention, medium water re-release characteristics, low nutrient leaching and ability to support healthy plant life. Whichever plant-soil combination meets these criteria, will be deemed suitable for FL green roofs from a stormwater Best Management Practice perspective. Any plants that are not viable within the 1 year study period will be deemed unsuitable for north central Florida. The plant-soil combination which has plants that rate the highest on the plant health scale described in Chapter 2, (with the least amount of nutrient leaching, and most amount of initial water retention balanced with a mid-range of new available pore space before the next storm), will be considered a good plant growing media combination for north central Florida green roofs. This study does not endorse any product. The study intends to help identify which of three known growing media (and three known plant types) help keep nutrient leaching to a minimum in green roofs runoff, and aims to provide the reader insight into any physical and chemical components of the three known growing media that may or may not affect nutrient leaching. In this way, any green roofer, land-use planner, or policy maker could use this information in a positive way to help tailor green roof media mixes for this region (by increasing certain physical/chemical characteristics that may be identified here) to be more beneficial to water retention, low nutrient leaching and positive plant health for the north Central Florida region. Land-use planners and policy makers can also use the information in a beneficial way in policy making regarding the management of green roofs and green roof runoff that will most beneficial to receiving water bodies.

Objectives

The objective of this study was to determine which plant-growing media combination at 15 cm (6 inch) depth had the lowest amount of nutrient leaching and how the nutrient concentrations changed over time. Three plant groups and three growing media types were tested and compared to each other and to several controls over a period of 6 months in a mesoscale field experiment at the University of Florida, Gainesville, FL. The determination of "optimal" plant-growing medium combination for a stormwater BMP was based on 1) plant viability and plant growth, 2) nutrient retention/release, and 3) water retention/release. This chapter deals exclusively with the nutrient leaching aspect of the green roof bin study.

The specific objectives of the nutrient component of the study were to:

1. Characterize the total load of N and P leached during the establishment phase of a shallow green roof in Florida (defined as the first 6 weeks after planting).
2. Quantify and compare the load and concentration of nutrients in leachate from the experimental green roof bins after establishment with no irrigation over a longer period of time (6 months).
3. Characterize the nutrient release characteristics of the plant-growing media combinations and determine which growing medium, plant and or growing medium-plant combination had the least amount of nutrient (TSS, TN and TP) release.

4. Determine if there was a (concentration based) first flush effect after controlled irrigation events, where the concentration of nutrients (TN and TP) was higher soon after the storm ended and lower as time proceeded.

Hypotheses

The null hypotheses related to nutrients for the establishment period of the green roof (first six weeks of growth) in a shallow north central Florida green roof 15 cm (6 inches) deep were:

H1o: There are no significant differences in the total load of N and P in the leachate among the three growing media types, three plant types or any of the growing media-plant combinations.

H2o: There are no significant differences between total load of N and P among the individual time periods during the six week establishment period.

The hypotheses regarding nutrient leaching for the 6 month study period were the same as for the 6 week period.

The alternate hypotheses regarding the controlled irrigation portion of the study (also called the Lysimeter Experiment in the previous chapter), where water samples were collected directly after irrigation every 6 weeks up to 24 weeks were:

H1a: There is a first flush effect of higher concentrations of nutrients in leachate immediately after irrigating and lower concentrations later.

H2a: Nutrient levels in leachate diminish over time (the 6 month study period) as excess nutrients are washed out of the system.

Materials and Methods

Experimental Set-Up

Plant-growing media combinations were packed into bins using ASTM standard methods described in Chapter 2 in “Experimental Set-Up”. The growing media characteristics of Hydrotech’s LiteTop mix (H), Building Logics’ medium (B) and UCF’s Black and Gold™ (U) are also described in detail in the “Experimental Set-Up” section of Chapter 2, as is the statistical design of the study. Bulk density and porosity for all three media are shown in Table 3-1. Additional tables about the physical and chemical properties of Hydrotech medium are in

Appendix J. Refer to Chapter 2 for details of how the bins were packed, set-up and for details about the growing media types, plant types and planting techniques; and Figure 3-1 shows the complete randomized block design of the 3 x 4 factorial design, plus controls for this experiment.

Experimental Procedure

The optimal plant-growing media combination study had two main collection methods of the leachate. The first was composite sampling, where leachate collected passively into 5 gallon buckets over 1 week intervals during the first 6 weeks of the experiment, and then was collected passively over 6 week increments up to week 24. The second method was a lysimetric method, consisting of a 1.27 cm controlled irrigation event with the bins being weighed and samples of leachate being taken directly after irrigation at varying time intervals—20 minutes, 1 hr, 4 hrs, 12 hrs, and 24 hrs after irrigation.

The composite leachate samples were produced over varying time periods. Water samples were taken from the buckets weekly during the first 6 weeks (weeks 1, 2, 3, 4, 5 and 6); these samples of the leachate were the result of both rainfall and irrigation that percolated through the growing media. For weeks 12, 18 and 24 the composite samples represented leachate from 6 weeks of time and were the result of rainfall only (no irrigation). Irrigation was discontinued after the first 6 weeks of the study (i.e. the establishment period).

The composite samples were analyzed for TP, TN and TSS and measured for volume. The load data from the composite samples were used to characterize: a) the total load of nutrients (TP, TN and TSS) in leachate of all the soil-plant combinations during the “establishment phase” of the green roof (defined here as the initial six (6) weeks of watering and growing of the plants); b) the total load for three additional six-week time periods, with samples being taken at 12, 18 and 24 weeks; and c) the concentration data from the composite sampling provided data to show at what rate nutrient leaching diminished in the various growing media-plant combinations over time, if at all.

The lysimetric method's primary purpose was to a) characterize changes in nutrient (TN, TP, TSS) concentrations directly after irrigation at varying intervals (20 min, 60 min, 6 hrs, and 24 hrs), and b) to identify whether a first flush effect was apparent in the runoff.

Table 3-1. Measured bulk density (BD) and porosity of the three growing media (B, H, U) before the study.

	BD (g/cm3)	SD	Porosity	SD
B	0.99	0.02	0.31	0.01
H	1.07	0.02	0.31	0.01
U	0.71	0.01	0.41	0.01

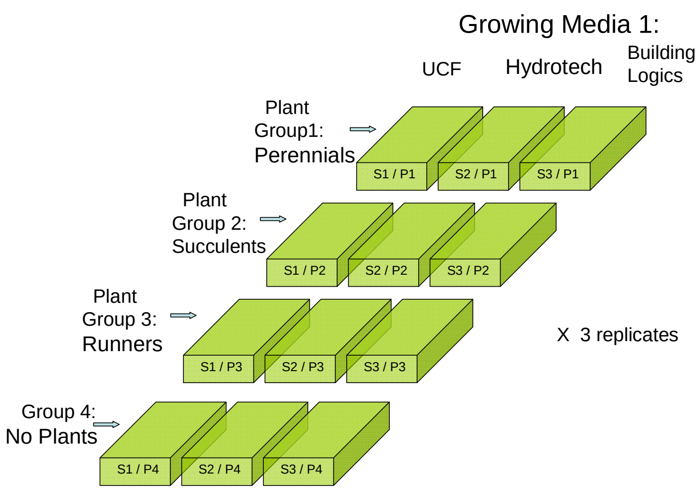


Figure 3-1. Complete Randomized Block Design of 3 growing media vs. 4 plant types with 3 replicates and 2 filter fabric controls and 2 empty bin controls (not depicted).

Sampling Protocol

Irrigation regime

The irrigation regime (Table 3-2) during the establishment period was the same as the irrigation regime used on the Charles R. Perry (CRP) green roof, so that comparisons could later be made between runoff data from Hydrotech bins in this study with runoff from Hydrotech Lite top mix used on the CRP green roof. This irrigation regime was an adaptation based on the results of Hardin's green roof study on optimal irrigation for Central Florida green roofs at UCF 2006 and personal communication with Wanielista UCF (2006).

Table 3-2. Irrigation regime for the growing medium-plant bins.

Days of Establishment Period (6 weeks)	Amount and Frequency of Irrigation
Day 1 to 3	1.27 cm 2x's a day
Days 4 to 7	1.27 cm 1x per day
Day 7 to 14	1.27 cm every other day
Day 14 to 21	1.27 cm every other day
Day 21 to 28	1.27 cm every third day
Day 28 to 35	1.27 cm every third day
Day 35 to 42	1.27 cm every third day

Rainfall measurements

Rainfall for the site was measured using a UF weather station located on top of the UF Dental Tower approximately 500 m from the site at N 29º 38' 22" and W 82º 20'43", at an elevation of 140 ft, using Peet Bros Ultimeter 2000. Rainfall patterns from the study period are compared to the 30-year average for Gainesville, Florida from NOAA's records for 1971-2000 (www.ncdc.noaa.gov/oa/climate/online/ccd/nrmpcp.txt).

Water quality sampling

Weekly composite samples of TSS, TN and TP were taken on Mondays on Week 1, Week 2, Week 3, Week 4, Week 5, Week 6 and Week 12, Week 18, Week 24 (Table 3-3). Samples were composite over time, meaning that all leachate from rain events and irrigation events from the week were passively collected through a tube and funnel into a 19 L (5 gallon) bucket covered with a lid that had a raised spout. The volume of leachate in the bucket was measured immediately before sampling. Water quality samples were taken directly from the bucket after stirring the leachate rapidly, scraping down the portions of the side of the bucket that were submerged (i.e. if an algal film or slime formed during the week's time, this film was scraped down and stirred vigorously into the water in the bucket). The sample bottles were acid washed in the lab, and triple rinsed with leachate in the field, before being filled with the sample and capped on-site. Water samples taken for TP analyses were immediately acidified after sampling, and refrigerated to 4°C, following USEPA standard procedures for TP samples. In the laboratory, 10 mL aliquots were sub-sampled from the field samples and digested using USEPA standard methods for a persulfate digestion (EPA Method 365.1) and then analyzed on an AQ2+ automated discrete analyzer (Seal Analytical, Inc. Mequon, WI 53092) following USEPA standard methods for TP analyses (EPA Method 365.1).

Before water samples for the lysimetric experiment were taken, the buckets were always emptied and scrubbed and before irrigating the plants and collecting the fresh leachate. The leachate from the irrigation was collected 20 minutes, 1 hour, 6 hours, 12 hours and 24 hours post-irrigation. The volume of leachate was measured at each of those intervals and water samples were sub-sampled (120mL) and analyzed for TP and TN (TKN and NO_3) using the same methods described for the composite samples. Since sampling for the lysimetric experiment occurred only when there were three days of sunshine in a row (as the water content monitoring portion of the lysimetric study was weather dependent), the sampling days occurred in or near the 1st week, 6th, 12th, 18th and 24th weeks of the study. However, in the event that a rain storm occurred on the scheduled collection days, the sampling was postponed by several days, hence the lysimetric sampling dates (Table 3-4) are different from the composite sampling dates.

Table 3-3. Composite sampling dates, time interval represented, water source and parameters measured.

Week	Sampling Date	Time Period	Leachate Source	Parameters Measured
Week 1	7/30/2007	1 week	Rain/Irrigation	Volume, TSS, TKN, NO_3, TP, Plant Health
Week 2	8/5/2007	1 week	Rain/Irrigation	Volume, TSS, TKN, NO_3, TP, Plant Health
Week 3	8/13/2007	1 week	Rain/Irrigation	Volume, TSS, TKN, NO_3, TP
Week 4	8/20/2007	1 week	Rain/Irrigation	Volume, TSS, TKN, NO_3, TP, Plant Health
Week 5	8/27/2007	1 week	Rain/Irrigation	Volume, TSS, TKN, NO_3, TP
Week 6	9/3/2007	1 week	Rain/Irrigation	Volume, TSS, TKN, NO_3, TP, Plant Health
Week 12	10/14/2007	6 weeks	Rain	Volume, TSS, TKN, NO_3, TP
Week 18	11/30/2007	6 weeks	Rain	Volume, TSS, TKN, NO_3, TP, Plant Health
Week 24	1/17/2008	6 weeks	Rain	Volume, TSS, TKN, NO_3, TP, Plant Health

Table 3-4. Lysimetric sampling dates, parameters measured and leachate source.

Week	Sampling Dates	Parameters Sampled	Leachate Source
Week 1-U	7/26/07-7/29/07	Leachate volume and TSS, TP, TKN, NO_3 at 20 min, 60 min, 6 hr	1.27 cm irrigation event (16 min)
Week 1-H	7/30/07-8/2/07	Leachate volume and TSS, TP, TKN, NO_3 at 20 min, 60 min, 6 hr	1.27 cm irrigation event (16 min)
Week 1-B	8/5/07-8/8/07	Leachate volume and TSS, TP, TKN, NO_3 at 20 min, 60 min, 6 hr	1.27 cm irrigation event (16 min)
Week 6	9/5/07-9/8/07	Leachate volume and TSS, TP, TKN, NO_3 at 20 min, 60 min, 6 hr	1.27 cm irrigation event (16 min)
Week 12	10/17/07-10/20/07	Leachate volume TSS, TP, TKN, NO_3 at 1 hour post-irrigation	1.27 cm irrigation event (16 min)
Week 18	12/5/07-12/8/07	Leachate volume and TSS, TP, TKN, NO_3 at 1 hour post-irrigation	1.27 cm irrigation event (16 min)
Week 24	2/3/08-2/5/08	Leachate volume and TSS, TP, TKN, NO_3 1 hour post-irrigation	1.27 cm irrigation event (16 min)
Week 60	9/8/2008--Bare Media only	Leachate volume and TSS, TP, TKN, NO_3 1 hour post-irrigation	2.54 irrigation event (32 min)

Statistical Analyses

Calculation of total loads

Total phosphorus and total nitrogen (sum of NO_3 and TKN) concentrations for each bin were multiplied by the leachate volume for each bin, resulting in total mg of P or N leached out of each bin for each time period (weeks 1, 2, 3, 4, 5, 6, 7-12, 13-18 and 19-24). The total phosphorus (TP) and total nitrogen (TN) loads for the establishment period (weeks 1, 2, 3, 4, 5, and 6) were compared to each other and correlated to the water$_{IN}$ (rainfall + precipitation) for those weeks. Differences in trends among the growing media types were analyzed using the Sen-slope estimator (Gilbert, 1987), the same method was used for comparing trends in the total load of nutrients (TP, TN) as well as, the individual nitrogen species (NO_3 and TKN), among plant types within a growing-media type.

For comparisons of load of nutrients over the 24 week time period--the TP loads were compared between 6 week periods, therefore for the entire establishment period, loads from each week in weeks 1-6 were summed together to give a total load for the period week 1-6 and is referred to hereafter as "Weeks 1-6" and is compared to the loads of "Week 7-12", "Week 13-18" and "Weeks 19-24".

Transformations of the data set

A log transformation was applied to the TP and TN load data sets (as well as for the individual nitrogen species) and an AR(1) cubic structure was used, after which the data set met underlying assumptions of normality necessary to use it in a linear mixed model, PROC GLIMMIX using SAS 9.2 and PROC MIXED for the ANOVAs.

The actual loads of TP leaching from the growing media-plant combinations in each bin as mg per bin were used as the input values for the PROC GLM model to test for significant differences in load over time and among plant-growing medium combinations. Using true loads (mg P per bin) was chosen over mg P/kg soil for the model input, because the mass of the bins varied with the growing media bulk density; so there was not an equal mass of soil in each bin, just an equal volume of soil.

Results and Discussion

Total Phosphorus Concentration and Load during 6-Week Establishment Period

During the initial 6 week establishment period, there was no definitive decreasing trend in TP concentration during the establishment period (first six weeks of growth) for any of the plant-growing medium combinations. Nor was there a trend of decreasing load; TP Load varied more with water inputs than time (Figure 3-2).

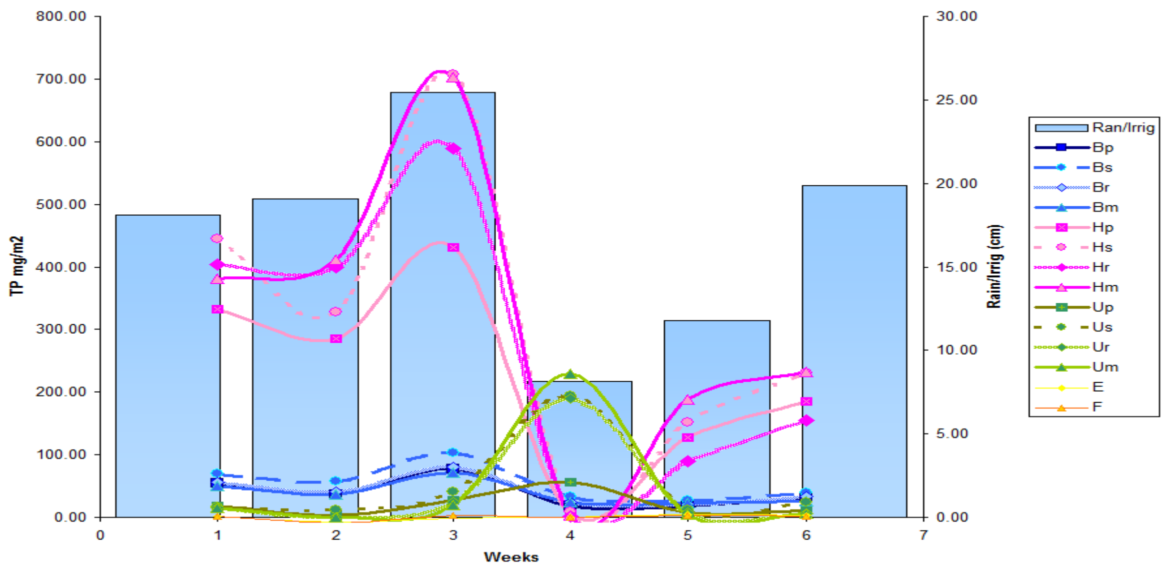


Figure 3-2. Weekly TP loads (lines) and precipitation/irrigation volumes (bars) for the establishment period (first six weeks of growth).

TP Concentrations and Loads among Growing Media Types over 6 months

TP concentrations in the composite samples of leachate representing runoff from 6 week periods, did not follow a decreasing trend over the 24 weeks (Figure 3-3), rather they seemed to vary with rain patterns and increases in concentrations at certain points in time may have been influenced by dry periods preceding heavy rains (Figure 3-4 and Figures 3-5). For example, the increase in TP concentrations for Weeks 7-12 may have been due to an accumulation of TP on the surface of the bins during the dry period as was noted in Moilleron et al. (2002) and Gromaire-Mertz et al. (1999), who noticed a distinct increase in particulates in runoff from roofs after a dry spell as compared to wet periods. Weeks 7-12 began with a dry 9 day period, followed by heavy rains (17 cm over several days) that caused an overflow of leachate in the buckets (Figure 3-6).

Infact, normally it is assumed that with more dilution, concentrations will be lower, as described by Gromaire-Mertz et al. (1999) who studied roof runoff in an urban area, where during high flows from excessive rain, concentrations were low, while light rain occurring after dry weather resulted in high concentrations, but similar loads.

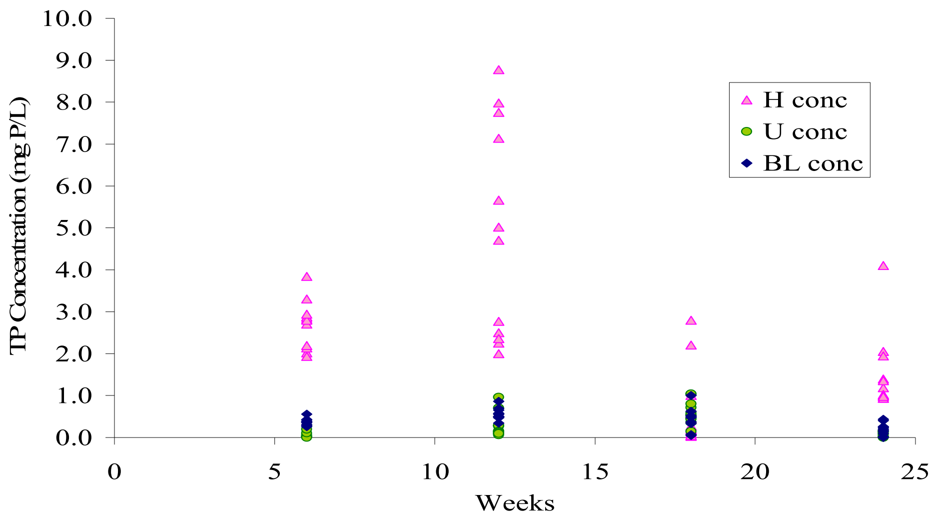


Figure 3-3. TP concentrations in leachate from all 40 bins, collected over four 6-week periods.

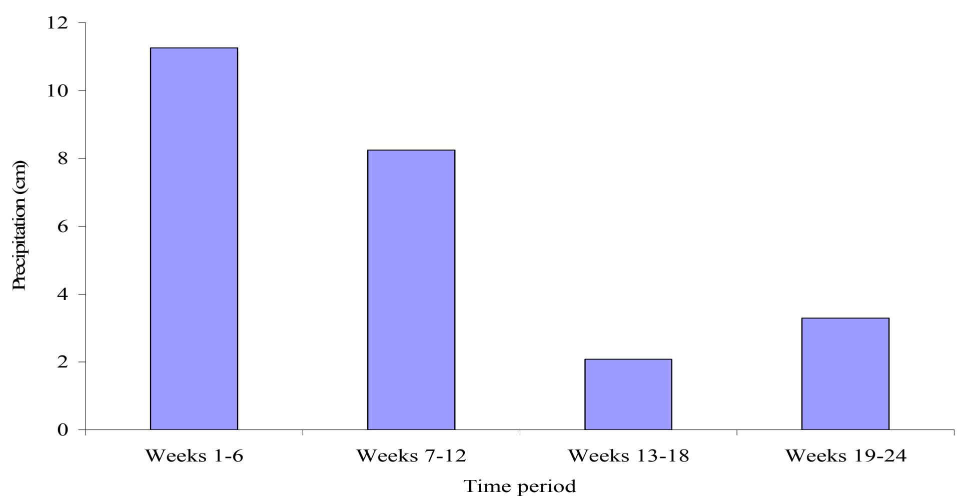


Figure 3-4. Precipitation for the four different 6-week time periods between 7/23/07 - 1/18/08.

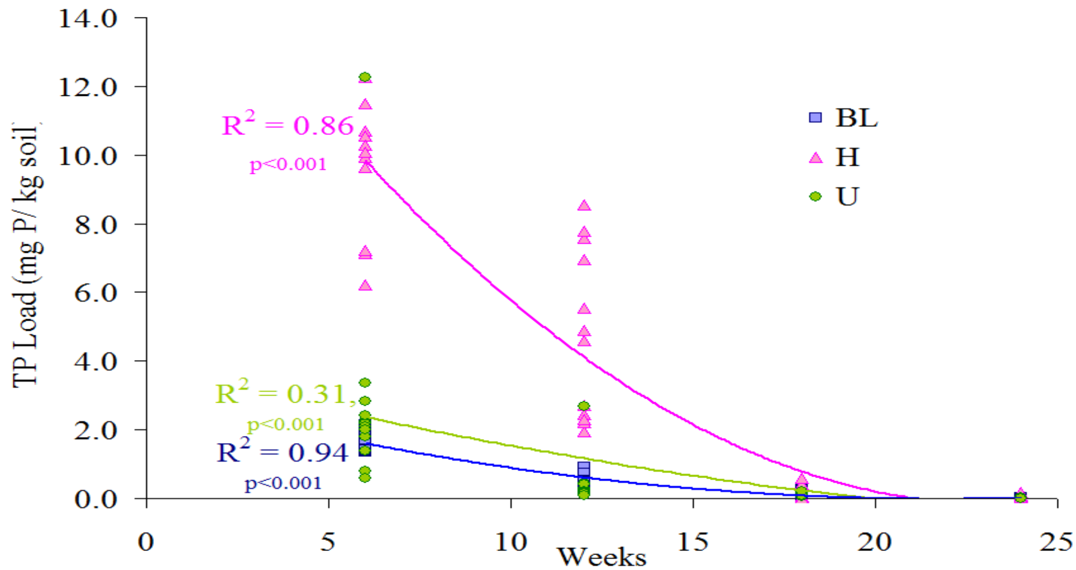


Figure 3-5. TP load as mg P/ kg dry soil from all 40 bins, based on leachate concentrations and volumes collected passively over 6-week periods up to 24 weeks. Regression equations for H: y = 0.0333x2 - 1.5542x + 17.983; for B: y = 0.0038x2 - 0.2694x + 3.8546 and for U: y = 0.0065x2 - 0.2827x + 3.0667.

In our case, the TP load leaching each medium type decreased over the 24-week study period (Figure 3-5), despite slight increases in concentration during periods of heavy rain (Weeks 7-12). Concentrations of TP in leachate from bins containing Building Logics (B) and UCF (U) growing media over the 24 week time period ranged between a minimum of below detection (0 mg L-1) (measured in Weeks 19-24) to a maximum of 1.0 mg L^{-1} (measured in Weeks 13-18), which are similar to TP concentrations in green roof runoff reported by Kim et al. (2006) in Korea (1.00-1.18 mg P L^{-1}), slightly lower than values reported in Moran (2005), and higher than TP concentrations in Berndtsson et al. (2009), who reported mean TP concentrations of 0.02 - 0.31 mg L^{-1} for a range of extensive and intensive green roofs in Sweden and Japan.

The range of concentrations of TP in Hydrotech leachate (0.04 mg L^{-1} in Week 18 to 10.60 mg L^{-1} in Week 4) were generally higher than other TP concentrations reported in the literature for green roof runoff (Berndtsson et al., 2009; Berndtsson et al., 2006; Kim et al., 2006); though some values were in the range of TP concentrations reported by Berghage et al. (2008) using the

SME (saturated media extract) method to test for TP levels directly in growing media (2.15 – 5 mg L^{-1}). Hydrotech TP values were, however, lower than those in urban street runoff from intensively developed residential and commercial watersheds in Korea (Lee and Bang, 2000).

The loads of TP per kg of growing media for all bins are shown in Figure 3-5; and the results of the ANOVA on with TP load as the response variable and growing media, plant types and time as factors are shown in Table 3-5.

Table 3-5. Results of the type III tests of fixed effects for the PROC GLIMMIX model on TP load (mg P per bin). (G_media, growing media; P_type, Plant type.)

Effect	Num DF	Den DF	F Value	Pr>F
G_media	2	24	121.74	<.0001
P_type	3	24	6.45	0.0023
G_media*P_type	6	24	5.00	0.0019
Week	1	105	5.92	0.0167
Week*week	1	105	18.73	<.0001
Wk*wk*wk	1	105	27.35	<.0001

Effect of Time on TP Load

Total P load decreased over time for all growing media, as can be seen in Figure 3-5 and in week 18 there were no significant differences in TP load among the three media. Differences among growing media types were more significant than differences between plant types, although there was a plant effect on TP leaching within growing media types.

There was a significant effect of time on TP load (p-value for “week” of 0.0167) (Table 3-5), therefore two-way ANOVA analyses of growing media and plant type were carried out for each six week period separately. Table 3-6 shows the p-values of these processes and how the p-values of growing media and plant type combinations changed over time.

Table 3-6. P-values for 2-way ANOVAs of growing media and plant type for four 6-week periods for TP load in bins (analyzed as mg per bin).

	Weeks 1-6	Weeks 7-12	Weeks 13-18	Weeks 19-24
Growing media	<.0001	<.0001	.7951	<.0001
Plant type	<.0001	.0120	<.0001	<.0001
G*P combination	.5864	.0008	.0003	<.0001

The results of the PROC GLIMMIX model with all weeks combined showed that the three growing medium types had TP loads that were significantly different ($p<0.001$) from each other. More specifically, based on the 2-way ANOVAs (Table 3-6), the TP load values in leachate among growing media were significantly different from each other in weeks 6 and 12 ($p< 0.0001$) and in week 18 there were no significant differences among the 3 growing media. In week 24, while the mean value of TP load per bin in H growing medium had dropped more than 12 fold from its original value (from 13.2 mg P kg^{-1} soil to 1.01 mg P kg^{-1} soil), the TP load values had risen slightly from the previous time period and were again significantly higher than that of both U and B growing media.

The TP load was affected directly by the amount of rain that fell on the bin. During heavy intense rains of large volume, more TP was leached out of the soil. The initial 6 week period was between the end of July and the beginning of September in 2007, which was a period of heavy rain and regular irrigation, and several brief dry spells. Week 6, irrigation was turned off and a hot dry spell occurred (Figure 3-6), stressing many of the plants (signs of heat stress were noticed on the leaves, followed by insect infestation on the perennials).

The period of time between weeks 7-12 (September-October) started out as relatively dry compared to the first six weeks of the study, but just before the 12 week sampling event, the bins were hit with heavy rains (end of September and mid-October) (Figure 3-6). Weeks 13-18 (October-December) was the driest period of the 4 time periods and weeks 19-24 (December-February) were also dry and successively cooler than the other time periods. The effect of these changes in weather on the plants could have affected the amount of particulate P leaching from parts of the plants that were degrading or senescing.

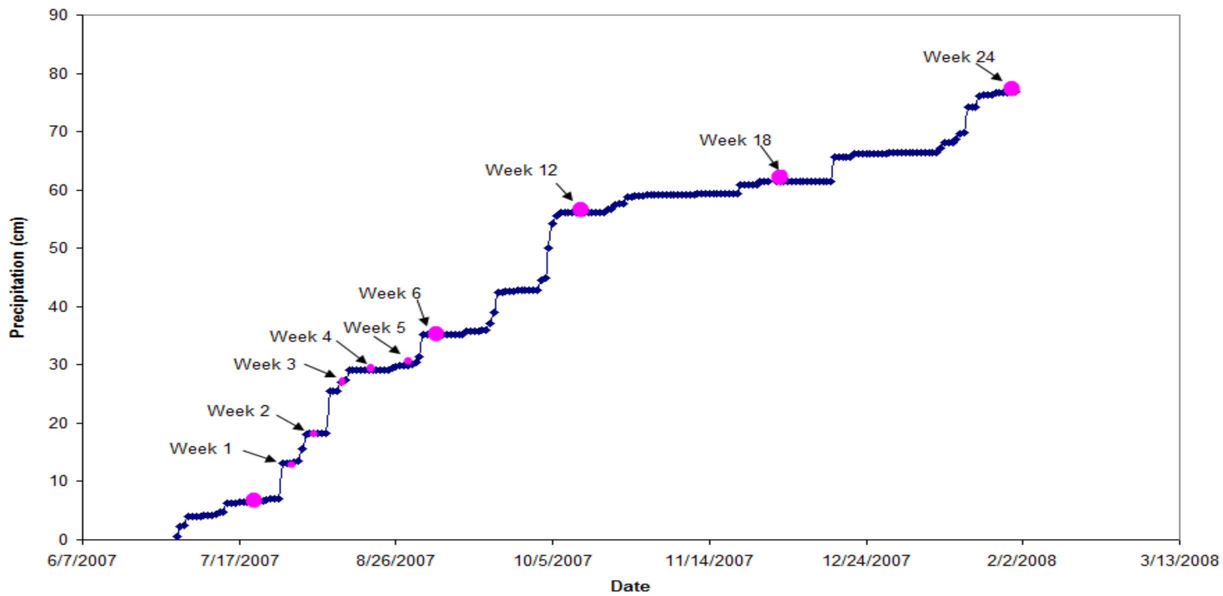


Figure 3-6. Cumulative hydrograph of precipitation during 24-week study period; sampling dates indicated by circles.

Effect of Plant Type and Plant-Growing Medium Combinations on Total Phosphorus in Green Roof Bins

The effect of plant type on TP load in leachate in the overall analysis, irrespective of growing media type, was that runners (r) had TP loads that were significantly lower than that of the two other plant types (succulents (s) and perennials (p)) and were significantly lower than bare media (m). Results of the LS-means analysis of the mean areal TP load over 24 weeks for all 12 growing media-plant combinations by GLIMMIX in SAS 9.2 are shown in Figure 3-7. Results of the LS means method for comparing interactions among plant–growing medium combinations on TP load over all time periods combined show that Um, Up, Ur, Us and Bp are not significantly different from the overall mean TP load for all plants over all time periods, while Bm, Br, Bs and Hm, Hp, Hr and Hs are significantly higher than the other plant-growing media combinations (Figure 3-7).

While the bins planted with runners had significantly less TP load in its leachate overall, the effect of plants is most significant in weeks 6 and 12, when plants are fully established and not yet severely affected by frost or lack of water. In time periods where the plants are dead or severely impaired, the difference in TP load can not necessarily be attributed directly to the effect of the original plant type in the bin. However, differences in P levels from bins with dead plants may relate to senescence and differences in loss of TP from the dead tissue as below ground biomass becomes incorporated into the soil or as plants above ground decay and decompose.

Figures 3-8, 3-9 and 3-10 show the effect of plant type on the cumulative loads of TP leaching from bins over time within each growing medium as an areal loading rate. From these figures one can see that U growing medium had the lowest range of TP load (159 mg P m^{-2} to 358 mg P m^{-2}), which was just slightly lower than the cumulative TP loads from B growing medium (339 mg P m^{-2} to 461 mg P m^{-2}) and both B and U had cumulative TP loads significantly less than that of H (2073 - 3288 mg P m^{-2}).

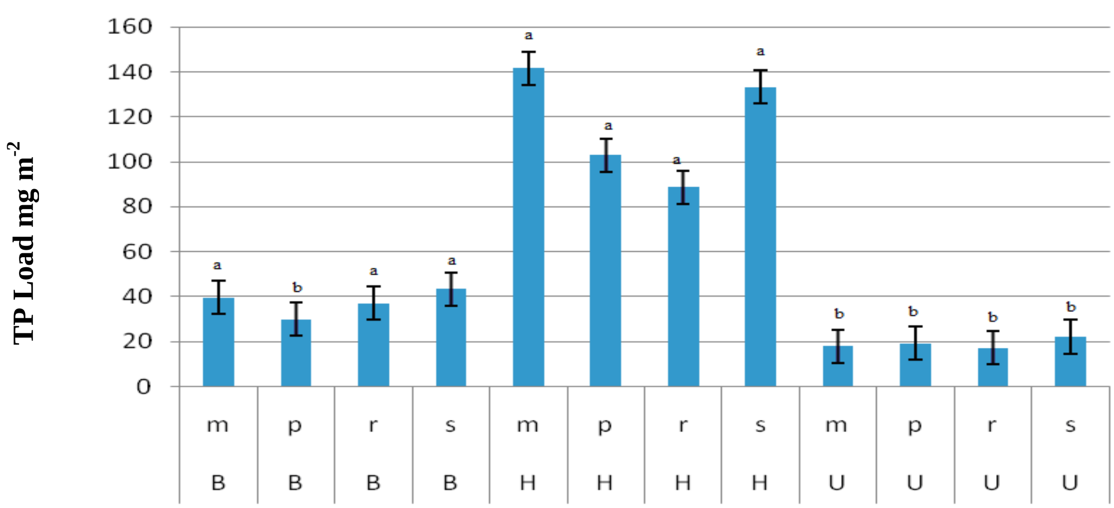


Figure 3-7. Mean values of TP load (with standard error) for each growing media-plant combination for the entire study period. (m, p, r, s represent plant types: bare media, perennials, runners and succulents, respectively; B, H, U represent growing media types—Building Logics, Hydrotech and UCF, respectively.)

Within B and U growing media, the plant with the highest cumulative TP load were the succulents. In the case of B growing media, succulents' TP load (461 mg P m^{-2}) was significantly higher than TP levels from bins planted with runners or perennials or bare media (with no significant differences among r, p or m.)

Within U growing media, the cumulative load of TP from perennials was significantly lower than all other plant types or bare media (with no significant differences among r, s or m.)

For Hydrotech growing medium, the cumulative loads of TP were highest in bins planted with bare media (3288 mg P m^{-2}), followed by succulents (2850 mg P m^{-2}); the difference in TP load between succulents and bare media was not significant. However the succulents and bare media both had TP loads significantly higher than bins planted with runners or perennials (2087 mg P m^{-2} and 2073 mg P m^{-2}, respectively).

Initial and Final TP Ash Concentrations in the Growing Medium

The TP ash growing medium concentration data shown in Table 3-7, indicate that growing media that started out relatively high in TP, such as the H and U medium (with respect to B), terminated with a respectively lower TP ash concentration in the media, as the TP washed out over time. The media behaved as a net source of TP in these cases. Interestingly, the TP ash growing medium concentration data over time for Building Logics indicates that TP is actually accreting in the soil (Table 3-7) as plant material accumulates, yet TP load data from the leachate collected from B bins shows that these growing medium-plant combinations also behaved as a source of TP like U and H plant-growing medium combinations, and not a sink (Figure 3-4).

The amount of TP leaching out of the bins cumulatively is higher than the TP ash levels in the growing medium before the study and before planting (Table 3-8)—this may indicate that part of the source of the TP load in the leachate is from a) fertilizers on the plant material, b) dry and wet deposition and c) plant senescence or organic P from the plant itself.

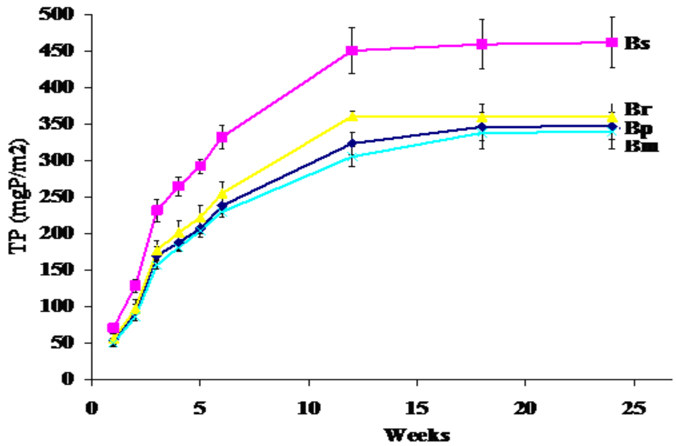


Figure 3-8. Plant effect on cumulative TP load in mg P m^{-2} for Building Logics growing medium.

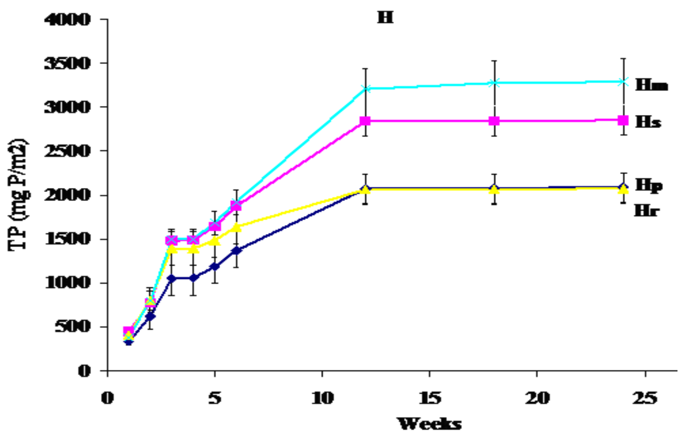


Figure 3-9. Plant effect on cumulative TP load in mg P m^{-2} for Hydrotech growing medium.

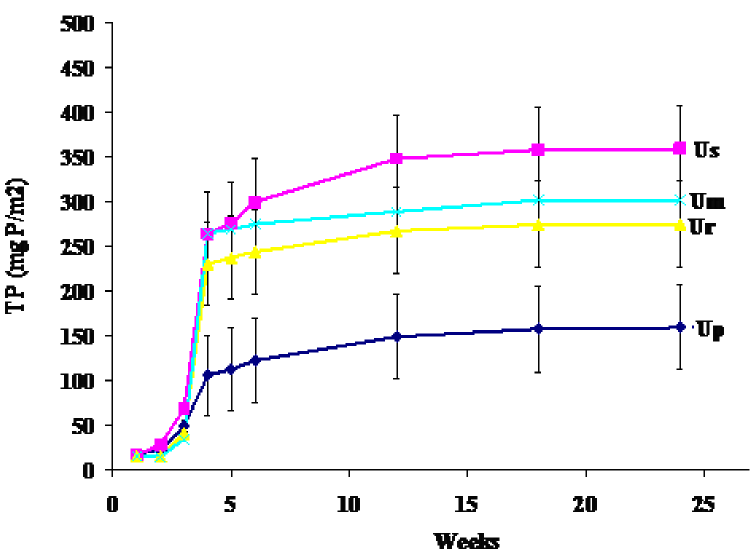


Figure 3-10. Plant effect on cumulative TP load in mg P m^{-2} for UCF growing medium.

In week 6, the plants were still growing and establishing themselves, and in weeks 6-12 they were also actively growing, as shown in the plant health graph shown in Figures 3-11, 3-12 and 3-13. At that point in time, the TP load from bins planted with succulents, regardless of soil type, were significantly higher than that of runners and perennials ($p<0.005$ value). There were no significant differences in the TP load between succulents and bare media, while bins planted with perennials have significantly lower TP loads than bare media.

The results from the two-way ANOVA for week 12 indicate, that when the plants were fully established and a large portion of the initial available TP had leached out of all the bins (regardless of soil or plant types), the only significant difference in TP load among any of the plant types or bare media, was between runners (which had a significantly lower TP load in its leachate) than succulents.

Table 3-7. Growing media TP ash concentrations (mass basis) before and after green roof bin study, and after 2-years in situ on the CRP green roof in FL for H and 4-yrs on YSC green roof in VA for B growing medium.

	TP mg P/kg soil		TP mg P/kg soil		TP mg P/kg soil
B before	0.18 ± 0.02	B 1yr	0.31 ± 0.07	B 4yr	0.84 ± 0.06
H before	0.94 ± 0.01	H 1yr	0.84 ± 0.35	H 2yr	0.68 ± 0.003
U before	0.66 ± 0.04	U 1yr	0.56 ± 0.01		

Table 3-8. Growing media TP ash concentrations (areal basis) before and after the green roof bin study, and after being in situ on a green roof (for 4 years for B and 2 years for H growing medium). Measured via TP ash on ball milled growing medium samples.

	TP mg P/m2		TP mg P/m2		TP mg P/m2
B before	32 ± 3	B 1yr	55 ± 12	B 4yr	149 ± 10
H before	167 ± 2	H 1yr	148 ± 61	H 2yr	120 ± 3
U before	117 ± 8	U 1yr	99 ± 30		

During weeks 13-18, an early frost affected runner plants and perennials; and another very cold period in weeks 19-24, killed all plants but two succulent species. In these time periods, bins with bare media had a significantly higher TP leachate load than any other plant type. In week 18 runners had significantly less TP in leachate than perennials.

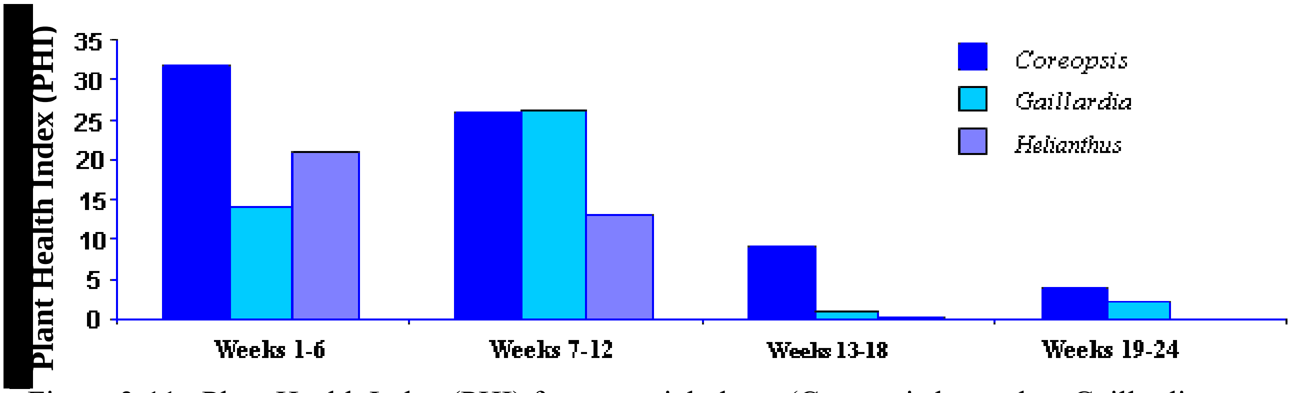


Figure 3-11. Plant Health Index (PHI) for perennial plants (Coreopsis lanceolata,Gaillardia pulchella and Helianthus debilis). PHI combines % coverage by species with plant health (1-5); PHI value of 35 indicates optimal species coverage (33% coverage of bin) and maximum (5) plant health.

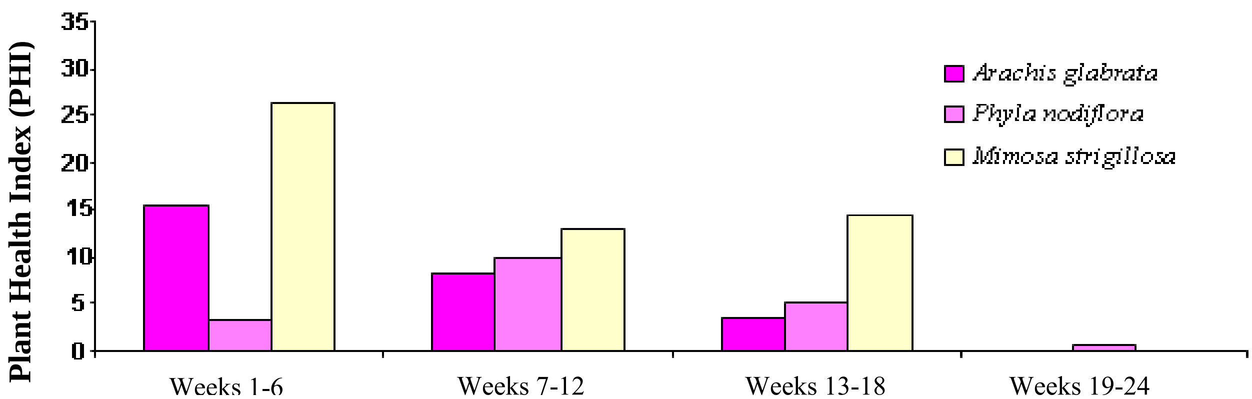


Figure 3-12. Plant health index (PHI) of Runner Type species (Arachis glabrata, Phyla nodiflora and Mimosa strigillosa. PHI combines % coverage by species with plant health (1-5);, with 35 indicating maximum desired coverage by the species (33% coverage of the bin) and maximum (5) plant health.)

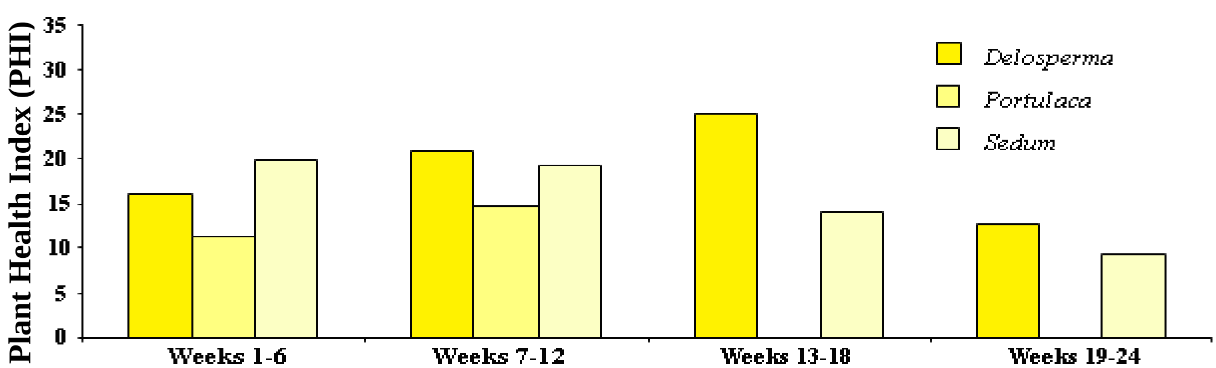


Figure 3-13. Plant health index (PHI) of succulent type plants (Delosperma cooperii, Portulaca grandiflora, Sedum acre). PHI combines % coverage by species with plant health (1-5);, with 35 indicating maximum desired coverage by the species (33% coverage of the bin) and maximum (5) plant health.

Nitrogen (TKN, NO_3 and TN) Concentrations and Load in Leachate during Establishment

Total nitrogen (TN) loads in this study were determined by summing the TKN loads with the nitrate loads. The nitrogen measured as TKN represents all reduced forms of nitrogen, such as organic-N, ammonia-N and ammonium-N; while nitrate-N represents the oxidized forms of N (NO_2-N and NO_3-N). Total N refers to all the forms of nitrogen summed together and is presented first in this section.

Cumulative areal loads of TN leached over the entire study period for the various plant-growing media combinations ranged from 700 mg m^{-2} for Up (UCF perennials) to 40,000 mg m^{-2} for Hs (Hydrotech succulents) (Figures 3-14, 3-15, and 3-16). The TN load by week and over all time periods combined varied more among growing medium types than plant types. After log transforming the total nitrogen load data per bin (mg TN per bin), PROC GLIMMIX in SAS 9.2 was used with AR(1) structure subject to bin, with TN load as the response variable and growing media and plant types and time as factors (see Table 3-9).

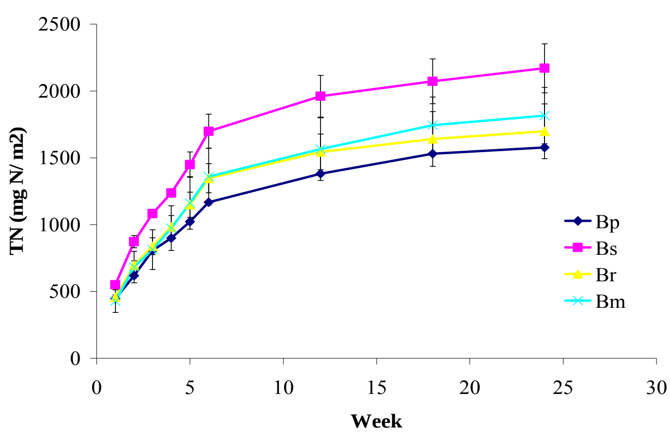


Figure 3-14. Cumulative TN load leached from various plant types within B growing medium over 24 weeks. B, Building Logics medium; p, perennial; s, succulents; r, runners; and m, bare medium.

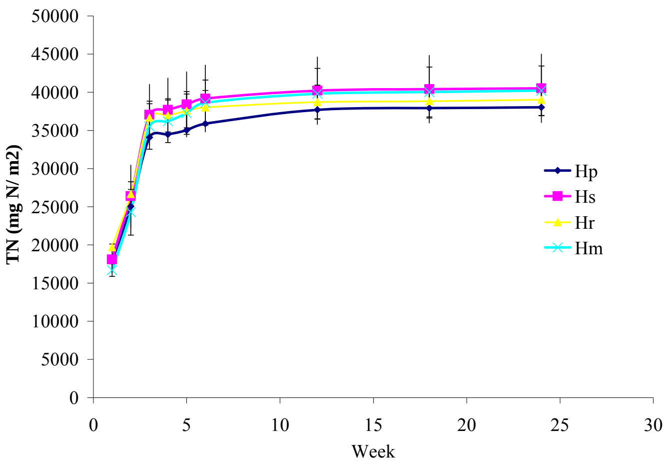


Figure 3-15. Cumulative TN load leached from various plant types within H growing medium over 24 weeks. H, Hydrotech growing medium; p, perennial; s, succulents; r, runners; and m, bare medium.

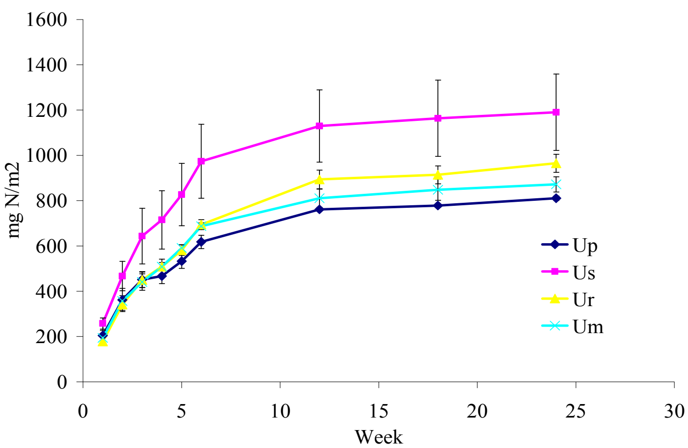


Figure 3-16. Cumulative TN load leached from the various plant types within U growing medium over 24 weeks. U, UCF growing medium.

Among the B growing medium bins, Bs cumulatively leached significantly more TN than Br and Bp (results of ANOVA within B medium bins); by week 18 there were no significant differences in load leached among the bins. For cumulative TN load leached from the U bins for various plant types, Us was significantly greater than other plant types and bare media. Up was significantly lower than Ur and Us (results of ANOVA within U medium bins). No significant differences in load are detected in any medium after week 12.

The results of the PROC GLIMMIX model for TN (details of model parameters and fit in Appendix K) was that over all weeks combined, the three soil types were significantly different

Table 3-9. Results of the type III tests of fixed effects for the PROC GLIMMIX model for TN areal load data from the 24 week green roof bin study.

Effect	Num DF	Den DF	F Value	Pr>F
G_media	2	24	90.43	<.0001
P_type	3	24	0.47	0.7090
G_media*P_type	6	24	5.00	0.8888
Week	1	106	181.92	<.0001
week*week	1	106	86.34	<.0001

(p<0.001) (Table 3-9). There was a significant effect of time on TN load (p-value for "week" of <0.0001, Table 3-9), therefore two-way ANOVA analyses of growing media and plant type were carried out for each six week period separately. Table 3-10 shows the p-values resulting from these ANOVAs; Appendix L shows the details of the analyses (F-values and model fit). Plant type had a significant effect on TN load in each time period (Table 3-10), while growing media only had a significant effect on TN load in the first six week period (Table 3-10). There was a slight growing media-plant interaction in the first six week time period (p=0.06) and no interactive effect of plant-growing media combinations on TN load was detected in subsequent time periods (Table 3-10).

Table 3-10. P-values for 2-way ANOVAs of growing media and plant type for TN load for each of the 6-week periods.

	Weeks 1-6	Weeks 7-12	Weeks 13-18	Weeks 19-24
Growing media	<.0001	0.6013	0.1629	0.4153
Plant type	<.0001	<.0001	<.0001	<.0001
G*P combination	0.0633	0.1384	0.7527	0.1055

Table 3-11 and Figure 3-17 show how succulents had the highest TN load, followed by bare media, perennials and runners in every time step. Mean TN load values for plant type are shown by time step in Table 3-11. The cumulative TN areal loading values for B and H (Table 3-12 and Figure 3-18) were high when compared to lysimeter studies on 50 m^{-2} plots in Ft. Lauderdale testing nitrogen leaching in St. Augustinegrass versus a mixed species landscape

(Erickson, 2005). They reported values of cumulative TN loss of 140 mgN m^{-2} and 250 mgN m^{-2} averages over a 1 year period, respectively for St. Augustinegrass and mixed species landscape (Table 3-13). In this study, the minimum mean cumulative TN loss for perennials was 170 mg N m^{-2} in U growing medium and occurred over only a 6 month study period. While significant losses of TN were not expected for U growing medium after week 18, because past this point in time there were no longer any significant differences in load between the time steps, it was unknown precisely what the 1 year load would have been; therefore an estimate of load based on the assumption that the load remained constant for the subsequent 6 months past the end of the study period was calculated. This estimate yielded a minimum of 206 mg N m^{-2} for the year, which falls between the annual average loads reported for St. Augustinegrass and mixed species landscape in Florida by Erickson (2005) in Table 3-13.

Table 3-11. Plant type effect on TN load by time period in mg N m^{-2}.

Plant Type	Weeks 1-6 Mean ± SE	Weeks 7-12 Mean ± SE	Weeks 13-18 Mean ± SE	Weeks 19-24 Mean ± SE
m	497 ± 0.18	42.6 ± 0.16	11.2 ± 0.16	8.99 ± 0.18
p	459 ± 0.18	39.4 ± 0.16	10.3 ± 0.16	8.31 ± 0.18
r	430 ± 0.18	36.9 ± 0.16	9.69 ± 0.16	7.78 ± 0.18
s	537 ± 0.18	46.1 ± 0.16	12.1 ± 0.16	9.72 ± 0.18

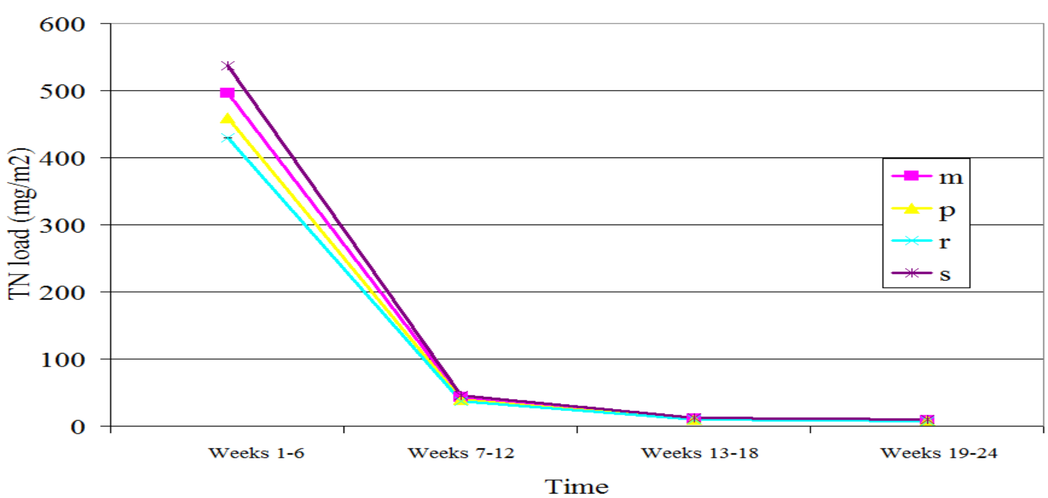


Figure 3-17. Plant type effect on TN load by time period (significant differences shown in Table 3-11).

Table 3-12. Growing medium effect on TN load (mg N/m2) by time period.

	TN Load (mg N m^{-2})							
	Weeks 1-6	SE	Weeks 7-12	SE	Weeks 13-18	SE	Weeks 19-24	SE
B	384	1.2	33	1.2	9	1.2	7	1.2
H	1694	1.2	145	1.2	38	1.2	31	1.2
U	169	1.2	14	1.2	4	1.2	3	1.2

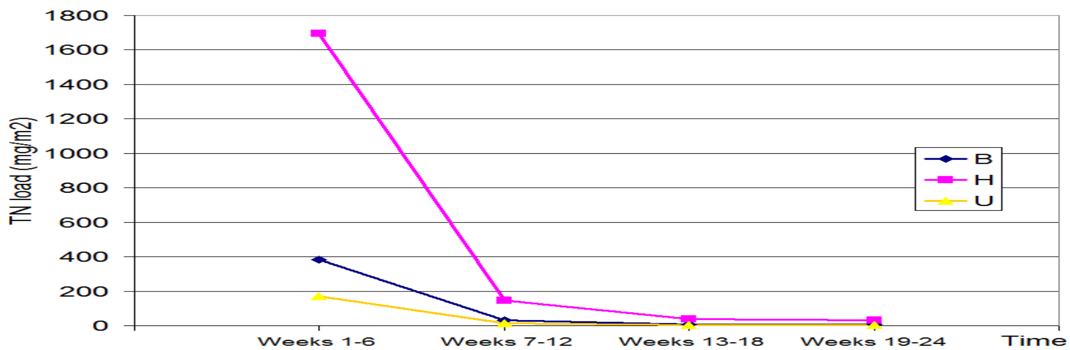


Figure 3-18. TN areal load by time period for growing media type (significant differences shown in Table 3-12).

Table 3-13. Comparison values of TN load from other studies in Florida and the Mid-west.

	TN Load		
St. Augustinegrass-FL	1.4 kg/ha	140	mg/m2
Mixed Species-FL	2.5 kg/ha	250	mg/m2
Prairie	0.15 kg/ha	15	mg/m2
No tillage corn	50.3 kg/ha	5030	mg/m2
Chisel plowed corn	44.8 kg/ha	4480	mg/m2
Unfert Poa pratensis	1.88 kg/ha	188	mg/m2

Source: Erickson et al. (2005)

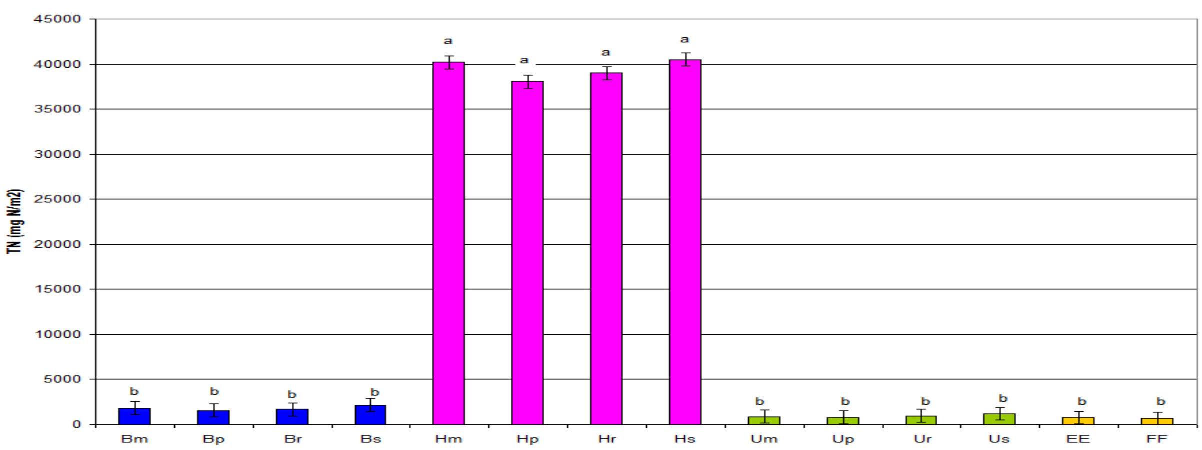


Figure 3-19. Cumulative TN load (mg N/m2) over 24 weeks for each of the plant-growing medium combinations. LS-Means with Tukey's test for comparison of significant differences among combinations. Bars not connected by the same letter are significantly different. Standard error bars are shown.

Effect of Plant, Growing Media, Interactive Effects and Time on TKN Load

TKN, a measure of the organic-N, ammonia and ammonium forms of N, comprised 80-98% of the total N in leachate for B bins, 4-6% of TN in H bins and 79-99% of TN in U bins in the first week of the study. In the case of the B and U bins, succulents were preferentially taking up TKN (NH_4 and organic N) over NO_3, as the leachate from Br bins contained 12-19% NO_3, while B bins with bare media had leachate with only 2-9% NO_3. In the case of the U bins, in those planted with succulents, the total N in the leachate consisted of 80-84% TKN, versus 90-98% TKN comprising the TN detected in the leachate from the bare media bins. This trend of greater uptake of reduced forms of N by CAM succulents was noted in Lüttge (2004). He states that "the ability of CAM succulents to use N is highly species specific and varies with age and environmental conditions" according to Wekmann et al. (1995) and Baatrup-Pedersen and Madsen (1999) in Lüttge (2004). Additionally he notes that while, various studies contrast each other with regards to preferential NO_3 versus NH_4 uptake in CAM plants, Fernances et al. (2002), and Nievola et al. (2001) and Endres and Mercier (2001 and 2003) all found that the CAM plants they tested preferred NH_4 and organic-N over NO_3 and glycine. The importance of the preference of reduced forms of N in a green roof system where irrigation comes from a cistern, is that since the water in the tanks during long periods of storage can become anaerobic, most of the N will be in reduced N forms when irrigation occurs, and will be plant available to succulents or other plants that prefer reduced forms on N over NO_3.

Helianthus, in a study by Kurvits and Kirkby (1979), was found to uptake both NO_3 and NH_4, with slight preference of NO_3 (along with enhanced cation uptake in NO_3 fertilized *Helianthus* plants), but enhanced P uptake was noticed in NH_4 fertilized plants NH_4.

The mean TKN loads in leachate were significantly different among growing media types ($p<0.0001$ at an $\alpha = 0.05$ level) in the 24 week study, based on the results of a mixed model

(GLIMMIX, SAS 9.2) using log transformed TKN load in mg per bin as an input and plants, growing media, interactive effects between plants and growing media and time as factors.

Table 3-14. Results of the type III tests of fixed effects for the PROC GLIMMIX model for TKN load data from the 24 week study. (Model fit shown in Appendix L.)

Effect	Num DF	Den DF	F Value	Pr>F
G_media	2	24	115.97	<.0001
P_type	3	24	1.83	0.1695
G_m*P	6	24	0.92	0.4960
Week	1	105	0.01	0.9190
Week*Week	1	105	3.71	0.0568

The trends of the cumulative loads of TKN follow that of TN presented in the previous section (Figures 3-20, 3-21 and 3-22), with one exception: the final cumulative load of Hr was significantly less than Hs and Hm for TKN. In the case of total-N, there were no significant differences in the overall cumulative load of TN among the 3 plant types and bare media within H growing medium (Figure 3-21). The significantly lower amount of TKN leached as compared to bare media and succulents, may indicate a preference of TKN uptake. Additionally, of the three plant types, succulents appear to have been the most heavily over fertilized and have the lowest N requirements and uptake of all the plants (Figure 3-23).

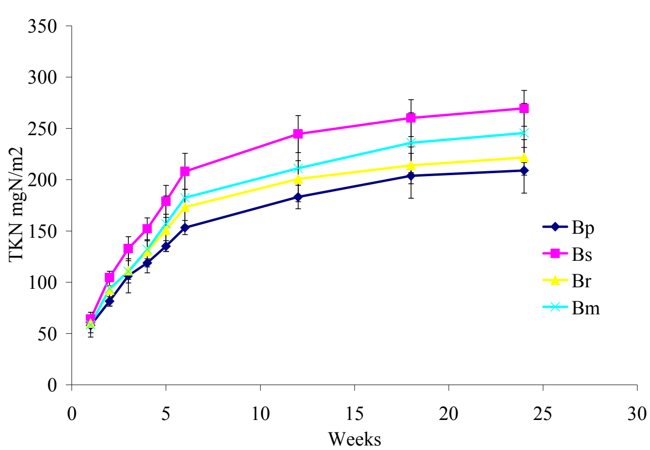


Figure 3-20. Effect of plant type within Building Logics growing medium over time on TKN load.

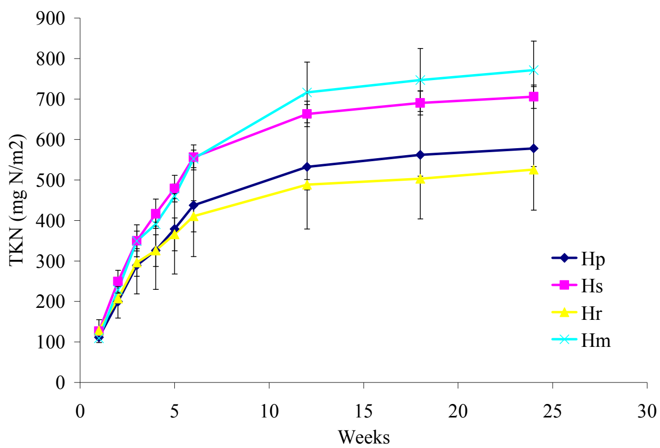


Figure 3-21. Effect of plant type within Hydrotech's growing medium over time on TKN load.

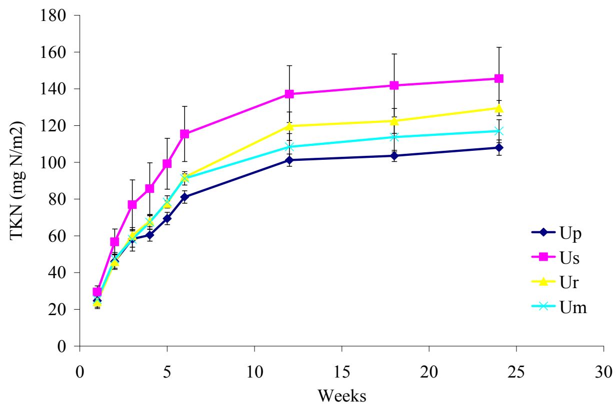


Figure 3-22. Effect of plant type within UCF's growing medium over time on TKN load.

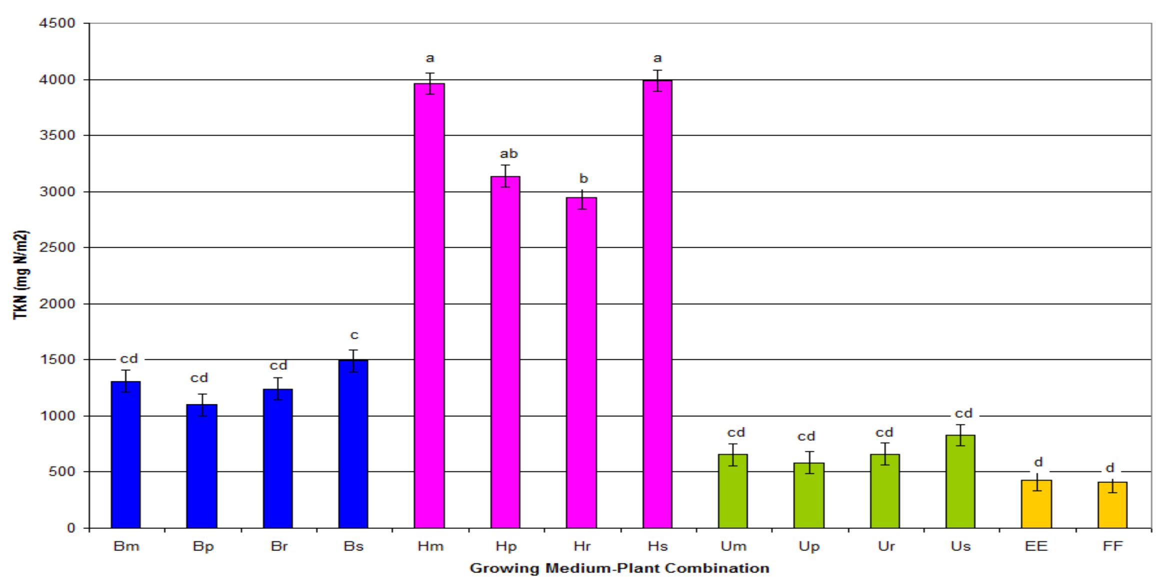


Figure 3-23. TKN areal loading rates for all plant-growing medium combinations for total load at the end of establishment period (6 weeks). Bars not connected by the same letter are significantly different.

Effect of Growing Media and Plant Type on Nitrate Loads during the Establishment Period

The largest differences in nitrate load among plant-growing medium combinations are due to growing medium type, rather than an effect of plant type. Similarly to all nutrients measured, bins containing Hydrotech growing medium had the highest nitrate load in leachate during the establishment period, ranging from a low of 83 mg per m^2 (for runners in week 4) and 18,000 mg per m^2 (for runners in week 1) (Table M-1 in Appendix M). In contrast, bins containing B and U media had nitrate loads in the ranges of 3.04 mg N m^{-2} to 86 mg N m^{-2} and 0.18 mg N m^{-2} to 45 mg N m^{-2}, respectively (Table M-1 in Appendix M). The minimum levels of nitrate in leachate for both B and U were in bins planted with perennials in week 4. The maximum nitrate loads for B and U growing media originated from bins planted with succulents in week 1. Nitrate levels in H decreased dramatically between weeks 3 and 4, from an average of 9150 mg N m^{-2} to an average of 190 mg N m^{-2} irrespective of plant type. For weeks 4, 5 and 6 the maximum nitrate load in leachate from H was 670 mg m^{-2}, which was 200 times lower than nitrate loads measured for weeks 1-3 (Table M-1 in Appendix M). Despite the dramatic reduction in nitrate loads emanating from H growing medium by week 4, it still had nitrate loads 3 to 50-fold higher than that of bins containing B growing medium and 20 to 600 times higher than nitrate loads of leachate from U bins, depending on plant type.

In bins planted with U and B growing media, the most noticeable plant effect was associated with those bins planted with succulent plants, which often showed significantly higher ($p<0.005$) nitrate loads in leachate (Figure 3-24) than other plant types. The trend of elevated nitrate loads emanating from bins planted with succulents was not as apparent in H growing medium (Figure 3-24).

Effect of Growing Media and Plant Type on Nitrate Load over 6 Months

For weeks 7-12 nitrate levels are below detection in leachate from bins containing UCF and Building Logics growing medium irrespective of plant type; for bins containing Hydrotech growing medium nitrate loads are in the range of 0 – 1150 ± 800 mg N m^{-2} in leachate (Table N-1 in Appendix N).

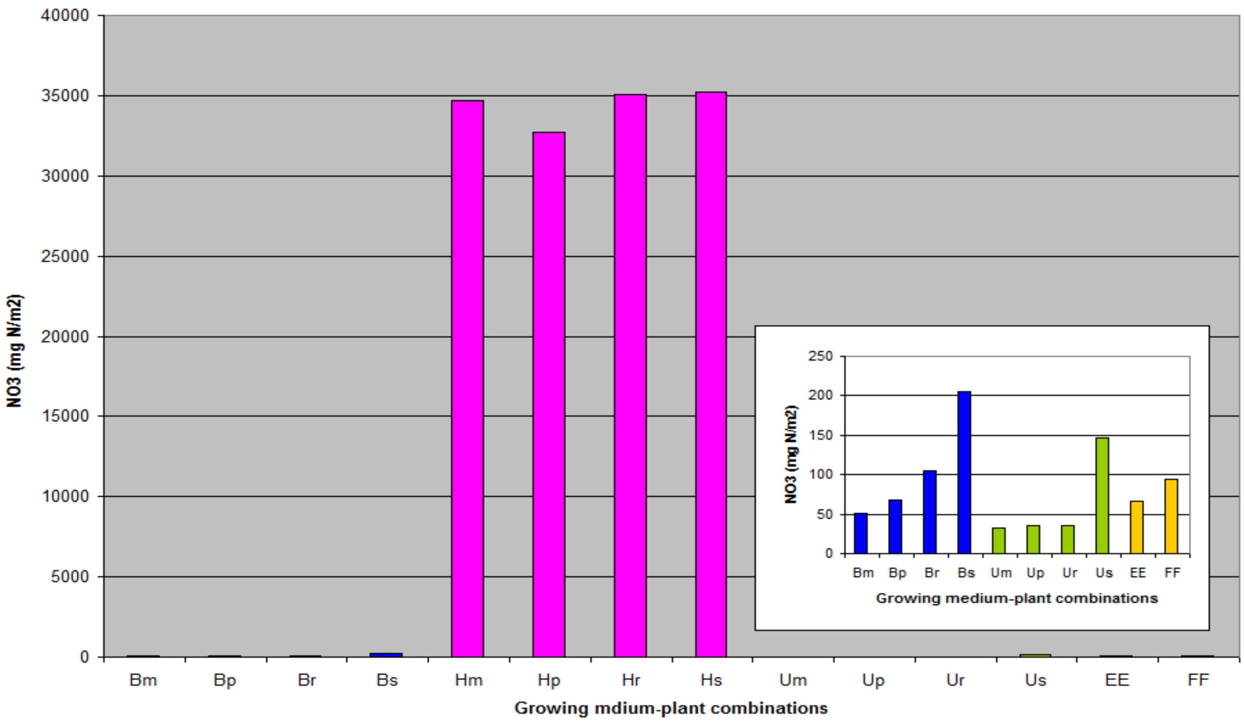


Figure 3-24. Effect of plant type on nitrate loads during the establishment period for all plant growing medium combinations, bars connected by the same letter are not significantly different.

By weeks 13-18 nitrate loads in all growing media types approach similar levels to each other and to the empty bins (Table N-1 in Appendix N). The mean nitrate loads in B, Empty, H, U bins respectively are 7.17 ± 3.8 mg N m^{-2}, 0.79 ±1.3 mg N m^{-2}, 1.05 ± 3.5 mg N m^{-2} and 0.20 ± 3.5 mg N m^{-2}. By week 24 the mean nitrate loads in leachate from B (16.8 ± 7.82 mg N m^{-2}), H (6.00 ± 4.66 mg N m^{-2}) are not significantly different from each other (Table 3-19). However the nitrate load in leachate from bins containing U (U = 0.26 ± 0.1 mg N m^{-2}) and empty bins (non-detectable) are significantly lower than the nitrate load from B leachate.

Initial and Final Nitrogen Concentrations and CN Ratios in the Growing Media

Nitrogen levels directly in the growing media were measured before and after the 24 week study in two ways, by elemental analysis in air dried soil that was ball milled and by water extraction. The results of these analyses are shown in Tables 3-15 and 3-16. As expected, only a small fraction of the TN in the growing media (as measured by the EA in dried ball milled samples) was water extractable N. For example, in all cases water extractable N is less than 1/10th the amount of N measured in the ball milled samples. This indicates that only a fraction of the total nitrogen present is available to plants.

Over time, in growing media that initially had high levels of TN in the growing media (H=958 mg N kg^{-1} soil and U=1867 mg N kg^{-1} soil), ended with lower levels of TN in the growing medium, as measured directly in the dry ball milled soil, as well as in the water extractable form. This decrease in TN in the media correlates to the initial decrease in organic matter in H and U growing media that was shown and discussed in Chapter 2. Additionally, B which experienced an increase in OM over 1 year (Figure 2-31 in Chapter 2), similarly had an increase in TN in the growing medium (Table 3-16).

Table 3-15. Results of water extractable-N analysis (1:10 (soil to water) water extraction, shaken for 1 hour; N is reported on a concentration and mass basis) for growing medium samples taken before and after bin study.

	Before Study N (mg N/kg soil)	After Study N (mg N/kg soil)
B	11.13	11.90
H	81.30	16.23
U	8.57	12.70

Table 3-16. Results of EA-TN analysis of air dried, ball milled soil, analyzed on the EA (Elemental Analyzer), reported on a mass basis for before and 1yr after green roof bin study and 2 yr and 4yr in situ on a green roof for B and H.

	TN (mg N/kg soil) mean ± SD				TN (mg N/kg soil) mean ± SD				TN (mg N/kg soil) mean ± SD		
B before	349	±	23	B 1yr	586	±	431	B 2yr	1426	±	134
H before	958	±	9	H 1yr	775	±	102	H 4yr	1324	±	313
U before	1867	±	19	U 1yr	1313	±	130				

Table 3-17. CN ratios of the growing media before and after the study; and for B and H media, CN ratios after being on a green roof for 2 years and 4 years, respectively.

	Before			After 1 year in green roof bins			After being in situ on a green roof			
Media	C:N		SD	C:N		SD		C:N		SD
B	26:1	±	1.4	32:1	±	1.2	BL 2yr	15:1	±	1.2
H	39:1	±	1.7	43:1	±	0.2	H 4yr	16:1	±	2.4
U	15:1	±	1.1	15:1	±	2.5				

Over time the CN ratio of the various growing medium types began to converge on 15:1 (Table 3-17). This was expected for a soil in Florida, where soils that have a CN ratio over 25 to 30 have N in the soil that generally becomes immobilized by the bacteria population and is not plant available until the ratio begins to drop below 25. The N becomes the most available to plants when the ratio begins to approximate 15:1 over time; organic N in Florida mineralizes at a rate of approximately 2% a year. Therefore excess N applied early to growing medium is not truly plant available and either becomes immobilized or exits in leachate. The growing media U began with a CN ratio of 15:1 and remained so over one year, meaning this medium had the most plant available N present in the soil and still had the lowest water extractable N to begin with of the three growing media (Table 3-15).

TSS Concentrations in Leachate

Total Suspended Solid measurements garnished from composite samples that accumulated in buckets over 6 weeks were indicative of suspended solids from algal growth during that time, rather than sediments leaching directly out of the growing medium, therefore TSS loads were not calculated for the various time periods. Algal growth, surprisingly, was not inhibited by the fact that buckets were opaque, placed in the shade and had lids, their white color still allowed for algal growth over time. If TSS is referred to as a measure of algal growth then one can note, that more algae grew in the buckets with higher nutrients—Hydrotech versus Building Logics, but the data as an indicator of suspended solids not related to algal growth was not usable for all time periods. Figure 3-25 shows the color/turbidity of leachate (composite samples) from the three soil types during a week algae was not present. BL had a reddish tinge, Hydrotech had a brown color and UCF had a yellowish aspect to the leachate. During the one-week intervals that the composite samples accumulated in the bucket no free floating algal growth was detected in the water column, however a thin film did form on the sides of the bucket.

Figure 3-25. Photo of leachate from Week 5—top bucket contains leachate from U growing medium, bucket on left contains leachate from B growing medium, and bucket on right is leachate from H growing medium.

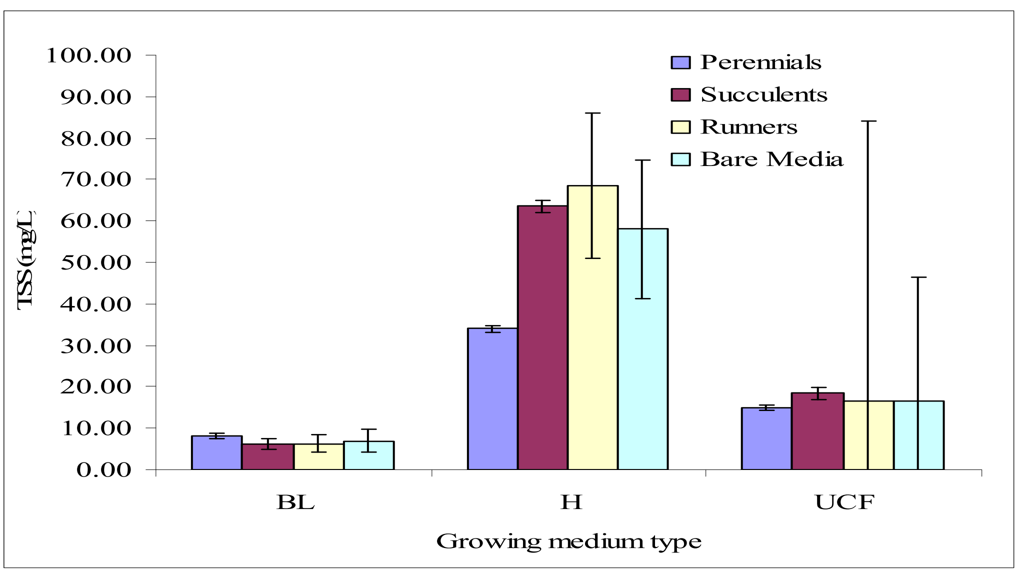


Figure 3-26. TSS (mg/L) concentrations measured in composite sample from Week 3 (no algae).

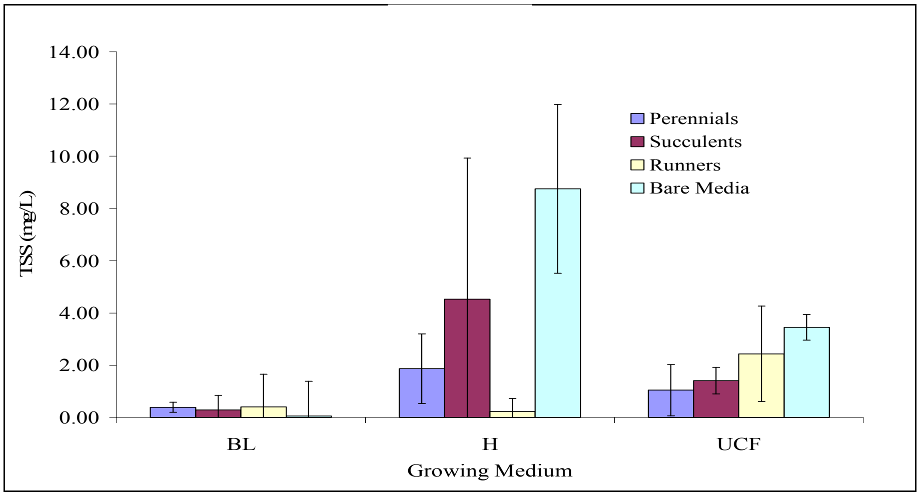


Figure 3-27. TSS (mg/L) concentrations in leachate from the lysimeter experiment collected Week 18 (no algae).

Week 3 TSS concentration data is shown in Figure 3-26 as an example of a week in the middle of the establishment period where no algae was noted in the water column and may be compared to Week 18 lysimetric water samples' TSS measurements, where algal growth was also absent (Figure 3-27). By comparing week 3 and week 18, one can notice TSS did decrease over time. Since the buckets were scrubbed each week during the first six weeks directly after composite sampling, which was directly before collecting leachate from the lysimeter experiment, TSS concentrations measured during lysimeter experiments did reflect the presence of normal suspended sediments rather than suspended particles of algae.

Results of the Lysimetric Method—Analysis for concentration based first flush (CBFF)

The results of the lysimetric method of sampling—collecting water quality samples at intervals of 20 min, 60 min, and 6 hrs after irrigation-- for Week 1 showed that TP concentrations did not change significantly over time (within the first 6 hours) for any plant-growing medium type, indicating that there was not a concentration based first flush effect in the leachate (Figure 3-28). Among media types, B and U growing media have significantly lower TP concentrations than Hydrotech for all plant types. Also, within Hydrotech and BL growing media type, there is a visible effect of plants on concentration: those planted with Perennials have lower TP concentrations than Bare Media (p=0.05) within Hydrotech soils for both Time 1 and Time 2. For Building Logics growing media, succulents appeared to have slightly higher TP concentrations at Times 1, 2 and 3 in Week 1 as compared to other plant types (p=0.05) (Figure 3-28).

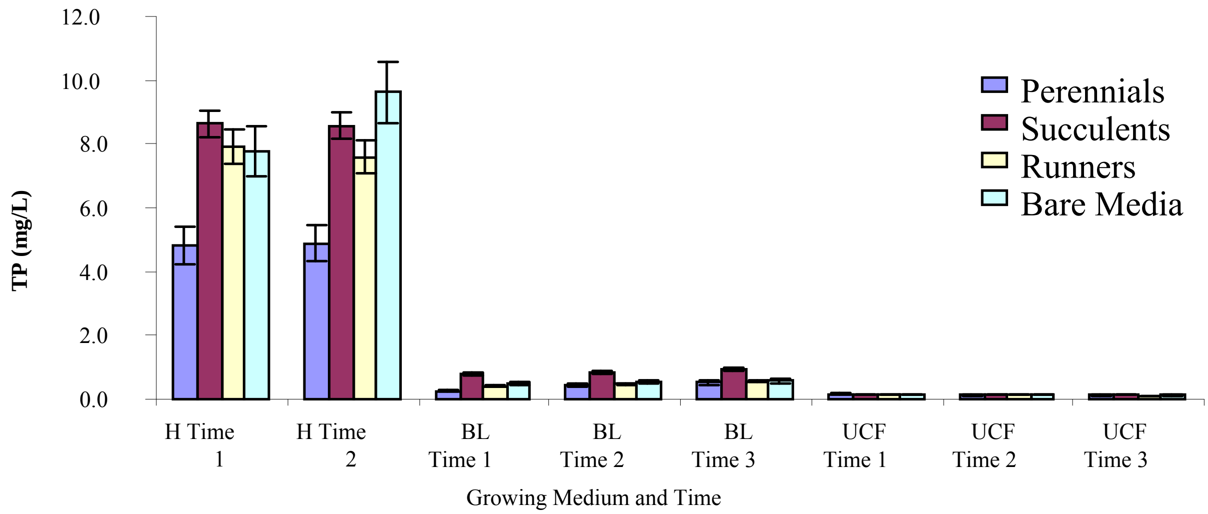


Figure 3-28. Lysimeter Week 1-Effect of time and plant type on TP concentrations in leachate from H (Time 1 and 2), B and U growing media (Time 1, 2 and 3). Time 1=20 minutes, Time 2=1 hour and Time 3 = 6 hours post-irrigation.

Correlations among Nutrients in Leachate, Retention and Water Input

TP load in leachate was most highly correlated with TKN, then TN and then NO_3 (Table 3-18). Nitrate and TN leachate loads were very highly correlated (0.99, $p < 0.001$). There was a slight negative correlation between TP/TKN and the amount of water retained. The more water that was received by the bins via rain and irrigation, the more quantity of nutrient was leached, this was seen more clearly for TP and TKN ($r^2 = 0.72$ and 0.73, respectively with $p<0.001$ each.) The input of water and the higher correlation of TP leaving may relate to organic P leaching due to particulates leaving the system and/or increased contact time with the soil.

Table 3-18. Pearson correlation coefficients among nutrient loads in leachate, water retention and $water_{in}$.

Pearson Correlation Coefficients, Prob > |r| under H0: Rho=0, Number of Observations						
	TP	TKN	NO_3	TN	Ret	Water_in
TP		0.97 <.0001 144	0.84 <.0001 144	0.86 <.0001 144	-0.31 0.0008 108	0.72 <.0001 144
TKN	0.97 <.0001 144		0.90 <.0001 144	0.92 <.0001 144	-0.28 0.0025 108	0.73 <.0001 144
NO_3	0.84 <.0001 144	0.90 <.0001 144		0.99 <.0001 144	-0.14 0.1334 108	0.51 <.0001 144
TN	0.86 <.0001 144	0.92 <.0001 144	0.99 <.0001 144		-0.15 0.0990 108	0.53 <.0001 144
Ret	-0.31 0.0008 108	-0.28 0.0025 108	-0.14 0.13 108	-0.15 0.09 108		-0.41 <.0001 108
Water_in	0.72 <.0001 144	0.73 <.0001 144	0.51 <.0001 144	0.53 <.0001 144	-0.41 <.0001 108	

Conclusions

The first goal of the study, to characterize the total load of TN and TP leached during the establishment phase (defined as the first 6 weeks after planting) of a shallow green roof in north central Florida, was met. The range of TP loads for the establishment period ranged from 110 mg P m^{-2} for Up to 1800 mg P m^{-2} for Hs and Hm for total phosphorus. For total nitrogen the range was 190 mg N m^{-2} (Ur) to 1800 mg N m^{-2} (Hs). It was found that the bulk of the nutrients, irrespective of nutrient type (TP, TN—TKN, NO_3), were leached out of all plant-growing medium combination in the first six week period, as compared to any other time period in the 24 week study period. For example, TN loads in leachate from the first 6 weeks of establishment comprised 89% of the cumulative load of TN for the entire 24 week study period for all growing media types.

The differences in nutrient loads (for all nutrient types) among growing media types were more significant than among plant types. For example, the TN load in the establishment period for H was 1694 mg N m^{-2}, which was 10 times higher than that of U (169 mg N m^{-2}) and 5 times higher than in B (384 mg N m^{-2}); for the subsequent time periods the difference in load among the growing medium types was less, and over time, the absolute values dropped ten fold for each growing medium to a range of 145 mg N m^{-2} to 31 mg N m^{-2} for weeks 12 to 24 respectively for H, 33 mg N m^{-2} to 7 mg N m^{-2} for B, and 1403 mg N m^{-2} for U, for weeks 12 to 24 respectively.

The null hypothesis that there would be no significant differences in total load of TN and TP among growing media for the establishment period or for the entire 24-week study period was rejected and the alternative hypothesis was accepted. Nutrient loads varied the most significantly among growing medium types and secondarily among plant types.

For all nutrients there was an effect of time, this was more slight in TKN loads ($p = 0.056$), and seen most strongly in TP loads ($p < 0.001$). TP concentrations from this study for leachate from B and U (ranging from b.d. to 1 mg/L over all time periods), were in a similar range to TP concentrations found in other green roof studies, slightly higher than those from Berndstonn et al. (2009) and (2006) and slightly lower than TP concentrations in Moran (2005). TP concentrations from H were much higher than values reported in the literature for green roofs (Berndstonn (2006 and 2009), Kim (2006) and Moran (2005). The hypothesis that there would be no significant differences in TP load among plant-growing medium combinations was rejected and the alternative hypothesis was accepted. Mean TP loads for each plant-growing medium combination were analyzed using the least squares means method for comparing interactions among plant–growing medium combinations on TP load over all time periods combined showed that for all plant types in U bins, as well as the plant-growing medium combination, Bp, were not significantly different from the overall mean TP load, while Bm, Br, Bs and all plant types in H bins were significantly higher than the overall mean. Mean TP loads for plant-growing medium combinations for the entire study period ranged from 18–22 mg P m^{-2}

for U (with Ur being the lowest and Us the highest within U), 30 - 42 mg m^{-2} for B (with Bp being the lowest and Bs the highest) and 90-140 mg m^{-2} for Hydrotech (with Hr being the lowest and Hm being the highest.

Plant effect on cumulative TP load over the whole study period was that perennials had the lowest load and succulents had the highest load within each growing media type. Total cumulative TP load for the various combinations ranged from a low of 150 mg m^{-2} for Up to a high of 3200 mg m^{-2} for Hs. Cumulative TP loads from leachate from Building Logics growing medium was in the middle with a range from 310 mg m^{-2} (Bm, Bp, Br) to 450 mg m^{-2} (Bs).

Plant effect on TN was that irregardless of growing medium type, TN loads from runners in each time period were significantly lower than TN loads from succulents, which always had the highest TN load in every time step (though not always significantly higher than bare media).

With regards to a concentration based first flush effect, it was found that for TP there was no CBFF within the first six hours (concentrations were measured 20 minutes post-irrigation, 1 hour post-irrigation and 6-hours post-irrigation). There were no significant differences in concentrations in these intervals, however there was a mass based first flush effect for the runoff in the first 20 minutes, simply because the majority of the leachate volume percolated through the medium in the first 20 minutes generating the most volume of any of the time increments and hence resulting in the greatest mass load of nutrients of any of the time increments.

The hypothesis that concentrations in leachate for all nutrients would diminish over the whole study period was accepted, as concentrations of TP, TN, NO_3, TKN did decrease in the lysimetric samples over the whole study period (24 weeks).

Implications of the findings are that since a) the nutrient loads in leachate varied most significantly among the growing medium types, but plant health did not vary significantly between media with even ten-fold differences in nutrient levels in leachate (for example TN loads in H versus U), and b) the nutrient levels in all the media approach the same levels between weeks 12 and 18, it is recommendable to not pre-fertilize or pre-mix excessive fertilizers into the growing medium before planting. The findings indicate that all excess nutrients were not plant available and were not taken up by the plants, but rather would have entered stormwater runoff, posing an ecological threat to receiving water bodies. (Excessive nutrients were being defined as any nutrient that washed out and was not taken up by the plants.)

It is suggested that green roofing media manufacturers in the sub-tropics (Florida) add the minimum levels of nutrients necessary for plant growth to growing media and test that those levels are not exceeded at any time. The initial nutrient content and make-up of the forms of N and P in U growing medium (high organic matter, even gradation of the material) resulted in less nutrient leaching for all nutrient types and excellent plant health. The plant health in bins containing U were comparable to plant health in bins containing H growing medium, which had the highest amount of excess nutrients in the leachate. It is unadvisable to connect green roof directly to receiving waterbodies before further treatment—such as bioretention, vegetative filter strips or wet detention at the ground level. It is recommendable to attach a cistern to the green roof system to recirculate the collected green roof runoff to re-utilize nutrients in the runoff either on the green roof itself or at the ground-level landscape.

In summary, the three growing media initially had nutrient loads in leachate that were significantly different, with Hydrotech having the highest nutrient loads and UCF with the lowest. Within 18 weeks all growing media had leached out the majority of their excess nutrients and began to have comparable levels of nutrients in the leachate (no significant differences among growing medium types). Despite the fact that Hydrotech's nutrient levels in leachate had dropped many-fold by the end of the 24 week study period, it was still the overall highest nutrient load contributor to leachate among the three growing medium types, irrespective of plant type.

Regarding plant types, it is interesting to note that two genera of succulents, Sedum spp. and Delosperma, which are known to do well in North Carolina (Moran 2004), but anecdotally have been said to do poorly in Florida, constituted two of three genera that survived all time periods (drought, frost and heavy rains). However, plant effect-wise these succulents did not improve water quality, infact leachate from bins containing succulents had nutrient loads that were significantly higher than leachate from other plant types and even bare media in 3 of the 4 time periods for TP.

While runners overall had the lowest TP loads among plant types, they were adversely affected by frost and perished in the cold. Therefore for future studies, instead of testing leguminous runners again, the plants that eventually colonized the abandoned bins on their own and survived without irrigation and survived frost should be tested, such as subtropical grasses—which also have the same morphological tendencies as the runners in this study.

Finally, in review, since 1) all the nutrients that leached out of the during the study would have entered directly to the storm water system had they been on a roof, 2) all growing media regardless of initial nutrient levels, eventually reached the same comparable nutrient loading levels in leachate by 18 weeks and 3) there were no noticeable differences in plant health between soil types U and H, despite differences in soil P and N levels, it is recommended for green roofs in Florida to begin with a low nutrient growing media from the start and to investigate the use of slow release fertilizers in growing media mixtures in the future.

CHAPTER 4
WATER QUANTITY AND QUALITY IN PAIRED GREEN ROOF STUDIES IN FLORIDA AND VIRGINIA

Introduction

Stormwater Best Management Practices (BMPs) can reduce runoff in various ways, such as interception, soil infiltration, evaporation, transpiration, rainfall harvesting, engineered infiltration or extended exfiltration (CWP, 2008). In the case of green roofs, differences in runoff retention are affected mainly by 1) the green roof design (growing medium depth, roof slope) and 2) climate (annual rainfall, size of the storms and duration since the previous storm) (CWP & CSN, 2008; Van Woert et al., 2006; Simmons et al., 2006). To review, from top down, green roofs consist of plants, growing medium, followed by a filter cloth, then drainage layer, than root barrier and impermeable membrane, then roof deck. The constituents chosen to create the growing medium can affect water retention; for example, the addition of organic matter and perlite to the medium can increase porosity and lower bulk density and affect water retention directly or by making the pore size distribution favorable to water retention (Brady and Weil, 2002).

Additionally, micro and meso structures in the growing medium, as well as the drainage layer (pores, irregularities, high surface area) can contribute to the retention characteristics (Simmons et al., 2008). As a result of all these factors that can influence rainfall retention in green roofs, the range of volumetric runoff reduction reported for northern climates varies tremendously (Table 4-1).

Green roofs in northern climates are reported in the literature to retain between 30% (Getter et al., 2007 in CWP, 2008) and 94% (Gangnes, 2007) of cumulative rainfall for the time period monitored. Simmons et al. (2008) reported retention rates for green roofs in the subtropics (Austin, Texas) where six different green roof designs with 10 cm of growing media planted with native perennial plants were tested with 12 mm, 28 mm and 49 mm events. The mean retention ranged from 100% (for <10 mm events), 28%-88% retention for the 12 mm event and 8% to 44% (for the 28 mm and 49 mm events) depending on the design of the green roof.

Table 4-1. Range of runoff reduction for green roofs in various climates, using the Köppen-Geiger climate classification system (Peel et al 2007).

Location	Climate/ Rainfall	Runoff Reduction	Reference
USA		40-45%	Jarrett et al (2007)
Germany	Temperate Oceanic Temperate Continental	54%	Mentens et al (2005) in CWP
Michigan	Temperate Continental	30-85%	Getter et al (2007) in CWP
Oregon	Temperate Mediterranean	68-69%	Hutchinson (2003) in CWP
N. Carolina	Warm oceanic climate	55-63%	Moran and Hunt (2005)
Pennsylvania	Warm continental climate	45%	Denardo et al (2005)
Michigan	Temperate continental	60-70%	Van Woert et al (2005)
Ontario	Temperate continental	54-76%	Banting et al (2005) in CWP
Georgia	Warm oceanic climate	43-60%	Carter and Jackson (2007)
Texas	Warm semi-arid climate	33%	Simmons et al (2008)
Seattle, WA	Cool oceanic climate	65%-94%	Gangnes (2007)

Climates listed are based on the Köppen-Geiger climate classification from Peel, M. C. and Finlayson, B. L. and McMahon, T. A. (2007).

Information in the table is adapted from Center for Watershed Protection (CWP) (2003).

Effect of Green Roof Growing Medium and Drainage Layer on Retention

Another factor that influences water retention in green roofs is the design of the drainage layer. Differences in retention found in Simmons et al. (2008) were largely attributed to drainage layer differences and secondarily, to the differences in constituents of the growing media used. Drainage layers can vary vastly in design, ranging from an aggregate layer with perforated pipes (UCF green roof), to a geotextile with nylon coils (eg. XeroFlor XF158 used by Van Woert et al. (2006) in Michigan), to egg carton like cups in a hard corrugated plastic, such as Zinco's Floradrain™ FD 25 drainage layer (used by Hydrotech, Inc. in this study). Differences in water retention due to the drainage layer can vary greatly between studies, for example, from 2 L m^{-2} for Xeroflor XF 158 to 3 L m^{-2} for Floradrain™ FD25 used in the Florida roof in this monitoring study, to even greater volumes for aggregate drainage layers (Gangnes, 2007).

As for the influence of individual constituents used in the growing medium, Simmons et al. (2006) noted that the green roof type that consistently had the highest retention had a higher proportion of perlite in the substance (95%) by volume.. In Portland, Oregon, Beyerlein (2005) found that two halves of a roof (built at the same time, with the same depth, same slope, and similar porosities) had different overall water retention due to differences in the constituents. The author found that the roof half containing 20% digested fiber, 10% compost, 22% coarse perlite and 28% sandy loam, retained significantly more water than the roof half consisting of 15% digested fiber, 25% encapsulated Styrofoam, 15% perlite and 15% coarse peat moss and 15% compost. In other words, the medium that contained sandy loam—a constituent with a finer pore size distribution than other components, such coarse peat moss, and more perlite rather than any Styrofoam had greater retention. While both Styrofoam and perlite have similar bulk densities of approximately 0.04 g/cm^3, perlite has a much higher water adsorption capacity than Styrofoam. The latter having a water adsorption capacity of 0.25%, while perlite, an expanded volcanic glass, has a 200% - 600% water content by weight. Sandy loam in the mix may have accounted for a higher proportion of finer pores than the coarser mixture with the same porosity, since fine pores allow for more evapotranspiration to occur (as compared to a coarse mixture of gravel), releasing more water from the medium between storms and consequently making more pore spaces available for water storage for the next storm.

While greater medium depth can be beneficial in providing more overall pore space for the storage of stormwater, Gangnes (2007) in Seattle, found that growing medium that is too thick will inhibit evaporation out of the lower layers of the growing medium stratum. He compared the decrease of soil moisture in 5.1 cm, 10.2 cm, 15.2 cm and 20.3 cm depths of growing medium after a 1.27 cm (1/2-inch) storm, and found that the soil moisture decreased between 0.5 cm and

1.27 cm in the growing media that were between 5.1 cm and 15.2 cm deep over 48 hours, while the soil moisture in the 20.3 cm deep growing medium decreased less than 0.25 cm over a period of 60 hours.

Effect of Climate and Rain Event Characteristics on Green Roof Water Retention and BMP Design

Climate and geographical location determine the rainfall pattern, rainfall intensity, evapotranspiration rates and vegetation of a region, therefore water retention of green roofs is highly influenced by the climate and is variable from climatic region to region (Table 4-1). The study areas, Gainesville, Florida and Merrifield, Virginia, both technically belong to the Humid Subtropical Climate (Cfa) according to the Köppen-Geiger climate classification system (Peel et al., 2007); with the Gainesville roof being located at the southern most extent of this classification, and the Virginia roof located at the northern most extent of this climate. Humid Subtropical (Cfa) is characterized by hot, humid summers (warmest mean monthly temperature >22°C) and cool winters (coldest mean monthly temperature between -3°C and 18°C). Humid Subtropical Climates are defined as receiving significant amounts of precipitation in all seasons. Winter rainfall in a Humid Subtropical Climate is attributed to large storms blown across the content by the westerlies and summer rainfall is largely associated with convective thunderstorms and occasional tropical storms or hurricanes.

While Virginia, technically also meets the Köppen-Geiger's definition of "humid subtropical climate without a dry season", based on its latitude, mean warm and cool month temperatures and rainfall patterns, American climatologists often adapt Köppen's definition of Humid Continental to include Virginia, by lowering the mean cool month temperatures (Peel et al., 2007).

Subtropical and tropical green roofs experience elevated ET rates, rainfall rates and peak intensity during rain storms that are often higher than in temperate regions (Wong et al., 2002; Kohler et al., 2001). Variation in storm volume and intensity can affect different attributes of the rainfall, such things as the erosivity of the rainfall and influences sediment yield and water quality of the runoff (Trimble, 2007), as well as when the peak of concentration occurs and the lag time to peak of the runoff. Similarly designed green roofs placed in different climates may behave very differently (for example, due to differences in ET rates of the same plants in different climates, and due to influence of storm cycles and length of dry periods on soil moisture and water retention), the location of the green roof may affect the performance of the green roof for water retention and may also affect water quality of the runoff. For this reason, the present study monitored two roofs in different extremes of one climatic region. I investigated how a 15 cm deep green roof behaved hydrologically in a sub-tropical climate in Gainesville, Florida, as well as how a 7 cm deep green roof in Virginia. I characterized to what degree these green roofs increased the peak to lag time, increased the delay to the start of runoff after rainfall begins and increased the duration of return flow and reduced the total volume of runoff, if at all. Quantification of these characteristics of a green roof should assist stormwater engineers in designing and rating green roofs as a possible BMP to control volume and peak runoff rates that can meet regional criteria for stormwater BMPs.

Stormwater BMPs in Florida are based on a “critical design storm” that has a specified peak intensity, duration and total volume depending on the region in question. Additionally, stormwater BMPs are regulated to retain a specified portion of the stormwater water, and attain a specified outflow rate within a set period of time, depending on the region and regulating body. For example, in the case of the Charles R. Perry Construction Yard (CRPCY) green roof; it is located within the Ocklawaha River Basin and regulated by the St. John's River Management District. Stormwater detention facilities in this watershed must be designed such that the post-development total runoff volume does not exceed the pre-development runoff for the 25-yr, 24-hr storm. Additionally, the rate of discharge from a water detention facility may not exceed the peak pre-development discharge rate for a 24-hour duration storm. Since the CRPCY green roof may be assisting in attenuating the peak runoff rate of a wide variety of storms and may be lowering the total of volume of runoff from storms (by detaining a portion of the runoff in the growing media and transpiring a fraction of that rain back to the atmosphere); green roofs in Gainesville may be able to partially fulfill the water quantity requirements for stormwater detention BMPs specified by the SJWMD for developments in the region and therefore reduce the need or lessen the size of on-the-ground stormwater detention facilities down-slope from a building covered with a green roof. The results of this project can be used by stormwater managers, such as the SJWMD or the Stormwater Planning Division of Fairfax County, Virginia and economists to determine the possible economic benefits of green roofs from a stormwater storage perspective.

Stormwater Detention BMPs and Critical Design Storms

In many regions stormwater detention in new developments are based on a large rain event, such as the 25-yr, 24-hr storm event in the Ocklawaha Basin, yet in a humid subtropical climate and humid continental climate (FL and VA), 80% of the storm events of the year are small storms (<2.54 cm in FL, and <2.4 cm in VA) (Casey Trees, 2007). For example, in Alabama, also located in the humid subtropical climate, over a nine year period, rain size and runoff was monitored by Pitt et al. (2007). They found that the majority of the storm events (65% of the rain events) were less than 1.27 cm and generated only 10% of the runoff for the time period, and the storms between 1.27 cm and 7.62 cm accounted for 30% of the rain events and generated the majority (75%) of the runoff volume. The larger storms (7.6 – 20 cm) made up only 3% of the storms and generated 13% of the runoff and storms greater than 20 cm were infrequent (less than <0.1% of the rain events) and generated <2% of the runoff for the study period (Pitt et al., 2007). Since small and medium sized storms both account for the majority of the storms during the year, as well as the majority of the runoff, Low Impact Developments (LID) techniques typically focus on detaining and treating the water from these storms, making large, costly and unsightly conventional stormwater facilities obsolete. By capturing 80% of the year's rain events, or at least attenuating these events, LID techniques, such as green roofs, reduce the need for as many large BMPs on the ground, such as wet detention, dry detention, and exfiltration trenches and even bioretention cells, which can save both space and money for the developer and the county. Coupled with cisterns, the reduction in total stormwater volume can be even greater than that of the green roof alone, reaching as much as 87% as reported by Hardin (2006) for Central Florida. Additionally, this water can be reused on site for either irrigation of the vegetation at ground level or reused for irrigation of the green roof during periods of low precipitation or high heat and ET.

Water Quality and Green Roofs

Rooftops as a source of urban stormwater

Urban areas contribute large amounts of stormwater runoff and pollutants due to impervious surfaces. In a highly urbanized city setting, approximately 72% of the land area is impervious (Schueler, 2001), and 40% of the imperviousness is comprised of rooftops (Urbonas, 2001; and Liptan, 2003); the other 60% of the imperviousness is "car habitat".

Rooftop runoff poses a greater threat to water quantity in urban watersheds than rural watersheds. This is because the runoff enters receiving water bodies more rapidly in urban areas than in rural settings due to the greater connectivity of roofs to gutters and storm sewers. The presence of pavement impedes infiltration to groundwater, increasing the proportion of water going to surface overland flow and increasing the velocity of the runoff. When surfaces are paved, vegetation that originally provided interception and evapotranspiration is removed, and natural depressions in the landscape, which normally detain 50% of the runoff, are eliminated (Dunne and Leopold, 1978). The volume and rate at which the runoff is delivered to the receiving water body is greatly increased (Andoh, 1997), resulting in a reduction of the hydrologic response time and greater recurrence of floods.

Deterioration of the receiving water bodies in urban areas is usually first noticed visually as channel erosion and degradation (Liptan and Strecker, 2003). The effects of stormwater runoff on water quality become evident later, when biological imbalance relative to predisturbance conditions occur (Stribling and Leppo, 2001).

Since sediment concentration is a function of a combination of rainfall intensity and runoff rate (Trimble, 2007), green roofs, that can effectively lower the runoff rate and runoff amount from a developed area, have the potential of lowering the amount of soil particles that it detaches and transports enroute to a receiving water body, or in the receiving water body itself. Secondly, because of the importance in the relationship between rainfall intensity, the kinetic energy of the rain drops formed and their erosive power, it is important that a green roof be vegetated, for positive effects of water quality with relation to sediment yield and adsorbed P associated with an increased sediment yield.

Rooftops contribute to stormwater pollution via two mechanisms, one is through the release of constituents from the roofing materials used—such as zinc, copper, polyaromatic hydrocarbons (PAHs), cadmium or lead (Clark, 2001) and secondly from atmospheric deposition—for example nitrogen, phosphorus and even pesticides (Moran, 2003; Dietz et al., 2005). Researchers in Michigan looking for sources of stormwater contaminants found rooftops to be the largest source of dissolved metals, while parking lots contributed the PAHs (Clark, 2001). Another study comparing old metal roofs with new built-up roofs and old wood roofs with tar, found the new built up roof to contribute 10 times as much total copper (0.13 mg L^{-1}) than the other two types; and found that the old metal roof contributed the highest amount of lead (0.035 mg L^{-1}) and zinc (11.9 mg L^{-1}) (Clark, 2001). Copper is the 3rd most utilized metal by man after aluminum and steel (Jolly, 2000 in Arnold, 2005), it is used in residential and commercial architecture because it is attractive, durable and a fire retardant. Currently copper products used in exterior architectural applications average 168.3 million kg/yr between 2001 and 2004 (Copper Development Association, 2005 in Arnold, 2005). Since copper is used in exterior applications, it weathers due to all forms of precipitation; the quantity of Cu that dissolves and is transported is a function of atmospheric chemistry precipitation and roof orientation. Estimated copper loading rate for roof runoff for the US based on 179 locations and the factors mentioned above (precipitation chemistry, amount of precipitation and roof aspect) is 2.12 g Cu/m2/yr with a range from 1.05 g Cu/m2/yr to 4.85 g/m2/yr, depending on location (Arnold, 2005). Copper in small quantities can be benign or beneficial, however even at low doses in the (ug/L) range, copper can become toxic to aquatic organisms and other forms of life (Arnold, 2005).

In Charlotte, North Carolina, atmospheric deposition constituted 10-30% of total phosphorus and nitrogen as nitrate, 30-50% of orthophosphorus, and 70-90% of total Kjeldahl nitrogen and ammonia in stormwater runoff (Wu, 1998 in Moran, 2003). Rural roofs, especially those located within a 1-3 mile area of agricultural areas receive atmospheric deposits of nitrogen

(N) and phosphorus (P), as well as pesticides in residential areas (Moran, 2003). In one Florida example, total inorganic nitrogen deposition was estimated to be 17 kg N ha^{-1} yr^{-1} or 9,700 metric tons yr^{-1} in the Tampa Bay Watershed. The ratio of dry to wet deposition rates for inorganic nitrogen was 2.3. Ammonia (NH_3) and nitrogen oxides (NO_x) contributed the most to the total N flux with 4.6 kg-N ha^{-1} yr^{-1} and 5.1 kg-N ha^{-1} yr^{-1}, respectively. Average wet deposition rates were 2.3 and 2.7 kg-N ha−1 yr−1 for NH_4 and NO_3, respectively (Poor et al., 2006).

There are three likely mechanism by which green roofs could reduce nutrient loads 1) retain or transform contaminant, 2) reduce volume of water thereby reducing contaminant load assuming concentration does not change, and 3) reducing volume thereby reducing velocities in downstream channels thereby reducing scour and sediment transport.

Green roofs can reduce contamination from rooftops by reducing the amount of water leaving the roof (De Nardo, 2003; Van Woert, 2005; Liptan, 2003; Villareal, 2004) and, by plant uptake and transformations of N and P deposited atmospherically or added by fertilization (Berndtsonn, 2006). In a second study in Sweden, Berndtsson et al. (2006) examined green roof runoff quality from green roofs over bicycle parks in Malmo, Sweden and green roofs covering a school in Augustenborg, Sweden. They found that the green roofs in Augustenborg acted as a sink for nitrogen, reducing TN by 58% (rain water contained 909 mg TN m^{-2} yr^{-1} and effluent from the roofs contained 378 mg TN m^{-2} yr^{-1}); and the roof behaved as a source for phosphorus and potassium. They also found that the green roofs behaved differently either due to age, parent materials or input levels with regards to metals in runoff. The newer green roof in Malmo acted as a sink for lead, while the older green roof on top of the school in Augustenborg behaved as a source for lead. The results of German study on vegetated roof research plots at the Technical

University of Berlin in contrast, reported that over a 3-year period the green roof plots were capable of retaining 95%, 88%, 80% and 68% of the loads of Pb, Cd, NO_3 and PO_4 (in Berndtsson et al., 2006) applied to the plots. The authors did notice that at low level inputs the roof could act as a source, but at high level inputs the green roof acted as a sink.

Since similarly designed green roofs placed in different climates may behave very differently, I am studying how a green roof behaves in a sub-tropical climate in Gainesville, Florida, as well as one in the transitional zone out of sub-tropical into humid continental, to characterize to what degree different green roofs in this climate will increase the peak to lag time, increase the delay to the start of runoff after rainfall begins and increase the duration of return flow and reduce the total volume of runoff. Quantifying these characteristics of a green roof will assist stormwater engineers in designing and rating green roofs as a possible BMP to control volume and peak runoff rates that can meet existing state-wide, county-wide or Water Management District-wide criteria for stormwater BMPs. Urban areas are one of the largest contributors of runoff and pollution to waterways.

Hypotheses and Objectives

Green roofs have been studied extensively in temperate climates for their effectiveness in reducing stormwater quantity. However, little is known about how effectively green roofs:

- function in subtropical climates, such as Florida and Virginia
- act as a source, sink or transformer of nutrients
- plant type influences green roof function

The general objectives of this portion of the research are to:

- Compare water retention capabilities and affect on lag time and peak runoff attenuation of green roofs as compared to modeled conventional roof runoff at two extremes of the subtropical climate type

- Determine if green roofs act as a source or sink for nutrients and metals in these same two subtropical locations

Hypotheses

The hypotheses for the two paired green roof/conventional roof monitoring studies were:

H1: The overall benefit of green roofs for water retention, peak runoff attenuation and increases in lag time to peak runoff will be less in green roofs in Florida than in Virginia, because of higher peak precipitation rates, greater total volume of rain events, and greater recurrence of convective storms in a humid subtropical climate (Florida) than in the transitional zone of the humid subtropical climate into a humid continental climate (Virginia).

H2: Green roofs' influence on water quality in stormwater runoff will be similar in Virginia and Florida and will act as a sink for nitrogen and source for phosphorus and sediment, and may be either a sink or source for metals, when compared to conventional roofs.

Specific Objectives

The specific objectives of the monitoring were to:

1. Determine whether green roofs can mitigate for stormwater quantity in the same manner at the two geographic extremes of one climatic zone, by quantifying the amount of stormwater retention, peak runoff attenuation, and increase in lag time to peak, if any, due to the presence of a green roof in both Florida and Virginia.

2. Measure water quality—concentration and load of nutrients (NO_3/NO_2, PO_4, TDS, TSS) and metals (Cd, Zn, Al, Fe, Cu)— in green roof and conventional roof runoff in Florida and Virginia to determine whether the green roofs are acting as a sink or source for N, P and metals, and whether they are behaving the same way (as a sink or source) for the same parameters in both extremes of one climatic region (Florida and Virginia).

Materials and Methods

Study Site 1: Florida

The Charles R. Perry Yard structure is a single story building with a green roof of approximately 241.5 m^2 (2600 square feet) with a 1:12 slope. The building is adjunct to the existing Rinker Hall. The green roof consists of 15 cm depth of Hydrolite® growing medium underlain by 5 cm of green roof underlayment material provided by American Hydrotech, Inc. (Table 4-2). The green roof was installed and planted in March 2007. It is visible from the second and third floor windows of the east side of Rinker Hall (Figures 4-1 and 4-2).

Table 4-2. Underlayment of the Hydrotech green roof. Source: Hydrotech Specification Sheet (2005).

Material	Purpose
MM 6125	Waterproof membrane
Surface Conditioner	concrete conditioner
FlexFlash F	membrane reinforcement
FlexFlash UN	flashings 12" x 100'
Hydroflex RB	protection/root barrier
Floradrain FD25	drainage/H2O retention
SystemFilter SF	Filter Fabric
LiteTop Intensive	6" LiteTop Intensive Soil

Figure 4-1. Photo of the Charles R. Perry Construction Yard after bituminous water proof layer was cold applied, photo taken from the third floor conference room, March 2007.

Figure 4-2. Photo of the installation of plants on the CRP green roof. Photo was taken from the third floor conference room of Rinker Hall in April 2007.

Growing media

The growing media used was Hydrotech's "Litetop" ®, which consists of 45-70% Lite Top Lightweight aggregate (0.015 cm to 0.95 cm aggregate), 0-30% Coarse to Medium Sand, 0-30% Perlite, Sphagnum, or Other Lightweight Soil Additive and 5-30% Approved Compost and Nutrient additives "as needed". Chapter 2 shows the results of our own analysis of grain size distribution of the bulk growing medium delivered by Hydrotech to UF, used on the CRP green roof and Chapter 3 contains the results of the TP/TN analysis of the medium. Table 4-3 shows the density and saturated water and air content, the OM and C:N ratio reported by Hydrotech and Table 4-4 show the nutrients added, also from the Hydrotech Specification sheet.

Table 4-3. Physical properties of Hydrotech LiteTop® growing medium. Source: Hydrotech Specification Sheet (2005).

Property	Value
Dry bulk density	0.6-1.1 g cm^{-3}
Saturated bulk density	1.0-1.5 g cm^{-3}
Saturated water capacity	> 40%
Saturated air content	> 10%
Organic matter content (mass %)	6 – 12%
C/N ratio	< 20
CEC	> 6

Table 4-4. Nutrients added to Hydrotech LiteTop® growing medium. Source: Hydrotech Specification Sheet (2005).

	Concentration Mass basis		Areal Loading Rate	
Nutrient (Plant Available)	Min g kg^{-1}	Max g kg^{-1}	Min g m^{-2}	Max g m^{-2}
Nitrogen(NO_3,NH_4)	0.047	0.236	7.7	38.3
Phosphorus	0.016	0.110	2.6	17.9
Potassium	0.094	0.236	15.3	38.3
Calcium	0.298	1.021	48.5	166.0
Magnesium	0.047	0.236	7.7	38.3
Sulfur	0.016	0.055	2.6	8.9
Iron	0.016	0.047	2.6	7.7
Manganese	0.016	0.047	2.6	7.7
Copper	0.004	0.008	0.6	1.3
Boron	0.004	0.008	0.6	1.3
Zinc	0.0002	0.0004	0.0	0.1

Cisterns and pump station

Two 5670 L cisterns, 1.6 m diameter by 2.9 m high were installed above ground located approximately 9.1 m from the building. Black polyethylene tanks were chosen over clear tanks to inhibit possible growth of algae. The water from these cisterns was delivered back to the roof through a 1 hp pump (see Appendix O). Cistern sizing was determined based on storage volume sufficient for 3 weeks of irrigation at a rate of 1.27 cm of water two times per week to reduce the need for supplemental water. The cisterns were located away from the building with pipes from the downspouts located underground (Appendix O). Firm, even, compacted beds of sand and gravel were constructed in February 2007 for the tanks.

Water from the cisterns (which consisted of rain runoff and irrigation runoff) were pumped from the cisterns to the roof via 3.175 cm (1 ¼") PVC pipes. These pipes ran horizontally underground to the edge of the CRP Construction Yard building and then vertically up the side of the building. Once on the roof, the irrigation water was transported laterally through one 1.9 cm (¾") PVC pipe along the edge of the green roof, and from there entered through connectors into each of forty-seven 1.27 cm dia. (½") Netafim® lines covering the roof surface evenly, laying perpendicular to the main PVC pipeline.

The pump station by Resources Recovery, Inc. consisted of a control panel, a filter box, a reservoir tank, a pump and junction box, a switch conduit, a pump intake pipe, irrigation tap, the purge tap and the primary tap. The control panel housed the electronics that operated the switches and pumps. A backflow preventer was installed on the incoming potable water line, however originally there was no backflow preventer on the incoming UF reclaimed irrigation line, which had allowed for sudden drops in water due to irrigation occurring on the UF campus located at an elevation lower than the cisterns. A check valve was added to the UF reclaimed irrigation line in April 2008 to prevent a siphon effect from occurring when UF Physical Plant

Department (PPD) would either 1) shut off its pump stations during heavy storms, causing the line to no longer be pressurized or 2) irrigate at an elevation lower than the cisterns, or 3) experience a break in an irrigation pipe at an elevation lower than the cisterns.

After the water was pumped to the roof and the green roof was irrigated, the runoff was collected by two 10.2 cm (4") drains, one for each half of the roof, which merged into one 10.2 cm (4") pipe underneath the eaves of the building and that turned vertical and carried the water underground to a Y-junction, where a valve controlled whether the runoff flowed to an existing stormwater drain or instead to the cisterns to be monitored. For the period of the study, the valve was switched to the cisterns.

Automated irrigation system

Netafim® micro-irrigation system, donated by Rainbird, Inc., was installed in March 2007. Tubing, 1.27 cm (½") in diameter was spaced 30.5 cm (12") apart in parallel rows, covering the entire roof. Irrigation times were set for 3 times weekly for 1.27 cm (34 min) at 5 am on Mondays, Wednesdays and Saturdays from March 2007 to July 2007 and later reset to 2 times weekly on Mondays and Thursdays at 5 am. Because of excessive runoff after irrigation, the duration was further reduced to 26 min in March 2008, the equivalent of 0.91 cm of water. When it was noticed that water was insufficient (plants browning slightly), the irrigation frequency was raised to 4 times weekly but the duration was lowered to 17 minutes (or 0.635 cm irrigation depth) starting June 27, 2008 (Monday, Wednesday, Friday, Sunday at 5 am). This new regime of more frequent, yet shorter duration irrigation events resulted in less runoff and greener plants. The final irrigation arrangement remained 0.635 cm of water, 4 times a week (for a total of 2.54 cm per week).

Study Site 2: Virginia

Yorktowne Square Condominium green roof was retrofit onto a 1968 condominium building in 2002 by Building Logics, Inc. (Figure 4-3) at the same time that a new conventional roof (bituminous asphalt shingle) was installed on a different section of the same building (Figure 4-4). The green roof was an EnviroTech system, construction of the roof consisted of a base sheet of tar covered with a 2-ply membrane with copper foil root barrier, which consisted of one ply Famobit P4 and another ply of Famogreen RET CU-P4, as the top ply. The two membranes consist of a high-grape polymeric bitumen sheet and was modified with age stabilizing amorphous polyalphaolefin (APAO). Hydrogel packs are laminated to the top surface of the APAO membrane. Drainage occurs through and around the gel packs and eliminates the need for a separate drainage layer. The storage of water in the underlayment is specified as 3L m-2. The Famobit layers were followed by a filter cloth and 6.35 cm of Building Logics growing medium planted with 8,400 plugs of *Sedum album*, *S. sexangular* and *S. reflexum*.

Figure 4-3. Green roof installed by Building Logics in 2002, planted with 8,400 sedum plugs (*S. album, S. sexangular,* and *S. reflexum*). Photo taken May 2005.

Figure 4-4. Conventional Roof at Yorktowne Square Condominiums, built in 2002, at the same time as the green roof on the adjacent building. Note puddling after rainfall, shown in foreground of photo.

Runoff was collected at the Yorktowne Square green roof in Virginia from May 2006 to September 2008 in two 3426 L (905 gallon) cisterns from 1/8th of each roof surface or 48.8 m2 (525 sq. ft.). Two Global Water WL15 Level Loggers pressure transducers monitored the stage height inside the cisterns and a rain gauge on top of the roof outfitted with RainLoader 2.1 software recorded rainfall.

Data Collection and Analyses

Rainfall data in Florida was collected by the UF Physics Department weather station using Texas Weather Instruments WRL-25 weather monitor, on campus located 400 m from the green roof. Rainfall and runoff data were collected in 5 minute increments and paired together to create cumulative and individual storm hydrographs. In Virginia, rainfall was monitored using a rain gage located on top of the green roof and data was collected using RainLoader2.1 software.

Green roof runoff flow rates and volume measurements were calculated based on change in stage height in the cisterns. The stage height was monitored using a Global Water (Gold River, CA) pressure transducer. Global Logger II (Ver. 2.1.2) software program was employed to download data bimonthly from July 2007 to September 2008 in Florida and from July 2006 to August 2008 in Virginia. In Florida, the pressure transducer was placed on the bottom of one of the two cisterns, which were connected to each other and had the same base level, so that the water levels in both cisterns were always equal. The measured water level was multiplied by the cross-sectional area of the two cisterns to yield the volume of runoff. Runoff volume was consequently divided by total roof area (415 m^2), resulting in centimeters of runoff per roof area, so that it could easily be compared to precipitation, which was also reported in cm.

In Virginia, one pressure transducer was placed in each cistern—one for the green roof and one for the conventional roof— and stage height was multiplied by the cross-sectional area of the cistern and divided by the roof area represented by the runoff (48.8 m^2), which was one-eighth of the green roof. The identical amount of roof area was monitored for the conventional roof as for the green roof, also the conventional roof had the same aspect and slope as the green roof and were the same age, as they were both rebuilt in 2002.

Analysis of cumulative rain and runoff

Cumulative runoff data from the Florida green roof was paired with cumulative rain data for each seasonal period where data existed. There were certain brief periods of time before March 2008, where leakages were occurring in the downspout from the roof, and the incoming irrigation line was acting as a siphon and emptying the cistern in Florida. Data from those periods of time were dealt with as follows: 1) for sudden draw-downs in cistern volumes during a storm or UF irrigation event due to the lack of check valve in the incoming UF irrigation line—the exact water lost from the cistern was added back to the data set; 2) for periods of time when the cisterns were overflowing, runoff was simulated (and indicated as such in the results) based on the relationship of rain intensity and runoff flow directly before and after the overflow—which yields a conservative estimate for green roof retention. The orifice of the input pipe to the cisterns and the orifice of the overflow pipe leaving the cisterns are both 10 cm in diameter, therefore in cases of overflow where saturation was already reached on the green roof, the exit flow rate was assumed to equal the inflow rate (rain rate + a delay).

In Virginia, cumulative runoff data from the green roof were originally paired with runoff from the conventional roof, however to be able to qualitatively compare retention rates to those measured in Florida, ultimately rainfall rates were chosen for comparison instead, so that the method in Virginia be identical to the method used in Florida.

Analysis of individual rain events

Individual rain events were analyzed by pairing the rain data with runoff data at 5 minute intervals to create storm hydrographs. The storm hydrographs were analyzed for 1) a reduction in total runoff volume, 2) a reduction in maximum runoff rate in cm hr^{-1}, 3) an increase in lag time between peak of rainfall and peak roof runoff, and 4) an increase in return flow period, (Figure 4-5).

The reduction of total runoff volume was the difference in runoff due to rainfall with a runoff coefficient of 1.0 compared to the measured runoff volume from the green roof. A runoff coefficient of 1.0 assumed that all rainfall becomes runoff instantaneously (Figure 4-6). The reduction in maximum runoff rate is the % difference in the maximum rain rate and the maximum green roof runoff rate, (Figure 4-7). This represents the reduction in the peak runoff rate that the green roof could provide for a worst-case scenario conventional roof, where the runoff coefficient equals 1 and where the maximum runoff rate for the conventional roof approximates the maximum rain rate. The lag time to peak concentration for a conventional roof under this assumption means that the peak runoff with a runoff coefficient of 1 would occur at the time of peak rainfall. Therefore, the increase in lag to peak here is defined as the time difference between when the maximum rainfall rate occurs and the time of maximum green roof runoff occurs; both values are reported in cm/hr. The return flow period of the green roof, also called the extension in green roof runoff, refers to that period of time after which rainfall had ended and runoff continued and is reported in hours and minutes. The delay in the start of runoff is the delay between the beginning of rainfall and the beginning of runoff. Water retention by the green roof, was characterized to be the decrease in total volume between rain fall and runoff; this value is reported as cm (of depth across the roof surface), Figure 4-6. The value reported as depth of rainfall or runoff across the roof surface can be multiplied by any other green roof's areal extent for quick comparisons in water retention. Percent water retention was defined as the quantity of water retained by the green roof system (media and drainage layer), calculated to be the difference between measured rainfall and measured runoff, divided by the total input: % Water RetentionGreen roof system = (Rainfall [cm]-Runoff [cm])/ Rainfall [cm]). Hydrographs reporting "modeled conventional roof runoff" refers to a runoff coefficient of 1, implying that all rain was transformed directly into runoff to be used for comparison to the green roof runoff.

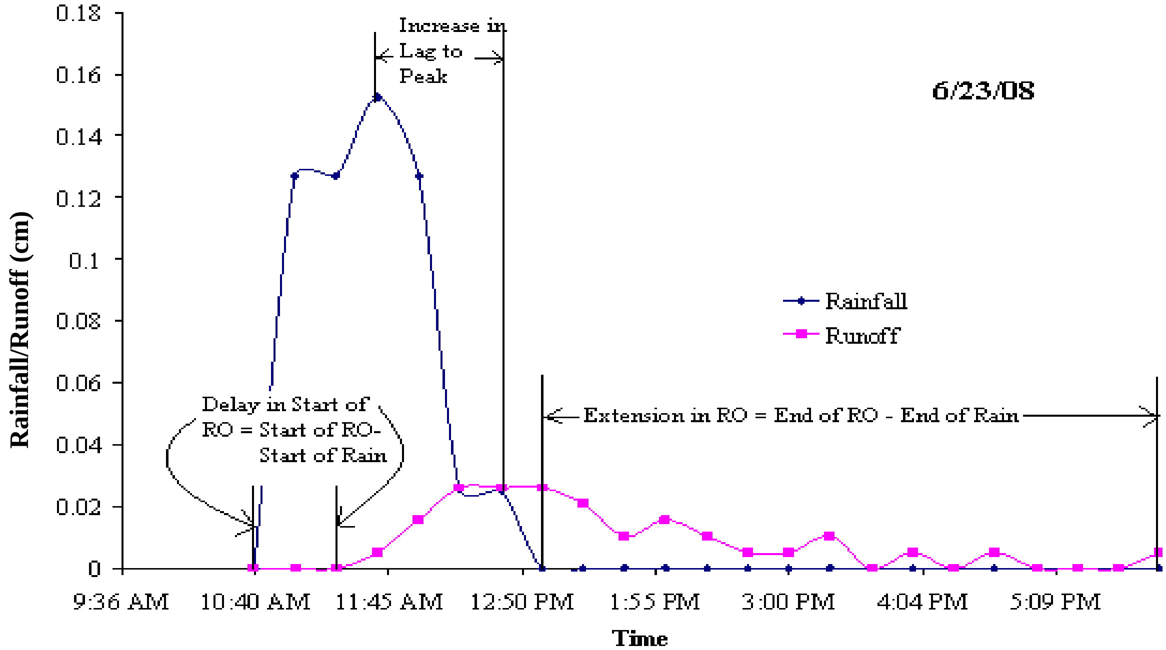


Figure 4-5. Example of analysis of individual hydrographs from a green roof (pink line) and modeled conventional roof runoff based on rainfall (blue line) to determine increase in delay in start of runoff and the increase in lag to peak and the increase in the extension of runoff from the green roof past the end of the storm event.

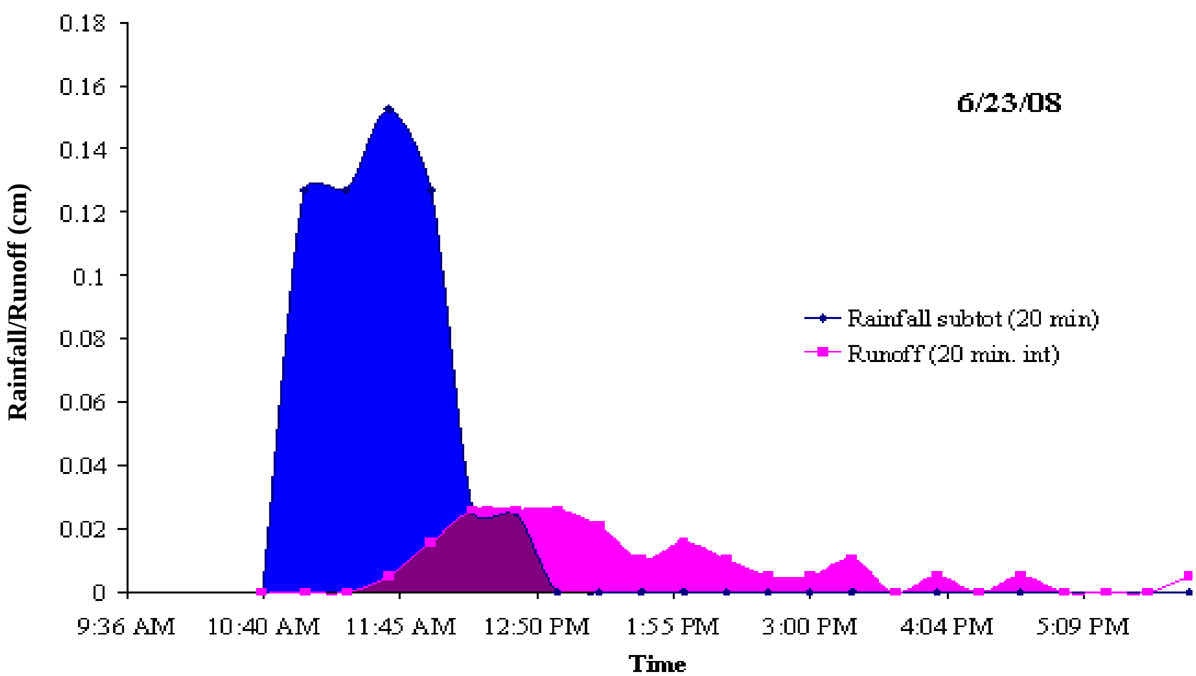


Figure 4-6. Example analysis of an individual hydrograph for storm water volume reduction due to the presence of a green roof. The difference in the areas under the curves, the blue line represents the amount of rainfall; the pink line is the green roof runoff. The difference between rainfall volume and runoff volume is the amount "retained" by the roof.

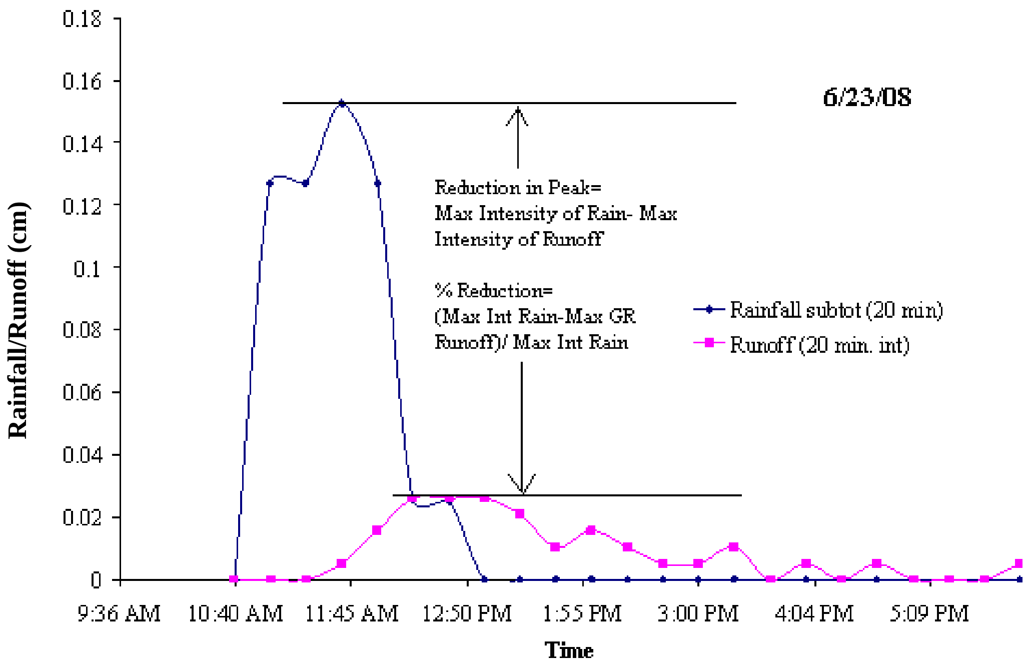


Figure 4-7. Example analysis of individual rain event and green roof hydrographs for reduction in peak storm runoff.

Collection of water quality data

Water quality was monitored in the runoff of the green roof and conventional roof by taking grab samples during 5 different storms over a two year period, with 5 samples/storm x 2 roofs. Water samples were analyzed for nutrients (NO_3/NO_2, TP, OP) and metals (Cu, Fe, Cd), as well as TSS, TDS and pH.

Water quality samples were taken as grab samples at various intervals during individual storm events with the goal of obtaining five samples per storm. The samples were taken in acid washed bottles in both Florida and Virginia. At the CRP green roof in Gainesville, FL, the runoff was collected by opening a Y-junction that was spliced into the iron 10.2 cm (4”) downspout pipe in June 2008 for the express purpose of water sampling during storms. The PVC Y-Junction was spliced into the downspout pipe downstream of two individual 10.2 cm (4”) roof drains merged into one 10.2 cm (4”) drain. During sampling, sample bottles were triple rinsed with the runoff, then held gently against the edge of the inside of the pipe in such a way that it would fill up as quickly as possible. Since the ultimate duration of the storm was unknown at the time when the first sample was taken (which was the first moment that there was enough runoff to sample in the down spout), 5 samples were only obtained in storms that lasted several hours. For storms that were less than an hour long, generally only 2 to 3 samples were obtained before the rain subsided. Water samples from the green roof were compared to water samples the conventional roof on top of Newell Hall on the University of Florida Campus in Gainesville, Florida.

Water samples were analyzed for nutrients (TP, SRP, NH_4, NO_3) on the AQ2+ (Spectrophotometer) semi-auto analyzer, total suspended solids (TSS) in the Wetlands Biogeochemistry Laboratory and metals using an ICP (Inductive Coupled Argon Plasma) Spectrophotometer in the Soil Testing Lab of Belle Glade, FL. The nutrients measured were TKN, NO3, NH3, SRP and TP. Metals analyzed were Fe, Cu, Zn, Cd, and Al, these metals were chosen for analysis for two reasons: 1) in urban areas, streets and rooftops are the top two contributors of Zn and Al, therefore we were interested in characterizing the levels coming off of a conventional roof and green roof and noting any differences that may be attributable to the green roof, and 2) in previous studies (Urbonas, 1998; and Kohler and Schmidt, 2003), green roofs have been shown to lower concentrations of metals than conventional roofs, therefore we wanted to see whether or not this trend would hold true in Florida and Virginia.

The same parameters were analyzed in Virginia by the Water Quality Laboratory of the Fairfax County Department of Health by Deborah Severson using the same EPA methods as used in the WBL laboratory.

Concentration data were transformed into load data by multiplying the concentrations of the measured parameter at a given time by the total volume of runoff that had occurred in the time increment represented by that measurement. Instantaneous flow rates used in load calculations were based on the measured changes in the stage height in the cisterns during the storms at the times when the grab samples were taken. The same method of measuring flow rates, based on continuous stage height measurement over time was used in Virginia as well.

Analysis of water quality data

Water quality data was analyzed by reporting total load for individual storms sampling. The conventional roof in Florida was sampled less frequently than the green roof and for storm events where comparisons were made without conventional roof pairs, the average concentration of all conventional roof levels measured during two storms was used for comparison. Total load for each storm was calculated by multiplying the concentration of the parameter sampled by the volume of runoff generated in the time period represented by the sample. The start of the time period represented by a sampling time is the mid-point between the present sampling time and the previous sampling time; and the end of the time period represented is the mid-point between the current sampling time and the next sampling time (Table 4-5). The amount of runoff in cm generated during the time period was multiplied by the surface area of the roof (214.5 m^2 for the CRP roof in Florida and 48.8 m^2 for the YSC green roof in Virginia) to yield liters of runoff for each time interval. For example, for the rain event sampled on 6/23/08 in FL, time intervals and water yield for each interval are shown in Table 4-5.

The volume of runoff was consequently multiplied by the concentration of each parameter to give the load for each time interval and then summed to yield the total load for each parameter for that rain event being analyzed. For example, for the rain event on 6/23/08, Table 4-6 shows how concentrations for time interval and summed for total loads per parameter for the rain event.

Table 4-5. Example of time interval represented by a sampling time and amount of runoff represented by the water sample during a storm (FL 6/23/08).

Sampling Time	Time Interval represented by sample	Runoff (cm) for the time interval	Vol (L)
11:10 AM	(Start of Runoff) 10:45am - 11:15am	0	0
11:20 AM	11:15am -11:31am	0.010	24
11:43 AM	11:31am -12:15pm	0.204	493
12:46 PM	12:15pm - 2:20pm	0.110	266
4:00 PM	2:20pm - 6:00 pm (End of runoff)	0.037	89
Total Volume			872

Table 4-6. Example of calculation of load by time interval based on concentrations in grab samples taken at various time intervals during a rain event on 6/23/08. This method was applied to all storms in both Florida and Virginia.

	Concentration					Load			
Time	NOx-N (mg L^{-1})	NH3-N (mg L^{-1})	TSS (mg L^{-1})	SRP (mg L^{-1})	Vol (L)	NOx-N (mg)	NH3-N (mg)	TSS (mg)	SRP (mg)
11:10 AM					0	0.0	0.0	0	0
11:20 AM	0.04	0.04	2.3	0.85	24	1.0	0.9	56	21
11:43 AM	0.03	0.05	2.6	0.59	493	15.2	22.2	1281	291
12:46 PM	0.03	0.05	2.2	0.84	266	8.6	12.0	585	224
4:00 PM	0.03	0.06	2.5	0.88	89	2.5	5.5	223	79
Load						27	41	2145	614

For the determination of load from a conventional roof, the concentration in the grab sample taken from the conventional roof was multiplied by the volume of rain (calculated as depth of rain that fell during the time interval multiplied by the contributing roof area), Table 4-6. The area of the conventional roof contributing to the runoff sampled in Florida, was 148.5 m^2. In the case of the YSC roof in Virginia, the conventional roof had an area of 48.8 m^2.

Results and Discussion

Hydrology Results—Charles R. Perry Green Roof in Gainesville, FL

Cumulative hydrographs of green roof runoff in response to irrigation and rainfall are shown in approximately three month intervals representing the various seasons. Individual storm hydrographs, are only shown for the water quality sampling rain events to highlight the response of the green roof to an individual rain event within a certain season. Comparisons to Virginia are discussed later in the Hydrology section on the YSC green roof in Virginia.

Figure 4-8. Charles R. Perry Construction Yard Green Roof on June 11, 2007, 12 weeks after establishment—241.5 m^2 (2600 sq. ft.), with 15 cm (6 inches) of Hydrotech LiteTop® growing medium.

Cumulative hydrographs—Charles R. Perry green roof in Gainesville, Florida

Cumulative hydrographs were created for three time periods over the entire study period for the Charles R. Perry Construction Yard: Summer-Early Fall 2007, Winter 2007-2008 and Spring 2008. The cumulative hydrograph and characterizations of the rain events and runoff for the Summer-Early Fall 2007 are shown below in Figure 4-9 and Tables 4-7 and 4-8. The cumulative hydrographs and related summary tables for Winter 2007-2008 and Spring 2008 are presented in Appendices O and P.

Summer-Early Fall 2007: The CRP roof was established in April 2007 and hydrological monitoring of the runoff began on July 7, 2007. The months of July, August, September and October, were considered to be representative of the "wet season", having a mean monthly rainfall of 148 mm. The cumulative hydrograph for the time period between July 7 and October

19, 2007 in Figure 4-9 shows the water added to the system by both rain and irrigation, and the response of the green roof in terms of runoff. The hyetograph shows the individual rain events that occurred during the time period, which allows the viewer to differentiate when the green roof runoff is increasing due to rain rather than irrigation. Thirty-six storms from this time period, ranging in size from 0.08 - 7.34 cm, and 32 irrigation events (0.83 cm each), were analyzed individually to: 1) determine the green roof's affect on peak rainfall intensity reduction and 2) determine the mean increase in lag time to peak rainfall due to the presence of the green roof, and 3) characterize the role of the green roof in creating a delay in the start of runoff, as well as, extending the duration of runoff past the time of storm cessation.

The characteristics of the 36 storms analyzed are shown in Table 4-7 and the results of the analysis for % decrease in peak intensity, increase in lag to peak, delay to start of runoff and extension of runoff duration past the end of storm event are shown in Table 4-8. Overall, the green roof retained 41% of the rainfall that occurred in the wet season. The median sized storm for this season had a duration of 1 hour and depth of 0.4 cm. On average, the green roof lowered the peak intensity of runoff due to rainfall by 71%. The range of delay in the start of runoff after the start of the storm was 0 hr to 3hr 30min, with a median value of 10 minutes. Runoff after the storm ended was extended by a mean of 6 hr 40 minutes.

Table 4-7. Characterization of 36 rain events captured in the "wet season" between July 7, 2007 to October 23, 2007, in terms of rain duration, rain amount (cm), green roof runoff duration, % volume storm water retention.

Type	Time since previous rain (hr)	Rain Duration (hr)	Rain depth (cm)	Runoff Duration (hr)	Runoff depth (cm)	Rainfall retention (%)
Total			45.2		26.7	41
Mean	17.0	1 hr 50 min	1.2	7 hr 50 min	0.7	52
Stdev	12.9	2 hr	1.6	4 hr 20 min	1.2	40
Median	14.3	1 hr	0.4	7 hr 30 min	0.2	50
Min	0.7	10 min	0.1	5 min	0.0	0
Max	48.3	6 hr 30 min	7.3	17 hr	4.2	100

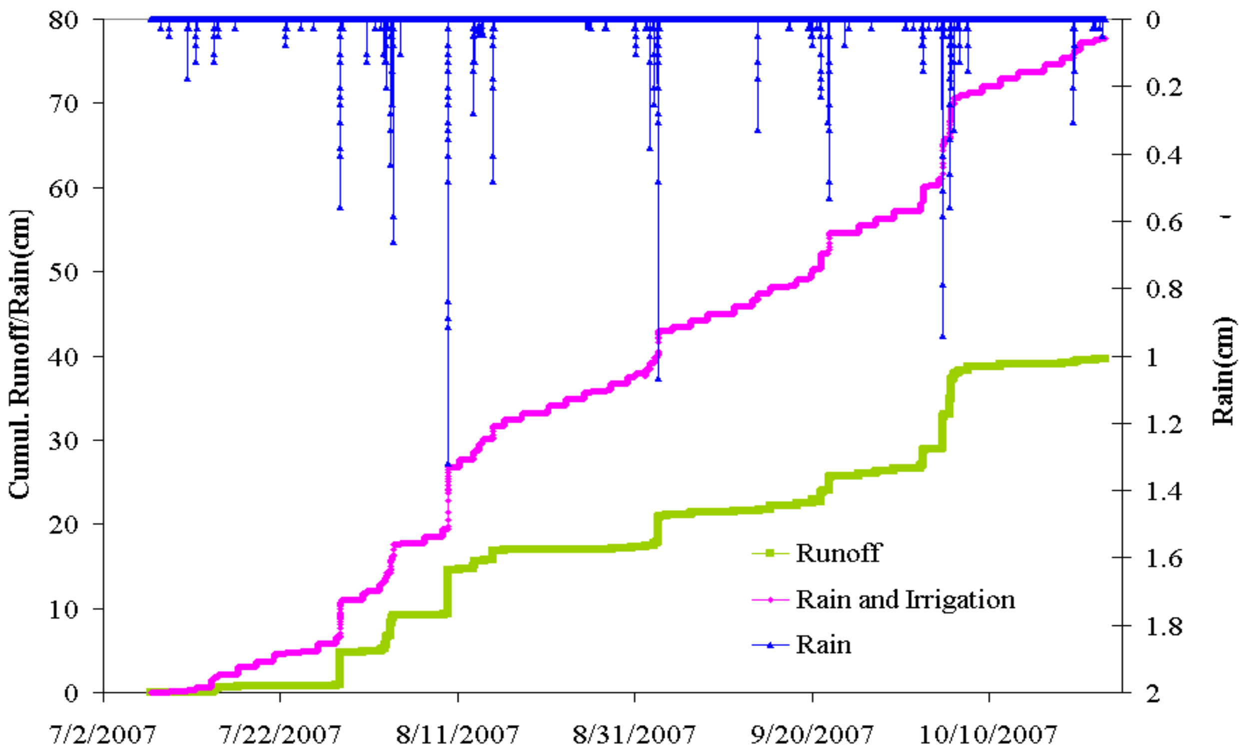


Figure 4-9. Cumulative green roof runoff hydrograph compared to cumulative rain and irrigation for "wet season", July 7, 2007 to October 23, 2007. Hyetograph, shown in blue to distinguish when the cumulative runoff is running off due to irrigation versus rain.

Table 4-8. Results of analysis of 36 rain events in the "wet season" between July 7, 2007 and October 23, 2007 for delay in start and extension of end of runoff, the maximum rain intensity, maximum runoff intensity (Max RO) and the percent decrease in peak intensity.

Type	Delay in Start RO (hr)	Extension of RO (hr)	Max Rain Intensity (cm/hr)	Max RO (cm/hr)	Reduction of Peak (%)
Mean	40 min	6 hr 40 min	3.3	1.1	71
Stdev	50 min	3 hr 20 min	3.8	1.6	27
Median	10 min	6 hr 40 min	1.7	0.3	79
Min	0 min	30 min	0.3	0.0	7
Max	3 hr 30 min	14 hr 20 min	15.8	5.1	100

Winter 2007-2008: The winter (dry) period began in late December and ended in late March with relatively low rain fall (82 mm per month), as compared to the wet season. Rainfall for this time period was characterized by medium-duration low-intensity storms (Appendix Q) emanating from storms blown across the content by the westerlies. The median duration and volume for rain events measured during the 2007-08 winter season was 1 hr 40 min and 0.5 cm depth (Table Q-2 in Appendix Q), slightly longer than the wet season storms. During this season, the roof was irrigated 2 times a week (Monday and Thursday mornings at 5 am for 34 minutes) for a total of 2.4 cm (0.9" inches) per week. In the cumulative hydrograph for this period, shown in Figure Q-1 in Appendix Q, the overall storm water retention for the winter period (dry season) was 34%, which was slightly lower than the retention during the "wet" season, which was unexpected.

Relationship of rain and irrigation to runoff within the dry season (Winter 2007-08): Two cumulative hydrographs are also shown for two shorter periods of time within the "dry" season of 2007 - 2008, to show more closely how the roof responds to irrigation versus rainfall. The response of the green roof to irrigation for the weeks of January 6 – 15, 2008 (Figure 4-10) and January 31 - February 12, 2008 (Figure 4-11) were chosen as demonstrations.

The total irrigation and rainfall for the weeks of 1/7 to 1/14/08 and 2/7 to 2/14/08 was 9.14 cm (3.6") or 20200 L (5332 gallons) of water, and of this, 44% was retained by the green roof. The water that flowed off the roof as runoff was detained in the cisterns without overflow, so all the rainwater for the runoff for this time period was kept out of the UF stormwater system. The relationships between storm intensity (cm/hr) and retention, total irrigation + rain fall and intensity and duration versus intensity are weak $R^2 < 0.05$. The strongest relationship between retention and another parameter for these two weeks is with "hours since last rain or irrigation event" with an $R^2 = 0.47$. The "hours since the last rain or irrigation event" influences the amount of pore space that will be available for the volume of the subsequent rain event or irrigation event to be stored. As the moisture condition at the time of the subsequent event depends on solar radiation and windspeed between the rain events, as this controls ET and indirectly the amount of pore space that will be available at the subsequent rain event.

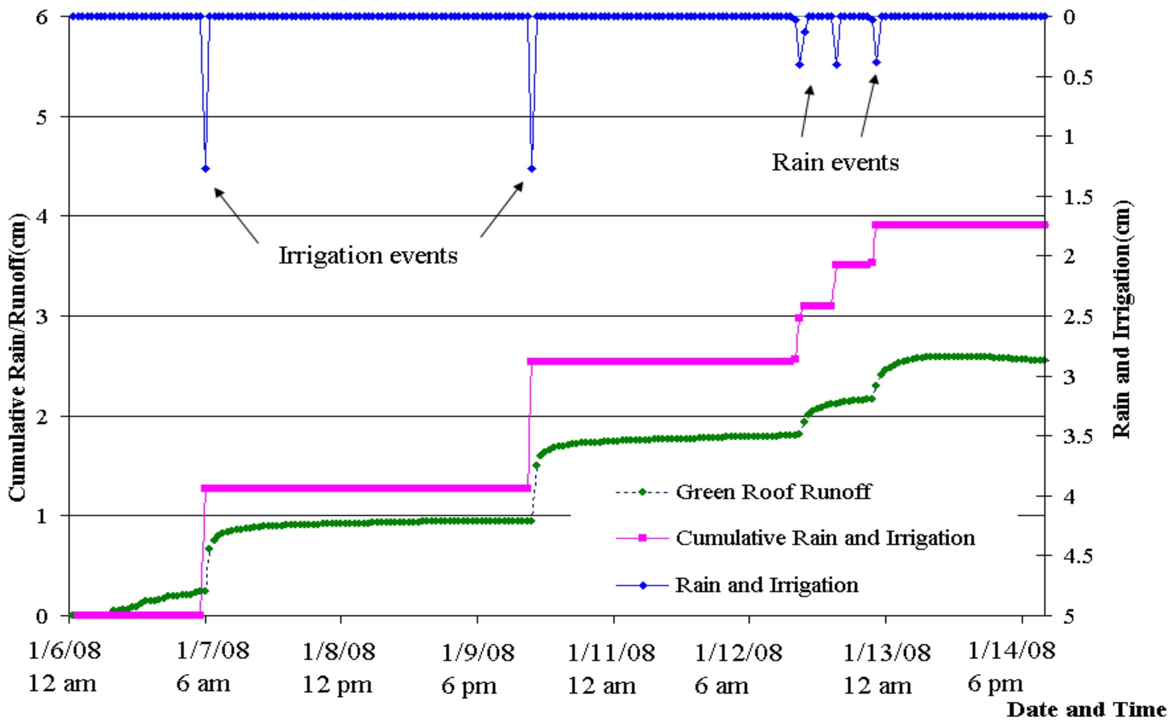


Figure 4-10. Hydrologic response of green roof to individual irrigation and rain events on a weeklong time scale in the "dry period"/winter months, 1/6/08 to 1/14/08.

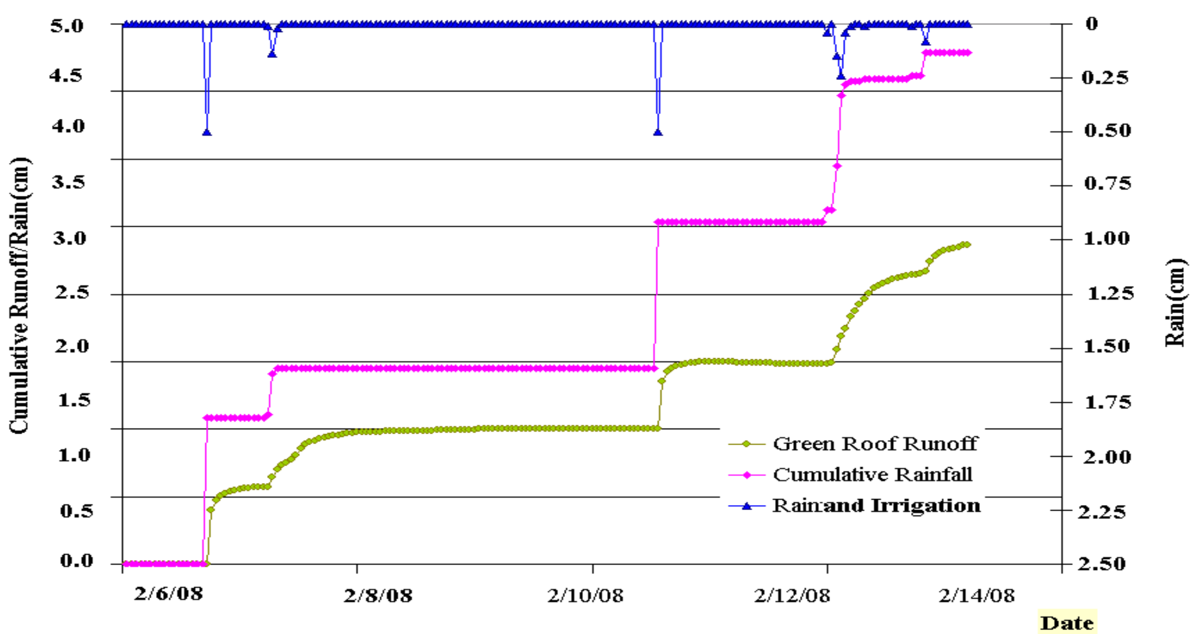


Figure 4-11. Hydrologic response to green roof to irrigation versus rain events in the "dry" period/ winter months, 2/6/08 to 2/14/08.

Table 4-9. Relationship between intensity (cm hr^{-1}), duration (hr), total volume of rainfall or irrigation versus green roof runoff and retention (%), for individual events shown in Figures 4-10 and 4-11, storms in the "dry"period/winter.

	Intensity (cm/hr)	Duration (hr)	Total Rainfall/ Irrigation (cm)	Total Vol (L)	Response Duration (hr)	Rainfall/ irrigation retained (L)	Rainfall/ irrigation retained (%)
Irrig 1/7/08	2.54	0.6	1.5	3066	12	1499	49%
Irrig 1/10/08	2.54	0.6	1.5	3066	13	1158	38%
Rain 1/12/08	0.18	3.0	0.5	1351	>8	602	45%
Rain 1/13/08	0.33	3.0	1.0	1960	17	837	43%
Irrig 2/7/08	2.54	0.6	1.3	3066	6	1548	50%
Rain 2/7/08	0.15	3.0	0.6	1044	5	462	44%
Irrig 2/11/08	2.54	0.6	1.3	3066	6	1669	55%
Rain 2/12/08	0.14	9.0	1.5	3558	30	1052	30%
Total				20177		8826	44%

An irrigation event and a storm shown in the cumulative hydrograph in Figure 4-11, that occurred on 2/7/08 are broken down into individual storm hydrographs (non-cumulative) in Figure 4-12. The peak flow from irrigation on 2/7/08 was reduced by 67% (from 1.27 cm hr^{-1} to 0.42 cm hr^{-1}), and the lag time was increased by one hour and the duration of return flow was extended by 6 hours. In the case of the small (3 hour, 0.5 cm) rain event on 2/7/08, the peak flow was also reduced by 74%, from a maximum of 0.35 cm h^{-1} to 0.09 cm h^{-1}, there was essentially no lag time as the roof had just been irrigated and was finishing running off when this storm started and the extension of runoff period was extended by 14 hours.

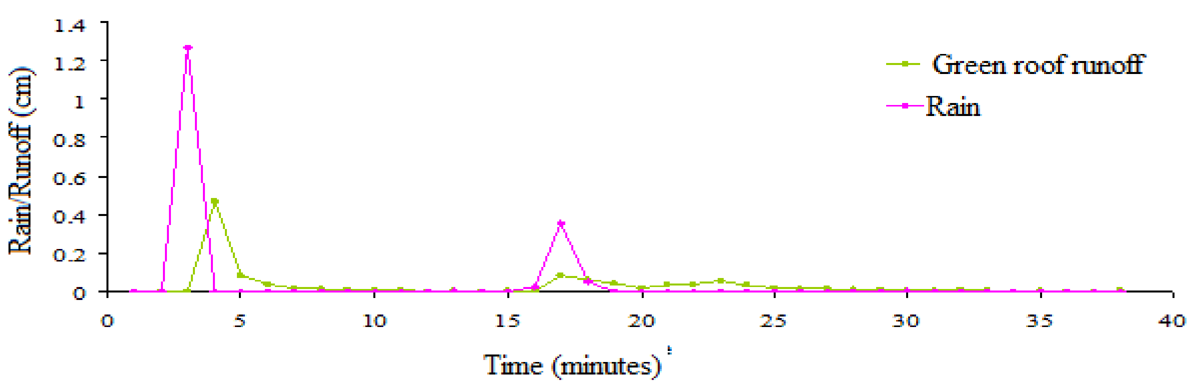


Figure 4-12. Hydrologic response of green roof to irrigation (1.27 cm) and a small precipitation event (0.5 cm) with wet antecedent moisture conditions on 2/7/08.

Validity of Excel spreadsheet water balance model and/or green roof bins as a model for calculating green roof runoff (Winter 2007-2008): As was expected for a green roof with wet antecedent moisture conditions, runoff began to occur much sooner than with dry antecedent moisture conditions. Most hydrologic models in existence (Cite Roofscapes, Villareal UH model) allocate $water_{IN}$ to recharging soil moisture first and then water surplus to runoff/leachate, however in the case of the Charles R. Perry Construction yard, saturation did not occur before roof runoff began.

In a Water Balance approach, using Excel, green roof runoff was modeled by having rainfall satisfy soil moisture first, then having surplus available for runoff; and initial moisture content of the soil at the time of the rain was calculated based on previous storm size and duration since previous storm and residual water content of the soil, using this approach, runoff was underestimated for all storms. I found that in actuality, unsaturated subsurface flow occurred from the green roof well before the growing medium was saturated. Runoff was occurring before the growing medium was saturated, most likely due to flow through preferential flow paths as described by Brady and Weil (2005). Water naturally flows several orders of magnitude higher through preferential flow paths such as burrows, worm holes and in channels left by decaying debris or old roots that have rotted away. In the case of this green roof, the size of the pores may not fine enough to hold the moisture, so water flows through by gravity drainage before the medium approaches saturation.

When comparing water retention of the Charles R. Perry Construction Yard green roof during the 12 hour period after irrigation with values measured during the lysimeter experiment on 15 cm of Hydrotech growing medium during the same season (dry/winter season), the retention curves are similar, implying that the measured water retention from the container study does reflect the behavior of water in the actual Charles R. Perry green roof in situ.

The water retention measured in the bin study, for a bin filled with 15 cm of Hydrotech growing medium and planted with perennials, measured in Week 12 (December) after planting, matches up with the water retention curves measured in situ for the CRP green roof in January.

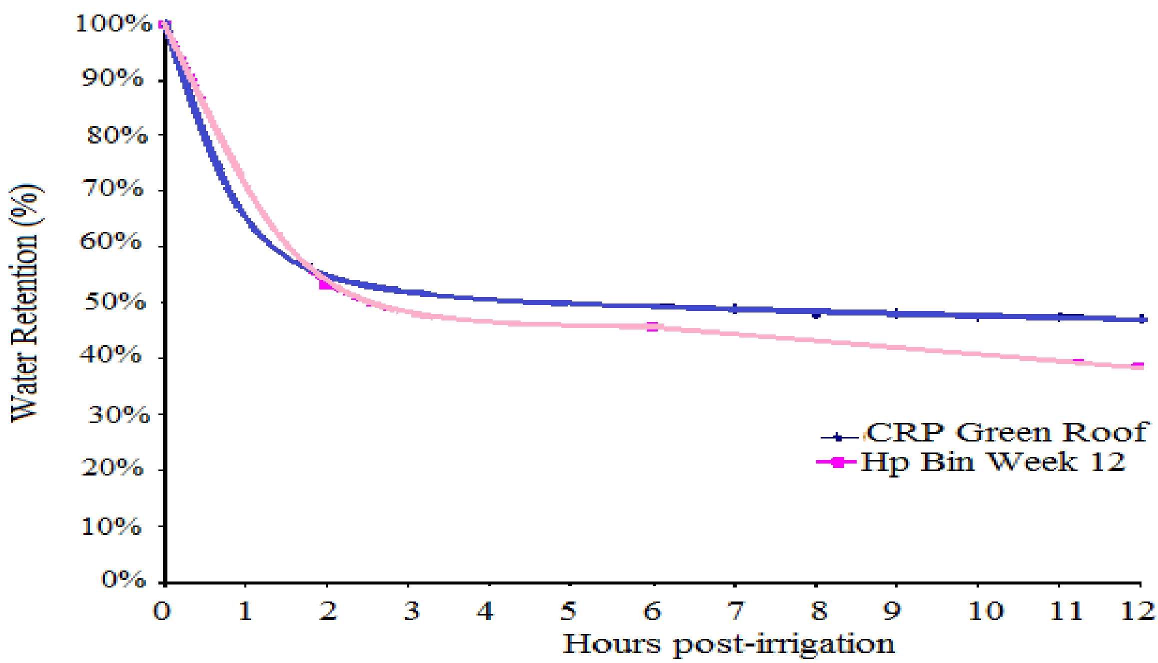


Figure 4-13. Comparison of % water retained directly after 1.2 cm of irrigation over 12 hours in the controlled bin study (pink line)--perennial plants in Hydrotech medium, Week 12/ (early Winter)—with retention after irrigation in situ on the Charles R. Perry Construction Yard green roof (blue line) during the winter season 2007.

Spring 2008: The median rainfall and irrigation event during the spring season was a 25 min event with 0.87 cm of water depth (Table in Appendix R), while the median rain event without including irrigation, was 0.42 cm of rain. Median retention for events in this period was 94% and there was a median delay time in the start of runoff and reduction of peak flow of 35 minutes and 94% (Appendix R). The fact that the water was being received from irrigation may affect the retention either due to lower antecedent moisture conditions of the growing medium, higher evapotranspiration rates due to lower ambient relative humidity at the time of watering.

Summer 2008: The overall retention for the 2008 wet season (June through the beginning of September) was 43%, which was similar to the overall retention reported for the wet season of 2007 (of 41%). A total of 38.7 cm of rain fell during this time period and 22.1 cm of this rain entered the cisterns as runoff (Figure in Appendix S).

The summer period of 2008 was characterized by 16 rainfall events ranging from 0.0254 cm to 9.09 cm and water retention by the roof ranging from 100% to 17%, respectively. The mean and median rain events were 2 hr, 1.2 cm and 35 min, 0.58 cm, respectively. On average, 53% of rainfall was retained, irrespective of storm size (Table S-1 in Appendix S). Cumulatively for the season, 25% of rain was retained (Table S-2 in Appendix S).

Hydrology Results—Yorktowne Square Condominium (YSC) Green Roof in Merrifield, VA

The cumulative hydrographs of runoff, as well as of the analyses of 82 individual storms, are shown in groupings of "season", similar to the Florida data: Summer (late June, July, Aug, early Sept), Fall (late Sept, Oct, Nov, early Dec), Winter (late Dec, Jan, Feb, early Mar), Spring (late Mar, April, May, early June) for each year, followed by a comparison of the retention of the green roof for Virginia (YSC) with the Florida green roof (CRP). The cumulative hydrograph for Summer-Early Fall 2006 is shown below, along with summary tables characterizing rain events and green roof runoff; cumulative hydrographs for subsequent time periods are in the appendices.

Summer- Early Fall 2006: The 23 storms sampled in Virginia in Summer/Early Fall 2006 (between July 12 and October 23, 2006) had a median duration of 3.8 hours and the median amount of rain was 0.74 cm (Table 4-10). The maximum intensity of the rain storms for this period were 4.87 cm hr-1 in Virginia, which is 3 times less than the maximum intensity measured in Florida (15.8 cm hr^{-1}) for the same time period (July to October). Median duration was 1 hour for Florida storms for the same season, meaning Florida storms were also on average three times shorter than the storms measured in Virginia. Total rainfall for the same period (July 7- Oct 23) in Gainesville, FL was twice as much as in Virginia, 45.2 cm of rain (with an additional 23 cm of irrigation), while total rainfall in Merrifield, VA was 24 cm (Figure 4-14). Overall retention, based on cumulative hydrographs for the same time period for Florida and Virginia were 50% and 64% respectively (Figures 4-9 and 4-14). Differences in retention may be due to the storms being shorter and more intense, with maximum intensities being three times higher in Florida than in Virginia. Additionally, the age of the growing medium may have influenced the formation of aggregates and addition of OM over time, which could also have a bearing on retention. Finally, the presence of irrigation, increased the antecedent moisture conditions in the Florida green roof, which could also have increased the runoff during storms, by reducing available pore space for storage.

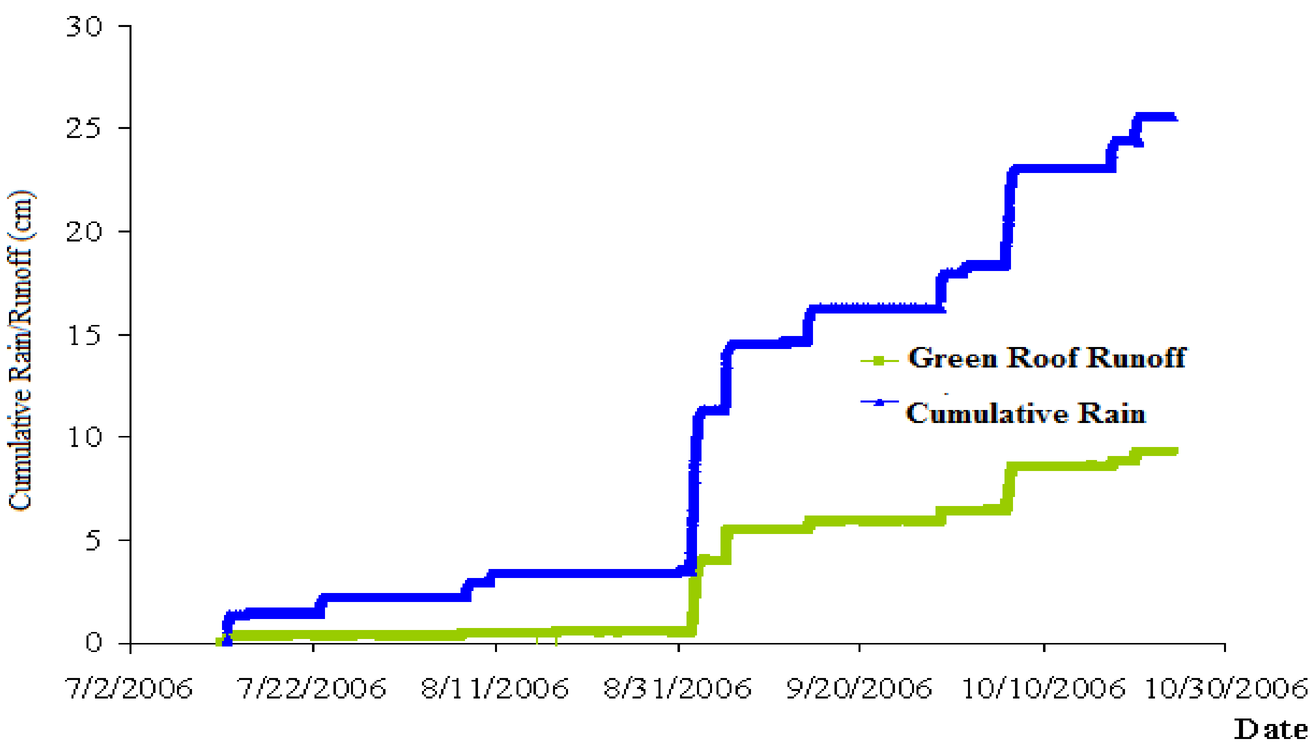


Figure 4-14. Cumulative stormwater runoff hydrograph for green roof and rainfall at YSC, Merrifield, VA green roof, Summer/Early Fall 2006 (7/12/2006-10/23/2006).

Table 4-10. Characterization of 23 rain events captured between July 12, 2006 and October 23, 2006 (Summer/Early Fall) in Merrifield, Virginia, for rain duration, rain amount (cm), maximum intensity, green roof runoff duration, and maximum runoff intensity.

Type	Duration (hr)	Rain (cm)	Max int (cm hr^{-1})	Duration RO (hr)	Amt RO(cm)	Max RO (cm hr^{-1})
Total	118.1	19.6		79.9	9.88	
Mean	6.22	1.31	1.12	8.88	0.52	0.17
Stdev	8.15	1.37	1.14	5.82	0.94	0.38
Median	3.58	0.74	1.21	8.38	0.00	0.00
Min	0.05	0.10	0.00	0.60	0.00	0.00
Max	27.5	4.72	4.87	21.2	3.48	2.08

Table 4-11. Mean, median and range of stormwater retention (%), delay in start and extension in end of runoff, reduction in peak intensity for 23 rain events between July 12, 2006 and October 23, 2006.

Type	%Retention	Delay in Start RO (hr)	Extension in end RO (hr)	Increase in Lag to Peak (hr)	% Reduction of Peak
Mean	85%	3.19	2.71	1.03	92%
Stdev	19%	1.98	2.22	0.95	13%
Median	99%	3.30	1.60	0.63	100%
Min	39%	0.15	0.90	0.25	57%
Max	100%	6.50	7.30	2.80	100%

Late Fall/Winter 2006: The late fall/winter time period consisted of 36 storms captured between November and March 2006-2007 (11/1/06 and 3/8/07) from the YSC green roof. The total amount of rainfall for this period was 31 cm, and of that approximately 70% was retained by the green roof for this period of time. This retention rate for Virginia is comparable to values reported for North Carolina and Pennsylvania (Moran 2005 and Berghage et al. 2009), who report 63% overall retention for North Carolina and greater than 50% for Pennsylvania. Rain storms for this season were characterized as having a median length of 5 hrs and a median amount of rain of 0.33 cm. The median duration and volume for rain events measured during the 2007-08 winter season in Florida (Dec 20- Mar 18) was 1 hr 40 min and 0.6 cm depth (Table T-1 in Appendix T), which indicates that on average storms in Virginia were approximately three times longer with half as much volume than Florida storms. The lower intensity of the storms in Virginia may explain why a larger proportion of storms were fully detained in Virginia than Florida (44% versus 28% of the storms).

Summer 2007: Summer 2007 includes 7 storms captured in June and 5 storms captured in August 2007. The summer 2007 period was a relatively dry summer with 94 mm of rain in June, 82 mm of rainfall in July and 81 mm in August which is 4%, 25% and 29% below the historical normal rainfall for those months, respectively. On average there were 3.5 dry days in a row before a rainfall with an average of 2 wet days in a row in June and August. Overall retention for June and August was 76%. The retention of rainfall per storm ranged from 45% to 100% with a median of 94% retention per storm. During a relatively dry period in Florida (April-June, 2008), where only 4 rain events occurred in 2 months, the median retention was 94% (despite regular irrigation during that time period) (Figure U-1 in Appendix U). Higher ET rates during the warm dry part of the year, may account for greater water uptake by the growing medium and plants and lower antecedent moisture conditions in the growing medium at the time of rainfall, which may explain the higher retention rates during these time periods in both locations.

Spring 2008: Spring 2008 was represented by 10 storms collected between April and May (note that corruption of pressure transducer files caused a loss of data prior to and post these dates, therefore spring data were limited to these 10 storms). Rain events during this period ranged from 0.05 cm to 9.75 cm, with the median storm size for this time period being 0.47 cm over 5.8 hours. Rainfall retention ranged from 41% to 100% with a median retention of above 90% (Table V-1, Appendix V). The median peak reduction was similarly high for this time period (94%), Table V-2, which was comparable to the values of retention and peak reduction found the previous "summer", June and August 2007 in Virginia, and similar to values found in Florida for the time period between April and June for this same year (2008), Table S-2.

Late Summer 2008: Late summer 2008, August-September, was a relatively dry period (the summer 2008 was categorized as moderate drought) followed by two large storms a few weeks apart-the remnants of Tropical Storm Fay on August 28th and rain from Tropical Storm Hanna on September 6th. The latter resulted in the cisterns overflowing. Overall retention from the first week of August to the middle of Tropical Storm Hanna was 65% (Appendix W). During Tropical Storm Hanna 17.2 cm of rain fell over 18 hours, up to the first 6 hours 65% of the incoming rain thus far was detained, after 6 hours the cisterns overflowed and measurements became invalid.

Differences in Water Retention among Seasons and by Rainstorm Size in Florida and VA

Differences in mean water retention by rain event size and reduction of peak runoff for Florida are shown in Tables 4-12 and 4-13. The 91 rain events were divided into terciles. Small rain events (< 0.254 cm, n =31) in Florida, regardless of season, had a mean retention of 0.79% ± 0.32%, which was significantly greater than retention for medium events (0.254 cm - 1.00 cm, n =30) and large events (>1.0 cm, n = 31) at a $p < 0.05$ level using Tukey's HSD (Table 4-12). There were no significant differences in retention between medium and large rain events in Florida (43% and 26% retention, respectively). There were significant differences in the reduction of the peak intensity among all size classes of rain events (Table 4-13), but no significant differences in extension of runoff past the end of a rain event (small = 7.8 hr, medium = 11 hr, large = 8.7 hr) in Florida.

In Virginia, 82 storms were sampled between December 2004 and September 2008 and analyzed for % stormwater retention (Table 4-14) and % decrease in peak runoff (Table 4-15. Storms during the sampling period in Virginia ranged between 0.0508 cm and 17.47 cm; 66% of these storms were less than 1.27 cm, 87% were < 2.54 cm and 97% were less than 7.62 cm in size.

In Florida, the 94 different storms ranged from 0.0254 cm to 9.09 cm in size between July 2007 and September 2008. The median sized storm in Florida was 0.44 cm and 8.75 hours long

Table 4-12. Differences in mean retention by rain event size for 91 storms between July 2007 and September 2008, in Gainesville, Florida. Rain event sizes not connected by the same letter are significantly different at the α = 0.05 level.

Rain Event Size	Mean Retention		SD	Significant Difference	N
Small (<0.254 cm)	0.79	±	0.3	a	30
Medium (0.254 cm – 1.00 cm)	0.43	±	0.4	b	31
Large (>1.00 cm)	0.26	±	0.2	b	30
Overall (all size classes)	0.49		0.4		91

Table 4-13. Differences in reduction in peak runoff by rain event size for 91 storms between July 2007 and September 2008, in Gainesville, Florida. Rain event sizes not connected by the same letter are significantly different at the α = 0.05 level.

Rain Event Size	Mean Peak Reduction		SD	Significant Difference	N
Small (<0.254 cm)	0.94	±	0.1	a	30
Medium (0.254 cm – 1.00 cm)	0.79	±	0.2	b	31
Large (>1.00 cm)	0.60	±	0.3	c	30
Overall (all size classes)	0.78		0.2		91

Table 4-14. Differences in mean retention by rain event size for 82 storms between December 2004 and September 2008 in Merrifield, Virginia. Rain event sizes not connected by the same letter are significantly different at the α = 0.05 level.

Rain Event Size	Mean Retention		SD	Significant Difference	N
Small (<0.254 cm)	0.98	±	0.1	a	26
Medium (0.254 cm - 1.3 cm)	0.84	±	0.1	b	28
Large (> 1.4 cm)	0.72	±	0.2	c	28
Overall (all size classes)	0.83		0.2		82

Table 4-15. Differences in reduction in peak runoff by rain event size for 82 storms between December 2004 and September 2008, in Merrifield, Virginia. Rain event sizes not connected by the same letter are significantly different at the α = 0.05 level.

Rain Event Size	Mean Peak Reduction		SD	Significant Difference	N
Small (<0.254 cm)	1.0	±	0.1	a	26
Medium (0.254 cm - 1.3 cm)	0.93	±	0.2	b	28
Large (> 1.4 cm)	0.79	±	0.3	c	28
Overall (all size classes)			0.2		82

while in Virginia, the median sized storm was 0.58 cm and 9 hours long. The storm size distribution was fairly similar in the two regions, in Florida, 76% of these storms were less than 1.27 cm,, 87% were < 2.54 cm, and 99% were less than 7.62 cm in size.

Refer to Appendix X for comparisons of storm duration, storm volume, average intensity, maximum intensity, stormwater retention and maximum storm water runoff intensity between Virginia and Florida.

Comparison of Hydrologic Dynamics of a Green Roof in FL and VA

Despite the greater depth and pore space available in the thicker Florida green roof, storms of the similar volume delivered over a longer period of time in Virginia, had higher rates of stormwater retention than in Florida. The reason for the higher retention rates in Virginia may be due to the fact that the storms sampled in Virginia were longer in duration than those in Florida—for example, the study period extending from July to October was averaged together for Virginia and storms lasted on average 9 hours (Table 4-10) while in Florida the storms from the same study period lasted 2 hours or less on average (Table 4-8), additionally Table V-1 shows that the median and mean duration values for Virginia for all storms combined were three times longer than those in Florida over the entire sampling period. The peak intensity was three-fold higher for the storms in Florida (for example, 3.3 cm hr^{-1} for storms between July and October 2007 on the CRP roof, versus 1.05 cm hr^{-1} for July to December 2007 in Virginia); the mean intensity of rain storms was also higher in Florida than Virginia (Table X-3, Appendix X). The variation in the duration of the storms and the intensity of the storms may explain why a roof with a thinner substrate (4.5 cm thick) could have greater retention than one that is 15 cm thick. The results of greater retention in the shallow Virginia roof were originally counterintuitive, taking into account that the green roof in Virginia was a) shallower and b) consisted of an equally porous medium as that in Florida, but with a larger pore size distribution and c) had less organic matter initially and d) contained succulent plants versus perennials.

Explanations for the differences in water retention between the two roofs may relate to: 1. Differences in the storm characteristics between the two regions—with Virginia having storms on average three times longer than those in Florida, as well as a lower mean storm intensity and lower maximum storm intensity, in any given season, 2. Changes in the VA growing medium over time, increase in OM and plant matter; 3. Differences in the underlayment in Florida and Virginia (Floradrain 25 versus Hydrogel packs) and unexpected changes in drainage of the underlayment over time that could possibly impede drainage and cause a perched water table, 4. Presence of Irrigation in Florida which may affect antecedent moisture conditions at the time of a rain event and available pore space.

The underlayment of the green roof in Gainesville, FL, consisted of Floradrain FD 25, a corrugated plastic layer with small cups that held 3 L m^{-2}. In the case of Virginia, the underlayment consisted of superabsorbent hydrogel packs adhered to the surface of the APAO layer with the same retention rating of 3 L m^{-2}. However the mechanisms by which the two underlayments function are quite different, for example the superabsorbent hydrogel packs function by absorbing 500% its dry weight in water and once saturated rills form between lines of gel packs to allow for drainage between the rills. One possibility that could lead to greater retention in this system, would be if rills are blocked and a perched water table were to form and more water were in turn detained and made available for ET over time.

Water Quality Results—Charles R. Perry Green Roof in Gainesville, Florida

Concentrations and loads from individual storm events

Nutrient and metals were sampled seven times from the Charles R. Perry (CRP) Green Roof; once, one week after planting in 2007 and then six times one year after establishment, during the summer of 2008, for nutrients (NO_3, NH_4, SRP, TP, and TSS) and metals (Fe, Cu, Cd, Zn, and Al). Sampling dates and size of storm events selected for water quality sampling are shown in Table Y-1, Appendix Y; characteristics of the green roof runoff for the same events are shown in Table Y-2.

Grab samples were taken at various intervals during the storm to create storm chemographs, exact times of sampling and their relationship to flow volumes are indicated by markers on the individual storm hydrographs for each storm shown in Figures Z-1 through Z-5 in Appendix Z. The individual storm hydrographs were analyzed for the effect of the green roof on hydrology as evaluated based on the reduction in maximum runoff rate, the increase in lag time to peak of concentration and the delay of the start of rain to start of runoff and the increase in duration of return flow of the water temporarily detained in the green roof medium in Table Z-2. Concentrations by time interval for nutrients measured are shown in Appendix AA, while means and standard deviations for entire storms for Florida are shown in Table 4-16.

Table 4-16. Summary of mean concentrations of nutrients and TSS for the six storms sampled in 2008 from the green roof (GR) and conventional roof (CR) runoff in Gainesville, FL.

Date	NOx-N(mg L^{-1})		NH_3-N(mg L^{-1})		TSS (mg L^{-1})		SRP (mg L^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
6/23/2008 GR	0.03	0.01	0.05	0.01	2.46	0.29	0.70	0.14
6/25/2008 GR	0.11	0.03	0.07	0.02	1.12	0.35	0.64	0.22
6/26/2008 GR	0.08	0.04	0.12	0.09	3.70	2.36	0.55	0.04
6/30/2008 GR	0.04	0.01	0.22	0.05	7.75	3.89	0.56	0.12
7/8/2008 GR	0.05	0.02	0.05	0.23	1.27	3.48	0.00	0.08
7/8/2008 CR	0.07	0.05	1.29	0.04	7.41	1.44	1.29	0.02
8/21/2008 GR	0.11	0.04	0.16	0.04	0.05	0.03	0.03	0.20
8/21/2008 CR	0.01	0.01	0.10	0.07	0.06	0.04	0.47	0.00

Table 4-17. Summary of mean concentrations of metals for six storms sampled in 2008 from the CRP green roof and conventional roof in Gainesville, FL.

Date	Cu (mg/L)		Fe (mg/L)		Cd (mg/L)		Zn (mg/L)		Al (mg/L)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
6/23/2008 CR	0.001	0.005	0.205	0.048			0.15	0.07	0.457	0.057
6/25/2008 CR	0.001	0.005	0.402	0.143	0.000	0.000	0.055	0.03	0.423	0.046
6/26/2008 CR	0.176	0.06	0.2747	0.102	0.0001	0.00062	0.047		0.2687	0.24
6/30/2008 CR	0.012	0.013	0.444	0.033	0.0001	5.6E-05	0.25	0.05	0.6841	0.33
7/8/2008 GR	0.000	0.002	0.282	0.025	0.00	0.00022	0.055	0.03	0.623	0.27
7/8/2008 CR	0.012	0.02	0.003	0.007	0.0001	0.00149	0.001	0.003	0.250	0.11
8/21/2008 GR	0.00	0.004	0.34	0.059	0.00	0.00027	0.47	0.9	0.671	0.13
8/21/2008 CR	0.15	0.084	0.01	0.017	0.00	0.00051	0.03	0.037	0.28	0.031

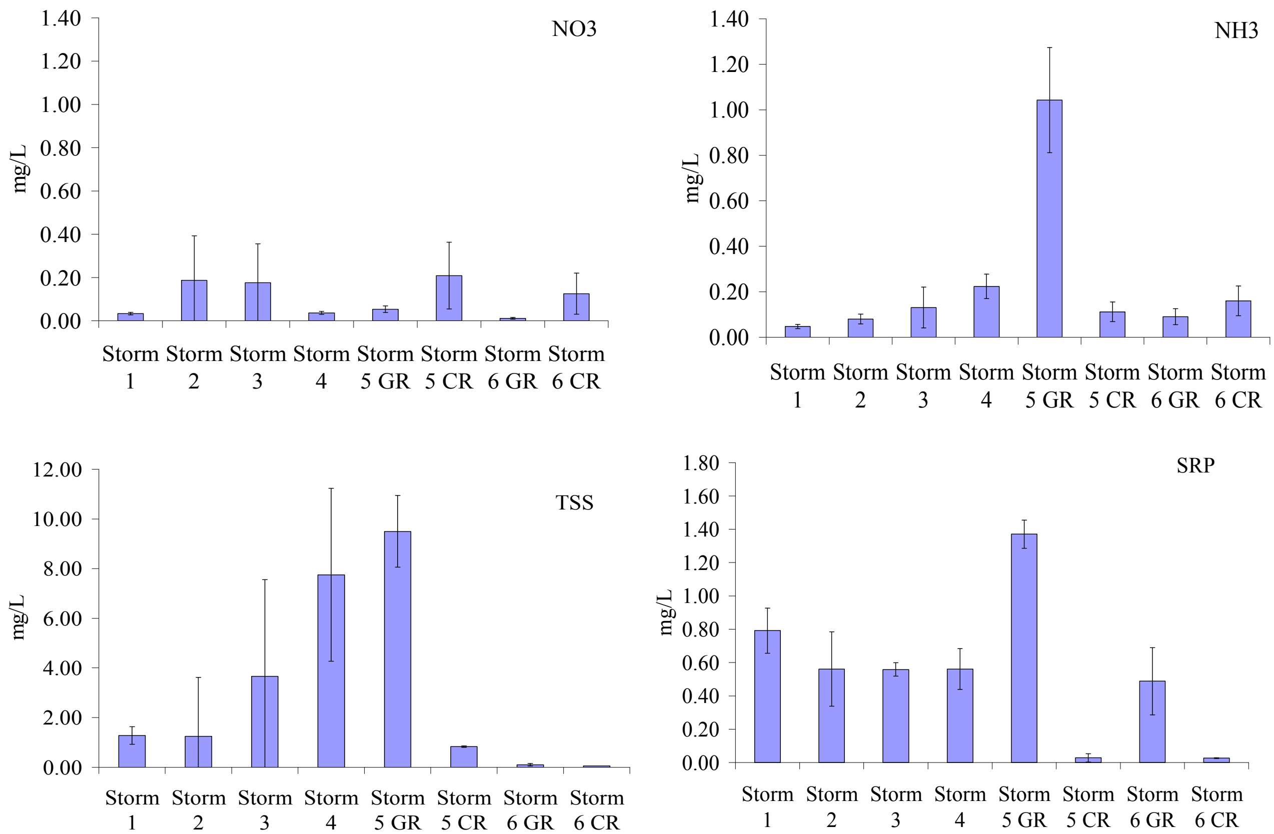
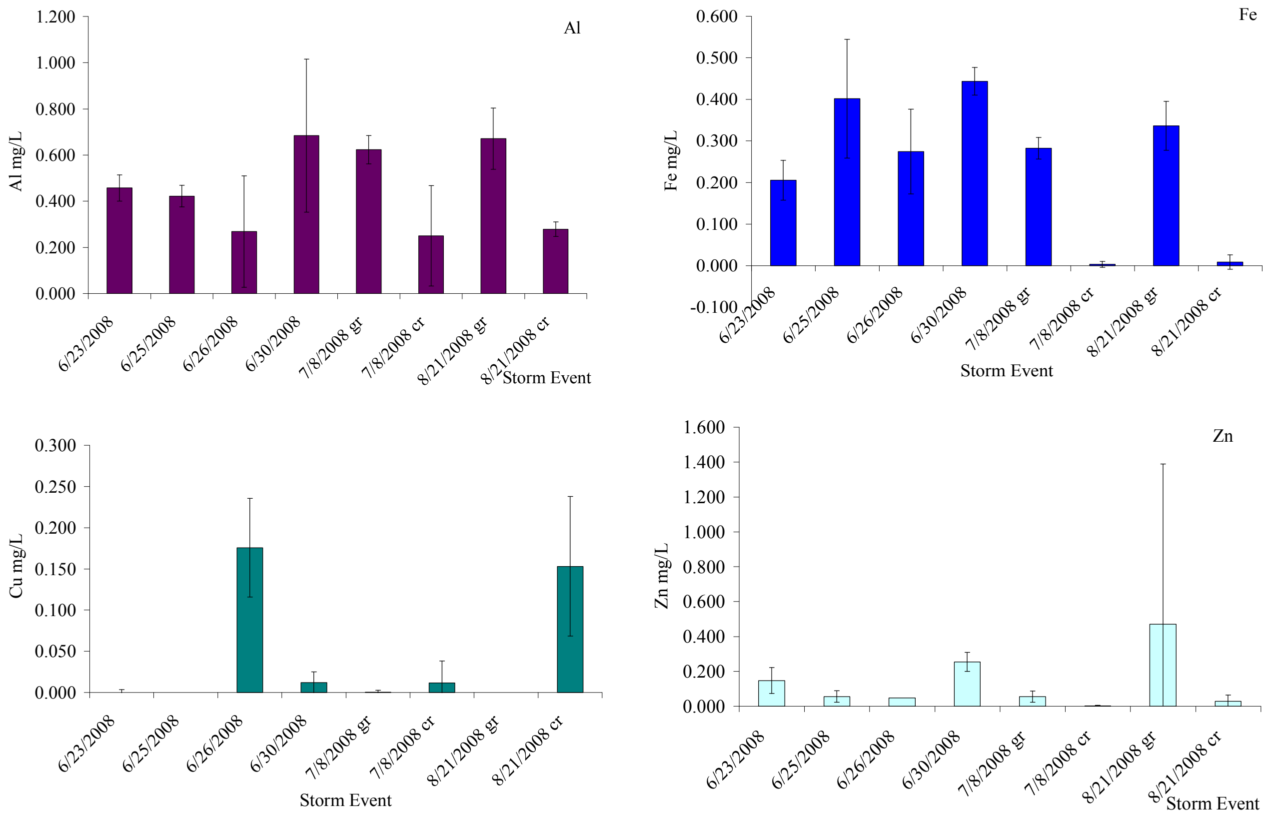


Figure 4-15. Mean nitrate, ammonium, SRP and TSS concentrations per storm event for green roof runoff (6 storms) and conventional roof runoff (2 storms) in summer 2008 from the CRP green roof in Gainesville, FL.



Figures 4-16. Metals concentrations (A) Aluminum, B) Iron, C) Copper and D) Zinc) in CRP green roof (gr) and conventional roof (cr) runoff in 2008 in Gainesville, FL.

Table 4-18. Total load of nutrients measured in 6 storms 2008 from CRP green roof in Florida.

Date	Vol (L)	NOx-N (mg)	NH_3-N (mg)	TSS (mg)	SRP (mg)
Total 6/23	870	27	41	2150	610
Total 6/25	100	11	7	110	64
Total 6/26	215	17	25	800	120
Total 6/30	190	7	43	1500	110
Total CR 7/8	11470	890	870	23800	82
Total GR 7/8	11100	780	14270	82200	14300
Total CR 8/21	26500	3030	4180	1380	700
Total GR 8/21	15400	200	1510	960	7300

Discussion--CRP-FL Water Quality Data

The values of SRP from the Charles R. Perry Construction Yard green roof runoff ranged from 0.25 to 1.44 mg L^{-1}, with a median value of 0.72 mg L^{-1} (Figure 4-15). In comparison to other green roofs, such as in Sweden (Berndtsonn, et al. 2006), our median SRP level (0.72 mg

L^{-1}) was slightly lower than the mean values reported for a green roof above the Bicycle Parking in Lund (1.4 mg L^{-1} and 0.9 mg L^{-1}), but greater than the mean SRP reported for the Canoe Club green roof in Malmo, Sweden (0.2 mg L^{-1}). The SRP concentrations from our green roof runoff were lower than SRP levels from reclaimed water in Florida, that of ConservII in Orlando, which is pumped at a rate of 46 million liters per day directly through sandy soil to the superficial aquifer. The mean SRP value for ConservII is 1.67 mg L^{-1} (Moura, 2009), for all rain events except 7/8/08, the median SRP level in green roof runoff was half that (0.72 mg L^{-1}). The implication is that reclaimed water sends 40 tons of P to the aquifer, while green roofs are sending loads on the order of grams to kg per year to surface water. The conventional roof runoff SRP levels (0 - 0.04 mg L^{-1}) were lower than background levels of SRP found in groundwater in Central Florida (0.05 mg L^{-1}). Conventional roof runoff of SRP ranges from 0.00 to 0.04 mg L^{-1} with a median value of 0.03 mg L^{-1}.

In North Carolina (Moran, 2005), both concentrations and amounts of total nitrogen and total phosphorus increased from rainfall to green roof outflow and from the control roof outflow to green roof outflow. It was determined that the growing medium, composed of 15% compost, was leaching nitrogen and phosphorus into the green roof outflow.

Water Quality Results—YSC Green Roof in Merrifield, Virginia

Stormwater runoff from five storms were sampled from both the conventional roof and the green roof at Yorktowne Square Condominiums (YSC) in Merrifield, Virginia between 2007 and 2008; 2 storms represented the spring time and 3 storms represented the summer time. The stormwater runoff was sampled between 3 and 5 times each storm. Concentrations of the nutrients/suspended and dissolved solid (NO_3, OP, TP, TDS and TSS) and metals (Cu, Cd, Fe and Pb) sampled are shown by time increment by storm in Appendices BB. Means and standard deviations are shown in Figure 4-17 and the total load for each roof is shown in Table 4-19 and 4-20.

Nutrient wise, TP and OP concentrations were always higher in the green roof runoff than in the conventional roof runoff. In general, the TP consisted of 80-90% orthophosphorus (SRP) from all the green roof runoff, while in CR runoff it was only 75% made of OP. There was greater variability between storms for both nutrients and metals than within storms. First flush effects were noticed for some parameters, where first flush can be defined on a concentration or mass load basis. When defined on a mass basis, the load of a nutrient or metal exiting the system is disproportional to the amount of flow occurring in the "initial portion" of the storm ('initial portion' can be defined as an indefinite portion of time closest to the start of the storm or predetermined volume, such as the first ½ inch of runoff).

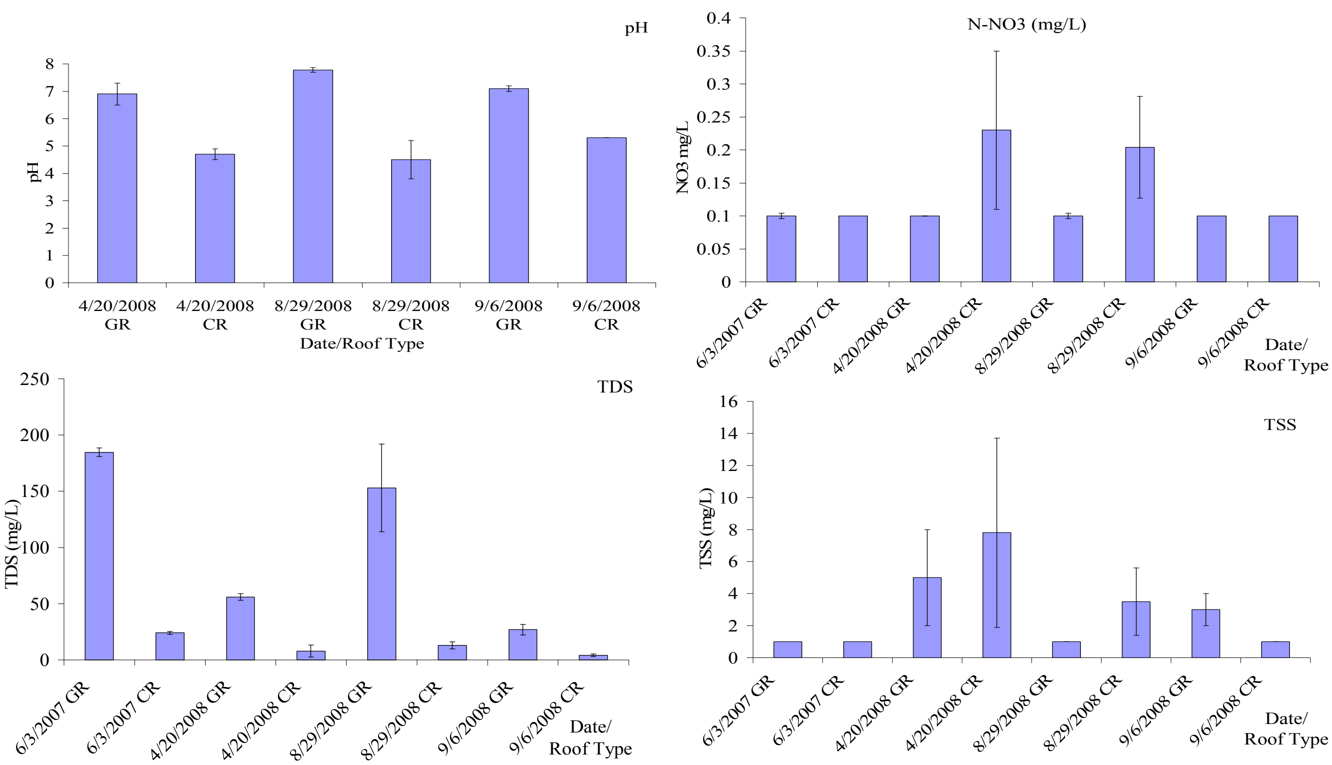


Figure 4-17. Mean concentratioins and SD for nutrients and metals measured in YSC green roof (gr) and conventional (cr) runoff in Merrifield, VA, 2007 and 2008.

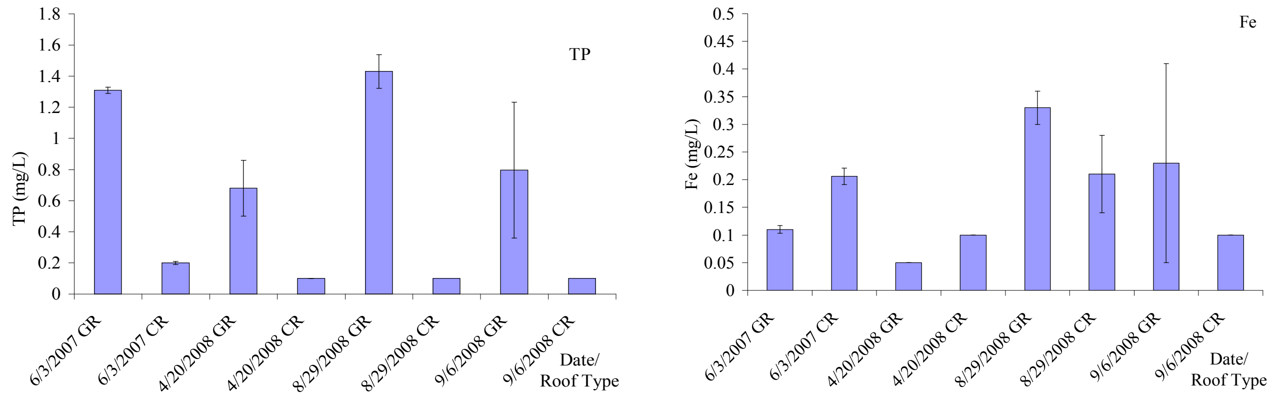


Figure 4-17. Continued

Table 4-19. Total load of nutrients measured in 4 storms in 2007-2008 from YSC green roof in Virginia.

Date	Vol (L)	N-NO3 (mg)	TP (mg)	SRP (mg)	TSS (mg)	TDS (mg)
6/3/2007 GR	340	38	450	410	340	63500
6/3/2007 CR	560	< 56	110	80	560	13400
4/20/2008 GR	1200	120	820	750	5150	67200
4/20/2008 CR	2730	640	< 270	< 270	12300	26800
8/29/2008 GR	420	< 42	596	494		60700
8/29/2008 CR	840	140	< 84	< 14		11400
9/6/2008 GR	2970	< 297	1896	1655	8770	87000
9/6/2008 CR	8020	< 802	< 802	< 80	8020	37300

Table 4-20. Total load of metals measured in 4 storms in 2007-2008 from YSC green roof in Virginia.

Date	Vol (L)	Cu (mg)	Fe (mg)	Pb (mg)	Cd (mg)
6/3/07 GR	340	<34.4	38		0.0
6/3/07 CR	560	<56.1	117		
4/20/2008 GR	1200	<247	<121	<2.8	
4/20/2008 CR	2730	<273	<273	64.0	
8/29/2008 GR	420	124	138	<2.0	0.232
8/29/2008 CR	840	<383	<144	<13.0	0.000
9/6/2008 GR	2970	<297	<377	<5.9	
9/6/2008 CR	8020	<802	<802	58.8	

Comparisons in Concentrations of Nutrients and Metals between roof types in FL and VA and between locations

Nutrients: The mean total phosphorus concentrations from the YSC green roof runoff in Virginia were significantly higher than conventional roof runoff concentrations at the $p < 0.001$ (ANOVA and pairwise t-test, SAS 9.2). SRP concentrations were also significantly greater in green roof runoff than conventional roof runoff for both the CRP green roof in Florida and theYSC green roof in Virginia, at the $p < 0.001$. When comparing the conventional roof runoff from the two locations, Florida and Virginia, there were no significant differences in OP concentrations, nor any significant differences in green roof runoff from the two locations ($p = 0.34$ and 0.36, respectively) (Table 4-21).

The results of the ANOVA and pairwise t-tests for nitrate concentrations, show that the NO3 concentrations are significantly lower in the green roof runoff than the conventional roof runoff in both Florida and Virginia (Table 4-21). There are no significant differences between NO3-N levels in conventional roof runoff between Florida versus Virginia, nor for green roof runoff for Florida compared to Virginia (Table 4-21). Ammonium was measured in Florida only, and there were no significant differences in the concentrations found in green roof runoff versus conventional roof runoff (Table 4-21). There was a significant difference in pH between conventional roofs and green roofs; the green roof buffered the pH, raising it from a mean value of 4.78 ± 0.14 in conventional roof runoff to a mean pH of 7.31 ± 0.14 in green roof runoff. This trend of buffering acidic rain was documented in Berghage, et al. (2007). They found that the growing media they tested in their field study would have at least 10 years of acid rain buffering capacity with no need of lime until 10 to 30 years (Berghage, et al. (2007).

There were no significant differences in TSS between the green roof runoff and the conventional roof runoff in either Florida ($p = 0.07$) or Virginia ($p = 0.66$), nor any significant differences in TSS concentrations in green roof from Virginia compared to that of Florida, nor for conventional roof runoff compared by location. However, there were significantly higher concentrations of TDS measured in green roof runoff in Virginia (the only place this parameter was measured) at a $p < 0.0001$ level (Table 4-21).

Metals: With respect to metals measured in the two sites, Aluminum concentrations were found to be significantly higher in green roof runoff in Florida, than in conventional roof runoff (Table 4-21). This may relate to the constituents used in the roof, for example the drain cover and drain itself on the green roof is fabricated of Aluminum, while the down pipes are cast iron. Possibly as a consequence of the newly installed iron downpipes, iron levels in the green roof runoff from the CRP roof were significantly higher than those measured in the conventional roof collected from the red ceramic tile roof atop Newell Hall (Table 4-21). More investigation would be necessary to pinpoint the source of the iron in the CRP green roof runoff, it is however apparent that the concentrations from the CRP roof are about 10-fold higher than Fe-concentrations measured in the Newell Hall runoff and nearly 2 times more than concentrations of Fe found in the Virginia green roof runoff. The difference in Fe concentrations in Florida is significantly different than the Virginia green roof concentrations to the $p < 0.0001$ level (Table 4-21); while the Fe concentrations in conventional roof runoff measured in Florida were significantly lower than the Virginia conventional roof runoff at a $p = 0.0129$ level (Table 4-21). No significant differences were found in between conventional roof runoff and green roof runoff for iron in Virginia (Table 4-21).

Copper concentrations from Virginia were higher in both conventional and green roof runoff than in Florida (Table 4-21), and in neither location were the Cu levels significantly different in the green roof runoff as compared to conventional roof runoff. Again, the presence of metals is likely due to the degradation and transport of building materials. Lead (Pb) was only measured in Virginia and was found to be significantly lower in the green roof runoff than the conventional roof runoff at a $p = 0.0023$ level. Cadmium was near 0 in all samples in both locations and not significantly different in green roof runoff as compared to conventional roof runoff in either location. Zinc was measured in both locations, though only 2 samples were taken in Virginia. In Florida, there were no significant differences in concentrations found in green roof runoff as compared to conventional roof runoff.

In summary, green roofs did mitigate for NO3-N in both locations, it increased pH levels relative to rainfall (measured in VA) and lead was significantly lower in green roof runoff (in Virginia) compared to conventional roof runoff. Metals behaved differently by location, for example Aluminum and Iron were found to be significantly higher in green roof runoff in Florida, but not in Virginia, and concentrations of metals varied more between locations than did nutrients. In the case of TP, OP, and TDS; levels were significantly higher in green roof runoff than conventional roof runoff in Florida and Virginia. TSS was surprisingly not significantly different in green roof runoff as compared to conventional roof runoff, however concentrations from Florida were significantly higher than those found in the green roof runoff in Virginia. The green roof does seem to have an impact on nutrient and metal concentrations and metal concentrations vary more by location than other parameters.

Metal concentrations in the CRP green roof runoff varied: Aluminum levels ranged from 0.1 mg L^{-1} to 0.8 mg L^{-1}, Iron ranged from 0.15 mg $^{L-}$1 to 0.40 mg L $^{-1}$; Zinc ranged from 0.01 mg L^{-1} to 0.24 mg L^{-1} for all samples, except one during the storm event on 8/21/08. Iron was lower in conventional roof runoff (0 - 0.05 mg L^{-1}) at $p<0.05$, using SAS 9.2, than in green roof runoff. There were no significant differences between conventional roof and green roof runoff for Fe

The mean concentration of Pb in YSC conventional roof runoff (0.034 ± 0.006 mg P L^{-1}) across all samples was significantly higher than the mean concentration of Pb in green roof runoff (0.002 ± 0.006 mg Pb L^{-1}) at the p <0.0023 level using an ANOVA and pooled t-test in

SAS 9.2. Compared to lead levels measured on other roofs, these levels are comparable to Pb levels in green runoff from both green roofs sampled by Berndstonn et al. in Sweden and lower than conventional roof runoff in Paris measured by Gromaire-Mertz et al. in 1999 (Table 4-22).

Table 4-21. Results of the ANOVAs, pairwise t-tests for nutrients and TSS and TDS between conventional roof runoff and green roof runoff in Florida and Virginia; and pooled t-tests between locations within conventional or green roof type.

Parameter (units)	Location	Conventional Roof (Mean ± S.E.)	*(n)*	Green Roof (Mean ± S.E.)	*(n)*	Prob > F
OP (mg P L^{-1})	Florida	0.164 ± 0.127	*9*	0.755 ± 0.085	*20*	p = 0.0007
	Virginia	0.076 ± 0.068	*20*	0.87 ± 0.068	*20*	p < 0.001
	FL vs VA	CR_{FL} vs $CR_{VA,}$ p = 0.34		GR_{FL} vs $GR_{VA,}$ p=0.36		
TP (mg P L^{-1})	Virginia	0.098 ± 0.06	*20*	1.12 ± 0.062	*20*	p = 0.0007
pH	Virginia	4.78 ± 0.14	*12*	7.31 ± 0.14	*12*	p < 0.0001
NO_3 (mg N L^{-1})	Florida	0.146 ± 0.029	*9*	0.055 ± 0.019	*20*	p = 0.014
	Virginia	0.122 ± 0.018	*20*	0.05 ± 0.02	*14*	p = 0.0154
	FL vs VA	CR_{FL} vs $CR_{VA,}$ p = 0.57		GR_{FL} vs $GR_{VA,}$ p = 0.80		
NH_3 (mg N L^{-1})	Florida	0.276 ± 0.12	*9*	0.276 ± 0.08	*20*	p = 0.99
TSS (mg L^{-1})	Florida	1.143 ± 1.27	*9*	3.95 ± 0.85	*20*	p = 0.078
	Virginia	2.96 ± 0.96	*14*	2.35 ± 1.00	*13*	p = 0.66
	FL vs VA	CR_{FL} vs $CR_{VA,}$ p = 0.27		GR_{FL} vs $GR_{VA,}$ p = 0.23		
TDS (mg L^{-1})	Virginia	13.47 ± 11.8	*17*	117. 2 ± 11.8	*17*	p < 0.0001

Table 4-22. Comparative values of green roofs, conventional roofs and urban lawns from various locations.

Collection Site	Location	pH	TSS ($mg\ L^{-1}$)	TP ($mg\ L^{-1}$)	PO_4-P ($mg\ L^{-1}$)	Tot-N ($mg\ L^{-1}$)	NO_3-N ($mg\ L^{-1}$)	NH_4-N ($mg\ L^{-1}$)	NH_3-N ($mg\ L^{-1}$)	Source/Reference
Green Roofs	Japan	5-7.5		0.01-0.02	0.01	0.03-1.0	0.01-1.2	0.1-1.0		Berndtsson, J., Lars B. and K. Jinno. 2009.
Green Roofs	Sweden	6-6.2		0.04-0.32	0.02-0.27	2.1-2.7	0.1-1.05	0.1-1.1		Berndtsson, J., Lars B. and K. Jinno. 2009.
Green Roof	North Carolina, US			0.61-1.4		0.9-6.9				Moran, A. 2005
Controls:Rain	North Carolina, US			0.05		0.05-2.3				Moran, A. 2005
Conventional Roof	North Carolina, US					0.7-7.1				Moran, A. 2005
Green roof	Gainesville, FL		0.06-9.50	0.59-1.46	0.49-1.37		0.01-0.19		0.05-1.04	Current study (Lang 2009)
Conventional Roof (Tile)	Gainesvillle, FL		0.06-0.83	0.40-0.75	0.03		0.13-0.21		0.11-0.16	Current study (Lang 2009)
Green Roof	Merrifield, VA		1-5	0.68-1.43	0.63-1.19		<0.10			Current study (Lang 2009)
Conventional Roof (Asphalt)	Merrifield, VA		1-7.8	<0.1-0.2	<0.1-0.15		<0.1-0.23			Current study (Lang 2009)
Urban Roofs	Paris, France		29-33							Moilleron et al. (2002)
Tile, Polyester, Gravel roof	Switzerland							0.52, 1.4, 0.2		Zobrist et al. (2000) in Berndstonn et al. (2009)
Green Roofs	Berlin, Germany	7.3 (Rain 6.1)				0.3-2.3				Kohler and Schmidt (2003)
Urban Roof	France		29 (3-304)							Gromaire-Mertz et al. 2005
Urban Roof	China		121.3	0.71		11				Ren and Wang (2006)
Controls:Rain	China		6.49	0.06		3.99				Ren and Wang (2006)
Road	China		176-567	0.71		7.40-13.62				Ren and Wang (2006)
Lawn	China		549	0.74		6.8				Ren and Wang (2006)
Roof runoff	Connecticut,US			0.019		1.2	0.5			Dietz and Claussen (2005)
Mixed natives	Ft. Lauderdale, FL						0.44±0.12**	0.16+/- 0.01**		Erickson et al. (2005)
St. Augustine Grass	Ft. Lauderdale, FL						0.05±0.01**	0.17+/- 0.01g/L**		Erickson et al. (2005)

*Range of median values are reported unless indicated otherwise by **

Comparison of Areal Loading Rates between Florida and Virginia

The areal loading rates (Table 4-23) were determined by dividing the total load for each storm by the surface area of the roof sampled, in the case of Florida, the roof was 214.5 m^2 and in Virginia, the roof section sampled was only 48.8 m^2, as a result, while Virginia often had lower concentrations, the maximum areal loading rates from Virginia often exceeded the loading rates from Florida for many constituents.

Table 4-23. Areal loading rate (mg m^{-2}) for nutrients sampled in green roof (gr) and conventional roof (cr) runoff from CRP roof in Gainesville, FL, 2008.

Date	L m^{-2}	NOx-N (mg m^{-2})	NH3-N (mg m^{-2})	TSS (mg m^{-2})	SRP (mg m^{-2})
6/23/08 gr	4.1	0.13	0.2	10.0	2.9
6/25/08 gr	0.5	0.05	0.0	0.5	0.3
6/26/08 gr	1.0	0.08	0.1	3.7	0.6
6/30/08 gr	0.9	0.03	0.2	7.0	0.5
7/8/08 cr	77	3.66	4	98	0.3
7/8/08 gr	51.6	3.6	66.4	382	66.7
8/21/08 cr	109	12	17	6	3
8/21/08 gr	71.8	1.0	7.0	4.5	33.9

Table 4-24. Areal loading rate (mg/m2) for nutrients sampled in green roof (gr) and conventional roof (cr) runoff from YSC roofs in Merrifield, Virginia, 2007 and 2008.

	L m^{-2}	NOx-N (mg m^{-2})	TSS (mg m^{-2})	TDS (mg m^{-2})	TP (mg m^{-2})	SRP(mg m^{-2})
4/11/07 gr	1.7	0.73	0.00	0	0.00	1.02
4/11/07 cr	2.1	0.92	0.00	0	0.00	0.06
6/3/07 gr	1.6	0.77	7.01	1296	9.09	8.32
6/3/07 cr	2.6	1.14	11.44	273	2.23	1.72
4/20/2008 gr	5.6	2.47	105	1372	16.8	15.33
4/20/2008 cr	12.7	13.09	252	548	5.57	5.57
8/29/2008 gr	1.9	0.85	--	1240	12.2	10.08
8/29/2008 cr	3.9	2.84	--	233	1.72	0.28
9/6/2008 gr	13.8	6.06	179	1777	38.7	33.78

Conclusions

The first hypothesis tested, that the overall benefit for green roofs for water retention, peak runoff attenuation and increases in lag time to peak runoff would be less in green roofs in Florida than in Virginia, was not rejected, though the original reason given, that it would be due to higher peak precipitation rates and greater recurrence of convective storms, was not isolated as the specific reason for the difference in retention between the sites. Storm size distributions in the two extremes of the subtropical climate were fairly similar for the study periods. Infact, the median depth of rain for the 82 rain events sampled in Virginia (0.63 cm) was slightly higher than the median depth of rain for the 91 rain events sampled in Florida (0.44 cm); and the maximum rain depth was nearly twice as high in Virginia (17.5 cm) as Florida (9 cm), which was unexpected. Duration of storms in Virginia, however, were on average at least 3 times longer than Florida storms. Explanations for the higher retention seen in the Virginia roof may relate to differences in the underlayment between the two roofs, the lower mean intensity of storms and greater duration of storms in Virginia, differences in organic matter due to the age of the roof or relate to the effect of irrigation on antecedent moisture conditions. These specific topics need to be studied further in greater detail to isolate why the Virginia roof had higher retention than the Florida roof, when in fact it was shallower.

The green roofs in both Florida and Virginia did detain significant portions of stormwater and significantly increase the lag time to peak and extend the runoff period from the roof. In Florida, small rain events (< 0.254 cm, n =31), had a significantly higher mean retention (79%) than either medium rain events (0.254 cm - 0.83 cm) or large events (>0.83 cm). There were no significant differences in retention between medium (43% retention) and large (26% retention) rain events in Florida, and no significant differences in extension of runoff past the end of a rain event (s = 7.8 hr, m = 11 hr, l = 8.7 hr) in Florida. In Virginia, the mean retention by size class differed significantly between small, medium and large rain events, with respective retention rates of (98%, 84% and 72%). The retention rates of the large events (72%) compared well to studies in neighboring and nearby states (North Carolina and Pennsylvania) (Moran 2005 and DeNardo 2003), though the small and medium events had retention rates that were unusually high in comparison. In both Florida and Virginia, there were significant differences in the reduction of the peak intensity among all the different size classes of the rain events, 94% for small events, 79% for medium events and 60% for large events for Florida, and 100%, 93% and 79% for small, medium and large events, respectively in Virginia.

The extension in end of runoff was not as great in Virginia as provided by the 15 cm thick green roof in Florida—the median extension time varied between 0.68 hours and 3.9 hours through the seasons for Virginia. In Florida, the median extension in runoff varied between 2.5 hours and 14 hours by season. These differences are attributed to the thickness of the Florida green roof and the pore-size distribution of the growing medium in the green roof, as well as differences in the underlayment (for example, Hydrogel packs do not re-release water until ET occurs to remove the water from the gel packs.)

The major objective for the hydrological analyses was to determine if the green roofs behaved similarly hydrologically in both extremes of the subtropical climate. This study found that for the two roofs studied, they did behave in the same manner, though at different intensities for water retention, peak reduction and increase in lag time, with water retention and peak reduction being greater in Virginia and with a greater difference in the effect on extension of runoff and increase in lag to peak in Florida than Virginia.

In terms of water quality analyses, the hypothesis tested was that the green roofs' influence on water quality (nutrients, metals, TSS and TDS) would be similar in both Virginia and Florida and that they would act as sinks for nitrogen and sources for phosphorus and suspended sediment; and would act similarly for metals in both regions (whether as a source or sink). It was found that the green roofs did infact act as sources for phosphorus, (both TP and OP), which was similar to finding in other studies from nearby states and other regions of the world. The green roofs did also act as a sink for nitrogen as nitrate as hypothesized, however no differences in concentrations were noticed between the green roofs and control roofs for NH_3-N. The green roofs did buffer pH, which was also similar to findings in other studies (Berghage, 2005, Kohler and Schmidt, 2003; DeNardo 2003).

Metals behaved differently by location, for example aluminum and iron were found to be significantly higher in green roof runoff in Florida, but not in Virginia; and lead concentrations were also significantly lower in green roof runoff than conventional roof runoff in Virginia. Concentrations of metals varied more between locations than did nutrients. For both metals and nutrients, variability between storms was greater than within storms, in both Virginia and Florida. Total Dissolved Solids (TDS) were significantly higher in green roof runoff as compared to conventional roof runoff, however total suspended solids (TSS) surprisingly was not found to be significantly different in green roof runoff as compared to conventional roof runoff. However, concentrations of TSS from the Florida green roof were significantly higher than those found in the green roof runoff in Virginia.

The load reductions attributable to the green roof, as compared to a conventional roof of the same size, varied with the size and intensity of the storms, by and large, the green roof seemed to lower nitrate and ammonium concentrations from 12-90% depending on storm size and intensity, but the presence of the green roof increased TSS, TP and SRP loads in most cases. The SRP load was often increased over 10-fold. It is recommended that the cost-savings implied by a reduced peak outflow rate and reduction in storm water volume and possible reduction in nitrate and ammonium loads be weighed against the externalities related to increased SRP loads leaving a green roof in a future study. The implied cost of treating runoff for SRP or TP should be taken into account when considering implementing green roofs in South Florida, especially in new developments in close proximity to the Everglades or surrounding areas, since the

Everglades ecosystem is a fragile, naturally low P ecosystem, and receiving waterbodies surrounding the area have a P limit of 10 ppb, which all green roof samples exceeded.

Furthermore, it is highly recommended that cisterns be used in conjunction with the green roof, as this will keep the green roof runoff out of the stormwater system and allow nutrients to be recycled to the roof and re-utilized by the plants. Additionally, the cisterns potentially can be used to gravity irrigate the landscape at the surface level (as is done in VA), implying a cost-savings related to not having to rely on potable or even reclaimed water. Based on the current findings, it may be worthwhile to study the possible benefit of green roofs in taking up atmospheric nitrogen, the assumed source of N from the conventional roof, whether deposited by wet or dry deposition. Additionally, investigating the feasibility and usefulness of treating grey water on a green roof with specific plants and re-using the water on-site, is another possible study emanating from this research.

Finally, the last recommendation is to use a low P growing medium for green roofs and to make guidelines for the State of Florida now, so that larger green roof companies can tailor their mixes to the specific needs of our state, especially with regard to the issues we have with P in streams and fragile ecosystems and water usage issues. Guidelines should specify that green roofs in certain areas, such as South Florida, must be accompanied by a cistern for on-site re-use; and reclaimed water should be used as make-up water for times when the cistern is deficient in providing irrigation water. Otherwise green roofs, if mismanaged, for example high nutrient content growing media are used, with over-irrigation using potable water and ornamental plants, could lead to a potential ecological disaster in Florida. If properly managed, green roofs have the potential of even treating grey water for N, and having that water be reused on site for irrigation of the ground landscape. In no case is it recommendable to have green roof runoff directly conveyed to a natural waterbody with concerns about P limitations.

CHAPTER 5
CONCLUSIONS

Green roofs have the potential to reduce storm water quantity in Florida and Virginia, however water retention and nutrient leaching depend largely on the growing media. Choice of plant material also affected performance of green roofs in terms of retention and nutrient leaching. Perennials performed well in water retention and evapotranspiration. Succulents had the best survivability through the subtropical climate (drought and frost), though had the least amount of nutrient uptake and water retention of the three plant types. Findings suggest that a growing media rating system—based on initial nutrient content and ability to support plants with little/no irrigation—should be developed for Florida green roofs, in order to avoid undesirable effects associated with runoff. Future research includes 12 green roof platforms to measure plant performance and nutrient leaching under drought conditions and elevated N-deposition in the optimal soil media-plant combination determined from the final results of this study.

Implications of Water Retention for Florida Green Roofs

The results of the hydrological dynamics study revealed that when designing a green roof for stormwater reduction control in Florida, the most important design factor influencing retention is the initial selection of growing medium type. When selecting from several growing media types, if interested in the greatest water retention for stormwater control, it is recommended to select the medium with the finest pore size-distribution of the available growing media. Also the greater the abundance of certain constituents such as organic matter, perlite and vermiculite also play a large role in increasing retention. Total porosity is actually less influential in determining overall retention of the medium.

In the bin study retention rates were comparable to those found in a studies in both temperate climates (DeNardo 2005) and in the subtropics eg. Texas (Timm and Rasmussen

2008). The retention rates ranged from a low of 24% for Building Logics medium with no vegetation to a maximum of 83% for UCF growing medium planted with perennial plants. Within each growing media type- retention ranged from 24-53% BL, 30-72% H and 31.2% -85% depending on the plant types present. Plants were found to be secondary to growing media characteristics in influencing water retention rates in the sub-tropics, in the plant-growing media used in this study. The influence of the plants increased retention by 11-22% depending on the growing medium. For growing media with large pores and large particles, the positive influence of plants increasing water retention directly after a storm is less. For example in Building Logics growing medium, water uptake by plant type was increased only by 11-14%, but in Hydrotech and UCF growing media, water uptake often increased by 15-22% due to the presence of plants.

Evapotranspiration rates ranged from 1.5 mm day^{-1} for unvegetated Building Logics medium to a maximum of 3.6 mm day^{-1} for UCF bins planted with perennials. There was a significant difference in the amount of water released by transpiration versus that of just evaporation within a growing media. Having plants present in the northern Florida climate green roof increased the amount of void pores available for water storage by two-fold. It was however noticed that the plant type most capable of transpiring the greatest amount of water, perennials, also suffered the most from heat stress during droughts and were consequently more susceptible to plant diseases and succumbed more easily to death than succulents. The succulents, while surviving the largest range of climatic variation during the study, did little to contribute to increased retention of water directly after storms. Bins containing succulents did have the highest water content and healthiest overall plants during the entire study, but contributed the least to nutrient retention or water retention. It is important to note that once a plant senesces, then which plant is present is irrelevant. For this reason the results of this study indicate that certain succulents do infact work well in the sub-tropics despite anecdotal information contrary to this finding.

In terms of the water release curves, water content was generally the lowest and retention directly after irrigating was the lowest in Building Logics growing medium and highest in UCF's Black and Gold™ mix. The ability of the perennials to evapotranspire out more water over the same period of time as the other plants resulted in a larger differential between the water content in those bins containing perennials and those containing no vegetation or succulents. Essentially, the water content in those planted with perennials and runners became successively less, to the point that the plants themselves which were responsible for transpiring the water out and creating the decreased water content in the bin, were in greater peril of suffering from plant diseases as a result; a case of a negative feed-back loop. It is recommended that for a roof with no irrigation in the north central Florida climate succulents be used, however in a situation where irrigation can be used, then it is recommended that a mix of succulents, perennials and runners be used together as each plant structure has a different adaptation which may make them compatible to be planted together. Furthermore, it is suggested that grasses be tested in vegetated rooftops in Florida, especially those turf grasses such as Bahia and tropical crabgrass, which colonized abandoned bins on their own during a drought after the original species planted in the bins senesced from lack of water and heat. These grasses can thrive on low water inputs and do not require mowing. It was hypothesized that the perennial peanuts performed poorly in the bin study and only mediocrely on the Charles R. Perry Construction Yard Roof because of issues with inoculation with *Rhizobium*. In the bin study, all excess soil was shaken off of the plants, while in the CRPCY study, plants were planted with soil around the roots, which may have allowed for more inoculation of the soil on the CRPCY roof; regardless Phyla nodiflora outperformed Rhizobium both in the bin study and on the CRPCY roof, in terms of survival and plant health.

Implications of Nutrient Loads for Florida Green Roofs

Similar to the case with water retention, the growing medium type is influencing the TP loads in the runoff from the green roof bins and green roofs themselves, more so than plant type. The three growing media started out with TP loads that were significantly different, with Hydrotech having the highest TP load in its leachate and UCF with the lowest. Within 18 weeks all growing media types leached out most of their excess TP from their soils and eventually had comparable levels of TP in the leachate (no significant differences among soil types by week 18). Despite the fact that the TP load in leachate from Hydrotech growing medium decreased from 325 mg to 25 mg, from Week 1 to Week 24, it was the overall highest TP load contributor to leachate among the three growing media types, irrespective of plant type.

). It was found that the bulk of the nutrients (TP, TN—TKN, NO_3) were leached out of all plant-growing medium combination in the first six week period, as compared to any other time period in the 24 week study period. For example, for TN loads from the first 6 weeks of establishment comprised 89% of the total load of TN for the entire 24 week study period for all growing media types. The differences in load among growing media types was more significant than among plant types. For example, the TN load in the establishment period for H was 1694 mg N m^{-2}, which was 10 times higher than that of U (169 mg N m^{-2}) and 5 times higher than in B (384 mg N m^{-2}); for the subsequent time periods the difference in load among the growing medium types was less, and over time the absolute values dropped ten fold for each growing medium to a range of 145 mg N m^{-2} to 31 mg N m^{-2} for weeks 12 to 24 respectively for H, 33 mg N m^{-2} to 7 mg N m^{-2} for B, and 1403 mg N m^{-2} for U, for weeks 12 to 24 respectively.

The null hypothesis that there would be no significant differences in total load of TN and TP among growing media for the establishment period or for the entire 24-week study period was rejected and the alternative hypothesis was accepted. Nutrient loads varied the most significantly among growing medium types and secondarily among plant types. For all nutrients there was an effect of time, this was more slight in TKN loads ($p= 0.056$), and seen most strongly in TP loads ($p<0.001$). TP concentrations from this study for leachate from B and U (ranging from 0 mg/L to 1 mg/L over all time periods), were in a similar range to TP concentrations found in other green roof studies, slightly higher than those from Berndstonn, et al. (2009) and (2006) and slightly lower than TP concentrations in Moran (2005). TP concentrations from H were higher than values reported in the literature for green roofs (Berndstonn (2006) and (2009), Kim (2006) and Moran (2005). The hypothesis that there would be no significant differences in TP load among plant-growing medium combinations was rejected and the alternative hypothesis was accepted. Mean TP loads for each plant-growing medium combination were analyzed using the least Squares means method for comparing interactions among plant–growing medium combinations on TP load over all time periods combined show that Um, Up, Ur, Us and Bp are not significantly different from the overall mean TP load, while Bm, Br, Bs and Hm, Hp, Hr and Hs were significantly higher than the other plant-growing media combinations. Mean TP loads for plant-growing medium combinations for the entire study period ranged from 18-22 mg P m^{-2} for U (with Ur being the lowest and Us the highest within U), 30-42 mg P m^{-2} for B (with Bp being the lowest and Bs the highest) and 90-140 mg P m^{-2} for Hydrotech (with Hr being the lowest and Hm being the highest. Plant effect on cumulative total TP load over the whole study period was that perennials had the lowest load and succulents had the highest load within each growing media type. Total cumulative TP load for the various combinations ranged from a low of 150 mg P m^{-2} for Up to a high of 3200 mg P m^{-2} for Hs. Cumulative TP loads from leachate from Building Logics growing medium was in the middle with a range from 310 mg P m^{-2} (Bm, Bp, Br) to 450 mg P m^{-2} (Bs).

Plant effect on TN was that irregardless of growing medium type, TN loads from runners in each time period were significantly lower than TN loads from succulents, which always had the highest TN load in every time step (though not always significantly higher than bare media).

With regards to a concentration based first flush effect, it was found that for TP there was no CBFF within the first six hours (concentrations were measured 20 minutes post-irrigation, 1 hour post-irrigation and 6-hours post-irrigation. There were no significant differences in concentrations in these intervals, however there was a mass based first flush effect for the runoff in the first 20 minutes, simply because the majority of the leachate percolated through the medium in the first 20 minutes generating the most volume of any of the time increments and hence the most mass of nutrients of any of the time increments was generated closest to the beginning of runoff.

The hypothesis that concentrations in leachate for all nutrients will diminish over time (the whole study period) was accepted, as concentrations of TP, TN, NO_3, TKN did decrease in the lysimeter samples over the whole study period.

Implications of the findings are that since the nutrient loads in leachate vary significantly among the growing medium types, but plant health did not vary significantly between media with even ten-fold differences in nutrient levels in leachate (for example TN in H versus U), and the nutrient levels in all the media approach the same levels between weeks 12 and 18, it is recommendable to not pre-fertilize or pre-mix excessive fertilizers into the growing medium before planting. The findings indicate that all excess nutrients are not plant available and are not taken up by the plants, but rather enter runoff, posing an ecological threat to receiving water bodies. (Excessive nutrients are being defined as any nutrient that washes out and is not taken up by the plants. It seems that aiming to have the minimum levels of nutrients necessary for plant growth and testing that those levels are not in excess is worthwhile, levels in U resulted in less leaching for all nutrient types and plant health in bins containing U were not significantly worse than plant health in bins containing H growing medium, which had the highest amount of excess nutrients in the leachate.

Effect of Plant Type on Nutrient Loads

Regarding plant types, it is interesting to note that two species of succulents, Sedum spp and Delosperma, which are known to do well in North Carolina (Moran, 2004), but anecdotally have been said to do poorly in Florida (pers. comm. Hardin 2006), made up two of three species that survived all time periods (drought, frost and heavy rains). However, plant effect-wise these succulents did not improve water quality, infact their leachate had P-loads that were significantly higher than other plant types and even surpassed the P-loads of leachate from bare media in 3 of the 4 time periods.

While runners overall had the lowest TP loads among plant types, they were adversely affected by frost and perished in the cold. Therefore for future studies, instead of testing leguminous runners again, instead the plants that eventually colonized the abandoned bins on their own and survived without irrigation and survived frost should be tested, such as subtropical grasses—which also have the same morphological tendencies as the runners from this study.

Since 1) all the total phosphorus that leached out of the during the study would have entered directly to the stormwater system had they been on a roof, and 2) all soils regardless of initial levels, eventually reached the same comparable levels by 18 weeks and 3) there were no noticeable differences in plant health between soil types despite differences in soil P levels, it would be recommendable to begin with a low nutrient growing media from the start or use an extremely slow release fertilizer in the mixture.

Another implication of green roofs for Since S. Florida houses 40% of Florida's residents in a land mass of 28% of the states area, and uses 50% of it's water—and will be growing at a rate of 78 million more people over 20 years, 85% of S. Florida's people reside in urban areas, majority of growth in SE Florida will be concentrated in the urban centers. South Florida, a region that naturally is a system of complex interconnected freshwater lakes, rivers , marshes, sloughs, ponds, prairies, forest, and estuaries extending over 18,000 square miles from the northern Kissimmee river to the Florida Keys (Kranzer, 2000). Urban areas when urbanized reach impervious areas of 72%, 40% of which is due to roofs. If applied to the land mass, water detention wise, gr could help with reducing water entering streams. However, water quality wise, we see that even in periods of low-flow and the return flow portion of the green roof runoff hydrograph, P-loading exceeds that of natural areas measured in regions of S. Florida –such as running off of agricultural fields or even STAs, which were created to treat water coming off of agricultural fields. Since the American lawn and irrigation accounts for 70% of water use in an urban area and nutrient export increases when agricultural areas are converted from dairy and ranch farms to divided parcels of urban housing, housing developments that could require cisterns combined with a green roof could see a reduction in peak demand of energy for cooling, less infrastructure for reclaimed water and less use of potable water for irrigation. Without hooking up a cistern or reuse system with a green roof in the tropics or sub-tropics, we could see an increase in water demands that are already high and further degradation of receiving water bodies. It is highly recommended that in Florida, green roofs be finer tuned to grow plants that need no irrigation, or absolutely require the use of some sort of recollection re-use of runoff on site. A person interested in installing a green roof because of interest in sustainability would no doubt gladly give the follow through of taking the appropriate measures to reuse the water onsite. Note- that roofs in general are most often directed directly to the stormwater conveyance system, therefore, even if reduction of water quantity is met, this P-laden runoff will go directly to the stormwater system, therefore either a rain garden on-site or a cistern is recommendable in conjunction with a green roof in Florida.

Again this dissertation is not a an endorsement of certain brands of growing media, rather it aims to highlight the characteristics of the growing medium that make it a good growing medium, that manufacturers can use when creating mediums. For example, the pore-size distribution, the amount of organic matter and the form/textural analysis of the OM, and the overall porosity and one engineering aspect that was not analyzed in this dissertation is the compactibility of the media. For example, Hydrotech and BL do tests to see much pressure the medium can withstand and not compress, so that it is indeed longlasting- it will take several years of monitoring UCF's mix to see how it performs over time with regard to this engineering aspect of the soil. However, from the stormwater perspective, we are not concerned that the amount of medium shrinks from 15 cm to 10 cm due to oxidation of OM, as senescing plants will accrete OM, (inhibiting seedling establishment at worst). In a case where only 5 to 7 cm of growing medium is being utilized and the roof to last 40 years one may be concerned with the medium wasting away, but even here plant senescence and regrowth can increase the medium thickness. No problems with oxidation of OM has been seen in VA in the 6 years it's been in place, nor problems with diminishing substrate or decrease in plant growth/health due to exhaustive use of nutrients and OM.

If green roofs are used as a BMP in Florida in new developments, a provision in the law must be created that will allow for positive credits for using of green roof as a BMP only if it is implemented in conjunction with a cistern or reuse of water on-site such as exfiltration, raingarden, wet or dry detention. Further points if irrigation is due to recycling roof's runoff (or collecting a smooth roof's runoff from a higher elevation and temporarily detaining it and using that for irrigation of the roof versus reclaimed or potable water) and lesser points if irrigation water is from reclaimed water and a ban on green roofs installed to use potable water for irrigation (or negative points). Additionally, plant choice—if succulents are chosen—we can assume not much is being done for water quality, but on the other hand irrigation may be reduced or possibly avoided during some seasons. If perennials are used, while stormwater detention can be expected to be slightly greater based on the results of this study, irrigation will ultimately be necessary and is recommended in short duration/high frequency applications, rather than long duration-infrequent applications, because it was found that runoff occurs before soil moisture storage capacity is 100% attained due to macropores, channels and the high permability of the growing medium, therefore it would be difficult, costly and take a long time to irrigate until soil moisture capacity is fulfilled.

Role of Green Roofs in Stormwater Hydrology and Water Quality in Florida as compared to Virginia

The goals of the research included 1) characterizing the effect of green roofs on urban stormwater hydrology for Florida and Virginia, and 2) characterizing the effect of green roofs on the water quality of runoff for Florida and Virginia.

The effect of the green roofs in both Florida and Virginia was that they did retain significant portions of stormwater and significantly increase the lag time to peak and extend the runoff period from the roof. In Florida, small rain events (< 0.4 cm, n =31), had a significantly higher mean retention (79%) than either medium rain events (0.42 cm - 0.83 cm) or large events (>0.83 cm). There were significant differences in retention between medium (43% retention) and large (26% retention) rain events in Florida, but no significant differences in extension of runoff past the end of a rain event (s = 7.8 hr, m = 11 hr, l = 8.7 hr) in Florida. In Virginia, the mean retention by size class differed significantly between small, medium and large rain events, with respective retention rates of (98%, 84% and 72%). The retention rates of the large events (72%)

compared well to studies in neighboring and nearby states (North Carolina and Pennsylvania) (Moran, 2005 and DeNardo, 2003), though the small and medium events had retention rates that were unusually high in comparison. In both Florida and Virginia, there were significant differences in the reduction of the peak intensity among all the different size classes of the rain events, 94% for small events, 79% for medium events and 60% for large events for Florida) and 100%, 93% and 79% for small, medium and large events, respectively in Virginia. The extension in end of runoff was not as great in Virginia as provided by the 15 cm thick green roof in Florida—the median extension time varied between 0.68 hours and 3.9 hours through the seasons. In Florida, the median extension in runoff varied between 2.5 hours and 14 hours by season. This difference is attributed to the thickness of the Florida green roof and the pore-size distribution of the green roof, as well as differences in the underlayment (for example, Hydrogel packs do not re-release water until ET occurs to remove the water from the gel packs.)

In summary of the major objective for hydrological analyses, it was to determine if the green roofs behaved similarly hydrologically in both extremes of the subtropical climate. This study found that for the two roofs studied, they did behave in the same manner, though at different intensities for water retention, peak reduction and increase in lag time, with water retention and peak reduction being greater in Virginia and a greater difference in the effect on extension of runoff and increase in lag to peak in Florida than Virginia.

In terms of water quality analyses, the hypothesis tested was that the green roofs' influence on water quality (nutrients, metals, TSS and TDS) will be similar in both Virginia and Florida and that they will act as sinks for nitrogen and sources for phosphorus and suspended sediment; and will act similarly for metals in both regions (whether as a source or sink). It was found that the green roof did infact act as a source for phosphorus, (both TP and OP), which is similar to other studies in nearby states and other regions of the world. The green roofs did also act as a sink for nitrogen as nitrate as hypothesized, however no difference in concentrations were noticed between the green roof and control roof for NH_3-N. The green roofs did buffer pH, which is similar to findings in other studies (Berghage, 2005; Kohler and Schmidt, 2003; DeNardo, 2003). Metals behaved differently by location, for example aluminum and iron were found to be significantly higher in green roof runoff in Florida, but not in Virginia, and lead concentrations were also significantly lower in green roof runoff than conventional roof runoff in Virginia. Concentrations of metals varied more between locations than did nutrients. For both metals and nutrients, variability between storms was greater than within storms, for each location. Total Dissolved Solids (TDS) were significantly higher in green roof runoff as compared to conventional roof runoff, however total suspended solids (TSS) was surprisingly not found to be significantly different in green roof runoff as compared to conventional roof runoff. However concentrations from Florida were significantly higher than those found in the green roof runoff in Virginia.

The load reductions attributable to the green roof, as compared to a conventional roof of the same size, varied with the size and intensity of the storms, by and large, the green roof seemed to lower nitrate and ammonium concentrations from 12-90% depending on storm size and intensity, but the presence of the green roof increased TSS, TP and SRP loads in most cases. The SRP load was often increased over 10-fold.

Summary

In summary, the green roofs did behave similarly in the two extremes of the climate and provided benefits of stormwater volume control by detaining and retaining stormwater. In terms of water quality, in both regions and in the Florida bin study, the green roofs did contribute nutrients to the runoff, TP in all three cases, though the total load of nitrate was noted to decrease in the in situ roof studies. It is recommended that green roofs in both Florida and Virginia receive positive points for stormwater detention, but for storm water quality follow a design similar to those used in this study—where green roof runoff was used on the landscape in Virginia, or held in a cistern and re-used in Florida, as was also done at UCF. Using a cistern in conjunction with the green roofs in Florida is highly recommendable and will take full advantage of nutrients in the runoff, keep excess out of stormwater systems and receiving water bodies and reduce irrigation needs. It is not recommendable in Florida to have green roof runoff go directly into impaired water bodies (or conveyance systems that lead directly into impaired water bodies.) The green roofs in Florida and Virginia did behave similarly in terms of being a P source and N sink, but differently with regards to metals. Future recommendations include investigating the possibility of using green roofs as a flow-through treatment wetland for treating high N grey water on-site, and testing plants that colonized abandoned bins and needed no irrigation—such as Tropical crab grass, that could potentially be used on green roofs that are out of sight and a model should be created weighing the economic value of the positive benefits of stormwater detention/retention and being an N-sink against the costs of TP entering the stormwater system and costs of maintenance. Provisions should be made in the Florida code governing the use of potable water for irrigation—and should promote the reuse of green roof runoff to the roof for irrigation, or secondarily reclaimed water and deter green roof users from directing green roof runoff directly into receiving water bodies.

APPENDIX A
IRRIGATION REGIME FOR GREEN ROOF BIN STUDY

Table A-1. Irrigation regimen of the green roof bins for the hydrologic and nutrient green roof study in Gainesville, FL, 2007.

Days of Establishment Period (6 weeks)	Amount and Frequency of Irrigation
Day 1 to 3	1.27 cm 2x's a day
Days 4 to 7	1.27 cm 1x per day
Day 7 to 14	1.27 cm every other day
Day 14 to 21	1.27 cm every other day
Day 21 to 28	1.27 cm every third day
Day 28 to 35	1.27 cm every third day
Day 35 to 42	Every third day

APPENDIX B
SPECIFICATIONS OF LITE TOP® GROWING MEDIUM—HYDROTECH USA

Property	Intensive
Grain Size Distribution	
clay fraction	0-2 %
passing #200 sieve	5-15 %
passing #60 sieve	10-25 %
passing #18 sieve	20-50 %
passing 1/8-inch sieve	55-95 %
passing 3/8-inch sieve	90-100 %
Density	
Application Density	0.7 - 1.1 g/cm^3 (44 lbs – 68 lbs/cf)
Saturated Density	1.0 - 1.5 g/cm^3 (62 lbs - 93 lbs/cf)
Dry Density	0.6 -1.1 g/cm^3 (38 lbs - 68 lbs/cf)
Water & Air Management (% vol.)	
saturated water capacity	>40 %
saturated air content	>10 %
Saturated Hydraulic Conductivity	>0.5 mm/min (>1.0 in/hr)
pH, Lime, and Salt Content	
pH (saturated paste)	5.5 - 7.5
carbonate content	<25 g/l
salts content (water extract)	<3.0 g/l (2.0 mmhos/cm)
Organics	
OM content	6 – 12 mass %
C/N ratio	<20
Nutrients** (plant available)	
nitrogen (NO3)	3 – 15
phosphorus	1 – 7
potassium	6 – 15
calcium	19 – 65
magnesium	3 – 15
CEC Capacity	>6 cmol/kg
Compost Fraction	
1) Meet or exceed USEPA Class A standard, 40 CFR 503.13, Tables 1 & 3 (chemical contaminants) and 40 CFR 503.32(a) (pathogens) and/or be permitted in the state of origin to produce Class A material.	
2) Meet US Compost Council STA/TMECC criteria or equal for Class I or II stable, mature product.	

* Values shall be adjusted due to availability of local materials or special project conditions related to plant

* Values shall be adjusted due to availability of local materials or special project conditions related to plant selection and/or environmental conditions.

** Nutrients shall be adjusted with appropriate slow-release fertilizer with micronutrient additions if below lower target range.

Source: Hydrotech USA, 2008.

APPENDIX C
PHYSICAL PROPERTIES OF STALITE

STALITE Lightweight Aggregate Properties and Gradations for Structural Applications

	3/4" (18mm)		1/2" (12.5mm)		3/8" (9.5mm)		Fines (#4 - 0)	
Typical Density (Unit Weight)	lbs/cf	kg/m³	lbs/cf	kg/m³	lbs/cf	kg/m³	lbs/cf	kg/m³
Dry Loose (ASTM C 29)	48	768	50	800	52	832	60	960
Dry Rodded (ASTM C 29)	55	880	56	896	58	928	65	1040
Saturated Surface Dry Loose (ASTM C 29)	50	800	52	832	53	848	55	880
Maximum Dry Density (ASTM D 4253)	60	960	-		-		-	
Damp Loose (ASTM C 29)	48 - 52	768-832	50 - 54	800-864	51 - 55	816-880	53 - 57	848-912
Typical Relative Density (Specific Gravity)								
Dry (ASTM C 127)	1.46		1.47		1.54		1.69	
Saturated Surface Dry (ASTM C 127)	1.52		1.53		1.60		1.75	
Range in Saturated Surface Dry (ASTM C 127)	1.47 - 1.54		1.49 - 1.55		1.57 - 1.64		1.70 - 1.80	
Sieve Size	% Passing		% Passing		% Passing		% Passing	
1" (25mm)	100		100		100		100	
3/4" (19mm)	90-100		100		100		100	
1/2" (12.5mm)	-		90-100		100		100	
3/8" (9.5mm)	10-50		40-80		80-100		100	
#4 (4.75mm)	0-15		0-20		5-40		91-96	
#8 (2.36mm)	-		0-10		0-20		59-75	
#16 (1.18mm)	-		-		0-10		39-55	
#30 (600um)	-		-		-		23-38	
#50 (300um)	-		-		-		15-27	
#100 (150um)	-		-		-		9-19	

STALITE
ROTARY KILN EXPANDED LIGHTWEIGHT AGGREGATE

Source: Stalite, 2008.

Figure C-1. Image of STALITE Lightweight Aggregate specifications sheet for properties and gradations of the material for structural applications.

STALITE Lightweight Aggregate Physical Characteristics for Structural Applications

Absorption	
Saturated Surface Dry (ASTM C 127)	6.0%
1 Hour Boil In Water	8.0%
Under high pumping pressure of 150 psi (1033 kPa)	9.4%
Soundness (% Loss)	
Magnesium Sulfate (ASTM C 88)	0 - 0.01%
Sodium Sulfate (ASTM C 88)	0 - 0.23%
25 Cycles Freezing and Thawing (AASHTO T 103)	0.22 - 0.80%
Toughness	
Los Angeles Abrasion (AASHTO T 96)	25 - 28%
Stability	
Angle of Internal Friction (Loose)	40°- 42°
Angle of Internal Friction (Compacted)	43°- 46°
Impurities	
Clay Lumps (ASTM C 142)	0
Organic Impurities (ASTM C 40)	0
Popouts (ASTM C 151)	0
Electrical Resistance	
Lab (AASHTO T 288)	30,000 - 40,000 ohm-cm
Field (ASTM G 57)	More than 500,000 ohm-cm
Aggregate Chemical Characteristics	
Ignition Loss (ASTM C 114)	0
Stains (ASTM C 641)	None
Sulfur Trioxide	Less Than 0.05 ppm
Chlorides (NaCl)	0.60 - 7.0 ppm
Soluble Salts	0.28 mmhos/cm
pH	7 - 9

Certified test reports available

STALITE
ROTARY KILN EXPANDED LIGHTWEIGHT AGGREGATE

Source: Stalite, 2008.

Figure C-2. Image of STALITE Lightweight Aggregate specifications sheet for physical characteristics of the material for structural applications.

APPENDIX D
MODEL FIT FOR WATER RETENTION ANOVAS

Table D-1. Details of the PROC GLM model used for the ANOVA analyses for water retention for Weeks 1-6.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.17095556	0.01554141	35.19	<.0001
Error	24	0.01060000	0.00044167		
Corrected Total	35	0.18155556			

R-Square	Coeff Var	Root MSE	Ret Mean
0.941616	5.239413	0.021016	0.401111

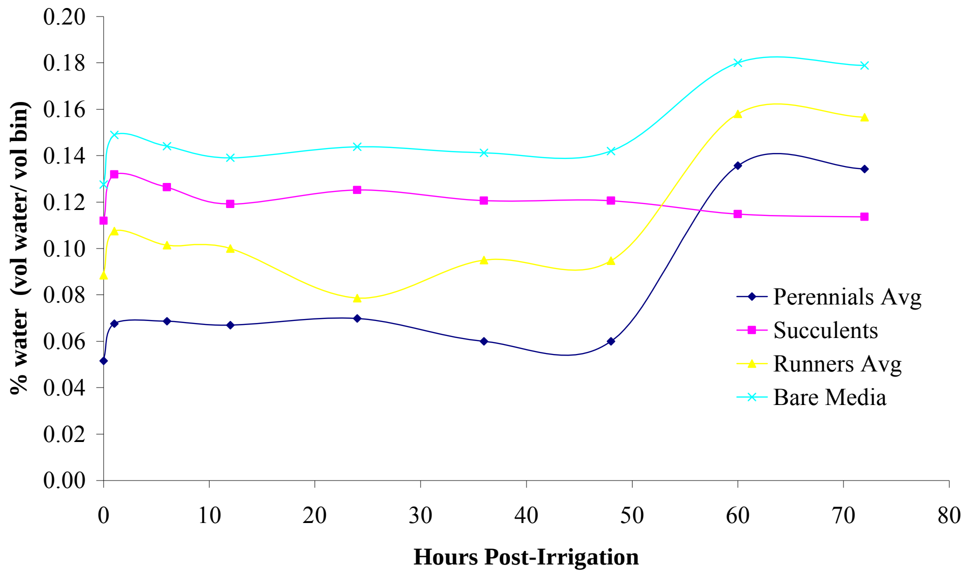
Source	DF	Type I SS	Mean Square	F Value	Pr > F
P_type	3	0.04328889	0.01442963	32.67	<.0001
G_Media	2	0.12053889	0.06026944	136.46	<.0001
G_Media*P_type	6	0.00712778	0.00118796	2.69	0.0385

Table D-2. Effect of plant type on water retention within growing medium types. Results of individual ANOVAS within each growing medium type and time period.

Growing Medium	Plant Type	Sampling Period						
		Weeks 1-6		Weeks 7-12	Weeks 13-18		Weeks 19-24	
BL	p	41%	a	Overflowed	58%	a	30%	a
	s	31%	b	Overflowed	53%	a	29%	a
	r	32%	b	Overflowed	53%	a	28%	a
	m	29%	b	Overflowed	36%	b	24%	b
H	p	46%	a	Overflowed	73%	a	40%	a
	s	40%	b	Overflowed	75%	a	46%	b
	r	46%	a	Overflowed	76%	a	47%	b
	m	39%	b	Overflowed	63%	ab	39%	a
UCF	p	53%	a	Overflowed	89%	a	51%	a
	s	42%	b	Overflowed	82%	b	52%	a
	r	44%	b	Overflowed	86%	ab	50%	a
	m	42%	b	Overflowed	74%	c	49%	a

APPENDIX E
WATER CONTENT CURVES FOR WEEKS 12, 18 AND 24

Lysimeter Week 12 Water Content (vol water/vol bin)-BL

A) 

Lysimeter Week 12 Water Content (vol water/vol bin)-H

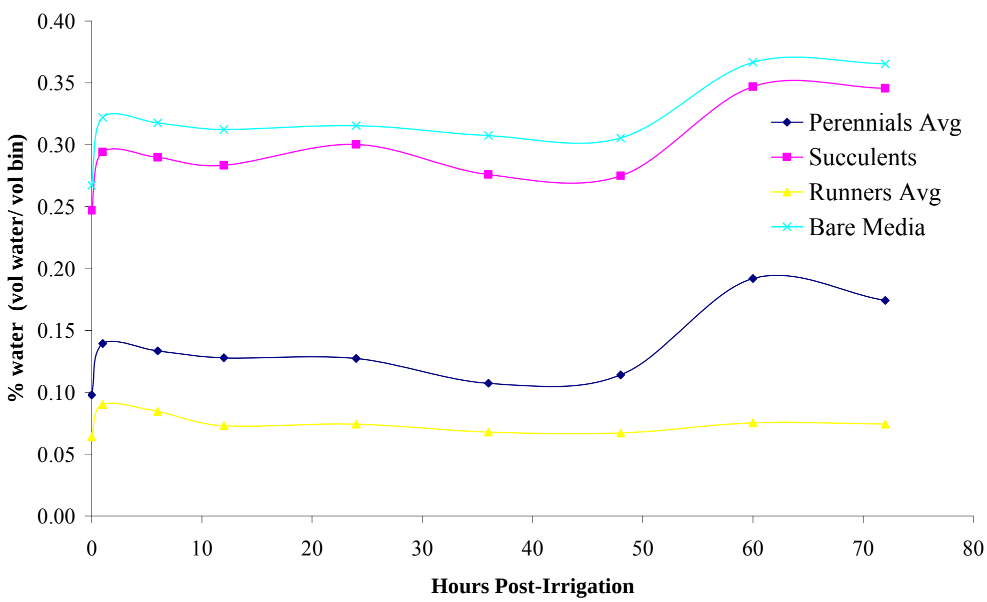
B) 

Figure E-1. Changes in water content for growing various plant types (p, r, s, m) in growing medium types B and H in Week 12, up to 72 hours post-irrigation with 1.27 cm water. Note 1.27 cm of rain fell between hours 48 and 60, causing an increase in water content.

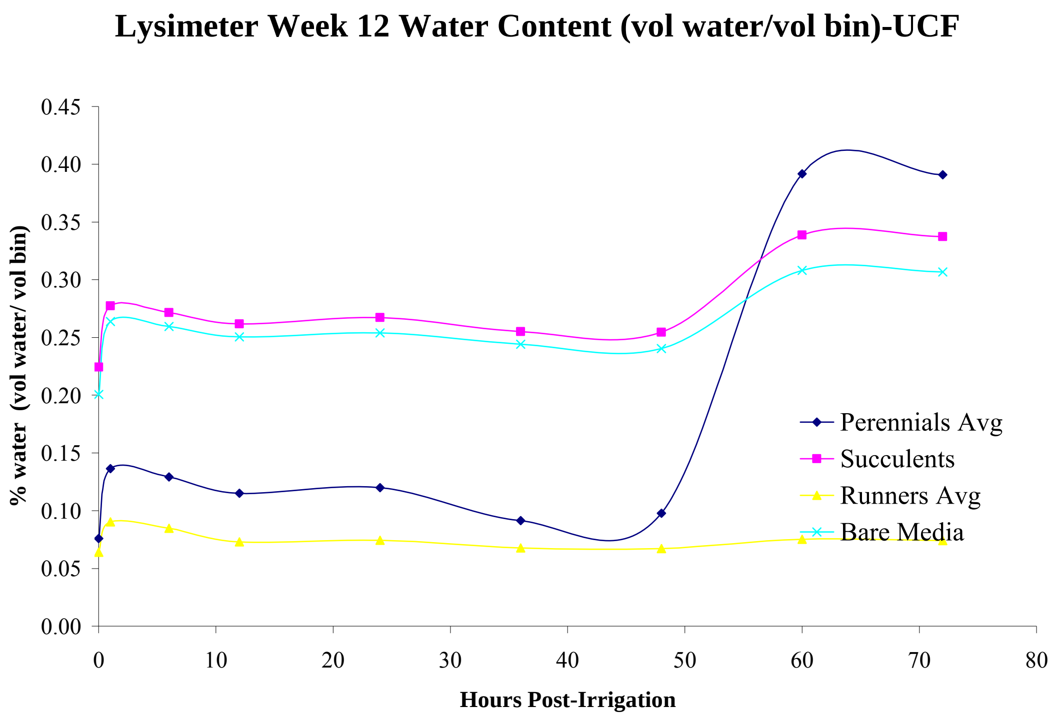


Figure E-2. Changes in water content for growing various plant types (p, r, s, m) in growing medium U in Week 12, up to 72 hours post-irrigation with 1.27 cm water. Note 1.27 cm of rain fell between hours 48 and 60, causing an increase in water content.

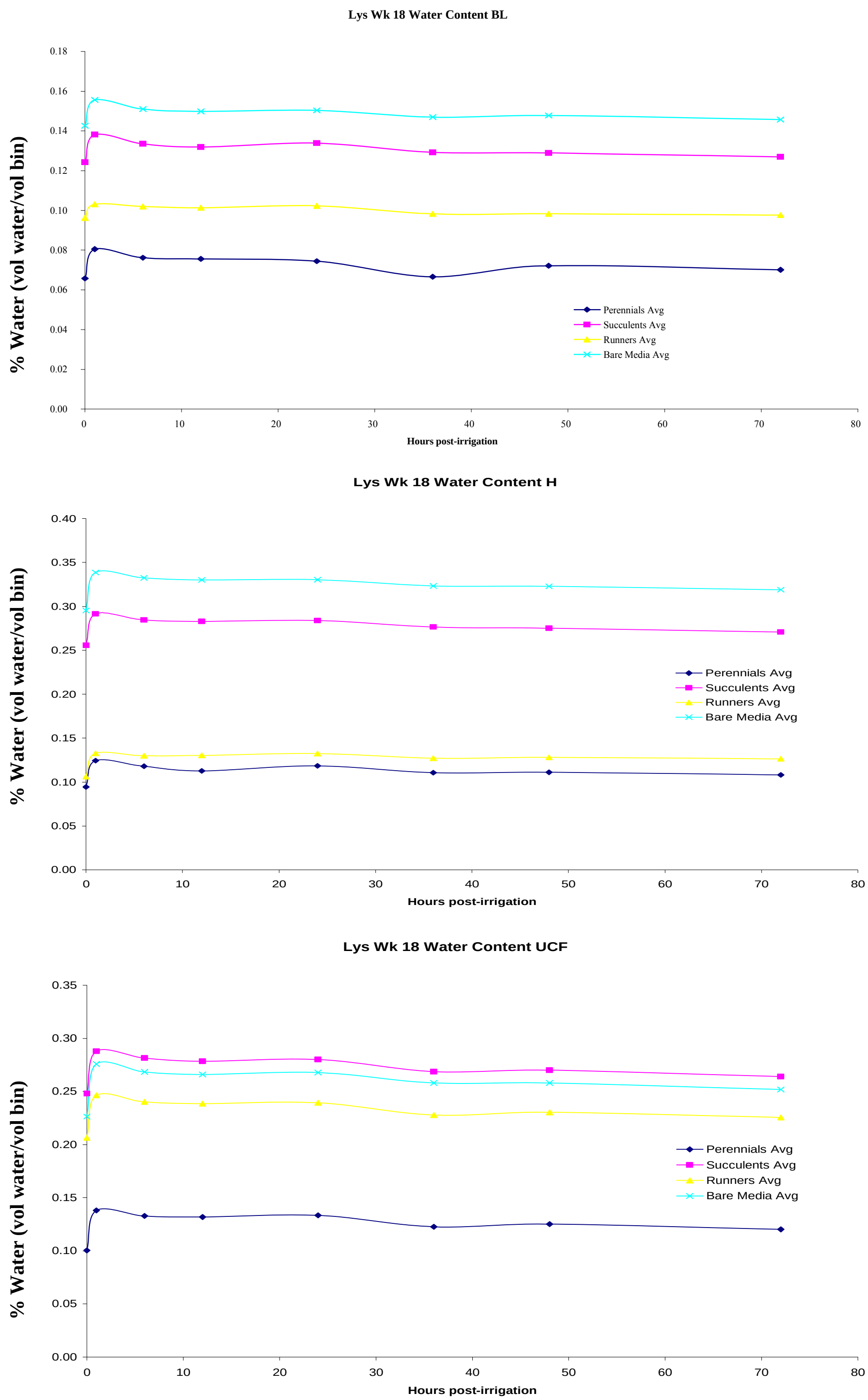


Figure E-3. Changes in water content in A) Building Logics, B) Hydrotech and C) UCF's Black and Gold growing media over 72 hours post-irrigation of 1.27 cm water in Week 18.

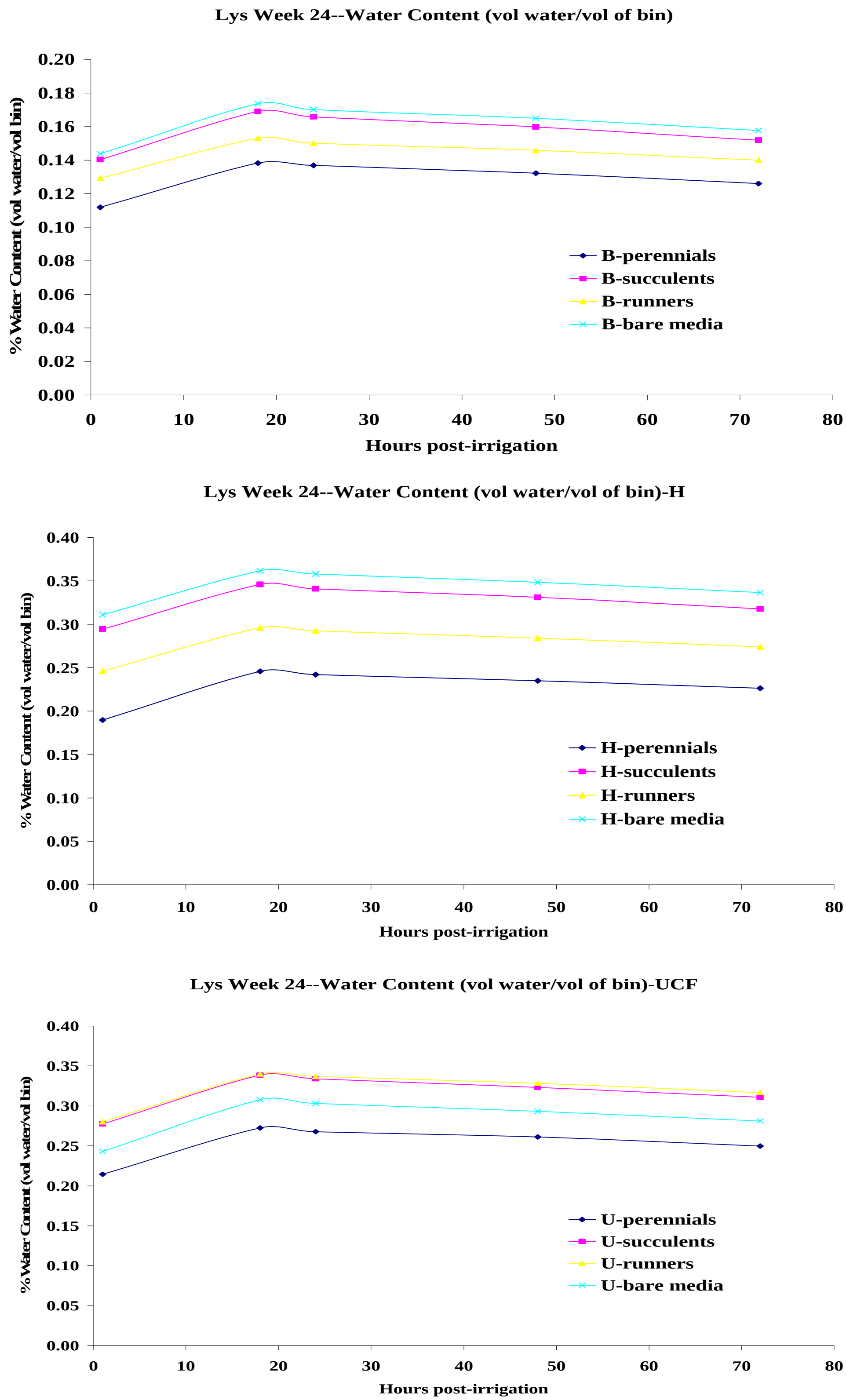


Figure E-4. Changes in water content in A) Building Logics, B) Hydrotech and C) UCF's Black and Gold growing media over 72 hours post-irrigation of 1.27 cm water in Week 24.

APPENDIX F
WATER RETENTION CURVES FOR WEEKS 6, 12, 18 AND 24

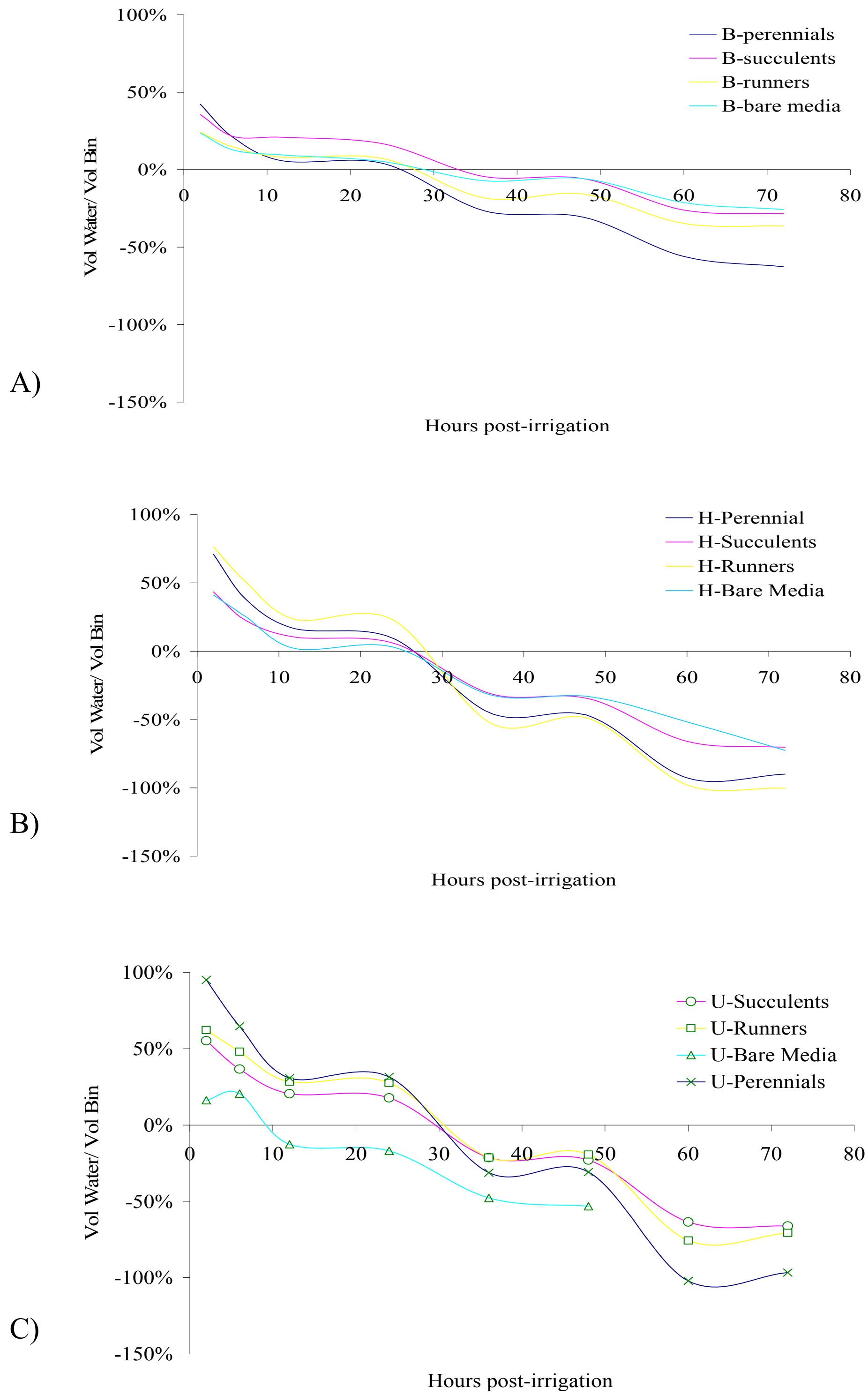


Figure F-1. Changes in water in retention in A) Building Logics, B) Hydrotech and C) UCF Black & Gold growing media over 72 hours post-irrigation of 1.27 cm water in Week 6 (9/5-9/8/2007).

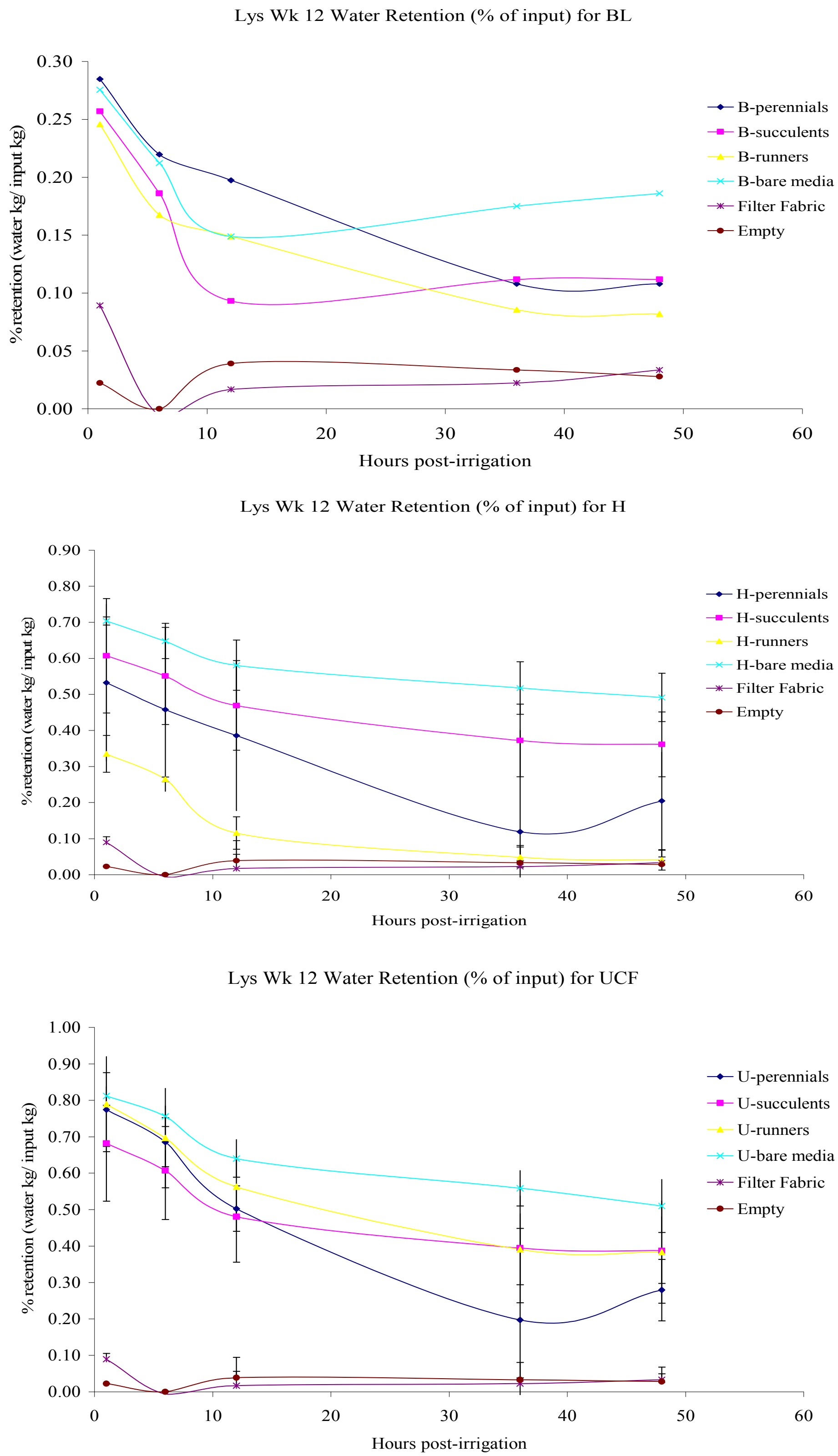


Figure F-2. Changes in water retention in A) Building Logics, B) Hydrotech and C) UCF's Black and Gold growing media over 72 hours post-irrigation of 1.27 cm water in Week 12.

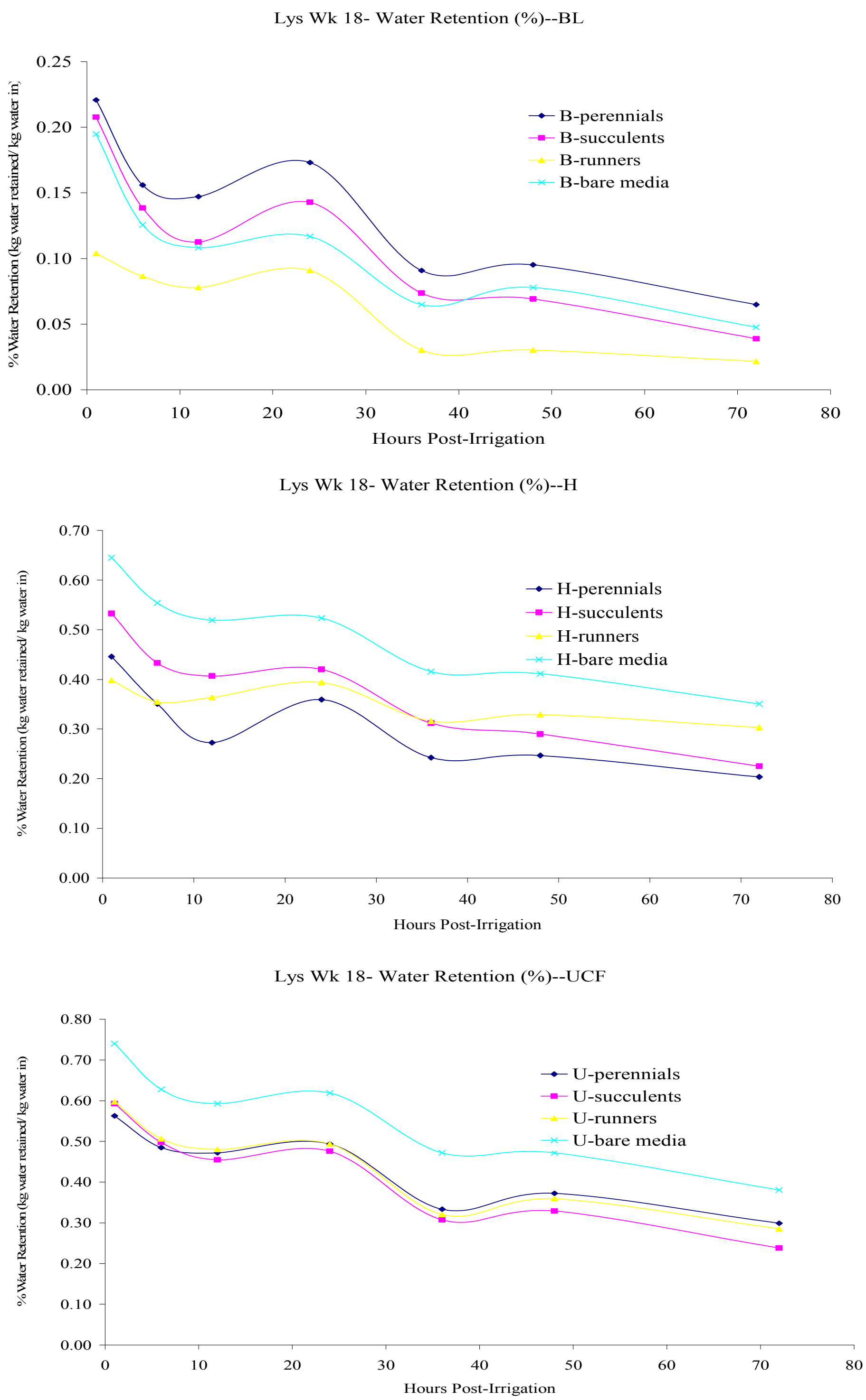
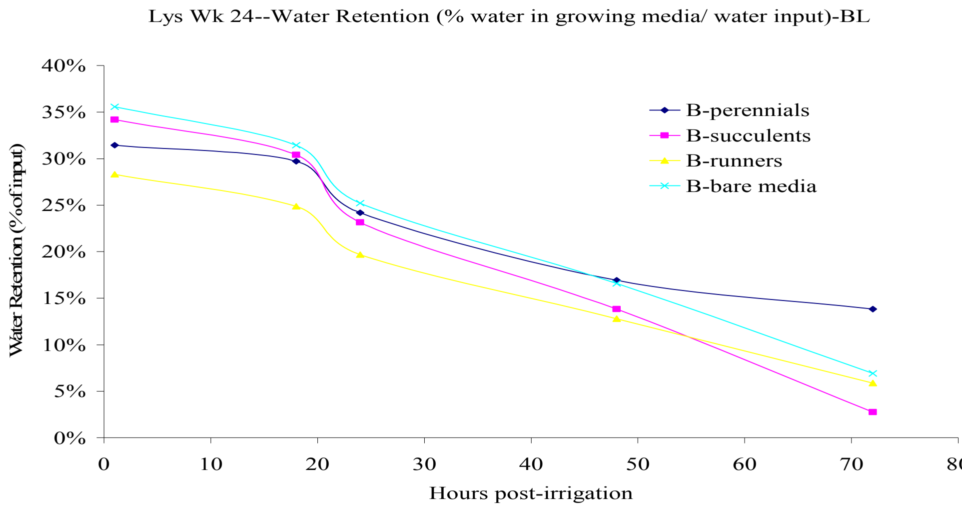
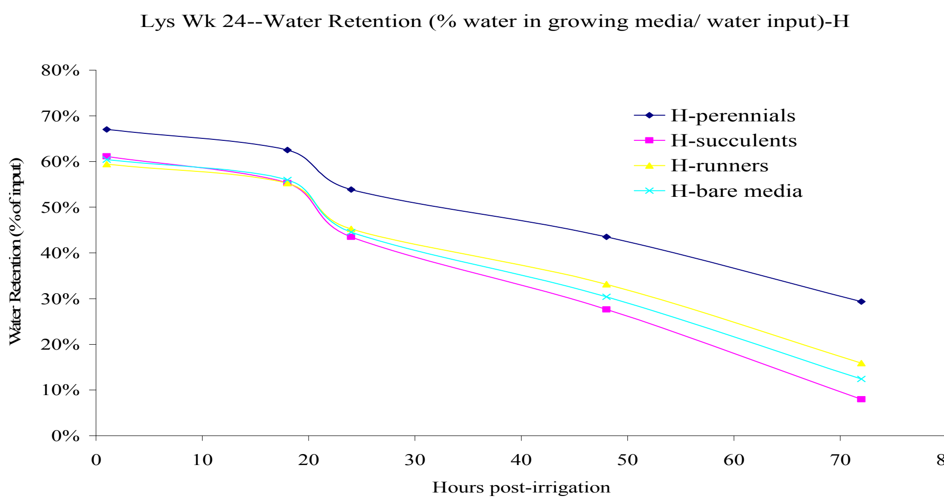


Figure F-3. Changes is water retention in A) Building Logics, B) Hydrotech and C) UCF growing media over 72 hours post-irrigation as a percent of water applied in response to a 1.27 cm irrigation event in Week 18 (December 5th, 2007) of the study period.





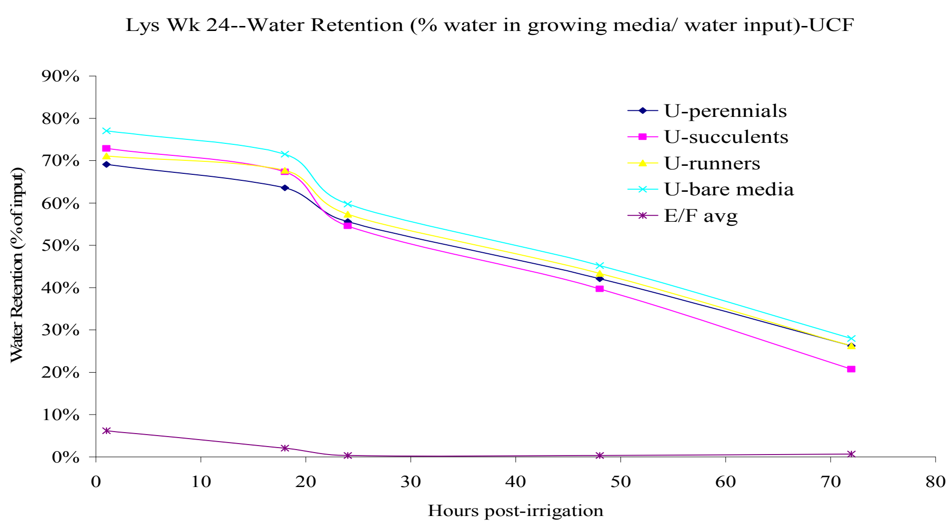


Figure F-4. Water retention in A) Building Logics, B) Hydrotech and C) U growing media over 72 hours post-irrigation (1.27 cm) as a % of water applied, in week 24 of the study.

APPENDIX G
MEAN WATER UPTAKE/RELEASE RATES FOR GROWING MEDIA AND PLANT-GROWING MEDIUM COMBINATIONS

Table G-1. Mean rates of water uptake (% volumetric water content/hr) for different growing medium types (B, H, U), based on slope of water uptake from water content curves for Weeks 6, 12, 18 and 24 found in Appendix E. Significant differences between slopes based on the results of the paired t-test at an α of 0.05 are denoted by different letters within a time period.

	Week 6			Week 12			Week 18			Week 24		
	Mean	Std Dev		Mean	Std Dev		Mean	Std Dev		Mean	Std Dev	
B	0.023	0.007	a	0.021	0.004	a	0.012	0.006	A	0.027	0.004	a
H	0.043	0.013	b	0.042	0.014	b	0.034	0.009	B	0.052	0.004	b
U	0.049	0.014	b	0.059	0.007	c	0.042	0.008	C	0.061	0.005	c

Table G-2. Mean rates of water uptake (% volumetric water content/hr) for different plant types from water retention curves for Weeks 6, 12, 18 and 24 for B, H and U found in Appendix C. Significant differences between slopes based on the results of the paired t-test at an alpha =0.05 level are denoted by different letters within a time period.

		Week 6			Week 12			Week 18			Week 24		
	Level	Mean	Std Dev		Mean	Std Dev		Mean	Std Dev		Mean	Std Dev	
B	m	0.017	0.006	a	0.021	0.001	a	0.013	0.003	a	0.030	0.002	a
	p	0.031	0.003	a	0.024	0.007	a	0.015	0.006	a	0.026	0.004	ab
	r	0.018	0.006	b	0.019	0.004	a	0.007	0.006	a	0.024	0.002	b
	s	0.026	0.004	ab	0.020	0.002	a	0.014	0.007	a	0.029	0.005	ab
H	m	0.030	0.004	a	0.055	0.001	a	0.043	0.009	a	0.051	0.005	a
	p	0.052	0.005	b	0.041	0.017	ab	0.030	0.003	ab	0.056	0.003	a
	r	0.056	0.008	b	0.026	0.004	b	0.027	0.009	b	0.050	0.002	a
	s	0.032	0.001	a	0.047	0.012	a	0.036	0.008	a	0.051	0.006	a
U	m	0.038	0.008	b	0.063	0.002	a	0.050	0.007	a	0.065	0.003	a
	p	0.070	0.004	a	0.060	0.008	a	0.038	0.011	a	0.058	0.004	a
	r	0.046	0.009	b	0.061	0.010	a	0.040	0.005	a	0.060	0.007	a
	s	0.041	0.003	b	0.053	0.007	a	0.040	0.007	a	0.061	0.004	a

APPENDIX H
ET RATES FOR PLANT-GROWING MEDIUM COMBINATIONS BY TIME PERIOD

Table H-1. Evapotranspiration Rates in mm/day for Week 6—Late Summer, based on change in mass over daylight hours on 9/6/07 and 9/7/07.

	ET Rate (mm day^{-1})			
	B	H	U	E/F
Plant Type	(mean ± SD)	(mean ± SD)	(mean ± SD)	(mean ± SD)
Perennials	3.0 ± 1	5.3 ± 1.8	6.1 ± 2.1	
Succulents	2.2 ± 0.5	3.6 ± 0.9	4.2 ± 0.3	
Runners	2.3 ± 0.3	5.6 ± 2.0	5.6 ± 0.6	
Bare Media	1.5 ± 0.7	3.6 ± 0.3	3.4 ± 0.6	
E/F				0.2 ± 0.1

Table H-2. Evapotranspiration Rates in mm/day for Week 12—Fall, based on change in mass over daylight hours on 10/18/07 and 10/19/07.

	ET Rate (mm day^{-1})		
	B	H	U
	(mean ± SD)	(mean ± SD)	(mean ± SD)
Perennials	1.40 ± 0.4	2.9 ± 1.2	4.2 ± 1.4
Succulents	0.70 ± 0.07	1.9 ± 0.09	1.8 ± 0.13
Runners	1.10 ± 0.4	1.5 ± 0.4	2.5 ± 0.4
Bare Media	0.40 ± 0.1	1.1 ± 0.1	1.4 ± 0.15

Table H-3. Evapotranspiration Rates in mm/day for Week 18—Early Winter, based on change in mass over daylight hours on 12/5/07 and 12/6/07.

	ET Rate (mm/day)		
	B	U	H
	(mean ± SD)	(mean ± SD)	(mean ± SD)
Perennials	1.07 ± 0.31	1.13 ± 0.22	1.55 ± 0.88
Succulents	0.67 ± 0.19	1.05 ± 0.26	1.64 ± 0.25
Runners	0.59 ± 0.07	0.75 ± 0.00	1.68 ± 0.73
Bare Media	0.50 ± 0.25	1.05 ± 0.15	1.43 ± 0.07

APPENDIX I
CHANGES IN ORGANIC MATTER CONTENT AND GRAIN-SIZE DEISTRIBUTION IN THE GROWING MEDIA, BEFORE AND AFTER THE GREEN ROOF STUDY

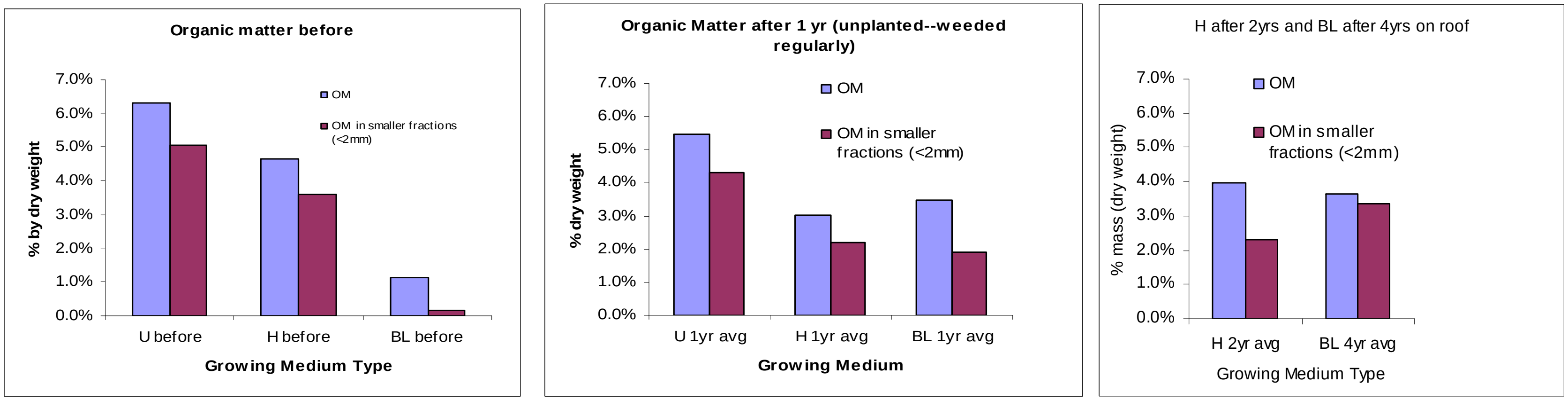


Figure I-1. Changes in total OM content before and after green roof study and in the top particle size fraction (> 2 mm).

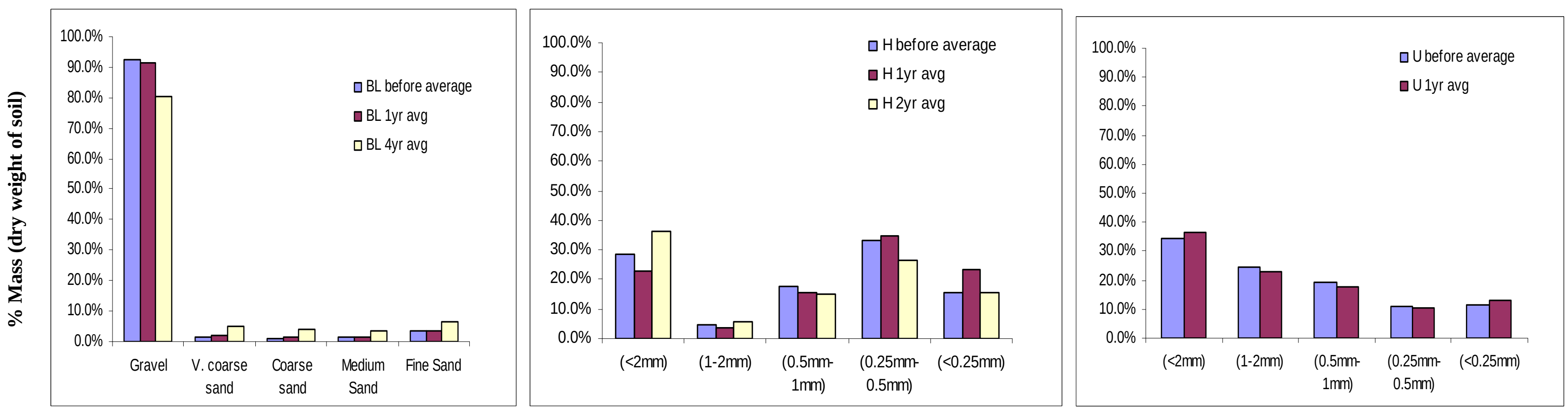


Figure I-2. Changes in grain size distribution of B, H and U's growing medium after 1 year in green roof bins and 4 years and 2 years on a roof top, for B and H, respectively.

APPENDIX J
PHYSICAL PROPERTIES AND MACRO AND MICRONUTRIENTS FOR HYDROTECH GROWING MEDIUM

Table J-1. Physical properties reported for Hydrotech growing medium.

Property	Value
Dry bulk density	0.6-1.1 g/cm3
Saturated bulk density	1.0-1.5 g/cm3
Saturated water capacity	>40%
Saturated air content	>10%
Organic matter content (mass %)	6-12%
C/N ratio	<20
CEC	>6 cmol/kg

(Source: Hydrotech specifications sheet, 2007).

Table J-2. Macro and micronutrients reported for Hydrotech growing medium.

	Min g/m3	Max g/m3	Min g/kg	Max g/kg	Min g/m2	Max g/m2
Nitrogen (NO3 +NH4)	50	252	0.047	0.236	7.7	38.3
Phosphorus	17	118	0.016	0.110	2.6	17.9
Potassium	101	252	0.094	0.236	15.3	38.3
Calcium	319	1092	0.298	1.021	48.5	166
Magnesium	50	252	0.047	0.236	7.7	38.3
Sulfur	17	59	0.016	0.055	2.6	8.9
Iron	17	50	0.016	0.047	2.6	7.7
Manganese	17	50	0.016	0.047	2.6	7.7
Copper	4.2	8.4	0.004	0.008	0.6	1.3
Boron	4.2	8.4	0.004	0.008	0.6	1.3
Zinc	0.2	0.4	0.0002	0.0004	0.0	0.1

(Source: Adapted from Hydrotech specifications sheet, 2007).

APPENDIX K
TN LOAD ANOVA MODELS USED FOR ANALYZING EACH 6-WEEK PERIOD

Table K-1. Details of the PROC GLM model used for the ANOVA analyses for TN load data for Weeks 1-6.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	108.3731002	9.8521000	1027.20	<.0001
Error	24	0.2301891	0.0095912		
Corrected Total	35	108.6032893			

R-Square	Coeff. .Var	Root MSE	Lntn Mean
0.997880	1.592610	0.097935	6.149322

Table K-2. Details of the PROC GLM model used for the ANOVA analyses for TN load data for Weeks 7-12.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	26.27858881	2.38896262	21.43	<.0001
Error	24	2.67488556	0.11145357		
Corrected Total	35	28.95347437			

R-Square	Coeff Var	Root MSE	lntn Mean
0.907614	8.774279	0.333847	3.804832

Table K-3. Details of the PROC GLM model used for the ANOVA analyses for TN load data for Weeks 13-18.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	27.23662857	2.47605714	3.56	0.0045
Error	24	16.70343325	0.69597639		
Corrected Total	35	43.94006182			

R-Square	Coeff Var	Root MSE	lntn Mean
0.619859	36.41717	0.834252	2.290821

Table K-4. Details of the PROC GLM model used for the ANOVA analyses for TN load data for Weeks 19-24.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	16.36982721	1.48816611	8.80	<.0001
Error	24	4.05981259	0.16915886		
Corrected Total	35	20.42963980			

Table K-5. Results of the ANOVA (degrees of freedom, sum of square, mean square and F-values) for TN load for weeks 1-6.

Source	DF	Type I SS	Mean Square	F Value	Pr > F
P_type	3	0.4320634	0.1440211	15.02	<.0001
G_Media	2	107.806018	53.9030091	5620.04	<.0001
G_Media*P_type	6	0.1350186	0.0225031	2.35	0.0633

Table K-6. Results of the ANOVA (degrees of freedom, sum of square, mean square and F-values) for TN load for weeks 7-12.

Source	DF	Type I SS	Mean Square	F Value	Pr > F
P_type	3	0.21146358	0.07048786	0.63	0.6013
G_Media	2	24.8529728	12.42648642	111.49	<.0001
G_Media*P_type	6	1.21415240	0.20235873	1.82	0.1384

Table K-7. Results of the ANOVA (degrees of freedom, sum of square, mean square and F-values) for TN load for weeks 13-18.

Source	DF	Type I SS	Mean Square	F Value	Pr > F
P_type	3	3.88950127	1.29650042	1.86	0.1629
G_Media	2	20.9816477	10.49082385	15.07	<.0001
G_Media*P_type	6	2.36547959	0.39424660	0.57	0.7527

Table K-8. Results of the ANOVA (degrees of freedom, sum of square, mean square and F-values) for TN load for weeks 19-24.

Source	DF	Type I SS	Mean Square	F Value	Pr > F
P_type	3	0.50119655	0.16706552	0.99	0.4153
G_Media	2	13.83974155	6.91987078	40.91	<.0001
G_Media*P_type	6	2.02888911	0.33814818	2.00	0.1055

APPENDIX L
TKN LOAD MODEL DETAILS (F-VALUES AND R-SQUARED VALUES) AND RESULTS FOR ANOVA ANALYSES

Table L-1. Details of the PROC GLM model used for the ANOVA analyses for TKN load for Weeks 1-6.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	16.81834862	1.52894078	115.15	<.0001
Error	24	0.31866454	0.01327769		
Corrected Total	35	17.13701316			

R-Square	Coeff. .Var	Root MSE	Lntn Mean
0.981405	2.174536	0.115229	5.299010

Table L-2. Results of the ANOVA (degrees of freedom, sum of square, mean square and F-values) for TKN load for weeks 1-6.

Source	DF	Type I SS	Mean Square	F Value	Pr > F
P_type	3	0.48541934	0.16180645	12.19	<.0001
G_Media	2	16.24423534	8.12211767	611.71	<.0001
G_Media*P_type	6	0.08869394	0.01478232	1.11	0.3839

APPENDIX M
NITRATE LOAD DATA FOR THE ESTABLISHMENT PERIOD

Table M-1. Nitrate loads per bin (mg per m^2) for each week of the establishment period (Weeks 1-6). Levels not connected by the same letter within a time period and growing medium type have a significant difference due to plant type.

Growing Medium	Plant Type	NO_3-N load in mg m^{-2}																							
		Week 1				Week 2				Week 3				Week 4				Week 5				Week 6			
		mean		S.E.		mean		S.E.		mean		S.E.		Mean		S.E.		mean		S.E.		mean		S.E.	
B	p	30.6	±	12.0	a	3.5	±	2.1	a	9.1	±	0.6	a	3.2	±	1.1	a	5.3	±	1.8	a	16.2	±	7.6	a
	s	89.3	±	14.0	b	33.0	±	28.0	a	7.9	±	0.4	a	15.5	±	4.7	b	20.9	±	7.1	a	39.7	±	7.4	a
	r	26.0	±	10.3	b	7.1	±	1.6	a	8.0	±	1.4	a	11.7	±	4.6	ab	15.0	±	5.2	a	37.6	±	4.4	a
	m	7.61	±	2.41	b	4.14	±	0.39	a	9.10	±	2.02	a	5.44	±	0.96	ab	8.12	±	1.49	a	16.07	±	7.62	a
H	p	17100	±	350	ab	6540	±	927	a	8390	±	730	a	122	±	52	a	266	±	181	a	427	±	130	a
	s	17200	±	950	ab	7390	±	1390	a	9920	±	200	ab	184	±	49	a	272	±	58	a	212	±	40	ab
	r	18800	±	255	b	6400	±	792	a	9370	±	790	ab	88	±	7	a	304	±	33	a	124	±	11	b
	m	16000	±	480	a	6710	±	1390	a	10400	±	150	b	381	±	15	b	581	±	16	b	702	±	35	c
U	p	27.2	±	13.3	ab	3.7	±	0.6	a	3.0	±	2.4	a	0.2	±	0.1	a	0.7	±	0.0	a	1.1	±	0.0	a
	s	47.0	±	0.4	a	13.2	±	9.3	a	31.8	±	13.5	b	8.4	±	2.7	b	14.7	±	4.9	b	31.0	±	9.5	b
	r	5.56	±	2.61	b	6.59	±	2.45	a	7.29	±	3.82	a	2.10	±	0.66	a	3.69	±	1.20	a	9.78	±	6.19	a
	m	12.2	±	4.5	b	4.8	±	0.3	a	7.1	±	1.8	a	1.6	±	0.2	a	2.5	±	0.2	a	4.3	±	1.9	a

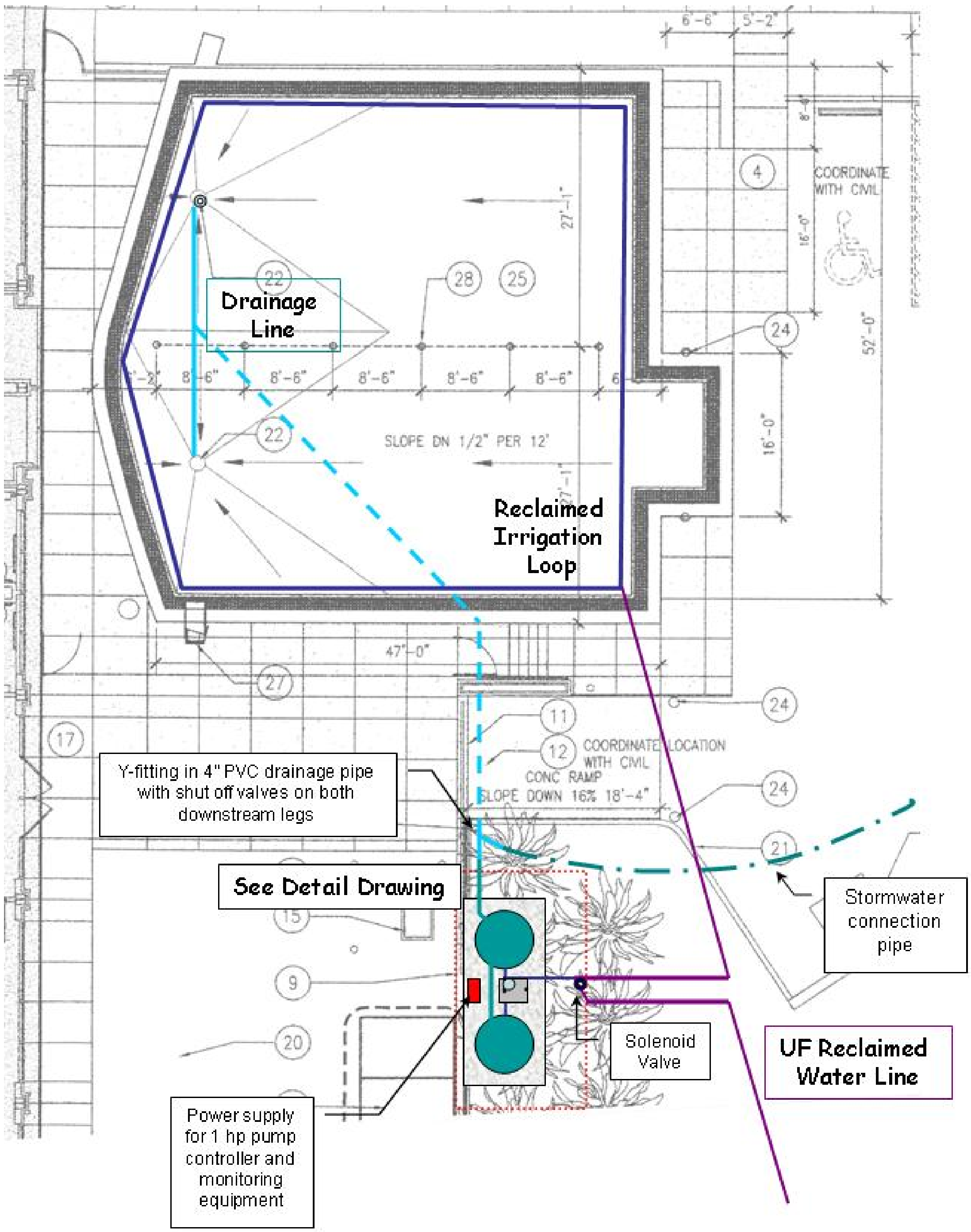
APPENDIX N
NITRATE LOAD DATA FOR THE 24-WEEK STUDY PERIOD

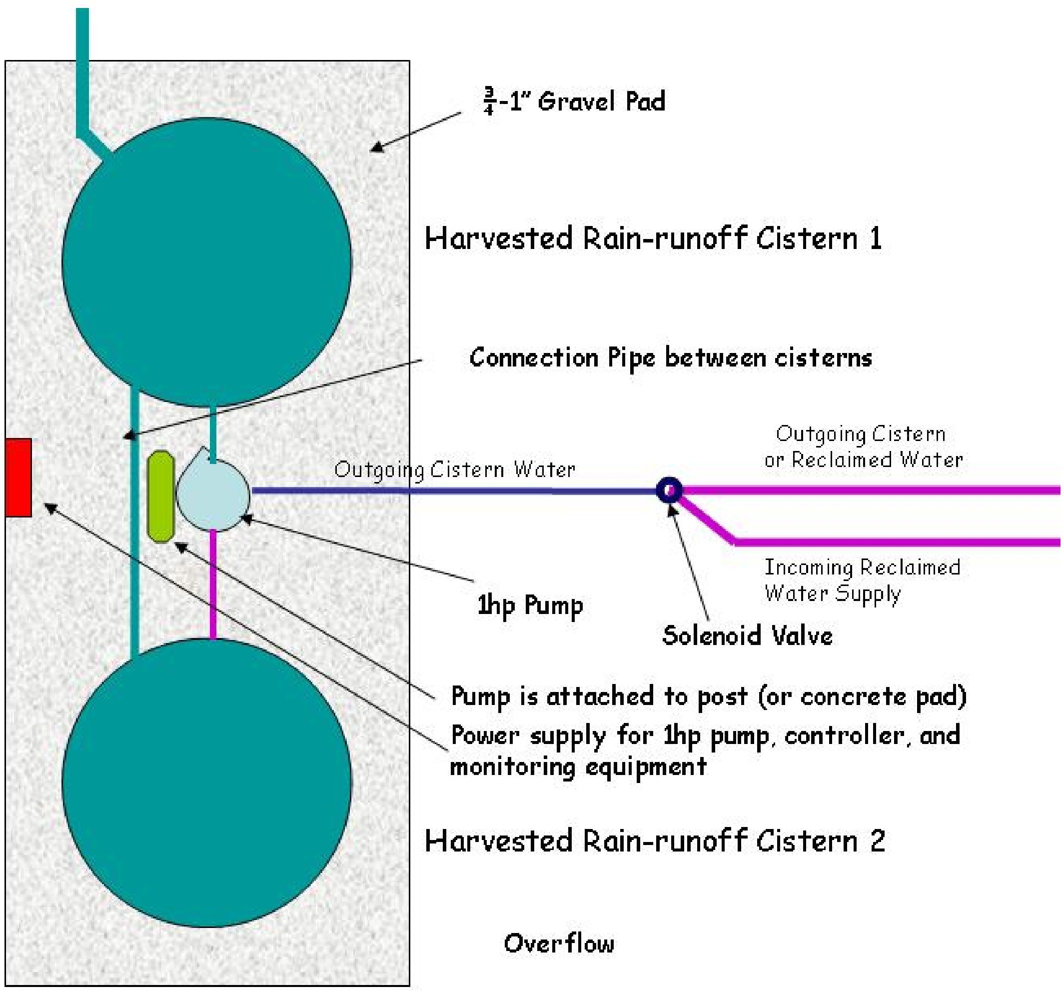
Table N-1. NO_3 load (mg m^{-2}) for all plant-growing medium combinations and all time periods over the 24 week study. Significant differences between plant types within a time step and growing medium type are indicated by different letters.

Growing Medium	Plant Type	N-NO_3 Load (mg m^{-2})															
		Weeks 1-6				Weeks 7-12				Weeks 13-18				Weeks 19-24			
		Mean		S.E.		mean		S.E.		mean		S.E.		mean		S.E.	
B	P	67.8	±	19.5	a	n.d.			a	0.47	±	0.044	a	9.16	±	6.46	a
	s	206	±	45	b	n.d.			a	0.66	±	0.034	ab	30.1	±	20.1	a
	r	105	±	13	a	n.d.			a	0.27	±	0.154	a	1.95	±	0.53	a
	m	50.5	±	6.4	a	n.d.			a	0.22	±	0.129	b	2.86	±	2.13	a
H	P	32700	±	2200	a	1150	±	818	a	0.56	±	0.028	a	1.29	±	0.50	a
	s	35200	±	2600	a	252	±	14.3	a	0.54	±	0.187	a	0.37	±	0.04	a
	r	35100	±	1280	a	155	±	77.7	a	0.65	±	0.217	a	21.9	±	17.4	a
	m	34700	±	1630	a	n.d.			a	2.47	±	0.782	b	0.47	±	0.19	a
U	P	35.9	±	16.2	a	n.d.			a	0.11	±	0.007	a	0.02	±	0.00	a
	s	146	±	36	b	n.d.			a	0.18	±	0.009	b	0.55	±	0.12	a
	r	35.0	±	14.0	a	n.d.			a	0.18	±	0.018	ab	0.42	±	0.30	a
	m	32.5	±	6.6	a	n.d.			a	0.27	±	0.035	c	0.06	±	0.02	a

* n.d. non-detectable

APPENDIX O
DRAWINGS OF CISTERN AND PUMP SET-UP FOR CHARLES R. PERRY GREEN ROOF





¾-1" Gravel Pad
Harvested Rain-runoff Cistern 1
Connection Pipe between cisterns
Outgoing Cistern
or Reclaimed Water
Outgoing Cistern Water
Incoming Reclaimed
Water Supply
1hp Pump
Solenoid Valve
Pump is attached to post (or concrete pad)
Power supply for 1hp pump, controller, and
monitoring equipment
Harvested Rain-runoff Cistern 2
Overflow

APPENDIX P
CHARLES R. PERRY GREEN ROOR HYDROGLOGY DATA BY INDIVIDUAL STORM

Table P-1. Summary of amount, duration, time of maximum intensity (peak) for rain events and runoff measured between 7/9/07 and 7/2/08 for the Charles R. Perry Construction Yard.

	Rain Event				Runoff				
Date	Duration	Amt(cm)	Max int (cm/hr)	Time of Max. Int	Duration RO	Amt RO (cm)	Max RO (cm/hr)	Time of Max RO	% Retention
7/9/2007	0:09	0.08	8.53	11:35		0.00			100%
7/12/2007	0:40	0.30	1.52	12:19	3:55	0.02	2.99	n/a	93%
7/14/2007	1:15	0.23	0.61	22:30	9:35	0.21	1.09	22:39	8%
7/22/2007	0:20	0.20	0.91	13:50	0:05	0.00	1.83		100%
7/24/2007	1:35	0.15	0.30	n/a		0.00	0.61		100%
7/28/2007	4:00	4.27	6.71	16:25	9:00	3.87	8.70	16:44	9%
7/31/2007	0:09	0.23	1.52	18:15		0.00	3.05		100%
8/3/2007	6:20	3.02	5.18	10:50	13:15	2.36	6.28	10:59	22%
8/9/2007	1:30	7.34	15.85	21:05	2:49	0.00	31.70		43%
8/12/2007	1:30	1.12	3.35	20:00	4:25	0.00	5.07	20:05	21%
8/13/2007	1:15	0.71	0.61	18:35	10:00	0.00	1.16	18:59	85%
8/14/2007	0:35	1.47	5.79	21:55	3:20	0.00	8.94	22:04	19%
8/25/2007	0:15	0.08	0.25	16:19	0:04	0.00	0.44	17:20	93%
8/27/2007	0:35	0.08	0.30	n/a		0.00	n/a	n/a	100%
8/30/2007	0:45	0.18	0.30	n/a		0.00	n/a	n/a	100%
8/31/2007	0:15	0.25	1.22	3:10	5:55	0.09	2.38	n/a	65%
9/2/2007	0:16	0.61	2.44	2:45	5:40	0.00	4.56	n/a	50%
9/2/2007	2:30	3.23	12.80	15:05	7:35	3.06	20.51	15:09	5%
9/13/2007	0:15	0.69	1.56	20:30	13:15	0.00	n/a	n/a	90%
9/19/2007	0:30	0.08	n/a	n/a		0.00	n/a	n/a	100%
9/19/2007	3:20	1.04	0.61	22:55	7:45	0.22	0.65	23:44	75%
9/20/2007	3:45	1.73	2.74	0:00	14:30	1.17	3.79	23:59	32%
9/21/2007	1:10	2.46	6.40	21:20	9:50	1.69	9.28	21:24	31%
10/2/2007	3:45	2.01	2.32	12:25	9:30	1.80	3.58	12:54	10%

Table P-1. Continued

Date	Rain Event				Runoff				
	Duration	Amt(cm)	Max int (cm/hr)	Time of Max. Int	Duration RO	Amt RO (cm)	Max RO (cm/hr)	Time of Max RO	% Retention
10/3/2007	0:55	0.13	0.30	n/a	6:20	0.07	n/a	n/a	43%
10/4/2007	6:35	4.78	11.28	16:35	16:55	3.98	21.99	18:19	17%
10/5/2007	0:50	0.71	3.96	0:20	15:10	0.75	6.86	0:24	0%
10/5/2007	4:35	3.81	6.71	14:35	8:35	4.00	8.76	14:35	0%
10/6/2007	0:40	0.28	1.52	15:25	6:10	0.25	2.86	15:34	12%
10/7/2007	0:55	0.33	1.83	12:45	7:20	0.41	3.28	n/a	0%
10/19/2007	0:35	0.33	1.83	15:00	9:00	0.30	3.59	n/a	13%
10/19/2007	0:35	0.3302	19:53	15:00	9:00	0.30	3.59	n/a	13%
10/19/2007	0:40	0.56	3.66	12:45	1:00	0.01	7.25	n/a	97%
10/21/2007	4:50	0.41	0.30	n/a	7:25	0.20	0.48	22:24	50%
10/21/2007	4:50	0.4064	7:18	n/a	7:25	0.20	0.48	22:24	50%
12/21/2007	1:50	0.46	0.61	2:40	4:20	0.149	0.0628	9:59	67%
12/30/2007	0:10	0.18	1.52	14:50	13:55	0.07	0.063	15:54	61%
1/12/2008	1:51	0.5588	0.61	15:50	15:40	0.366	0.126	17:09	35%
1/16/2008	0:40	0.127	0.30	8:30	8:00	0.042	0.063		67%
1/19/2008	14:05	4.0894	2.44	3:40	2:25	2.179	1.383	3:59	
1/26/2008	0:55	0.1778	0.30	9:09	12:50	0.06	0.063	0:29	66%
1/28/2008	1:46	0.0762	0.30	n/a		0	0.000		100%
2/7/2008	5:50	0.5588	2.13	18:10	20:30	0.45	0.126	18:43	19%
2/12/2008	0:40	0.254	1.22	23:35	14:43	12.4	0.251	23:43	
2/12/2008	2:56	1.2192	1.83	19:50	0:00	0	1.005		100%
2/12/2008	7:30	1.5748	0.61	16:40	11:20	1.142	0.063	17:08	27%
2/21/2008	0:34	1.27	2.16	5:15	14:35	1.065	1.760	5:30	16%
2/23/2008	2:40	2.9464	6.10	2:35	12:05	1.39	0.063	9:59	
2/26/2008	6:25	1.3716	3.96	13:23	1:45	1.167	0.691		15%
3/4/2008	1:30	1.0668	5.18	14:25	10:40	0.897	1.508	14:25	16%
3/8/2008	0:15	0.4318	0.30	13:25	22:00	0.228	0.063	19:47	47%

Table P-1. Continued

Date	Rain Event				Runoff				
	Duration	Amt(cm)	Max int (cm/hr)	Time of Max. Int	Duration RO	Amt RO (cm)	Max RO (cm/hr)	Time of Max RO	% Retention
6/23/2008	1:20	0.56	0.61	n/a	17:55	0.21	0.1257		62%
6/25/2008	0:15	0.30	1.22	14:20	19:15	0.06	0.0628		80%
6/26/2008	2:20	0.38	0.30	n/a	18:00	0.02	n/a		95%
6/27/2008	1:00	0.30	0.61	17:20	16:20	0.27	0.0628		11%
6/28/2008	0:20	0.0508	n/a	n/a					100%
6/30/2008	0:35	0.36	0.63	15:05	19:50	0.1	0.0628		72%
7/2/2008	0:50	0.66	0.91	19:00	9:25	0.27	0.063		59%
7/8/2008	6:05	4.75	6.71	17:10	11:35	4.33	8.6093		9%
7/12/2008	1:25	0.71	2.13	12:30	2:35	0.32	0.7541		55%
7/12/2008	0:55	0.08	2.13	n/a					100%
7/13/2008	0:05	0.03		n/a					100%
7/15/2008	0:35	0.15	0.30	n/a	7:30	0.03	0.06284		80%
7/15/2008	1:15	5.41	13.72	13:45	19:00	1.35	4.52459		75%
2/18/2008	5:08	1.77	1.83	10:00	21:08	1.226	0.817	10:13	31%
7/2/2008	10:47	1.07	0.91		0:50	0.78	0.0200		27%

Table P-2. Charles R. Perry Construction Yard Green Roof--Summary of rain events and runoff volume and duration, and percent of stormwater retention for 2007-2008 by season.

July 7, 2007 to October 23, 2007

Type	Antecedent	Rain Duration (hr)	Rain Duration (hr)	Rain (cm)	Duration RO (hr)	Runoff (cm)	% retention
Total				45.2		26.7	41%
Mean	17.0		1 hr 50 min	1.2	7 hr 50 min	0.7	52%
Stdev	12.9		2 hr	1.6	4 hr 20 min	1.2	40%
Median	14.3		1 hr	0.4	7 hr 30 min	0.2	50%
Min	0.7		10 min	0.1	5 min	0.0	0%
Max	48.3		6 hr 30 min	7.3	17 hr	4.2	100%

December 20, 2007 to March 18, 2008

	Antecedent Moist (duration [hrs] since last storm)	RainDuration (hrs)	RainDuration (hrs)	Rain (cm)	Duration RO (hr)	Runoff (cm)	% retention
Total Rain/Runoff				22.3		14.8	34%
Mean	36.0		2 hr 20 min	1.0	10 hr 50 min	1.2	33%
StdDev	26.0		2 hr 5 min	1.0	7 hr 35 min	2.2	52%
Median	31.8		1 hr 40 min	0.6	11 hr 40 min	0.5	33%
Min	3.3		5 min	0.0	0 hr	0.0	0%
Max	96.0		7 hr 30 min	4.1	22 hr 30 min	10.5	100%

April 11 to June 7, 2008

Type	Antecedent Moist (duration [hrs] since last storm)	RainDuration (hr)	RainDuration (hr)	Rain (cm)	Duration RO (hr)	Runoff (cm)	%retention
TOTAL RAIN				13.60			89%
Mean			25 min	0.76	2hr 20min		90%
Stdev			12 min	0.30	50 min		11%
median			23 min	0.87	2hr 30 min		94%
Min			5 min	0.03	30 min		61%
Max			1hr	1.09	3 hr 45 min		100%

Table P-2. Continued.

Jun 13 to Jul 26, 2008							
Type	Antecedent Moist (duration [hrs] since last storm)	RainDuration (hr)	RainDuration (hr)	Rain (cm)	Duration RO (hr)	Runoff (cm)	% retention
TOTAL RAIN				23.8		10.6	55%
Mean			2 hr	1.1	13 hr 20 min	0.7	67%
Stdev			3 hr	1.8	7 hr 20 min	1.3	33%
median			1 hr	0.4	17 hr 10 min	0.2	75%
Min			5 min	0.0	45 min	0.0	9%
Max			10 hr 50 min	5.4	19 hr 45 min	4.3	100%

July 26 to September 15, 2008							
Type	Antecedent Moist (duration [hrs] since last storm)	RainDuration (hr)	RainDuration (hr)	Rain (cm)	Duration RO (hr)	Runoff (cm)	%retention
TOTAL RAIN				20.71		15.58	25%
Mean			2 hr	1.22	11 hr	0.92	53%
Stdev			2 hr 45 min	2.18	8hr 45 min	1.84	38%
median			35 min	0.58	6 hr 50 min	0.17	64%
Min			5 min	0.03	0 hr	0.00	0%
Max			9 hr 15 min	9.09	32 hr 15 min	7.44	100%

Table P-3. Delay in start of runoff after rain began, extension of runoff after rain stopped, increase in lag time to peak runoff and % reduction in peak runoff for rain events July 2007 to July 2008 for the Charles R. Perry Construction yard Green Roof.

Date	Delay Start RO	Extension End RO	Increase Lag to Peak	% Reduction of Peak
7/12/2007	2:20	5:35	n/a	96%
7/14/2007	0:15	8:35	0:09	79%
7/22/2007	0:50	0:35	n/a	100%
7/24/2007	No runoff			100%
7/28/2007	0:10	5:10	0:19	30%
7/31/2007	No runoff			100%
8/3/2007	0:00	6:55	0:09	21%
8/9/2007	0:10	4:32	n/a	100%
8/12/2007	0:14	3:09	0:05	51%
8/13/2007	0:05	8:50	0:24	90%
8/14/2007	0:00	2:45	0:09	54%
8/25/2007	1:01	0:50	1:01	75%
8/27/2007	No runoff			
8/30/2007	No runoff			
8/31/2007	0:15	5:55	n/a	95%
9/2/2007	0:10	5:34	n/a	87%
9/2/2007	0:05	5:10	0:04	60%
9/13/2007	0:15	13:15	n/a	
9/19/2007	No runoff			
9/19/2007	1:30	5:55	0:49	7%
9/20/2007	1:00	11:45	0:00	38%
9/21/2007	0:15	8:55	0:04	45%
10/2/2007	0:05	5:50	0:29	54%
10/3/2007	0:35	6:00	n/a	
10/4/2007	0:05	10:25	1:44	95%
10/5/2007	0:00	14:20	0:04	73%
10/5/2007	0:00	4:00	0:00	31%
10/6/2007	0:10	5:40	0:09	88%
10/7/2007	0:05	6:30	n/a	79%
10/19/2007	0:05	8:30	n/a	97%
10/19/2007	0:05	8:30	n/a	97%
10/19/2007	0:35	0:55	n/a	98%
10/21/2007	3:25	6:00	n/a	59%
10/21/2007	3:25	6:00	n/a	59%
12/21/2007	5:59	8:29	7:19	90%
12/30/2007	0:15	14:00	1:04	96%
1/12/2008	0:50	14:39	1:19	79%
1/16/2008	1:10	8:30		79%
1/19/2008			0:19	43%
1/26/2008	0:45	12:40	15:20	79%
1/28/2008				100%

Table P-3. Continued

2/7/2008	0:10	14:50	0:33	94%
2/12/2008			0:08	79%
2/12/2008	0:05	3:55	0:28	90%
2/21/2008	0:13	14:14	0:15	19%
2/23/2008			7:24	99%
2/26/2008	0:05	19:25		83%
3/4/2008	1:05	10:15	0:00	71%
3/8/2008			0:00	100%
3/8/2008	1:55	23:40	6:22	79%
6/23/2008	0:45	17:20		79%
6/25/2008	0:30	19:30		100%
6/26/2008	1:00	16:40		0%
6/27/2008	0:20	15:40		90%
6/28/2008				100%
6/30/2008	0:20	19:35		90%
7/2/2008	0:20	8:55		93%
7/8/2008	0:10	6:50		
7/12/2008	0:00	1:10		65%
7/12/2008				100%
7/13/2008				100%
7/15/2008	0:15	7:10		100%
7/15/2008	0:15	18:00		67%
2/18/2008			0:13	55%
7/2/2008	0:20	14:23		98%

Extension End RO = Time b/w end of storm and end of RO
Increase Lag Time to Peak =time of max rain- time of max ro
% Reduction of Peak (Max Intensity) ([peak rain-peak r.o]./peak rain

Table P-4. Summary table of mean, standard deviation, median and range for all rain events and runoff from Charles R. Perry Construction Yard Green roof between July 2007 and July 2008.

				Runoff				
Date	Day	Duration	Amt(cm)	Max int (cm/hr)	Duration RO	Amt RO (cm)	Max RO (cm/hr)	% Retention
Total			76.58			55.55		27%
Mean		2 hr	1.14	2.77	10hr	0.88	3.54	54%
Stdev		2hr 20m	1.53	3.45	6hr 15m	1.84	5.91	36%
Median		1 hr	0.46	1.52	9 hr	0.21	1.12	53%
Min		5 min	0.03	0.25	0min	0.00	0.00	0%
Max		10hr45m	7.34	15.85	22hr50m	12.40	31.70	100%

APPENDIX Q
CUMULATIVE HYDROGRAPH AND SUMMARY TABLES FOR WINTER 2007-2008, CHARLES R. PERRY GREEN ROOF IN FLORIDA

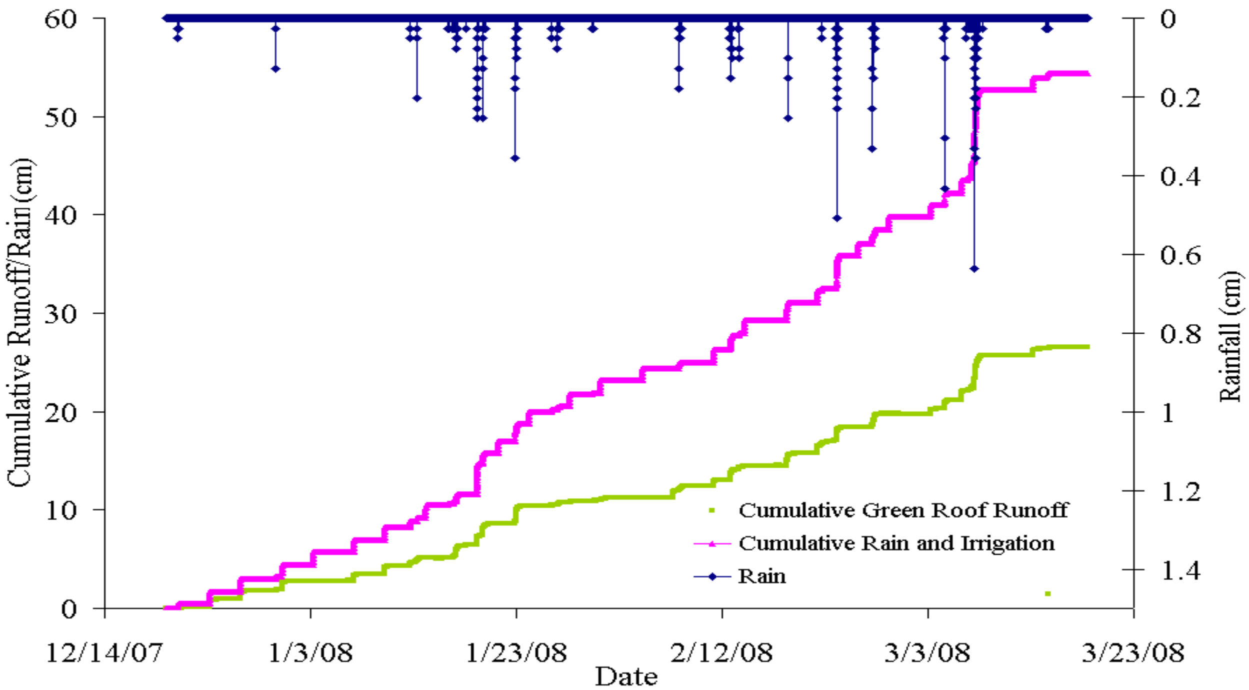


Figure Q-1. Cumulative hydrograph for 12/20/07 to 3/18/08 for CRP green roof in FL. Pink line shows cumulative irrigation and rainfall, green line shows cumulative green roof runoff, and blue line shows individual rain events.

Table Q-1. Mean, median and range of rain event size, hours since previous storm, and green roof runoff response for rain events between 12/20/07 and 3/18/08 for CRP roof, FL.

	Hours since previous storm	Rain Duration (hrs)	Rain (cm)	GR Runoff Duration (hr)	Runoff (cm)	% Retention
Total			22.3		14.8	34%
Mean	36.0	2 hr 20 min	1.0	10 hr 50 min	1.2	33%
StdDev	26.0	2 hr 5 min	1.0	7 hr 35 min	2.2	52%
Median	31.8	1 hr 40 min	0.6	11 hr 40 min	0.5	33%
Min	3.3	5 min	0.0	0 hr	0.0	0%
Max	96.0	7 hr 30 min	4.1	22 hr 30 min	10.5	100%

Table Q-2. Mean, median and range of delay in start of runoff, extension of runoff, and % reduction of peak intensity for rain events between 12/20/07 and 3/18/08 for CRP roof in FL.

	Delay in Start Run Off (hr)	Extension of Run Off (hr)	Max. Rain Intensity (cm/hr)	Max. Run Off (cm/hr)	% Reduction of Peak Intensity
Mean	1 hr 10 min	12 hr	1.7	0.5	74%
StdDev	1hr 40 min	6 hr	1.6	0.6	24%
Median	40 min	14 hr	1.2	0.2	79%
Min	0 hr	1 hr 10 min	0.3	0.0	19%
Max	6 hr	23 hr 45 min	6.1	1.8	100%

APPENDIX R
HYDROLOGIC SUMMARY TABLES FOR SPRING 2008, CHARLES R. PERRY GREEN ROOF IN FLORIDA

Table R-1. Characterization of 14 irrigation events and 4 rain events captured between April 11, 2008 to June 7, 2008, for rainfall or irrigation duration and volume, green roof runoff duration and volume, and % volume rainfall or irrigation retention.

Type	Rainfall or Irrigation. Duration (hr)	Rainfall or Irrigation Depth (cm)	Duration RO (hr)	RO (cm)	Rainfall or Irrigation Retention (%)
Total/Overall		13.60		1.53	89%
Mean	25 min	0.76	2 hr 20 min	0.08	90%
Stdev	12 min	0.30	50 min	0.10	11%
Median	23 min	0.87	2 hr 30 min	0.05	94%
Min	5 min	0.03	30 min	0.00	61%
Max	1hr	1.09	3 hr 45 min	0.34	100%

Table R-2. Results of analysis of 14 irrigation events and 4 rain events between April 11, 2008 and June 7, 2008 for % decrease in peak intensity, increase in lag to peak, delay to start of runoff and extension of runoff duration past the end of storm event.

Type	Delay in Start (min)	Extension (hr)	Max Rain/Irrig. Int. (cm/hr)	Max RO (cm/hr)	% Reduction of Peak
Mean	35 min	2 hr 15 min	0.08	0.31	0.84
Stdev	14 min	50 min	0.10	0.36	0.18
Median	25 min	2 hr 30 min	0.05	0.12	0.94
Min	5 min	35 min	0.00	0.00	0.37
Max	50 min	3 hr 35 min	0.34	1.32	1.00

APPENDIX S

CUMULATIVE HYDROGRAPH AND HYDROLOGIC SUMMARY TABLES FOR SUMMER 2008, CRP GREEN ROOF IN FLORIDA

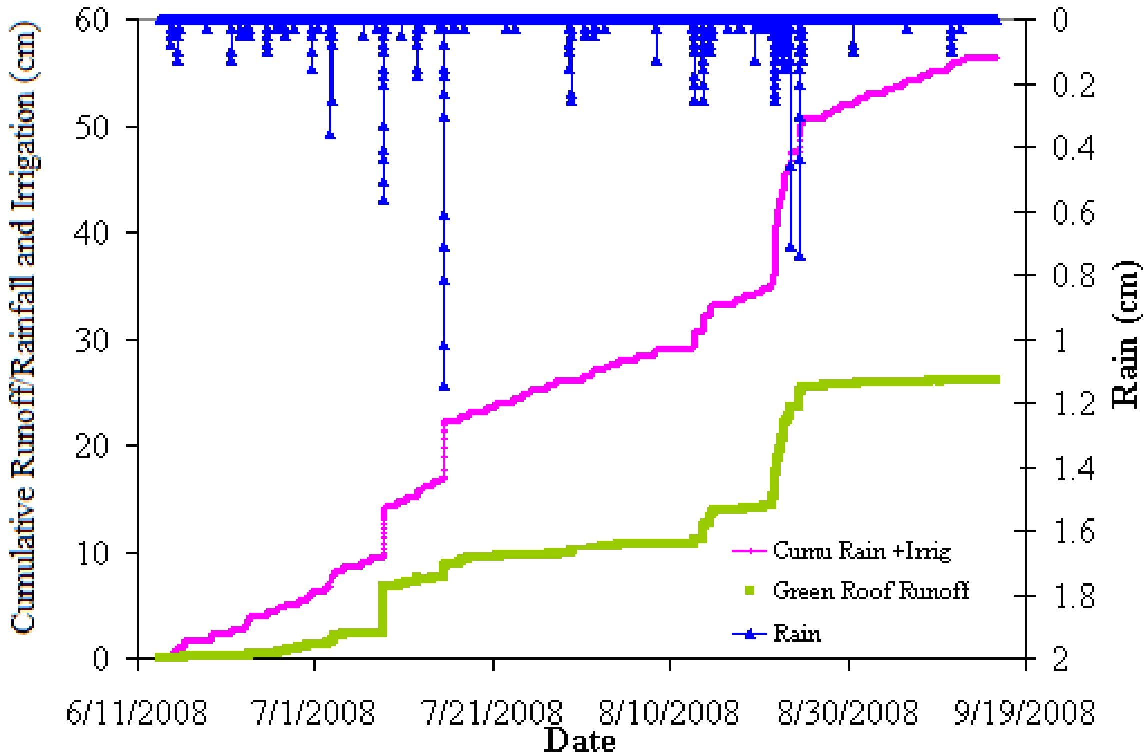


Figure S-1. Cumulative green roof runoff compared to cumulative rainfall and irrigation for wet season months (June 7th to September 15th) in 2008, hyetograph shown in blue.

Table S-1. Characterization of 17 rain events captured between July 26, 2008 to September 15, 2008, in terms of rainfall duration, rainfall depth (cm), green roof runoff duration and depth and percent rainfall retention.

Type	Rain Duration (hr)	Rain (cm)	Duration RO (hr)	Runoff (cm)	% Retention
Total Rain/RO		20.71		15.58	25%
Mean	2 hr	1.22	11 hr	0.92	53%
StdDev	2 hr 45 min	2.18	8 hr 45 min	1.84	38%
Median	35 min	0.58	6 hr 50 min	0.17	64%
Min	5 min	0.03	0 hr	0.00	0%
Max	9 hr 15 min	9.09	32hr15m	7.44	100%

Table S-2. Mean, median and range of delay in start and extension in end of runoff, reduction in peak intensity for 17 rain events between July 26, 2008 and September 15, 2008.

	Delay in Start (min)	Extension (hr)	Max Rain Int (cm/hr)	Max RO (cm/hr)	% Reduction of Peak
Mean	40 min	12 hr	1.26	0.18	65%
StdDev	40 min	12 hr	0.83	0.18	87%
Median	60 min	7 hr 25 min	0.75	0.45	21%
Min	20 min	14 hr 30 min	0.62	0.06	96%
Max	0 min	1 hr 10 min	0.00	0.00	31%

APPENDIX T
CUMULATIVE HYDROGRAPH AND HYDROLOGIC SUMMARY TABLES FOR FALL/WINTER 2006-2007, YSC GREEN ROOF IN VIRGINIA

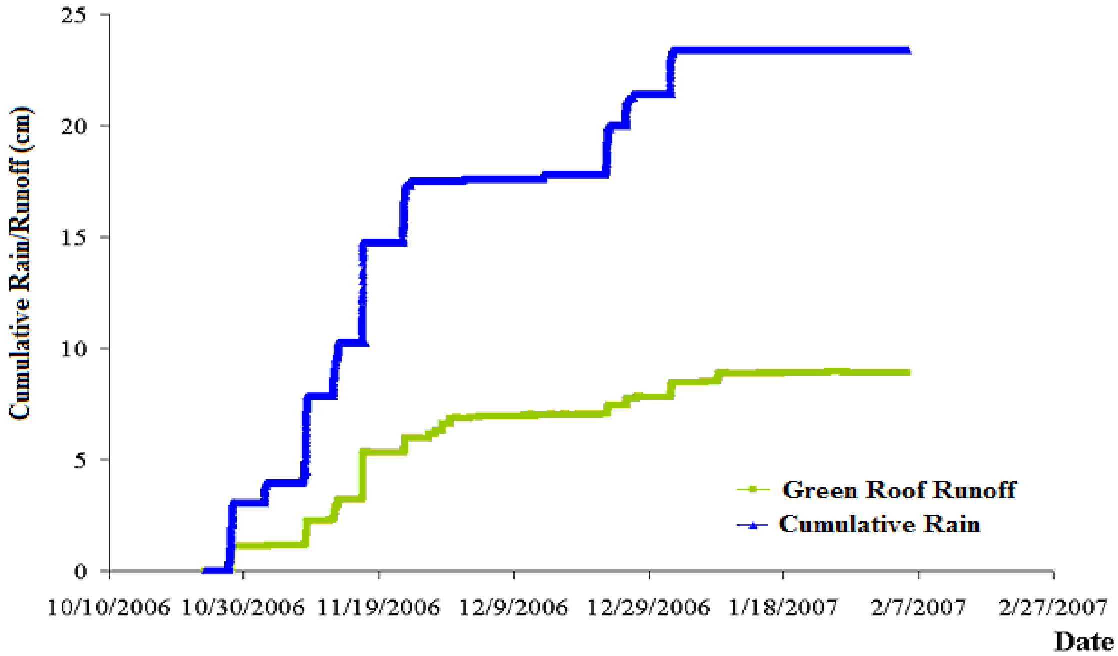


Figure T-1. Cumulative hydrograph of green roof runoff versus cumulative precipitation for YSC, Merrifield, VA for fall/early winter 2006 - 2007 (October 24, 2006 to February 7, 2007).

Table T-1. Characterization of 36 rain events captured between November 1, 2006 and March 8, 2007 (Late Fall/Winter) in Merrifield, Virginia from the YSC green roof, for rain duration, rain amount (cm), maximum intensity, green roof runoff duration, and maximum runoff intensity.

Type	Duration (hr)	Rain (cm)	Max int (cm hr^{-1})	Duration RO (hr)	Amt RO(cm)	Max RO (cm hr^{-1})
Total	242.98	31.41	27.03	177.06	8.90	
Mean	6.75	0.90	0.77	9.32	0.24	0.08
Stdev	6.42	1.09	1.10	5.65	0.45	0.11
Median	4.96	0.33	0.30	8.92	0.00	0.02
Min	0.05	0.05	0.00	0.60	0.00	0.00
Max	23.16	4.47	4.27	20.25	2.14	0.41

Table T-2. Mean, median and range of stormwater retention (%), delay in start and extension in end of runoff, reduction in peak intensity for 36 rain events captured between November 1, 2006 and March 8, 2007.

Type	%Retention	Delay in Start RO (hr)	Ext end RO(hr)	Increase in Lag to Peak (hr)	% Reduction of Peak
Mean	83%	3.41	5.08	3.78	96%
Stdev	23%	3.19	4.77	3.25	6%
Median	98%	3.09	3.36	2.70	100%
Min	19%	0.00	0.00	0.00	73%

Max	100%	14.16	18.50	9.58	100%

APPENDIX U
CUMULATIVE HYDROGRAPH AND HYDROLOGIC SUMMARY TABLES FOR SUMMER 2007, YSC GREEN ROOF IN VIRGINIA

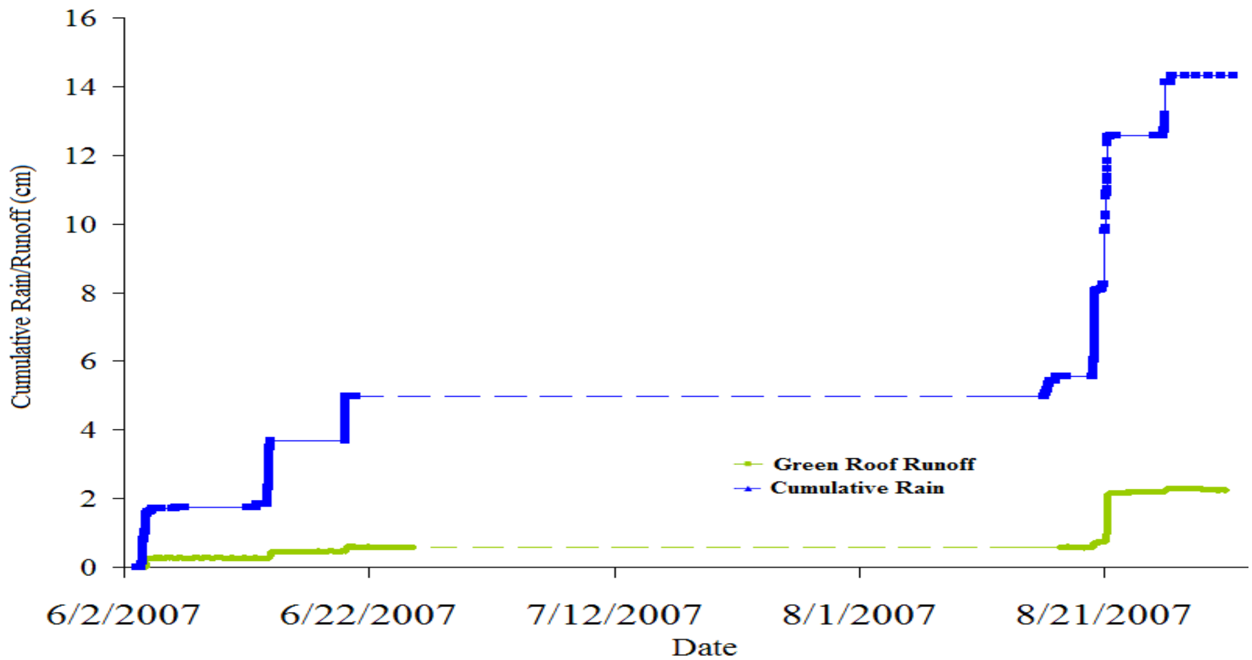


Figure U-1. Cumulative hydrograph of rainfall and runoff from the YSC green roof in Merrifield, VA for June and August 2007 (July data was unavailable due to technical difficulties).

Table U-1. Characterization of 12 rain events captured in June 2007 and August 2007 (summer) in Merrifield, Virginia from the YSC green roof, for rain duration (hr), rain amount (cm), maximum intensity (cm hr^{-1}), green roof runoff duration (hr), and maximum runoff intensity (cm hr^{-1}).

Type	Duration (hr)	Rain (cm)	Max int (cm hr^{-1})	Duration RO (hr)	Amt RO(cm)	Max RO (cm hr^{-1})
Total	67.20	11.14		49.02	2.04	
Mean	6.11	0.93	1.81	6.13	0.19	0.18
Stdev	7.66	0.85	2.57	3.46	0.42	0.07
Median	2.58	0.94	0.61	5.00	0.05	0.18
Min	0.08	0.05	0.04	3.42	0.00	0.04
Max	23.16	2.59	9.14	13.70	1.43	0.24

Table U-2. Mean, median and range of stormwater retention (%), delay in start and extension in end of runoff, reduction in peak intensity for 12 rain events collected in June and August 2007.

Type	%Retention	Delay in Start RO (hr)	Ext end RO(hr)	Increase in Lag to Peak (hr)	% Reduction of Peak
Mean	90%	3.55	3.94	2.14	89%
Stdev	16%	3.51	2.71	1.97	21%
Median	94%	4.00	3.60	1.50	100%
Min	45%	0.33	0.10	0.50	33%
Max	100%	10.00	8.50	6.25	100%

APPENDIX V
CUMULATIVE HYDROGRAPH AND HYDROLOGIC SUMMARY TABLES FOR SPRING 2008, YSC GREEN ROOF IN VIRGINIA

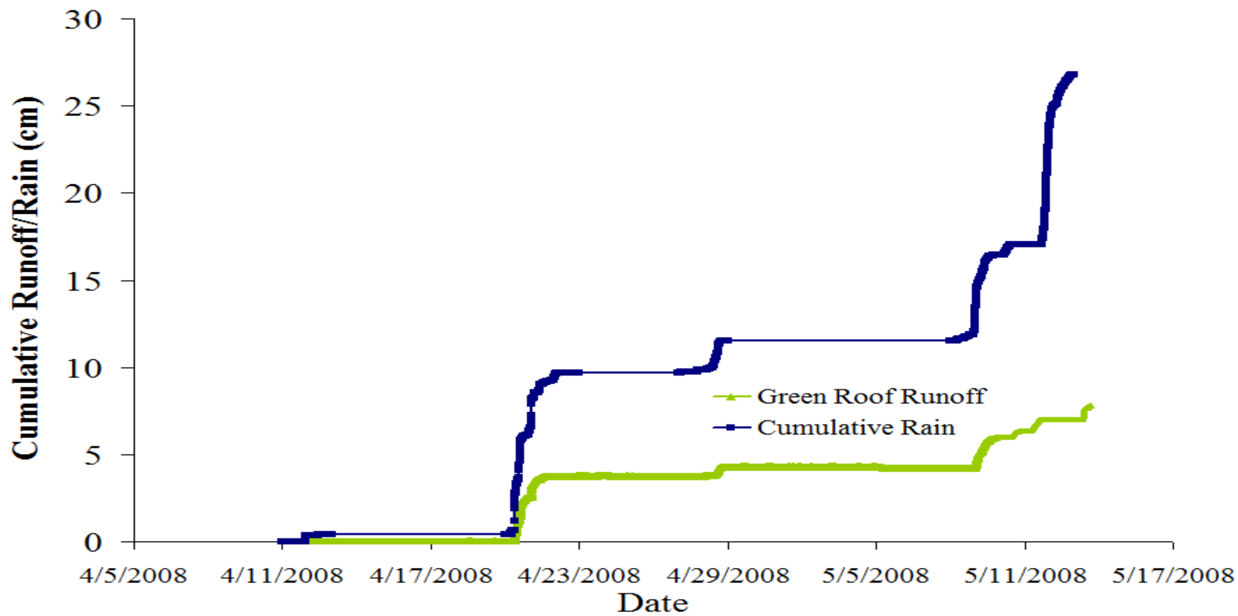


Figure V-1. Cumulative hydrograph of green roof runoff and rainfall for April and May 2008 for YSC green roof in Merrifield, VA.

Table V-1. Characterization of 10 rain events captured in April and May 2008 (Spring) in Merrifield, Virginia from the YSC green roof, for rain duration (hr), rain amount (cm), maximum intensity (cm hr^{-1}), green roof runoff duration (hr), and maximum runoff intensity (cm hr^{-1}).

Type	Duration (hr)	Rain (cm)	Max int (cm hr^{-1})	Duration RO (hr)	Amt RO (cm)	Max RO (cm hr^{-1})	Amt retained(cm)
Total	223.0	46.33			16.01		30.13
Mean	7.44	1.49	1.05	9.34	0.44	0.17	0.84
Stdev	6.34	1.78	1.17	5.53	0.78	0.38	0.99
Median	5.40	0.89	0.91	8.92	0.00	0.00	0.43
Min	0.17	0.03	0.00	0.60	0.00	0.00	0.00
Max	23.25	7.65	4.87	21.17	3.48	2.08	4.16

Table V-2. Mean, median and range of stormwater retention (%), delay in start and extension in end of runoff, reduction in peak intensity for 10 rain events collected in April and May of 2008.

Type	%retention	Delay in Start RO (hr)	Ext end RO(hr)	Increase in Lag to Peak (hr)	% Reduction of Peak
Mean	85%	3.85	2.78	2.79	92%
Stdev	19%	2.37	1.66	2.93	13%
Median	99%	3.30	2.90	2.04	100%
Min	39%	0.15	0.90	0.25	51%
Max	100%	10.00	7.30	8.90	100%

APPENDIX W
CUMULATIVE HYDROGRAPH AND HYDROLOGIC SUMMARY TABLES FOR LATE SUMMER 2008, YSC GREEN ROOF, IN VIRGINIA

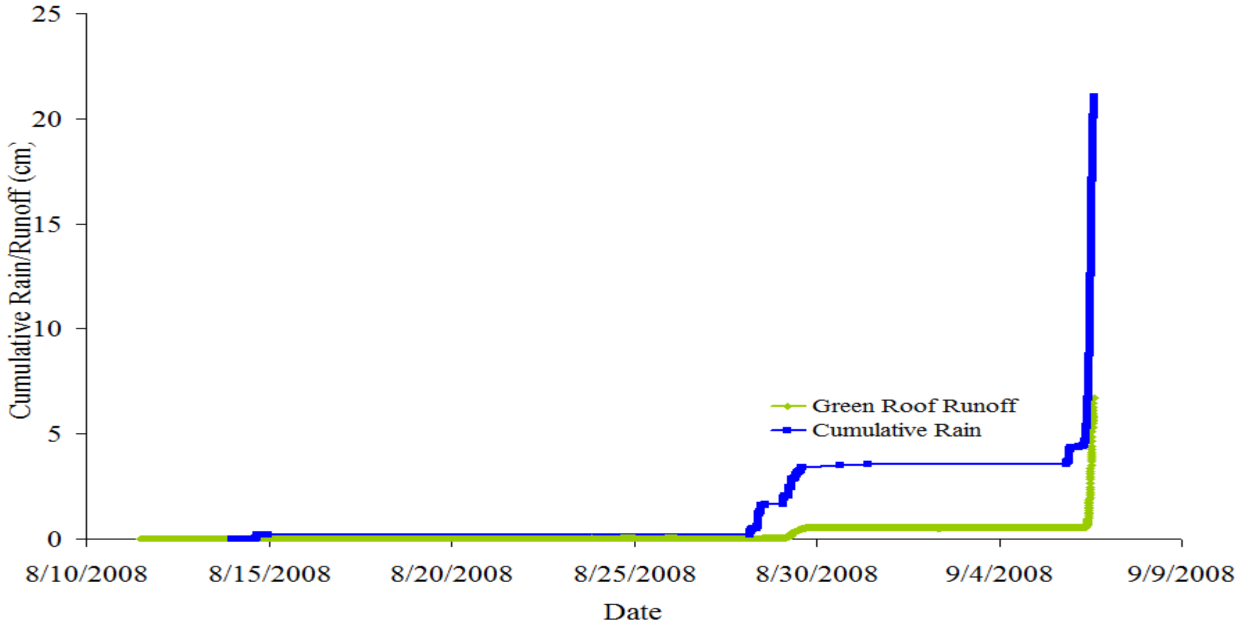


Figure W-1. Cumulative hydrograph of rainfall and green roof runoff for August-September 2008 for YSC greenroof in Merrifield, VA.

Table W-1. Characterization of 10 rain events captured in August and September 2008 (Lat Summer) in Merrifield, Virginia from the YSC green roof, for rain duration (hr), rain amount (cm), maximum intensity (cm hr^{-1}), green roof runoff duration (hr), and maximum runoff intensity (cm hr^{-1}).

Type	Duration (hr)	Rain (cm)	Max int (cm/hr)	Duration (hr)	RO Amt RO (cm)	Max RO (cm hr^{-1})
Total	42.39	20.85			26.15	6.72
Mean	8.48	4.17	0.08	4.57	8.72	1.34
Stdev	8.13	7.48	0.04	2.64	4.79	2.71
Median	10.90	1.47	0.05	3.05	6.00	0.05
Min	0.08	0.05	0.05	3.05	5.90	0.00
Max	18.33	17.47	0.15	9.14	14.25	6.19

Table W-2. Mean, median and range of stormwater retention (%), delay in start and extension in end of runoff, reduction in peak intensity for 12 rain events collected in August and September of 2008.

Type	%Retention	Delay in Start RO (hr)	Ext end RO(hr)	Increase in Lag to Peak (hr)	% Reduction of Peak
Mean	87%	6.28	0.60	0.18	91%
Stdev	17%	5.83	0.89	0.11	12%
Median	97%	6.00	0.00	0.18	99%
Min	65%	0.60	0.00	0.10	74%
Max	100%	12.25	2.00	0.25	100%

APPENDIX X

COMPARISON OF STORM DURATION/ SIZE, INTENSITY, STORM WATER RETENTION, AND REDUCTION IN RUNOFF INTENSITY FOR VA AND FL

Table X-1. Comparison of length of Virginia and Florida storms sampled during study period.

	Virginia Storm Length (hr)	Florida Storm Length (hr)
Range	0.05 to 27.5 hr	0.08 to 10.7 hr
1st Quartile	1.2 hr	
Median	4.9 hr	1.0 hr
3rd Quartile	12.1 hr	
Mean	7.04 ± 6.9 hr	1.9 ± 2.8 hr

Table X-2. Comparison of storm size of Virginia and Florida storms sampled.

	Virginia Storm Size (cm)	Florida Storm Size (cm)
Range	0.0254 to 17.47 cm	0.0254 to 9.09 cm
1st Quartile	0.102 cm	0.178 cm
Median	0.635 cm	0.445 cm
3rd Quartile	1.6 cm	1.295 cm
Mean	1.4 cm ± 2.5 cm	1.09 ± 1.59 cm

Table X-3. Comparison of average rain intensity of Virginia and Florida storms sampled.

	Virginia Rain Intensity (cm hr^{-1})	Florida Rain Intensity (cm hr^{-1})
Range	0.0032 to 4.1 cm hr^{-1}	0.022 to 7.3 cm hr^{-1}
1st Quartile	0.070 cm hr^{-1}	0.23 cm hr^{-1}
Median	0.17 cm hr^{-1}	0.47 cm hr^{-1}
3rd Quartile	0.58 cm hr^{-1}	1.03 cm hr^{-1}
Mean	0.59 ± 1.4 cm hr^{-1}	0.86 ± 1.45 cm hr^{-1}

Table X-4. Comparison of maximum rain intensity of Virginia and Florida storms sampled.

	Virginia Max. Intensity (cm hr^{-1})	Florida Max. Intensity (cm hr^{-1})
Range	0 to 9.14 cm hr^{-1}	0 to 15.8 cm hr^{-1}
1st Quartile	0.13 cm hr^{-1}	0.38 cm hr^{-1}
Median	0.61 cm hr^{-1}	1.2 cm hr^{-1}
3rd Quartile	1.6 cm hr^{-1}	2.43 cm hr^{-1}
Mean	1.39 ± 1.9 cm hr^{-1}	2.32 ± 3.1 cm hr^{-1}

Table X-5. Comparison of storm water retention of Virginia and Florida storms sampled.

	Virginia	Florida
Range	0 to 100%	0 to 100%
1st Quartile	74%	15%
Median	96%	55%
3rd Quartile	100%	94%
Mean	86% ± 19 %	49% ± 43%

Table X-6. Comparison of max. stormwater runoff intensity from green roofs in VA and FL.

	Virginia R.O. Max. Intensity (cm hr^{-1})	Florida R.O. Max. Intensity (cm hr^{-1})
Range	0 to 2.4 cm hr^{-1}	0 to 8.6 cm hr^{-1}
1st Quartile	0.0 cm hr^{-1}	0.06 cm hr^{-1}
Median	0.07 cm hr^{-1}	0.13 cm hr^{-1}
3rd Quartile	0.23 cm hr^{-1}	0.69 cm hr^{-1}
Mean	0.17 ± 0.33 cm hr^{-1}	0.74 ± 1.4 cm hr^{-1}

APPENDIX Y
SUMMARY OF HYDROLOGIC CHARACTERISTICS OF RAIN EVENTS AND CORRESPONDING GREEN ROOF RUNOFF FOR WATER QUALITY SAMPLING EVENTS FOR CRP GREEN ROOF IN GAINESVILLE, FLORIDA, 2008

Table Y-1. Characteristics of rain events sampled—storm start and finish times, duration, total rain (cm), mean intensity, maximum intensity and lag to peak (min).

Date	Rain Start	Rain End	Duration (hr)	Total Rain (cm)	Rain Mean Intensity (cm hr^{-1})	Rain Max Int (cm hr^{-1})	Lag to Peak (min)
6/23/2008	10:40 AM	12:45 PM	2.0	0.58	0.39	0.61	1 hr
6/25/2008	2:05 PM	2:25 PM	0.3	0.30	0.91	1.22	15 min
6/26/2008	5:05 PM	7:35 PM	2.5	0.38	0.16	0.30	20 min
6/30/2008	2:50 PM	3:30 PM	0.7	0.36	0.53	1.83	15 min
7/8/2008	4:40 PM	7:50 PM	3.2	4.67	1.48	6.71	30 min
8/21-8/22/08	12:40 PM	7:00p8/22	30.0	10.20	0.34	2.13	4hr 25m

Table Y-2. Characteristics of green roof runoff for rain events sampled for water quality in 2008—Start/Finish times of green roof runoff, runoff duration, runoff volume (cm depth across roof surface), mean runoff rate (cm hr^{-1}), maximum runoff rate (cm hr^{-1}) and lag to peak (min).

Date	Runoff Start Time	Runoff End Time	Runoff Duration	Runoff Volume (cm)	Mean R.O. rate (cm hr^{-1})	Max RO (cm hr^{-1})	Lag to Peak (min)
6/23/2008	11:30 AM	5:40 PM	5.2	0.194	0.038	0.06	1 hr 20m
6/25/2008	2:40 PM	5:10 PM	2.5	0.042	0.0168	0.06	1 hr 30m
6/26/2008	5:40 PM	11:20 PM	6.1	0.089	0.0146	0.12	2 hr 40m
6/30/2008	3:15 PM	11:05 PM	7.25	0.1	0.0138	0.12	n/a
7/8/2008	4:55 PM	11:30 PM	6.6	4.33	0.6561	6.3	40 min
8/21-8/22/08	1:00 PM	1:40 P 8/23	48	7.43	0.1548	1.908	4 hr 40m

Table Y-3. Summary of reduction in maximum runoff rate, increase in lag to peak, delay in start of runoff, extension of runoff past the end of storm and % storm water retention by the green roof for storms used for water quality sampling in 2008.

Date	Reduction in Max. R.O. Rate (%)	Increase in Lag to Peak (min)	Delay to Start of Runoff (min)	Increase in duration of Return Flow (hr)	Retention (%)
6/23/2008	90%	20 min	50 min	4 hr 55min	67%
6/25/2008	80%	1hr 15 min	1 hr 30 min	2 hr 45min	86%
6/26/2008	69%	1 hr 20 min	35 min	5 hr 45min	77%
6/30/2008	93%	No peak	25 min	7 hr 35 min	72%
7/8/2008	6%	10 min	15 min	3 hr 40 min	9%
8/21-8/22/08	10%	15 min	20 min	18 hr	27%

APPENDIX Z
INDIVIDUAL STORM HYDROGRAPHS FOR WATER QUALITY SAMPLING EVENTS, CRP GREEN ROOF, FL, 2008

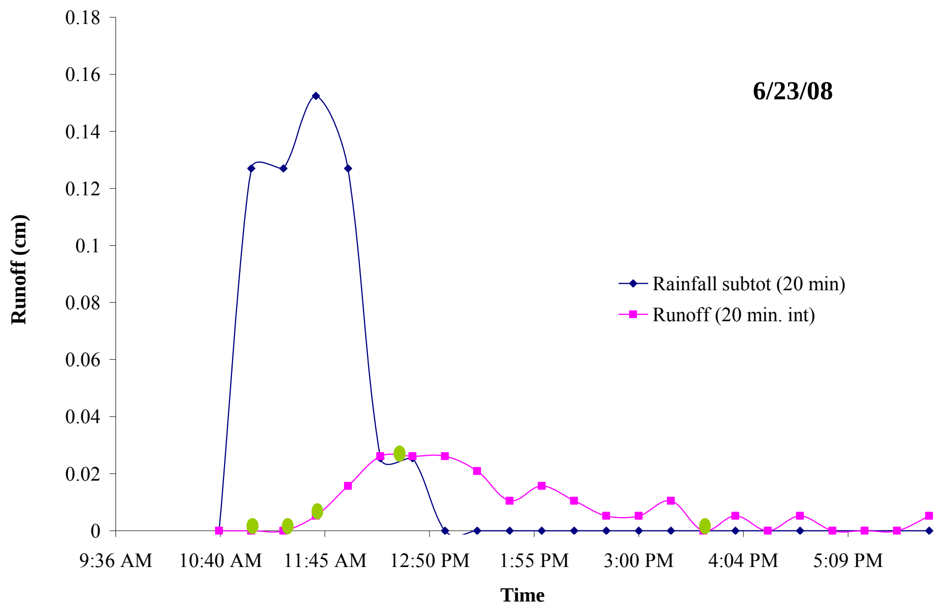


Figure Z-1. Storm hydrograph for rain event on 6/23/08. Green dots indicate when grab samples were taken from the green roof runoff.

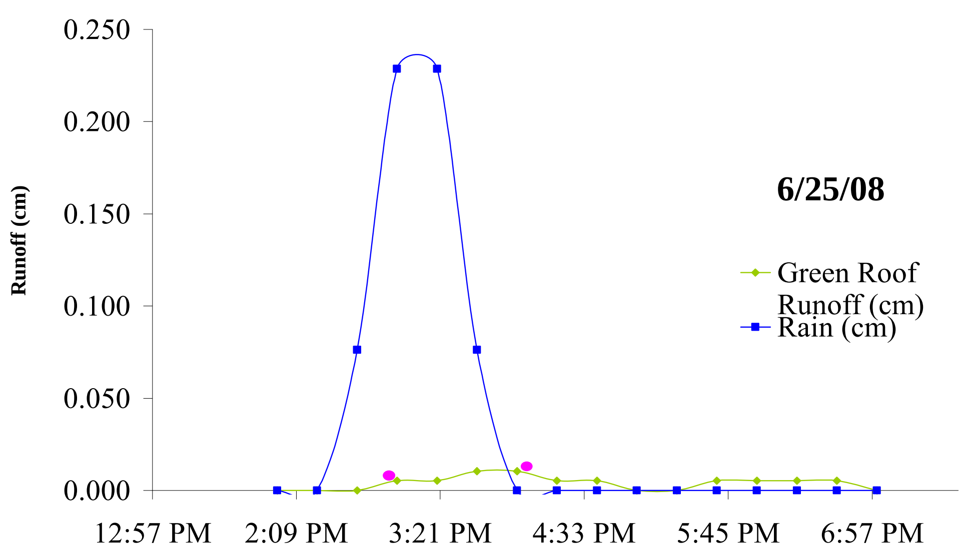


Figure Z-2. Storm hydrograph for rain event sampled on 6/25/08. Pink dots indicate when grab samples were taken from the green roof runoff.

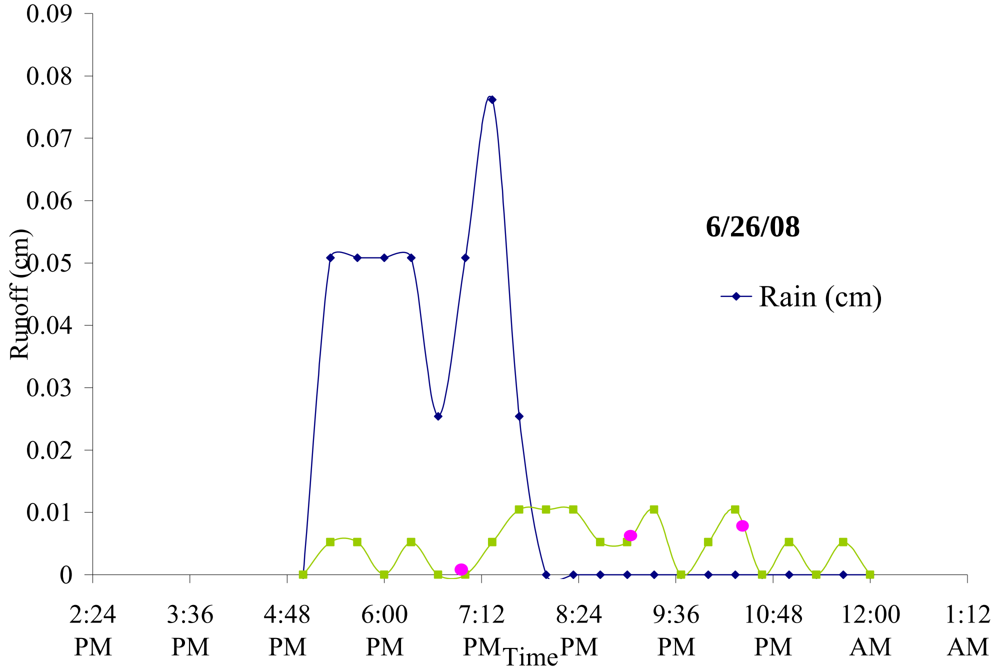


Figure Z-3. Storm hydrograph for rain event sampled on 6/26/08. Pink dots indicate when grab samples were taken from the green roof runoff.

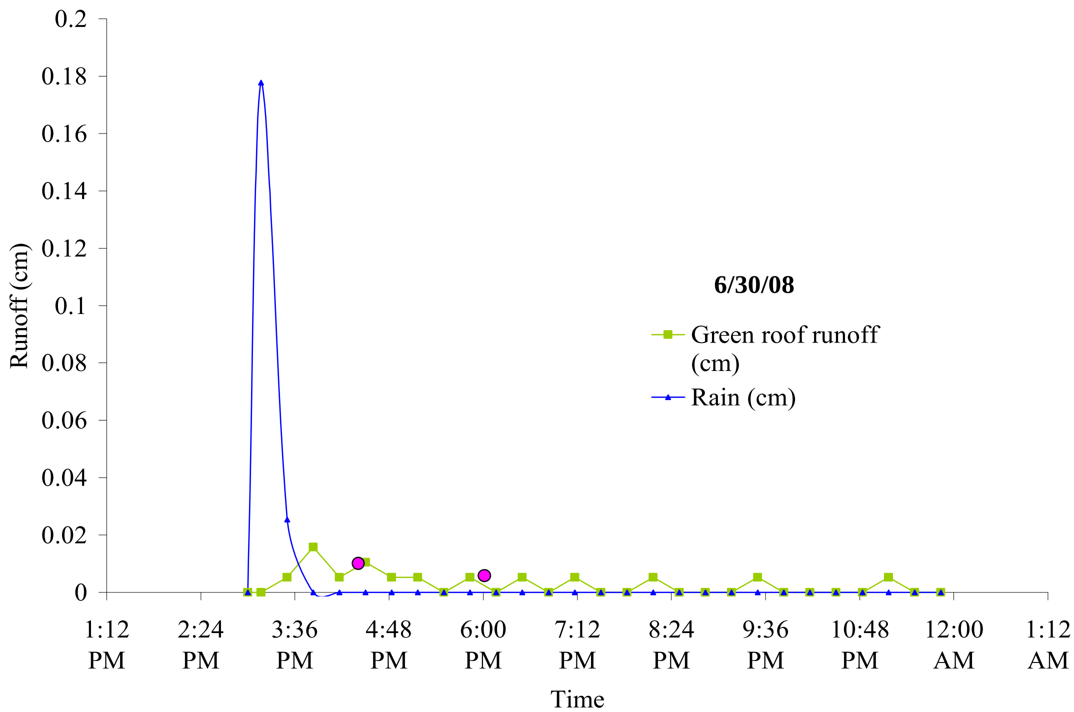


Figure Z-4. Storm hydrograph for rain event sampled on 6/30/08. Pink dots indicate when grab samples were taken from the green roof runoff.

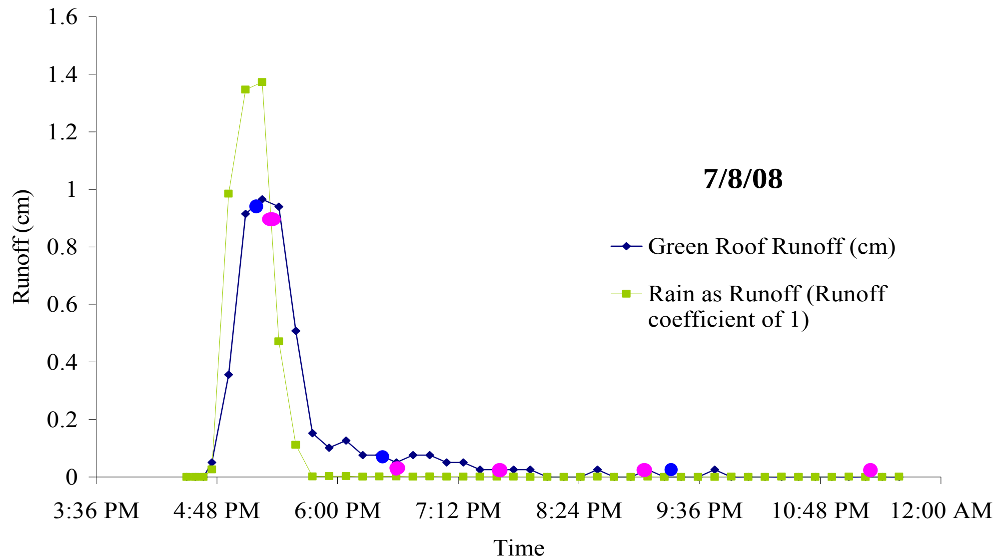


Figure Z-5. Storm hydrograph for rain event sampled on 7/8/08. Pink dots indicate when grab samples were taken from the green roof runoff; blue dots indicate timing of grab samples from conventional roof runoff.

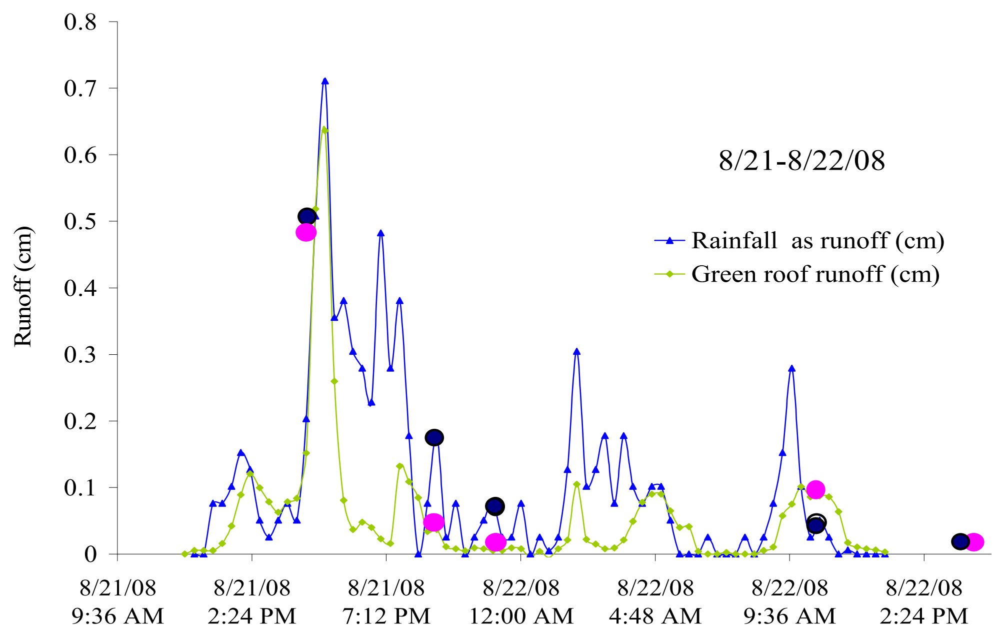


Figure Z-6. Storm hydrograph of runoff from the green roof and a conventional roof of the same size based on rainfall and a runoff coefficient of 1. Pink dots indicate when grab samples were taken from the green roof runoff, blue dots refer to the moments of conventional roof runoff sampling.

APPENDIX AA
WATER QUALITY DATA BY TIME INTERVAL FOR RAIN EVENTS SAMPLED IN FLORIDA AND VIRGINIA

Table AA-1. Concentrations of nitrate, ammonium, TSS and SRP from six rain events in 2008.

Sampling Date	Time	NOx-N (mg/L)	NH3-N (mg/l)	TSS (mg/L)	SRP (mg/L)
6/23/2008	11:10 AM				
	11:20 AM	0.04	0.04	2.3	0.85
	11:43 AM	0.03	0.05	2.6	0.59
	12:46 PM	0.03	0.05	2.2	0.84
	4:00 PM	0.03	0.06	2.5	0.88
6/25/2008	2:20 PM	0.33	0.10	1.50	0.40
	4:00 PM	0.04	0.07	1.00	0.72
6/26/2008	6:56 PM	0.06	0.09	5.50	0.51
	9:12 PM	0.03	0.07	1.00	0.59
	10:30 PM	0.18	0.23	4.50	0.57
6/30/2008	4:20 PM	0.03	0.19	10.50	0.47
	6:00 PM	0.04	0.26	5.00	0.65
7/8/2008 cr	5:15 PM	0.03	0.06	2.50	0.00
	6:25 PM	0.30	0.14	0.00	0.04
	9:20 PM	0.29	0.13	0.00	0.04
7/8/2008 gr	5:21 PM	0.08	1.36	7.50	1.26
	6:35 PM	0.04	0.96	5.00	1.43
	7:35 PM	0.05	1.20	11.50	1.29
	9:15 PM	0.05	0.92	14.00	1.44
	11:30 PM	0.06	0.78	9.50	1.43
8/21/2008 cr	4:25 PM	0.03	0.12	0.11	0.03
	8:56 PM	0.05	0.09	0.00	0.02
	10:45 PM	0.10	0.26	0.05	0.03
	11:56 AM	0.19	0.14	0.07	0.03
	4:00 PM	0.25	0.19		0.03
8/21/2008 gr	4:35 PM	0.02	0.15	0.10	0.46
	8:40 PM	0.01	0.09	0.14	0.25
	10:48 PM	0.01	0.09	0.11	0.81
	12:00 PM	0.01	0.06	0.07	0.46
	4:10 PM	0.01	0.06		0.46

Table AA-2. Concentrations of nutrients, pH, TSS and TDS from rain events in 2007-08 in VA.

Date	Time	N-NO3 (mg/L)	N-NO2	TP	OP	pH	TSS (mg/L)	TDS (mg/L)
4/11/2007 gr	11:00 AM	<0.10	<0.10		0.12			
4/11/2007 gr	3:00 PM	<0.10	<0.10		0.15			
4/11/2007 cr	11:00 AM	<0.10	<0.10		0.00			
4/11/2007 cr	3:00 PM	<0.10	<0.10		0.01			
6/3/2007 gr	9:45 AM	<0.10	<0.1	1.29	1.20		<1	181
6/3/2007 gr	1:00 PM	<0.10	<0.10	1.33	1.21		<1	183
6/3/2007 gr	3:10 PM	<0.10	<0.10	1.31	1.20		<1	184
6/3/2007 gr	5:20 PM	<0.10	<0.10	1.30	1.23		<1	184
6/3/2007 gr	9:14 PM	<0.10	<0.10	1.28	1.10		1	191
6/3/2007 cr	9:45 AM	<0.10	<0.10	0.2	0.15		<1	25
6/3/2007 cr	1:00 PM	<0.10	<0.10	0.2	0.16		<1	23
6/3/2007 cr	3:10 PM	<0.10	<0.10	0.2	0.16		<1	26
6/3/2007 cr	5:20 PM	<0.10	<0.10	0.19	0.14		<1	24
6/3/2007 cr	9:14 PM	<0.10	<0.10	0.19	0.15		<1	23
4/20/2008 gr	9:30 AM	<0.10		0.87	0.81	6.3	8	52
4/20/2008 gr	11:45 AM	<0.10		0.78	0.72	6.8	7	55
4/20/2008 gr	13:35 PM	<0.10		0.61	0.55	7.1	2	57
4/20/2008 gr	16:15 PM	<0.10		0.47	0.42	7.3	<1	59
4/20/2008 cr	9:30 AM	0.34		<0.10	<0.10	4.9	<1	8
4/20/2008 cr	11:45 AM	0.16		<0.10	<0.10	4.6	9	9
4/20/2008 cr	13:35 PM	<0.10		<0.10	<0.10	4.8	6	14
4/20/2008 cr	16:15 PM	0.33		<0.10	<0.10	4.6	15	<1
8/29/2008	7:27	<0.11		1.26	1.01	7.7	Insuff	84
8/29/2008	9:40	<0.10		1.49	1.24	7.8	Insuff	174
8/29/2008	10:30	<0.10		1.39	1.24	7.7	Insuff	167
8/29/2008	11:44	<0.10		1.51	1.27	7.8	1	174
8/29/2008	14:29	<0.10		1.51	1.21	7.9	Insuff	167
8/29/2008	7:37	0.13		<0.10	<0.10	3.4	Insuff	14
8/29/2008	9:28	0.13		<0.10	<0.10	5.1	Insuff	9
8/29/2008	10:36	0.21		<0.10	<0.10	4.7	2	14
8/29/2008	11:38	0.24		<0.10	<0.10	4.6	5	15
8/29/2008	14:29	0.31		<0.10	<0.10	4.8	Insuff	11
9/6/2008	9:34	<0.10		1.3	1.11	7.2	4	28
9/6/2008	11:34	<0.10		0.57	0.5	7	3	31
9/6/2008	15:29	<0.10		0.52	0.46	7.1	2	22
9/6/2008	9:30	<0.10		<0.10	<0.10	5.3	<1	3
9/6/2008	11:40	<0.10		<0.10	<0.10	5.3	<1	5
9/6/2008	15:24	<0.10		<0.10	<0.10	5.3	<1	5

Table AA-3. Concentrations of metals sampled in 5 storms in Virginia from YSC green roof and conventional roof runoff in 2007 and 2008.

Date	Roof Type	Cu (mg/L)	Fe (mg/L)	Pb (mg/L)	Cd (mg/L)	Zn (mg/L)	Al (mg/L)
4/11/2007 gr	11:00 AM		0.086		0	0.041	0
4/11/2007 gr	3:00 PM		0.095		0	0.045	0
4/11/2007 cr	11:00 AM		0.005		0	0.040	0
4/11/2007 cr	3:00 PM		0.023		0	0.044	0
6/3/2007 gr	9:45 AM	<0.10	0.12		0		
6/3/2007 gr	1:00 PM	<0.10	0.11		0		
6/3/2007 gr	3:10 PM	<0.10	0.11		0		
6/3/2007 gr	5:20 PM	<0.10	0.10		0		
6/3/2007 gr	9:14 PM	<0.10	0.11		0		
6/3/2007 cr	9:45 AM	<0.10	0.20		0		
6/3/2007 cr	1:00 PM	<0.10	0.19		0		
6/3/2007 cr	3:10 PM	<0.10	0.21		0		
6/3/2007 cr	5:20 PM	<0.10	0.23		0		
6/3/2007 cr	9:14 PM	<0.10	0.20		0		
4/20/2008	9:30 AM	0.44	<0.10	0.003			
4/20/2008	11:45 AM	<0.10	<0.10	<0.002			
4/20/2008	13:35 PM	<0.10	<0.10	<0.002			
4/20/2008	16:15 PM	<0.10	<0.10	<0.002			
4/20/2008	9:30 AM	<0.10	<0.10	0.012			
4/20/2008	11:45 AM	<0.10	<0.10	0.011			
4/20/2008	13:35 PM	<0.10	<0.10	0.037			
4/20/2008	16:15 PM	<0.10	<0.10	0.042			
8/29/2008	7:27	0.64	0.36	0.006	insuff		
8/29/2008	9:40	0.18	0.34	<0.002	0.001		
8/29/2008	10:30	0.12	0.32	<0.002	insuff		
8/29/2008	11:44	0.15	0.32	0.005	0.001		
8/29/2008	14:29	0.11	0.29	0.002	Insuff		
8/29/2008	7:37	0.61	0.14	insuff.	Insuff		
8/29/2008	9:28	<0.10	0.14	insuff.	Insuff		
8/29/2008	10:36	<0.10	0.29	0.041	0		
8/29/2008	11:38	<0.10	0.26	0.088	0.001		
8/29/2008	14:29	<0.10	0.22	0.088	0		
9/6/2008	9:34	<0.10	0.36	<0.002	0		
9/6/2008	11:34	<0.10	insuff	0.002	Insuff		
9/6/2008	15:29	<0.10	<0.10	<0.002	0		
9/6/2008	9:30	<0.10	<0.10	0.014	0		
9/6/2008	11:40	<0.10	<0.10	0.003	Insuff		
9/6/2008	15:24	<0.10	<0.10	0.005	0		

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BIOGRAPHICAL SKETCH

Sylvia Lang was born in Madison, Wisconsin in June. She moved with her family to Michigan when she was 2 and then to Virginia when she was 5, where she lived until she was 23. She entered Jefferson High School for Science and Technology in Northern Virginia the year after it opened, then went to the College of William and Mary and studied environmental geology and Spanish literature. Sylvia worked in an outdoor school in rural Virginia directly after college and then moved to Costa Rica for several years to perfect her Spanish and work in environmental sciences. She returned to the US to pursue a Master's degree at Colorado State University in watershed sciences. Her research project for her master's was The Effect of Logging on Erosion in a Wet Tropical Forest, which took her to a remote area of Costa Rica—the Osa Peninsula. Sylvia enjoyed the tropics very much and worked as a consultant for a year in El Salvador for the Center of Tropical Agriculture (CATIE) on a Strategic Watershed Management Plan for the Trinational Watershed Rio Lempa after her master's. She spent some time teaching students about watersheds in Northern Virginia and outdoors in Costa Rica again on the Osa Peninsula with American high school students. After spending much time quantifying and identifying problems in Watershed Management, she realized increasing urbanization is one factor that is impacting watersheds everywhere in the world, and when she happened upon green roofs as a BMP to help increasing water volumes leaving impervious areas, she decided to make it her dissertation topic to investigate the usefulness of this BMP in the sub-tropics.