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Green roof water quality impacts and physicochemical stability

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GREEN ROOF WATER QUALITY IMPACTS AND PHYSICOCHEMICAL STABILITY

by

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ABSTRACT

Green roofs can provide environmental benefits and conserve energy; this research evaluated green roof stormwater management, nutrient loading, and erosion prevention for two green roof media.

During a pilot study, the runoff quantity and composition from green roof material was evaluated continuously under field conditions for two different media, both tested under planted and unplanted conditions. Water quantity results show over a 40% reduction in runoff from just the growing media and over 60% reduction in runoff with established plants in green roof media over the eight month study.

Previous studies have reported a “first flush” of excess nutrients but without evaluating the duration and intensity of this phenomenon throughout the first year of the roof’s life. Total phosphorus at 30 mg/L and nitrogen concentrations above 60 mg/L were observed in green roof runoff initially, with concentrations decreasing over time to 5 and 10 mg/L, respectively. In addition, elevated total organic carbon concentrations were observed, with concentrations of 500 mg/L initially, decreasing to below ten percent of initial concentrations. Media type and age were the largest influences on carbon and nutrient concentrations. Understanding runoff nutrient kinetics can better aid in developing procedures to minimize nutrient runoff and predict nutrient loading more accurately.

In testing physical stability, both wind tunnel testing and sampling of total suspended solids in runoff were performed. The green roof drainage and filter fabric systems proved effective at preventing water-based erosion, with median total suspended solids concentrations for both below 20 mg/L. Because wind erosion can occur, surface stabilizers (i.e. adhesives) are available to secure green roof media. Green roof adhesive and plant cover were evaluated through wind tunnel testing; both reduced wind scour down to one-tenth of observed scour without any cover, providing protection against wind erosion.

ACKNOWLEDGMENTS

This research would not have been possible without the help of several individuals. Dr. Burken, has been a fountain of new ideas and encouragement since I first worked with him as an undergraduate, covered in mussel and clam guts. Now, four years later, I am extremely grateful for Dr. Burken's leadership and guidance during this research, as well as the lack of shellfish involved with green roofs. Dr. Showalter set this project in motion and has been a great help throughout. In addition, a big thank you goes to Dr. Mendoza for being available to answer any questions and review this work.

Supplies, funding, and support for this research came from a varied group. All green roof supplies were donated from industry, with Helene Hardy-Pierce of GAF, providing the built-in-place GAF Gardenscapes roof along with additional gardenscapes supplies for pilot-scale testing. Likewise, Kelly Luckett donated Green Roof Blocks™ as well as Arkalyte growing media. Vic Jost of Jost Greenhouses was a great help in selecting plant species for both the pilot-scale research and built-in-place green roof. Chemical testing of the green roof media was conducted by the Missouri Plant and Soil Extension.

On campus support was essential to this project. The full-scale built-in-place green roof would not have been possible with the help of Missouri S&T's physical facilities and landscaping staff: Chuck Bouse, Ted Ruth, and Jim Duncan. The artistic help of Luce Meyers along with the over fifty volunteers who came out to plant in the April cold and rain, provided us with this new S&T landmark. Dr. Finaish and Jim Schneider assisted our wind-tunnel testing by providing their lab's wind tunnel along with their expertise.

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1. INTRODUCTION

1.1 URBAN STORMWATER MANAGEMENT

Urban stormwater management is a unique challenge; as impervious surfaces such as streets, buildings, and parking lots increase, excess stormwater running off of these surfaces reach sewer systems faster and in larger quantities than before. In cities with combined sewer systems, increased runoff can cause combined sewer overflows (CSO’s) and impact neighboring watersheds and public health. To address CSO’s by increasing stormwater sewer conveyance and/or storage, which is referred to as grey infrastructure, is extremely expensive and disruptive to a city. In 2007, the EPA estimated the costs of controlling CSOs throughout the country at approximately $56 billion (MacMullan 2007). Green infrastructure alternatives use plants and natural systems to treat and reduce stormwater in conjunction or instead of increased grey infrastructure. Because natural systems can address stormwater on a local level and often offer more cost-effective solutions, these projects are becoming increasingly popular. In addition, green infrastructure can offer ecosystem services, community recreational areas, and add aesthetically to a cityscape. However, implementing effective green infrastructure can require collaborative work among the city, engineers, ecologists, and operators of the infrastructure.

1.2 GREEN ROOFS

Green roofs have been used as a part of the green infrastructure solution to stormwater. Green roofs, or vegetated rooftops, reduce stormwater by allowing for evapo-transpiration through plants as well as storing some of the rainwater in the growing media. Engineered green roofs have been used extensively in Germany since the early 1980’s and have an increased implementation in the US in the last 15 years (FLL 1995). Green roofs are divided into two categories: extensive and intensive. Extensive roofs are those that are constructed with a substrate depth of less than 15cm and due to their shallow depths are often limited to grasses and drought tolerant plants such as *Sedums* (Rowe 2010). The advantages of an extensive roofing system is that they are lighter due to less growing media and are often less costly in regards to capital cost as well as operation and maintenance costs than intensive green roofs. Intensive roofs are those that require depths of substrate over 15cm and can support more variety of plant life including shrubs and small trees. Intensive roofs are designed as public places and often require maintenance just as landscaping at ground level.

Extensive green roofs are constructed of several layers. Metal roof decking with an insulation board above it make the base; this could be an existing roof that is being retrofitted with a green roof. Next, above the waterproofing, a drainage layer overlaid by a geotextile (root barrier) supports the engineered growth media. Modular green roofs involve a metal roof decking and insulation board base with a roofing membrane just like any other standard roof. Then, the green roof modules are placed on the roof. Both types are shown below in Figure 1.1.

Figure 1.1. Built in place green roof on Missouri S&T's Emerson Electrical Engineering Hall (shown left) and modular roofing trays, Green Roof Blocks^{TM}.

Though the water retention capabilities of a green roof are well studied, the water quality with regard to nutrient loads is far from fully understood. Lack of longitudinal studies with adequate data makes understanding the concentrations in runoff over time difficult. In addition, characterizing the erosion of green roof media by both wind and water needs to be more fully developed in order to better understand how a green roof ages and the efficacy of products designed to stabilize green roof media.

2. GOALS AND OBJECTIVES

The primary goal of this study was to evaluate a green roof's stormwater retention properties as well as water quality impacts. In particular, the nutrient loading in green roof runoff as well as erosion of green roof media need to be assessed over time to better understand such impacts of green roofs, especially immediately after implementation. To reach this goal, specific objectives were established as follows:

- Objective: Measure runoff from various green roof media under natural meteorological conditions.
    - Hypothesis: Growing media and planted conditions will reduce total runoff throughout the year, but show seasonal variation due to plants.

- Objective: Evaluate a green roof's effect on nutrient concentration, organic carbon content, and suspended solids in runoff over time after installation.
    - Hypothesis: Growing media and planted conditions will increase phosphorus, nitrogen, organic carbon and suspended solids concentration in roof runoff while also increasing the total turbidity. A "first flush" of high values for each will be seen initially and then the concentrations will decrease rapidly similar to rainwater composition within the first month.

- Objective: Determine impact of wind erosion on green roof systems related to media type, plants, and adhesives.
    - Hypothesis: Planted and adhesive treated media will show significant reduction in wind erosion.

Each objective was assessed in the research covered herein. Data and conclusions generally supported hypothesis, however, impaired water quality was observed over the eight-month study. Concentrations did decrease over time, just at a much slower rate than originally hypothesized. Through this research, knowledge of green roof stormwater impacts and stability of media was gained.

3. LITERATURE REVIEW

3.1 GREEN ROOF TECHNOLOGIES

Built-in place extensive green roofs consist of a root barrier, drainage material, filter fabric, growing media, and plants all placed upon a conventional roof structure as shown in Figure 3.1. The drainage material and filter fabric may be combined into one, allowing for simpler installation. In addition, modular extensive roofs combine all the components into easy to handle trays or other individual units that can be placed on a rooftop.

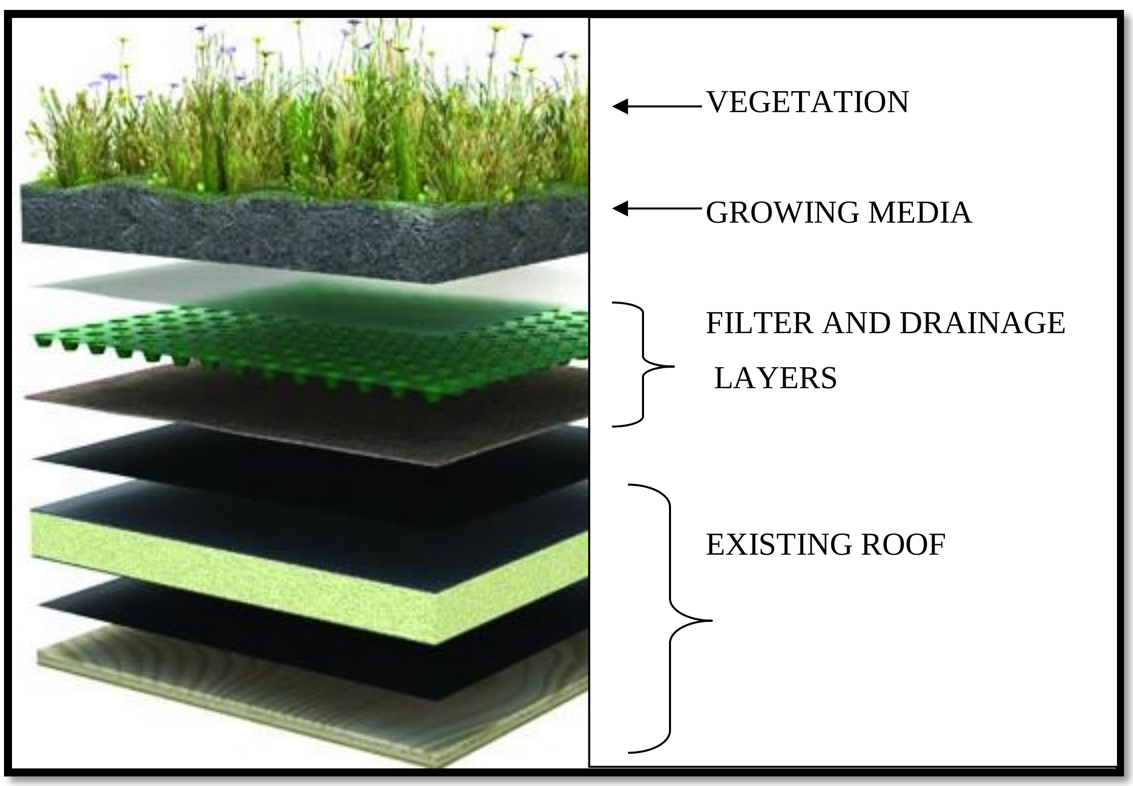

Figure 3.1. Layers of a green roof (Adapted from dcgreenworks.org)

The growing media stores some rainwater from each rain event and re-releases water vapor into the air via evaporation. The plants aid in this through transpiring the water from the media as well. In this way, the plants on a green roof act as soil stabilizers and phyto-hydraulic control. Stormwater management is important for cities with impervious areas and large storm events, and particularly important for combined sewers, as combined sewers require all stormwater be treated along with the sanitary waste.

Green roofs have been shown to reduce the runoff after a rainfall event by up to 50 to 100% depending on the size of the event and saturation of the growth media before the storm (Carter and Rasmussen 2006). Because green roofs can delay the runoff of storm water as well as decrease the volume, less stress is placed on the city’s storm water control and management systems. Similar to natural soil behavior, the water retention of green roofs on a percent basis are higher for smaller storms than large ones. In 2006, Carter and Rasmussen’s *Sedum* extensive roofs retained 88% of water during small storms (less than 25.4 mm) and only 48% of rainfall during large storms (greater than 76.2mm).

3.1.1. Green Roof Media. All green roofs start with growing media to support vegetation and protect the roof. The most common growing media used are lighter than topsoil and chosen based upon their ability to drain, and support plant growth. A common growth medium, Sopraflor (Soprema Inc. Dummondvile, QC, and Canada) contains crushed brick, blonde peat, perlite, sand and vegetable compost (MacIvor and Lundholm 2011). Pumice, haydite (shale or slate heated), bottom ash, volcanic and fine arkalyte expanded clay are also common components of green roof growing media (Alsup and others 2010), (Morgan and others 2011). Monterusso et al. used a soil mix consisting of 60% heat expanded slate, 25% grade sand, 5% aged compost, and 10% peat (2005). Green roof media varies extensively, as there are no US standards or guidelines for green roof media, however all contain a light-weight inorganic base along with added organic matter and fertilizer.

Green roof media inorganic component is most commonly created by heating shale, slate, or clay to high temperatures causing them to expand, resulting in a lower bulk density for the mix. Such heating methods are the most energy intensive part of a green roof and thus requires the most energy and accounts for most of a green roof's carbon footprint (Mickovski and others 2013).

Green roof media varies over time with respect to chemical and physical properties. Data in Table 3.1 show the variation over a 5 year period by Getter (2007). As green roof media ages, the pore spaces and water holding capacity increase allowing for more effective water retention and cooling, showing the importance of a green roof's age. This study shows plants alter the media in which they grow not only by adding organics from decaying plant matter, but also in improving the very function of the media by increasing water holding capacity.

Table 3.1: Media variation over time showing increase in organic matter and water holding capacity. (Adapted from Getter (2007))

Substrate Age	**Sample Organic matter (%)**	**Pore space (%)**	**Free airspace (%)**	**Water holding capacity (%)**
Initial substrate	2.33	41.41	21.43	17.07
5-year-old substrate	4.25	81.84	14.4	67.44
Analysis per A&L Great Lakes Laboratories, Inc., Ft. Wayne, Indiana.				

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3.1.2. Green Roof Plant Selection. The other essential component of green roofs is the plants. The extensive green roof plants must be capable of enduring fluctuating extreme temperatures as well as drought-like conditions at times in the thin, 3-15 cm, substrate placed on the roof. Because of these conditions, succulents have been the most common plant choice, with *Sedum* species being most widely used.

However, a study by Blanusa et al. (2013) evaluated broad-leaf perennials as an alternative. *Sedums* close their stomata to maintain adequate water within the plant during drought conditions. Through crassulacean acid metabolism(CAM), the plants open their stomata to receive CO_2 during the night to prevent excessive losses from leaves and store the CO_2 as an acid to use for photosynthesis the next day when they close their stomata again to protect against the hotter, dryer day climate. Therefore, the *Sedum* leaves have higher temperatures during the day and reduced ET in dry conditions. Blanusa et al. (2013) questioned whether a plant capable of preserving water would be as effective at using large quantities of water during non-drought conditions. Blanusa (2013) evaluated other perennials as well as a *Sedum* mix to determine the cooling advantages of broader-leafed species. The research indicated that during extreme highs, a broad-leaf Stachys was capable of cooling the air above it significantly more than the *Sedums* in extreme heat conditions, however is not as resilient as *Sedum* species without additional growing media (at least 20cm).

Monterusso *et al.* (Monterusso and others 2005) studied 20 different taxa of plants in Michigan, to be used for green roof, evaluating the growth index over 800 days and found that though other native species grew, the nine *Sedum* species were capable of rapid initial growth, survival in both the cold winters and hot summers, and were drought tolerant. Two native species also showed promise, but one could not reach coverage as quickly and the other had difficulty withstanding extreme winter conditions. Overall, previous research supports *Sedum* species suited to the site's conditions as the best plants for extensive green roofs due to growth and survival.

3.2 RUNOFF REDUCTION

Several studies have reported varying water retention capacities of green roofs; however impacts appear to be dependent upon roof slope, growing media, antecedent rainfall, and weather conditions (Carter and Rasmussen 2006), (Getter and others 2007), (Carpenter and Kaluvakolanu 2011), (Hilten and others 2008). Because of the varying factors affecting runoff amounts, models to account for each of these variables have been proposed. However, a complete model to easily predict any green roof's function at various locations has yet to come to fruition. Most models are site-specific and are not translatable to other locations.

3.2.1. Soil-based Runoff Prediction. One of the ways to estimate runoff has been through calculating a curve number for the soil and thus determining percent runoff from this number. This method assumes a constant water storage capacity in the soil and does not account for past rainfall or ET losses in the soil, which is an integral part of the roof's function. Carter and Rasmussen (2006) estimated a green roof curve number to be 86; this study also indicated media depth can predict runoff reduction through an exponential relationship, however with an R^2 value of 0.648, not all of the variation in runoff can be explained by media depth alone. In addition, this model would need to be recalibrated with each new media modeled, as growing media properties can vary significantly and this model is dependent on the water storage available in the media.

Models similar to this one include Getter's work (2007). By calculating curve numbers for the same green roof media at a constant depth but at different roof slopes, a strong relationship between slope and curve number was shown (See figure below). This range of values (84-90) agrees with the 86 that Carter and Rasmussen established for their less than 2% sloped roof, as shown in Figure 3.2. This data is difficult to apply to other roofs, as no other variables were considered, though it very clearly shows that slope of green roofs impact their water storage ability.

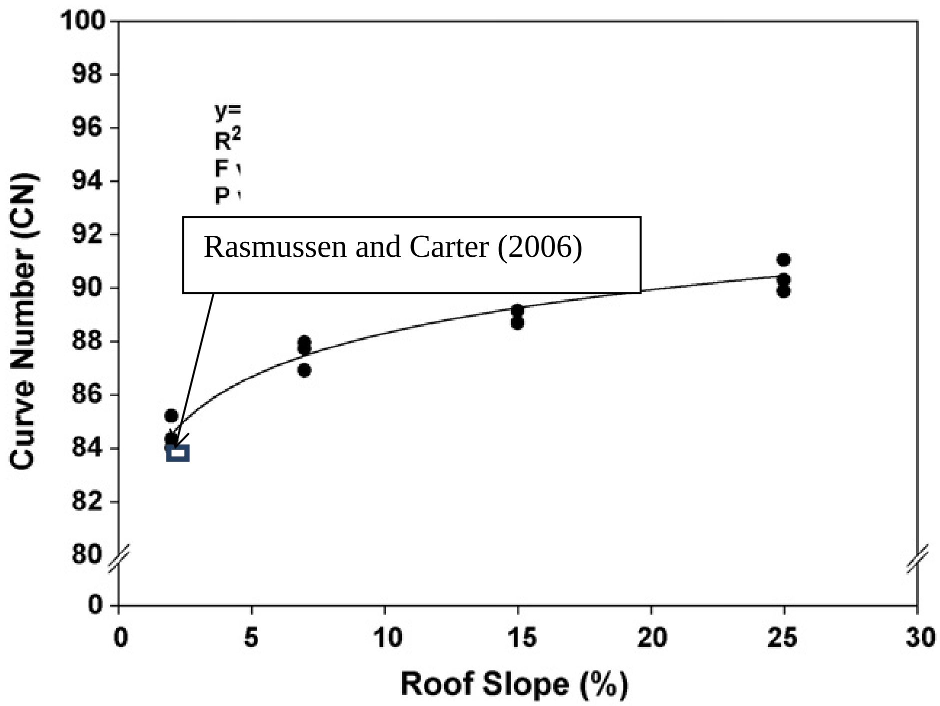

Figure 3.2. CN related to slope for green roofs of identical media, plants, and age. The work agrees with the curve number relationship. (Adapted from Getter 2007)

3.2.2 .Evapo-Transpiration Studies. Rezaei et al. (2005) revealed Sedums ET rate varies with the soil moisture content and can be modeled based upon days since irrigation. In this study, lysimeters consisting of a load cell connected to a data logger were used to determine the amount of water in each green roof module at all times. This study's modeling component was empirical curve fitting data, which showed transpiration via plants decreased water content more than evaporation alone. The water uptake was modeled based upon days sine watering and the slope, media, etc. were kept constant. Sedum spurium planted tray water loss was modeled as 3.52* 0.849day, whereas daily water loss equal to 1.94*0.852day was the best fit for unplanted trays as shown below in Figure 3.2.

Comparisons between ET models and actual *Sedum* data were made by Starry in 2011, showing that calculated ET reference can be less accurate for *Sedum* species. Overall, this study shows the need for a more detailed crop coefficient and potentially separate ones for arid and moist soil conditions, as shown in Figure 3.3.. The similar shape of the Penman-Monteith model and those planted with *Sedum spurium* display the potential of using the Penman-Montheith equation if a crop coefficient was used.

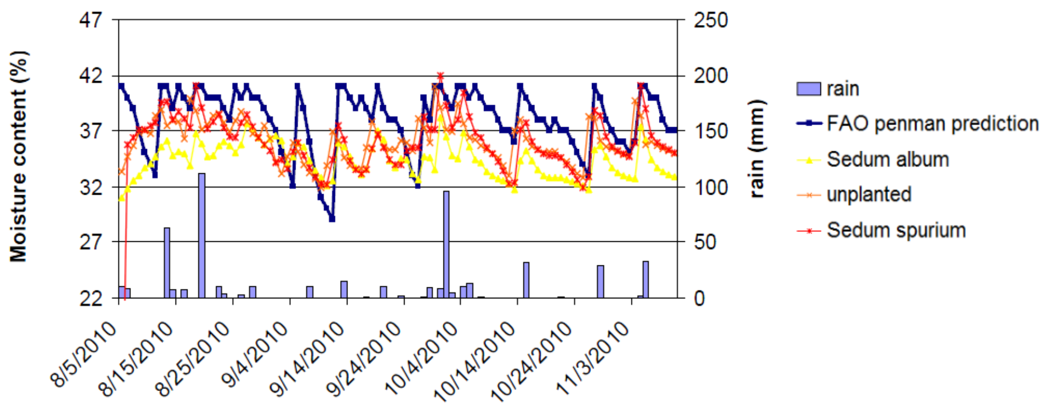

Figure 3.3: Comparison of Sedum ET and Penman-Monteith reference ET (Adapted from Starry et al. (2011))

3.2.3. Comprehensive Runoff Models. Metselaar (2012) using the SWAP (Soil Water Atmosphere and Plant) model, attempted to incorporate a wide range of green roof runoff variables into a single model. Using Penman-Monteith ET equation along with the Darcy-Buckingham equation for fluid flow through a porous media, a built-in-place green roof was modeled. This model seems to incorporate the needed factors to better model green roof water holding, evaporation, transpiration, and runoff. However, taking it one step further to calibrate and validate the model with data from several green roofs would demonstrate the model's predictive capabilities.

Water quality of green roof runoff varies from roof to roof which makes predicting the effects of a green roof difficult to assess. Media type and age, drainage materials, meteorology, and plants used can impact water quality aspect such as erosion-induced pollutants (suspended solids and increased turbidity) as well as nutrient loading.

3.3 GREEN ROOF WATER QUALITY

3.3.1. Suspended Solids and Turbidity. Suspended solids are defined as particles that cannot pass through a 2 micron filter (EPA Method 340). Total suspended solids can include clays, silts, fine organic debris, and other particulate matter in suspension. High levels of suspended solids can decrease the amount of light penetrating through water, causing a reduction of photosynthesis in aquatic plants. High suspended solids can also cause more rapid heating of a body of water. Suspended solids from discharges to water bodies also result in sediment build up, which can affect aquatic ecosystems, overall. Suspended solids are regulated under the clean water act for point discharges and are associated with poor water quality. The turbidity of water is a measurement of the amount of light that can pass through it without being scattered by particles and is one of the first measurements of water quality. Green roofs can increase suspended solids and turbidity after installation.

In work by Morgan et al. (2011), the highest turbidity levels from the green roofs investigated were seen during the first flush with a steep decline in mean turbidity afterward, with first flush turbidity values between approximately 550 to 120 NTU and turbidities of 150 to less than 50 NTU after the second simulated rainfall event. Similarly, the study found much higher TSS values (1050 to 250 ng/L) after the first watering event than the second (300 to 75 ng/L). The turbidity levels varied significantly between media used. Discharge from vegetated haydite media was still above the 50 mg/L TSS regulation after 15 watering events. After the 13^{th} watering event, the vegetated volcanic rock media was below 50 mg/L. In comparison, it only took vegetated bottom ash and arkalyte 9 and 5 watering events respectively to reach the 50 mg/L regulation limit. For traditional roofs, Morquecho et al. (2005) reported turbidity levels of runoff ranging from 2 to 22 NTU and TSS values at 29 mg/L were reported by Gromaire et al. (2008). When comparing the solids concentrations in runoff from the vegetated and conventional roofs, even the lower solids events from green roofs were elevated when compared to the conventional roof concentrations.

Because both TSS and turbidity decrease over time after planting, Morgan et al. (2011) concluded that the media causes the change in water quality more than the vegetation type. Additionally, changes in TSS and turbidity vary by media type in unplanted pots as well. Overall, the haydite and volcanic rocks produced higher TSS and turbidity values than the arkalyte and bottom ash. Because after the first flush, the differences between vegetated and non-vegetated plots' TSS and turbidity were not significant, Morgan et al. (2011) concluded that the plants were only able to reduce TSS and turbidity during the first flush and have no significant impact on the values afterwards. Long-term impacts have not been evaluated.

3.3.2. Nitrogen. Nitrogen concentrations from green roof runoff can be related to type of soil, age of the green roof, and the use of fertilizers on the roof. However, research on green roof nitrate retention is conflicting. Some studies have shown decreased total nitrogen in green roof runoff (Carpenter and Kaluvakolanu 2011), unchanged concentrations (Gregoire and Clausen 2011;Berndtsson et al. 2009; Kohler 2011), and yet, still others show increased nitrate and total nitrogen concentrations (Retzlaff 2008; Monterusso et al. 2005). Berndtsson et al. (2009) found that nitrate-nitrogen is generally retained by the vegetation and the total nitrogen concentration for green roof runoff and precipitation are roughly the same. Therefore, Berndtsson suggested the roots may be releasing organic nitrogen. Monterusso et al. (2005) showed that the thinnest soil system produced the highest release of nitrates and an increase in nitrate-nitrogen was found to be dependent upon the plant type, with native plants having the lower releases and *Sedum* seed systems having the highest. In addition, nitrogen concentrations decreased with age of the roof. Retzlaff (2008) studied nutrients in green roof runoff and found significantly higher nitrate concentrations in green roofs regardless of their growth media (arkalyte, glass, haydite, rooflite, pumice) with the recycled glass, lava, and Rooflite media having the highest concentrations; showing that the growth media may be related to the nitrogen concentrations in the runoff. Kohler et al. (2002) reported observations of reduced nitrate-nitrogen loads in green roof runoff dependent upon water volume reduction. From Morgan et al. (2013), built-in-place green roofs' runoff resulted in nitrate concentrations of 3.0 to 70.3 ppm over a 15-month period, which was higher than the control roof's consistent measurements of 4.0 ppm or less.

An important variable affecting nitrogen leaching is the age of the green roof media. For example, in Carpenter and Kaluvakolanu (2011), less nitrate leached from the green roof tested than a stone ballast roof. However, this three year old green roof was irrigated for the first two years, which appeared to effectively flush all of the excess nutrients from the green roof before the experiment began. Such long-term, longitudinal data is lacking from many studies.

3.3.3. Phosphorus. Rain water generally contains small concentrations of phosphorus; however, urban runoff can attain higher levels of phosphorus from fertilizers, bird droppings', etc. If a green roof is fertilized, that too can increase the phosphorus levels of the runoff. Some green roof studies find almost all phosphorus is released as phosphates and that there are example green roofs that do not show any release of phosphorus ((Berndtsson and others 2009; Berndtsson and others 2006). Kohler et al. in 2002 observed a reduction of phosphate phosphorus dependent upon time. After four years, the phosphate phosphorus load reduction went from 26% to 80%, which was concluded to be due to vegetation development and time since fertilization.

Carpenter (2011) showed a decrease in phosphate total mass and concentrations off of a new green roof when compared to asphalt and stone covered roof. Though the differences were not significant, the roof was definitely not a significant source of phosphate. Again, much like nitrogen concentrations above, this low phosphorus concentration is most likely due to the roof's age. Teemusk and Mander (2007) found that concentrations of total phosphorus were relatively low, with all below 0.15 mg/L; much like Carpenter, the roofs tested were all at least 3 years old. In addition, the roof Teemusk and Mander sampled once a year did show a decrease over time. The decrease in phosphorus over time has been shown, but no longitudinal study or models have been put forth to show this process mechanistically.

Gregoire and Clausen (2011) monitored a five month old modular green roof, which showed to be a nitrogen and phosphorus sink; the green roof media's chemical composition was not given other than it was a combination of expanded shale, composted biosolids, and perlite which makes determining the difference between this study and others difficult.

Vijayaraghavan et al. (2012) studied green roofs sections that were 2 months old at the start of sampling. Results showed phosphate concentrations over 40 mg/L; however the study only included four rain events. Nitrogen concentrations were not significantly greater than the control.

Toland et al. (2012) studied green roofs during their second growing season and observed median TP concentrations of 3-4 mg/L, a ten-fold increase when compared to the control roof. Elevated TP supports that age impacts green roof runoff concentrations of nutrients. TN concentrations were elevated when compared to the control roof with values of 1.5-2 mg/L as well. Often the same study will evaluate total nitrogen or nitrate as well a total phosphorus or phosphate. Several of these studies and their findings are shown below in Table 3.2. The variability in concentrations display the complexity of nutrient dissolution and concentrations in runoff.

Table 3.2. Green roof runoff nutrient concentrations for several studies

Media	Planted	Roof Age	TN (mg/L)	NO_3 (mg/L)	TP (mg/L)	PO_4 (mg/L)	Study
Pro-grow extensive mix: gravel, sand, silt, clay, pumice, compost, paper fiber	*Sedum Hispanicum*	0	N/A	17.9	10.3		Beck, Johnson, and Spolek (2011)
Pro-grow extensive mix, With 7% biochar	*Sedum Hispanicum*	0	N/A	22.5	8.3		Beck, Johnson, and Spolek (2011)
Pro-grow extensive mix	*none*	0	N/A	178	22.1		Beck, Johnson, and Spolek (2011)
Pro-grow extensive mix, With7% biochar	*none*	0	N/A	36.5	12.8		Beck, Johnson, and Spolek (2011)
75% expanded shale,15%composted biosolids, and10%perlite	*Sedum species*	0.42	0.490 (control 0.896)	0.369 (control 0.702)	0.043 (control 0.197)	0.025 (control 0.165)	Gregoire and Clausen (2011)
crushed lava, calcareous soil, clay, shredded peat--3cm deep glued to geotextile	*Sedum album and Sedum acre*	1	2	N/A	0.3	N/A	Berndtsson, Emilsson, and Bengtsson (2006)

Table 3.2. Green roof runoff nutrient concentrations for several studies (continued)

14 cm deep crushed volcanic rock, compost, blonde peat, cooked clay, and washed sand	*Wildflowers*	1	1.11	N/A	0.318	0.241	Seters, Rocha, Smith, and MacMillan (2009)
Heat expanded clay--Fines without compost (0.15 to 2.36 mm)	*Sedum species*	1.4	0.75	N/A	0.15	0.1	Toland, Haggard, and Boyer (2012)
Heat expanded clay--Fines with 15%compost	*Sedum species*	1.4	1.5	N/A	4	3	Toland, Haggard, and Boyer (2012)
Heat expanded clay--Coarse with 15% compost	*Sedum species*	1.4	2	N/A	3	2.5	Toland, Haggard, and Boyer (2012)
prefabricated vegetation layer with sedum plants (thickness 3 cm)	*Sedum species*	2	1	N/A	1.5	N/A	Berndtsson, Emilsson, and Bengtsson (2006)
Tartu green roof media	*Sedum species*	3	1.7	N/A	0.273	N/A	Teemusk and Mander (2011)
crushed lava, calcareous soil, clay, shredded peat--3cm deep glued to geotextile	*Sedum species*	7	0.75	N/A	0.2	N/A	Berndtsson, Emilsson, and Bengtsson (2006)
DAKU green roof media based on natural inorganic volcanic	*Sedum mexicanum*	1 year	N/A	15	40 mg/L	30	Vijayaraghavan et al. (2012)

3.3.4. Total Organic Carbon. Of the studies on organic carbon in green roof runoff, concentrations of total organic carbon (TOC) Beck, Johnson, and Spolek (2011) simulated rain events for a green roof media under varying conditions and found elevated organic carbon in the runoff. Amending the soil with biochar showed to decrease TOC concentrations in runoff, as did plants. Teemask and Munder (2011) also evaluated TOC concentration of their five month old roof, and found concentrations below 20 mg/L. Because organic carbon on its own is not a pollutant it is not often characterized. However, TOC can lead to increased biological oxygen demand in the water (BOD) which can lead to decreased oxygen in water bodies downstream when TOC loads are extremely high. BOD testing would be a more accurate way of assessing any potential impacts from excess carbon in green roof runoff.

3.4 EFFECTS OF WINDS

Winds are often higher at higher elevations and can scour growth media. Knowing wind velocities can help to determine what plants will be the best selection. Wind blankets, geotextile materials used to cover a green roof, can protect from high winds and maintain the integrity of the roof. Because wind blankets are designed to slowly decompose, it can also be advantageous by providing organic matter to the growth media (Luckett 2009). By anchoring a wind blanket in place and then cutting small holes for plants to grow, a green roof can be better supported while its vegetation increases. In a study by Retzlaff et al. in 2009, fully vegetated (with *Sedums*) modular green roofing trays withstood 193 km/h wind speed and a partially vegetated tray withstood 120 km/h before losing any growth media, further detail can be found in Table 3.3. The unvegetated modular system began losing soil at only 48km/h (30 mph) simulated winds. The experiment was shut down after substantial scouring at this wind speed. Further research is needed to evaluate green roof performance under high winds for various media and planted conditions.

Table 3.3. Summary of Wind Tunnel Results (Retzlaff et al. 2009)

Vegetated/Not Vegetated	**Highest Speed without Scour (mph)**	**Duration of Test at highest wind speed**	**Mass of material collected on Filter (grams)**
Fully Vegetated	140	5 min	11.65
Unvegetated	30	Catastrophic failure	Large aggregate displaced (ND)
Unvegetated with Binding Agent A	140	5min	Not determined
Unvegetated with Binding Agent T	90	Catastrophic failure	1141.68
Vegetated with Binding Agent A	140	5 min	40.12
Unvegetated with burlap wind blanket	140	5 min	Not determined
Unvegetated with netting	50	Catastrophic failure	Not determined

PAPER

GREEN ROOF WATER QUALITY AND QUANTITY IMPACTS

ABSTRACT

Green roofs can provide environmental benefits while conserving energy. Evaluation of green roof runoff quantity, nutrient loading, and erosion prevention of green roof systems and associated modeling are needed to better understand benefits of green roofs at various locations and for differing designs.

During the pilot study, the runoff quantity and composition from green roof material was evaluated continuously under field conditions for two different media both tested under planted and unplanted conditions. Water quantity results show over a 40% reduction in runoff from just the growing media and over 60% reduction runoff with established plants in green roof media under natural meteorology.

Previous studies have reported a "first flush" of excess nutrients but without evaluating the duration and intensity of this phenomenon throughout the first year of the roof's life. Research, presented here, showed total phosphorus concentrations at 30 mg/L and nitrogen concentrations above 60 mg/L in green roof runoff initially, with concentrations decreasing over the study. Media type and age were the largest influences on phosphorus and nitrogen concentrations. Understanding and modeling runoff nutrient kinetics can better aid in developing procedures to minimize nutrient runoff as well as determining overall environmental impacts of green roofs.

1. INTRODUCTION

1.1. Urbanization Impacts

Urbanization drastically impacts stormwater. As roads, buildings, sidewalks, and parking lots are added to the landscape, pervious surfaces decrease, as does the ability for stormwater to infiltrate. In addition, conventional stormwater control includes underground sewers for transport, reducing any chance of evapo-transpiration that would normally occur in the natural state. This large, almost instantaneous delivery, increases as urbanization increases, which in many cities means large upgrades needed to prevent overflows. In cities with combined stormwater and sanitary sewers, overflows mean releasing bacteria and harmful human waste into waterways, which is regulated by the US EPA's Clean Water Act (CWA). Several cities are facing lawsuits from the USEPA over their combined sewer overflows (CSO's). St. Louis alone is committing $4.7 billion dollars in upgrades to prevent CSO's (WEF 2011).

In addition, cities impact the weather, including through the Urban Heat Island Effect. This is the documented increased air temperature in cities compared to outlying rural areas due to the heat being absorbed in asphalt and paved/impervious surfaces and radiating back up into the city. According to the USEPA (2013), cities have been shown to be up to twelve degrees Celsius warmer than surrounding areas at night due to the Urban Heat Island and up to 3 degrees Celsius warmer during the day. This can have exacerbate heat waves as well as add to A/C costs.

1.2. Green Technologies

To address both heat island and stormwater effects of today's cities, green technologies have been developed and implemented. Green technologies are those that address stormwater quantity and/or quality through natural treatment systems. Through vegetation, easily draining soils and rocks, and natural storage, stormwater can be treated, stored, used, and reduced. Rain gardens, bioswales, and wetlands can all be used to store water, release it through evapotranspiration, and reduce nutrients through plant uptake. Rainwater storage is also provided through infiltration into gravel or native soils. Green roofs take the same principles as the other technologies and implement them at the source—on rooftops. In addition, permeable pavers can be used to allow for infiltration and reduced runoff. Storing stormwater on site and releasing it through evapo-transpiration decreases the quantities of water that must be conveyed through conventional sewers, potentially removing the need for costly upgrades.

Before implementing a green technology, understanding its impacts to both water quantity and quality is essential for it to be an effective solution. Assessing ecological effects by working not only with engineers and city planners, but also ecologists and horticulturists is essential for a project's success. In addition, operation and maintenance needs and costs must be addressed as well.

Though green infrastructure has increased on both coasts in cities such as Portalnd and Philadelphia, lesser investments in the Ozark region shows the need to display and better understand this technology in the lower Midwest climate. However, collecting enough data to be able to translate findings to other climates is also important.

1.3. Green Roofs

Green roofs are a proven technology to decrease stormwater runoff through their growing media storage and evapotranspiration of water from the plants. Green roofs come in two varieties: intensive and extensive. Intensive green roofs are those with over 15cm deep growing media, and are implemented as areas for people to enjoy and use as a rooftop park. Vegetative options vary and can even include trees and large shrubs. However, to maintain these roofs structural reinforcement is usually required. Intensive roofs are installed for commonly for their stormwater benefit, and are characterized by less than 15cm deep growing media. Structural reinforcement needs are less common, and they are often not designed for large live loads of people using the space. In addition, extensive roofs have less vegetation options and are most commonly planted with succulents such as *Sedum* species.

Since their industrial use as stormwater management tools in Germany beginning in the 1970's, much research has been done to quantify environmental impacts of green roofs. Several studies have evaluated the runoff reduction of green roofs in various conditions. In addition, Getter (207) have shown that green roofs change over time and as the media and plants mature, water storage of the media increases. In addition, studies have shown metal concentrations can be a concern depending on the growing media of the green roof tested (Ye 2012), but less attention has been put on nutrients and organics in runoff.

Mixed findings and varying conditions in each study have made the question of “what eutrophication effects can be expected from green roofs” unanswered. Cite articles that found decrease, cite those that increased. Nutrient loads over time can vary with media age, amounts of irrigation, roof slope, and media depth, as well as vegetation type. Because green roofs are a living system of several components, it is essential to understand the dynamics of the system in order to assess environmental impacts at a particular site. Monitoring chemical composition as well as quantity of runoff from green roofs will allow better understanding of the system.

2. MATERIALS AND METHODS

2.1. Green Roof Media

The two media tested were an Arkalyte mix and GAF's Gardenscapes^{TM} green roof media. The Arkalyte mix was allowed to 'mature' 1 year, being excess from a past green roof research project (Luckett, 2011). The GAF gardenscapes media was delivered directly from GAF and has not been used on any previous projects. The media characteristics were characterized by the MU Agronomic Soil Testing Services (Columbia, MO) with analysis summarized below, Table 2.1 (Nathan *et al*. 2012). The Bray IP for Phosphorus for Arkalyte and GAF media were 59.5 mg/kg and 1,065mg/kg respectively, showing high phosphorus concentrations in the GAF media before testing. The recommended maximum P concentration in soil for agriculture is 60 mg/kg (120lb/acre). In addition, the green roof media was re-tested after it was 9 months of exposure during the pilot study and found to vary over time.

Table 2.1. Analysis of Green Roof Media for typical Agronomic Properties (Acceptable range for variation in samples were determined to be pH: +/-0.2, P, K, Mg, OM: + /-10%)

#10 Sieved Samples	ARKALYTE-NEW	ARKALYTE-9 months old	GAF-NEW, cubic foot sacks	GAF-9 months old	GAF-1 month old, supersack
pH	7.4	7.7	7.6	7.8	7.9
Phosphorus (P) (mg/kg)	60	46	219	212	82
Potassium (K) (mg/kg)	121	49	1065	215	137
Calcium (Ca) (mg/kg)	3405	1930	1815	1794	2151
Magnesium (Mg) (mg/kg)	208	101	334	286	348
Organic Matter (%)	12.7	9.0	6.4	7.9	7.3
CEC (meq)	19.1	10.6	14.6	11.9	14.0

2.2. Green Roof Plants

With the assistance of Jost Greenhouses (St. Louis, MO) *Sedum* species was selected based upon their survivability in the Missouri Ozarks region. A Midwest Mix of 15 different species (*Sedum acre, oreganum, aizoon, pulchellum, album, reflexum, ellacombianum, sexangulare, floriferum, seiboldii, hispanicum, spurium, stoloniferum, rupestre,kamtschaticum, acre 'Octoberfest', telephium, hybridum 'Czar's Gold', and Phedimus takesimensi*s) as well as *Sedum kamschaticum* were chosen and planted on a 5x5 grid in the green roof blocks to aid in rapid plant coverage. The trays and plants began in our greenhouse to allow the plants to become established and due to the drought conditions of summer 2012, were not placed on the roof until late August 2012. Once the trays were moved to the roof, plants relied solely on rain water. This ensured that we could assess the plants viability at a pilot-scale before implementing a full-scale built-in-place green roof in the spring.

2.3. Pilot-Scale Tests

Green Roof Blocks™ , 60.8 cm by 60.8cm (2ft by 2ft), are used to study the impacts of media constituents and plants on water quantity and quality of green roof runoff. Green Roof Blocks™ are aluminum trays used for modular green roofs that were designed and constructed in St. Louis. The Green Roof Blocks™, i.e. 'trays', were donated to the project by Kelly Luckett, CEO of Green Roof Blocks.

To simulate field conditions in a controlled study, these trays were tested on top of the Butler-Carlton Civil Engineering Hall and runoff was sampled after each rain event. This set-up allowed us to test different media and planted/non-planted conditions on a smaller scale with a more controlled runoff collection system for accurate measurement of runoff as well as easy sampling for chemical analysis. Figure 2.1 shows the set up for each tray in the experiment and the Green Roof Blocks™. Table 2.1 shows the tested variables for each tray.

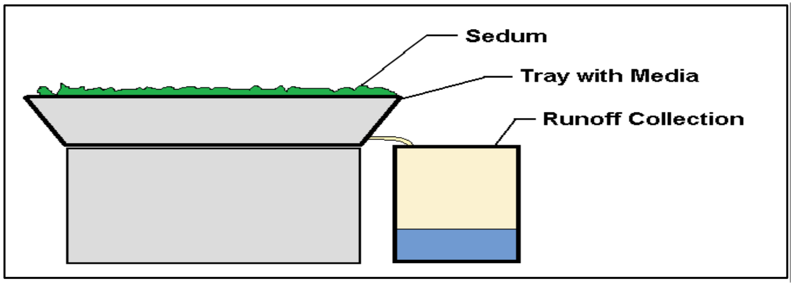

Figure 2.1. Pilot scale testing of media and *Sedums*, with schematic of test system on left and photo of Green Roof Block^{TM} as placed on Missouri S&T.

Table 2.2. Experimental Set-Up for Green Roof Blocks^{TM} in the controlled experimental arrangement

Green Roof Trays	Number of Trays
Planted with Arkalyte	3
Unplanted with Arkalyte	3
Planted with GAF	3
Unplanted with GAF	3
Control-Empty	1
Total	13

2.4. Meteorological Data

Site data was characterized by the Missouri S&T weather station data reported by the National Weather Service. This weather station on campus provides precipitation data for each day of the study, which is compiled through the National Climatic Data Center.

2.5. Water Quality Analysis

Water samples taken after each storm event were tested for total nitrogen, total phosphate, total organic carbon, total suspended solids, and turbidity. The turbidity of the water sample was measured in accordance to EPA method 180.1. The bench top Hach 2100P turbidimeter was calibrated before each sampling day and with every 10 samples a standard was tested to verify the calibration. Total suspended solids (TSS) were measured by Method 2540 D from Standard methods for the examination of water and wastewater. Total phosphorus was measured using a Hach DR/2400 Spectrophotometer following EPA procedure 365.2 for freshwater samples. Samples were digested in acid and heat to allow for hydrolysis of inorganic forms; organic phosphate is converted to orthophosphate through heating and reaction with persulfate. Once cooled, the sample in mixed with ascorbic acid and reacts with molybdate to produce a phosphate/molybdate complex.

Total organic carbon (TOC) and Total Nitrogen (TN) were tested using a Shimadzu TOC-L TOC analyzer. TOC was tested using the 680°C combustion catalytic oxidation method for TOC. To calculate total organic carbon, total carbon was measured by heating the sample in an oxygen-rich environment with a platinum catalyst. The carbon in the sample is converted to CO_2 , cooled, dehumidified, and measured via NDIR (nondispersive infrared sensor). Sparging the oxygenated sample allows for the inorganic carbon to be converted to CO_2 and measured via the NDIR as well. TN was tested through the 720°C catalytic thermal decomposition/chemiluminescence method. The sample is reacted with oxygen to form nitric monoxide, the nitric monoxide is reacted with ozone to form semi-stable nitrogen dioxide. When this semi-stable nitrogen dioxide turns into stable nitrogen dioxide, light is emitted which is measured and correlated to the total nitrogen concentration in the sample.

2.6. Green Roof Runoff Water Balance

Using the meteorological data, runoff collected, and soil properties, a model to predict quantities of runoff was developed to help predict the functionality of green roofs in the future. Estimates of reference ET were made with agricultural weather station data from Cook County. Using a water balance, the precipitation as measured from the Missouri S&T on-campus weather station as well as measured runoff and storage capacity of soil types allows for an estimate of a crop coefficient for a mix of *Sedum* species.

3. RESULTS AND DISCUSSION

3.1. Green Roof Runoff Reduction

Each Green Roof Block^{TM} tray configuration exhibited a reduction in runoff when compared to the empty control tray. The storage of stormwater in green roof media as well as the ET from plants allows green roofs to reduce stormwater runoff, Figure 3.1. The results since August 2012 show a significant reduction in green roof runoff, which can be attributed to both the plants and the growing media. Sixty percent reduction in runoff by planted GAF media was the highest cumulative reduction over the past eight months of this study. Media as well as plants attributed to the runoff reduction, with media playing the largest part due to its varying storage ability.

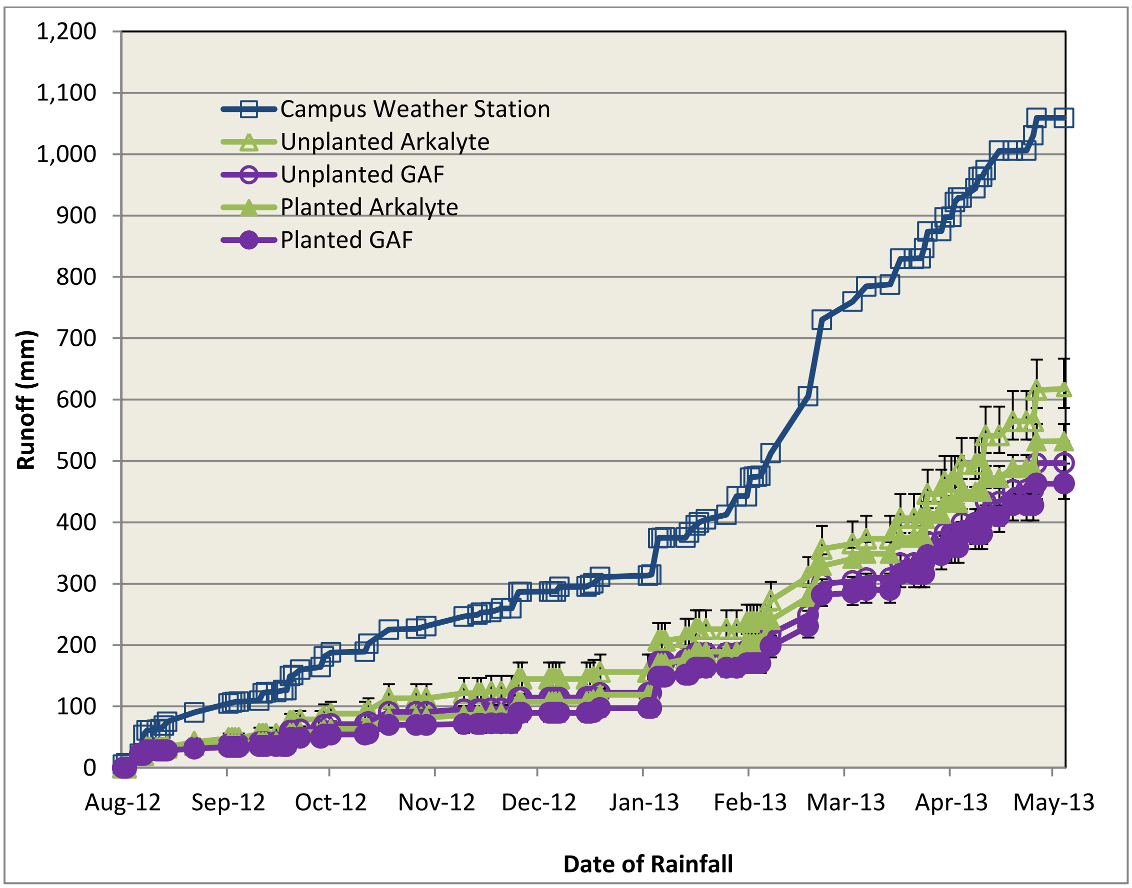

Figure 3.1. Cumulative runoff from pilot scale tests performed in Green Roof Blocks^{TM}

3.1.1. Impact of Plants

The impact of plants can be seen seasonally, as the reduction in runoff varied per season. The percent reduction varies seasonally, Table 3; and the storm size influences the reduction rate with larger storms this spring resulted in a smaller reduction in runoff on a percent basis and with wet seasons also showing a reduced overall impact on total flow. When the plants were dormant over winter, less variation between the planted and unplanted trays was observed, as would be expected under low evapo-transpiration conditions. The plants had over a 20% additional reduction (14mm compared to 21 mm of runoff during a 29 mm storm) in stormwater runoff in the fall, even though they had been planted just 2-5 months old. In the fall, planted GAF reduced runoff by a total of 20mm and Arkalyte reduced runoff by 54mm when compared to the unplanted trays of the same media. Greater impacts of plants are expected as they mature and increase coverage.

Plant effects vary seasonally and were shown to be statistically significant in fall and spring, but not in winter as shown below. The sum of runoff each season was compared using a 2-way analysis of variance (ANOVA) to assess effects of plants and differing media types, as shown in Table 3.1. No interactions between plants and media were found to be significant.

Table 3.1 Statistical significance of plant and media conditions on runoff volume

	Fall	Winter	Spring
Plants	0.0031	0.1181	0.0445
Media	0.0828	0.0003	0.0779
Planted*media	0.8387	0.8611	0.2648

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3.1.2. Variability between Green Roof Media

Media type impacted storm water storage and storm water runoff reduction greater than other experimental variables. The differences between the two unplanted media trays were constant throughout the experiment with a roughly 20% increase in water storage from the GAF tray relative to Arkalyte, with over 100mm in additional reduction in runoff from unplanted GAF than unplanted Arkalyte, as shown in Table 3.2. As the media each had different compositions and bulk density, their storm water retention is expected to vary. Green roof media has been shown to change over time both physically and chemically. It is difficult to say if the difference between the Arkalyte and GAF media were due to the additional year of aging experienced by the Arkalyte or if they were created differently, or a combination of the two.

Table 3.2. Median total runoff during the study for sampled storms

Condition	Median Runoff during study (mm)
Total Rainfall	1059
Planted Arkalyte	504
Unplanted Arkalyte	557
Planted GAF	435
Unplanted GAF	455

3.1.3. Green Roof Runoff Water Balance

Using the meteorological data collected, runoff measured, and media properties, creating a water balance can help to predict a green roof's behavior before implementation. Pennman-Monteith evapotranspiration for a standard reference crop can be calculated and then adjusted with a crop-coefficient for the *Sedum* mix. In addition, available water storage after each day can be calculated and used as a variable input for the next day's performance. By enabling a water-budget approach to predict the green roof's performance, a better understanding of benefits of green roofs in the central

Midwest can be determined. The results for this comparing an unplanted Arkalyte tray with the water balance is shown below without a crop coefficient. The time step for this analysis was one day. With the soil's infiltration and drainage measured as green roof "runoff" and assuming no sheet flow, the hydrologic true "runoff" condition equal to zero.

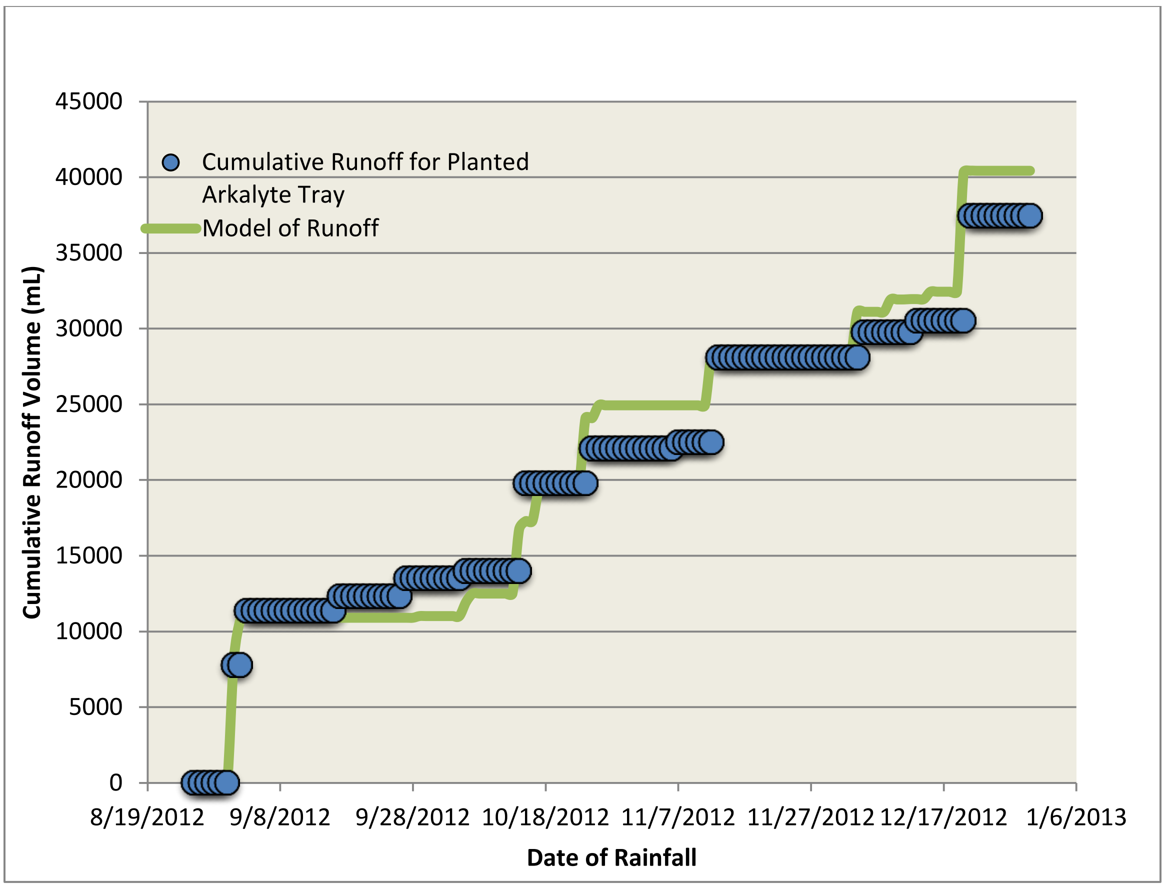

Figure 3.2. Cumulative runoff from pilot scale tests performed in Green Roof BlocksTM compared to the runoff predicted from a water-balance model.

3.2. Green Roof Runoff Nutrient Loading

Green roof media available for commercial use most often have proprietary compositions most media are all made up of similar components. The most common growing media used are lighter than topsoil and chosen based upon their ability to drain and support plant growth. However, additional fertilizers are also added to the mix to sustain the green roof vegetation, which many roofing companies guarantee will keep the plants alive. Increased nutrients can lead to large algal blooms which starve water of oxygen when they die, and can lead to deoxygenation of the water body and potentially deadly conditions for aquatic life.

3.2.1. Nitrogen Loading over Time

Total nitrogen concentration was expected to demonstrate a “first flush” of high concentrations and then reduce over time. A steady decrease in nitrogen concentrations has been observed during this study, see Figure 4.3. The TN concentration plotted as a function of time in Figure 3.3 also displays the total rainfall amount for the storm event as the size of each plotted data point. Storm size appears to have little impact on the concentration of TN in the runoff. Solubility of nitrate compounds can be as high as over 40% nitrate at 25 degrees C from sodium nitrate concentrations. This dissolution of nitrogen is not limited by reaching a maximum solubility concentration. This reaction most likely comes from nitrogen moving from non-available forms to a more labile concentration and then being flushed out. Each rain event, less nitrogen is available allowing for less of a concentration leaving each time reducing the amount of nitrogen in the runoff.

When considering the total nitrogen mass/area produced from each tested condition, the runoff volume was multiplied by the measured concentration and the divided by the area of the tray. The largest total nitrogen releases occurred in the winter months and GAF media had consistently higher concentrations of TN than Arkalyte.

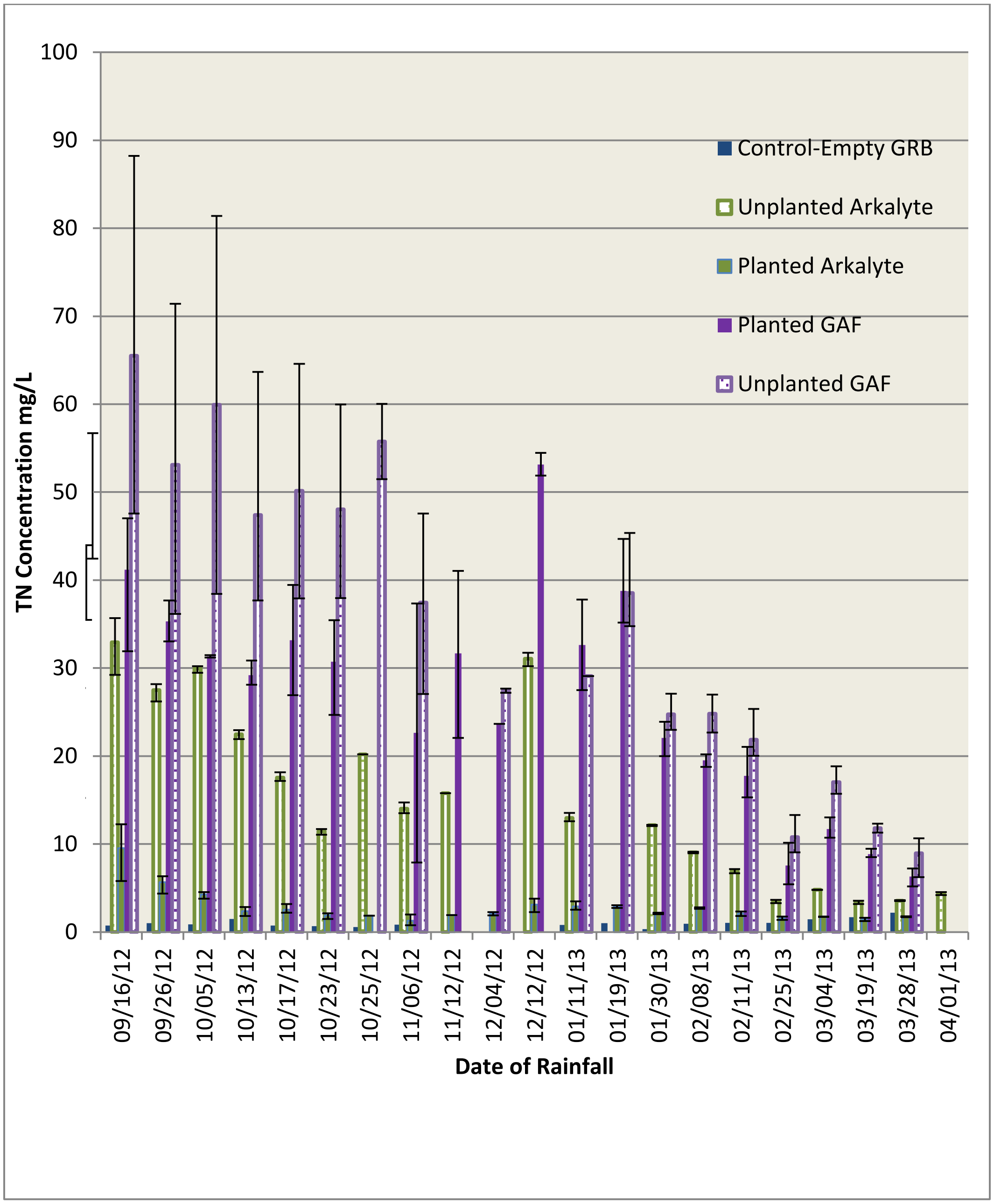

Figure 3.3. TN concentrations for each storm event, with error bars showing max and min (n=3).

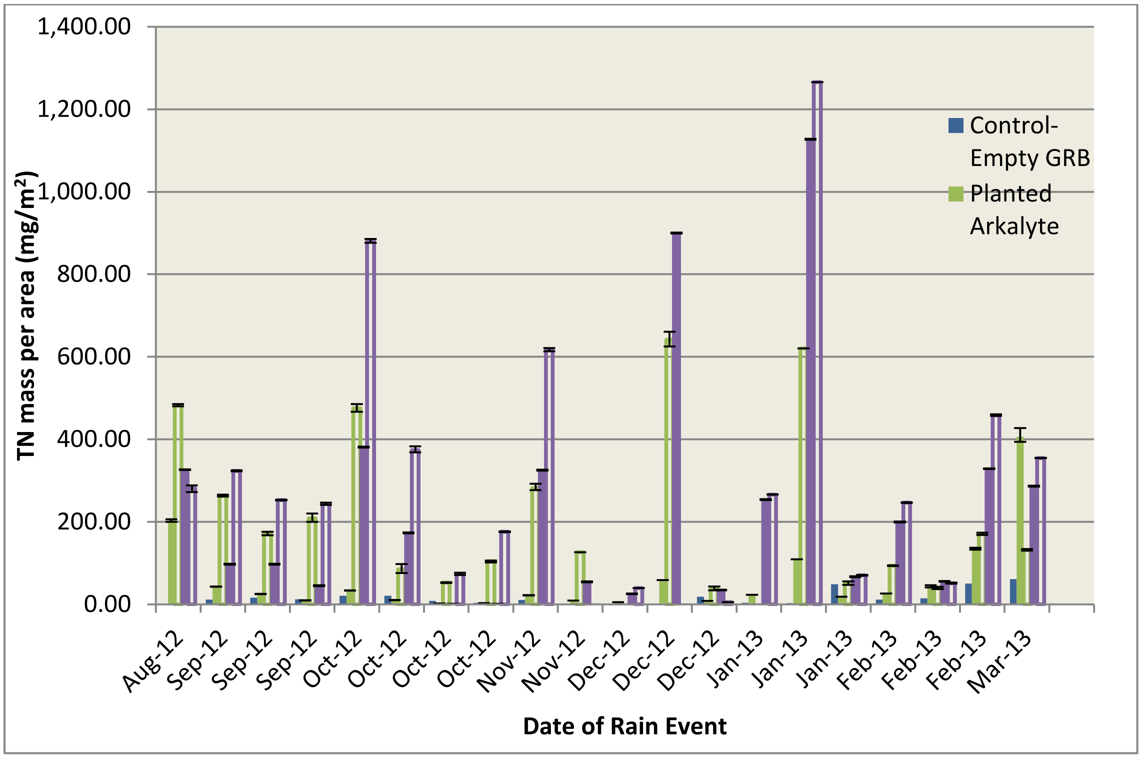

Figure 3.4. Total Nitrogen per area of green roof for each Green Roof Block™, the mass per area varied dramatically per storm event, as it was highly influenced by storm size.

The cumulative mass of TN per area over the course of the study shows a large discrpency between planted and unplanted Arkalyte, which is similar to the difference shown above in concentrations. However, plants varied the mass of TN over the course of the study less, showing interactions between the plant and media affects. In addition, a 15x increase in total nitrogen from the control to the planted GAF roof shows there are large impacts from green roofs immediately after installation. Plants and media were shown to influence TN total mass per tested tray condition (p-values<0.05.

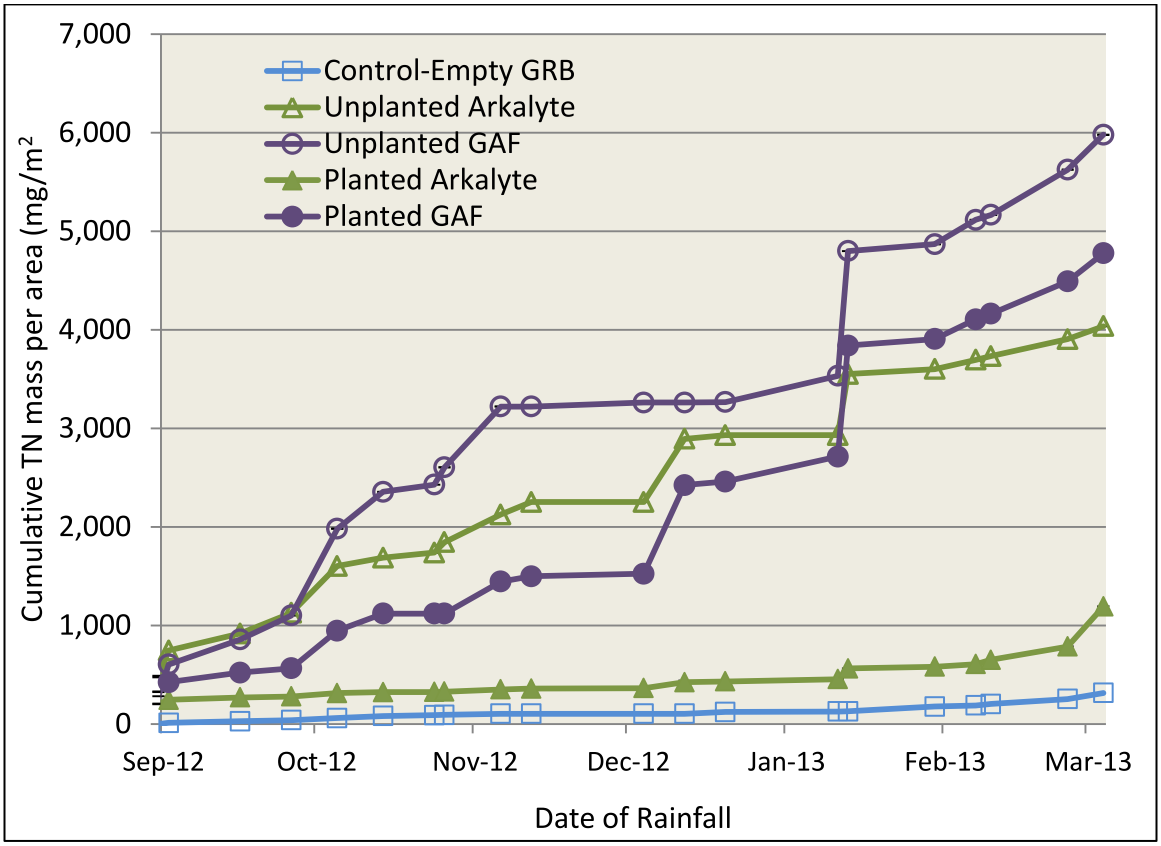

Figure 3.5. Cumulative TN per area over the course of the study.

3.2.2. Phosphorus Loading over Time

Concentrations of total phosphate (PO43) have been monitored each storm event, as shown in Figure 3.6. Concentrations varied greatly through the test period, though the phosphate discharged through the test period from GAF media was consistently higher than Arkalyte, showing media composition has the largest effect on phosphate runoff. The planted trays show lower phosphate concentrations throughout the testing. This could be due to the fact that planted roots can keep the soil stabilized and prevent media from reaching the runoff. Phosphate discharge most often occurs in natural systems from adsorption to soil grains which are then eroded away and into a water body. Additionally, plants uptake of phosphate could be reducing the concentrations in the soil that are capable of dissolving into the water. However the differences are seen throughout the winter, when the plants were dormant, which supports the explanation that plants are acting as a media stabilizer.

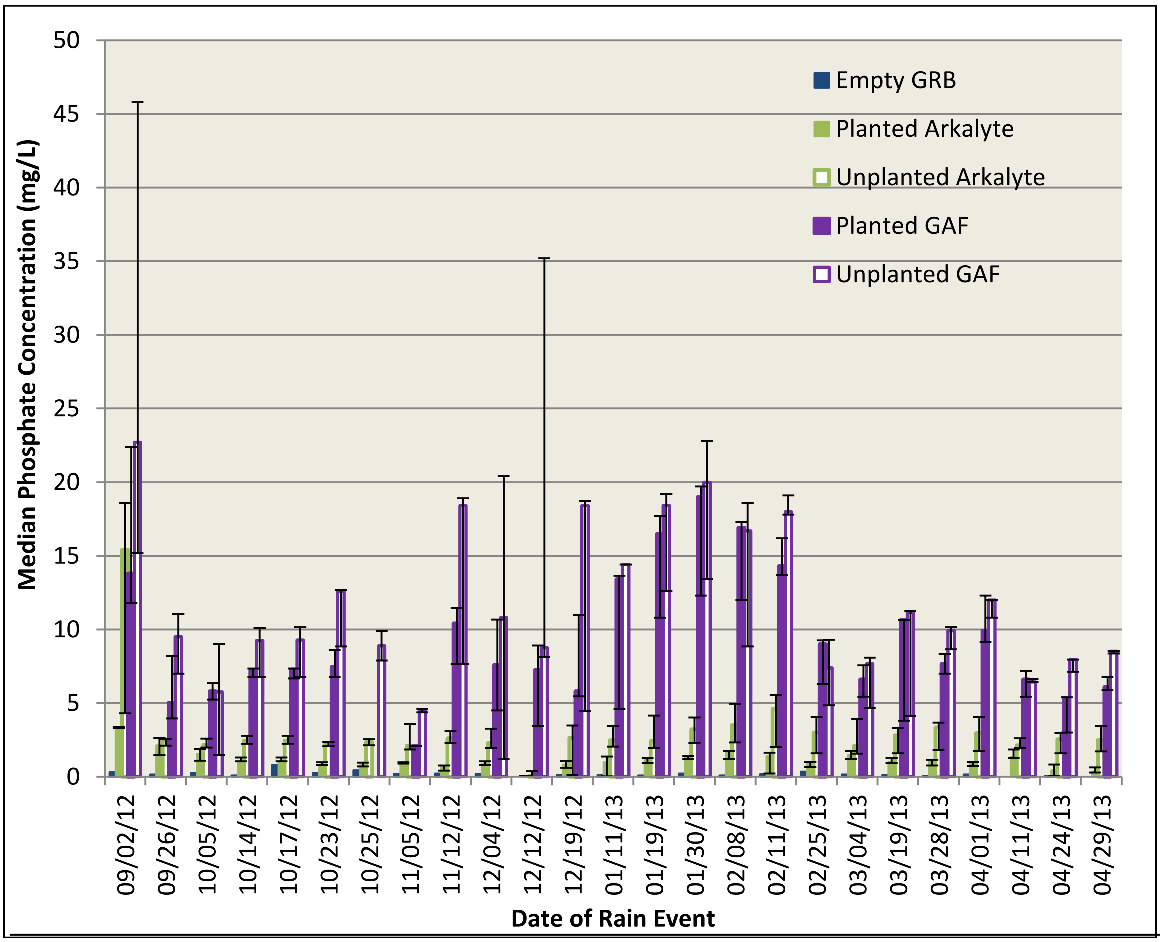

Figure 3.6. Phosphate concentrations over time with bar height equivalent to median phosphate concentrations and error bars showing min and max (n=3).

When considering impacts to waterbodies downstream, concentrations are much less important than total load of phosphate being added to the system. Phosphorus loading was assessed as well, and even when accounting for the decrease in runoff quantity with a green roof, an elevated load of phosphate was still observed, as shown in Figure 3.7.

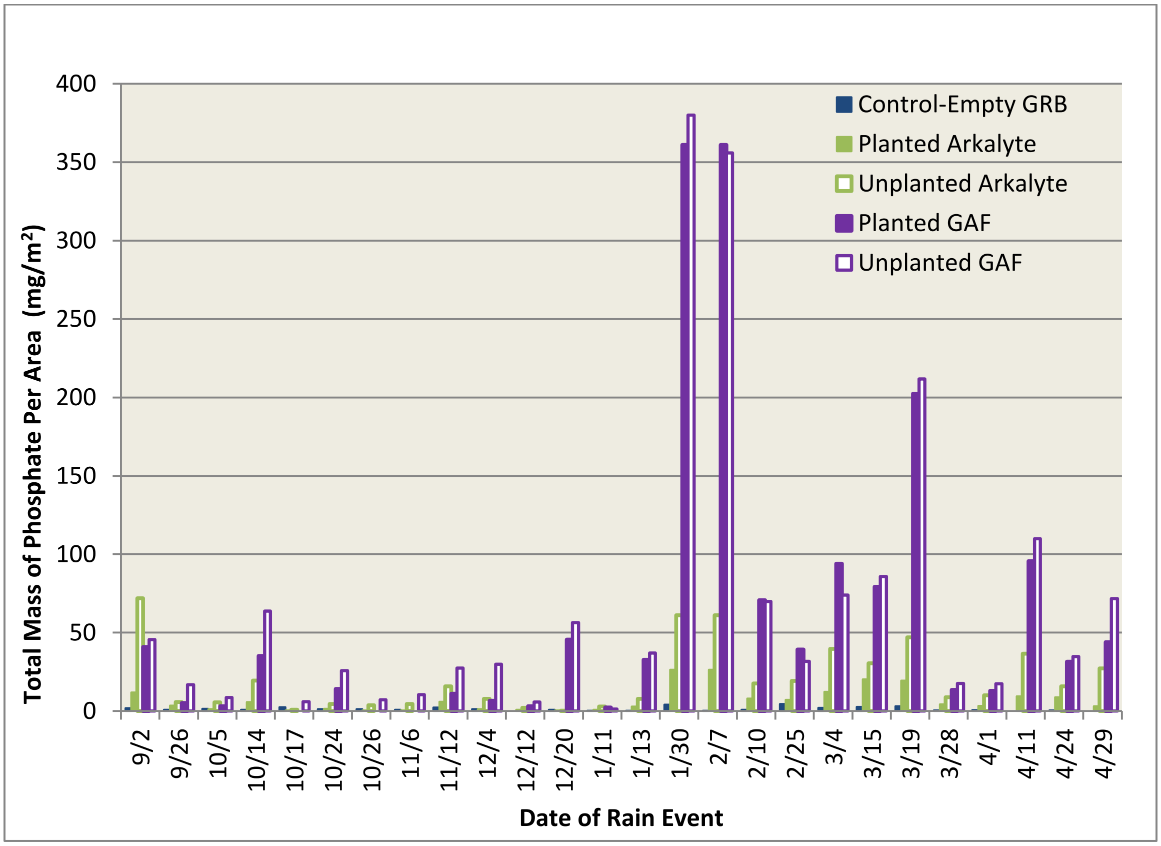

Figure 3.7. Median mass of phosphate per green roof area.

Phosphate total mass was significantly influenced by media type (p-values <0.001) throughout the year. In addition, plant and media interactions were significant (p-value 0.0011). GAF had much higher phosphate concentrations, which can be expected, as it had excessively high phosphate. Below, cumulative phosphate mass per area is shown in Figure 3.8. The plants' effects on phosphorus concentrations can be seen in the winter months when they are dormant and the difference between the planted and unplanted GAF decreases.

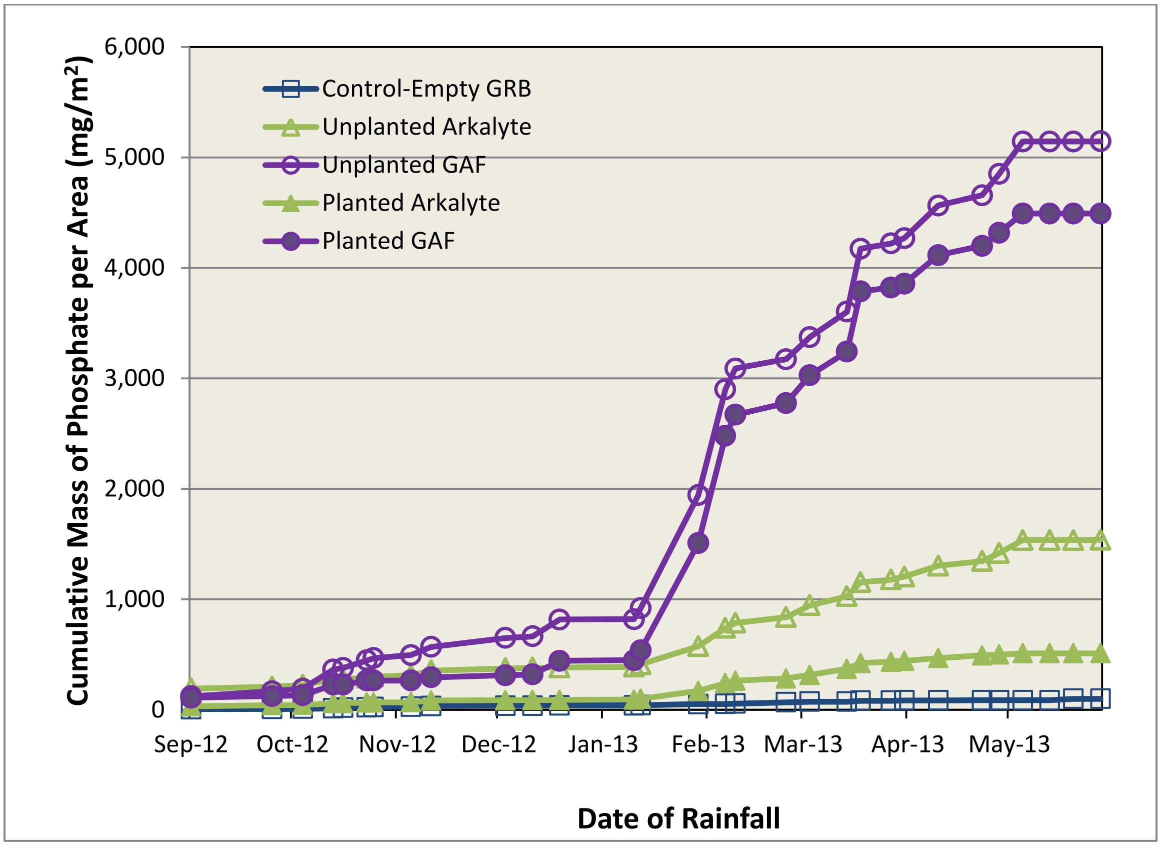

Figure 3.8. Cumulative mass of phosphate per area of green roof.

3.3. Water Erosion Control Experiments

To determine the water quality impacts due to media particles in the runoff, total suspended solids (TSS) were measured for each rain event. TSS remained relatively unchanged over time and at acceptable concentrations. TSS concentrations from wastewater treatment plants into water bodies are often set at limits similar to 20 mg/L. All TSS values were below this standard, which shows the effectiveness of the drainage mats designed to maintain the growing media. Figure 4.5 below shows the average TSS for each tested tray condition. The TSS increased for the unplanted condition supporting the theory that plants do play a role in stabilizing the media from water erosion during storm runoff. Large variation in the empty control GRB™ is due to the fact that during large storm events, especially with high winds, the growing media from the adjacent trays was blown into the control tray. The blown-in media was then carried with the runoff from the tray, which added to the total suspended solids. Similar effects would be observed during large events on a full-scale, conventional roof, as nearby debris and leaves would be carried toward the roof drain.

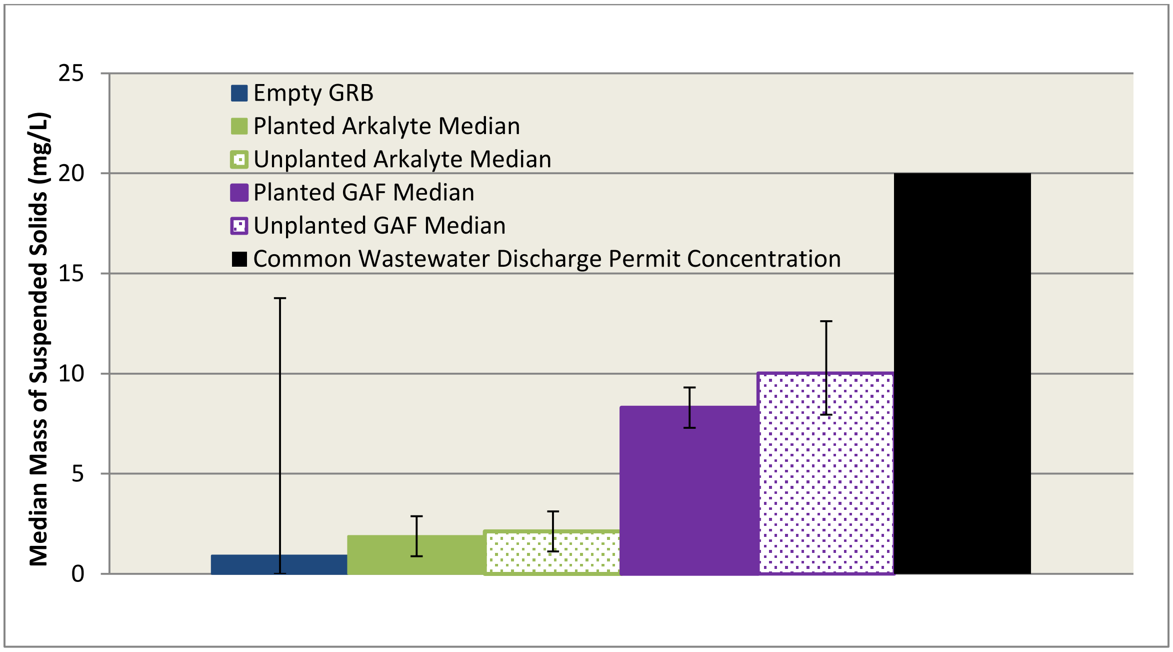

Figure 3.9. Median total suspended solids over the course of the study for each condition tested in Green Roof Blocks™, showing the effectiveness of the filtering layers of both systems.

Total mass of suspended solids in runoff from each condition were also assessed and compared to the control condition. The median values of the Arkalyte media were very similar to the control total suspended solids, whereas the GAF were approximately three times larger. The discrepancies in TSS between the two media is most likely due to the age of the media. Arkalyte was a year old when our project received the media, so it is likely that more fines were washed from the media before this testing began. The statistical significance of both media and planted conditions on log transformed total suspended solids were assessed via an ANOVA table, which resulted in both media and planted conditions significant ($p<0.05$). Figure 3.10 below shows the total mass of solids lost from each tray with the error bars representing the max and min for each 3-tray triplicate. The suspended solids were influenced by media type than planted condition.

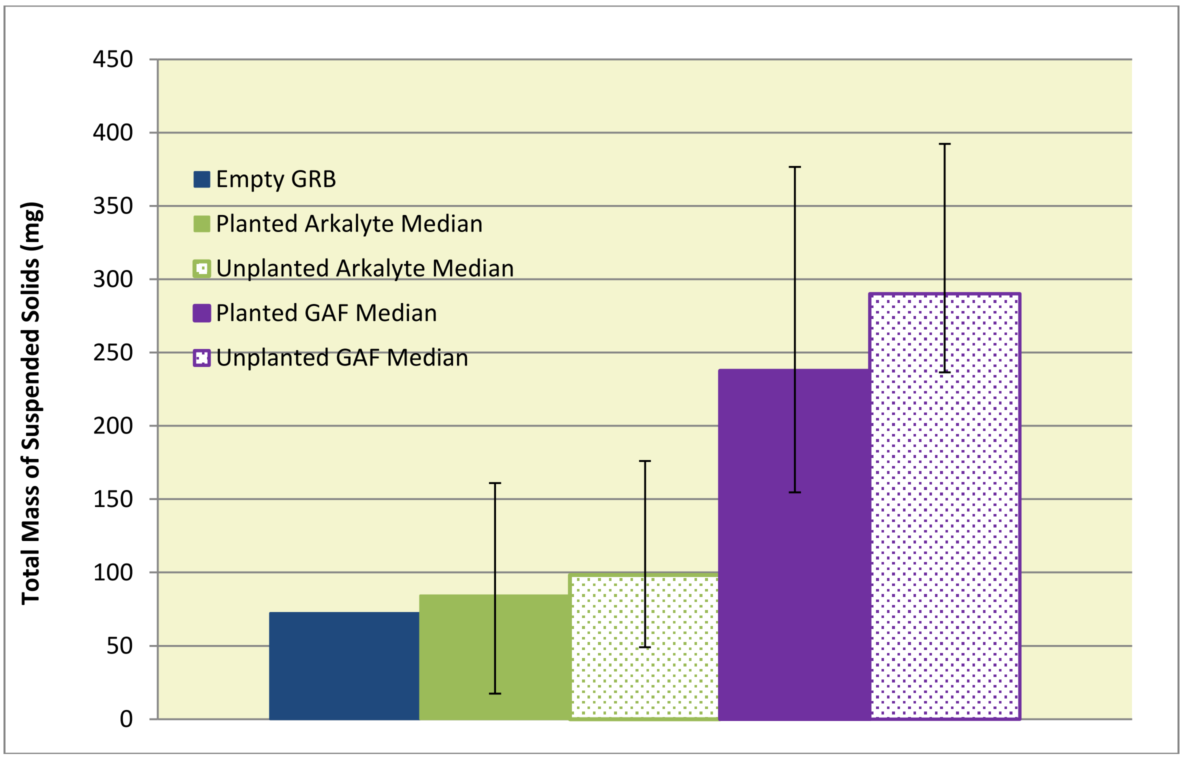

Figure 3.10. Total mass of suspended solids in green roof runoff during the study, showing the impacts of both media and planted conditions.

4. CONCLUSIONS

Green roofs have been championed as an effective resource for urban water management by reducing the stormwater loads reaching grey infrastructure. Runoff reduction of over 60% for storms below 2 inches observed further support that this is an effective way to reduce urban stormwater. However, the concentrations of nitrogen and phosphorus leaching out of new green roof media are a concern for water quality downstream, as excess nutrients have the potential to increased eutrophication of lakes and rivers downstream of cities. In addition, the large amounts of organics dissolved in the green roof runoff add to the total BOD (biological oxygen demand) in the water, potentially leading to low dissolved oxygen for aquatic life. Such effects will not be seen on a watershed scale from one roof, but with city policies encouraging or even mandating green roofs be incorporated into the urban structures, all effects from this implementation must be considered. Altering the amount of organic matter, type of organic matter, and/or fertilizers used could all lead to a more “green” green roof.

Drainage fabrics tested in this study prove to be an adequate control of solids and prevent an excessive amount of media to be lost due to water erosion. Though TSS was increased when compared to the control, concentrations were all below guidelines for TSS in runoff.

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SECTION
4. WIND EROSION CONTROL STUDY

Wind erosion is a major concern for green roofs between the time of planting and the plants reaching full coverage. Wind erosion of unplanted and planted green roof sections were tested along with, "Green Roof Glue," an adhesive to stabilize the growing media.

The eight tested trays for each medium were filled and subjected to the following treatments (each with a duplicate):

a. unplanted without green roof glue
b. unplanted with green roof glue
c. planted without green roof glue
d. planted with green roof glue

For the 4 planted trays, 3 *Sedum* Midwest Mix plugs and 1 *Sedum kamschaticum* plug per tray were planted and allowed to grow for 5 weeks before testing.

The green roof glue was applied with a garden sprayer to the trays treated with glue 2 days prior to testing. For an 81 square inch ($0.052m^2$) pan, approximately 3.0 mL of green roof glue was applied to the growing media surface. The glue was applied evenly and sprayed from approximately 3from the surface of the trays.

The green roof blocks were last watered 2 weeks before testing. The planted green roof blocks were at approximately 50% plant coverage. The modified filter was measured before each test began. The filter support structure shown was installed in the wind tunnel and the filter was placed against the support structure. The tray holder, shown in Figure 6, was bolted into the floor of the wind tunnel and the tray being tested was secured into the tray holder. Beginning with 6 m/s and increasing by 1.5 m/s every 30 seconds, each tray was tested at increasing wind speeds up to 13 m/s. After completion of this experiment, the filter was removed and massed to determine the amount of material lost during testing.

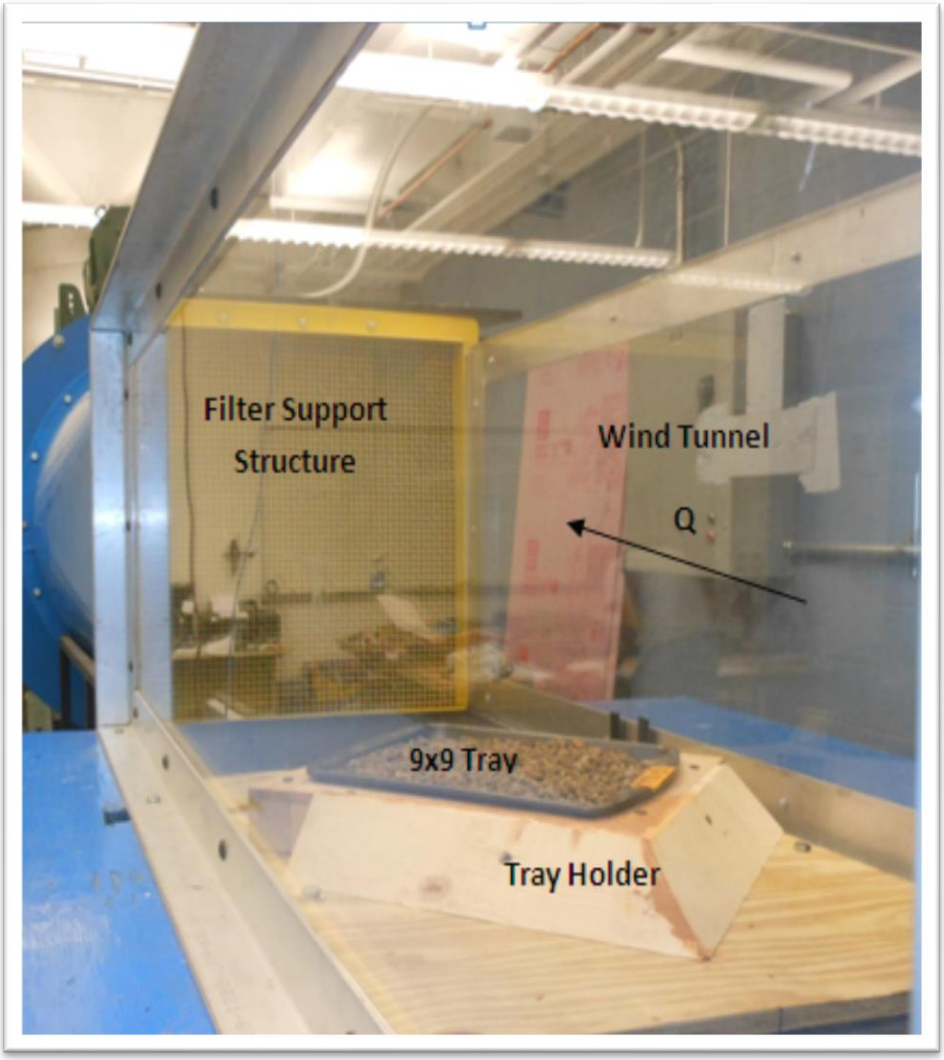

Figure 4.1. Wind tunnel testing apparatus

None of the tested trays experienced a substantial loss of growth media. The unplanted trays without green roof glue experienced the most material loss. A decrease was shown in material loss for the planted and glued trays with the planted trays providing a wind blanket protection for the growth media. Fines were observed to be lost around 10 m/s (30ft/s) wind speeds and pebbles were displaced. Wind scour of growth media mass for each combination tested is plotted in figure 7.

The hypothesis that both the green roof glue and planted conditions would decrease the amount of growth material lost in a windy condition was supported. The media composition impacted the amount of media lost from each tray, as GAF eroded more in all tests. This could be from the increased fines in GAF when compared to the

Arkalyte mix or the aging of the Arkalyte mix (which had an entire year to erode away its finer particles).

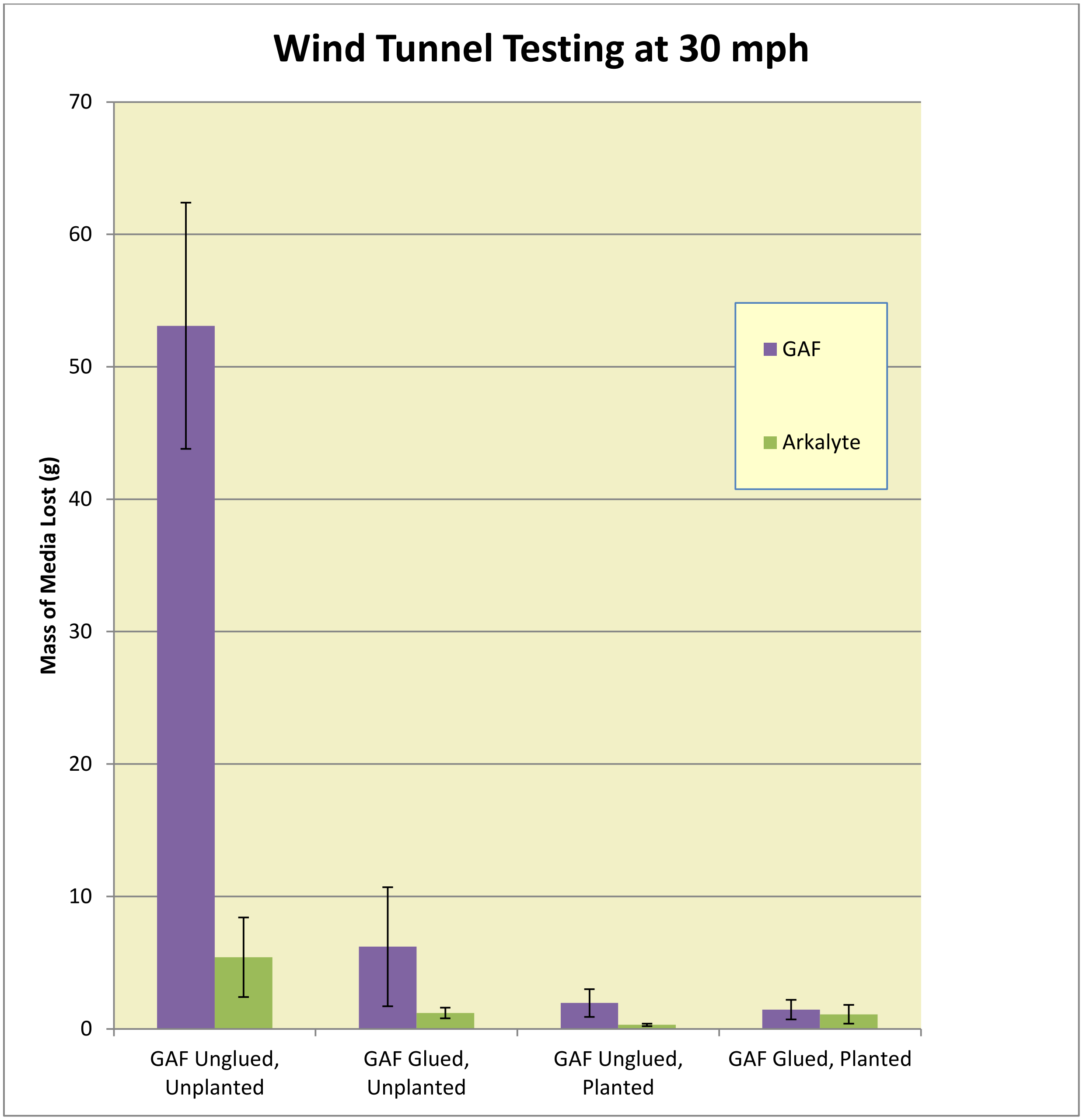

Figure 4.2. Median mass of media lost during wind tunnel experiments for both media types tested with error bars showing max and min (n=3).

5. SUMMARY AND CONCLUSIONS

In conclusion, the goal of this study was reached through evaluating stormwater retention and water quality from green roofs. The first hypothesis that media and plants will reduce runoff from green roofs was supported, as was the seasonality of the water retention impacts of plants. In addition, the second hypothesis that nutrient concentrations as well as organic carbon concentrations and suspended solids concentrations decrease over time was supported. However, the concentrations remained higher than conventional roofs for nutrients. Lastly, wind erosion was decreased by both plants and green roof adhesives, as expected in the third hypothesis.

From this research, the impacts of green roof installation on a watershed's chemical composition as well as the quantity of drainage into the water shed's body of water can be better understood. Elevated phosphate and nitrogen from green roof runoff remain after eight months and if a significant portion of a watershed was covered in green roofs,observable effects could exist through eutrophication. Though green roof materials are effective at water retention, the increased load of nutrients and organic carbon are still significant. Though there wasn't a large observed physical removal of green roof media particulate through erosion via water or air, the effects on water quality are most likely from media-water interaction.

6. RECOMMENDATIONS FOR FUTURE WORK

Future work should include further monitoring of nutrients, dissolved carbon, and water quantity throughout the summer months. Understanding green roof water quality impacts include creating a water-balance model for any green roof, no matter the slope, media depth, media type, and vegetation. Research presented here has not evaluated varying media depth or slope, though findings from others can be used to calibrate and validate the model. By developing this model, cities and citizens will have a more precise way of evaluating the hydraulic benefits of green roofs in the southern and central Midwest.

In addition, heat flux measurements will be conducted on our campus's 307square meter (3,300 square feet) built-in place green roof to evaluate the heat island reduction impacts a green roof can have in the central Midwest. Coupling heat flux data with water storage and evaporation, a complete heat flow model can be created to better understand the benefits of green roofs when it comes to energy uses as well as environmental heating of a city. In addition, the green roof will be compared to a conventional black roof as well as a white TPO membrane to assess the effects of both reflective and green rooftops.

APPENDIX

Water Quantity Data for Each Pilot-Scale Condition Tested

Date	Volume in Empty GRB	Planted Arkalyte, 1	Planted Arkalyte, 2	Planted Arkalyte, 3
8/31/2012	18925	7780	9000	7380
9/2/2012	6000	3600	3000	4000
9/16/2012	6000	950	2000	2000
9/26/2012	5200	1180	2040	1660
10/5/2012	5160	480	1445	510
10/14/2012	10600	5800	4600	5600
10/17/2012	3000	3381.670656	380	740
10/24/2012	4800	2300	1200	750
10/26/2012	2660	0	1000	360
11/6/2012	4740	400	580	900
11/12/2012	9700	5600	7650	5600
12/4/2012	5820	1670	1880	1560
12/12/2012	1300	760	1430	680
12/20/2012	8520	6940	7080	7160
1/11/2013	1380	620	1320	1140
1/13/2013	3550	2640	3300	2960
1/30/2013	19000	19000	19000	19000
2/7/2013	3960	2160	2750	2600
2/10/2013	5340	4540	4220	5100
2/25/2013	13000	4900	6100	4600
3/4/2013	13440	13500	14340	13900
3/15/2013	19000	12500	15000	14000
3/19/2013	21500	19000	19000	19000
3/28/2013	5600	4040	3980	4920
4/1/2013	4460	2820	3300	3160
4/11/2013	12000	10240	9520	9300
4/19/2013	10107.85075	13500	15000	15000
4/24/2013	9200	5600	7280	6540
4/29/2013	12500	9250	1200	10000

Water Quantity Data for Each Pilot-Scale Condition Tested (continued)

Date	Unplanted Arkalyte, 1	Unplanted Arkalyte, 2	Unplanted Arkalyte, 3
8/31/2012	7920	9600	4750
9/2/2012	5500	4700	3800
9/16/2012	3200	2700	3000
9/26/2012	3070	2000	1900
10/5/2012	3550	2020	2200
10/14/2012	8200	6800	8600
10/17/2012	60	1820	330
10/24/2012	4150	650	620
10/26/2012	1520	2020	1540
11/6/2012	2100	1600	2080
11/12/2012	8500	6500	7400
12/4/2012	3610	2100	3220
12/12/2012	1400	670	760
12/20/2012	8200	7180	7640
1/11/2013	1490	800	940
1/13/2013	3350	3000	2930
1/30/2013	19000	19000	19000
2/7/2013	2560	1770	1860
2/10/2013	5160	4960	4900
2/25/2013	3450	3730	5360
3/4/2013	13700	13260	12700
3/15/2013	15000	14000	14000
3/19/2013	19000	19000	12400
3/28/2013	2660	2740	4080
4/1/2013	3400	2320	3280
4/11/2013	13020	11780	12480
4/19/2013	15000	14000	15000
4/24/2013	8120	6680	7340
4/29/2013	11000	10500	10500

Water Quantity Data for Each Pilot-Scale Condition Tested (continued)

Date	Planted GAF, 1	Planted GAF, 2	Planted GAF, 3
8/31/2012	8600	8120	6480
9/2/2012	3000	2900	3000
9/16/2012	1100	1400	125
9/26/2012	1030	1580	460
10/5/2012	700	895	10
10/14/2012	4100	6250	4200
10/17/2012	513.3333333	410	320
10/24/2012	2000	2170	1640
10/26/2012	0	0	0
11/6/2012	270	1020	0
11/12/2012	5200	5710	5100
12/4/2012	809	1110	0
12/12/2012	530	230	440
12/20/2012	5740	6580	6560
1/11/2013	290	420	470
1/13/2013	2300	2500	2500
1/30/2013	19000	19000	19000
2/7/2013	1570	1060	1200
2/10/2013	4180	4200	4150
2/25/2013	2720	3500	2000
3/4/2013	10740	11020	9590
3/15/2013	12000	12000	12000
3/19/2013	19000	19000	19000
3/28/2013	2180	1100	520
4/1/2013	1780	1810	1480
4/11/2013	9700	9960	9300
4/19/2013	12000	11000	11000
4/24/2013	4750	5520	4050
4/29/2013	8050	8500	8000

Water Quantity Data for Each Pilot-Scale Condition Tested (continued)

Date	Unplanted GAF, 1	Unplanted GAF, 2	Unplanted GAF, 3
8/31/2012	9660	7500	8000
9/2/2012	1800	3300	1000
9/16/2012	1900	1800	1800
9/26/2012	1810	1700	1800
10/5/2012	1630	1490	1410
10/14/2012	7050	7200	6470
10/17/2012	243.3333333	670	820
10/24/2012	2280	3410	2620
10/26/2012	480	840	380
11/6/2012	1020	1300	1200
11/12/2012	6200	6490	5700
12/4/2012	1700	1670	1495
12/12/2012	600	620	390
12/20/2012	6300	6420	6560
1/11/2013	0	0	205
1/13/2013	2700	2520	2480
1/30/2013	19000	19000	19000
2/7/2013	780	1380	1000
2/10/2013	4380	3900	4280
2/25/2013	2450	1070	1760
3/4/2013	11300	8800	9880
3/15/2013	11500	11500	10500
3/19/2013	19000	19000	19000
3/28/2013	1380	900	2470
4/1/2013	1940	1650	1700
4/11/2013	11210	9560	6680
4/19/2013	13000	13000	13000
4/24/2013	5870	6020	4250
4/29/2013	9000	9000	0

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