An Investigation into the Hydrologic and Geochemical Processes Contributing to Green Roof Performance

by

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Abstract

Low Impact Development (LID) techniques for site design are increasingly being utilized to mitigate the negative impacts associated with stormwater runoff, and green roofs are one such application. The ability of green roofs to reduce the total and peak volumes of stormwater runoff has been fairly well documented, but performance varies in different climate zones, and there is limited information available regarding green roof effectiveness in New England, a region whose weather patterns are notoriously variable from season to season and often even day-to-day. Additionally, there are questions regarding the impact that green roofs have on water quality, especially regarding phosphorus. While many green roofs have been found to leach phosphorus into stormwater runoff within the first few years after installation, it is assumed that this phenomenon will not continue after the green roof vegetation has been established. However, it is still unclear whether or not this assumption is valid, and very few research projects have focused on providing the necessary insight into the hydrologic and geochemical processes that are contributing to this observed problem.

The Nitsch/Magliozzi Green Roof, located atop WPI's newest residence hall, was donated to enhance the sustainability of the building and to foster continued research and education. This roof provided an opportunity to better characterize the relationship between rainfall and runoff volumes, phosphorus sorption/desorption in the growing medium, and plant uptake processes. Comparisons of grab samples of stormwater from both the green and non-green portions of the roof within the first few seasons following installation confirmed that phosphorus was leaching into the runoff, and some seasonal trends were observed. For example, the highest concentrations (3-13 mg/l $P\text{-}PO_4^{-3}$) were observed during an especially rainy summer. In order to gain a better understanding into the nature of this occurrence, laboratory experiments on sections of this same green roof were designed and set up in WPI's greenhouse.

A series of simulated rainfall events were conducted, a mass balance approach was used to analyze flow, and the phosphorus content of the water, plants, and soil were assessed. For flow attenuation, the green roof panels performed as expected under different rainfall and antecedent moisture conditions. Additionally, the greenhouse experiments provided improved insight into the nature of the relationship of phosphorus between the flow conditions, plant uptake, and soil processes, as well as its distribution throughout a storm. The laboratory data further provides a basis for estimating performance of a green roof and its long-term impact on stormwater quality. In a broader context, the findings also serve to inform future extensive green roof designs and subsequent research efforts.

for Jonathan, Mary, and Phineas

Thanks for your patience.

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1.0 Introduction

In a natural water cycle, precipitation works its way into surface waters by flowing over land or by infiltrating through the subsurface to the groundwater table, where it then contributes to the base flow in streams. Not all rainfall, however, ends up in lakes and streams. Some evaporates directly back into the atmosphere. Some is utilized by vegetation and lost to transpiration. This process provides a balanced distribution of water throughout the environment.

Anthropogenic activities interrupt this balance. A lot of water is detoured, moved, stored, and utilized for human consumption, industry, and power generation. As land is developed, impervious surfaces create barriers to infiltration and increase the speed of overland flow. This stormwater reaches surface water bodies more quickly, in greater volumes, and contaminated with sediments and other pollutants. As a result, stormwater becomes something that needs to be managed.

Low Impact Development (LID) is a term to describe site design techniques that minimize the human footprint on the environment, especially the water cycle. Many LID strategies focus on mimicking pre-development conditions and minimizing impervious surfaces. Aside from paved transportation infrastructure (roads, sidewalks, parking lots, etc.), building roof surfaces are a significant contributor to impervious surface areas. Green roofs are a LID technique used to manage stormwater generated from roofs.

A green roof is designed to provide a layer of vegetation that primarily to helps manage stormwater in urban environments, but also provides aesthetic and ecological value. Green roofs have been shown to be effective at reducing the volume and peak flows of stormwater, as well as delaying the time to peak flow conditions. However, performance varies in different climate zones, and there is limited information regarding green roof effectiveness in New England, a region whose weather patterns are notoriously variable from season to season and often even day-to-day. Additionally, there are questions regarding the impact that green roofs have on water quality, especially regarding phosphorus. While many green roofs have been found to leach phosphorus into stormwater runoff within the first few years after installation, it is assumed that this phenomenon will not continue after the green roof vegetation has been established. However, it is still unclear whether or not this assumption is valid, and very few research projects have focused on providing the necessary insight into the hydrologic and geochemical processes that are contributing to this observed problem.

This project investigated a green roof's impact on stormwater flows and quality. The Nitsch/Magliozzi Green Roof, located atop WPI's newest residence hall as shown in Figure 1.1, was donated to enhance the sustainability of the building and to foster continued research and education. It provided an opportunity to explore the function and performance of green roof technology. Its modular design also allowed for sections of the roof to be transported to a laboratory environment for in-depth analysis. There, a series of simulated rainfall events were conducted and the phosphorus content of the water, plants, and soil were analyzed. The intent was to better characterize the relationship between rainfall and runoff volumes, phosphorus sorption/desorption in the growing medium, and plant uptake processes in order to better inform future extensive green roof designs and subsequent research efforts.

Figure 1.1: Nitsch/Magliozzi Green Roof After Installation, August 2008

1.1 Goals of Research

The goals of this research were to provide insight into the hydrologic and geochemical processes that contribute to green roof performance. The specific objectives included the following:

- Determine the effectiveness of a green roof in attenuating stormwater flow
- Document a green roof's impact on water quality, specifically regarding phosphorus
- Identify the key components of the processes that are likely leading to the highest variability in observed water quality parameters – hence, the highest potential that a change in design could lead to significant improvements

These objectives are intended to provide a foundation for future research efforts to explore the behavior of phosphorus in soil solutions and its implications for stormwater treatment.

1.2 Scope of Project

This thesis report documents the research that took place from June 2009 through April 2010. The research was conducted through a combination of field monitoring of the East Hall roof, laboratory testing of green roof panels under simulated rainfall conditions, bench-scale testing of phosphorus desorption from the growing medium, and laboratory analyses of water quality, soil characteristics, and plant phosphorus content.

The field monitoring program focused on the seasonal variations of water quality throughout a complete growing season. At East Hall, modifications to the roof drainage system were made by the building designer, Canon Design, to accommodate the installation of flow meters and water sampling ports from pipes that drain nearly equal areas of both the green and non-green portions of the roof. The green roof area that drains to one of the sampling stations is shown in Figure 1.2.

Figure 1.2: Nitsch/Magliozzi Green Roof atop East Hall at WPI

The water quality monitoring ports allowed for effective sampling of the green roof runoff. However, the data obtained from the flow meters that were installed was not dependable, nor was it reflective of the expected flows in the drainage pipes. Repeated attempts to modify the calibration and scale of the meters were unsuccessful, and it was recognized that it would not be easy to make alterations to roof drains in an active residence hall. Therefore, it was decided that the field component would concentrate on water quality and flow monitoring would be reserved for future research.

Consequently, to characterize both the stormwater retention performance and water quality characteristics of the green roof, a laboratory testing program was developed. For this program, two (2) of the green roof panels were brought into the WPI greenhouse (housed in Salisbury Labs and maintained by the Biology Department). A stand was constructed for each panel over which simulated rainfall could be applied and runoff could be collected and measured. This approach was intended to predict stormwater retention performance of the roof, provide deeper insight into the transformations of phosphorus in the green roof panels, and develop a process by which continued, in-depth study could be performed under controlled laboratory conditions. A more detailed description of the methods for this research can be found in Chapter 3, and the results characterizing the nature of the impacts of the roof on flow retention and water quality are included in Chapters 4 and 5.

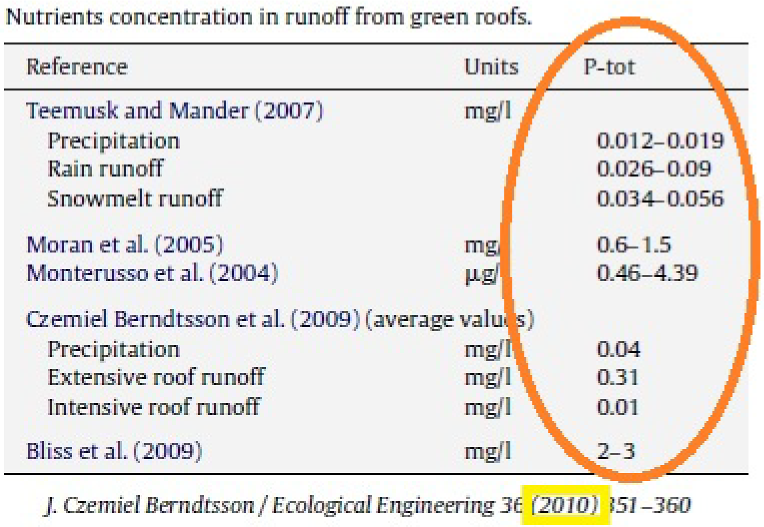
1.3 Motivation

The potential role of green roofs in controlling stormwater pollution and protecting water quality represents the motivation for this research. The Clean Water Act regulates surface water with pre-treatment standards and authorizes the National Pollutant Discharge Elimination System (NPDES) permitting requirements. The broad intent of the act is to regulate both point and non-point source water pollution. The Act set up the system of Total Maximum Daily Loads (TMDLs) as a measure for water quality – essentially regulating all inputs into a surface water body in relation to its existing water quality characteristics. In addition, the Act's Phase I & Phase II rules require communities to mitigate the negative impacts associated with stormwater runoff. (EPA 2008)

Stormwater transports a variety of contaminants to water bodies, including sediment, naturally-occurring nutrients, as well as constituents with anthropogenic causes. One of the more prevalent stormwater nutrients of concern is phosphorus, in large part because it is considered the primary limiting nutrient in freshwater and has a considerable effect on the eutrophication of inland lakes, ponds, and reservoirs. Concentrations in surface waters as low as 0.015 mg/l could contribute significantly to eutrophication, while concentrations greater than 0.1 mg/l are considered indicative of hypereutrophic conditions. (Reddy 2008) Stormwater typically contains between 0.34 and 0.59 mg/l, depending upon land use, and may be the most significant source of phosphorus in many freshwater bodies. (New York 2007) For example, a 2005 study of a small lake (320 acres) in West Brookfield, Massachusetts estimated that 98% of the phosphorus loading was contributed by stormwater. (ESS 2005) The form, speciation, and partitioning of phosphorus in stormwater can vary considerably, but dissolved reactive phosphorus is of particular concern because it is the most readily available for biological uptake and, as such, has the greatest impact on eutrophication.

The most significant human contribution of phosphorus in stormwater has been through the use of fertilizers. Animal wastes that are used as fertilizers have less nitrogen than phosphorus, and have often been applied in amounts to ensure sufficient nitrogen loading to crops. As a result, phosphorus is applied in greater amounts than utilized in plant uptake. While some of the phosphorus adsorbs to soil, erosion can transport the particulate-bound phosphorus to waterbodies, and infiltrating rainwater can dissolve the phosphorus in the subsurface once all of the soil binding sites are filled. (Reddy/DeLaune 2008; Colman 2005) This phenomenon can also take place on a green roof. Fertilized or compost-rich substrate is typically utilized when green roofs are first planted for the purposes of providing adequate nutrients for young plants to establish. Over-fertilization, however, is likely to lead to a long-term source of phosphorus in green roof runoff.

Several studies have reported increased phosphorus concentrations from green roofs compared to precipitation and traditional roofs. Some examples are shown in Figure 1.3. The growing medium is largely considered to be the source of phosphorus.



Nutrients concentration in runoff from green roofs.

Reference	Units	P-tot
Teemusk and Mander (2007)	mg/l	
Precipitation		0.012–0.019
Rain runoff		0.026–0.09
Snowmelt runoff		0.034–0.056
Moran et al. (2005)	mg/	0.6–1.5
Monterusso et al. (2004)	µg/	0.46–4.39
Czemiel Berndtsson et al. (2009) (average valu s)		
Precipitation	mg/l	0.04
Extensive roof runoff	mg/l	0.31
Intensive roof runoff	mg/l	0.01
Bliss et al. (2009)	mg/l	2–3

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Figure 2.1: Green Roof Phosphorus Concentrations

Ultimately, improved insight into the processes leading to green roof effectiveness in managing stormwater management is needed in order to establish design criteria for optimal performance. Applications of hydrology, soil science, and plant science are needed to fully understand the process.

2.0 Background

This chapter provides a breadth of information on green roof technology, design, and research. A review of the literature regarding green roof performance is included, which covers previous studies regarding both stormwater attenuation and water quality impact. This chapter also describes design criteria related to the hydrologic and chemical processes that are contributing to the effectiveness of green roofs, with an emphasis on phosphorus transformations.

2.1 Green Roof Technology

A green roof is designed to accommodate vegetation, primarily for the purpose of managing stormwater in urban environments, but also to provide aesthetic and ecological value. Designs are commonly categorized as either extensive or intensive. Extensive roofs typically have less than 6 inches of growing medium, are light-weight, and can be nearly maintenance-free. Intensive green roofs require greater structural support to hold the weight of deeper growing media, larger shrubs and trees, and people. Intensive green roofs are often designed to accommodate human use and enjoyment, while extensive roofs primarily serve building functionality. (Miller 2009)

Figure 2.1 depicts the typical layers of an extensive green roof. While the specific design may vary, the layers serve some basic, essential functions. A waterproofing layer is needed to protect the underlying roof structure, and a drainage layer is often included to provide a means by which runoff can drain from the roof. The drainage layers also provides some additional storage to protect the soil from becoming over-saturated and possibly damaging the plants. For extensive roofs, the weight of the growing medium layer is usually minimized by using lightweight substrate rather than a heavy soil.

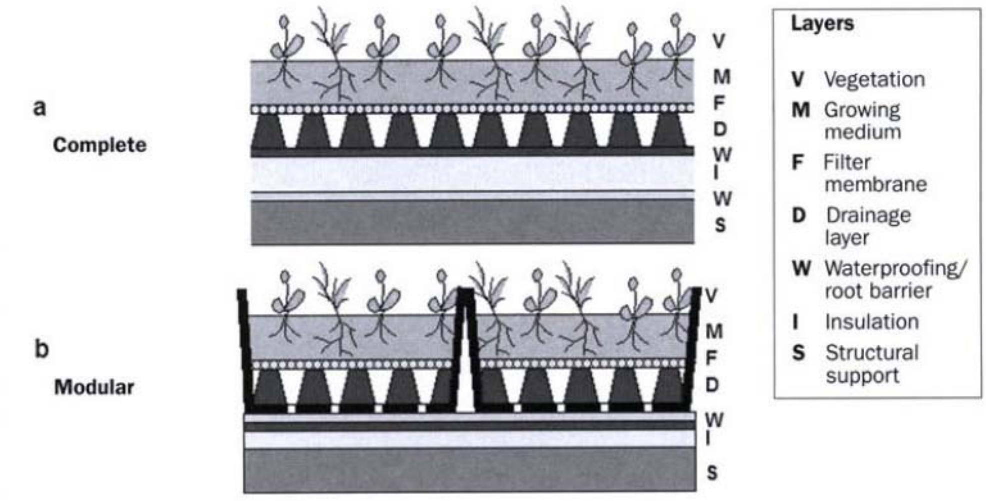


Figure 2.1 Extensive Green Roof Layers ***(Oberndorfer et. al. 2007)***

2.2 Previous Studies Regarding Green Roof Flow Attenuation

Stormwater Best Management Practices (BMPs) are typically implemented with the broad goals of reducing downstream flooding and improving water quality. (Dzurik 2003) Low Impact Development (LID) techniques try to meet these goals by providing on-site storage and infiltration or by slowing the movement of water off the site. This is typically accomplished by mimicking pre-development conditions and minimizing impervious surface areas. Replacing an impervious rooftop with a vegetated one would seem to serve this function. However, a green roof does not take advantage of groundwater infiltration to provide the long-term storage that is attained with natural landscape cover. Yet, there is still a benefit. Numerous studies have been undertaken to quantify a green roof's contribution to stormwater management.

A few researchers have utilized green roof performance studies to develop a Curve Number (CN) for use in the NRCS watershed runoff model (Carter 2005; Getter 2007). The CN values they have developed range between 84 and 88 (depending on roof slope), which are less than the 98 value assigned to impervious surfaces, but certainly more than the CN values typical for pervious areas, which could be significantly less than 80 depending on the infiltration capacity of the soil. (USDA NRCS 1986).

However, the flow attenuation performance of a green roof is more complex than implied by imposing a CN value for the prediction of peak runoff. Effectiveness is often impacted by climate patterns, antecedent soil moisture content, and the intensity, size, and duration of rainfall. Tables 2.1 and 2.2 provide an overview of reported retention capacities of extensive green roofs. Many studies, such as those listed in Table 2.1, report retention rates in terms of antecedent conditions or on a seasonal basis. (Kloss 2006; Moran 2004; Liptan and Strecker 2003; Hutchinson 2003; Stovin 2008; Liu and Minor 2005; Johnston 2004) Alternatively, some researchers publish results in terms of storm size. (Carter and Rasmussen 2006; Bliss et. al. 2009) These are listed in Table 2.2.

Table 2.1: Green Roof Flow Retention Performance based on Season

Location	Average Annual Runoff Reduction	Average Peak Flow Reduction	Average "Wet" Season Runoff Reduction	Average "Dry" Season Runoff Reduction
Chicago, Illinois	75%			
North Carolina	62-63%	78-87%		
Portland, Oregon	30% (27-month avg.)		10%-35%	65%-100%
Portland, Oregon	69%			100% ("warm" weather)
Sheffield, United Kingdom	34%	57%		
Toronto, Canada				57% (fall and summer)
University Park, PA (Penn State Research Center)	80%			
Vancouver, British Columbia	48%		5-30%	>80%

Table 2.2: Green Roof Flow Retention Performance based on Size of Storm

Location	Reduction for Small Storms (<1")	Reduction for Medium Storms (1-3")	Reduction for Large Storms (>3")	Considerations
Athens, Georgia	~88%	>54%	~48%	CN of 86 developed
Pittsburg, PA	21-71%	16-38%		
Vancouver, British Columbia	30%		<5%	Results of winter data

2.3 Previous Studies Regarding Green Roof Water Quality Impacts

Green roofs are included as a stormwater Best Management Practice (BMP) in the Massachusetts Department of Environmental Protection (MassDEP) Stormwater Handbook. (MassDEP) Specifically, the Stormwater handbook notes “no active removal” of Total Suspended Solids (TSS) and “increases” in Total Phosphorous (TP) and Total Nitrogen (TN). Also, the ability for green roofs to remove zinc or pathogens is “not reported.” The research literature is either inconclusive or in conflict with these noted efficiencies.

For phosphorus, several studies have reported increased phosphorus concentrations from green roofs compared to traditional roofs. The growing medium is largely considered to be the source of phosphorus. For example, a study of two roofs in Portland, Oregon found higher concentrations of phosphorus in green roof runoff on a roof with higher concentrations of phosphorus in the substrate. (Hutchinson 2003) Berndtsson also notes this trend in his review of the literature, as well as the reported findings that the concentration of phosphorus found in green roof runoff will decrease over time. It is surmised that the decrease is a function of both plant growth and of soil phosphorus content. (Berndtsson 2010) A 2005 study to investigate water quality impacts of extensive green roofs found phosphorus in runoff of three of four extensive roofs in southern Sweden. The roof constructed in 1994 was not determined to be leaching phosphorus into runoff. That study attributed the source of phosphorus to the fertilized soil media, although recognition was paid to the potential for bird droppings to be a cause. The study also concluded that phosphorus discharge would only be a concern within the “establishment” period of extensive green roofs, i.e. 2-3 years post construction. (Berndtsson et. al. 2006)

Also notable, there are some inconsistencies in reported forms of measured phosphorus. Some studies report significant dissolved phosphate concentrations, while others have determined that total phosphorus concentrations are significantly higher than that found in its dissolved phosphate form. (Berndtsson 2010)

2.4 Green Roof Performance Factors

Green Roof performance is a function of a variety of design criteria, pertaining to the roles of both the growing medium and the vegetation. The physical characteristics of the substrate will affect its hydrologic performance, while the chemical composition will have a significant impact on the quality of stormwater runoff. Similarly, the plants' ability and efficiency at taking up both water and nutrients play a critical role. (Berndtsson 2010)

2.4.1 The Role of the Soil

The thickness of the soil layer is one factor that influences the hydrologic performance of a green roof. A study conducted in Germany found that extensive roof layers ranging from 2-20 cm in thickness had corresponding annual runoff reductions of 40-60%. (Ker Wood 2009) Thicker layers will provide more storage, which may remain in the soil as pore water and eventually to be taken up by plants and lost to transpiration during dry periods between storms.

Additionally, the soil moisture content affects storage. Field capacity refers to the amount of water that a soil layer can hold before free drainage begins. (Sumner 2000) In the context of a green roof, the field capacity can be considered the maximum moisture content (percentage by weight or by volume) that can be attained before rainwater that has infiltrated the growing medium will leave the roof as runoff. (Berndtsson 2010) As such, the moisture content of the soil prior to a rain event has a direct impact on the amount of available storage that can be utilized for stormwater retention.

2.4.2 The Role of Vegetation

The vegetation on a green roof is an important component of its design and overall performance. For flow retention, plants assist in minimizing runoff in a few ways. First, the plants provide an initial abstraction, allowing evaporation to be utilized to its maximum role. Secondly, plants will uptake moisture in the soil for use in growth and development. The hydrogen reacts with sugars in the plant cells, while the oxygen is released to the atmosphere as a waste product. Essentially, the soil provides temporary storage for water that will be transpired by the plants. As such, the plants' uptake of moisture from the soil regenerates the soil's water storage capacity.

For extensive green roofs, which are intended to be maintenance-free and lightweight, Sedum and Delosperma are commonly selected because they are known to be effective for water uptake, as well as drought resistant. The Massachusetts Stormwater Manual recommends these and other perennial varieties and discourages the use of grasses and herbs that require irrigation or deeper substrates. (MassDEP 2008) In a 2007 study, conducted at Pennsylvania State University, three common species of plants (Delosperma Nubigenum; Sedum Spurium; and Sedum Sexangulare) were found to contribute as much as 40% of water retention function of green roofs. Within the first 5 days following a rain event, the plants almost doubled the holding capacity of the soil media by uptaking excess moisture. Alternatively, the impact of plant uptake was found to be reduced during more extensive dry periods, and the soil was found to provide the bulk of the benefit. That research concluded that the plants' maximum functionality occurs with frequent (every 3-5 days), relatively small storms (.5-inch), making them ideal for use in the northeastern region of the United States. (Berghage 2007)

2.4.3 Phosphorus Behavior in the Subsurface

Generally, phosphorus can dissolve into water or be removed as it moves through the subsurface by a combination of desorption, adsorption, and precipitation. These processes result from reactions with aluminum, iron, and/or calcium. (Minton 2005) The variability of green roof soil type, phosphorous concentration, pH, temperature, and soil moisture content makes it difficult to predict which of these processes will dominate and how prevalent phosphorous transformations will be.

In natural waters, phosphorus is typically present as phosphoric acid (H_3PO_4) and its dissociation products, ($H_2PO_4^-$, HPO_4^{-2}, and PO_4^{-3}). (Fetter 1993) Phosphoric acid is a triprotic acid with the following pK_a values: $pk_{a1} = 2.16$; $pK_{a2} = 7.2$; and $pK_{a3} = 12.35$. (Benjamin 2002) As shown in Figure 2.2, pH affects the proportion of each phosphate species. This relationship is an important consideration when the form of phosphorous is dependent upon its ability to participate in sorption/desorption and precipitation reactions with sediment. As indicated, phosphorus is typically present in water as $H_2PO_4^-$ or HPO_4^{-2}.

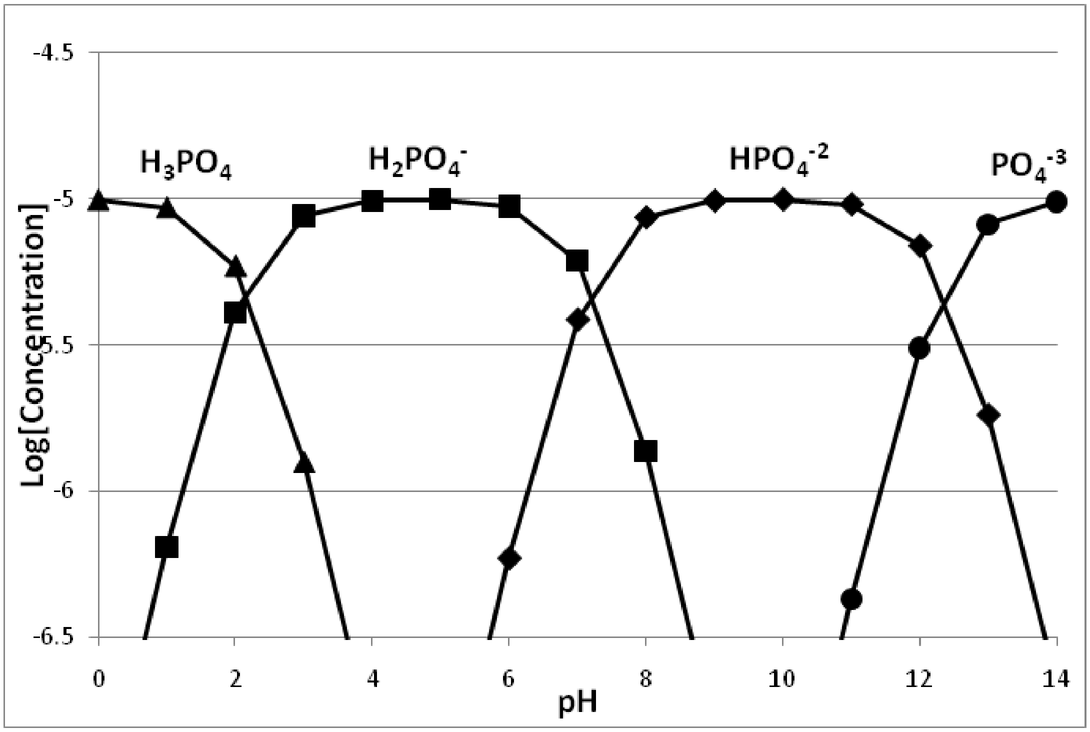


Figure 2.2: log-concentration diagram for Phosphoric Acid for a 10^{-5} M TOT-PO_4 (0.31 mg/l) system

Studies regarding phosphorus sorption have indicated that phosphorus will bond with two types of soil sites. The Langmuir two-surface sorption isotherm, which has been used to describe the partitioning of phosphorus in water/sediment mixtures, is as follows: (Fetter 1993)

$$\frac{C^*}{C} = \frac{\propto_1 \beta_1}{1+\alpha_1 C} + \frac{\propto_2 \beta_2}{1+\alpha_2 C}$$

Where C* = mass of solute sorbed per dry unit weight of solid
C = equilibrium concentration of solute in solution
α_1 = the bonding strength at type 1 sites
α_2 = the bonding strength at type 2 sites
β_1 = the maximum amount of solute that can be sorbed at the type 1 sites
β_2 = the maximum amount of solute that can be sorbed at the type 2 sites

In the natural subsurface environment, phosphorus typically reacts with aluminum, calcium, and/or iron to form mineral precipitates. As illustrated in Figure 2.3, phosphorus in waters with near-neutral pH would be expected to be primarily attached to sediments, with less than 20% present in its dissolved phase. For green roofs, where the growing medium is an engineered substrate, the anticipated form of phosphorus is not well-documented.

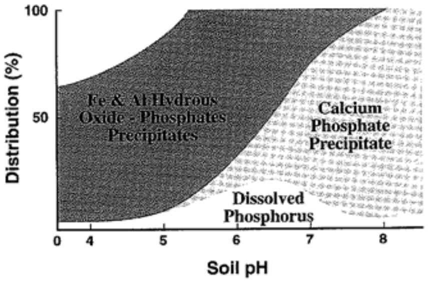


FIGURE 12.9
Phosphorus forms and soil pH[162]

Figure 2.3: Phosphorus Precipitation (Minton 2005)

Temperature will also affect phosphorus desorption in green roof soil. A study by Singh designed to investigate the role of temperature on phosphorus uptake of lettuce plants found that increases in temperature led to increased phosphorus uptake and yield, largely as a result of the observed increase in desorption as temperature increased. Temperatures of the study ranged between 17.2°C and 29.4°C. (1977) Alternatively, Aduloju and Olaniran documented that *adsorption* increases with increasing temperature. (2001) Their study agreed with previous studies that at higher temperatures, phosphate is sorbed more than at lower soil temperatures. Notably, those studies involved acidic soils, whose pH ranged from 5.3-5.4, while the soil in Singh's research was slightly alkaline at 6.2. Chien adds additional insight to this relationship. His research documents that the temperature at which P is initially sorbed will play a major role in its desorption and subsequent availability for plant uptake. Specifically, P desorption will show its maximum increase with increasing temperature when the P adsorption occurs at 25°C. (Chien 1982)

Moisture content will similarly play a role in phosphorus desorption. Consider Colman's findings that, as low-phosphorus-concentration water moves through the subsurface, its available solubility contributes to desorption of phosphorus from phosphorus-laden soil particles. (Colman 2004) One could then surmise that more water would lead to more desorption. Sui and Thompson, in a separate investigation applied the Langmuir two-surface sorption isotherm to study the availability of different binding sites in more detail. An interesting conclusion was that increasing liquid/solid ratios increased the desorption of phosphorus, regardless of whether or not the soil had been amended with the biosolids that were the focus of their study. (Sui and Thompson 2000) In addition, increased moisture content in soils is known to enhance the ability for plants to uptake phosphorus. (Sumner 2000).

Lastly, there are studies that indicate that phosphorus-laden soils can contribute phosphorus to infiltrating water for very long periods of time. Colman modeled the fate of phosphorus plumes in the subsurface. (Colman 2004) The model assumed that wastewater containing 12 mg/l of phosphorus was applied to an infiltration bed at 3 gal/ft^2/day for 50 years. After the loading of phosphorus ceased, his model predicted it would take 50 years before effluent concentrations were reduced to an amount lower than concern for eutrophication (set at 0.015 mg/l for the model). Similarly, a study in the Netherlands found that after 5 years of not applying any phosphorus to a grassland pasture, soil solution phosphorus reductions decreased by 30-90%. However, this reduction was achieved by "mining" the phosphorus (i.e. mowing and removing the grass), and the decline was only observed in uppermost layer of soil.

In conclusion, the hydrologic performance of green roofs and their impact on water quality are influenced by a complex combination of parameters related to the soil, the vegetation, and chemical behavior of phosphorus in water-soil mixtures.

3.0 Methods

The research for this project was conducted through a combination of field monitoring of the East Hall roof, laboratory testing of green roof panels under simulated rainfall conditions, bench-scale testing of phosphorus desorption from the growing medium, and laboratory analyses of water quality, soil characteristics, and plant phosphorus content.

3.1 Approach

At East Hall, modifications to the roof drainage system were made by the building designer, Canon Design, to accommodate the installation of flow meters and water sampling ports from pipes that drain nearly equal areas of both the green and non-green portions of the roof. Initial monitoring efforts were primarily aimed at testing the accuracy of the flow meters and setting up the water quality monitoring system. Methods were developed for wiring the flow meters to data logging devices, a second data logger was purchased, and a grant was obtained from the USGS to assist with the purchase of a water quality monitoring sonde (Hach Hydrolab).

However, the data obtained from the flow meters was not dependable, nor was it reflective of the expected flows in the drainage pipes. It was determined that almost all rain events were producing flows that were lower than the sensitivity of the equipment. After repeated attempts to modify the calibration and scale of the meters were unsuccessful, an alternative approach for studying the stormwater retention performance of the green roof was developed.

Two (2) of the green roof panels were brought into the WPI greenhouse (housed in Salisbury Labs and maintained by the Biology Department). A stand was constructed for each panel over which simulated rainfall could be applied and runoff could be collected and measured. For water quality monitoring, the same approach envisioned for installation in East Hall was used. Runoff was detoured through a flow-through device attached to a water quality monitoring sonde (Hach Hydrolab), and grab samples were collected at key points during the "storms." Soil and plant samples were also collected. All samples of water, plant, and soil were analyzed in the Civil and Environmental Engineering water quality laboratory.

This approach was intended to predict stormwater retention performance of the roof, provide deeper insight into the transformations of phosphorus in the green roof panels, and develop a process by which continued, in-depth study could be performed under controlled laboratory conditions.

3.2 Field Monitoring of East Hall Roof

This section describes the methods used to assess the field conditions of the study roof. An overview of precipitation data and analysis, as well as the sampling regime of roof runoff is provided.

3.2.1 Precipitation Data Collection and Analysis

Precipitation data is a significant input to any hydrologic study. WPI is fortunate to be located in close proximity to a National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) data collection station, which is located at Worcester Regional Airport (<5 miles away). Hourly precipitation and other climate data is available in real-time at their weather observation website (NOAA Weather Observations), which maintains the most recent 72 hours of data and in archived data sets at the National Climate Data Center website (NOAA Climate Data Center), which provides hourly precipitation data sets dating back to 1951. This information was useful in providing context for the stormwater grab samples collected from the Nitch/Magliozzi Green Roof at East Hall. It was also analyzed for the purposes of appropriately designing the simulated rainfall events in the greenhouse.

In order to determine whether the data available through NWS could, in fact, be utilized for the purposes of this research, a tipping bucket rain gage was installed on the East Hall roof during a few heavy rainstorms in October 2009 and compared to NWS data obtained from Worcester Regional Airport. Figures 3.1 and 3.2 illustrate the comparisons between the two data sets. On October 18, the rain gage at WPI recorded slightly more rainfall (0.36 inches) over the course of the storm. However, the following week, the Worcester Regional Airport gage recorded a slightly higher volume – nearly the same difference over the duration of the rainfall event. While this slight inaccuracy may not have been desirable for comparison to actual flows coming off of the roof on those days, the annual data set from the NWS station was deemed appropriate for its intended uses.

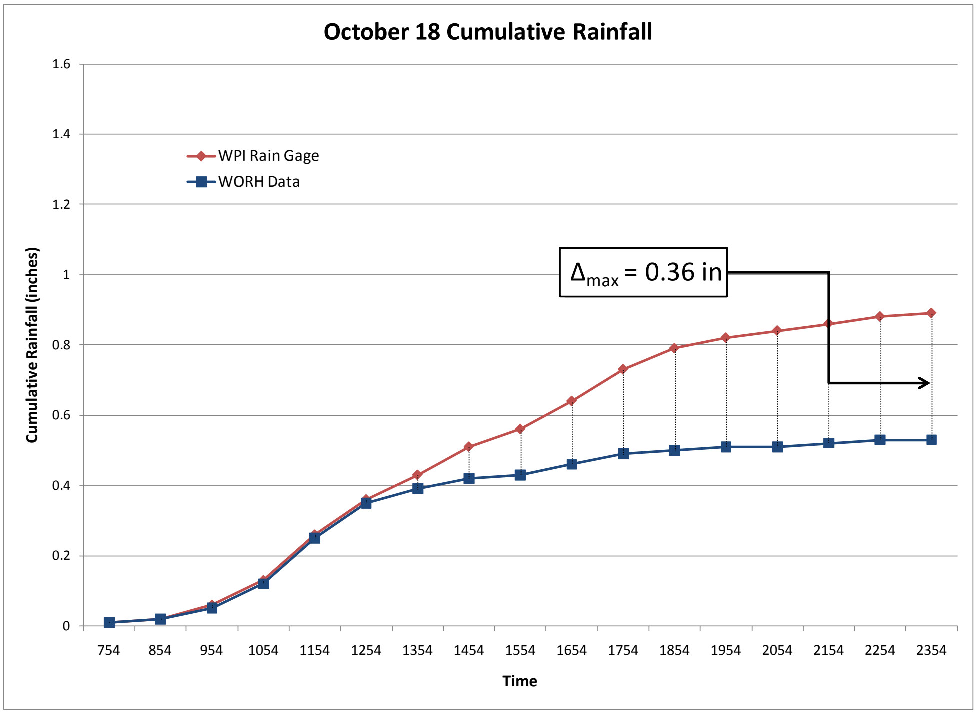


Figure 3.1: First Rain Gage Comparison Test

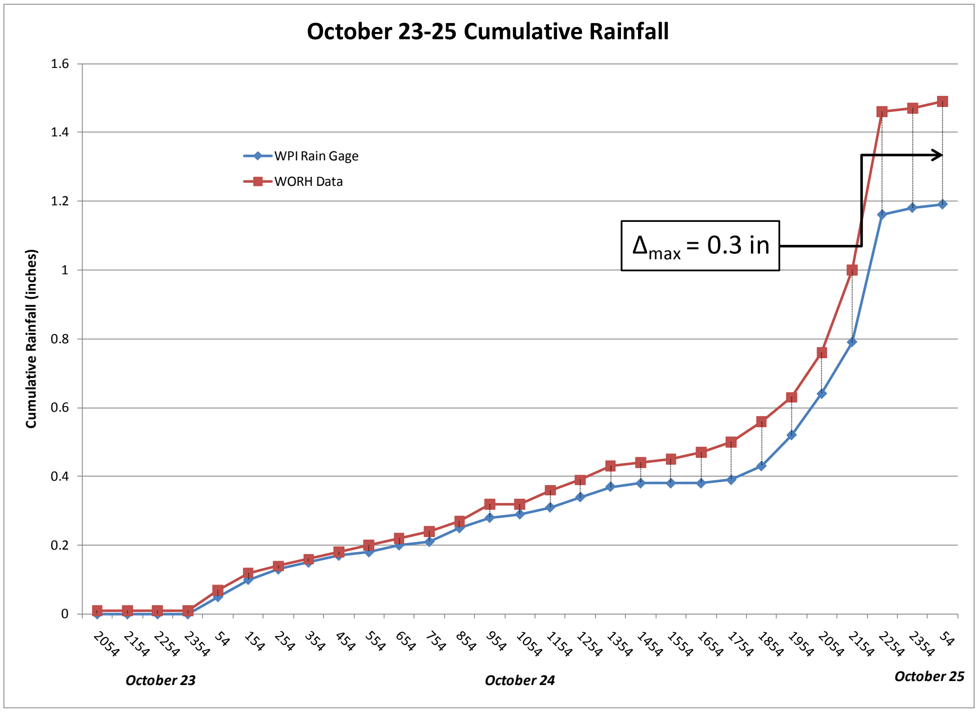


Figure 3.2: Second Rain Gage Comparison Test

NWS precipitation data from Worcester Regional Airport Information has been compiled for the time period beginning April 1, 2009 and ending April 15, 2010. This generally coincided with the timeframe during which the green roof flow meters were being tested and when stormwater grab samples began to be collected. The data is continually updated since stormwater grab samples continue to be obtained on a weekly basis from the green roof. The daily precipitation amounts are shown in Figure 4.2, Figure 4.4, Figure 4.6, and Figure 4.8, which also display the concentrations of total phosphorus in the stormwater runoff from both the green and white roofs.

The entire data set (provided in Appendix A) was then reviewed to determine typical storm sizes that have been experienced during the study period. A total of 159 storms were recorded. Storms were considered separate events when the duration between precipitation recordings was 2 hours or greater. Table 3.1 indicates the average, high, and low storm sizes.

Table 3.1: Worcester Area Rain Patterns (April 1, 2009-March 31, 2010)

	Cumulative Rainfall (in)	Duration (hours)	Intensity (in/hr)	Highest Hour (in)
average	0.35	6.48	0.05	0.11
highest	4.14	61	0.54	1.16
lowest	0.01	1	0.0025	0.01
total	56.3			

3.2.2 Stormwater Grab Samples

Two flow meters and sampling ports have been installed within the storm drain system of East Hall: one to measure drainage from the green roof; and the other to measure drainage from the "non-green" portion of the roof. The configuration of the station that monitors the green roof is shown in Figure 3.3. The white roof sampling station is configured in the same manner.

Figure 3.3: East Hall Green Roof Monitoring Station

For water quality, two of the sampling taps can be utilized to maintain a continuous flow of stormwater through the Hach Hydrolab water quality monitoring sonde, which can continuously monitor pH, conductivity, dissolved oxygen, turbidity, and temperature. However, this function has yet to be utilized since the ability to simultaneously measure runoff flow rates is not yet online. Instead, the third available tap was used to extract manual samples for analysis in the laboratory.

The samples were collected directly into 50-ml sample bottles after being rinsed three times with a small amount of sample from the tap. The samples were immediately refrigerated until they were analyzed in the laboratory, usually within 2-3 days. Some samples are shown in Figure 3.4. It was fairly common for samples to be colored dark yellow as demonstrated by the June 8 white roof sample (fourth from left), especially after periods with little-to-no rain. However, the yellow coloring did not necessarily coincide with high phosphorus concentrations. The phosphorus content of the June 8 sample was determined to be 0.34 mg/l Tot-P-PO_4^{-3}, while the clearer sample to its right (June 11) measured 0.49 mg/l Tot-P-PO_4^{-3}.

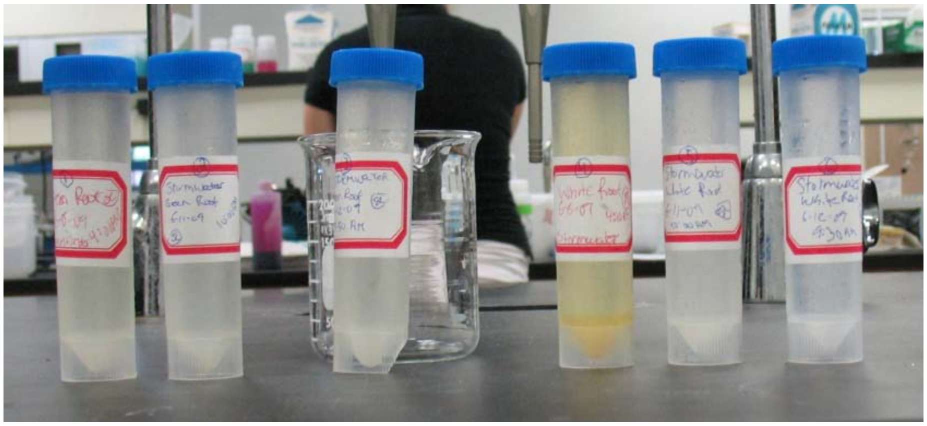


Figure 3.4: Green and White Roof Samples, June 2009

3.3 Simulated Rainfall Events in Greenhouse

3.3.1 Apparatus Design

Two stands were designed and constructed for use in the greenhouse experiments as shown in Figure 3.5. An 8-foot folding banquet table provides the supporting structure. The upper two layers of plastic framework were modified from plastic storage shelving, purchased at a nearby home improvement retail store. Each stand's top layer supports three (3) irrigation lines, which are each pierced with two (2) small holes that deliver water in drops at equal distances from each other. These drops fall to the second layer, which is comprised of standard plastic window screen, through which the water drops are dispersed into a diverse, but fairly consistent rainfall pattern.

Figure 3.5: Greenhouse Equipment Configuration

The influent to all six (6) irrigation lines is pumped from one source at a flow rate controlled by the pump shown at center, which has the ability to pump at low enough flow rates to mimic rainfall patterns observed in the study area. The influent stored in the orange bucket shown bottom-center in Figure 3.5 was collected from the white roof storm drain in East Hall. It had been observed that stormwater runoff from the white roof often had little to no phosphorus after rainfall events. As such, the storm drain from the white roof could be used as a rainwater collector for use in the greenhouse experiments, which would be preferable to using tap water or laboratory-grade e-pure water since the background levels of various water quality parameters would more closely mimic field conditions. This greenhouse “rainwater” was collected from the white roof storm drain after or during rain events, and tested. Total influent phosphorus concentrations ranged between 0 and 0.39 mg/l Tot-P-PO_4^{-3}.

The white plastic basins in which the green roof panels are placed are stand-up shower bases, whose outlet drains to a funnel and tube to the hydrolab flow-though device, as pictured in Figure 3.6. From the hydrolab, the water flows through another ¼-inch tube to outlet collection buckets, which are placed on scales. The mass of water was recorded every minute throughout the duration of the greenhouse tests.

Figure 3.6: Hydrolab Flow-through Device

3.3.2 Design of Simulated Rainfall Events

On March 19, March 25, April 7, and April 16, four (4) storm events were simulated in the greenhouse at the lowest flow rates that effectively produced rainfall patterns in the irrigation system described above. These low rates ranged between 70 and 80 ml/min. As indicated in Table 3.2, three of these experiments corresponded to average storm sizes (0.37 inches) observed in Worcester over the past year, as presented previously in Table 3.1. Since the antecedent conditions on April 16 were very dry in the greenhouse, the experiment was run for an extended period of time in order to achieve a steady-state condition between the inflow and outflow. On April 17, a higher flow rate was used, which corresponded with the highest recorded storm intensity in Worcester with the study period.

Table 3.2: Various Greenhouse Flow Rates & Corresponding Storm Sizes

	Q_{in} (ml/min)	Duration (min)	Volume (L)	Volume (in^3)	Simulated Rainfall (in)	Simulated Intensity (in/hr)
19-Mar	69.7	51	3.56	217.03	0.19	0.22
25-Mar	79.8	88	7.02	428.39	0.37	0.25
7-Apr	69.0	97	6.69	408.48	0.35	0.22
16-Apr	73.1	171	12.50	763.15	0.66	0.23
17-Apr	182.0	37	6.73	410.98	0.36	0.58

During the rainfall simulation tests, water samples would ideally be collected from the outlet tubing at key points during the “storm”:

- when runoff first began flowing out of the outlet tube;
- when approximately one equipment storage volume had passed through the hydrolab flow-through device (this would best represent a “first flush” condition);
- when the runoff flow rate reached a steady-state with the inflow rate (sometimes this was the same point as the “first flush” just described;
- at regular intervals of equipment storage volumes (when feasible); and
- at the point at which runoff had nearly ceased.

Additionally, a sample was collected from the outflow bucket at the conclusion of the experiment after mixing the contents of the bucket. This sample would best represent the Event Mean Concentration (EMC). This consistent set of samples was not collected for every storm event since the testing process was modified slightly from storm-to-storm to achieve the best simulation process.

Similarly, soil samples were collected before most tests, at steady-state for all tests, and after one of the tests (4-16). The "steady-state" soil samples were considered the point at which field capacity had been reached. As discussed in more detail in Chapter 4 – Analysis & Results, the moisture contents of the soil at steady-state were fairly consistently at or near 25%.

Lastly, plant samples were obtained on each testing day for the purposes of monitoring growth and changes in phosphorus content. The one exception was that a plant sample was not taken on the last test date (April 17) since a sample had been taken the previous day.

3.4 Laboratory Analyses

3.4.1 Measuring Phosphorus Content in Water, Soil, and Plants

The total phosphorus content of the water, plant, and soil samples were obtained through a nitric-sulfuric acid digestion process followed by colorimetric analysis using a Hach DR/3000 Color Spectrophotometer. This process is modified from EPA METHOD #: 365.2 (EPA 1971), and utilizes nitric acid and molybdovanadate instead of ammonium persulfate as the reagent to determine total phosphorus. For future researchers, a step-by-step method has been provided in Appendix B. In general, the process utilizes nitric and sulfuric acids as solvents to remove phosphorus from any particulate matter in the samples. The samples are then neutralized with Sodium Hydroxide and diluted back to their original volume and analyzed colorimetrically with the use of molybdovanadate and a Color Spectrophotometer. The samples are reduced to a yellow-colored complex, which is proportional to the phosphorus concentration. This process utilizes standard solutions of Tot-P to develop a calibration curve, and results are converted to Tot-P-PO_4^{-3}.

For soil and plant samples, the digestion process is nearly the same, except that there are a few additional preparatory steps. For soil samples, nitric acid is used as the preliminary solvent. The samples are filtered and then digested in sulfuric acid, after which point they are analyzed in the same fashion as the water samples. For plants, only the terminal parts of the plant (leaves) are used. They are first oven dried overnight, and then digested in the same manner as the soils. Also, the results are reported in mg/l as total phosphorus (Tot-P).

This research also made use of ion chromatography (IC) to measure dissolved phosphorus concentrations. Again, step-by-step instructions have been provided in the appendix for future researchers. (Appendix C). Samples are filtered through a 0.45-micron filter before injection into the IC unit and, as such, results represent dissolved phosphorus concentrations. The IC is calibrated with standard known solutions of phosphorus as phosphate, and so results are expressed in mg/l as $P\text{-}PO_4^{-3}$. The IC also provided concentrations of other anions, including fluoride, chloride, nitrite, nitrate, bromide, and sulfate. These values are provided in Appendices D and E.

For two of the storms, some cations were also measured using atomic absorption. The greenhouse samples collected on March 25 were analyzed sodium, calcium, magnesium, potassium, iron, manganese, and copper. Similarly, the samples collected from the April 7 simulated rain event was analyzed for iron. These results are included in Appendix E with the results of the anion analysis.

3.4.2 Analysis of Physical Characteristics of the Soil

All soil samples collected in the greenhouse during the simulated rainfall events were analyzed for moisture content. This was done by weighing the samples as collected, then drying at 105°F for 24 hours. After drying, the samples were weighed again with the mass that was lost to evaporation being utilized to determine the moisture content of the initial sample.

$$\text{Moisture Content} = \frac{(original\ \ soil\ mass\,)-(oven\ \ dry\ \ soil\ mass\,)}{original\ \ soil\ mass} \qquad \textit{(equation 3.1)}$$

In addition to the greenhouse samples, a representative soil sample was obtained from the East Hall roof the day after 4.16 inches of rain fell over a 56-hour time period (March 29-31, 2010). The entire sample was analyzed for moisture content as described above.

In addition, the large sample (almost 500g after drying) was alliquotted for use in additional analyses. Five (5) aliquotted portions were analyzed for phosphorus content, resulting in values as displayed in Table 3.3. The average value was calculated to 770 mg/kg Total Phosphorus, with a standard deviation of 256. While three of the samples were very similar, the high and low values demonstrate the variability of the green roof growing medium.

Table 3.3: Phosphorus Content of Green Roof Soil

	mg Tot-P/kg soil
Portion 1	1172
Portion 2	779
Portion 3	717
Portion 4	461
Portion 5	719

The properties of the soil in situ were analyzed by extracting two cores from the greenhouse roof panels. The two cores are shown in Figure 3.7. The core taken from Stand A is on the left. These cores were weighed and then saturated as shown in Figure 3.8. Approximately 50ml of water was used to reach this saturated condition. After weighing again, the cores were poured onto drying pans, and all soil particles were rinsed onto the pans as depicted in Figures 3.9-3.11. They were then placed in the drying oven for 24 hours at 105°F and weighed again.

Figure 3.7: Soil Cores from Greenhouse Green Roof Panels

Figure 3.8: Saturated Green Roof Panel Cores

Figure 3.9: Stand A onto drying pan

Figure 3.10: Rinsing out all sediment

Figure 3.11: All sediment onto drying pan

3.4.3 Soil Flush Tests

To further explore the phosphorus desorption characteristics of the green roof soil, a flush test was conducted. An aliquotted portion of the representative roof sample, with a mass of 11.963 g, was placed in a filter-funnel apparatus as shown in Figure 3.12. The filter had a screen size of 0.117 inches. Laboratory-grade e-pure water was used for 10 consecutive flushes. A fresh volume of 50 ml was measured and poured slowly onto the soil for each flush. The filter-funnel was placed in a 250-ml beaker to capture the rinse water. After the water had finished draining, the filter funnel was placed over the next beaker for another flush. All ten flushes were injected into the Ion Chromatography unit, and four of the flushes (numbers 1, 2, 6, and 10) were also analyzed for total phosphorus using the color spectrophotometer. After the flush test was concluded, the soil remaining in the filter-funnel was oven-dried for 24 hours and analyzed for total phosphorus using nitric-sulfuric acid digestion as described previously.

Figure 3.12: Soil Flush Test

4.0 Results & Analysis

This chapter presents the data collection and analysis results of this research. The information collected from the water quality field monitoring of the East Hall Roof has been analyzed and presented, and trends and observations are discussed. The results from the greenhouse experiments are presented in detail and include analyses for both flow attenuation of the green roof panels as well as water quality analysis of runoff. Lastly, the results and implications of additional laboratory analyses of the growing medium as well as the vegetation at various stages of growth are included here.

4.1 Field Monitoring of East Hall Roof

Runoff was collected from the storm drains of the both the green and white roof at various times in different seasons throughout the year. All samples were analyzed for total phosphorus as phosphate (Tot-P-PO_4^{-3}), while those collected since December 2009 were additionally analyzed for dissolved phosphate. Appendix D provides a complete listing of the results of these analyses.

Sometimes these samples were collected during or just after a storm, while other times the samples were collected during dry conditions, and therefore represent the phosphorus content of the water that has remained in the drainage pipes. While this variability of the stormwater samples limits the ability to accurately characterize the quality of the green and white roof runoff, the information presents some helpful trends regarding the seasonal variation of this building's stormwater impact.

4.1.1 Summer 2009

Figure 4.1 depicts the Nitsch/Magliozzi green roof in early summer 2009. The vegetation is in full bloom. The light purple colors are the blooms of the chive plants, while the reds and golds are the various sedum plant varieties. At this mature growth stage, one anticipates that the vegetation is providing its maximum benefit to green roof performance.

Figure 4.1: Nitsch/Magliozzi Green Roof in Summer 2009
(Photo courtesy of Fred DiMauro, WPI, Assistance Vice President for Facilities)

Figure 4.2 depicts total daily precipitation as well as the phosphorus content of various samples of stormwater collected from both the white and green roofs. As indicated, June 2009 was an especially rainy month. Rainfall occurred on 21 days of the month, which is not typical for the Worcester area. Grab samples of stormwater from the drainage pipe sampling ports were first collected in June 2009. These initial samples were analyzed for total phosphorus (Total-P), and the values indicated in Figure 4.2 are of total phosphorus as phosphate (Tot-P-PO_4^{-3}). The highest value observed was in runoff from the green roof collected on July 7 at 3:45 PM, which was during the hour in which 0.55 inches of rain were recorded at Worcester Regional Airport. This was one of the highest rainfall intensity hours recorded all year, and this sample contained the highest amount of total phosphorus measured in all grab samples during the study period. Other samples were collected during less intense rainfall or after the rain had stopped. The second and third highest concentrations of phosphorus (7.05 and 3.37 mg/l P-PO_4^{-3}) were measured in the samples taken a few weeks prior, on June 12 and June 22, respectively. No other grab samples exhibited concentrations higher than 3 mg/l P-PO_4^{-3} within the entire study period.

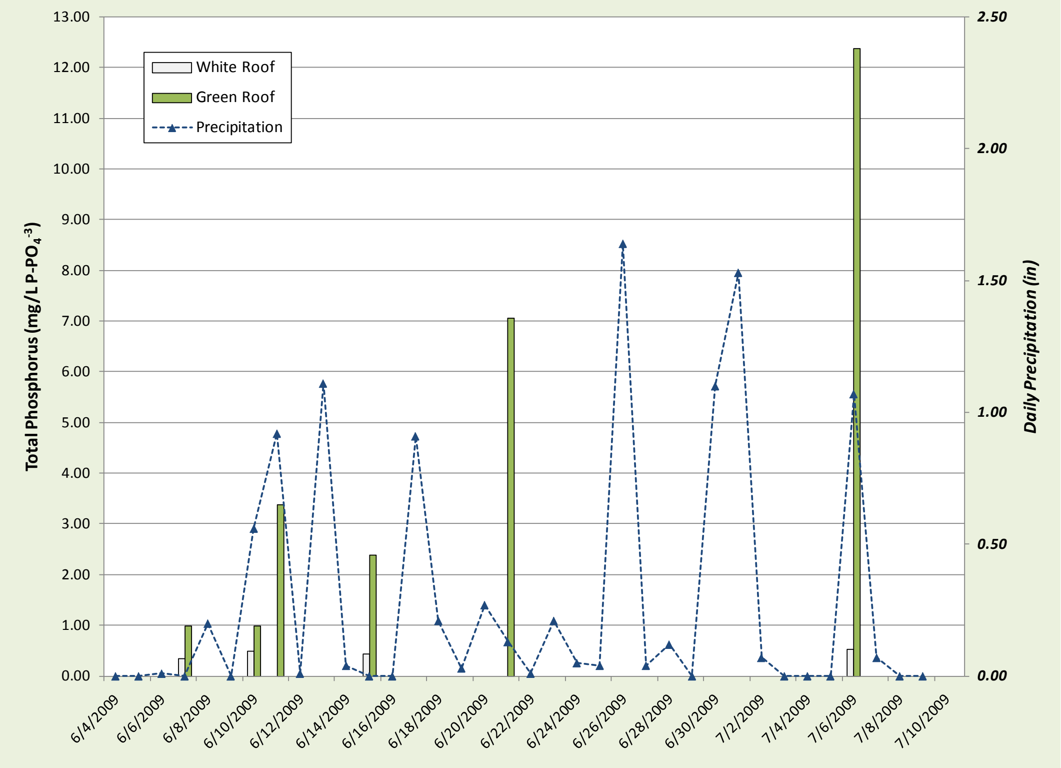


Figure 4.2: Summer 2009 Roof Runoff Phosphorus Content

4.1.2 Autumn 2009

Figure 4.3 shows the roof vegetation at the end of its growing season. The gravelly upper soil layer is also visible. These perennial plants will remain dormant until spring. The decayed vegetation will not be removed, but will decompose into the growing medium. Some of this vegetation (the dried sedum blooms shown in the foreground) was still intact as pictured when two of these green roof panels were brought into the greenhouse for further study in March 2010. The phosphorus content of the decayed plant material was determined to be 0.6 mg/g Tot-P.

Figure 4.3: Green Roof, November 2009 (DiMauro)

Figure 4.4 illustrates the daily precipitation observed between mid-October through mid-December 2009. Also shown are the total phosphorus concentrations of the grab samples collected during that timeframe. The most significant observation in the samples analyzed in autumn 2009 is the spike in phosphorus concentration measured in the runoff collected from the white roof storm drain (4.0 mg/l P-PO_4^{-3}) on December 14. While this is the highest white roof concentration and exceeded the green roof concentration that day, all other green roof concentrations were consistently higher than those measured in the white roof samples. Yet, also notable, the green roof runoff phosphorus concentrations were reduced from those observed in the summer. The highest green roof concentration observed this season was 1.25 mg/l P-PO_4^{-3} on December 14, just before the official start of the winter season.

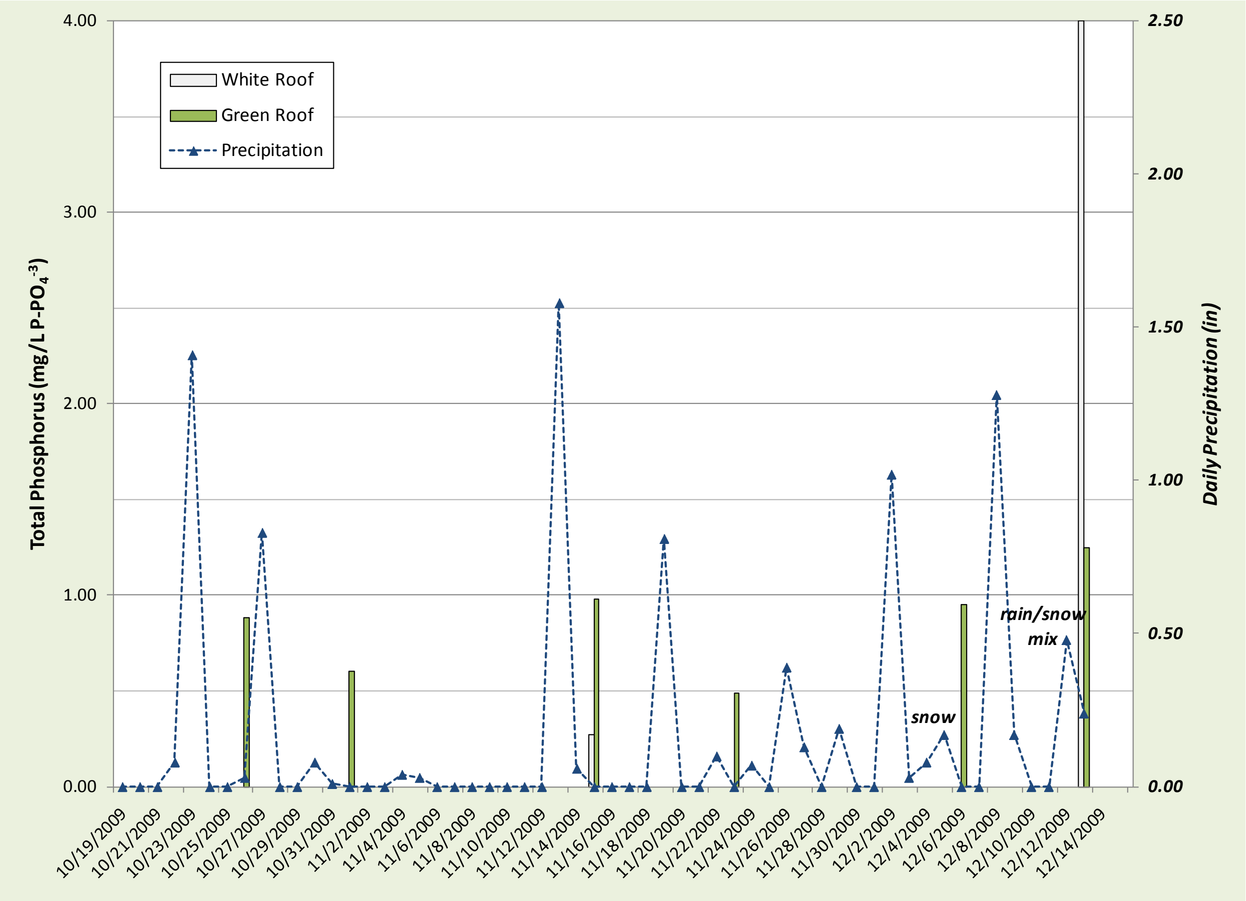


Figure 4.4: Autumn 2009 Roof Runoff Phosphorus Content

4.1.3 Winter 2010

Figure 4.5: Green Roof, January 2010 (DiMauro)

Figure 4.5 depicts the green roof under light snow cover in January 2010. This was a common sight during this particular winter. Somewhat atypical for Worcester, there were not many large storms, and very little accumulation. In addition, there were several rain events, instead of snow. It is unknown if snow cover, such as that pictured, had enough contact time to melt before the rain events washed it away.

During this season, unanticipated high phosphorus concentrations were observed in the white roof runoff, especially in those samples collected on February 2 and March 8 as shown in Figure 4.6. Not only did the phosphorus concentrations exceed those in the samples from the green roof, but they also represent the highest values recorded for the season. Note the precipitation patterns preceding those two dates. In both cases, a heavy rainfall had occurred and then was followed by 8-10 days of no precipitation or only very light snowfall. As a result, the stormwater had been stagnant in the pipe for a little over on week. It is possible that the cast iron pipe could be a contributing source.

In addition, as indicated in the tabulated results provided in Appendix D, no phosphorus was detected in the white roof samples that passed through a 0.45-micron filter, i.e. all phosphorus measured was associated with larger sediment particles.

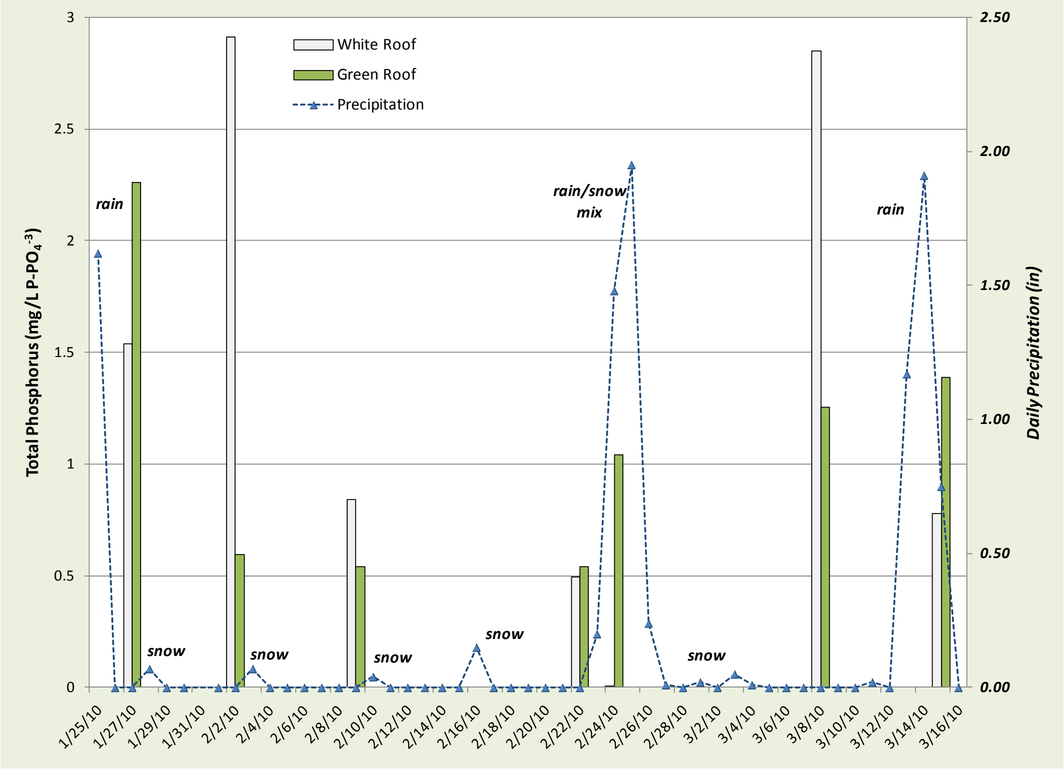


Figure 4.6: Winter 2010 Roof Runoff Phosphorus Content

4.1.4 Spring 2010

Figure 4.7 shows an image of the green roof during its second spring. The mature perennials are quickly reviving from their dormant winter state, and most panels are fully vegetated. The portion of the roof that drains through the sampling port station on the first floor is the 925-ft^2 area to the left of the walkway furthest from the camera – encircled in yellow on Figure 4.7.

Figure 4.7: Green Roof, April 2010 (DiMauro)

The samples collected this spring have shown a continuing presence of phosphorus in green roof runoff, with values ranging between 0.96 and 1.59 mg/l P-PO_4^{-3} as shown in Figure 4.8. It is not clear why the concentrations decreased on April 7 and April 19 from a nearly consistent runoff concentration of about 1.5 mg/l Tot-P-PO_4^{-3}. The white roof concentrations, as observed the previous summer and early autumn, are always lower than the green roof concentrations.

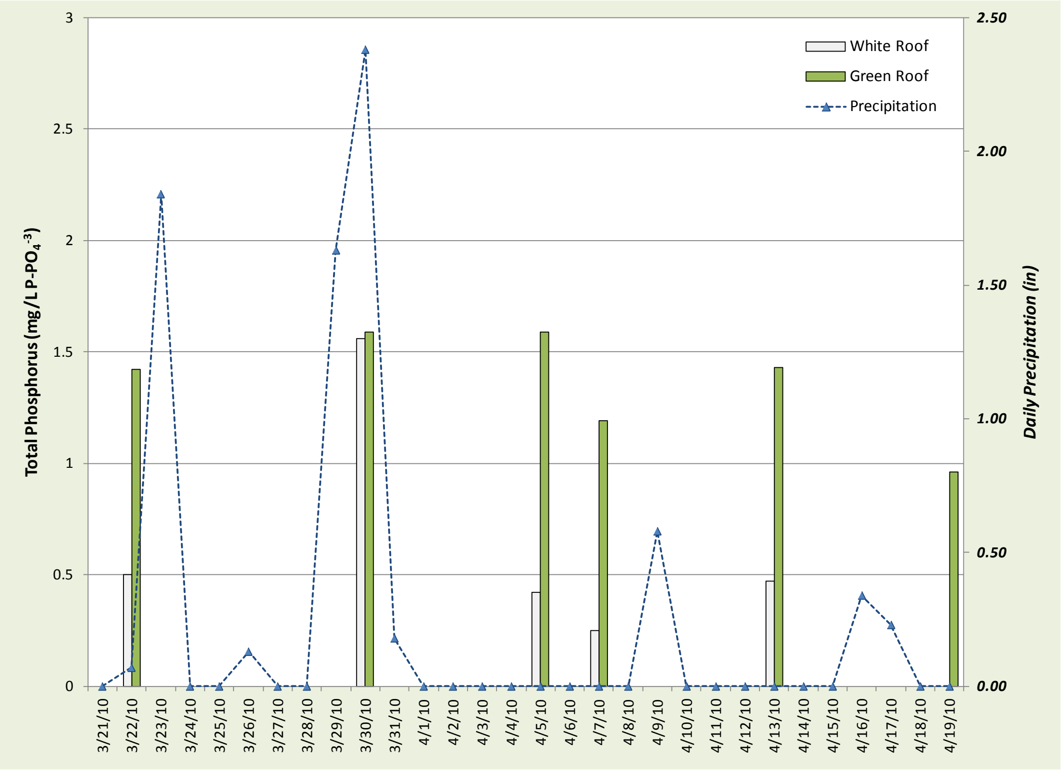


Figure 4.8: Spring 2010 Roof Runoff Phosphorus Content

In summary, the concentration of total phosphorus in the green roof runoff is quite often in the range of 1 to 1.5 mg/l P-PO_4^{-3}. There were times during the autumn and winter when concentrations dropped to approximately 0.5, but the most significant observation are the much higher concentrations observed during the summer.

4.2 Laboratory Testing of Green Roof Panels

To provide more insight into the question regarding the higher concentrations observed in green roof runoff during the summer, two (2) of the 4-ft^2 panels from the green roof were brought into the greenhouse laboratory for further study. The two panels were carefully selected to minimize the variability between the panels. Although the plants were dormant when retrieved from the roof, green roof panels with similar plant varieties at comparable stages of establishment were chosen. The objectives of the greenhouse experiments were to accelerate the growth process and observe trends in phosphorus transformations under conditions by which rainfall could be controlled, and the characteristics of the soil, plants, and runoff could be closely monitored. Simulated rainfall events were designed and performed over a one-month time period beginning in mid-March 2010.

4.2.1 Rainfall and Runoff Flow Characteristics of the Green Roof Panels

Five (5) simulated storm events were conducted in the greenhouse. As indicated in Table 4.1, three (3) of the storms were considered indicative of spring weather, while two (2) had much drier antecedent conditions and are more representative of summer storms. Those events described as “light” simulated the lower intensity precipitation (0.2-0.32 in/hr), while the “heavy” storm was conducted at a much higher rainfall intensity (0.58 in/hr). The test performed on April 7 did not reach a steady state condition between the inflow and outflow, but this is a likely scenario in the field. The April 7 storm delivered a total of 0.51 inches of rain. As detailed in Chapter 3 – Methods, the “average” storm that was observed in Worcester during the previous year delivered less rain than the Light Summer Rain A simulated event. It is highly probable that the green roof runoff from East Hall does not always reach a state. Still, a second storm (Light Summer Rain B) was conducted for a longer duration so that water quality parameters could be more easily compared to the spring storms, all of which did achieve a steady state.

Table 4.1: Characteristics of Simulated Greenhouse Storm Events

Name	Date	Antecedent Soil Moisture Content	Duration (min)	Influent Volume (L)	Simulated Rainfall (in)	Simulated Intensity (in/hr)
Light Spring Shower	3-19	*Not measured*	51	4.02	0.21	0.25
Light Spring Rain	3-25	26.0%	88	7.58	0.40	0.27
Heavy Spring Rain	4-17	21.8%	37	8.33	0.44	0.72
Light Summer Rain A	4-7	9.0%	97	9.66	0.51	0.32
Light Summer Rain B	4-16	11.0%	171	14.75	0.78	0.27

The five (5) hydrographs depicted in Figures 4.9-4.13 have been prepared to demonstrate the runoff flow characteristics of the green roof panels. All had similar patterns of steep slopes in flow rate after the pumps were shut off, which indicates that the roof panels drained quickly after each storm. Also notable, most storms achieved a steady outflow rate, nearly equal to the inflow rate before the pumps were turned off.

The Light Spring Shower depicted in Figure 4.9 was conducted at the lowest simulated rainfall intensity (0.25 in/hr) and resulted in the smallest total precipitation (0.21 inches of rainfall). During this first test, the outflow was not measured after the pumps were turned off, so the tail end of the hydrograph was estimated using the flow data from the Light Summer Rain B test from April 16.

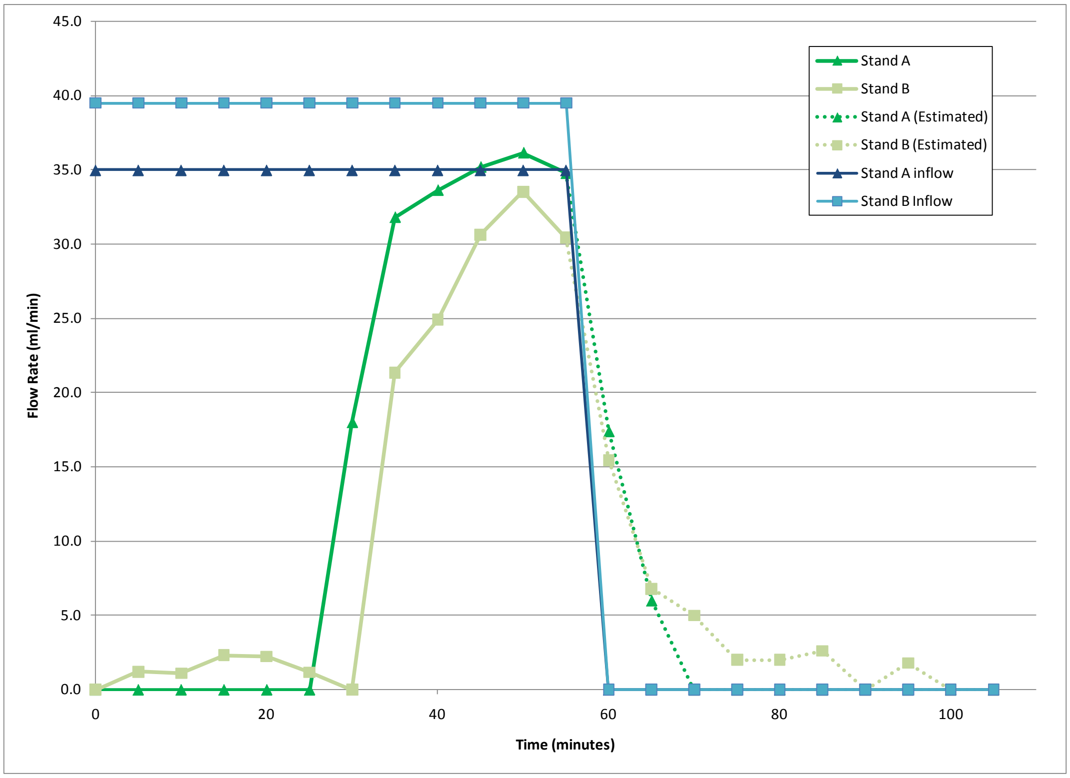


Figure 4.9: Light Spring Shower (3-19-2010)

Figure 4.10 illustrates the flow rates for the Light Spring Rain event, which was conducted at a similar rainfall intensity as the Light Spring Shower event, but was continued for a longer duration, resulting in almost double the total rainfall (0.4 inches). Again, the outflows reached a steady rate before ending the simulated storm event. This time, the plants were removed from the bases and the pumps were left running. The flow rates were measured again for the incident precipitation measurement described in more detail in Section 4.2.2 below. As such, the tail end of this hydrograph was also estimated.

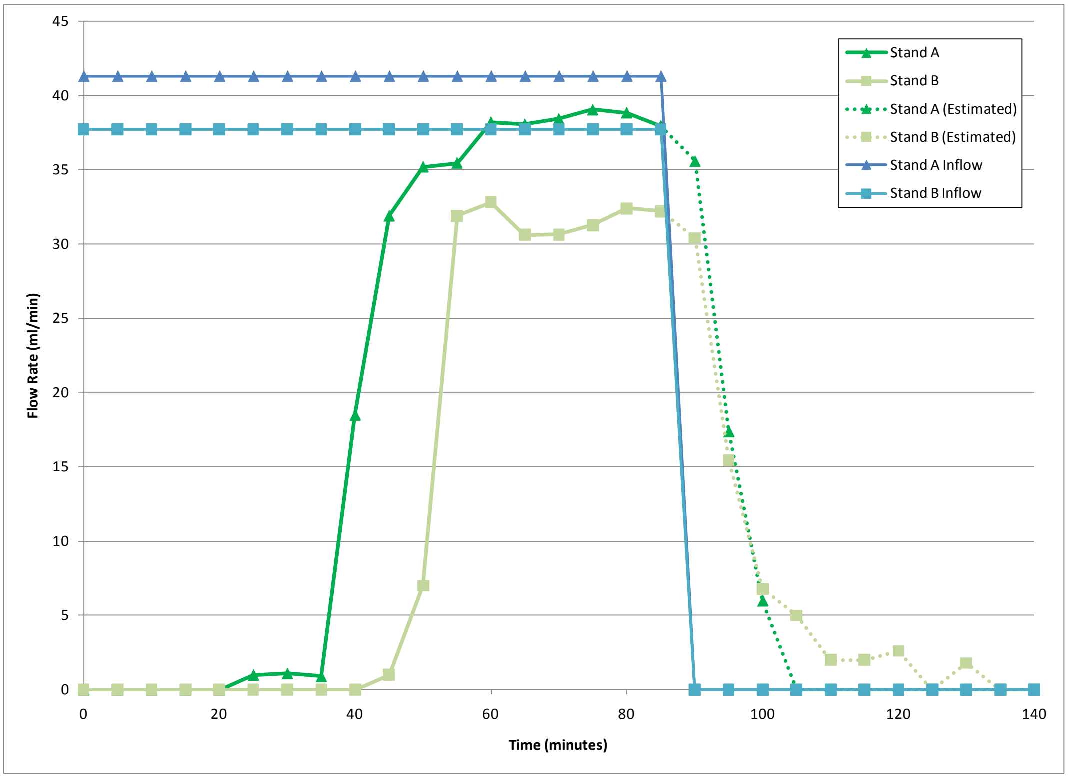


Figure 4.10: Light Spring Rain (3-25-2010)

The Heavy Spring Rain event, represented in Figure 4.11, achieved a steady state between the inflow and the outflow in about 40 minutes, at which point the pumps were turned off and the outflow drainage was monitored. This storm produced runoff the most quickly (5 min from start of rain event).

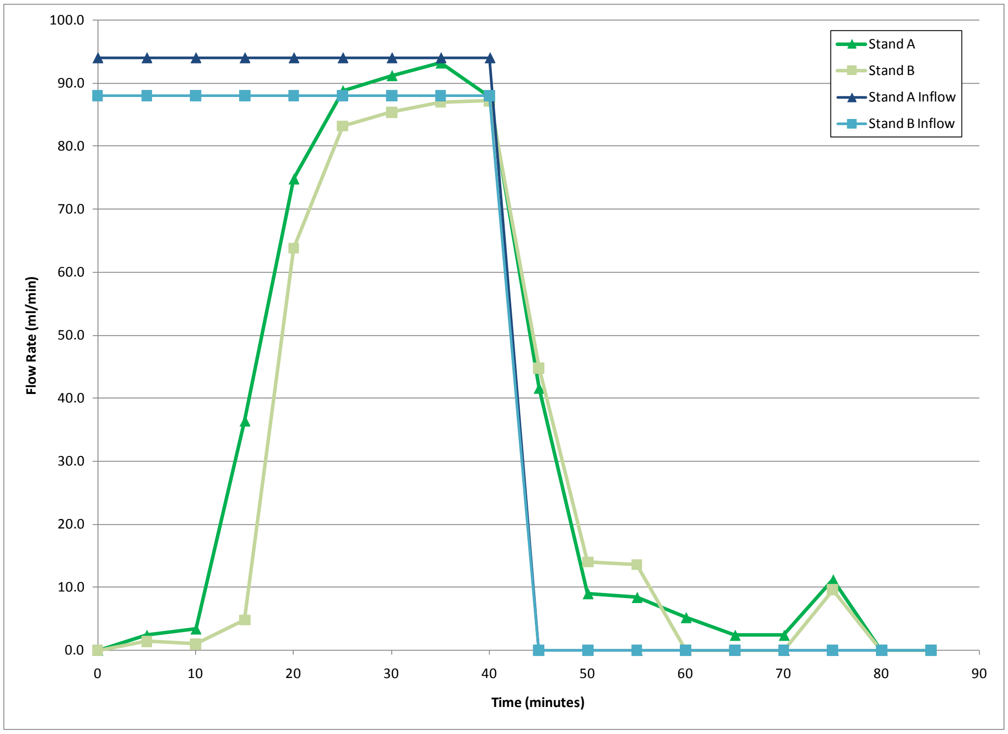


Figure 4.11: Heavy Spring Rain (4-17-2010)

The hydrograph in Figure 4.12 was developed with the data from the Light Summer Rain "A" storm, which was performed on the warmest day in the greenhouse, following two weeks without precipitation. The green roof panels were very low in moisture content. Runoff was not observed until nearly one hour into the test. Further, after more than 90 minutes of simulated rainfall, the outflows had still not reached a steady state. The pumps were turned off and the runoff slowly stopped flowing.

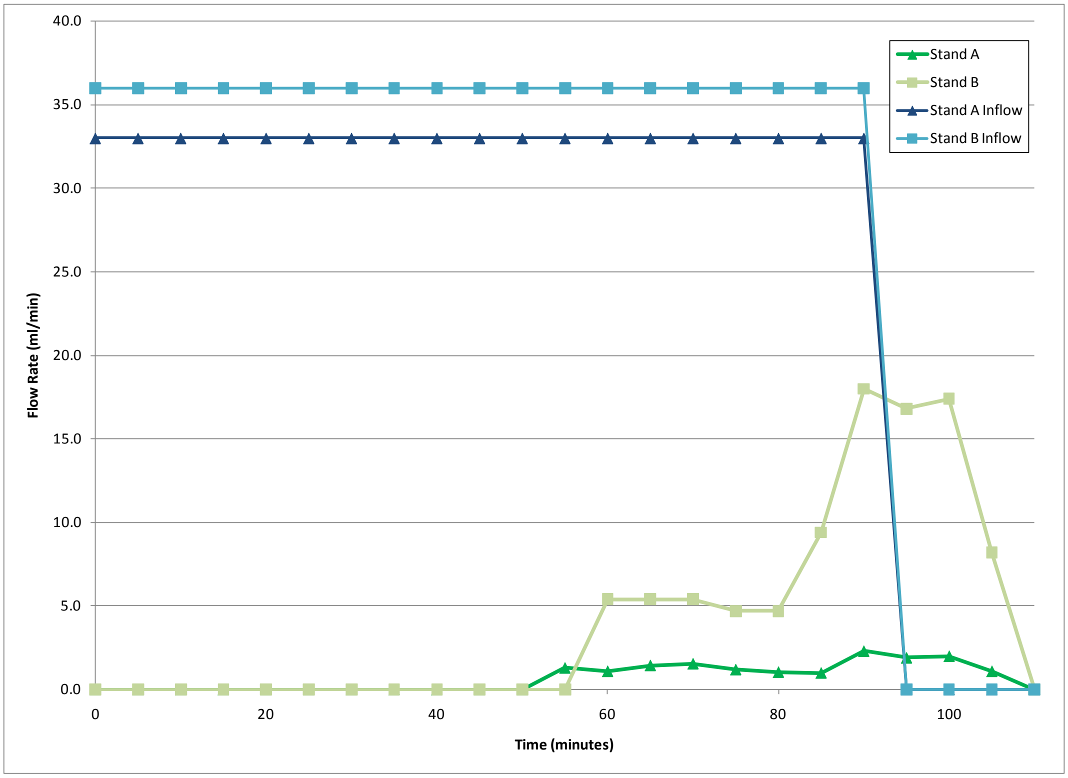


Figure 4.12: Light Summer Rain A (4-7-2010)

Figure 4.13 displays the runoff distribution for the Light Summer Rain B event. Again, the antecedent moisture content of the soil was low. In fact, on Stand A, the moisture content was 9.3%, compared to 12.6% on Stand B. Although the inflow rate for Stand A was slightly higher, and the outflow began sooner than on Stand B, the outflow rate for Stand A did not quite reach steady state. On Stand B, steady state was achieved in about 2 hours. Notably, the outflow rate ceased much more quickly on Stand B then on Stand A.

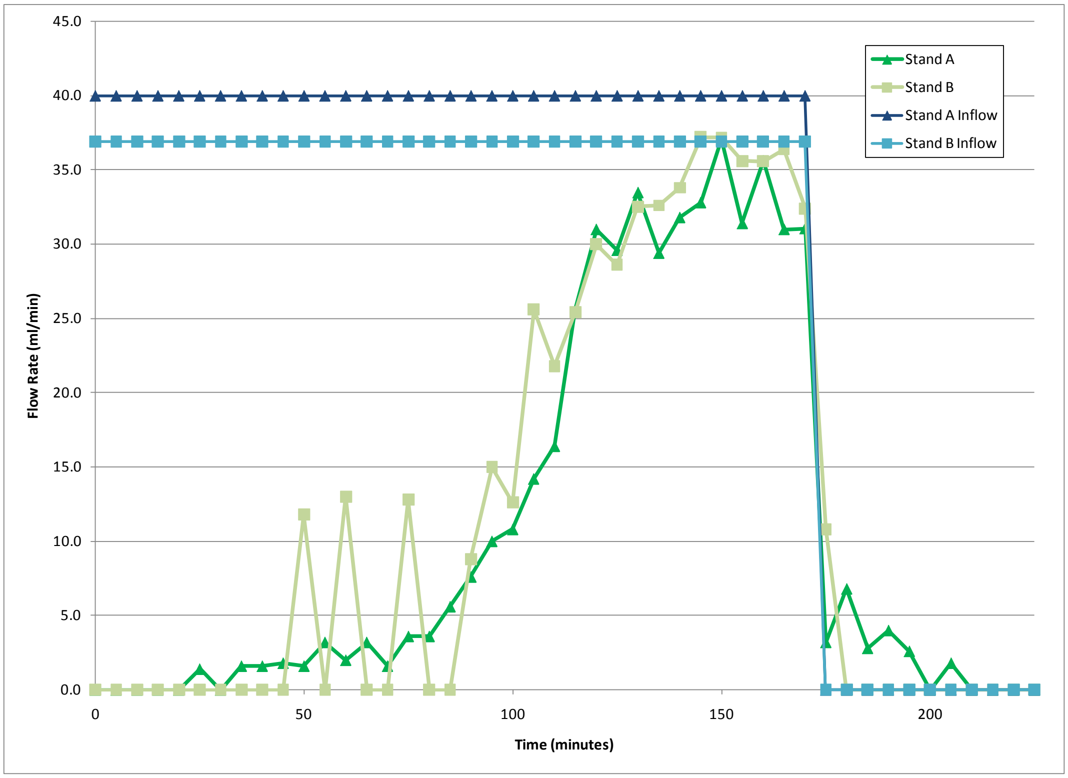


Figure 4.13: Light Summer Rain B (4-16-2010)

In summary, the time that it took for each stands' runoff to begin flowing and the time it took to reach its peak flow rate appears to be related to both the inflow rate and the antecedent soil moisture content (θ). Table 4.2 lists theses comparative values.

Table 4.2: Comparisons of Flow Rate, Moisture Content, and Timing of Outflow

	Stand A				Stand B			
	θ (soil moisture content)	Inflow Rate (Q_{in}) (ml/min)	Time to Outflow (min)	Time to Peak (T_p) (min)	θ (soil moisture content)	Inflow Rate (Q_{in}) (ml/min)	Time to Outflow (min)	Time to Peak (T_p) (min)
Light Spring Shower (3-19)	*Not obtained*	35	30	50*	*Not obtained*	39.5	5	50
Light Spring Rain (3-25)	25.7%	41.3	25	75	26.3%	37.7	45	60
Heavy Spring Rain (4-17)	20.3%	94	5	35*	23.3%	88	5	40*
Light Summer Rain A (4-7)	8.8%	33	55	90	9.2%	36	60	90
Light Summer Rain B (4-16)	9.3%	40	25	150	12.6%	36.9	50	150*

**indicates that a steady state between inflow and outflow was achieved*

4.2.2 Flow Retention Performance of the Green Roof Panels

The flow retention capabilities of the green roof panels were determined for each of the five (5) simulated greenhouse storms. Performance values were obtained by analyzing the water budget as represented in the following equation:

$$Plant \,\&\, Soil\ Storage = \sum inflows - \sum outflows \qquad \textit{(equation 4.1)}$$

$\sum inflows = P_{inc}$

where P_{inc} = Incident Precipitation

$\sum outflows = V_{out} = ET + R_{equ} + R$

where ET = Evapotranspiration

R_{equ} = Equipment Storage

R = Runoff

The incident precipitation (P_{inc}) values were determined using outflow rates that were measured before placing the plants on each stand. Prior to each greenhouse storm event, the influent pump was turned on with the stand basins empty. Outflow was collected through the hydrolab and into the outflow buckets, whose weights were recorded every minute. Once a consistent outflow rate was established, the influent pump was left on and the plants were placed underneath the simulated rainfall. This rate was multiplied by the duration of the storm to obtain the incident precipitation volume.

Evapotranspiration was determined by comparing the incident precipitation with the known influent volume that was pumped through the drip lines to create the rainfall events. The inflow volumes (V_{in}) were obtained by weighing the influent bucket before and after each test. The difference between the influent volume and P_{inc} was assumed to be lost to evapotranspiration (ET).

For the runoff values, outflow volumes were collected separately for Stand A and Stand B as described above. The Runoff volumes (R) were the cumulative volumes that were collected in each outflow bucket. Equipment storage (R_{equ}) was also measured at the end of each test, and represents the volume of outflow that was contained within the tubing and hydrolab device before entering the outflow buckets.

To validate this analysis, during the Light Summer Rain B test conducted on April 16, the plant and soil storage was measured by weighing the green roof panels before and after the test. The resulting difference in the weights of the panels was 7.52 kg, which corresponds very closely to the 7.34 liters calculated for plant/soil storage as described above.

Table 4.3 summarizes the water budget volumes, which are expressed in liters.

Table 4.3: Green Roof Panel Flow Retention Performance

	Light Spring Shower (3-19)	**Light Spring Rain (3-25)**	**Heavy Spring Rain (4-17)**	**Light Summer Rain A (4-7)**	**Light Summer Rain B (4-16)**
Influent Volume (V_{in})	*Not obtained*	7.58	8.33	9.66	14.75
Incident Precipitation (P_{inc})	3.80	6.96	6.74	6.69	13.14
Evapotranspiration (ET)	NA	0.63 (8%)	1.59 (19%)	2.96 (31%)	1.61 (11%)
Plant/Soil Storage (S)	1.37	2.92 (38%)	0.86 (10%)	5.59 (58%)	7.34 (51%)
Equipment Storage (R_{equ})	0.58	0.58	0.58	0.58	0.58
Runoff Volume (R)	1.85	3.46 (46%)	5.30 (64%)	0.52 (5%)	5.22 (35%)

These findings are consistent with the published literature as presented in Chapter 2. For example, the reduced retention capacity observed on April 17 during the Heavy Spring Rain event is a common trend that has been reported for extensive green roof performance. At high rainfall intensities, the field capacity of the green roof panels is quickly exceeded, and the thin layer of the extensive green roof design does not provide much storage capacity. However, the evapotranspiration rate during that storm was higher than the "Light Summer Rain" of the previous day. Although the temperature and relative humidity in the greenhouse were nearly the same on those two days, the increased ET is likely a function of the green roof vegetation's ability to rapidly uptake water when it becomes available, and the plants had not been irrigated since a week prior on April 7. So, although the growing medium did not provide much storage during the Heavy Spring rain, the plants' uptake of water did provide a stormwater retention benefit. Also notable, the temperature in the greenhouse on April 7 was the warmest of all events, likely leading to more evaporation, which would explain the higher ET value.

The improved performance during the "Light Summer Rain" events, however, is primarily more a function of the soil than of the plants. The low moisture content in the soil for Light Summer Rain "A" on April 7, which was about 9% prior to the simulated rain event, provided enough storage to retain 58% of the influent volume. The Light Summer Rain event "B" on April 16 had similar antecedent moisture conditions (11% soil moisture content), and the panels stored 51% of the influent volume. In contrast, the moisture content of the soil at the beginning of the Light Spring Rain Event on March 25 was the highest of all tests (26%), and the green roof panels retained only 38% of the influent volume, despite the fact this simulated storm used the smallest volume of water of all five (5) events.

Figure 4-14 further illustrates these changes in soil moisture content between and during the simulated rain events. Notable, the Heavy Spring Rain (4-17) event on both stands, as well as the Light Summer Rain (4-16) on Stand B reached a steady state between the inflow and outflow. As such, the moisture contents represented are indicative of the field capacity of the panels.

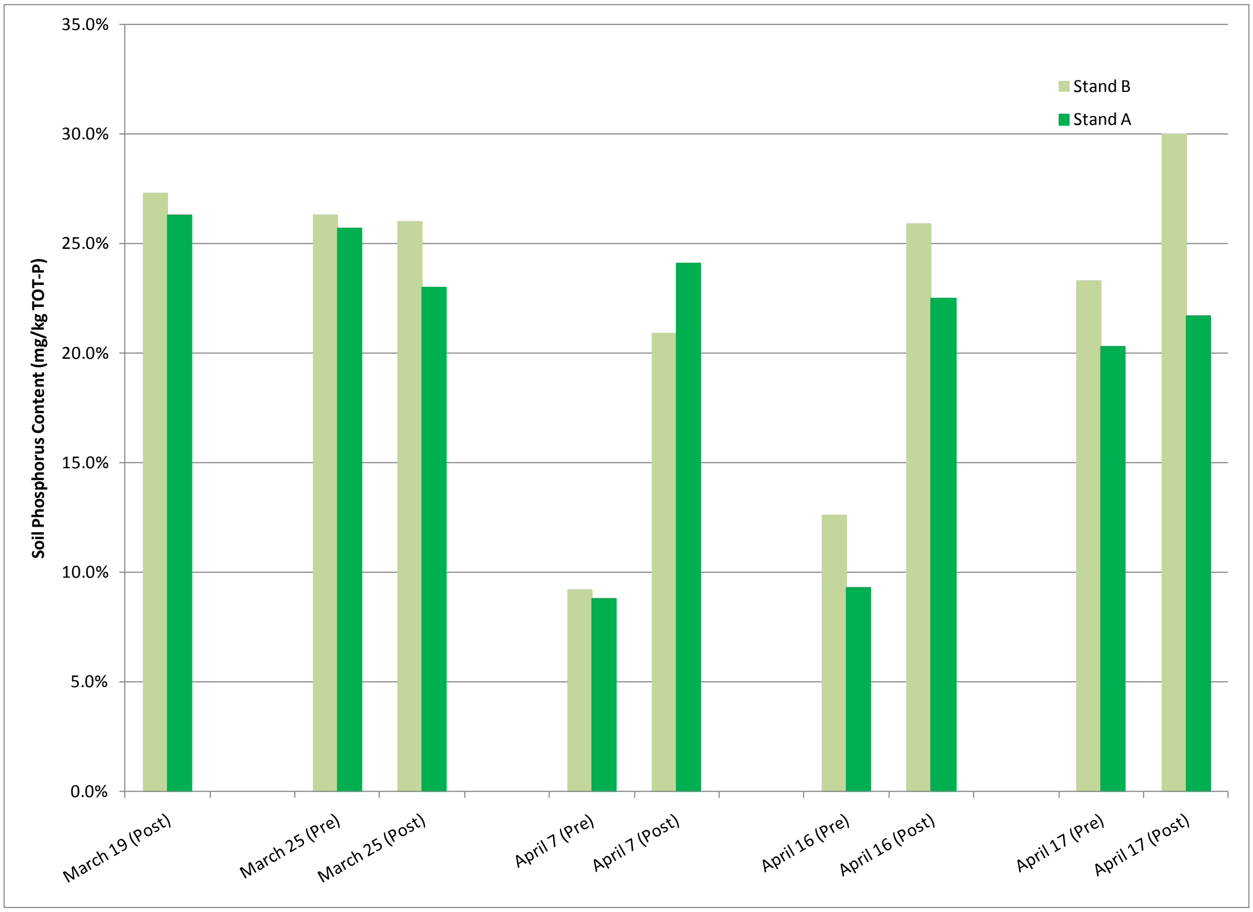


Figure 4.14: Changes in Soil Moisture Content

4.2.3 Water Quality Characteristics of Green Roof Panel Runoff

Phosphorus

Each of the simulated greenhouse storm event runoff samples were analyzed for phosphorus. Table 4.4 displays the total phosphorus measured in the outflow mix samples expressed as Event Mean Concentrations (EMC). The EMC for a storm is expressed as the total mass of a pollutant divided by the total volume of runoff for a given rainfall event. Since the outflow buckets contained the entire volume of runoff from each greenhouse test, the concentrations of the samples can be considered the EMC. These values are generally comparable to those measured in the roof grab samples.

Table 4.4: Event Mean Concentrations (EMC) Tot-P-PO_4^{-3} in Greenhouse Tests

	Stand A			Stand B		
	Influent Concentration mg/l P-PO_4^{-3}	Runoff EMC mg/l P-PO_4^{-3}	Load mg P-PO_4^{-3}	Influent Concentration mg/l P-PO_4^{-3}	Runoff EMC mg/l P-PO_4^{-3}	Load mg P-PO_4^{-3}
Light Spring Shower (3-19)	0.20	1.24	1.31	0.20	0.70	0.55
Light Spring Rain (3-25)	0.39	2.15	4.43	0.39	2.39	3.35
Heavy Spring Rain (4-17)	ND	1.99	5.53	ND	3.18	8.01
Light Summer Rain A (4-7)	0.12	0.41	0.16	0.12	2.37	1.04
Light Summer Rain B (4-16)	0.16	1.99	1.01	0.16	2.82	7.78

The distribution of phosphorus concentrations in runoff throughout a storm is also of interest. Figure 4.15 depicts the beginning and ending vales for total phosphorus. The flush point represents the concentration of the runoff samples taken just after the simulated storm event reached a steady-state condition between the inflow and runoff flow rate. Interestingly, the end point runoff samples exhibited higher phosphorus concentrations than the “first flush” samples in nearly all of the simulated rainfall events. Note also that Stand B has consistently produced runoff with higher phosphorus concentrations than Stand A.

Also, the April 7 (Light Summer Rain A) event did not reach a steady state. The data presented for Stand B, especially, is not as consistent with the results from the other experiments, although an increase was observed. As shown previously in Figure 4.12, the runoff flow rate for Stand B on April 7 was the lowest observed at less than or approximately 2 ml/min.

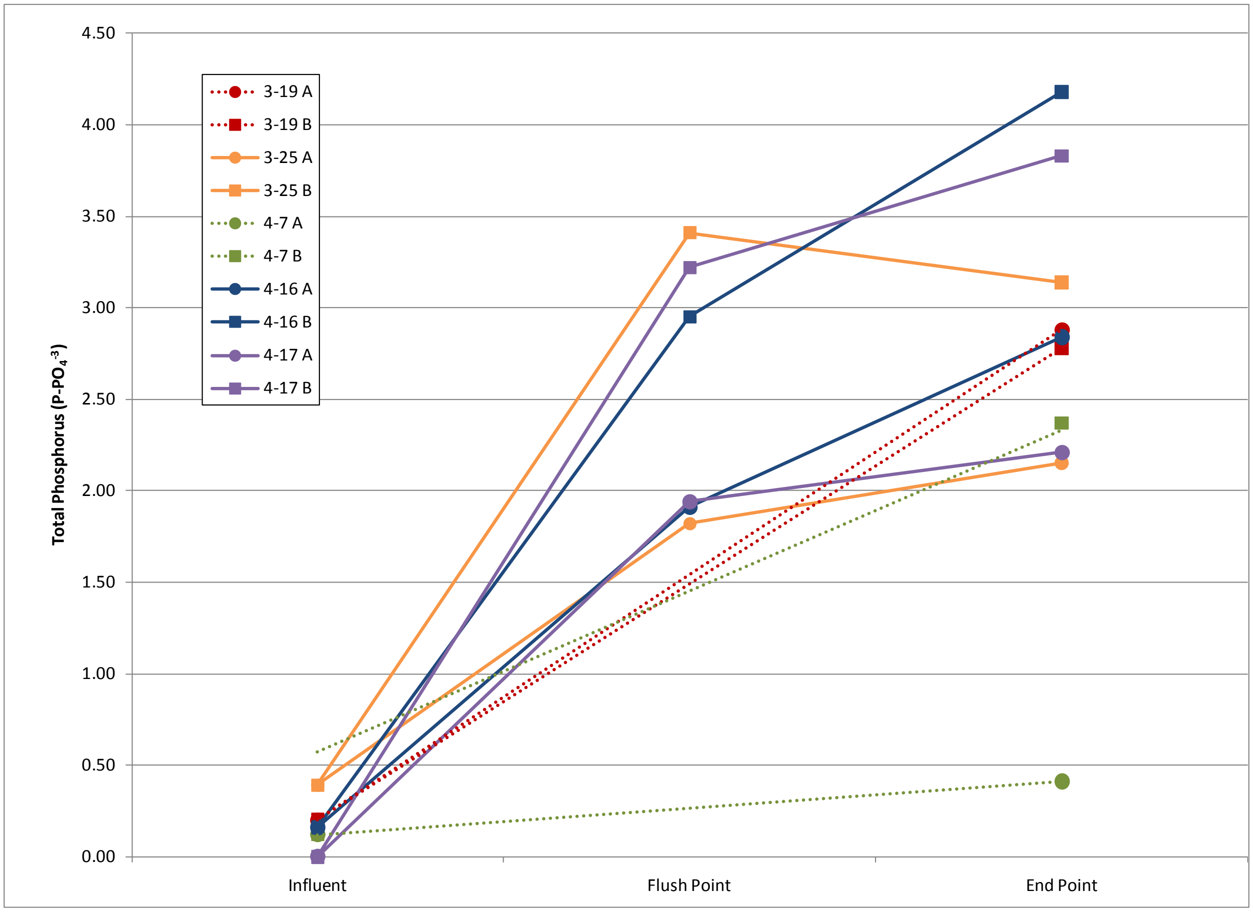
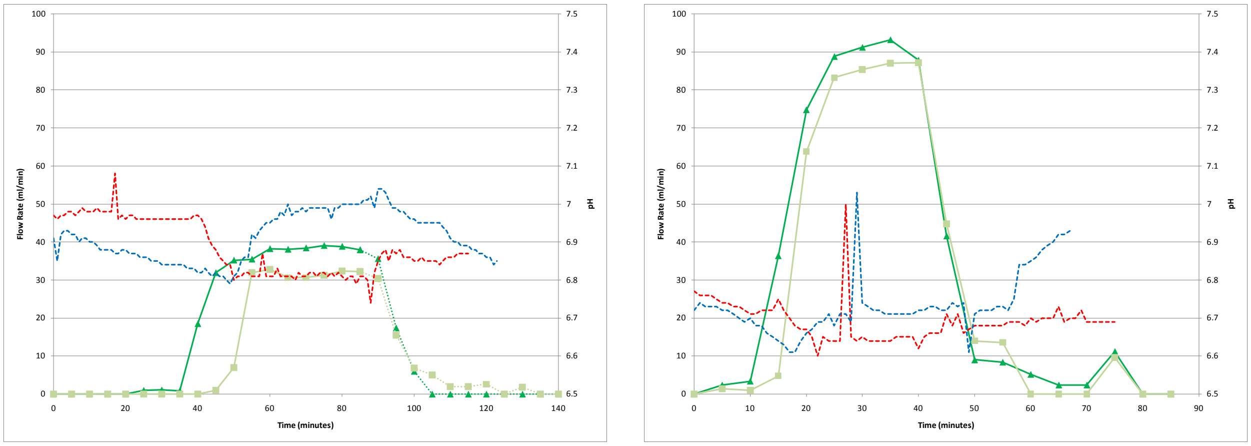


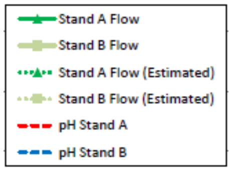
Figure 4.15: Phosphorus Distribution in Simulated Storm Events

pH

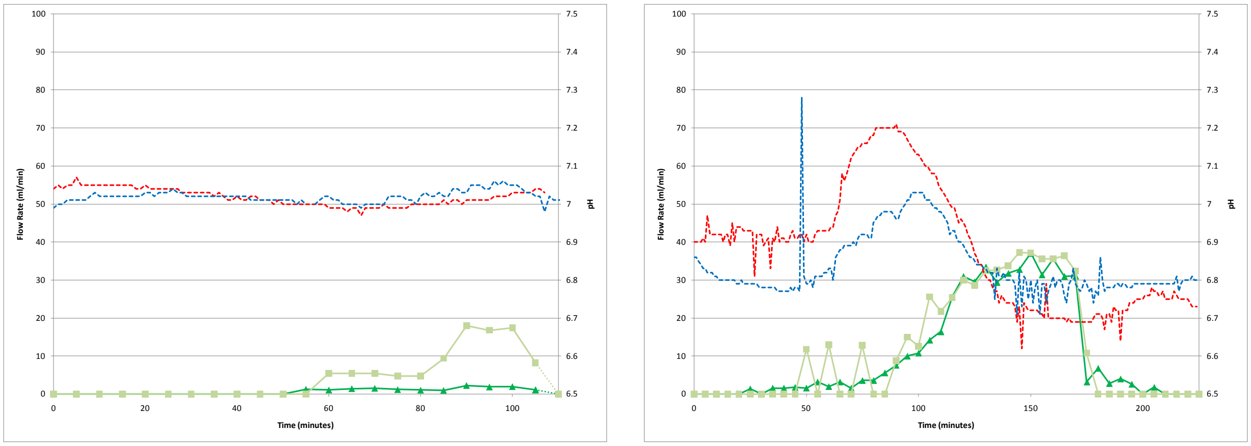
The hydrolab data is also helpful in providing insight regarding the changes in water quality throughout a storm. Figures 4.16 (a)–(d) show the changes in pH in relation to the flow patterns of four (4) of the greenhouse rainfall events. The pH values during the Heavy Spring Rain event seem to follow the shape of the hydrograph. This trend is also observed for Stand B during the Light Spring Rain event on March 25, although it is unclear why the reverse trend is exhibited for Stand A. The pH fluctuated less during the summer storms with less moisture content in the soil. The summer storms' antecedent moisture contents were 9.0% (Summer A) and 11.0% (Summer B). In contrast, the values for soil moisture content before conducting the spring rainfall event tests were 26.8% (light spring rain) and 26.0% (heavy spring rain).



(a) Light Spring Rain (3-25)



(b) Heavy Spring Rain (4-17)



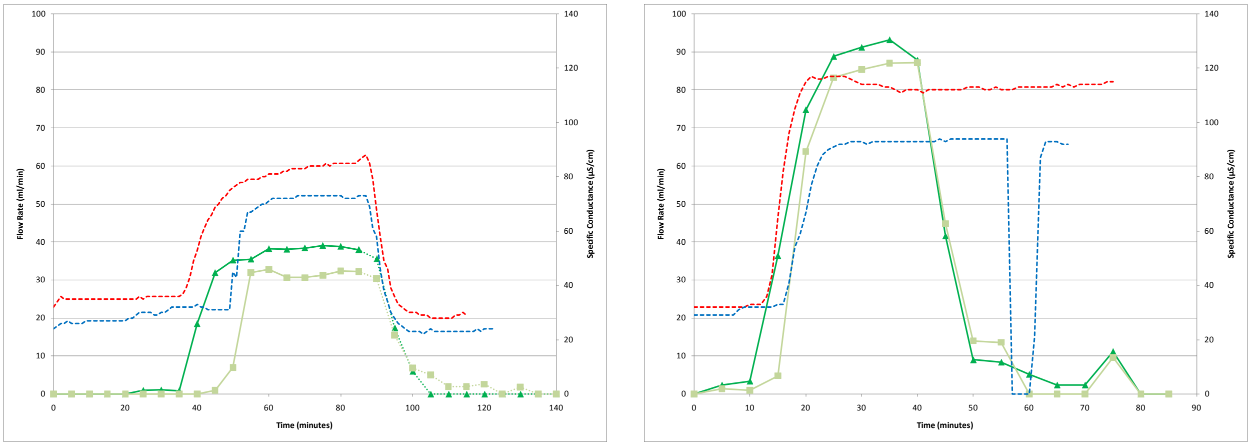
(c) Light Summer Rain A (4-7)

(d) Light Summer Rain B (4-16)

Figure 4.16: pH throughout Simulated Storm Events

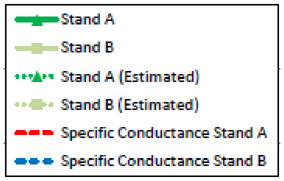
Specific Conductance

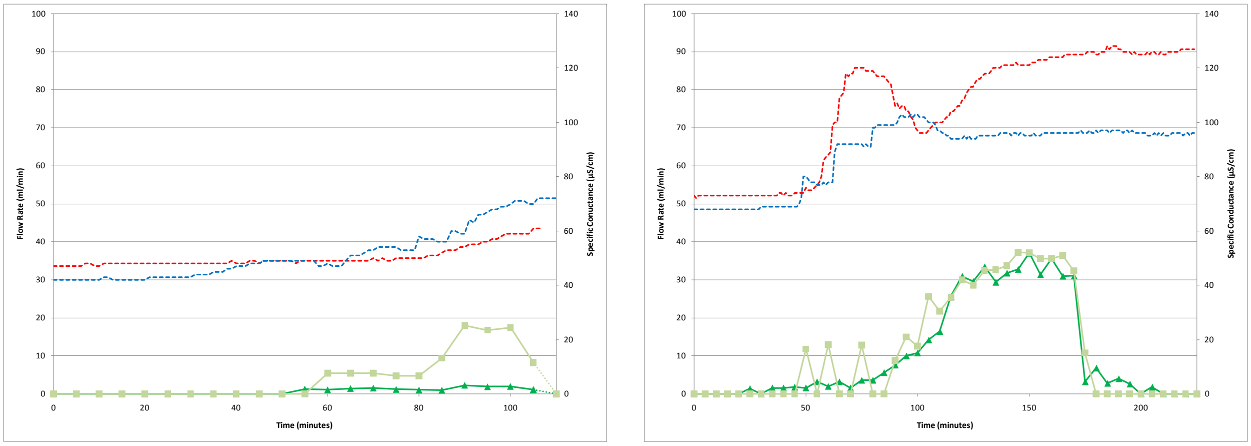
Figures 4.17 (a) – (d) show specific conductance results as measured with the hydrolab. Specific conductance is a measure a measure of water's ability to conduct an electrical current, which increases with in the presence of increased amounts of ions. As such, conductivity is considered an indirect measure of dissolved solids such as chloride, nitrate, sulfate, phosphate, sodium, magnesium, calcium, and iron. Generally, the specific conductance in all tests increased throughout the storm. The water quality results, detailed in Appendix E, are consistent with these plots.



(a) Light Spring Rain (3-25)

(b) Heavy Spring Rain (4-17)





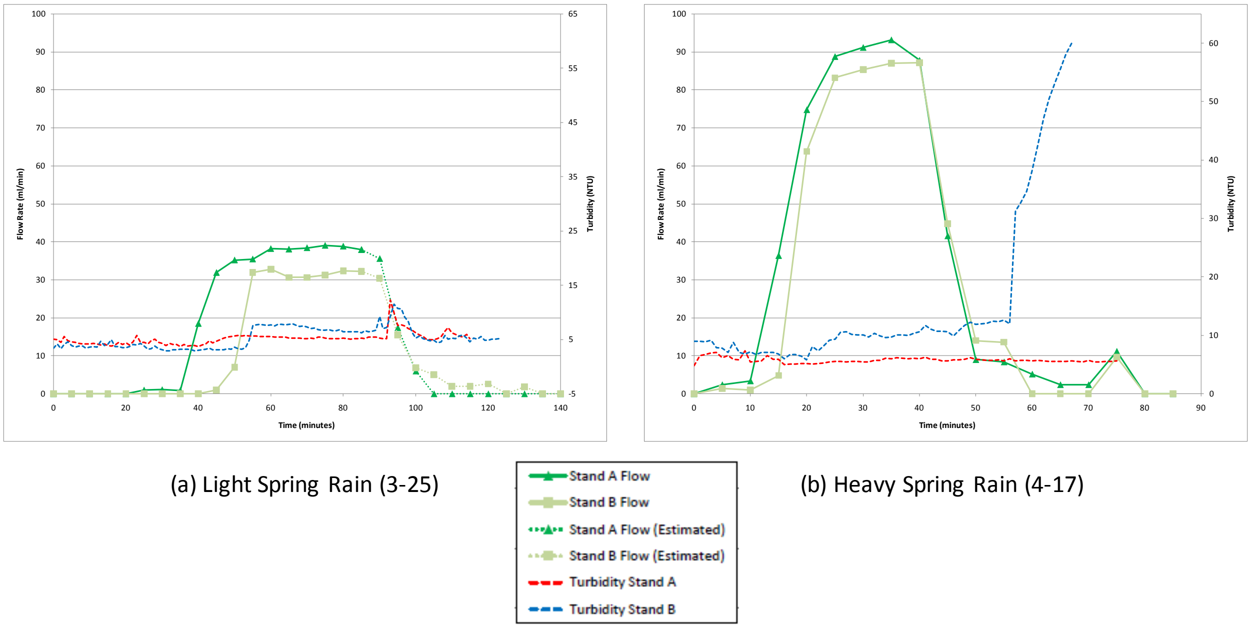
(c) Light Summer Rain A (4-7)

(d) Light Summer Rain B (4-16)

Figure 4.17: Specific Conductance throughout Simulated Storm Events

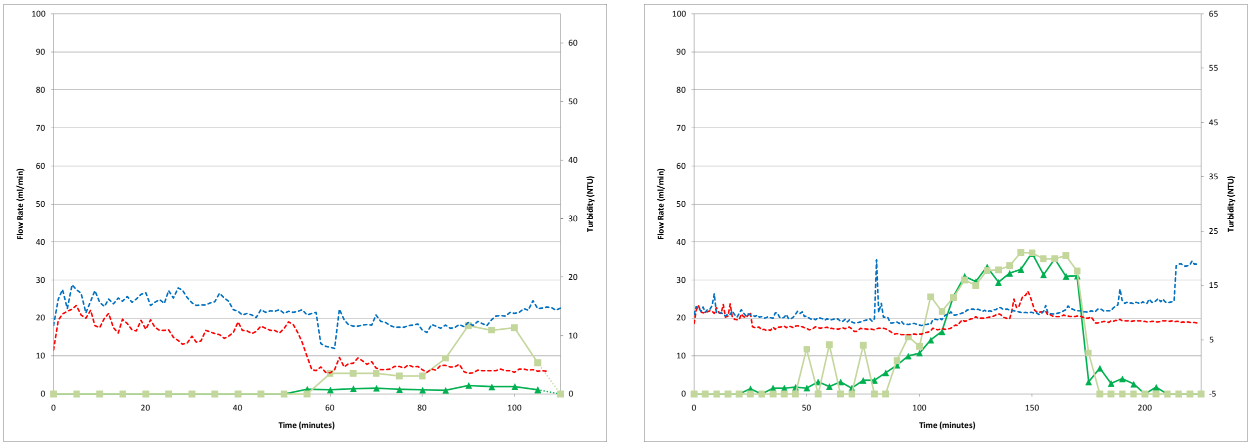
Turbidity

Figures 4.18 (a) – 8 (b) illustrate the changes in turbidity in four (4) of the simulated rain events. For the majority of the tests, the turbidity remained fairly consistent throughout the storm, and (with one exception) remained at values lower than 20 NTU. The spike in turbidity on Stand B in the Heavy Spring Rain is the likely contributor to the high total phosphorus EMC observed (3.18 mg/l P-PO_4^{-3}).



(a) Light Spring Rain (3-25)

(b) Heavy Spring Rain (4-17)



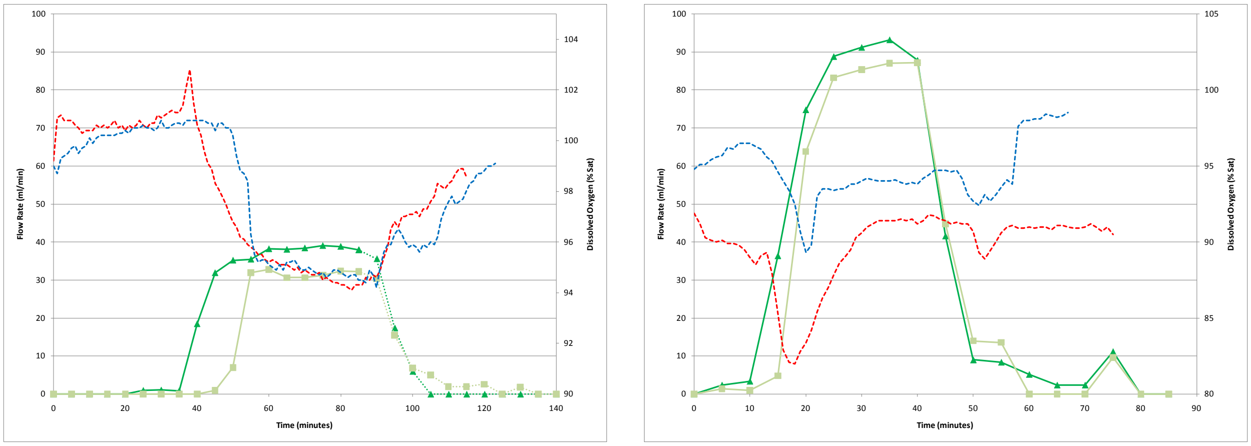
(c) Light Summer Rain A (4-7)

(d) Light Summer Rain B (4-16)

Figure 4.18: Turbidity throughout Simulated Rainfall Events

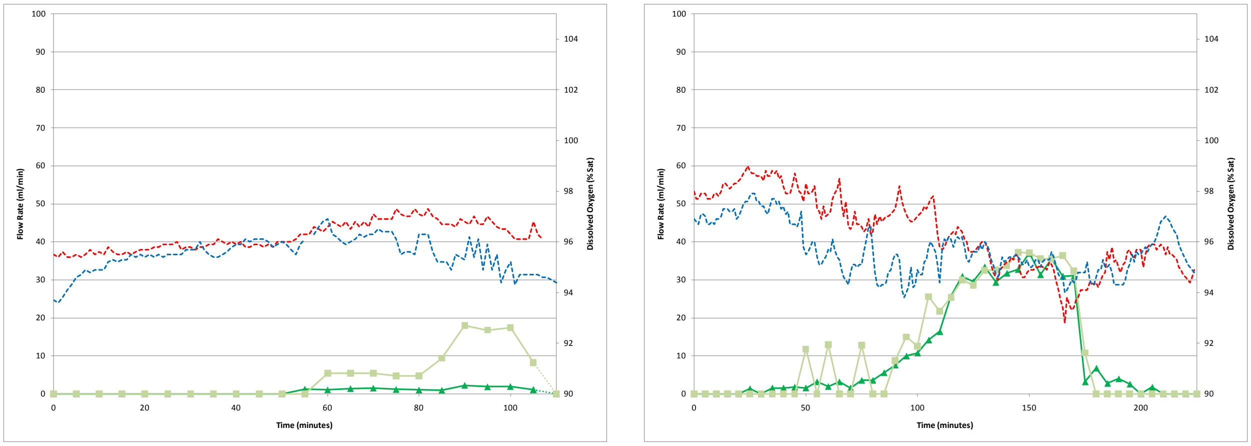
Dissolved Oxygen

As shown in Figures 4.19 (a) – (b), the runoff from both stands was well–saturated with oxygen (over 90%). Early in the storm, the water that is being is analyzed is the rainfall that was applied before the plants were placed in the stands. As such, the plots show that the amount of oxygen in the rainfall decreased as it infiltrated through the green roof panel.



(a) Light Spring Rain (3-25)

(b) Heavy Spring Rain (4-17)



(c) Light Summer Rain A (4-7)

(d) Light Summer Rain B (4-16)

Figure 4.19: Dissolved Oxygen throughout Simulated Rainfall Events

Phosphorus Partitioning

When examining the partitioning of phosphorus, it is interesting to note that the two greenhouse tests that resulted in the lowest total phosphorus also exhibited the lowest portion of phosphorus present in its dissolved form. This trend does not correspond with the field data, however. Generally, it appears that the majority of the phosphorus measured from the roof was sorbed to sediment. In contrast, the majority of the phosphorus in the runoff from the simulated rain events was in solution. It appears that the roof runoff contained phosphorus-contaminated sediment that was not present in the greenhouse. Such sediment may have included bird droppings, pollen, or pipe scale.

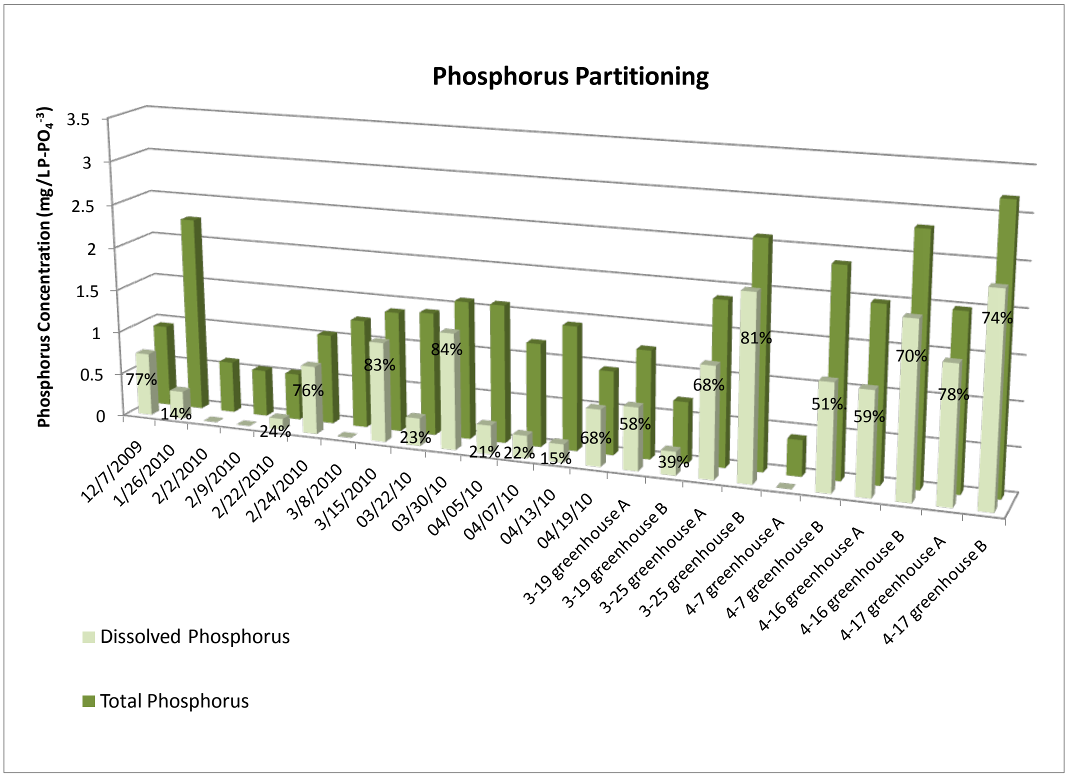


Figure 4.20: Phosphorus Partitioning

4.3 Characteristics of the Green Roof Soil

Various samples of the green roof growing medium have been analyzed, including a representative soil sample from the East Hall roof, a core from each green roof panel utilized in the greenhouse tests, and small samples from the green roof panels collected at various times during the simulated storm events. The soil was analyzed for moisture content, phosphorus concentrations, bulk density, and porosity. The intent was to identify the basic soil properties and to characterize the relationship between changes in soil phosphorus content and runoff phosphorus concentrations.

4.3.1 Physical Characteristics

The properties of the soil in situ were analyzed by extracting two cores from the greenhouse roof panels. As detailed in Chapter 3 – Methods, the cores were weighed, saturated, weighed again, oven-dried, and then weighed a third time to obtain the data displayed in Table 4.5.

Table 4.5: Greenhouse Core Analysis

	Stand A	**Stand B**
Mass as Collected (g)	90.7	76.9
Saturated Mass (g)	144.5	125.8
Dried Mass (g)	71.2	56.6
Moisture Content (%)	21.5	26.4
Volume (in^3)	7.2	7.0

This information is useful in determining the bulk density of the green roof growing medium. Bulk density is defined as follows (Sumner 2000):

$$\text{Bulk density } (\rho_b) = \frac{oven\ dry\ soil\ mass}{original\ \ volume} \qquad \textit{(equation 4.2)}$$

For Stand A: $\rho_b = \frac{71.2}{7.2} = 9.9$ g/in^3 For Stand B: $\rho_b = \frac{56.6}{7.0} = 8.1$ g/in^3 Average = 9.0 g/in^3

Additionally, the porosity was determined as follows:

Porosity (ϕ) = $\frac{Volume\ \ of\ Void\ Spaces}{Total\ \ Volume}$ *(equation 4.3)*

For Stand A: $\phi = \frac{(144.5-71.2)ml}{7.2in^3} \times \frac{.061\ in^3}{ml} = \underline{0.62}$

For Stand B: $\phi = \frac{(125.8-56.6)ml}{7.0in^3} \times \frac{.061\ in^3}{ml} = \underline{0.60}$

Since the porosity represents the amount of void space within the soil, calculated here to be about 60%, and the field capacity of the green roof panels has been previously demonstrated to be less than 30%, then flow through the green roof panels is not considered saturated flow.

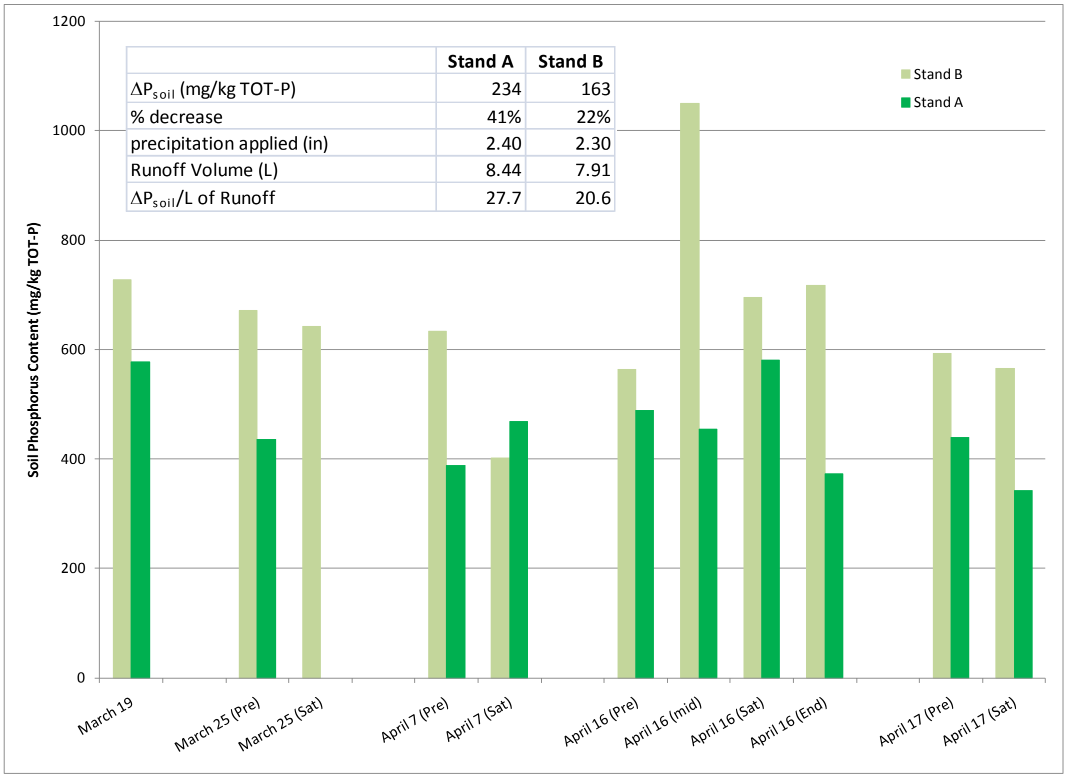
A representative soil sample was obtained from the East Hall roof the day after 4.16 inches of rain fell over a 56-hour time period (March 29-31, 2010). The entire sample was weighed, dried, and the moisture content was calculated to be 29.2%, which was very comparable, although slightly higher, than most soils samples that were taken during the simulated storm events at steady-state conditions as shown in Table 4.6. Additionally, five (5) aliquotted portions from the representative roof sample were analyzed for phosphorus content, resulting in an average value of 770 mg/kg Total Phosphorus on the green roof.

Table 4.6: Soil Sample Characteristics at Field Capacity

	Stand A		Stand B	
	Moisture Content	Phosphorus Content (mg/kg TOT-P)	Moisture Content	Phosphorus Content (mg/kg TOT-P)
Roof Sample (4-5)	**29.2%**	**770**		
Light Spring Shower (3-19)	26.3%	577	27.3%	728
Light Spring Rain (3-25)	23.0%	*not available*	26.0%	642
Heavy Spring Rain (4-17)	21.7%	581	30.0%	696
Light Summer Rain B (4-16)	22.5%	343	25.9%	565

4.3.2 Changes in Phosphorus in Green Roof Panel Soil

Table 4.6 also indicates that, as time passes, the phosphorus content in the soil decreases, but only slightly. Figure 4.21 expands this data set to include all soil analyses conducted on samples taken at other points during the greenhouse rain events. Generally, this trend of decreasing soil phosphorus concentration is confirmed. While the concentrations fluctuate over the study period, both Stands exhibit lower phosphorus concentrations than when the tests were initiated. As indicated, the amount or rate of decrease was not consistent between each stand, but the change in soil phosphorus content – as related to runoff volume – does present more closely correlated finding. Stand A exhibited a change of 27.7 mg/kg TOT-P for each liter of runoff volume, compared to 20.6 on Stand B.



	Stand A	Stand B
ΔP_{soil} (mg/kg TOT-P)	234	163
% decrease	41%	22%
precipitation applied (in)	2.40	2.30
Runoff Volume (L)	8.44	7.91
ΔP_{soil}/L of Runoff	27.7	20.6

Figure 4.21: Changes in Soil Phosphorus Concentration over Greenhouse Study Period

These observed decreases in soil phosphorus content did not necessarily lead to decreases in phosphorus concentration in the greenhouse runoff over the one-month study period. However, other studies have indicated that, over time, the content of phosphorus in green roof stormwater runoff will decrease. These studies have also indicated that the source of the phosphorus is the growing medium, to which fertilizer is typically added to aid in early plant growth for newly installed green roofs. As discussed previously, it has been assumed that phosphorus content in stormwater will be reduced (possibly eliminated) once the plants have been established, possibly in 2-3 years after installation.

4.3.3 Laboratory Soil Flush Tests

In order to develop a better prediction of potential future phosphorus reductions in green roof runoff, the representative roof soil sample was utilized in a laboratory flush test to determine how much water would need to be applied to attain reduced runoff phosphorus concentrations. As detailed in Chapter 3 – Methods, approximately 12 g of soil sample were flushed ten times with 50ml of water each time. Figure 4.22 displays the total and dissolved phosphorus concentrations measured after each flush. The % of total phosphorus that was present in its dissolved form is also indicated. Interestingly the total phosphorus in the first flush was close to the same concentration as the highest value observed from the field data (12.38 mg/l Tot-P-PO_4^{-3} on July 7, 2010).

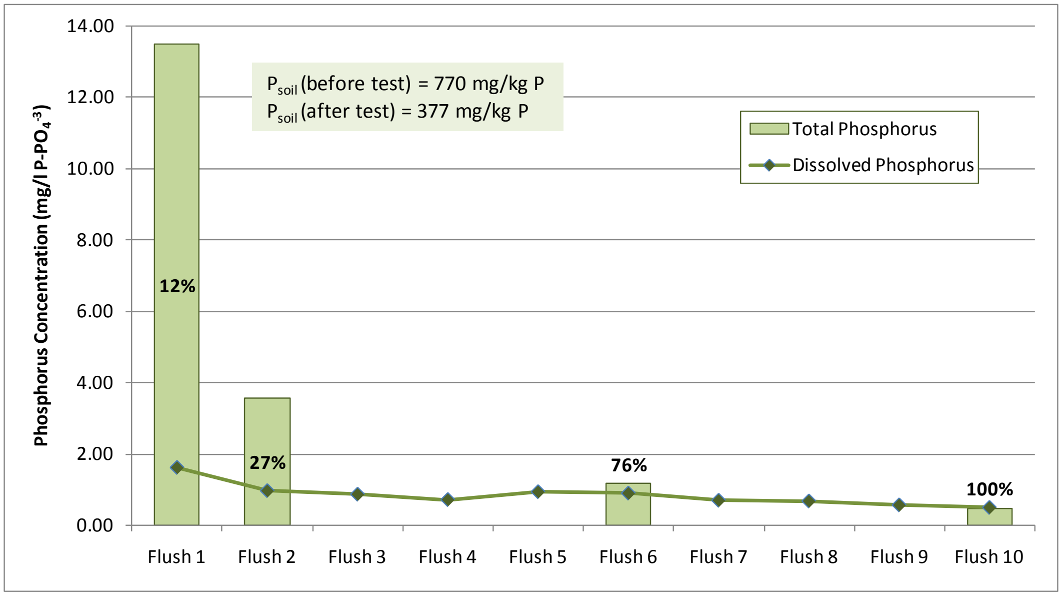


Figure 4.22: Soil Flush Test (April 2)

The first few flushes produced fine particulate matter in the runoff as shown in Figure 4.23. By the 3rd flush, the sediment was no longer visible, and by the 6th flush, the concentration of total phosphorus had been drastically reduced to values closer to the dissolved concentration. By the end of the test, all fine particulate had been flushed and all phosphorus present was in solution.

Figure 4.23: Runoff from Soil Flush Test

It is important to note that the reduction in phosphorus concentrations in the flush water appears to be a time-dependent process based on the manner in which this experiment was conducted. During the experiment, flushes 1-4 were applied at fairly consistent intervals (approximately 2-3 minutes apart). A longer time elapsed before flush 5 was applied (approximately 10-15 minutes). As a result, a slight increase in concentration of dissolved phosphorus between flushes 4 and 5 was observed, after which a steady decrease continues as shown in Figure 4.22. It is possible that the ability for phosphorus to desorb from the sediment was regenerated during this delay.

In order to correlate the volume of flush water used in the laboratory experiment to an equivalent rainfall volume that might be experienced on the roof, the bulk density was used to determine the total estimated mass of green roof soil on East Hall. The volume of soil was calculated to be 1504 ft^3 by multiplying the area of green roof panels (4512 ft^2) by the depth of the growing medium (4 inches). Applying the bulk density, the estimated mass was determined:

$$1504ft^3 \times \frac{9g}{in^3} \times \frac{12^3\ in^3}{ft^3} = 23.4 \text{ million g of soil}$$

On a per unit area basis, this translates to 36 g soil for every square inch of green roof panel. Since nearly 12g of soil was used in the flush test, this theoretically would represent about 1/3 of a square-inch of roof. As such, the 500 ml of water applied can be roughly equated to about 92.5 inches of rainfall:

$$\frac{500\ ml}{0.33in^2} \times \frac{L}{1000ml} \times \frac{gal}{3.785\ L} \times \frac{231\ in^3}{gal} = 92.5\ in$$

This represents about 2 years worth of precipitation in the Worcester area.

To correlate these results to the observations from the greenhouse tests as presented previously, the change in soil phosphorus content per liter of runoff was 814 mg Tot-P /kg soil, as compared to a change of 21-28 experienced over the duration of the greenhouse tests. The two most likely factors affecting the significantly different values are the rate of flushing and the role of vegetation. The bench-scale flush test applied the equivalent of approximately two years worth of rainfall in less than one hour, while the greenhouse tests were conducted at rainfall intensities similar to what would be expected in the field. Also, there was no vegetative uptake of phosphorus in the soil flush test, but the role of the vegetation in the green roof is clearly something that needs to be considered.

4.4 Characteristics of Green Roof Vegetation

The greenhouse provided the environment in which the growth cycle of the green roof vegetation between simulated storm events could be monitored while analyzing changes in runoff phosphorus concentrations. The following figures depict the growth of the vegetation over the course of the greenhouse testing period.

Stand A

Figure 4.24, March 19

Figure 4.25, April 7

Figure 4.26, April 17

Stand B

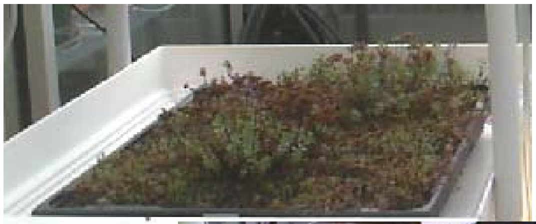


Figure 4.27
March 19

Figure 4.28, April 7

Figure 4.29, April 17

The plants were analyzed for total phosphorus content on four of the test dates. As expected, the phosphorus content of the plants increased as they grew. Also of interest, is the change in moisture content between test dates. The 10% increase in moisture content between March 25 and April 7 coincides with a decrease in soil moisture content (26% on March 25 to 9% on April 7). With nearly two weeks of no precipitation in the greenhouse, the plants extracted the moisture from the soil, as expected of these drought-resistant plant varieties.

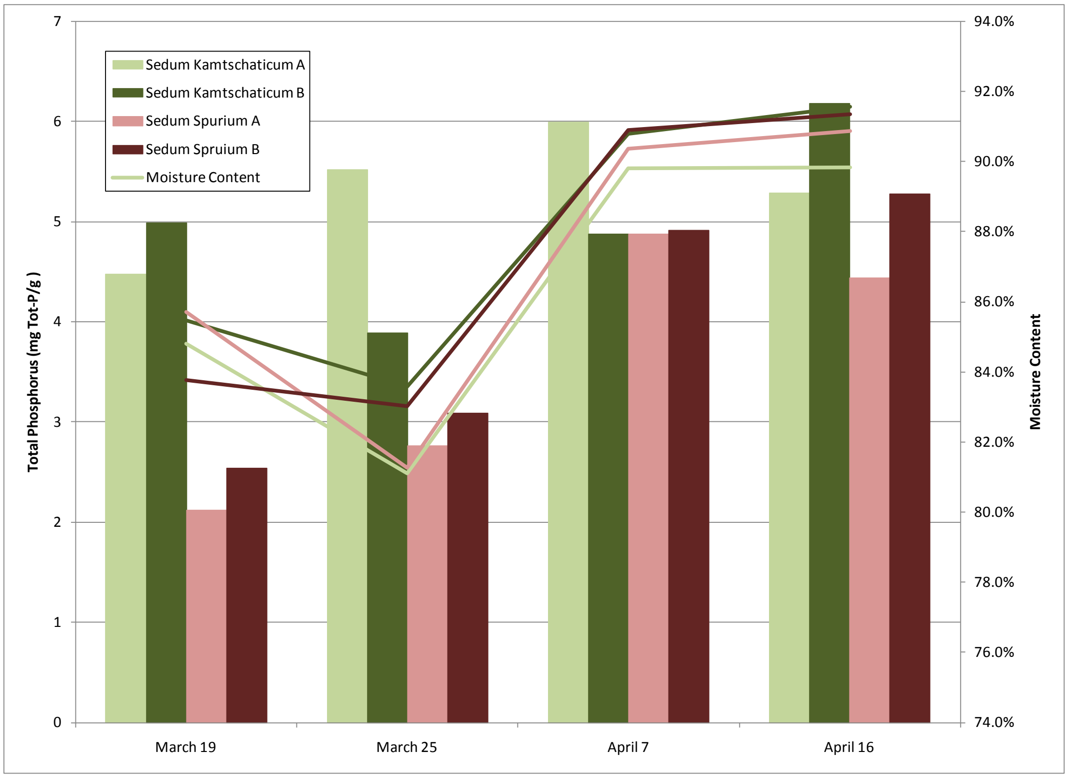


Figure 4.30: Patterns of Growth in Green Roof Vegetation

5.0 Conclusions & Recommendations

This chapter reviews the goals of this research and discusses the findings as they pertain to each of these goals. For flow attenuation, the green roof panels performed as expected under different rainfall and antecedent moisture conditions. Additionally, the greenhouse experiments provided improved insight into the nature of the relationship of phosphorus between the flow conditions, plant uptake, and soil processes, as well as its distribution throughout a storm. The laboratory data further provides a basis for estimating performance of a green roof and its long-term impact on stormwater quality. In a broader context, the findings also serve to inform future extensive green roof designs and subsequent research efforts.

5.1 Effectiveness of Stormwater Flow Attenuation

The first objective of the research was to determine the effectiveness of a green roof in attenuating stormwater flow. The findings that resulted from the greenhouse experiments are consistent with the published literature. For example, the reduced retention capacity observed during higher flow conditions is a common trend that has been reported for extensive green roof performance. At high rainfall intensities, the field capacity of the green roof panels is quickly exceeded, and the thin layer of the extensive green roof design does not provide much storage capacity. However, while the growing medium did not provide much storage during the heavier simulated rain event, the green roof vegetation’s ability to rapidly uptake water when it becomes available did provide a stormwater retention benefit.

The improved performance during the lower flow conditions, however, is primarily more a function of the soil than of the plants. The highest retention rates in the simulated rain events were observed when the antecedent moisture content was low (9-11%). In contrast, the moisture content of the soil at the beginning of the Light Spring Rain Event was the highest of all tests (26%), and the green roof panels retained only 38% of the influent volume, despite the fact this simulated storm used the smallest volume of water of all five (5) events. Clearly the growing medium's field capacity is a critical design factor that is indicative of green roof performance.

5.2 Impact on Water Quality

Initially, the grab samples collected from both the green and white roofs raised questions about increases in phosphorus concentrations, especially the significantly elevated values observed during the rainy summer months of this study period. The greenhouse experiments that were conducted in March and April were aimed at investigating potential reasons for the increased phosphorus content in the green roof runoff. The quality of the runoff from the green roof panels was similar in nature to the samples collected from the roof, and the results from the greenhouse tests are considered indicative of conditions on the roof.

The information regarding the partitioning of phosphate between its dissolved and sorbed phases provides an important clue regarding the high concentrations of total phosphorus exhibited in the summer green roof samples and winter white roof samples. For the high concentration green roof samples, the dissolved concentrations of phosphate were actually much lower than those observed in the greenhouse test runoff samples. Also, *dissolved* phosphorus was not detected in the white roof runoff. Hence, more of the phosphorus found in the roof runoff was sorbed to sediment and other particles that may not have been present in the greenhouse environment. The soil itself has measurable phosphorus content and fine particles may have been released into the runoff during the heavy summer rainfall. This was certainly the trend that was observed in the bench-scale soil flush test. Other material that could have contributed phosphorus to the roof samples could include bird droppings, pollen, and/or pipe scale.

Also, for all greenhouse tests, the phosphorus concentrations (and other constituents as well) showed up in the "first flush" runoff samples and continued to increase throughout the duration of the storm and after the simulated rainfall had stopped. This trend was consistently observed in all storms, regardless of their size or intensity. These results indicate that the desorption of phosphorus from the growing medium happens quickly, and the soil is not rapidly depleted of its phosphorus content. Also, the green roof panel whose soil was higher in phosphorus concentration (Stand B) also produced runoff with higher phosphorus concentrations than the other panel tested in the greenhouse (Stand A). Meanwhile, the growth of green roof plant material and its associated nutrient uptake processes did not appear to reduce the amount of phosphorus that ended up in the runoff. These results confirm that the growing medium is the source of phosphorus in runoff. However, while a bench-scale laboratory experiment indicated that phosphorus levels in runoff may decrease over time, the rate of desorption is not constant and cannot be easily predicted. Additional investigations will be needed in order to predict the long-term impact of a green roof on phosphorus loading.

5.3 Design Considerations

A third goal of the research was to identify the key components of the processes that are likely leading to the highest variability in observed water quality parameters – hence, the highest potential that a change in design could lead to significant improvements. Clearly, soil storage was a significant factor and is heavily influenced by antecedent moisture content. Soil moisture content is a function of both weather, which clearly cannot be controlled, and plant variety, which generally can be controlled. These results should help future designers determine whether the weather patterns in a particular location where a green is being considered will be hindrance to the effectiveness of a green roof. Areas experiencing significant amounts of rainfall that may keep the soil at field capacity would not be a good choice. However, selecting plant varieties that quickly uptake water, such as sedum and delosperma, will provide the ability to regenerate the holding capacity of the growing medium and will improve the performance of green roofs. Also, efforts should be taken to engineer new soil media that will maximize the field capacity of green roof designs.

For water quality, the leaching of phosphorus from the growing medium must be taken into consideration when designing a green roof. Previous studies have made assumptions that the leaching of phosphorus will decrease over time and many have predicted that the phenomenon will only occur for a few years after installation. However, the results of this study indicate that this assumption may not be valid. The long-term phosphorus loading resulting from a green roof may continue longer than previously assumed. Until additional investigations are conducted to develop a prediction model, the impacts of a green roof must be given careful consideration if being installed where phosphorus levels in stormwater are a concern. Further, it is recommended that phosphorus use be minimized in the growing medium. The typical green roof plant varieties, such as those studied here, do not appear to uptake very much of this nutrient, even in their first few establishment years.

5.4 Foundation for Further Study

The methods utilized in this research, as detailed in Chapter 3, provided a unique way to analyze the complex relationships between phosphorus transformations in green roof vegetation, growing medium, and stormwater runoff. Since the nature of phosphorus sorption and desorption is still not well-understood, it is recommended that research continue to be conducted in this manner to further explore the implications of green roof technology on the surrounding environment.

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APPENDIX A

Worcester Regional Airport Precipitation Data

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Storm Date	Total consecutive Rainfall (in)	Duration (hours)	Intensity (in/hr)	Highest Hour (in)
April 7, 2009 (1)	0.01	1	0.01	0.01
April 22, 2009 (1)	0.01	1	0.01	0.01
May 8, 2009	0.01	1	0.01	0.01
May 9, 2009 (1)	0.01	1	0.01	0.01
May 27, 2009 (2)	0.01	1	0.01	0.01
May 28, 2009	0.01	1	0.01	0.01
June 7, 2009	0.01	1	0.01	0.01
June 9, 2009 (2)	0.01	1	0.01	0.01
June 9, 2009 (3)	0.01	1	0.01	0.01
June 11, 2009	0.01	1	0.01	0.01
June 23, 2010	0.01	1	0.01	0.01
June 24, 2009 (2)	0.01	4	0.00	0.01
June 25, 2009 (1)	0.01	1	0.01	0.01
June 25, 2009 (3)	0.01	1	0.01	0.01
June 27, 2009 (1)	0.01	1	0.01	0.01
June 27, 2009 (2)	0.01	1	0.01	0.01
June 27, 2009 (3)	0.01	1	0.01	0.01
June 28, 2009 (1)	0.01	1	0.01	0.01
June 28, 2009 (2)	0.01	1	0.01	0.01
June 29, 2010	0.01	1	0.01	0.01
July 2, 2009 (1)	0.01	1	0.01	0.01
July 6, 2009	0.01	1	0.01	0.01
July 8, 2009 (1)	0.01	2	0.01	0.01
July 24, 2009 (1)	0.01	1	0.01	0.01
July 26, 2009 (1)	0.01	1	0.01	0.01
August 5, 2009	0.01	1	0.01	0.01
August 11, 2009	0.01	1	0.01	0.01
August 13, 2009 (2)	0.01	1	0.01	0.01
October 23, 2009	0.01	1	0.01	0.01
November 1, 2009	0.01	1	0.01	0.01
November 5, 2009	0.01	1	0.01	0.01
January 24, 2010	0.01	1	0.01	0.01
February 4, 2010 (2)	0.01	1	0.01	0.01
March 1, 2010 (1)	0.01	1	0.01	0.01
March 1, 2010 (2)	0.01	1	0.01	0.01
March 4, 2010	0.01	1	0.01	0.01
March 11, 2010 (2)	0.01	1	0.01	0.01
April 3, 2009 (2)	0.02	1	0.02	0.02
April 7, 2009 (2)	0.02	2	0.01	0.02
April 18-19, 2009	0.02	3	0.01	0.01
April 25, 2009	0.02	1	0.02	0.02
May 1, 2009 (1)	0.02	1	0.02	0.02
May 4, 2009	0.02	1	0.02	0.02

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Storm Date	Total consecutive Rainfall (in)	Duration (hours)	Intensity (in/hr)	Highest Hour (in)
May28-29, 2009	0.02	3	0.01	0.01
June 24, 2009 (3)	0.02	2	0.01	0.01
June 25, 2009 (2)	0.02	3	0.01	0.01
July 8, 2009 (3)	0.02	3	0.01	0.01
July 27, 2009	0.02	2	0.01	0.02
July 29, 2009 (2)	0.02	3	0.01	0.02
August 13, 2009 (1)	0.02	1	0.02	0.02
October 15, 2009	0.02	1	0.02	0.02
March 11, 2010 (1)	0.02	1	0.02	0.02
May 1, 2009 (2)	0.03	1	0.03	0.03
June 24-25, 2009	0.03	4	0.01	0.01
July 2, 2009 (2)	0.03	3	0.01	0.03
July 7, 2009 (1)	0.03	2	0.02	0.03
August 13, 2009 (3)	0.03	3	0.01	0.02
October 27, 2009	0.03	4	0.01	0.01
October 28, 2009 (2)	0.03	2	0.02	0.02
February 4, 2010 (1)	0.03	3	0.01	0.01
February 24-25, 2010	0.03	5	0.01	0.01
May 24, 2009	0.04	2	0.02	0.02
June 15, 2009	0.04	1	0.04	0.04
June 26, 2009	0.04	8	0.01	0.01
July 8, 2009 (2)	0.04	3	0.01	0.03
July 26, 2009 (2)	0.04	2	0.02	0.04
July 30, 2009 (2)	0.04	3	0.01	0.03
Ocotber 13, 2009 (2)	0.04	1	0.04	0.04
October 31, 2009 (1)	0.04	5	0.01	0.01
October 31, 2009 (2)	0.04	3	0.01	0.02
February 16, 2010 (1)	0.04	3	0.01	0.02
February 26, 2010	0.04	1	0.04	0.04
March 31, 2010	0.04	3	0.01	0.02
March 3, 2010	0.05	6	0.01	0.01
May 30, 2009	0.06	2	0.03	0.04
June 18, 2009	0.06	4	0.02	0.03
July 2, 2009 (2)	0.06	2	0.03	0.05
July 29, 2009 (1)	0.06	2	0.03	0.05
November 5-6, 2009	0.06	3	0.02	0.03
March 22, 2010	0.06	4	0.02	0.02
May 31, 2009	0.07	2	0.04	0.05
July 30, 2009 (1)	0.07	2	0.04	0.06
August 10, 2009	0.07	1	0.07	0.07
November 25, 2009	0.07	7	0.01	0.02
January 28, 2010	0.07	4	0.02	0.02
February 3, 2010	0.07	6	0.01	0.02

APPENDIX A: Worcester Regional Airport Precipitation Data

Storm Date	Total consecutive Rainfall (in)	Duration (hours)	Intensity (in/hr)	Highest Hour (in)		
August 22, 2009 (2)	0.08	1	0.08	0.08	87	0.54717
October 9, 2009	0.1	6	0.02	0.04		
November 23, 2009	0.1	7	0.01	0.04		
June 20-21, 2009	0.11	9	0.01	0.02		
February 16, 2010 (2)	0.11	6	0.02	0.03		
May 14, 2009	0.12	8	0.02	0.05		
July 24, 2009 (2)	0.12	3	0.04	0.08		
June 28-29, 2009	0.13	11	0.01	0.05		
March 26, 2010	0.13	7	0.02	0.04		
May 29, 2009	0.14	3	0.05	0.09		
April 22, 2009 (2)	0.15	5	0.03	0.06		
June 21-22, 2009	0.15	27	0.01	0.02		
June 24, 2009 (1)	0.16	8	0.02	0.04		
April 1-2, 2009	0.17	9	0.02	0.08		
May 5, 2009	0.17	10	0.02	0.04		
May 17, 2009	0.17	4	0.04	0.15		
June 21, 2009	0.17	12	0.01	0.05		
October 3-4, 2009	0.17	3	0.06	0.12		
December 5-6, 2009	0.17	12	0.01	0.02		
June 9, 2009 (1)	0.18	3	0.06	0.11		
November 30, 2009	0.19	6	0.03	0.05		
Februrary 26-27, 2010	0.19	7	0.03	0.08		
July 7, 2009 (3)	0.2	1	0.20	0.20		
August 21, 2009	0.21	2	0.11	0.20		
October 9-10, 2009	0.21	4	0.05	0.13		
May 27, 2009 (1)	0.22	7	0.03	0.13		
Ocotber 13, 2009 (1)	0.23	8	0.03	0.06	26	0.163522
April 10-11, 2009	0.28	10	0.03	0.07		
April 11, 2009	0.28	6	0.05	0.09		
May 6, 2009	0.3	7	0.04	0.14		
May 9, 2009 (2)	0.32	3	0.11	0.30		
August 22, 2009 (1)	0.32	1	0.32	0.32		
August 23, 2009	0.33	3	0.11	0.16		
December 9-10, 2009	0.36	2	0.18	0.19		
March 23, 2010	0.37	6	0.06	0.10		
September 28, 2009	0.41	4	0.10	0.23	9	0.056604
October 7, 2009	0.5	12	0.04	0.16		
November 27-28, 2009	0.52	27	0.02	0.08		
October 18, 2009	0.53	16	0.03	0.13		
May 6-7, 2009	0.6	9	0.07	0.18		
May 7, 2009	0.62	2	0.31	0.47		
October 3, 2009	0.62	17	0.04	0.29		
April 3, 2009 (1)	0.65	11	0.06	0.40		

APPENDIX A: Worcester Regional Airport Precipitation Data

Storm Date	Total consecutive Rainfall (in)	Duration (hours)	Intensity (in/hr)	Highest Hour (in)		
September 27, 2009	0.65	19	0.03	0.08		
April 21, 2009	0.68	9	0.08	0.22		
December 13-14, 2009	0.7	7	0.10	0.21		
April 6, 2009	0.73	9	0.08	0.19		
April 20-21, 2009	0.76	9	0.08	0.22		
October 28, 2009 (1)	0.8	15	0.05	0.12		
September 11-13, 2009	0.81	42	0.02	0.16		
November 20, 2009	0.81	8	0.10	0.34		
July 7, 2009 (2)	0.84	2	0.42	0.55		
July 21-22, 2009	0.84	25	0.03	0.28		
July 17-18, 2009	0.86	5	0.17	0.62		
July 11-12, 2009	0.9	6	0.15	0.47	19	0.119497
December 3, 2009	1.05	10	0.11	0.33		
June 18-19, 2009	1.06	27	0.04	0.13		
July 1, 2010	1.1	15	0.07	0.43		
June 14, 2009	1.12	8	0.14	0.47		
December 9, 2009	1.28	12	0.11	0.19		
July 31, 2009	1.29	11	0.12	0.40		
June 12, 2009	1.47	11	0.13	0.30		
October 23-24, 2009	1.48	25	0.06	0.46		
March 22-23, 2010	1.48	13	0.11	0.24		
July 2, 2009 (1)	1.5	5	0.30	0.60		
June 27, 2009 (4)	1.61	3	0.54	1.16		
January 25, 2010	1.62	16	0.10	0.45		
November 14-15, 2009	1.64	32	0.05	0.30		
February 23-24, 2010	1.67	25	0.07	0.14		
August 28-19, 2009	1.72	23	0.07	0.30		
February 25-26, 2010	1.95	19	0.10	0.27	16	0.100629
July 23-24, 2009	2.57	15	0.17	0.49		
March 13-15, 2010	3.83	61	0.06	0.21		
March 29-31, 2010	4.14	51	0.08	0.38		

could be missing some storms here

	Cumulative Rainfall (in)	Duration (hours)	Intensity (in/hr)	Highest Hour (in)		
average	0.36	6.53	0.05	0.11	**average**	
highest	4.14	61	0.54	1.16	**highest**	
lowest	0.01	1	0.0025	0.01		
total	56.46					0.006289
median	0.07					
number of storms	159					

APPENDIX B

TOTAL PHOSPHORUS PROCEDURE

(NITIRC-SULFURIC ACID DIGESTION & COLOR SPECTROPHOTOMETRY)

APPENDIX B

Worcester Polytechnic Institute

Department of Civil & Environmental Engineering

Determining Total Phosphorus using Sulfuric Acid-Nitric Acid Digestion and a Hach DR/3000 Color Spectrophotometer

adapted from Wen, Huajing, "Analytical Procedures for Nutrients in Water," WPI (2005)
with input from Don Pellegrino, WPI CEE Lab Manager

Preparations

1. Turn the color spectrophotometer on. It will need approximately 2 hours for the lamp to warm sufficiently to prevent drifting of absorbance readings.
2. Prepare a set of standards with known concentrations of phosphorus including and just beyond the range of expected results. The analysis of these standards will provide the calibration curve from which the unknown samples will be analyzed.
   - Using a stock solution, standards can be prepared as follows:

$$x\,ml = \frac{C\,mg}{L} \times \frac{ml}{0.1\,mg} \times 100\,ml \times \frac{1\,L}{1000\,ml}$$

where x = volume (ml) of stock solution needed
C mg/L represents the desired standard concentration
0.1 mg/ml is the concentration of the stock solution
100 ml represents the volume of standard that will be prepared
1 L/1000 ml is used to convert ml to L

   - For example, if a 0.5 mg/L (PPM) standard solution is desired, the above equation determines that 0.5 ml (or 500 μl) of 0.1 mg/ml stock solution would be needed

$$x\,ml = \frac{0.5\,mg}{L} \times \frac{ml}{0.1\,mg} \times 100\,ml \times \frac{1\,L}{1000\,ml} = 0.5\,ml$$

Digestion of Aqueous Samples

All aqueous samples, standards, and blanks should be digested using the same procedure, as follows:

1. Pour 25 ml of sample or standard (or e-pure water for blank) into a clean beaker
2. Add 5 ml conc. HNO_3 and 1 ml conc. H_2SO_4. Add the nitric acid first.
3. Cover the beaker with a watch cover – making sure there is a small gap between the cover and the top of the beaker to allow room for release of evaporated gases. Heat gently on a preheated hot plate under hood. The sample should simmer, but not boil. Heat until the sample is "down to fumes," which means that there will be visible white fumes in the beaker, and the sample will have been reduced down to a volume of about 1 ml.
4. Remove watch covers, remove beakers from hot plate, and allow to cool.

APPENDIX B

Digestion of Soil, Sediment, and/or Plant Material

Solid samples, such as sediment or plant material should be digested using the following procedure:

1. Place a known mass of sample into a clean beaker
2. Add ~40 ml of e-pure water to the sample in the beaker
3. Add 10 ml conc. HNO_3
4. Cover the beaker with a watch cover – making sure there is a small gap between the cover and the top of the beaker to allow room for release of evaporated gases. Heat gently on a preheated hot plate under hood. The sample should simmer, but not boil. Heat for a few hours and then leave overnight, stirring occasionally as needed.
5. Next day, warm slightly and filter through #4 filter paper, rinsing all solid material very well with e-pure water. Add enough e-pure to bring the filtrate up to a known volume. The preferred volume is 25 ml, but dilution to higher volumes may be necessary if phosphorus levels are anticipated to be high. For example, for soil in the range of 500-800 mg Tot-P/kg, diluting the filtrate up to 500 ml produced results within the standard calibration curve for the spectrophotometer (0.2-10 PPM).
6. Pour 25 ml of filtrate into a clean beaker.
7. Add 1 ml conc. H_2SO_4.
8. Cover the beaker with a watch cover – making sure there is a small gap between the cover and the top of the beaker to allow room for release of evaporated gases. Heat gently on a preheated hot plate under hood. The sample should simmer, but not boil. Heat until the sample has been reduced to about 10 ml. Carefully add a few drops of hydrogen peroxide to the beaker and observe. Vigorous bubbling indicates consumption of organic matter. Continue to carefully add hydrogen peroxide dropwise until sample remains a clear color or until bubbling has ceased.
9. Continue to heat sample until “down to fumes,” which means that there will be visible white fumes in the beaker, and the sample will have been reduced down to a volume of about 1 ml.
10. Remove watch covers, remove beakers from hot plate, and allow to cool.

Analysis with DR/3000 Color Spectrophotometer

Zero instrument with a blank.

1. Transfer digested blank from beaker into a clean sample cell.
2. Add 1 drop of phenolphthalein indicator solution, and as much 5N NaOH solution as required to produce a faint pink tinge.
3. Once the pink tinge has appeared, add E-pure water to the 25-ml mark.
4. Add 1 ml Molybdovanadate to the sample cell. (Note: a small amount of yellow tinge might be present in the blank because of the reagent. Darker tinges will develop in samples with higher concentrations of phosphorus.)
5. Press: **3 Timer** (a 3-minute reaction period will begin. The display will indicate 3 minutes and then decrease in increments of tenths until 0 is reached.)
6. Press: **Manual Program**, then rotate the wavelength selector dial to a setting of 400 nm. (This will likely already be set appropriately)

7. After the timer beeps, place the sample cell into the cell holder. The 25-ml mark on the cell should face the front of the instrument for proper orientation. Close the compartment door.
8. Zero the instrument by pressing **Zero Abs**. The display should then read 0.000 Abs. If not, press the **ZERO** key again.
9. Empty and rinse the sample cell. Use the same cell for each successive standard and unknown sample.

Note: When there is no sample cell in the compartment, the absorbance may range between -0.075 and -0.081 or so. If this reading does not stay stable between sample analyses, the lamp may not have warmed up sufficiently. Delay further testing until the absorbance readings remain stable.

Analyze standards and samples

1. Transfer digested standard or sample from beaker into the same sample cell used to analyze the blank and zero the instrument. Filter if necessary to remove particulate material or turbidity. Use up 5 ml E-pure water to rinse the beaker (and filter).
2. Repeat steps 2-7 above.
3. Pres **Abs.** and read the absorbance or %T from the display.
4. Empty and rinse the sample cell. Use the same cell for each successive standard and unknown sample.

APPENDIX C

Anion Analysis Procedure

(ION CHROMATOGRAPHY)

Worcester Polytechnic Institute

Department of Civil & Environmental Engineering

>> Ion Chromatography Laboratory Procedures<<

Introduction // How to Use this Document

This lab procedure is not intended to replace training sessions with the IC. Nor does it contain all details that can be found in the IC User's Manual. Instead, it has been prepared as a lab reference – to be consulted to refresh the USER's memory on certain steps in the process of analyzing samples with the IC.

Manual manipulations of data that may be needed on a case-by-case basis are probably not covered in detail within this document.

Some Basic Terminology

Standards – These refer to injections of samples with known quantities of various constituents and are used to create a calibration curve

Unknowns/Samples – These refer to injections that will be analyzed

Blanks – For any sample in a sequence labeled as "blank," the injection valve IS NOT activated – only eluent is run through the system

Matrix – For any sample labeled as "matrix," the IC will allow the injection of a blank (which can be used later in the analysis to account for background levels) *Note: Typical WPI procedure has been to inject a blank at the beginning of each sequence, but it is labeled as an "unknown." It is not used as a matrix, but is used to ensure a baseline is established before standards and unknowns are injected.*

Program – tells the IC how to run a sequence

Sequence – tells IC about the injections – standards, blanks, and unknowns

Method – A method tells the IC how to interpret (quantify) the results of the analyses. It is stored as a .QNT file. The method file converts the area under the peaks found in the chromatogram to amounts, or measured concentrations.

Reports – There are various formats to choose from for the purposes of reporting results

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Starting Up the IC

1. Start the Hardware first
2. Next, start the computer
3. Then, start the panels
    - Check connected
    - Pump – start with half flow rate (0.6 ml/min) >> once the PSI has reached a value higher than 1000, increase the pump rate to 1.2 ml/min
    - *If PSI levels are bouncing, there is probably an air bubble in the system. This can be resolved by turning the valve and selecting "prime"*
4. Next, turn on the suppressor (mode = on) after checking that the current is appropriate for the column installed (113 for the anion column)
5. Turn on EG and CR-TC
6. Blue Dot >> Acquire all
7. Let sit for about 30 minutes to establish a baseline

Creating a Program

1. Under "File," select "New…Program File"
2. When dialog box appears, select "create program using wizard"
3. Timebase: Select "CEE11_1" under "my computer"
4. Gradient Type >> Isocratic
    - Press 200-3000
    - Flow rate 1.2 μl/min

these are settings unique to the particular column (anions, in this case)

5. EG >> Start @ 38
6. Manual Injection
7. Duration (depends on loop size) – 30 seconds is adequate
8. Acquisition – check them all
   Note: ECD_Tot >> everything
   ECD_1 >> accounts for zeroing
9. Options "yes" on autozero
   cell temperature = 30°C
   column temperature (depends on column) = 30°C for the anion column
10. Accept next 3 screens
11. "Title" and review
12. Save to folder CEE11_1\Programs\

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Creating a Sequence

1. Under “File,” select “New…Sequence”
2. When dialog box appears, select “create sequence using wizard”
3. Timebase: Select “CEE11_1” under “my computer”
4. Unknowns >> this screen is where you set up for each sample
    - number of vials = number of samples
    - start position >> make sure you account for appropriate number of standards/blanks that will precede the samples
    - volume of sample = volume of loop being used
5. Standards >> same inputs as unknowns
6. CEE Lab Manager typically includes one blank at beginning of sequence – it should be entered as an “unknown” with a start position of 1
7. Methods and Reporting >> using the “browse” function, select the appropriate program, method, and report files (use default and modify later if unknown)
8. Preferred Channel = CEE11_1
9. Sequence Name >> use date that sequence is run in the file name and store in Directory CEE11_1\Sequences

Running a Sequence

A sequence can be started from either panel, but starting from the anion basic panel will likely lead to better results

1. Under “New,” select “Batch”
2. Select “Start” (perform a “ready check first”)

Viewing Results

- Double-clicking on a sample from the sequence pane will display the results for that sample
- “Peak Calipers” shows the window of expected retention time. When viewing results, right-click on the graph window and select “decoration.” The peak caliber tab can be used to select “show peak calipers” and “show all caliper drop lines”

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Creating a Method (QNT file)

1. From within a sequence, double-click on any sample (Details regarding that sample will appear)
2. On the menu bar, select QNT Editor to manipulate the method
3. Within the QNT Editor, follow the bottom tabs across as indicated below.

“General”

- How are results interpreted? – Enter dimension amount (usually PPB)
- Mode of Calibration
    - Total – all samples in sequenced that are labeled as “standards” will be used to calibrate
    - Fixed – standards from previous sequences can be utilized
- Blank run and matrix subtraction is available on this tab if needed

“Detection”

1. Minimum area – arbitrary amount (typically has been set to .005)
2. This is the tab where “inhibit integration” can be turned on or off at specified times – which will eliminate the detection of negative peaks or others that the User would like to not include in the reported results, because they are not accurately reflecting constituents or amounts.

“Peak Table”

Autogenerate peak table

- Right-click on line 1
- select “autogenerate peak table”
- pop-up window – click “ok”
- Name peaks by clicking on “default - #” cell
- right-click and select “edit field”
- rename appropriately
- Save before closing window
- Double-click on a standard
- Click “QNT Editor” button
- “Assign Standards on Basis of…” select >Name<
- Select all standards
- Auto generate
- Apply
- ok
- In table, manually type in standard concentrations
- Calibration Type – set to “linear” – the program will automatically force the calibration curve through zero. This can be changed by double-clicking “calibration type” and unchecking “force through zero” in the pop-up window

"Amount Table"

- no changes

"Peak Tracking"

- no changes

"Calibration"

- If "ok" appears, then all the peaks were found in the specified time intervals
- If using standards from a previous sequence for calibration
  - Mode in "general tab" should be set to "fixed"
  - Right-click on line and select "append standard"
  - Using "browse" function, select standards of choice

The last two tabs in QNT editor are not likely to be used

A few Notes on Methods

1. When a sequence is developed, a method (.QNT file) can be selected. If the USER does not select a method file, a "default" method will be imported. This "default" method is stored in the "methods" folder and is titled "default." When the USER manipulates this method and saves as a new method, the new QNT file will be saved within the sequence folder only. The USER should copy and paste the new method into the "methods" folder if he/she wants to have that available for future use. Please do not overwrite the "default" method in the "methods" folder as that provides the most consistent base file from which to work.
2. Each sample in the sequence needs to be updated with the most appropriate method. See column labeled "method." Click and a list of available method files will appear. After the appropriate method file is selected, it can be applied to all samples, using the "fill column" function. Use F9 as a shortcut – or right-click on the column heading and selecting "fill column."
3. In order to select the desired "method," a copy of that method must be saved within that sequence folder. If it is, it will be listed in the upper window. If it is not, it will not be a choice that appears in the pull-down menu in the method column.
4. In some cases, manual manipulations may need to be performed on one or more samples for functions such as deleting peaks or changing baselines. If the User does not want these manipulations applied to all the samples in the sequence, such manipulations must be saved as "manual manipulations," instead of as a change to the QNT file.
5. If amount tables need to be added, double-click on one of the amount columns
   - "Unassigned standards detected" window appears
   - Click "ok"
   - "Assign standards on the basis of…" >>Name<< should be selected
   - Click "new"
   - Type name (e.g. 200 ppb)
   - Click "enter"
   - Click "unassigned" and drag standard onto new column name you just created
   - click "ok" and enter amounts in table

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Using standard calibration curves from previous sequences

1. Open QNT Editor
2. On the “General” Tab, change mode to “fixed”
3. On the “Calibration” tab, right-click on line and choose “append standard”
4. Using browse function, select the appropriate standards from sequence in which the standard was analyzed as a standard – This will have to be completed one at a time
5. In some cases, the amount table may also need to be updated – see *“Peak Table”* steps 8-15

Comparisons

1. To see the results of all samples in the sequence, select all samples
2. right-click
3. select “compare”
4. choose ECD_1
5. right-click on graph
6. select “decoration”
7. “Comparison” – turn offset off >> “signal”

APPENDIX D

Grab Sample Laboratory Results

APPENDIX D: Grab Sample Phosphorus Results

Date	White Roof P concentration (mg/L)	Green Roof P concentration (mg/L)	Time of Sample	Method	Observations
	Total Phos-PO_4^{-3}	**Total Phos-PO_4^{-3}**			
06/08/09	0.34	0.98	4:00 PM	Color Spec	stagnant (pre-storm) - white roof very yellow in color
06/11/09	0.49	0.98	10:00 AM	Color Spec	after mild rain
06/12/09	0.00	3.37	9:30 AM	Color Spec	after heavy rain
06/16/09	0.43	2.39		Color Spec	rain 2 days prior
06/22/09	0.00	7.05		Color Spec	
07/07/09	0.52	12.38	3:15 PM	Color Spec	
10/27/09	ND	0.88	10:30 AM	I/C	
11/02/09	ND	0.60	2:15 PM	I/C	
11/16/09	0.27	0.98	4:30 PM	I/C	after heavy rain (2 days)
11/24/09	ND	0.49	late morning	I/C	
12/07/09	ND	0.95	10:30 AM	Color Spec	cold - snow 2 days prior
12/14/09	4.00	1.25	3:00 PM	Color Spec	cold freezing rain over weekend
01/26/10	1.54	2.26	4:00 PM	Color Spec	after heavy rain
02/02/10	2.91	0.60	6:00 PM	Color Spec	no rain - very light snow?; white - cloudy -
02/09/10	0.84	0.54	9:30 PM	Color Spec	no rain; green - yellowish with sediment;
02/22/10	0.50	0.54	3:00 PM	Color Spec	no rain; green - clear; white - slightly
02/24/10	0.01	1.04	11:45 AM	Color Spec	during rain; green - clear; white - clear
03/08/10	2.85	1.25		Color Spec	no rain or snow
03/15/10	0.78	1.39		Color Spec	after heavy rain
03/22/10	0.50	1.42	4:30 PM	Color Spec	before rain
03/30/10	1.56	1.59	5:30 PM	Color Spec	during rain (after 2 days of heavy rain)
04/05/10	0.42	1.59	11:00 AM	Color Spec	no rain since last week
04/07/10	0.25	1.19	10:00 AM	Color Spec	no rain since last week
04/13/10	0.47	1.43	2:30 PM	Color Spec	no rain since last week
04/19/10	ND	0.96	11:45 AM	Color Spec	no rain since weekend
	Dissolved Phos-PO_4^{-3}	**Dissolved Phos-PO_4^{-3}**			
12/01/09	ND	1.02	noon	I/C	after heavy rain
12/07/09	ND	0.90	10:30 AM	I/C	cold - snow 2 days prior
12/07/09	not tested	0.73		I/C	
01/26/10	ND	0.32	4:00 PM	I/C	after heavy rain
02/02/10	ND	ND	6:00 PM	I/C	no rain - very light snow?
02/09/10	ND	ND	9:30 PM	I/C	no rain
02/22/10	ND	0.13	3:00 PM	I/C	no rain
02/24/10	ND	0.79	11:45 AM	I/C	during rain
03/15/10	not tested	1.29		Color Spec	after heavy rain
03/15/10	ND	1.15		I/C	after heavy rain
03/22/10	ND	0.32	4:30 PM	I/C	before rain
03/30/10	ND	1.34	5:30 PM	I/C	during rain (after 2 days of heavy rain)
04/05/10	ND	0.33	11:00 AM	I/C	no rain since last week
04/07/10	ND	0.26	10:00 AM	I/C	no rain since last week
04/13/10	ND	0.21	2:30 PM	I/C	no rain since last week
04/19/10	ND	0.65	11:45 AM	I/C	no rain since weekend

APPENDIX E

Greenhouse Sample Laboratory Results

APPENDIX E: Greenhouse Sample Data

	Color Spectrophotometry		Ion Chromotography						
outside of calibration range	**Total P-PO_4^{-3} mg/L (PPM)**	**Dissolved P-PO_4^{-3} mg/L (PPM)**	**Dissolved P-PO_4^{-3} mg/L (PPM)**	**Nitrite**	**Nitrate**	**Fluoride**	**Chloride**	**Sulfate**	**Bromide**
3-19 Rain	0.20	*not tested*	ND	ND	0.02	0.03	1.55	0.72	ND
3-19 Outflow A	2.88	*not tested*	1.19	0.02	3.90	0.19	1.12	3.52	ND
3-19 Outflow A duplicate	*not tested*	*not tested*	1.20	0.02	3.94	0.19	1.16	3.59	ND
3-19 Outflow B	2.78	*not tested*	2.18	ND	0.44	0.58	2.20	4.28	ND
3-19 Outflow B duplicate	*not tested*	*not tested*	2.39	ND	0.46	0.61	1.79	4.35	ND
3-19 Outflow Mix A	1.24	*not tested*	0.72	ND	2.63	0.14	1.57	2.55	ND
3-19 Outflow Mix B	0.70	*not tested*	0.27	ND	0.17	0.14	3.31	2.20	ND
3-19 Soil Sat A	577 mg/kg	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-19 Soil Sat B	728 mg/kg	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-19 Sedum Kamtschaticum (A)	4.48	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-19 Sedum Kamtschaticum (B)	4.99	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-19 Sedum Spurium (A)	2.12	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-19 Sedum Spurium (B)	2.54	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*

Moisture Content	**Wet Weight**	**Dry Weight**	**Moisture Content**	
3-19 Soil Sat A	6.78	5.00	26.3%	avg
3-19 Soil Sat B	7.39	5.37	27.3%	26.8%
3-19 Sedum Kamtschaticum (A)	0.28	0.04	84.8%	
3-19 Sedum Kamtschaticum (B)	0.41	0.06	85.5%	
3-19 Sedum Spurium (A)	0.58	0.08	85.7%	
3-19 Sedum Spurium (B)	0.42	0.07	83.8%	

APPENDIX E: Greenhouse Sample Data

	Color Spectrophotometry		Ion Chromotography						
outside of calibration range	**Total P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Nitrite**	**Nitrate**	**Fluoride**	**Chloride**	**Sulfate**	**Bromide**
3-25 Rain	0.39	*not tested*	ND	ND	0.21	0.02	0.37	0.87	ND
3-25 First Flush A	1.82	*not tested*	1.38	ND	3.02	0.25	1.26	8.18	ND
3-25 Mid 1 A	*not tested*	*not tested*	1.62	0.01	4.07	0.29	1.09	10.80	ND
3-25 Mid 2 A	*not tested*	*not tested*	1.62	0.02	4.43	0.29	1.15	11.59	ND
3-25 Mid 3 A	*not tested*	*not tested*	1.55	0.02	4.73	0.28	1.26	12.05	ND
3-25 Outflow A	2.15	*not tested*	1.55	0.03	4.89	0.28	1.22	12.20	ND
3-25 Outflow A Mix	1.88	*not tested*	1.27	0.02	3.46	0.23	1.26	9.26	ND
3-25 First Flush B	3.41	*not tested*	2.43	ND	0.17	0.66	0.73	7.63	ND
3-25 Mid 1 B	*not tested*	*not tested*	2.82	ND	0.18	0.72	0.44	8.63	ND
3-25 Outflow B	3.14	*not tested*	2.63	ND	0.12	0.64	0.43	8.10	ND
3-25 Outflow Mix B	2.59	*not tested*	2.11	ND	0.16	0.57	0.73	6.94	ND
3-25 Soil Pre A	436 mg/kg	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Soil Pre B	672 mg/kg	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Soil Sat B	642 mg/kg	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Sedum Kamtschaticum (A)	5.52	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Sedum Kamtschaticum (B)	3.89	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Sedum Spurium (A)	2.76	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Sedum Spurium (B)	3.09	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*

Moisture Content	**Wet Weight**	**Dry Weight**	**Moisture Content**	
3-25 Soil Pre A	15.45	11.48	25.7%	avg
3-25 Soil Pre B	7.90	5.82	26.3%	26.0%
3-25 Soil Sat A	7.86	6.05	23.0%	
3-25 Soil Sat B	5.23	3.87	26.0%	25%
3-25 Sedum Kamtschaticum (A)	0.95	0.18	81.1%	
3-25 Sedum Kamtschaticum (B)	1.85	0.30	83.6%	
3-25 Sedum Spurium (A)	1.21	0.23	81.3%	
3-25 Sedum Spurium (B)	1.86	0.32	83.0%	

APPENDIX E: Greenhouse Sample Data

	Color Spectrophotometry		Ion Chromotography						
outside of calibration range	**Total P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Nitrite**	**Nitrate**	**Fluoride**	**Chloride**	**Sulfate**	**Bromide**
4-7 Rain in	0.12	*not tested*	ND	ND	0.10	0.07	0.70	2.55	ND
4-7 Rain out	0.06	*not tested*	ND	ND	0.38	0.09	1.66	3.66	ND
4-7 Outflow Mix A	ND	*not tested*	ND	ND	0.33	0.08	1.53	3.39	ND
4-7 Outflow Mix B	0.06	*not tested*	ND	ND	0.36	0.11	1.84	3.99	ND
4-7 Equip Storage A	0.41	*not tested*	ND	0.06	0.61	0.09	4.04	4.62	ND
4-7 Equip Storage B	2.37	*not tested*	1.22	0.07	0.49	0.41	3.21	9.45	ND
4-7 Soil Pre A	389	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-7 Soil Pre B	634	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-7 Soil Sat A	468	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-7 Soil Sat B	401	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-7 Sedum Kamtschaticum (A)	5.99	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-7 Sedum Kamtschaticum (B)	6.56	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-7 Sedum Spurium (A)	4.88	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-7 Sedum Spurium (B)	4.91	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*

Moisture Content	**Wet Weight**	**Dry Weight**	**Moisture Content**	
4-7 Soil Pre A	10.818	9.863	8.8%	avg
4-7 Soil Pre B	5.010	4.550	9.2%	9.0%
4-7 Soil Sat A	6.789	5.153	24.1%	
4-7 Soil Sat B	5.565	4.402	20.9%	0.23
4-7 Sedum Kamtschaticum (A)	1.765	0.180	89.8%	
4-7 Sedum Kamtschaticum (B)	1.565	0.144	90.8%	
4-7 Sedum Spurium (A)	1.830	0.176	90.4%	
4-7 Sedum Spurium (B)	1.667	0.152	90.9%	

APPENDIX E: Greenhouse Sample Data

	Color Spectrophotometry		Ion Chromotography						
outside of calibration range	**Total P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Nitrite**	**Nitrate**	**Fluoride**	**Chloride**	**Sulfate**	**Bromide**
4-16 Rain in	0.16	*not tested*	ND	0.26	7.05	0.05	1.33	8.72	ND
4-16 First Outflow A	0.54	*not tested*	ND	0.30	7.46	0.05	1.88	9.77	ND
4-16 Mid 1A	1.91	*not tested*	0.86	0.32	7.03	0.17	2.61	15.93	ND
4-16 Mid 2A	*not tested*	*not tested*	1.70	0.20	4.95	0.28	2.23	27.59	ND
4-16 Mid 3A	2.78	*not tested*	1.80	0.20	4.91	0.29	2.10	30.31	ND
4-16 Mid 4A	*not tested*	*not tested*	1.80	0.21	5.46	0.28	2.07	30.91	ND
4-16 End A	2.84	*not tested*	1.76	0.21	5.44	0.29	2.07	31.93	ND
4-16 Outflow Mix A	1.99	*not tested*	1.18	0.23	5.88	0.24	2.61	25.28	ND
4-16 First Outflow B	0.11	*not tested*	ND	0.27	7.26	0.07	1.98	9.75	ND
4-16 Mid 1B	2.95	*not tested*	1.61	0.28	5.71	0.39	2.30	16.02	ND
4-16 Mid 2B	*not tested*	*not tested*	2.62	0.20	3.28	0.51	1.51	19.30	ND
4-16 Mid 3B	3.22	*not tested*	2.68	0.19	3.02	0.53	1.38	19.73	ND
4-16 Mid 4B	*not tested*	*not tested*	2.71	0.18	2.80	0.53	1.33	20.16	ND
4-16 End B	4.18	*not tested*	2.73	0.18	2.72	0.55	1.32	20.64	ND
4-16 Outflow Mix B	2.82	*not tested*	1.98	0.21	4.11	0.44	1.87	18.08	ND
4-16 Soil Pre A	489	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Soil Pre B	564	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Soil First Outflow A	455	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Soil First Outflow B	1050	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Soil Sat A	581	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Soil Sat B	696	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Soil End A	373	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Soil End B	718	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Sedum Kamtschaticum (A)	5.29	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Sedum Kamtschaticum (B)	6.18	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Sedum Spurium (A)	4.44	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-16 Sedum Spurium (B)	5.28	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*

	Color Spectrophotometry		Ion Chromotography						
outside of calibration range	**Total P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Nitrite**	**Nitrate**	**Fluoride**	**Chloride**	**Sulfate**	**Bromide**
Moisture Content	**Wet Weight**	**Dry Weight**	**Moisture Content**	Time					
4-16 Soil Pre A	12.261	11.120	9.3%	avg					
4-16 Soil Pre B	8.264	7.221	12.6%	11.0%					
4-16 Soil First Outflow A	8.481	7.066	16.7%						
4-16 Soil First Outflow B	4.641	3.594	22.6%						
4-16 Soil Sat A	8.631	6.686	22.5%						
4-16 Soil Sat B	9.112	6.752	25.9%	0.24					
4-16 Soil End A	8.498	6.867	19.2%						
4-16 Soil End B	7.265	5.584	23.1%						
4-16 Sedum Kamtschaticum (A)	3.016	0.307	89.8%						
4-16 Sedum Kamtschaticum (B)	3.697	0.312	91.6%						
4-16 Sedum Spurium (A)	2.537	0.231	90.9%						
4-16 Sedum Spurium (B)	2.394	0.207	91.4%						

	Color Spectrophotometry		Ion Chromotography						
outside of calibration range	**Total P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Nitrite**	**Nitrate**	**Fluoride**	**Chloride**	**Sulfate**	**Bromide**
4-17 Rain In	ND	*not tested*	ND	0.14	2.76	0.04	0.59	3.49	ND
4-17 First Outflow A	1.94	*not tested*	1.62	0.10	1.62	0.27	0.66	34.35	ND
4-17 End A	2.21	*not tested*	2.00	0.15	2.79	0.30	0.76	31.46	ND
4-17 Outflow Mix A	1.99	*not tested*	1.55	0.12	2.30	0.26	0.75	29.67	ND
4-17 First Outflow B	3.22	*not tested*	2.60	0.09	0.86	0.56	0.48	20.63	ND
4-17 End B	3.83	*not tested*	2.96	0.09	0.80	0.62	0.43	22.40	ND
4-17 Outflow Mix B	3.19	*not tested*	2.37	0.09	1.05	0.51	0.51	19.08	ND
4-17 Soil Pre A	440	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-17 Soil Pre B	593	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-17 Soil Sat A	343	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
4-17 Soil Sat B	565	*not tested*	*not tested*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*

Moisture Content	**Wet Weight**	**Dry Weight**	**Moisture Content**	Time

APPENDIX E: Greenhouse Sample Data

	Color Spectrophotometry		Ion Chromotography						
outside of calibration range	**Total $P\text{-}PO_4^{-3}$ mg/L (PPM)**	**Dissolved $P\text{-}PO_4^{-3}$ mg/L (PPM)**	**Dissolved $P\text{-}PO_4^{-3}$ mg/L (PPM)**	**Nitrite**	**Nitrate**	**Fluoride**	**Chloride**	**Sulfate**	**Bromide**
4-17 Soil Pre A	7.010	5.585	20.3%	avg					
4-17 Soil Pre B	8.364	6.413	23.3%	21.8%					
4-17 Soil Sat A	7.693	6.024	21.7%						
4-17 Soil Sat B	7.262	5.086	30.0%						
4-16 Rain Sample	0.74	*not tested*	ND	0.09	4.54	0.03	5.57	6.69	ND
4-17 Rain Sample	ND	*not tested*							

Moisture Content (Cores)	**Wet Weight**	**Dry Weight**	**Moisture Content**
4-19 Core A	90.700	71.200	21.5%
4-19 Core B	76.90	56.60	26.4%

Average Saturated Phos. Content	
Stand A	492.25
Stand B	606.40

	Atomic Absorption (Cations)						
	Sodium	**Calcium**	**Magnesium**	**Potassium**	**Iron**	**Manganese**	**Copper**
3-25 Rain	0.41	1.8	0.17	0.31	0.29	<.1	<.1
3-25 First Flush A	*nt*	*nt*	2.5	*nt*	0.11	*nt*	*nt*
3-25 Mid 1 A	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Mid 2 A	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Mid 3 A	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Outflow A	0.95	4.9	3.2	0.71	0.12	<.1	<.1
3-25 Outflow A Mix	0.98	4.4	2.6	0.7	0.14	<.1	<.1
3-25 First Flush B	*nt*	4.3	2.7	*nt*	0.19	*nt*	*nt*
3-25 Mid 1 B	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*	*nt*
3-25 Outflow B	1.6	4.4	2.9	0.69	0.18	<.1	<.1
3-25 Outflow Mix B	1.62	4.1	2.5	0.76	0.19	<.1	<.1

	Atomic Absorption (Cations)						
	Sodium	**Calcium**	**Magnesium**	**Potassium**	**Iron**	**Manganese**	**Copper**
4-7 Rain in	*nt*	*nt*	*nt*	*nt*	2.93	*nt*	*nt*
4-7 Rain out	*nt*	*nt*	*nt*	*nt*	1.72	*nt*	*nt*
4-7 Outflow Mix A	*nt*	*nt*	*nt*	*nt*	0.64	*nt*	*nt*
4-7 Outflow Mix B	*nt*	*nt*	*nt*	*nt*	0.47	*nt*	*nt*
4-7 Equip Storage A	*nt*	*nt*	*nt*	*nt*	1.69	*nt*	*nt*
4-7 Equip Storage B	*nt*	*nt*	*nt*	*nt*	1.72	*nt*	*nt*

APPENDIX E: Greenhouse Sample Laboratory Results

Moisture Content	**Wet Weight**	**Dry Weight**	**Moisture Content**
4-1 Roof Sample	695.50	492.50	29.2%

	Phos. in soil (mg/kg P)	(3 points)	(3 points) - no high or low		
Portion 1	1172	Average	889	Average	738
Portion 2	779	Std. Dev.	247	Std. Dev.	35
Portion 3	717	(5 points)			
Portion 4	461	Average	770		
Portion 5	719	Std. Dev.	256		

	Color Spectrophotometry		Ion Chromotography						
4-2 Flush Test	**Total P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Dissolved P-PO$_4^{-3}$ mg/L (PPM)**	**Nitrite**	**Nitrate**	**Fluoride**	**Chloride**	**Sulfate**	**Bromide**
Flush 1	13.48	*not tested*	1.62	0.13	12.82	0.03	0.15	0.58	ND
Flush 2	3.56	*not tested*	0.97	0.18	2.75	0.04	0.18	1.10	ND
Flush 3	*not tested*	*not tested*	0.87	0.12	0.98	0.04	0.07	0.40	ND
Flush 4	*not tested*	*not tested*	0.72	0.10	0.78	0.05	0.06	0.25	ND
Flush 5	*not tested*	*not tested*	0.94	0.08	8.78	0.04	0.11	0.24	ND
Flush 6	1.19	*not tested*	0.90	0.08	5.69	0.03	0.12	0.33	ND
Flush 7	*not tested*	*not tested*	0.70	0.07	2.54	0.04	0.10	0.18	ND
Flush 8	*not tested*	*not tested*	0.68	0.08	0.86	0.03	0.16	0.20	ND
Flush 9	*not tested*	*not tested*	0.57	0.06	1.01	0.03	0.09	0.13	ND
Flush 10	0.46	*not tested*	0.50	ND	0.41	0.02	0.07	0.11	ND

	% dissolved
Flush 1	12.0%
Flush 2	27.2%
Flush 6	75.6%
Flush 10	108.7%