WATER QUALITY IMPACTS OF A GREEN ROOF
In Comparison to Other Land Uses

By

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This thesis has been submitted in partial fulfillment of requirements for the Master of Science degree in Water Resources and Environmental Engineering at Villanova University.

Dedicated to my grandparents

who inspired my passion for conservation and my interest in engineering:

Bruno Talvacchia

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Abstract

Recent studies on green roof water quality have indicated that extensive green roofs are a source of phosphates, and occasionally nitrates, as compared to conventional roofing systems. However, due to the presence of soil media and vegetation, green roofs should be compared to other vegetated sites, as opposed to conventional roofs, for a fairer comparison. In this study, the impact of green roofs on surface water quality is placed in the context of other vegetated land uses, including two types of stormwater control measures (SCMs) as well as non-SCM sites. Site runoff and SCM effluent were evaluated for nitrogen and phosphorus species, chlorides, total suspended solids, and total dissolved solids. Comparisons of concentrations against EPA recommended criteria suggested that the green roof generally retained nitrogen and released phosphorus. Green roof performance was similar to that of a wooded area, a grassy area, and a mixed-use area, while it was outperformed by a rain garden and a constructed stormwater wetland.

To better gage the effect of the green roof's volume retention performance on its water quality impact, a nutrient mass balance was conducted for the green roof, and mass loads for the comparison sites were calculated. Mass balance estimation suggests that the green roof's water quality impacts could be mitigated by its volume retention capabilities. The green roof exports less nutrients than are input to the system from fertilization and atmospheric wet deposition, although overall it exports more than wooded areas, based on drainage area-scaled values. Findings may be used to guide land use planning including implementation of green infrastructure and management of urban green spaces. It is suggested that if nutrient export is a concern and space is available, green roof overflow could be diverted to other SCMs which are designed to remove excess nutrients from stormwater runoff.

1.0 Introduction

1.1 Motivation for Research

Over the past 20 years the state of the practice for stormwater management has been shifting from traditional "grey infrastructure" to "green infrastructure." Rather than investing heavily in upgrades to storm sewer systems and treatment facilities to increase their flow volume capacities, municipalities are striving to keep more stormwater onsite through the implementation of sustainable stormwater control measures or SCMs, as well through management of urban and suburban green spaces. Green infrastructure allows for increased storage and infiltration in the urban watershed, and helps restore the regional hydrologic cycle to its pre-development state. Research into stormwater control measures has validated their functionality and cost-effectiveness.

Green roofs are one such type of SCM shown to be effective in retaining stormwater (Nawaz et al. 2015, Wadzuk et al. 2013, Fassman-Beck et al. 2013, Carson et al. 2013, VanWoert et al. 2005). However, recent studies have shown that green roofs are a source for some pollutants, particularly nitrogen and phosphorus species, as compared to conventional roofing systems that do not provide stormwater control (Toland et al. 2012, Berndtsson et al. 2006, Berndtsson et al. 2009). Most of the studies on green roof quality compare green roof performance to vegetation-free retention systems or to non-stormwater control roofing systems. They do not, however, compare green roof performance to that of other vegetated land uses. Because they are living systems, a relative comparison of green roof performance to vegetated land uses and to other living-system stormwater control measures is warranted.

Because the green roof is a vegetated system, comparing its water quality performance especially for nutrients to other vegetated systems, is a fairer scenario than comparing it to conventional plant-free roofing materials. Many green roof studies are concerned with quality performance as it relates to metals and other inorganic constituents. This is because green roofs have additional drainage layers and soil media, which may leach inorganic elements or compounds; on the other hand they also have retention capabilities that may give them an advantage over conventional roofing system components like sheet metal, slate shingles, and/or tar sealants. Comparing the green roof to zero is unfair because regardless of the design, the system will export some small quantity of nutrients or trace metals. For this study in particular, the green roof is predicted to have some small amount of atmospheric nutrient deposition as well as contributions from fertilizer, therefore it is more realistic to compare it to precipitation as the control.

In densely urbanized areas, urban green spaces like wooded and grassy areas are frequently converted to impervious uses such as parking lots and building space. The goal of green infrastructure is to increase the pervious surface area of a watershed to allow for greater stormwater retention and detention, effectively returning the hydrograph to a distribution that reflects a pre-development model. For densely urbanized areas, this may encompass the re-establishment of equivalent green spaces to grassy and wooded areas. Both were included in the study as non-SCM background vegetated land uses.

It may be argued that grassy lawns are typically a poor-quality alternative to long-established natural habitat, because they have a much smaller species distribution. In addition, their usefulness for stormwater management is inconsistent: they frequently include soils that have been disturbed and compacted by development. However, they do allow some amount of infiltration and a small amount of storage. Green infrastructure is often better at controlling stormwater than many grassy areas – as reflected by the high curve numbers of urbanized green spaces – and has the added benefit of stormwater treatment. Wooded areas are better at capturing runoff than other non-SCM land use counterparts, but this depends on a variety of factors including the age and quality of the woodlot, slopes, and the characteristics and construction history of the site and adjacent areas.

Finally, the green roof was compared to two other types of stormwater control measures, which are also used for stormwater treatment and pollutant removal. The question of whether green roofs can be used for stormwater treatment has been brought up before, and indeed they have been observed to retain some metals (Alsup et al. 2013). However, pollution control is currently not a standard design consideration for extensive green roofs, and little is known about their performance regarding nutrients. Therefore their performance was compared to two SCMs which have been observed to retain nutrients.

1.2 Villanova Green Roof

The Villanova green roof is a component of the Villanova Urban Stormwater Partnership's (VUSP) stormwater demonstration park, located in Villanova, PA. The green roof structure is a retrofit of the original roof and has been used for research for the past 10 years. The old rooftop was sealed and a multi-layer base was installed which includes an impermeable geomembrane; an insulation later; a cup-tray system for water storage and drainage; and a geotextile for separation of the water storage system from the soil media particles to prevent clogging. Three to four inches of soil media for extensive green roofs lies atop the drainage layers and supports a selection of sedum plants and some chives. The green roof's ability to capture stormwater runoff is dependent on the combined function of the drainage layer, soil media, and plants.

The Villanova green roof is a full research site and as such it is equipped with instrumentation to measure temperature, relative humidity, wind speed, rainfall accumulation and snowmelt. In addition, a weighing lysimeter resting on three load cells allows for measurement of evapotranspiration losses as a portion of the green roof's water budget. A tipping bucket rain gauge and ultrasonic depth sensor collect overflow volume data for low and high flows, respectively. Finally, an autosampler collects volume-specified overflow samples. The green roof is also used for demonstration purposes to educate the public about sustainable stormwater management.

1.3 Research Goals

The goals of this research were as follows

1) *To determine the water quality performance of a fertilized green roof by providing a relative comparison to conventional vegetated sites in urban areas, as well as to contrast its performance against reference water quality criteria.* This was done by sampling green roof overflow as well as wash-off from three other urban land use types, and testing these samples for a suite of water quality parameters. Where available, reference criteria specific to each water quality parameter was included in the land use comparison.
2) *To compare water quality performance of the green roof to other stormwater control measures.* Using a similar approach and the same reference criteria as in the previous objective, green roof outflow was compared to outflow from a constructed stormwater wetland and a bioinfiltration rain garden.
3) *To estimate the overall performance of the green roof by examining the interplay between hydrological performance and water quality performance.* A mass balance estimation of each water quality parameter was conducted for the green roof using rainfall and overflow

data to approximate annual overflow volumes, which were multiplied by concentration statistical averages. In addition, estimates of mass export were calculated for the vegetated sites and SCMs used for comparison to the green roof.

2.0 Literature Review

2.1 Green Infrastructure for Stormwater Management

Stormwater management is a major challenge faced by municipalities as well as private developers. Due to the effects of increased urbanization and of climate change, conventional methods for stormwater management must evolve to handle both higher volumes of runoff and more frequent inundations. Areas that were once rural cropland or forested cover are being converted to residential, commercial, and industrial land use regimes. Watersheds characterized by a loss of vegetative cover and an increase in percent of impervious cover have a reduced capacity for rainfall infiltration and storage. As a result of this reduced capacity, more rainfall is converted to runoff, which not only causes problems related to higher volumes and rates of flow; but also presents a water quality challenge. Increased surface runoff in urbanized areas causes degradation of stream and river embankments, erosion of poorly stabilized slopes, higher frequency of flash flooding, and inundation of infrastructure used for stormwater conveyance during large storm events.

The runoff also carries pollutants from roadways and fertilized land which impacts receiving waters. In heavily developed areas with older stormwater conveyance systems, it is common to have stormwater and wastewater conveyed via the same sewer pipes and conduits. Many larger, older cities in the U.S., such as Philadelphia, New York, Baltimore, Boston, and Seattle, have combined sewer systems to carry wastewater to treatment facilities. As the storage potential and infiltration capacity in a sewershed decreases, peak flowrates and volumes increase; excessive runoff can overburden storm sewers and treatment facilities that were originally designed to manage lower flows. Combined sewer overflows (CSOs) cause environmental contamination of land and receiving surface waters, posing problems for communities and natural ecosystems.

Traditional stormwater management has consisted of underground conveyance and storage systems, which are designed to address quantity issues. Over the past 25 years however, strategies for stormwater management have shifted the focus to retaining more stormwater on-site, thereby reducing the volume which must be conveyed downstream. Green infrastructure practices such as bioinfiltration and bioretention rain gardens, vegetative swales, stormwater wetlands, and green roofs provide ecosystem benefits such as stormwater retention and storage, peak flow reduction, infiltration, and pre-treatment (Davis et al. 2010, Dovel et al. 2015, Lewellyn et al. 2015, Jones and Wadzuk 2013, Spolek 2008). These are all sustainable options which require less capital investment and cost of maintenance than traditional grey infrastructure, and at the same time provide social, economic, and ecological benefits to communities. Implementation of green infrastructure can increase the standard of living in urban neighborhoods. Community residents with access to green space tend to have better mental health. Improved patient recovery rates have been observed at medical facilities where patients have access to "healing" gardens. Green infrastructure can also be used to promote native plant communities and support natural habitat for wildlife (MacIvor and Lundholm 2011).

2.2 Green Roofs and Their Benefits

Green roofs are a sustainable stormwater management strategy in that they provide on-site retention of stormwater volume (Berghage et al. 2009). Implemented in Germany since the 1970s, they have more recently been recognized in the United States as a useful strategy to address urban stormwater runoff from impervious rooftops (Getter and Rowe 2006). Other recognized co-benefits of green roofs include their ability to improve air quality in cities (Yang et al. 2008); the energy savings for buildings through insulating effects (Spolek 2008); and their potential to help mitigate the urban heat island effect (Susca et al. 2011). They may on occasion offer runoff quality improvements over conventional roofing systems (Alsup et al. 2013, Rowe 2011).

The volume of runoff which green roofs are capable of retaining is dependent on properties such as the desired depth and type of media. Media depth and water storage capacity may be dependent on the roof structure, especially if the green roof is a retrofit. Green roofs typically fall into two categories which are dictated by the depth of soil media. Extensive roofs should have a minimum of approximately four inches of media, although depths as low as two inches have been tested (Fassman-Beck et al. 2013). These more common green roof types are typically planted with sedums and other hardy, drought-tolerant plant species (Nagase and Dunnett 2010). Intensive green roofs have media depths equal to or greater than 12 inches and may be planted with a greater variety of species, including shrubs and small trees (Roehr and Fassman-Beck 2015). Intensive roofs require greater structural support from buildings and therefore are typically factored into building plans, whereas extensive roofs may be installed on rooftop retrofits with minimal impact on the supporting structure depending on the age and weight-bearing capacity of the original roof (Fassman and Simcock 2012).

The ecological services provided by green roofs are partly attributed to the selection of plants used. Extensive green roofs are typically planted with *Sedum* species; these are particularly hardy, drought-tolerant species which can withstand the extreme conditions that characterize their habitat (Nagase and Dunnett 2010). These conditions include shallow, nutrient-poor soil media, high daily rates of solar radiation, wind effects such as scour, and occasional intense rainfall and temporary saturation. These conditions reduce the likelihood of survival for other species, including many native forbes and grasses, however sedums are physiologically adapted to these environmental stressors and can survive longer. Green roofs may benefit aesthetically when sedum foliage changes color as a result of environmental stressors.

Green roofs can have a direct positive impact for avian and other species, simply by providing habitat and sanctuary in urban areas where habitat is otherwise limited by development. The city of Portland, OR conducted an ecoroof avian monitoring study at three different sites. They found both greater avian abundance and greater species richness at the ecoroofs than at conventional control roofs, and comparable to ground-level bird-friendly monitoring sites (Portland 2013). In addition, during a 5-year green roof plant evaluation study conducted at Chicago Botanic Gardens, a variety of bird, insect, and animal species were observed to visit the 16,000-square foot evaluation site (Hawke 2015).

2.3 Green Roofs and Stormwater Volume

The primary function of a green roof is hydrological. Green roofs reduce stormwater runoff through storage within the soil media and plant tissues; and also via evapotranspiration (Marasco et al. 2014, Wadzuk et al. 2013). These studies have quantified the role of evapotranspiration in green roof performance using methods developed first by Penman and later expanded upon by others into the Penman-Monteith, Priestly-Taylor, and Hargreaves methods. The amount of evapotranspiration is a function of several factors including rainfall patterns, solar radiation, relative humidity, wind exposure, temperature, atmospheric pressure, plant coverage and stomatal resistance (Feller 2011, Schneider 2011).

Stomatal resistance in particular is dependent on the physiology of individual plant species and cultivars. Sedums, like other succulents, are very efficient at conserving water; their tissues are highly adapted to store water and release it slowly though their stomata. Use of crop coefficients with commonly-used equation models for ET have often been used for estimating the amount of water released by homogenously-planted agricultural crop fields. There are some practicalities in applying these methods to extensive sedum-planted roofs, including the relatively limited selection of species with which such rooftops are planted. The potential for such methods does face its challenges, however: green roofs have much smaller footprints compared to most crop fields. Other factors, such as the impacts of drainage around the planted roof perimeter and impacts of adjacent buildings, must be taken into account when gauging the accuracy of crop coefficients for extensive green roofs.

The amount of rainfall that a green roof is designed to capture varies depending on regional rainfall and climate characteristics. In Philadelphia for example, green roofs and other stormwater control measures (SCMs) are often designed to capture the first inch of runoff, which can be upwards of 90% of annual rain events (Lewellyn et al. 2015). However, total annual rainfall for other regions, such as the Florida panhandle, may comprise less frequent but far more intense storm events, while for still other regions the rainfall may be characterized by mostly small but frequent events, such as in the Pacific Northwest. By altering the design volume based on regional rainfall data, a reasonable percentage of capture for a green roof or other SCM may be achieved.

In general the hydrological performance of green roofs is dependent on regional climate conditions. Storage may represent a lower percentage of the overall water balance for a green roof over periods of higher than average rainfall. Hydrological performance has been extensively evaluated, and typical retention rates during the growing season have been shown to vary between 50 and 90 percent of the total water balance (Berghage et al. 2009, VanWoert et al. 2005).

2.4 Quality Impacts on Waterways

Rainfall that does not infiltrate soils, find surface storage, or evapotranspire back to the atmosphere, becomes runoff, flowing over vegetated pervious and impervious areas. As it flows, it picks up pollutants from fertilized lawns and cropland, roadways, and other industrially and commercially developed land. The runoff eventually makes its way to receiving waters such as rivers, streams, lakes, and wetlands, where the pollutants conveyed with it also end up. Protection of receiving waters was first legislated by the U.S. Environmental Protection Agency in the early 1970s with the Clean Water Act (CWA), an expansion on the 1948 Federal Water Pollution Control Act, for the purpose of ensuring sources of clean water for drinking and recreational purposes as well as to safeguard natural habitat (EPA 1972). Aquatic habitats are highly sensitive to changes in dissolved ion concentrations and turbidity. The CWA mandates states to set limits on a wide range of water quality criteria. For example, Code 25 of the Commonwealth of Pennsylvania requires that limits be set for point source pollution (DEP 2010). However, the EPA has not set limits for nutrient contaminants such as nitrogen and phosphorus, although these have been shown to affect wetland ecology. Non-governmental entities such as the Chesapeake Bay Foundation work with states in the Chesapeake Bay watershed to reduce nutrient loading in the Bay. The EPA has also published criteria for recommended concentrations based on ecologically unaffected waterways (EPA 2000a).

Pennsylvania's Stormwater Management Plan and the NDPES program require stormwater discharge permits for developing on building sites greater than one acre; developers must also demonstrate plans for control of runoff and sediment from their sites (EPA 2014). Many of the benefits of using green infrastructure for stormwater control are quality-related. Bioinfiltration and bioretention SCMs, such as rain gardens, permeable pavements, infiltration trenches, stormwater wetlands, and swales, can be designed to treat stormwater directly through physical means such as particle settling for suspended solids, and sorption of metals and nutrients to the SCMs' soils and bottom sediments (Komlos and Traver 2012, Welker et al. 2012, Wadzuk et al. 2010). These SCMs also provide biological treatment through mechanisms such as plant uptake. Outflow quality is improved and contaminants are prevented from entering downstream receiving waters.

2.5 Green Roofs and Stormwater Quality

While green roofs are effective in managing stormwater quantity, their designs do not yet account for water quality (Berndtsson et al. 2009). Water quality aspects of green roofs must not be overlooked because as living systems, they can contribute to non-point source stormwater discharge into local waterways, in quantities that are dependent on the storm size which the green roof is designed to capture. Input of contaminants may come from adjacent rooftops, human application, or atmospheric deposition through rainfall. Green roof effluent may convey dissolved ions, which may impact the health of the receiving waters. Therefore, it is important to ascertain whether or not green roofs are sources of pollutants, to ensure the sustainability of green roofs as a best management practice, and to recommend improvements for design.

As much as 50 percent of the impervious surfaces area in densely urban watersheds may be impervious rooftops (Hakimdavar et al. 2014). Their implementation may result in a rooftop behaving more like other vegetated land in the typical urban watershed (PADEP 2006). As green roofs become more common, design and maintenance practices will play an important role in the overall contribution to urban runoff quality as sources, non-sources, or sinks for pollutants. Recent studies have suggested that green roofs are a source for pollutants (Toland et al. 2012). Effluent, or overflow not retained in the system or evapotranspired, may carry dissolved nutrients and metals (Berndtsson 2010). Green roofs, being living systems, may leach nutrients due to various factors including but not limited to plant decomposition and fertilizer releases (Emilsson et al. 2007). Aspects of green roof runoff quality are discussed in more detail in the following paragraphs.

2.5.1 Metals

In evaluating green roof runoff quality, research has focused mostly on export of metals and compared them to non-vegetated roofs, because depending on the materials used, conventional roofing materials are often a source for these contaminants. Green roofs may offer quality improvements for metals by exporting less than conventional rooftops, but they have been shown to export some metals (Alsup et al. 2013). With regards to water quality treatment of runoff for metals, green roofs perform inconsistently at best. Occasional sink behavior was observed in a comparison study of simulated green roof systems containing different substrates, however, this sink behavior was not consistent over a 22-month period. When stacked against US EPA water quality criteria for several different metals, the green roof systems did not release runoff in concentrations below either acute or chronic toxicity standards for those elements. Furthermore, significant difference between mean runoff concentrations for the various green roof systems and for a conventional EPDM roof was not always observed (Alsup et al. 2013).

This inconsistent behavior was also observed by Berghage et al. (2009), who compared green roofs to flat asphalt roofs, and the behavior may be a function of the green roof soil media characteristics. For instance, some metals such as calcium may be exported if the substrate has a high concentration of calcium carbonate. Sodium was shown to be exported, while other metals (Mn, Z, and Fe) were released in concentrations that were below detection, and it was unclear whether or not the exported quantities should be of concern (Berghage et al. 2009). Similar results were obtained by Berndtsson et al. (2006) for a wider range of compounds which included heavy metals cadmium, chromium, copper, in addition to zinc and manganese.

Some studies have suggested green roofs may aid in reducing stormwater pollutants by acting as sinks for metals (Köhler et al. 2002, Gregoire and Clausen 2011, Vijayaraghavan and Joshi 2014). Still, Berndtsson (2009) does not recommend considering extensive green roofs as a rainfall-runoff treatment option, particularly for metals, as the media is often too shallow and porous to effectively retain metals. In addition to comparing runoff quality to non-vegetated controls, it is a good idea to compare runoff concentrations against environmental reference standards, since the runoff ultimately ends up in receiving waters which may be considered ecologically sensitive, or necessary drinking water sources. A three-year study conducted in Toronto used Ontario receiving water guidelines as reference values for metals concentrations in green roof runoff (Van Seters et al. 2009). Metal concentrations leached from green roof media in this study did not meet the levels recommended for surface waters in Ontario.

2.5.2 Nutrients from Fertilizers and Compost Amendments

There is a wide range of studies which consider metals in green roof runoff; however, more attention should be paid to nutrient concentrations, in particular nitrogen and phosphorus, and the factors which affect them. Despite the occasionally favorable behavior regarding metals retention, studies have cited green roofs as sources for nutrients such as phosphorus as well as organic matter (Köhler et al. 2002). A study by Toland et al. (2012) investigated water quality effects of compost amendments to green roof soils on outflow quality data. Three green roofs with different soil substrate mixtures were compared to three different conventional grey roof configurations; in addition, the roof runoff quality samples were compared to samples taken from several urban streams. The streams' drainage areas were representative of a variety of watershed land uses: percentages of urban land use cover ranged from 25 to 90.5. The green roofs with soil mixtures amended by compost were shown to export nutrients, particularly phosphorus, at levels that were statistically significantly greater than the green roof not containing compost and the conventional roof systems. In addition, comparisons of the green roof effluent to stream data helped place the green roof effluent in context to receiving waters and showed that in systems where the green roof media had been amended by compost at the industry standard of 15 percent, effluent nutrient concentrations were greater than those observed over the range of urban streams also tested.

Where field studies can prove that a green roof is effective at retaining runoff volume, the concern about overall pollutant mass quantities exported may be lessened. Gregoire and Clausen (2011) performed a study which evaluated the performance of a green roof for nutrient retention versus input rainfall and a single control site, which consisted of a pre-cast concrete slab overlain with a bituminous coal tar roof membrane. Nutrient concentrations exported from the green roof in this study were greater than those observed in precipitation and from the control. However, an analysis of mass export suggested that the green roof actually retained nutrients and metals by virtue of its volume retention capacity.

Nutrient retention or release may be dependent on the identity of the ion. For example, Berghage et al. (2009) saw a retention of nitrate by the green roof as compared to a flat asphalt roof; the rooftops being sampled were in a region where atmospheric deposition of nitrogen is typically high, and sink behavior was observed for the green roof being tested. However, phosphorus and potassium were released at significantly higher loading rates than for the flat asphalt roofs. Similarly, a study by Berndtsson et al. (2006) revealed both source and sink behavior for extensive green roofs. These roofs showed higher concentrations of phosphorus and potassium as compared to rainfall input, while retaining nitrogen from the same source.

Substrate composition is an important design factor to consider where nutrient export is a concern. Van Seters et al. (2009) linked nutrient leaching to media composition, and also analyzed the chemical composition of green roof media. Concentrations did not differ significantly from agricultural soil samples taken in Ontario (Van Seters et al. 2009). Long et al. (2010) found that small amounts of activated black carbon have been shown to be beneficial for green roof pollutant and volume retention.

FFL 2008 guidelines recommend fertilizing green roofs at rates which balance substrate fertility (Clark and Zheng 2013). Fertilizer applications, when necessary, should be consistent with the nutritional requirements for healthy plant growth in order to achieve expected ET rates and soil moisture uptake, but should also be low enough to prevent nutrient leaching. Berndsston et al. (2009) does not recommend fertilizing green roofs, due to their propensity to release phosphorus. Berghage et al. (2009) observed two identical green roofs, fertilized only at installation, behave as a source for phosphorus and a sink for nitrogen.

2.5.3 Additional Factors Affecting Runoff Quality

Substrate depth may play a role in nutrient retention, particularly for phosphorus. Berndtsson et al. 2009 compared an extensive roof in Sweden to an intensive roof in Japan. Both extensive and intensive roofs behaved as sinks for some nitrogen species; the extensive roof behaved as a source for phosphorus while the intensive roof did not. The runoff quality samples from the green roofs in this study were compared to urban runoff samples found in literature.

These samples were taken mainly from impervious surfaces, such as streets, highways, conventional roof systems, residential driveways, and mixed-use urban residential or commercial settings. Green roof quality was within range of the values found in literature, or slightly lower. Comparing results from different studies may not always be helpful in drawing conclusions about extensive green roofs and phosphorus, however. A study comparing intensive roofs to extensive roofs in Australia in fact found the opposite result, with intensive roofs observed to be a greater source for phosphorus than extensive (Razzaghmanesh et al. 2014). Buccola et al (2008) found that antecedent soil moisture conditions as well as substrate depth may also play a role in overall quality performance.

Finally, the age of the green roof may play a role in water quality performance. Older roofs with more established vegetative cover do not export nutrients, including phosphorus, as much as younger roofs, particularly where the roof is fertilized as part of the plant installation regime but not fertilized thereafter (Berndtsson et al. 2006). Van Seters et al. (2009) observed a decrease in the amount of total phosphorus exported from an extensive green from the first year of operation to the third year, but observed an increase in the amount of nitrate released. Metal concentrations were also observed to change, particularly with regards to copper export which increased as the roof system aged.

2.5.4 Plants

There has been a lack of research into the long-term performance dynamics of green roofs. Green roof hydrological and temperature-mitigating performance is affected by plant coverage, and designs assume a period of growth after installation, followed by a static system of coverage until the end of the roof's life (Piana and Carlisle 2014). However, such an approach does not take into account the ecological factors impacting plant coverage. Piana and Carlisle

(2014) conducted a temporal and spatial evaluation of plant coverage and species distribution on a green roof with vegetation that had time to become well-established. The study found that the green roof vegetation did in fact change over time: species richness increased, and spatial distribution of the different plant types evolved as well. Buccola et al. (2008) noticed that the selection of plant species chosen in laboratory studies had a partial effect on the quality of runoff. Nitrogen-fixing species such as clover tend to release nitrate in significantly higher concentrations than nitrogen-consuming species such as ryegrass.

3.0 Methodology

This section will describe the instrumentation and procedures used to sample the green roof for water quality. In addition, equipment and techniques used to sample the background sites and additional stormwater control measures will also be described. Laboratory procedures for quality testing will be explained, as well as analysis and consolidation of the data where necessary. Finally, basic details concerning the collection of overflow volume data for the green roof, rain garden and constructed stormwater wetland will be discussed.

Fertilization procedures for the green roof involved application twice annually during the growing season, as recommended by the design team at the time of installation. This maintenance practice was continued to promote healthy plant growth, which is essential for water storage in plant tissues. Applications of a standard fertilizer with an N-P-K ratio of 18-6-8 were made usually once during the spring (May) and once in summer (July). Each application was about 2 pounds of fertilizer over the total plant area, for a rate of about 0.06 ounces per square foot or 18.4 grams per square meter.

3.1 Water Quality Instrumentation and Sampling

Sampling for the study included a green roof, several background sites, a rain garden, and a constructed stormwater wetland. Sample names associated with each location and for each land use comparison are provided in Table 1.

Table 1: Sample names and descriptions

Samples included in Land Use Comparison I	
GR P	Precipitation sample
GR OUT 1	Green roof first flush sample
GR OUT 2	Green roof event mean concentration
FFW	Wooded area first flush
FFG	Grassy lawn first flush
FF02	Parking lot/lawn first flush
Samples included in Land Use Comparison II	
OVER	Rain garden whole-storm composite sample
AS OUTLET 1	Constructed stormwater wetland outlet first flush sample
OUTLET (all)	Constructed stormwater wetland outlet event mean concentration
GR OUT 1	Green roof first flush sample
GR OUT 2	Green roof event mean concentration

3.1.1 Green Roof Overflow Sampling

Quality testing of the green roof overflow began in August of 2012. The overflow drains from the south corner of the green roof (Figure 1) before being channeled down through the coffee shop below and exiting the building. Overflow sampling was initially collected as a single grab sample from behind a Thelmar weir, which is housed in the overflow box downpipe of the overflow outlet (Figure 2). An ultrasonic pressure transducer behind this weir is used to collect overflow volume data for larger flows (> 0.4 gallons per minute). The discrete or grab quality sample, originally named GR OUT, represented a composite sample of each individual storm event. Sample volumes of at least 150 mL were collected into plastic Nalgene sample bottles that had been acid-washed.

A High Sierra tipping bucket is used to measure green roof overflows that are lower than 0.05 gallons per minute, and is installed just up-pipe of the v-notch weir box (Figure 3). In March 2013 a Global Water WS750 autosampler was installed adjacent to the overflow structure in the CEER holy grounds to collect both a first flush overflow sample (GR OUT 1) and a composite overflow sample (GR OUT 2). See Figure 4 and Figure 5 for details of the pump configuration and sampling set-up. Sample is transferred from the PVC housing of the tipping bucket gage through tubing to the autosampler. As the tipping bucket tips, it transfers half the volume into a collector, which is a half-piece of PVC pipe adhered to the inside of the cylindrical rain gauge housing. The collector was connected to the plastic autosampler containers via clear mesh-reinforced flexible hoses. Although the hoses were replaced in early 2015 with copper tubing to prevent passage of sunlight into the sampling equipment (to prevent algal growth), only data prior to 2015 was included in the study therefore the sampling equipment remained consistent for the remainder of the sampling period.

The autosampler is signaled by a Campbell Scientific data logger (CR1000). GR OUT 1 is collected in a 300-millileter increment when 0.75 gallons (2.84 liters) of overflow have passed through the tipping bucket rain gauge. GR OUT 2 is a composite sample, collected after GR OUT 1 and in 200 mL quantities for every 18.5 gallons of overflow that are recorded on the data logger, up to 32 times. Depending on the duration and volume of any given sampling event, GR OUT 2 may have contained a lower sample volume than GR OUT 1.

Typical first flush samples are collected based on the initial volume of runoff from a drainage area that is assumed to produce the highest concentrations of pollutants (Schriewer et al. 2008, Berndtsson 2010). This volume is usually specific to a site or drainage area, being dependent on amount of impervious cover, soils, bedrock, vegetation, and slope. First flush sampling is appropriate for runoff from smaller areas, and while not typically collected from green roofs, a green roof first flush sample was included in the study partly to demonstrate the phenomenon from this type of surface. The green roof usually retains at least the first 0.64 (0.25 in) of rainfall, and most often up to the first 2.0 cm (0.8 in) of rainfall (Zaremba et al. 2016). Since the green roof media and drainage layers retain and delay the release of rainfall, the first flush must be based on a specified amount of overflow volume from the system. Because very little overflow quantity data had been recorded prior to the start of quality sampling, there was little empirical basis for the system's performance and consequently the first flush volume had to be somewhat arbitrarily assigned for sampling purposes. Better approximations to the actual first flush volume can now be made based on the compilation of quality and quantity data over three years of monitoring.

Figure 1: Green roof overflow drain

Figure 2: Interior of the green roof overflow weir box

Figure 3: High Sierra Tipping bucket instrument in its housing; shown with PVC sample cup and copper pickup tubes for autosampler feed.

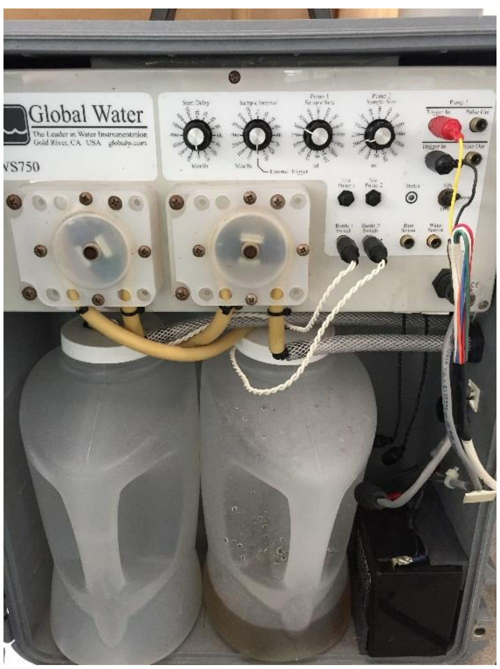


Figure 4: Global Water WS750 sampler with sampling bottles in place. Bottle 1 containing sample is positioned on right, beside the battery

Figure 5: Global Water WS750 pump configuration and control panel.

3.1.2 Precipitation Sampling

Precipitation was sampled to determine the amount of pollutant input that could be attributed to rainfall. Since the green roof is located in a densely populated metropolitan region, it was predicted that some amount of nitrates would be deposited on the green due to the presence of atmospheric nitrous and nitric oxides. Precipitation used for water quality testing was collected in a PVC container, which was acid-washed and placed out on the green roof shortly before a rain event (Figure 6).

Figure 6: PVC container used to sample precipitation on the green roof

3.1.3 Background Sampling

Three vegetated sites were included in the study as background sites to provide a comparison of the green roof to other land uses. Background vegetated sites, which were also sampled for water quality, included a grassy lawn, a wooded area, and a mixed-use drainage area. The grassy lawn was located on a gentle slope in front of the St. Augustine Center, with the sample name FFG (an abbreviation for First Flush Grassed). The slope of the drainage area for the grassy lawn measured at 0.0919 m/m. The length of its flow path measured 25.7 m at the longest reach and 18.0 m at the shortest reach. The wooded area was located on County Line Road behind St. Mary's Hall; its sample name was FFW (abbreviation First Flush Woods). The mixed use area was sampled at the inlet of the bioinfiltration rain garden at the traffic island on west campus, and its sample was FF02. The mixed use site included both lawn and parking lot area, and was at least 50 percent impervious. A map of campus with the locations of the background sampling sites is provided in Figure 7. A photo of the location of FFW is provided in Figure 8. Figure 9 displays a photo of the sampling drainage area for FFG at the time of site selection; the indicated possible location became the site of first flush sampler installation shortly after the photo was taken.

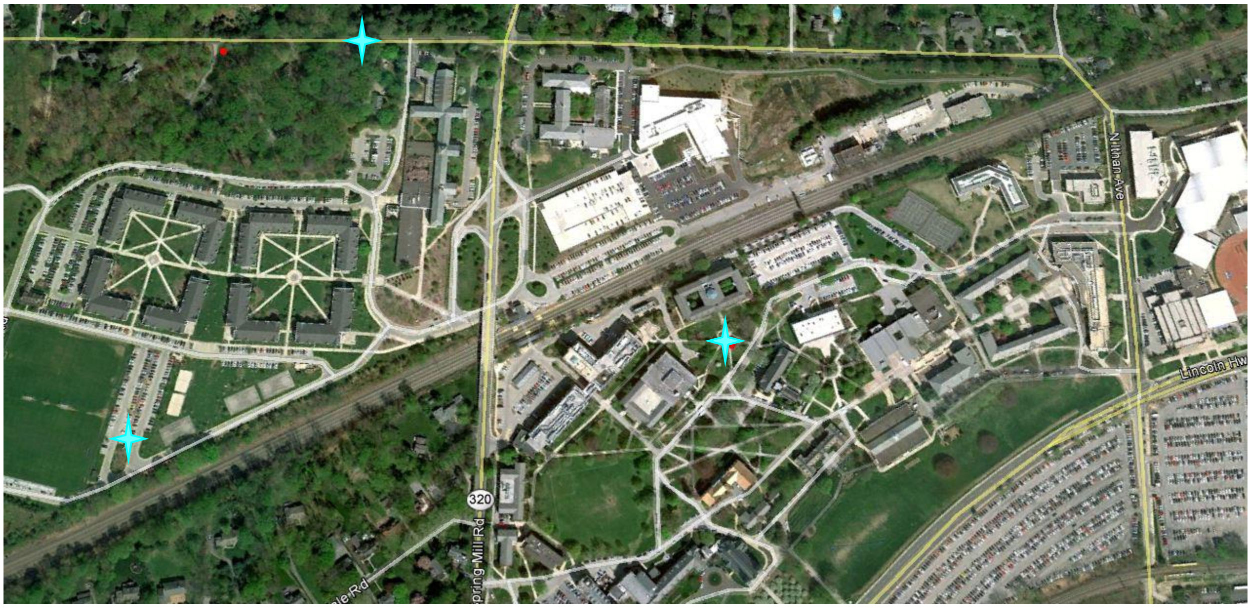


Figure 7: Location of the first flush samplers for background site sampling

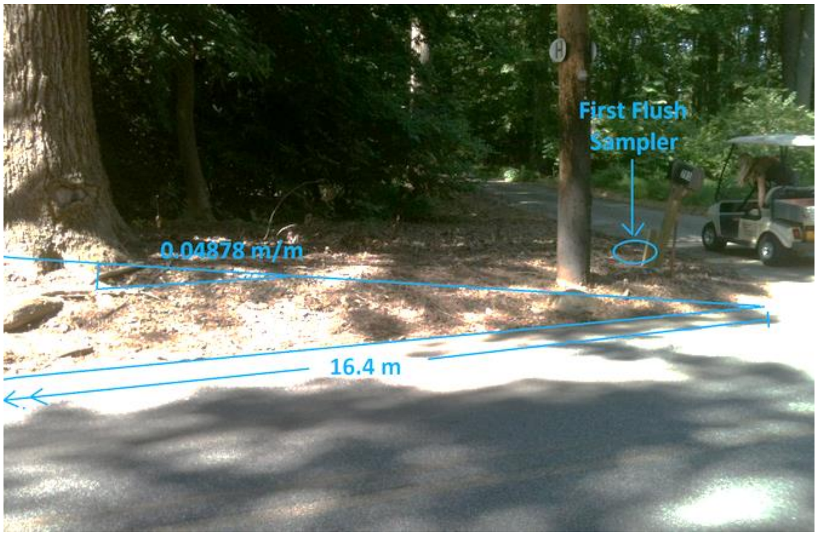


Figure 8: Location of FFW sampling site

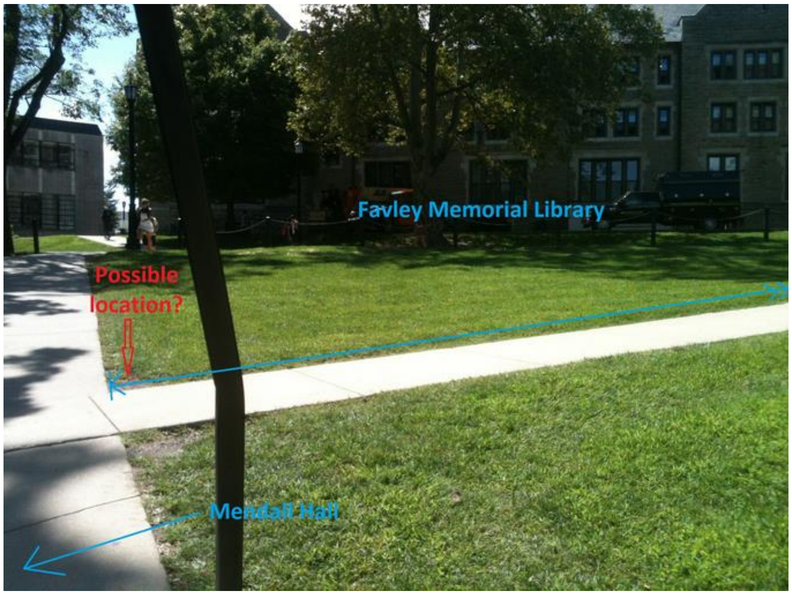


Figure 9: Location of FFG sampling drainage area

Drainage areas for FFW and FFG were selected to provide similar slopes and overland flow path lengths. The original slope of the wooded area into the sampler was 0.0487 m/m with a flow path length of approximately 16.4 m, according to 2012 survey data (Burlotos 2013). Samples were collected from GKY first flush samplers installed at each site. The GKY samplers consisted of a housing unit which is installed permanently in the ground, and a 5-liter plastic sample container which was placed out at each site prior to storm testing with the sampler housing lids secured and the port flaps open. Each sampler housing unit rests on a 0.3 m (12 in) layer of gravel below ground. The total gravel volume was 0.03m^3 (1.2 ft^3). Four holes were drilled in the corner of the sampler housing for drainage. Sampler housing was placed so that the rim was flush with the ground surface, and the vessel was surrounded and separated from the adjacent soil by a bentonite liner. The sample collected from the FFW container was usually visibly turbid, and typically brown and opaque. See Figure 10 for a profile of the sampler set up. In Figure 11, FFG's housing including lid is pictured with the sample container being removed after a storm event. In Figure 12, the sampler housing is pictured after a heavy rain event with water ponded in the bottom, possibly due to accumulation of fines.

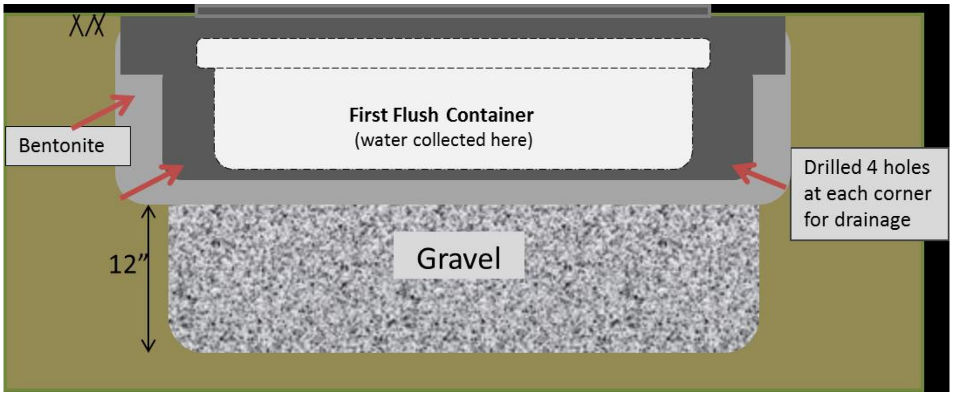


Figure 10: Profile of first flush set-up

Figure 11: GKY sampler housing with sample container at FFG

Figure 12: GKY sampler housing at FFW

3.1.4 Wetland and Rain Garden Sampling

Water quality samples from the constructed stormwater wetland were collected at the wetland outlet location. Events occurring through the end of April 2014 were sampled after the storm using 350 mL glass sample bottles that had been acid-washed in HCl. These sample bottles represented a discrete or "grab" sample; two duplicate samples, OUTLET 1 and OUTLET 2, were taken for each testing event.

Most of the storm events occurring on or after April 30th, 2014 were sampled using an American Sigma 900MAX autosampler system. The autosampler was programmed according to rainfall volume accumulation within a 24-hour time frame, and sample collection was triggered by a Campbell Scientific CR1000 data logger which recorded rainfall data from an American Sigma tipping bucket rain gage. Sampling was divided between four HACH 575 mL polyethylene sample bottles, with three samples taken per bottle. When the sample bottles were collected after a storm event, the contents of each bottle were treated as a single sample. Bottle samplers were named as follows and filled based on the following rainfall increments:

- ***AS-OUTLET 1:*** *0.20 in., 0.23 in., 0.25 in.*
- ***AS-OUTLET 2:*** *0.45 in., 0.50 in., 0.55 in.*
- ***AS-OUTLET 3:*** *0.60 in., 0.70 in., 0.80 in.*
- ***AS-OUTLET 4:*** *1.00 in., 1.25 in., 1.50 in.*

The first sample which collected up to the first 0.25 inches of rainfall was assumed to represent a first flush sample. Samples were only collected for storms which produced a volume of 0.25 in. or greater of rainfall. Due to the random rainfall volumes associated with each storm, not every storm produced all four samples. The American Sigma autosampler interior and its bottle configuration for the wetland are illustrated in Figure 13 and Figure 14 (Neptune 2015). The sampling location at the wetland outlet structure is depicted in Figure 15.

Figure 13: American Sigma autosampler housing for sample bottles.

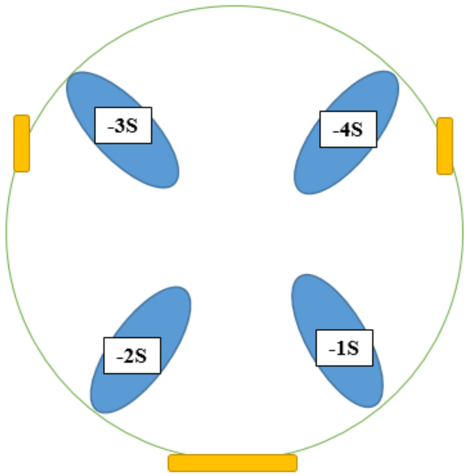


Figure 14: Configuration of the wetland sample bottles

Figure 15: Outlet structure of the stormwater wetland

Overflow from the bioinfiltration rain garden is allowed to pond behind a V-notched weir used to measure overflow volume. A mount which can hold a single sample bottle was constructed to facilitate overflow collection in the event that the ponded water overtopped the weir. The overflow sample was referred to as OVER and was collected via a 1-L wide-mouth Nalgene bottle, placed out prior to each storm testing event. Not every event produced OVER, due to the efficiency of the rain garden and overflow system for runoff retention (Heasom et al. 2006). Normal capture efficiencies of 60 percent or greater can be expected for the system. This type of performance is typical for a properly-designed bioinfiltration SCM which contains sandy loam in the fill media at typical design ratios, and collects runoff from a drainage area that has approximately 50 percent imperviousness with silty soil characteristics (Zhang and Guo 2014). The bioinfiltration outlet structure with weir in place and water ponded behind is shown in Figure 16. The smaller inset depicts the sample bottle for OVER mounted downstream of the weir for sample collection prior to storm testing.

Figure 16: Bioinfiltration rain garden outlet structure and sampling equipment

3.1.5 Event Sampling Justification and Frequency

Testing events were only justified if at least two green roof samples could be collected for the same event. The green roof, originally designed to retain the first 1.85 inches of rain from a given storm, was observed to actually retain about 0.8 inches of rainfall (Zaremba et al. 2016). Discrepancy between the design target retention volume and actual retention volume is discussed in previous students' work. Testable rainfall events were defined as having at least 0.25 inches of rainfall recorded within a 24-hour period; this volume threshold, although lower than the observed retention capacity of the green roof, was maintained because overflow volumes were also dependent on antecedent moisture conditions of the soil media. For instance, if a heavy rain event occurred a couple of days prior to a testing event associated with a smaller rainfall volume, the effects of the larger event could cause the system to produce overflow from the smaller event if the soil media was already at field capacity. Testing occurred approximately eight times per year, or as storm capture opportunities allowed.

3.2 Water Quality Testing

3.2.1 Testing Parameters

The green roof and the associated campus sampling sites were evaluated for nutrient data only; no metals were included in the study. Water quality testing parameters included nitrites (NO_2), nitrates + nitrites (NO_X), orthophosphate (PO_4), chloride (Cl^-), total Kjeldahl nitrogen (TKN), total Kjeldahl phosphorus (TKP), total suspended solids (TSS), and total dissolved solids (TDS). Beginning in January 2014, ammonia (NH_3) was added to the list of testing parameters. In addition, two parameters, nitrates (NO_3) and total nitrogen (TN) were calculated based on the results of other tests (see the section "Water Quality Data Analysis" for details).

3.2.2 Laboratory Procedure

All precipitation collectors, overflow sample bottles, and GKY first flush sampling containers were washed with a solution of 10% hydrochloric acid (HCl) between storm events. Samples were collected and brought back to the Water Resources Laboratory, where they were divided between smaller Nalgene sample bottles that had been acid-washed in hydrochloric or nitric acid, and were used immediately for testing or preserved for later testing. Sample holding times for the various tests are listed in Table 2.

Table 2: Laboratory-tested nutrient and other quality parameters

Nutrient Test	***Holding Time***	***Preservation Required***
TSS	None	No
TDS	None	No
NO_2	24-48 hours	No
NO_X	24-48 hours	No
PO_4	24-48 hours	No
TKN	up to 30 days	Yes
TKP	up to 30 days	Yes
Cl^-	24-48 hours	No
NH3	24-48 hours	No

Parameters which were tested immediately upon collection were TSS and TDS. Total suspended solids were tested according to EPA methods. One beaker and one filter were used per sample. A vacuum filtration apparatus was used to draw the sample through a Whatman 47-mm microfiber filter which had been dried out in an oven at over 100 °C for 3-4 hours, weighed per gram units, and stored in a desiccator prior to use for filtering. After filtering, the filters were again dried in an oven at over 100 °C for 4-6 hours, then left to cool in a desiccator before the final filter weight was taken.

Total dissolved solids were tested according to EPA Methods. Prior to filtering, the beakers used to collect the filtrate from TSS testing were acid-washed, dried in an oven at 400 °C for several hours, cooled and stored in a desiccator, and the initial weight in grams was taken. Once the filtrate was collected, the beakers were placed back in an oven at 400 °C for 24 hours to remove the liquid component. The beakers were allowed to cool in desiccators prior to taking the final beaker weight. TSS and TDS concentrations were determined based on the mass difference between the initial pre-weigh and final post-weigh values of the filters and beakers, respectively; mass values were converted to concentration units using the pre-set volume that was used to test each sample. For most samples, this volume was 300 ml. Where the available sample volume was smaller than this pre-set amount, calculations were adjusted in the TSS/TDS data spreadsheet to account for the lower volume.

All other tests (NO_2, NO_X, PO_4, TKN, TKP, NH_3, and Cl^-) were run on a Systea Scientific LLC EasyChem Plus spectrophotometer (the "EasyChem"). All tests with the exception of Total Kjeldahl Nitrogen and Total Kjeldahl Phosphorus were run with 24-48 hours of sample collection, using raw samples that had been transferred to new EasyChem cups. Samples used for TKN and TKP underwent additional sample processing prior to analysis in the EasyChem. These samples were first preserved on the day of collection using a concentrated solution of sulfuric (H_2SO_4) acid. EPA Method 351.2 was followed for TKN preparation; 25 mL of each sample was combined in a digestion tube with 5mL of copper sulfate digestion matrix and a few boiling chips. Standards and blanks were similarly prepared. All samples, standards, and blanks were heated in a TKN digester at 160° C for 60 minutes and then at 380° C for 90 minutes. After digestion, the samples were re-diluted with Milli-Q water in 25-ml glass volumetric flasks and shaken for complete mixing before being used to fill 5-mL EasyChem sample cups. Total Kjeldahl Phosphorus was processed according to EPA Method 365.1 and 365.4 using an autoclave. Five milliliters of each sample were combined in glass vials with 0.040 g of ammonium persulfate and 0.1 ml of 11N H_2SO_4 before digestion in the autoclave at 121° C and at a pressure of 15 psi for 30 minutes. The digested samples were then transferred to EasyChem sample cups for testing.

3.3 Water Quality Data Analysis

3.3.1 Quality Assurance/Quality Control

In compliance with laboratory QC/QA procedures, the data were filtered to eliminate data points which could be reasonably attributed to instrument inaccuracies and scale calibration errors. Outliers were filtered as soon as possible following a testing event. Methods for data filtering are described in the Quality Assurance Project Plans provided by the Water Resources Laboratory.

3.3.2 Use of Detection Limits

Detection limits varied for each laboratory testing event based on instrument calibration accuracy. Detection limits were assigned only to lab-tested parameters which included NO_2, NO_X, PO_4, TKN, TKP, Cl^-, NH_3^-, TSS, and TDS. To obtain consistent detection limits across all testing events, median detection limit values were used in the analysis for each parameter. In order to not consistently overestimate values which were reported at the lower limit of detection, a.k.a. a non-detect, data minima found to be equal to the lower detection limit for each parameter were replaced with a value equal to half that detection limit, as recommended in literature (EPA Technical Guidance Manual 2011; MacDougall 1980).

For example, the median lower detection limit for water quality parameter NO_2 was 0.01 mg/L for 18 testing events between October 2012 and December 2014. The lowest reported values for NO_2 were at this median detection limit for sample categories GR P, GR OUT 1, GR OUT 2, and FF02; therefore those minimum values were replaced with a value of 0.005 mg/L.

3.3.3 Calculated Water Quality Parameters

Two quality parameters were added to the evaluation after samples had been collected, tested, and reported. Nitrate (NO_3) was calculated based on reported values for NO_2 and NO_X using the following equation:

$$NO_3\left(\frac{mg}{L}\right) = NO_X\left(\frac{mg}{L}\right) - NO_2\left(\frac{mg}{L}\right)$$

When calculating NO_3, where NO_2 values were reported at or below their detection limit, the method used for calculating NO_3 was to subtract half the value of the detection limit for NO_2 from the reported value for NO_X. Where NO_X values were reported to be below their detection limit, the value for NO_3 was likewise reported at the detection limit for NO_X and was not calculated using the above equation. Where both NO_2 and NO_X were reported at or below detection limits, values for NO_3 were not calculated.

Total nitrogen (TN) was calculated based on reported values for NO_X and TKN using the following equation:

$$TN\left(\frac{mg}{L}\right) = NO_X\left(\frac{mg}{L}\right) + TKN\left(\frac{mg}{L}\right)$$

When calculating TN, where NO_X values were reported at or below their detection limit, TN was calculated by adding half the value of the detection limit for NO_X to the reported value for TKN. Where TKN values were reported at or below their detection limit, TN was calculated by adding the reported value for NO_X to half the value of the detection limit for TKN. Where both NO_x and TKN would have been reported at or below the limits of detection, TN would not be calculated, however due to the usually detectable nature of NO_X and TKN, this circumstance did not occur.

3.3.4 Data Sample Consolidation

Data from the green roof, background sites, wetland, and rain garden were grouped into various sample categories to reflect either first flush samples or composite event samples, and the data in these categories were the basis for the graphical comparisons discussed in the Results and Discussion section. Land Use Comparison I consisted mostly of first flush categories, and little data consolidation was needed. However, to achieve a fairer SCM comparison for Land Use Comparison II, and also to increase the data point count among some sample categories, some samples were combined with others. Sample categories were either first flushes or composite storm samples. Data for OVER from the bioinfiltration rain garden already represented a single composite storm sample and therefore solely comprised the OVER sample category in the graph figures. No first flush sample out of the bioinfiltration rain garden was included in the study, due to the nature of the system's design. The green roof first flush could be sampled directly using the WS750 autosampler. In addition, first flush data from the wetland's outlet were inferred by separating data points associated with the first rainfall sampling increment of 0.2 – 0.25 inches of rainfall, and grouping them into their own sample category. However, composite storm sample categories had to be generalized for the green roof as well as for the wetland, due to changes in sampling techniques within the study period. These generalized categories were GR OUT (all) for the green roof and OUTLET (all) for the wetland. The methods for deriving the green roof composite sample category and the wetland composite sample category are described in the following paragraphs.

Due to updates in green roof sample collection methods that occurred in the spring of 2013, the original event mean concentration sample taken from behind the overflow weir (GR OUT) was replaced with two new samples collected by the WS 750 sampler. These samples included a first flush sample (GR OUT 1) and an event mean concentration sample of the remaining storm volume (GR OUT 2). For the purpose of data consolidation, data collected using the old method (GR OUT data) was lumped with data collected using the new method (GR OUT 2 data). By consolidating the data in this way, more data was available for the concentration comparisons in Land Use Comparison I and Land Use Comparison II.

In the automated sampling process, the event mean concentration sample was collected after the first flush sample, so that a small amount of the total overflow was not included in the EMC sample. It was assumed that the volume attributed to the first flush was negligible with respect to the rest of the roof runoff volume for the average overflow-producing storm event, and therefore no flow-weighted difference in concentrations between the grab samples and the automated samples despite the loss of a small volume (0.75 gal) of overflow for first flush sampling purposes. From a concentration-based perspective, it was acknowledged that the EMC data collected via the automated method would not be representative of the full concentration gradient, although it would be approximate to the event mean concentration for an entire storm. From a mass perspective, there would be even less of an effect because of the insignificance of the first flush volume.

Similarly, the wetland outlet samples were collected using two different sampling methods. For sampling events where the grab method was used, duplicate samples (OUTLET 1 and OUTLET 2) were averaged to obtain a single event mean concentration. For testing events where sampling was automated via the American Sigma autosampler, a single event mean concentration was obtained by averaging the data for all automated outlet samples available per storm. Data for averaged grab samples and for averaged automated samples were lumped to obtain the composite category “OUTLET (all)” in order to consolidate the two testing methods.

The rationale behind lumping the wetland outflow samples across two sampling methods was validated using T-test analyses of data for storms where both grab and automated methods were used. Each pollutant parameter was tested for two samples with two-tailed distributions of the sample means. An alpha value of 0.05 was selected. For most pollutants in this study, no statistically significant difference was observed between pollutant concentrations obtained from different sampling methods. Nitrates (NO_2) were an exception where the p-value was less than alpha: 0.0106 assuming unequal variance for the two sample sets (Neptune 2015a) (personal communication). For the same sample sets and assuming equal variance, the p-value was a little higher at 0.0769. These findings could be attributed to the fact that NO_2 has a low persistence in the wetland due to the efficiency of bacteria which convert NO_2 to NO_3 as part of the nitrogen cycle; the bacterial processes may also be aided by the hydraulic retention capability of the wetland during and immediately following storm events. The nitrogen removal efficacy of the wetland has been documented previously (Wadzuk et al. 2010). In the case of NO_2 a few hours' time difference in sample collection could make a difference in the levels observed at the outlet, and the instantaneous collection of the autosampler would have an advantage in accuracy over grab-sample collection, which may have occurred anywhere from 0 to 12 hours after rainfall ended. However, for all other pollutants no statistically significant difference was observed, therefore in all other cases it was reasonable to assume that the sampling method would not bias the test results.

3.3.5 Graph Design

For each quality parameter, box-and-whisker plot groupings were constructed to compare the various sample categories relative to one another for Land Use Comparison I (in which the green roof was compared to non-SCM land uses) and for Land Use Comparison II (where the green roof was compared to other SCMs). Summary statistics of the concentration data were recorded for each parameter, including mean, median, third and first quartile, maxima, and minima. Upper and lower box boundaries were demarcated by the third and first quartiles, respectively. Upper and lower whiskers were represented by the data maxima and minima, respectively. Median values for the sample categories were represented by a line across the middle of the box. All summary statistics are available in Appendix A: Descriptive Statistics. Where applicable, recommended concentrations based on standard reference values were included in the graphs and represented by solid lines (EPA 2000a, b, DEP 2010).

**Note: there was a high sample reading for FFW on storm date 6/19/14 equal to 27.369 mg/L for TKN which was checked in the lab files and found to be valid. This represented the maximum value for the sample category (FFW), however for this instance the value was replaced with the upper median detection limit of 8.000 mg/L for TKN in order to provide better resolution among the other sample categories.*

3.4 Volume Data Collection and Calculation

3.4.1 Green Roof Overflow Volumes

Green roof overflow volumes are measured using a High Sierra Tipping Bucket mechanism for low-flow measurement (0.0 – 0.05 gpm), and a 12-inch Thelmar Weir with a Senix ToughSonic Ultrasonic Transducer (Distance Sensor) for larger flow measurement (>0.05 gpm). Overflow measurements were calculated for all events with cumulative amounts equal to or greater than 0.05 in. of rainfall within a 6-hour period. Cumulative overflows for each measurable event were defined from the starting point at which the tipping bucket tipped, until an elapse of two hours with no bucket tips recorded. Total overflows for each storm event were calculated by adding flows measured via the tipping bucket to flows measured via the distance sensor.

3.4.2 Background Vegetated Site Runoff Calculations

Since no flow monitoring devices could be installed at the vegetated drainage areas that were not SCMs (wooded, grassy, and mixed-use sites), the NRCS Curve Number method was used to calculated runoff volumes for each of the background sites. These calculated volumes were used to develop estimates of pollutant loads generated at each background site. Drainage areas were surveyed and calculated in terms of acreage. Rainfall data recorded in inches for each sampling event were measured in three locations: at the green roof, at the bioinfiltration rain garden, and at the site of a vegetative swale a short distance from the grassy site. Background sites were assigned a rain gage based on proximity. Initial abstractions for the wooded and grassy sites (FFW and FFG) were calculated using one curve number at each site, selected according to land use type (Mays 2011). Soil types and land uses are listed in **Error! Reference ource not found.**. The following equations were used to calculate runoff as a portion of rainfall depth:

$$P_e(in.) = \frac{(P - I_a)^2}{P - I_a + S_i}$$

$$I_a = 0.2 * S_i = 0.2 * (\frac{1000}{CN_i} - 10)$$

Where:

P = rainfall

I_a = *Initial abstractions*

S = Storage

DA = Drainage area

CN = Curve Number

For example, using rainfall data at the grassy area for the storm event dated 4/30/2014:

$$P_e(in.) = \frac{(5.31\ in.\ -0.899\ in.)^2}{(5.31\ in - 0.899\ in. + 4.493\ in.)} = 2.186\ in.$$

$$I_a = 0.2 * \left(\frac{1000}{69} - 10\right) = 0.2 * 4.493 = 0.899\ in.$$

Drainage areas were determined based on survey data collected for each site. Runoff depths were multiplied by the drainage area (DA), and mass loads that were washed off from each storm event were determined by the following equation, using NO_X data and calculated runoff for the 4/30/2014 storm event at the grassy location:

$$NO_X(g) = P_e(in) * \frac{1\ ft}{12\ in} * DA\ (acres) * \frac{43560\ ft^2}{1\ acre} * \frac{28.3168\ L}{1\ cf} * NO_X\left(\frac{mg}{L}\right) * \frac{1g}{1000\ mg}$$

$$NO_X(g) = 2.186\ in * \frac{1\ ft}{12\ in} * 0.0604\ acres * \frac{43560\ ft^2}{1\ acre} * \frac{28.3168\ L}{1\ cf} * 0.114\ \frac{mg}{L} * \frac{1g}{1000\ mg}$$

$$= 1.547\ g\ NO_X$$

For the background site whose drainage area comprised parking lot and lawn (FF02), two curve numbers were used to approximate the runoff volume from the pervious and from the impervious areas. Runoff volumes for the total mixed use drainage area were calculated by adding runoff volumes attributed to the fraction of the total area that was impervious pavement, and to the fraction that was pervious grassy lawn.

$$Pe\ (in.) = \frac{\left(P - I_{a,i}\right)^2}{P - I_{a,i} + S_i} * \%(i) + \frac{(P - I_{a,p})^2}{P - I_{a,p} + S_p} * \%(p)$$

Where:

% p = pervious land use fraction

% i = impervious land use fraction

For example, using rainfall data for the 4/30/2014 storm at the mixed use area:

$$Pe\ (in.) = \frac{(4.89\ in. - 0.041\ in.)^2}{4.89 in. - 0.041 in. + 0.204\ in.} * 0.44 + \frac{(4.89\ in. - 0.50\ in.)^2}{4.89\ in. - 0.50\ in. + 2.5\ in.} * 0.56$$

$$= 3.61\ in.$$

Mass loads washed off from the mixed use location were determined by the following equation, using NO_2 data and calculated runoff for the 4/30/2014 storm event:

$$NO_2(g) = P_e(in) * \frac{1\ ft}{12\ in} * DA\ (acres) * \frac{43560\ ft^2}{1\ acre} * \frac{28.3168\ L}{1\ cf} * \ NO_2\left(\frac{mg}{L}\right) * \frac{1g}{1000\ mg}$$

$$NO_2(g) = 3.61\ in * \frac{1\ ft}{12\ in} * 1.02\ acres * \frac{43560\ ft^2}{1\ acre} * \frac{28.3168\ L}{1\ cf} * \ 0.095\ \frac{mg}{L} * \frac{1g}{1000\ mg}$$

$$= 35.843\ g\ NO_2$$

Curve numbers for the background sites, their respective drainage areas, calculated initial abstractions, storage quantities, and estimated numbers of wash-off events per year are listed in Table 3**Error! Reference source not found.** below. Rainfall depths and runoff estimates are reported in Figure 47 - Figure 49 of the Results and Discussion section to provide context for the retention capabilities of these vegetated sites. Vegetated land uses have value for stormwater control that is proportional to the amount of site disturbance and soil compaction, and their value is also related to soil type and porosity, quality of the vegetation cover, geographical size, and ratio to impervious land use. Values for the rainfall and runoff data calculated for the background sites (shown in Figure 47 – Figure 49) are reported in Table 13: Rainfall and Runoff for Background SitesTable 13.

Table 3: Curve number and drainage area characteristics for background first flush sites

	DA (acres)	Hydrologic soil group	CN	Land Use Fraction	I_a (in.)	S_i (in.)	Wash-off events per year:
Wooded	0.0188	B	60	100%	1.333	6.667	7
Grassy Lawn	0.0604	B	69	100%	0.899	4.493	14
Mixed Use	1.02	B	98	44% Impervious parking lot	0.041	0.204	63
		B	80	56% Grassy Lawn	0.500	2.500	

3.4.3 Wetland Outflow volumes

The process of measuring outflow volumes from the wetland was more complex because, due to natural system design, wetland outflow is continuous. Outflows may be categorized based on flowrates, and for monitoring purposes are generally grouped into either baseflow events or storm flow events. Baseflows represent wetland outflows that are lower and slower; in the case of the Villanova wetland, baseflows are conditions defined by flow rates less than 0.10 cfs, and/or followed by a period of 72 hours in which no rainfall has occurred. Baseflow conditions, which are reflective of natural wetlands and waterways, are attributed to the influence of groundwater discharge and water table levels at adjacent banks and floodplains. Baseflows are indicative of wetland functional hydraulics; wetlands should not exhibit extended periods of non-flow or dry basins (EPA 2000a). Stormflows represent higher discharge volumes which are the result of runoff from the contributing watershed. Stormflow volumes, peak flow rates, and the duration of stormflow conditions are dependent on a variety of factors including rainfall intensity and duration, antecedent flow conditions, storage capacity of the wetland and of the contributing watershed, and water table conditions. For the Villanova wetland, stormflows initiated by storm events are defined by cumulative rainfall amounts greater than 0.10 inches within 24 hours; storm events occurring in quick succession are differentiated by at least 6 hours of no rainfall.

Volume-based performance data for the wetland was available through previous studies which evaluated effects on storm- and baseflow volume reductions. For the purposes of this comparison study, baseflow events were excluded and only wetland storm events were used, since a comparison of wetland baseflow quality to green roof overflow quality would not be fair due to the impossibility of green roof quality monitoring for events less than 0.25 inches of rainfall. In estimating mass loads, stormflow volumes were calculated for those events in which the green roof and wetland were tested simultaneously. Volume calculations were accomplished using an EPA SWMM model which input rainfall data, inflow volumes and rates, and drainage area characteristics. Details for the development and subsequent use of this model may be found in theses by Rinker (2013) and Pittman (2011).

3.4.4 Bioinfiltration Rain Garden Volumes

Overflow volumes for testing events at the bio-infiltration rain garden were modeled using a basin model which took into account the drainage area characteristics and curve number volumes of the inflow. Inflow volume data were developed from rainfall data recorded onsite. A curve number of 80 was assigned to the pervious area, which comprised approximately 56% of the drainage area, while a CN of 98 was assigned to the impervious portion comprising approximately 44% of the drainage area. The pervious portion of the drainage area was assumed to have a type B soil with an unknown ratio of engineered fill; some degree of compaction due to the high-traffic location near a dormitory and associated parking lot; and covered primarily with grassy vegetation typical of a suburban lawn. Infiltration in the basin was modeled using the Green and Ampt method and was assumed to have a uniform wetting front. Model output included overflow that did not infiltrate to the groundwater table but instead exited the underdrain. Additional details regarding the bioinfiltration rain garden basin model have been discussed in Heasom et al. (2006).

3.4.5 Lack of Event Data

There were a handful of storm testing events for which green roof overflow volume data and rainfall data were both missing. This missing data was attributed to issues with calibrating the instruments which led to inaccurate readings; to the system being offline for maintenance; and/or to a temporary lack of power supply to the monitoring instrumentation.

4.0 Results and Discussion

The green roof was tested for a total of 18 storm events, with some green roof testing events overlapping with wetland testing, while the rest overlapped with rain garden testing. Table 4 summarizes the storm testing events used in the following comparisons. Data for the following water quality parameters was collected: NO_2, NO_X, PO_4, TKN, TKP, NH_3, Cl^-, TSS, and TDS. Other water quality parameters were calculated or inferred from the collected data including nitrates (NO_3), total nitrogen (TN), and total phosphorus (TP) inferred from TKP. Nutrient concentrations presented in the following subsections were graphed using techniques described in section Graph Design. Due to a lack of viable data points, NH_3 was ultimately not included in the analysis of the green roof's performance. The little data that could be collected is reported in Table 5.

Table 4: Summary of storm testing events for water quality analysis of the green roof, background sites, and other SCMs

Storm Date	Precipitation depth* (in.)	SCMs tested	Green Roof overflow volume (gal)	Modeled Rain Garden overflow volume (cf)	Modeled Wetland outflow volume (cf)
10/2/2012	0.42	GR, CSW	No Data	0	No Data
10/29/2012	0.57	GR, BRG	No Data	10593	No Data
11/7/2012	0.15	GR, BRG	23.1	0	--
1/31/2013	1.81	GR, BRG, CSW	449.7	2566	No Data
3/25/2013	0.43	GR, CSW	87.5	00	51,967
6/27/2013	0.62	GR, BRG	26.3	0	--
10/7/2013	0.63	GR, CSW	2.5	0	38,139
10/10/2013	0.44	GR, BRG	17.1	0	--
3/29/2014	0.86	GR, BRG	No Data	0	--
4/15/2014	0.62	GR, BRG	No Data	0	--
4/30/2014	4.89	GR, BRG, CSW	1700.4	13806	460,362
6/19/2014	0.12	GR, BRG	0.1	0	--
7/14/2014	0.55	GR, CSW	15.2	0	41,895
8/12/2014	0.88	GR, BRG	87.1	0	--
10/8/2014	0.38	GR, BRG	9.5	0	--
11/7/2014	0.47	GR, BRG	100.0	0	--
11/17/2014	1.00	GR, CSW	322.9	76	81,736
12/2/2014	0.41	GR, CSW	151.1	0	32,003

**Precipitation values reported at the bioinfiltration rain garden, with rainfall depth for the 6/19/2014 storm supplemented using data measured at the green roof.*

Table 5: Data for ammonia NH_3

Storm Date	GR P	GR OUT 1	GR OUT 2	FFW	FFG	FF02	OVER
3/29/2014	0.146	**0.030**	**0.030**	0.698	0.296	0.119	0.071
8/12/2014	0.251	0.071	0.143	--	--	0.065	--

**Bold values indicate lower detection limits.*

4.1 EPA Recommended Ambient Water Quality Criteria

The United States Environmental Protection Agency conducted an extensive evaluation of natural waterways and water bodies for all ecoregions of the country. The result was a published set of recommended criteria for rivers and streams, and another set for lakes and wetlands (EPA 2000a, b). These documents are broken down by ecoregion, a term used to describe regions that have shared geomorphological characteristics. Ambient nutrient concentrations for NO_X, TKN, TN, and TP were taken from rivers, streams, lakes, and wetlands which were considered representative of pristine ecological conditions.

The EPA gives two sets of recommended criteria for TN; a “calculated” set, based on reported levels of all other contributing nitrogen species sampled and tested in the reference ecosystems, and a “reported” set, based on direct observed measurements of total nitrogen within the same freshwater ecosystems. Differences between the two sets of criteria are further explained in the EPA reports (EPA 2000a, b). For this study, both sets of criteria were included in the comparisons because the calculated and reported values differ even for surface waters in the same category (Figure 22 - Figure 23 and Figure 33 - Figure 34). These differences may be attributed to the variable persistence of individual nitrogen species, to the detection limits of the sampling methods, or other sources of sampling error.

These ambient conditions were used to establish recommended target concentrations for all other waterways within ecoregions, but the criteria could also be applied to runoff for receiving waters. To provide a set of reference values for the relative concentration comparisons, these criteria were included in the boxplot analysis where the criteria matched the laboratory-tested parameter. As per the map of east coast EPA ecoregions (see Figure 17), the Villanova campus where all test sites were found is located within Sub-region 64 of the Aggregate Ecoregion 9. Specific target concentrations for the Sub-Region are summarized in Table 6 below.

Table 6: US EPA recommended water quality criteria for surface waters

Water Quality Parameter	USEPA Rivers & Streams (mg/L)	USEPA Lakes & Reservoirs (mg/L)
TKN	0.3	0.35
Total Nitrogen as NOX	0.995	0.605
TN Calculated	1.295	0.955
TN reported	2.225	0.818
TP	0.04	0.045

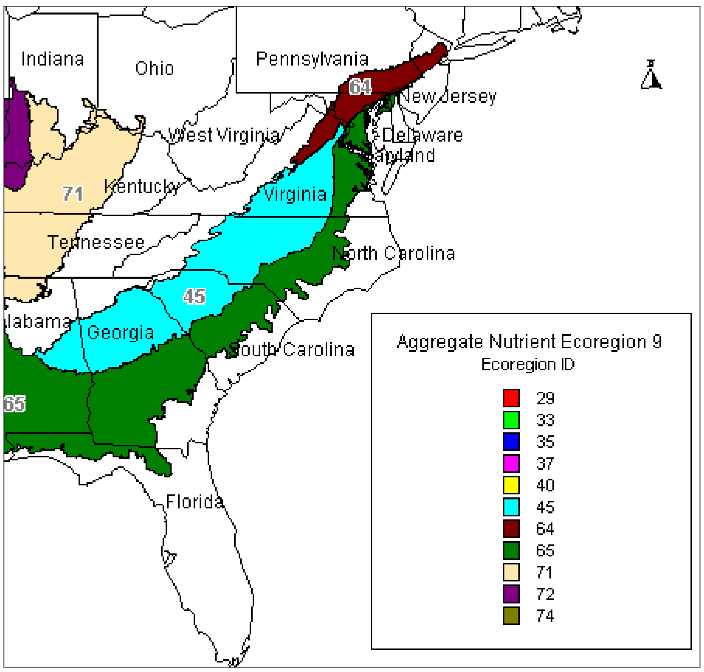


Figure 17: Map of EPA Ecoregion 9 (EPA 2000a).

4.2 Pennsylvania Department of Environmental Protection Agency Code 25

The Pennsylvania Department of Environmental Protection's Code 25 outlines environmental protection requirements within the state, and Chapter 93 is designated for Water Quality Standards for all surface waters within the state. Standards are based on protected water uses which are described in the chapter (PA DEP, 2010). Reference values are presented in Table 7 for TDS and Cl^- concentrations, which are taken from Section 93.7 and applied to the following comparisons. No true standard reference value for TSS could be identified; however an arbitrary reference value was assigned which represents the approximate upper concentration limit which may be typically found in tidal rivers at least 175 km from the mouth of the Delaware Estuary (USACE 2013). This value does not represent a standard reference based on healthy ecological conditions, but only the ambient conditions for waterways sampled in the Delaware Estuary. For Pennsylvania, water quality parameters are assigned a critical use, which the standards are designed to protect, such as Potable Water Supply or PWS (DEP 2010). Standards may be represented as maximum concentrations, monthly concentrations, or both, that may be found in a protected-use waterway while maintaining acceptable conditions for the parameter's critical use.

The TSS reference value used here is also applicable in other geographic regions of the country as an ecological threshold. For example, Rowe et al. (2003) recognized that the concentration value of 25 mg/L is the background level necessary to maintain a healthy salmonid population in the Cascadian watershed. For streams where the background concentration in an undisturbed watershed was typically below 25 mg/L (i.e. clear water and pristine habitat conditions), effects on biota were observed when the concentration jumped above this level. Rowe et al. (2003) did not recommend allowing the concentration to be more than 25 mg/L higher than ambient conditions during a 24-hour period, or not more than 5 mg/L higher than ambient conditions for long-term exposures lasting 24 hours to 30 days.

Table 7: PA DEP water quality criteria

Water Quality Parameter	Symbol	Maximum	Unit	Monthly	Unit
Chloride	Ch	250	mg/L	--	--
Nitrate plus Nitrite	N	10	mg/L	--	--
Total Dissolved Solids	TDS	750	mg/L	500	mg/L
Total Suspended Solids	TSS	25	mg/L	--	--

4.3 Land Use Comparison I

Land Use Comparison I consisted mostly of first flush samples representing the green roof and background sites. This comparison allows the green roof's quality performance to be evaluated relative to other vegetated sites, which are expected to export some nutrients and pollutants via site runoff. Samples included in this comparison were GR P, precipitation sampled directly at the green roof (see section 3.1.2); GR OUT 1, the green roof first flush sample (section 3.1.1); GR OUT 2, the green roof overflow event mean concentration (section 3.1.1); FFW, first flush from the wooded site (section 3.1.3); FFG, first flush from the grassy site (section 3.1.3); and FF02, first flush from the mixed use parking lot/grassy lawn (section 3.1.3). Though not a first flush sample, GR OUT 2 was included to provide some context for the first flush effects observed in GR OUT 1.

A comparison of the sites for each water quality parameter is provided in Figure 18 - Figure 28. Where applicable, pollutant standards or recommended criteria were included. Neither established standards nor recommended criteria which were applicable to the region's watershed and geological characteristics could be identified for some parameters including NO_2, NO_3, and PO_4. The reader is encouraged to refer to graphs with reference standards to get a qualitative sense of these other performance parameters

4.3.1 Nitrogen

Recommended criteria for NO_x, TKN, and TN are provided on the appropriate graphs. Ranges and recommended levels for NO_X should be referenced for inferring ecologically acceptable concentrations of the constituent nitrogen species NO_2 and NO_3. Usable data point counts are listed for each sampling location. As in Figure 18, median green roof nitrite levels were lower than median levels for any of the background sites; the wooded site had the highest median at 0.157 mg/L, while the grassy site had the greatest data range (between 0.018 and 0.514 mg/L) and standard deviation (0.153 mg/L).

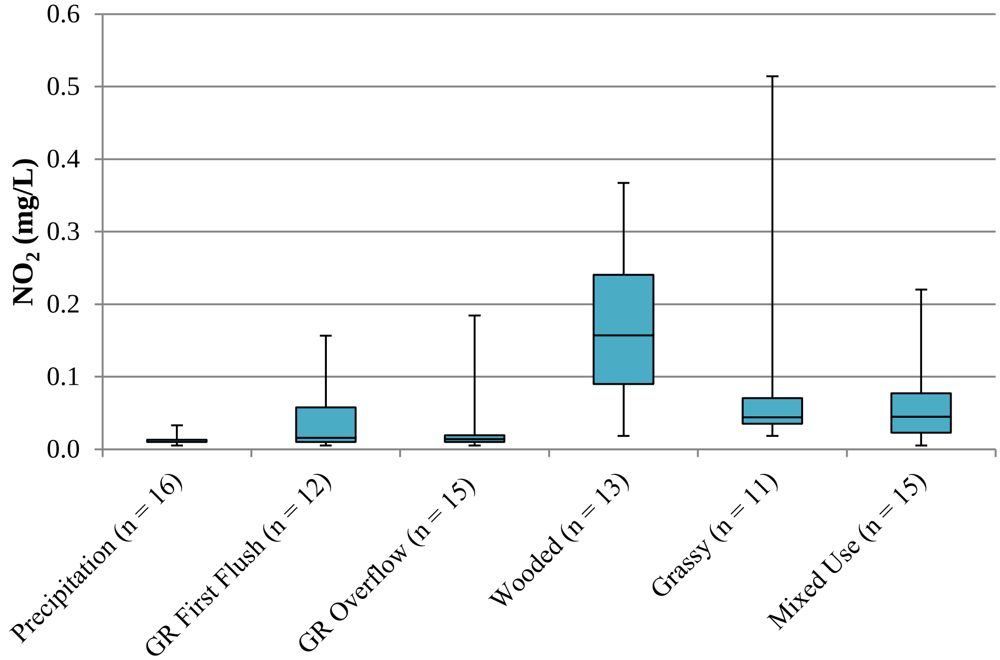


Figure 18: Comparison of green roof performance to background sites for nitrites

On the other hand, when comparing the same sites for nitrates the opposite scenario was observed, with the green roof samples having the higher medians, ranges, and standard deviations of data than the background sites (Figure 19). For nitrates there is visual evidence of the first flush phenomenon for the green roof: the first flush had the greatest median concentration (1.078 mg/L) and greatest standard deviation (1.994 mg/L). Green roof overflow had the widest range of data (0.110 to 6.372 mg/L). Small amounts of nitrates were observed in the precipitation samples, which could be a result of wet, or even dry, atmospheric deposition (see section 4.5.1). Regional atmospheric nitrogen deposition has linked with acidification of freshwater lakes and streams (Fenn et al. 2008).

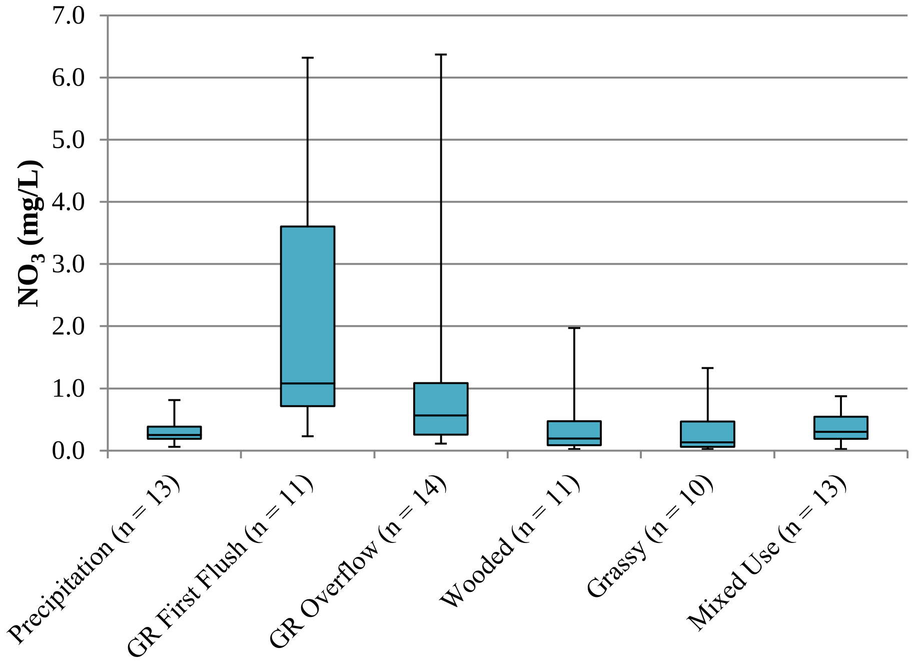


Figure 19: Comparison of green roof performance to background sites for nitrates

A similar scenario was observed for both nitrites and nitrates (NO_x), with the green roof samples having the higher medians and spread of data (Figure 20). The green roof first flush had the greatest median (1.095 mg/L) and standard deviation (2.025 mg/L); green roof overflow (sampled event mean concentration) had the greatest data range (0.115 mg/L to 6.557 mg/L). The green roof first flush was the only sample which surpassed the EPA recommended NO_x level of 0.995 mg/L for rivers and streams. Assuming NO_x is only NO_2 and NO_3, it may be concluded that NO_3 accounts for the majority of NO_x and that NO_2 does not persist in the green roof media.

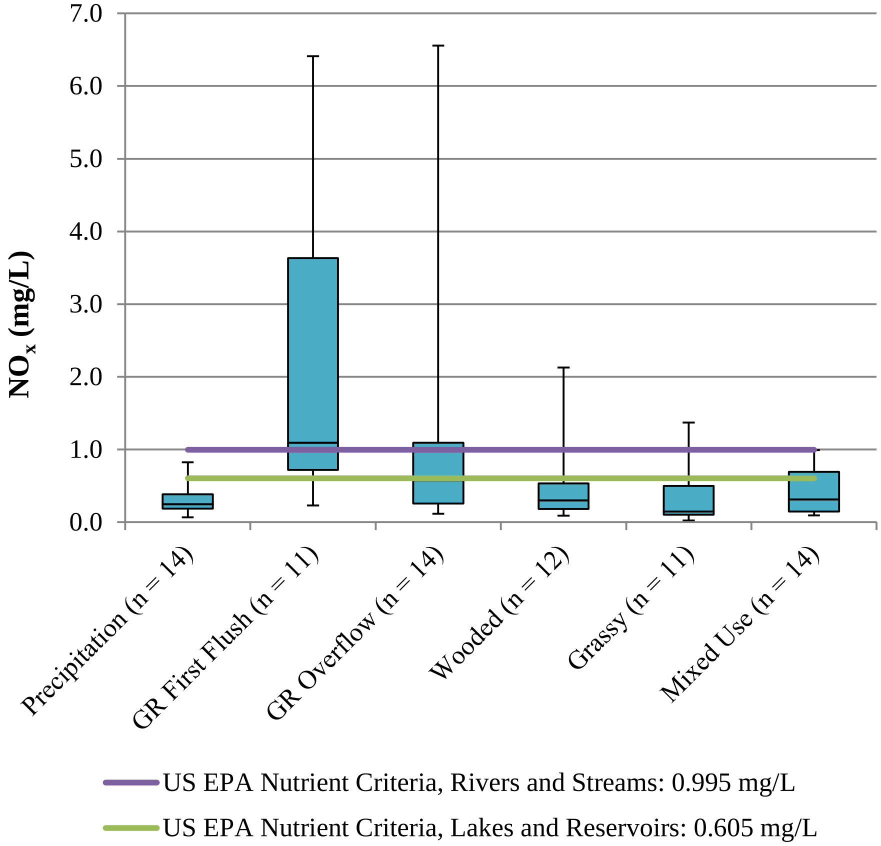


Figure 20: Comparison of green roof performance to background sites for nitrites plus nitrates

Green roof performance for TKN was comparable to that of the background sites in that data medians for all sampling locations exceeded the EPA recommended criteria of 0.300 mg/L for rivers and streams (Figure 21). The green roof first flush had the highest median at 2.395 mg/L, however the wooded site had the greatest standard deviation (7.800 mg/L) and greatest data range (0.345 to 27.369 mg/L), although the full range was capped at 8.000 mg/L in order to provide better resolution to the other data groupings.

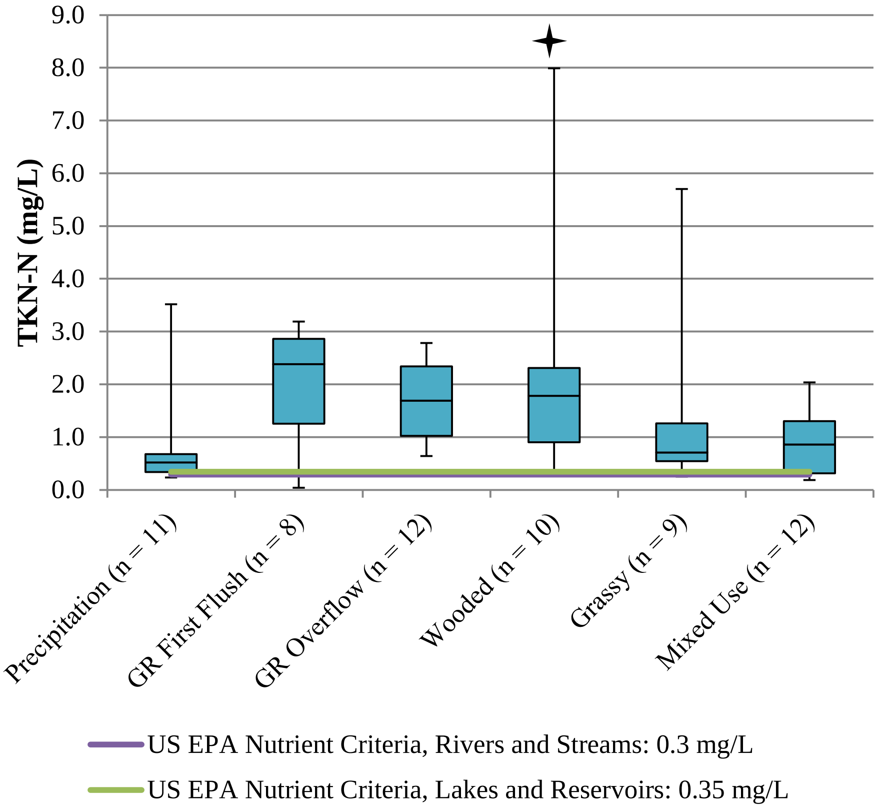


Figure 21: Comparison of green roof performance to background sites for Total Kjeldahl Nitrogen

Total nitrogen concentrations were calculated from TKN and NO_x data for all sampling locations. Here the first flush phenomenon is visually evident for the green roof samples, with the green roof first flush having the highest median concentration (3.972 mg/L) (Figure 22 and Figure 23). Green roof samples as well as the wooded and mixed use areas had median concentrations higher than EPA recommended levels of 1.295 mg/L based on calculated ambient conditions for rivers and streams (Figure 22). Stacked against a different set of recommended levels, based this time on reported ambient conditions for rivers and streams, the background sites perform a little better although the green roof still appears to be releasing excessive nitrogen (Figure 23). As in the case with TKN, the widest range of data and greatest standard deviation can be observed at the wooded area, with TKN accounting for the greater constituent in the ratio of TKN and NO_x for TN.

Such a wide spread of data for the wooded area may be attributed to the presence of fertilizer in the runoff that entered the FFW sampler, or to a release from the soils or vegetation found in the drainage area. Campus landscape maintenance activities involve applications of lawn fertilizers twice annually, with occasional fertilizing of trees and shrubs (Hollytone and similar products), although it is quite unlikely that the vegetation in the wooded area received direct applications. However, the sampling site was in close proximity to a student center with landscaped lawns, to a roadway, and to adjacent residential properties which may also have been fertilized. Surface runoff from the road and from these properties may have entered the FFW sampling area and deposited excess nitrogen in the sampler. The wooded area was not observed to be raked or mowed during sampling period, and it was assumed that such activities occurred at the sire infrequently, if at all. Vegetation debris was likely left alone In-depth checks of the data ruled out the possibility that the high readings might be attributed to sampling or testing anomalies, otherwise the data would have been discarded.

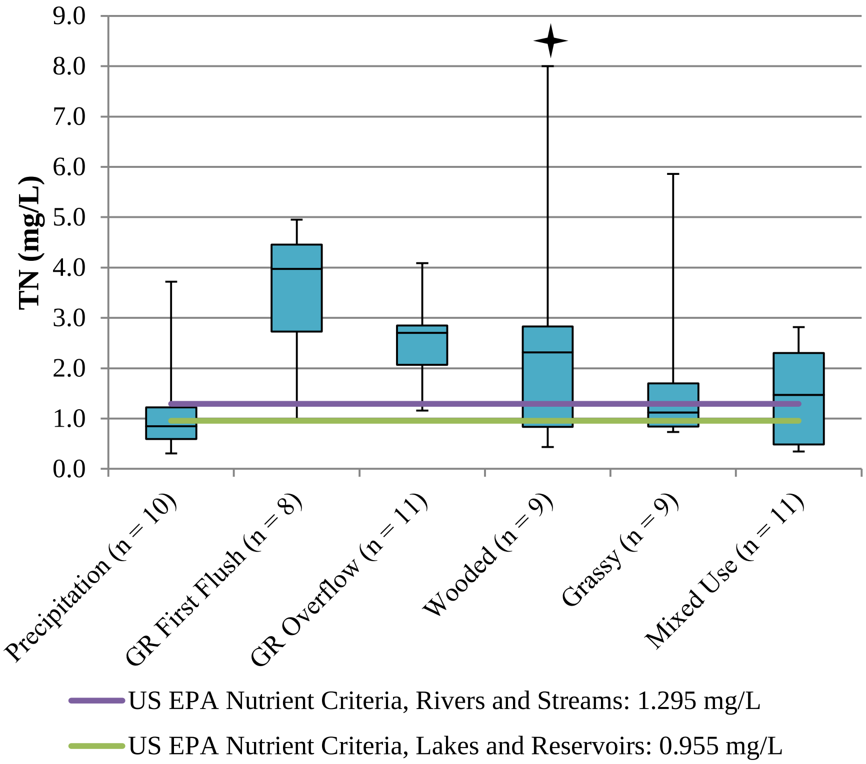


Figure 22: Comparison of green roof performance to background sites for Total Nitrogen, with reference values as calculated by the EPA (section 4.1)

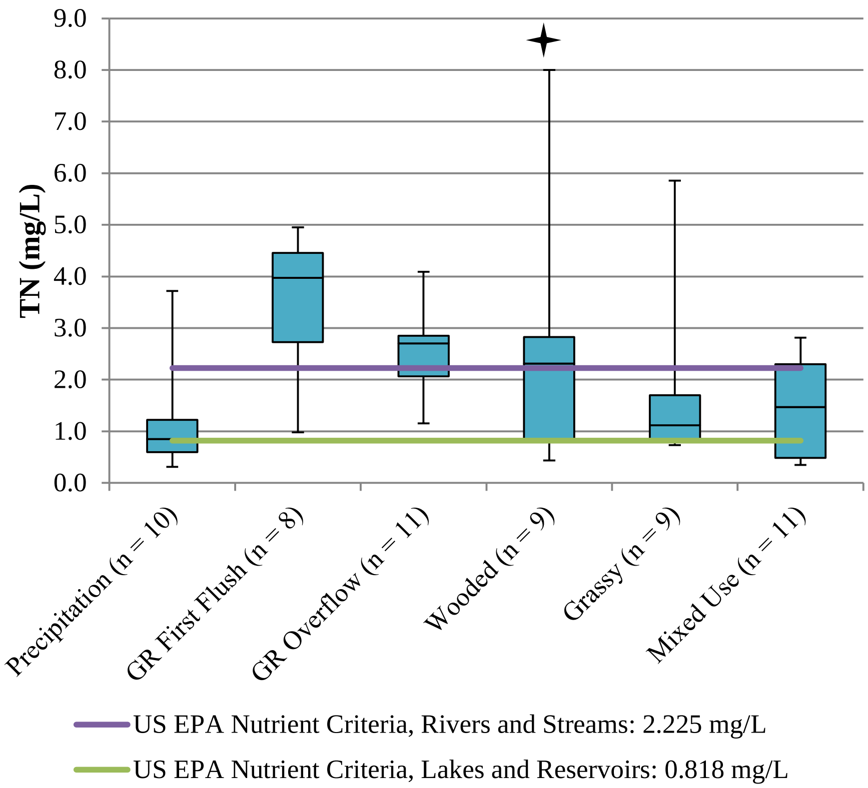


Figure 23: Comparison of green roof performance to background sites for Total Nitrogen, with reference values as reported by the EPA (section 4.1)

The source of all the nitrates in the green roof samples could be from fertilizers, decaying plant matter, or from rainfall containing nitric acid. Fertilization is a likely source of nitrogen; fertilization procedures for the Villanova green roof are discussed in the Methodology (section 3.0), with quantities reported later in this chapter (section 4.5.1). The plant community on the green roof was well established, being more than a year old at the time that sampling began, and by the end of the study period some dead plant matter was observed to have amassed below the healthy vegetation. It is possible that as the old vegetation began to decay, additional nitrogen was released, although further study of nitrogen release rates from the green roof sedums would be needed to validate this possible explanation.

Nitrite and nitrate levels were much lower in the precipitation than in the green roof samples, as expected, but were not zero. The source of the nitrites and nitrates may have been from acid rain. Acidic rainfall may be due to the presence of either nitric or sulfuric acid. It is possible that acidic rainfall containing HNO_3 entered the green roof media during the study period, and the HNO_3 was converted to NO_x. Acidic rainfall was observed in the green roof precipitation sample for some sampling events, but the low pH approached neutral levels after having passed through the media and then entering the overflow sampling equipment. The mechanisms of this observed neutralization are not currently known, although possible explanations include physical processes, impacts of temperature change, and/or bacterial activity in the soil media. Further study is needed to confirm the presence of nitrifying bacteria in the green roof media.

A closer look at the precipitation data provided additional information. Precipitation that was considered truly acidic (i.e. with a pH less than 4.5) was not observed during the study period. However, precipitation samples for six events had pH readings less than the typical "clean rain" threshold of 5.6 (EPA). A brief evaluation of pH data for the precipitation, first flush, and EMC samples at the green roof indicate that there is a difference between the pH of the rain going in and the pH of the outflow samples. Assuming the data were normally distributed and pH was not affected by the volume of rain that fell, a paired t-test of log-transformed pH readings for the precipitation vs the first flush and versus the event mean concentration (two tails in both cases) showed statistically significant difference. However, it should be noted that pH is dependent on several factors including temperature; further analysis is needed to confirm that the rainfall is indeed being neutralized by the media. Results of this test are given in Table 8.

Table 8: pH difference between rainfall and green roof overflow

Precipitation versus First Flush		**Precipitation versus EMC**	
n:	10	n:	13
Mean:	0.12	Mean:	0.08
Stnd. Dev.	0.0376	Stnd. Dev.	0.0718
Stnd. Error (d)	0.0119	SE(d)	0.0199
T-value =	9.83	T-value =	3.956
Degrees of freedom:	9	Degrees of Freedom	12
α =	0.05	α =	0.05
P value =	6.38E-06	P value =	0.00253
P-value is << than 0.05		P-value is << than 0.05	

4.3.2 Phosphorus

Only two parameters for phosphorus were evaluated in the study. Inorganic orthophosphate (PO_4) is the biologically available form of phosphorus that is used by plants, and is therefore an occasional limiting factor for aquatic plant growth and algal growth in freshwater ecosystems, provided nitrogen is available in abundant supply. More severe cases of algal blooms lead to eutrophication, and may be the result of excessive concentrations of orthophosphate contributed from agricultural or residential surface runoff, from water or wastewater treatment operations, or from commercial and industrial point sources. Occasionally, excessive phosphorus may be the result of regional soil and bedrock composition.

The green roof had higher median concentrations for orthophosphate than any of the background sites. As with nitrogen species the first flush had the greatest spread of data (range between 0.393 and 4.009 mg/L; standard deviation of 1.132 mg/L), but overflow event mean concentration actually had the highest median concentration (1.281 mg/L) (Figure 24). No recommended nutrient criteria for orthophosphate could be identified for surface waters in the region where the study took place. Therefore the graphs depicting TKP should be used for inferring ecologically acceptable orthophosphate concentrations.

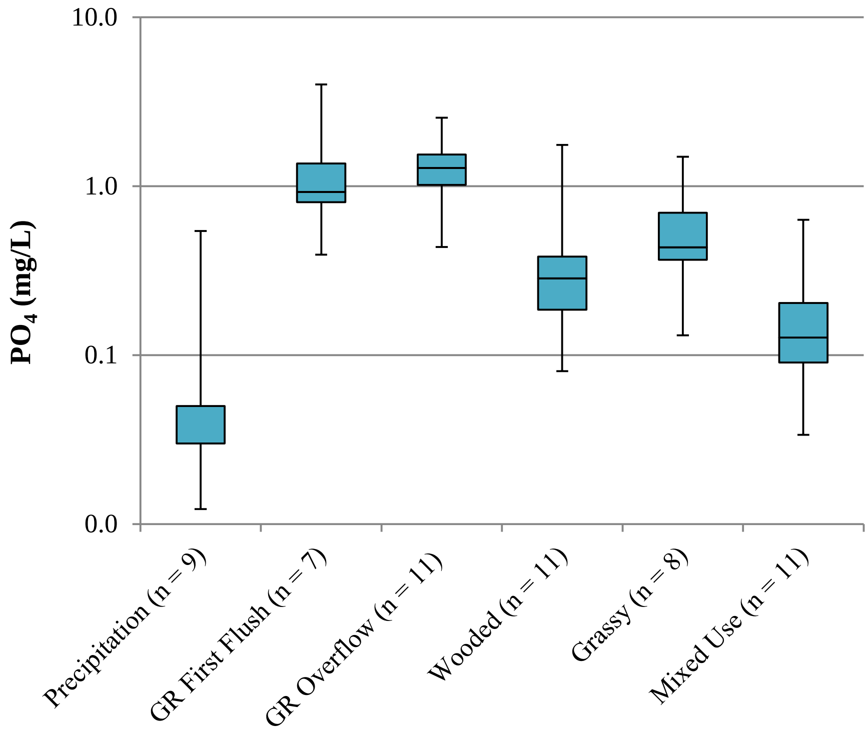


Figure 24: Comparison of green roof performance to background sites for orthophosphate

For water quality monitoring purposes, TKP and total phosphorus (TP) are considered the same. The EPA recommends a maximum concentration of 0.040 mg/L of TP for rivers and streams, and a maximum of 0.045 mg/L for lakes and wetlands. These exceedingly low levels are recommended because of the large impact that even a small change in ambient phosphorus concentrations may have on natural ecosystems. As such, no sample set was able to meet the criteria (Figure 25). Median concentrations for precipitation were at 0.050 mg/L, and were maximized at 0.790 mg/L, suggesting that phosphorus may be present in rainwater as a result of wet atmospheric deposition. Dry atmospheric deposition would have only accounted for a very small, if not negligible, quantity in the precipitation sampler because the sampler was only placed outside for collection a few hours prior to the start of rainfall.

The other sampling locations exhibited phosphorus levels far in exceedance of the recommended levels, with the next lowest median concentration at 0.430 mg/L for the wooded area (Figure 25). The green roof event mean concentration had the highest median concentration at 1.355 mg/L, while the grassy area had the widest range (0.355 to 9.350 mg/L) and standard deviation (2.753 mg/L). Wide spreads of data were also observed for the green roof first flush (range of 0.387 to 6.822 mg/L) and for the wooded drainage area (range of 0.100 to 6.091 mg/L). These sites all had one or two very high readings for which dilutions were accounted by the EasyChem testing instrument, but after checking the data output it was concluded that these data could not be discarded. High readings such as these might be explained by the sudden release of phosphorus due to soil disturbances at the sampling sites. Since the high readings for the grassy and wooded sites were from a testing event that occurred in June, it is possible they coincided with fertilizer applications at or near the sampling area. The high value for the green roof first flush was from a November testing event, which did not coincide with any fertilizer applications to the green roof. The remaining possible explanation for this high reading is the effects of disturbances to the shallow soil media from a routine weeding.

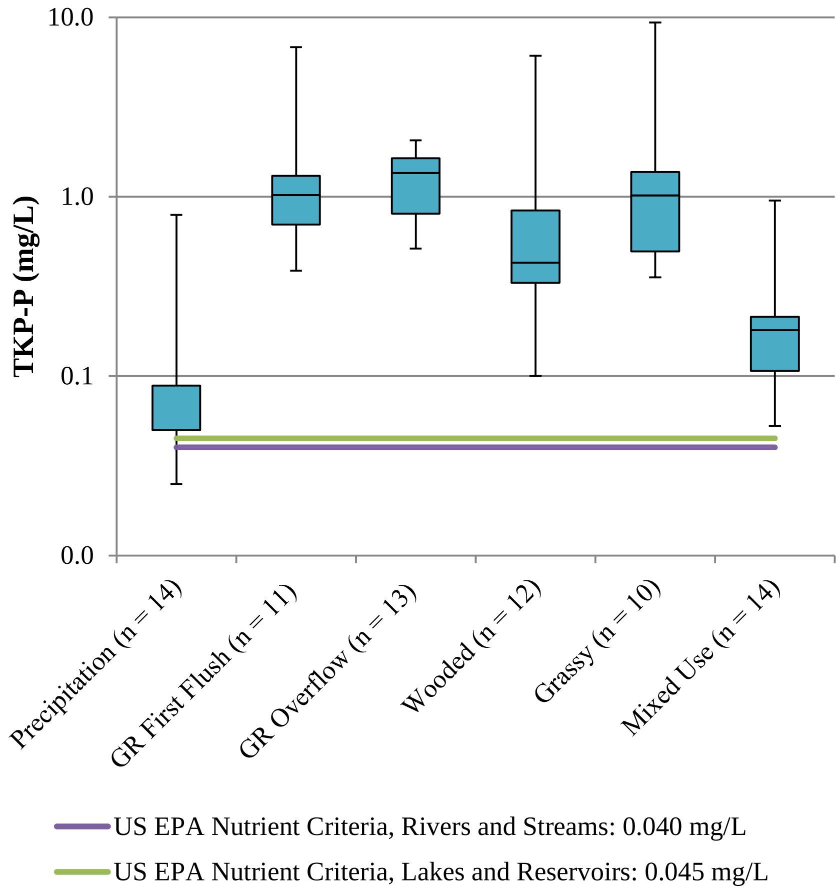


Figure 25: Comparison of green roof performance to background sites for Total Kjeldahl Phosphorus

4.3.3 Chlorides, TDS, and TSS

Chlorides, while not a nutrient parameter, were included in the study because of the ecological impacts of elevated chlorides from runoff on plant communities in receiving bodies of water. High levels of chlorides were not expected for the green roof because green roofs are not exposed to dissolved chlorides from salt applications in the way that ground-level land uses such as lawns, parking lots, or even woodlots may be exposed. Concentrations are compared to the PA DEP standard for chlorides in Figure 26. Vertical scales for chlorides, TSS, and TDS are displayed logarithmically with base 10 (Figure 26 – Figure 28). As expected, the green roof samples had the lowest median concentrations (5.111 mg/L for the first flush), while the wooded area had the highest median (21.81 mg/L), as well as the widest range (1.000 to 1395 mg/L) and greatest standard deviation (403.2 mg/L). The sampler at the wooded area was located not far from a driveway and a roadway, and considering the maximum reading was associated with a March sampling event, such performance can be expected from winter de-icing practices. Median concentrations for all sampling locations were an order of magnitude below the acute threshold of 250 mg/L.

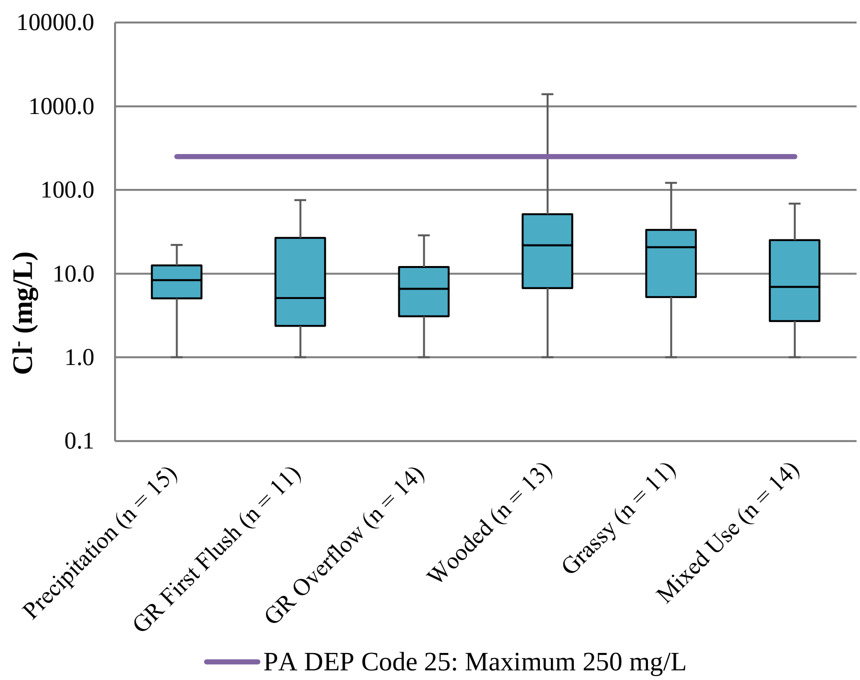


Figure 26: Comparison of green roof performance to background sites for chlorides

Surprisingly, precipitation had a higher median concentration (8.402 mg/L) than the green roof. This might have been the result of the type of acid which the precipitation sampler was cleaned with between storm testing events. The sampler was washed with a dilute concentration of HCl, and although it was thoroughly rinsed with deionized water, it is possible that a small amount of the interior surface area (i.e. a narrow groove about halfway down the depth of the sampler) was not thoroughly rinsed. Baselines for the precipitation sampling methods were tested using the original precipitation sampler washed in hydrochloric acid, as well as a smooth-interior Nalgene sample bottle washed in nitric acid and another washed in hydrochloric acid. All three sample bottles were placed out on the green roof in the usual sampling location shortly before two different rainfall events, and were collected the following day. In both cases, the original sampler washed with HCl did not produce readings higher than either the data average or median. The results of the two baseline tests are provided in Table 9 below.

Table 9: Results of baseline precipitation sampler testing

Test Date	**Sample**	**Description**	**Cl^- (mg/L)**
2/23/2015, 1st file	GR P1	Control: washed in HCl	5
	GR P2	smooth-interior washed in HCl	12
	GR P3	smooth-interior washed in HNO3	5
Test Date	**Sample**	**Description**	**Cl^- (mg/L)**
2/23/2015, 2nd file	GR P1	Control: washed in HCl	5
	GR P2	smooth-interior washed in HCl	5
	GR P3	smooth-interior washed in HNO3	5

Standards for total dissolved solids are established for Pennsylvania at an acute threshold of 750 mg/L and a long-term monthly threshold of 500 mg/L. The green roof performed similarly to the wooded area with median concentrations at 140 mg/L and 142 mg/L, respectively (Figure 27). As with chlorides, the wooded area showed the greatest spread of data (range of 43.0 to 1750 mg/L; standard deviation of 469.5 mg/L). The maximum TDS value at the wooded site occurred for the same March testing event which produced the extremely high chloride reading discussed above, indicating correlation between these two parameters. Data for all sample sets were well below the monthly threshold.

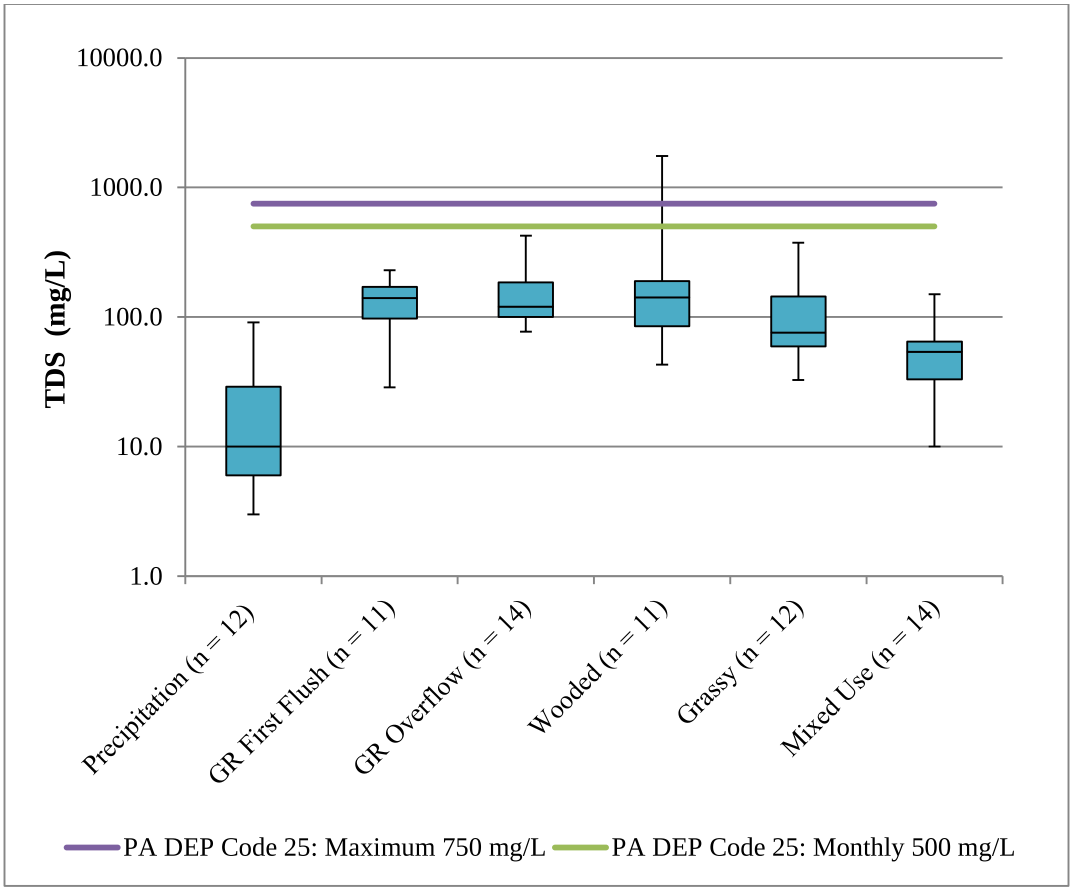


Figure 27: Comparison of green roof performance to background sites for Total Dissolved Solids

Green roof samples outperformed the background sites for total suspended solids, with median concentrations falling below the typical concentration of 25 mg/L for waterways far upstream of the Delaware Estuary (Figure 28). Once again, the wooded site had the highest median concentration (244 mg/L), data range (23 to 2443 mg/L), and standard deviation (776.9 mg/L). The fact that the wooded area underperformed relative to all other sampling sites may be attributed to site disturbances in and around the sampler location. Water turbidity was frequently observed within the FFW sampler at sample collection. Vegetation cover and land use type may have an impact on the quality of surface water runoff but is subject to difficulties in accurately sampling runoff. Surface runoff is subject to a number of other variables such as the amount of site disturbance, adjacent land uses, soils and geology, and vegetation density and establishment.

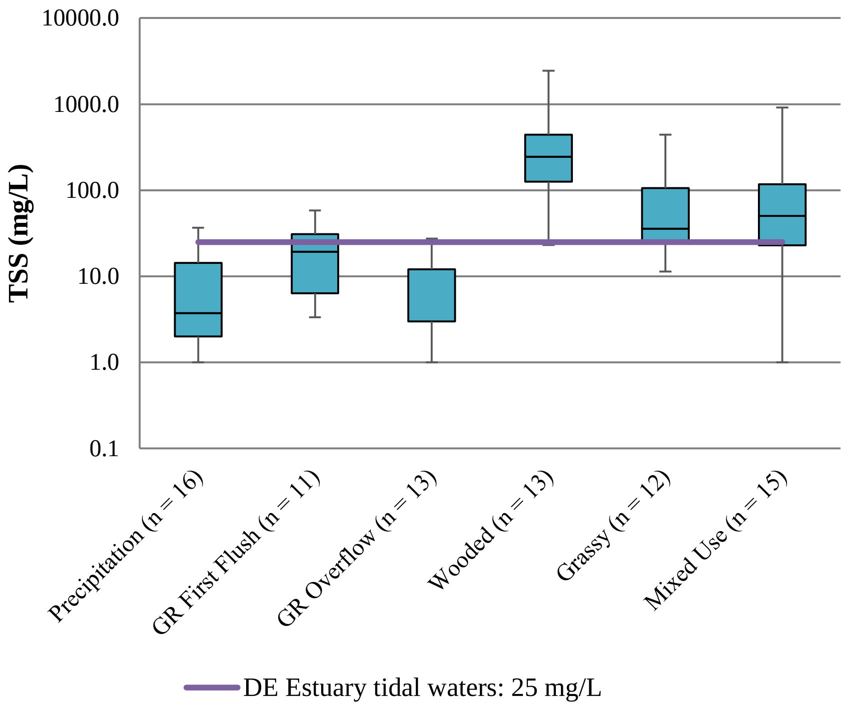


Figure 28: Comparison of green roof performance to background sites for Total Suspended Solids

Evaluation of runoff concentrations from the green roof and the background first flush sites reveals that the green roof's performance against other vegetated sites varies with each water quality parameter. However, the generalization may be made that the green roof does not export nitrogen at concentrations which greatly exceed recommended criteria, but exports phosphorus at higher concentrations than recommended criteria. When comparing different nitrogen species, the green roof performed similarly to or better than the grassy, wooded, and mixed-use areas for nitrites and TKN, but not as well as these sites for nitrates or total nitrogen. The green roof released total phosphorus in concentrations comparable to that of the grassy site, and green roof runoff had higher concentrations of orthophosphate than any of the background sites. Fewer chlorides were released in green roof runoff, as expected, because it was not affected by mineral salt applications or roadway pollutants. There was a similar rate of release of total dissolved solids, but much lower rate of release of total suspended solids, from the green roof as compared to the background sites.

Stacking effluent concentrations against EPA recommended criteria reveals further insights about green roof quality performance. Median effluent concentrations from the green roof as well as background sites were approximately equal to or lower than the recommended criteria for nitrates in rivers and streams. On the other hand, no median concentrations from the green roof or background sites met the recommended levels for TKN, while only grassy and mixed use sites fell below the recommend levels for total nitrogen as reported for rivers and streams. No sites met recommended levels for total phosphorus in rivers and streams (which are exceedingly low at 0.040 mg/L for rivers and streams). On the other hand, all SCMs' median concentrations met standard maximum and monthly criteria for chlorides, as well as standard monthly criteria for total dissolved solids.

The higher rates of nutrient release from the green roof over background sites is expected to be the result of fertilization. Effluent concentrations were substantially greater than those observed from rainfall input, which would presumably classify the green roof as a source of pollutants. From the perspective of a relative comparison, the green roof does not perform substantially better than other vegetated sites. However, sampling procedures cannot take into account performance conditions which may occur outside of the testing time frame. The green roof is known to be effective at retaining stormwater runoff volume, which must be considered when evaluating overall quality performance. Depending on its hydrological performance, a green roof may retain or release nutrients by virtue of its runoff retention (or lack thereof). Mass export calculations help provide some context for the effects of volume retention. The Villanova green roof is known to be effective at retaining stormwater volume (Wadzuk et al. 2013).

4.4 Land Use Comparison II

Land use comparison II focused on comparisons of effluent from three different stormwater control measures: the green roof, a bioinfiltration rain garden, and a constructed stormwater wetland. The rain garden and the wetland are both sinks for runoff contaminants (Wadzuk et al. 2010, Komlos and Traver 2012), and therefore overflow samples from these SCMs were expected to have low pollutant concentrations. The pollutant discharge quantities are a function of the volume of overflow produced for a storm event; the volume is affected by a variety of factors including precipitation depth, duration, and intensity, antecedent substrate moisture conditions and ponding depth.

The same green roof samples from Land Use Comparison I were compared against an event mean concentration (OVER) discharged from the rain garden overflow drain, a first flush from the stormwater wetland outlet (AS-OUTLET 1), and an event mean concentration for the wetland inferred from averages of all rainfall-based automated samples or all grab samples taken per storm event (see section 3.1.4 for details). In this way, three event mean concentrations from three different SCMs are compared in addition to two first flush samples. Data for the rain garden and wetland were included only if the dates of testing coincided with testing of the green roof. A comparison of the SCM's performance in each water quality parameter is provided in Figure 29 - Figure 39, with reference values included where applicable.

4.4.1 Nitrogen

As with Land Use Comparison I, ecologically acceptable concentrations of the nitrogen species NO_2 and NO_3 should be inferred from the NO_X graph. All SCMs had median nitrite concentrations within 0.01 and 0.03 mg/L, with the green roof samples having the greatest data spread (Figure 29). The green roof event mean concentration had the greatest range (0.005 to 0.184 mg/L) but the lowest median concentration (0.014 mg/L). This erratic performance seems to suggest that the green roof sometimes retains nitrites, but occasionally releases them in spikes. An evaluation of the sampling dates did not show that any of the testing events coincided with a fertilizer application.

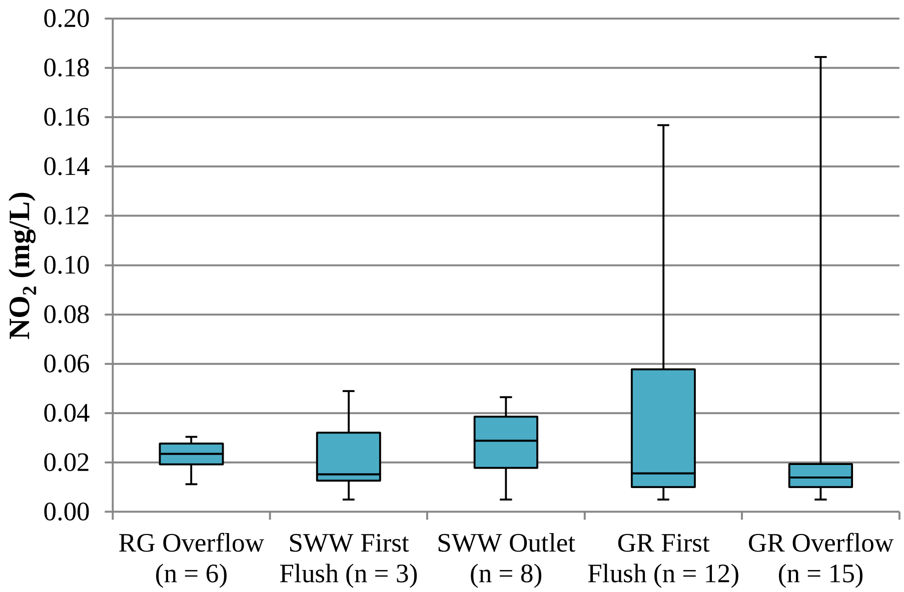


Figure 29: Comparison of green roof performance to rain garden and wetland for nitrites

As with nitrites, the green roof samples had the greatest spread of data for calculated nitrates, with maximum levels reaching above 6.0 mg/L (Figure 30). The green roof first flush had the highest median concentration (1.078 mg/L) and standard deviation (1.994 mg/L) while the green roof event mean concentrations reported the highest range (0.110 to 6.372 mg/L). The green roof's highly variable performance for nitrate retention could be attributed to fluctuations in volume retention capacity which depend on antecedent moisture conditions, temperature and rainfall amount (Buccola et al. 2008). Seasonal variations and nutrient needs of the vegetation, as well as timing of fertilizer applications, may all be impacting factors. Finally, the quality of the overflow sampling line between the green roof media and autosampler could be an unknown contributor. It is possible that nutrient or pollutant deposits may have built up inside the overflow pipe over time. Contamination may also have occurred from mold or algal buildup inside the sample feed tubes and inside the sample cup affixed to the interior of the tipping bucket housing. The tipping bucket was located next to a sunny window, and the PVC container used to house the tipping bucket was clear enough for light to pass through easily. Although a protective foil screen was used to shield the tipping bucket from sunlight, any tears in the foil along with warmth and the constant presence of moisture would have promoted algal or mold growth inside the sampling container. The area of the tipping bucket housing around the sampling container was occasionally cleaned, however this practice was not rigorously or frequently conducted due to the delicacy of the tipping bucket and the challenge of accessing the bottom of the housing unit.

Baseline tests are recommended in section Redesign of Green Roof Sampling5.3 to determine the impact of the sampling equipment on green roof quality data, and a reconfiguration of the sample container is also presented in Appendix C: Sampling Redesign. Well-designed extensive green roof systems should have an outlet or overflow pipe to channel excessive runoff off the rooftop. For quality-monitoring purposes, the outflow pipes should be considered a key component of the system and not neglected when considering the overall green roof impact on runoff quality.

The wetland and rain garden had more precise data groupings than the green roof, with data ranging only between 0.005 and 0.05 mg/L. The low and narrow range may be an indicator of good SCM performance in terms of runoff treatment, although it should be noted that the amount of data for the wetland and rain garden that was included in the study was less than that of the green roof (see the data counts on the horizontal axes).

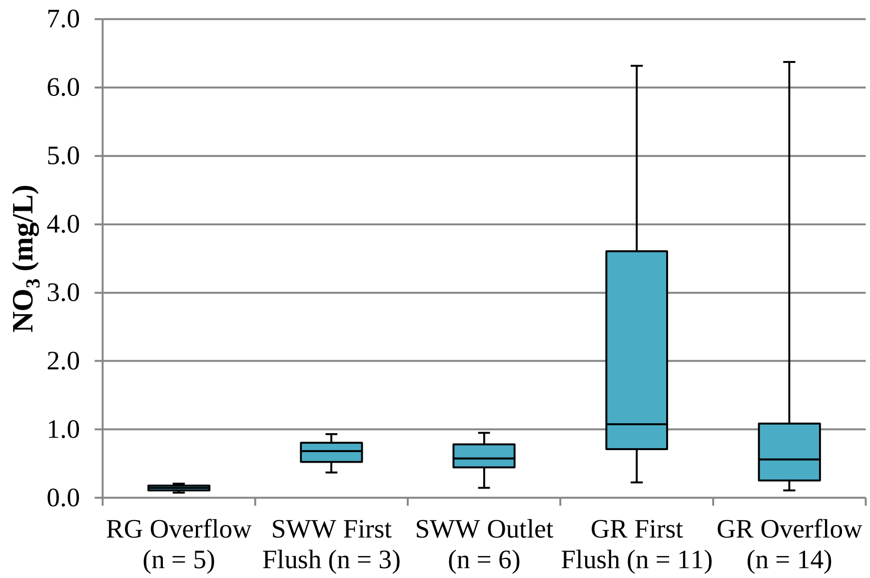


Figure 30: Comparison of green roof performance to rain garden and wetland for nitrates

Since NO_3 constitutes the majority of NO_X for the study data, similar data characteriestics were observed for the green roof, rain garden, and wetland, including the comparable median concentrations but highest data spread for the green roof samples (Figure 31). In addition, these median concentrations were all close to or or below the EPA recommended value of 0.995 mg/L for rivers and streams. Due to the green roof's high data varability, it would not be fair to suggest that the green roof's performance is within these recommended values all of the time, however based off the data it may be sutggested that the green roof meets the criteria long-term. It is possible that without fertilizer applications, this performance could be improved considerably, and green roofs should not be considered an obvious NO_x polluter as compared to other SCMs designed for nutrient retention.

Also of interest is the wetland's performance against EPA recommended levels for NO_x: the wetland's median values for its first flush and event mean concentrations were 0.699 mg/L and 0.596 mg/L, respectively (Figure 31). The first flush data is slightly above the EPA level of 0.605 mg/L for lakes and wetlands but below the recommended level for rivers and streams. The wetland event mean concetration reported below both recommended criteria for lakes and streams, and rivers and wetlands. The Villanova stormwater wetland is the headwaters for Mill Creek, a designated trout stream in Montgomery County (Dovel et al.2015).

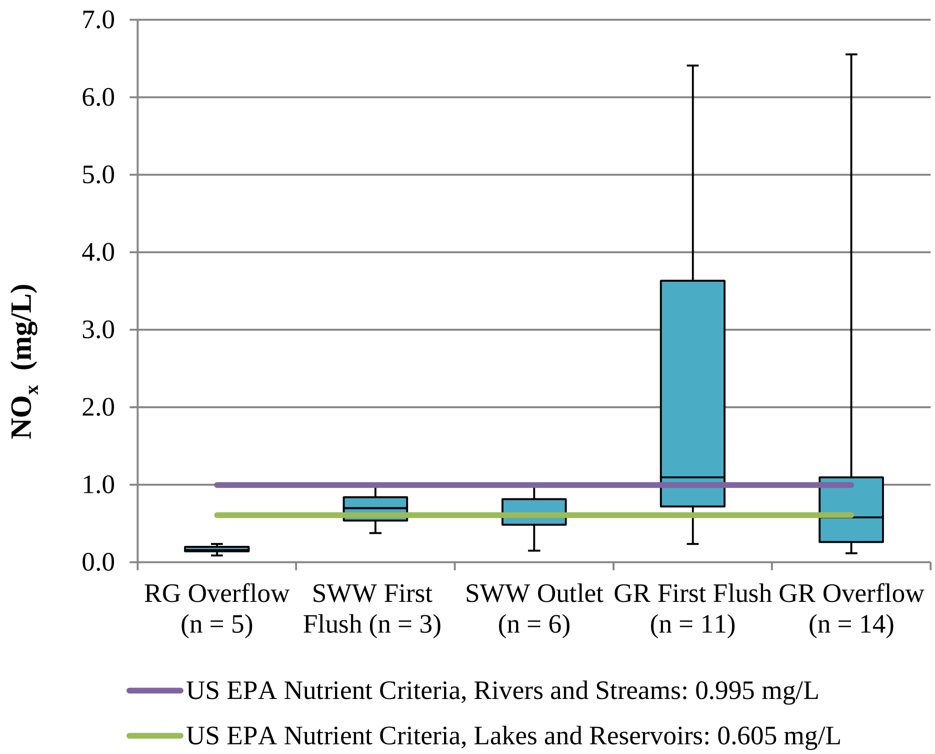


Figure 31: Comparison of green roof performance to rain garden and wetland for nitrites plus nitrates

When comparing SCMs for Total Kjeldhal Nitrogen and for Total Nitrogen, once again the green roof has a higher data spread than either the rain garden or the wetland (Figure 32 – Figure 34). It should also be noted that the green roof had higher median concentrations than the other SCMs for these nitrogen parameters. Furthermore, green roof total nitrogen export concentrations are in excess of EPA recommended levels (Figure 33 – Figure 34). For TKN, the green roof first flush had the greatest median concentration (2.395 mg/L) and data spread (range of 0.50 – 3.201 mg/L, standard deviation of 1.054 mg/L). TKN concentrations for the green roof were nearly always aboev EPA recommended criteria (Figure 32). All SCMs had median concentrations higher than the recommended 0.300 mg/L for rivers and streams. The wetland was higher than the recommended level of 0.350 mg/L for lakes and wetlands at 0.369 mg/L for its first flush and 0.762 mg/L for its event mean concentration.

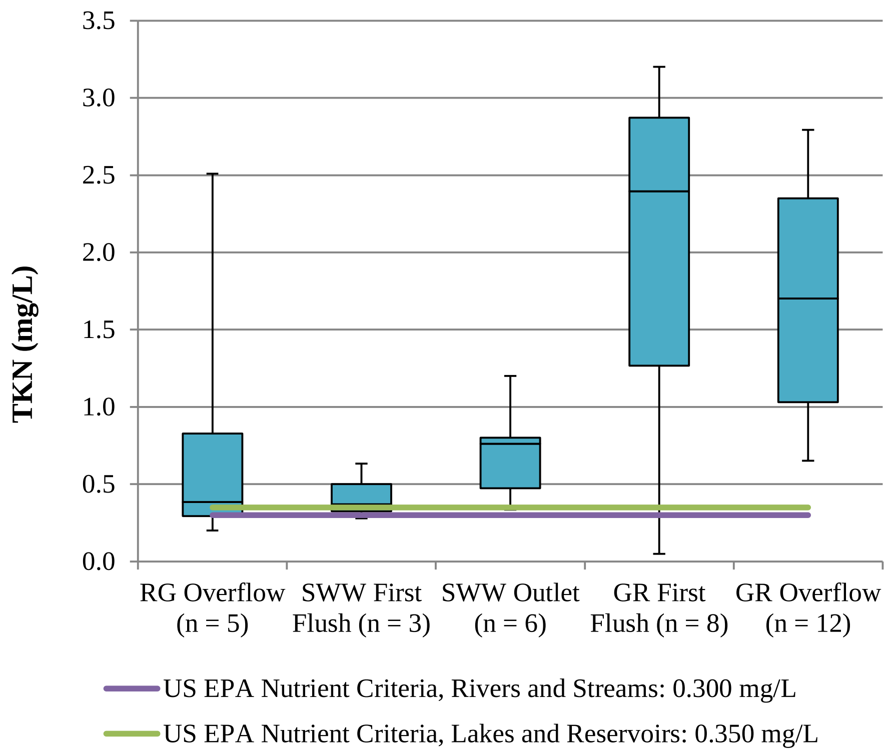


Figure 32: Comparison of green roof performance to rain garden and wetland for Total Kjeldahl Nitrogen

Total Nitrogen performance was less stringent with respect to all SCMs, given that the recommended criteria based on reported values must account for all nitrogen species that may be present in Eco-region IX surface waters. The green roof was the only SCM with median TN concentrations above the recommended as-calculated and as-reported levels for rivers and streams (3.972 mg/L for the first flush and 2.703 mg/L for the event mean concentration) (Figure 33 and Figure 34). The wetland outlet was slightly higher (median 0.978 mg/L for the first flush, 1.264 mg/L for the event mean concentration) than either as-calculated or as-reported criteria for lakes and wetlands. Despite having a somewhat wider range of data that the wetland, and a small data pool, the rain garden was the only SCM to meet all as-calculated and as-reported criteria for total nitrogen, suggesting that the bioinfiltration system performs very well in terms of nitrogen export.

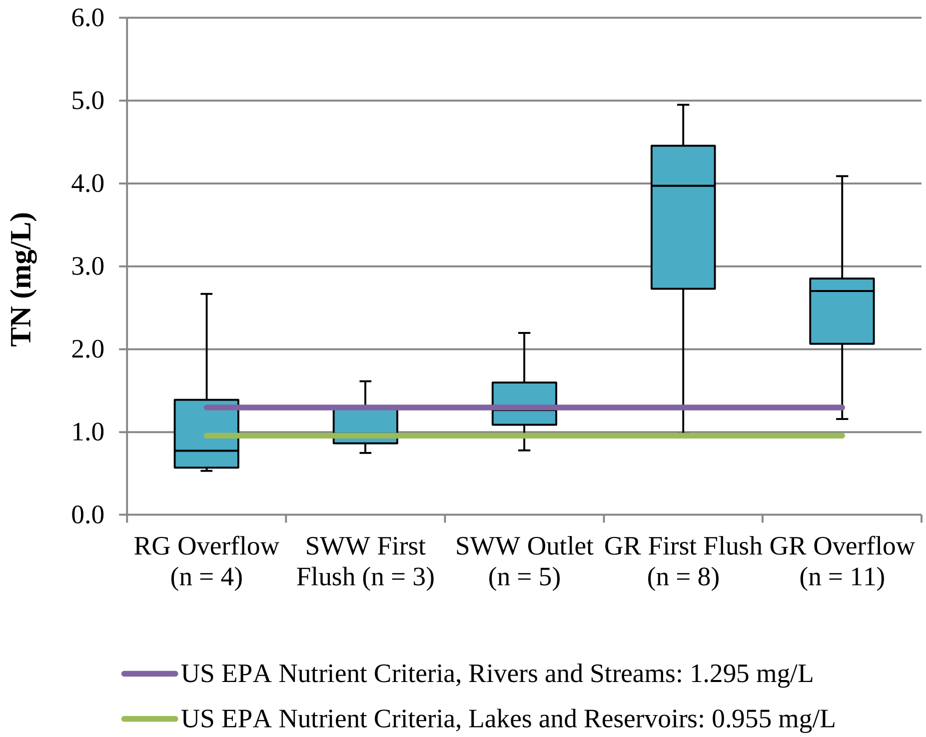


Figure 33: Comparison of green roof performance to rain garden and wetland for Total Nitrogen, with reference values as calculated by the EPA (section 4.1).

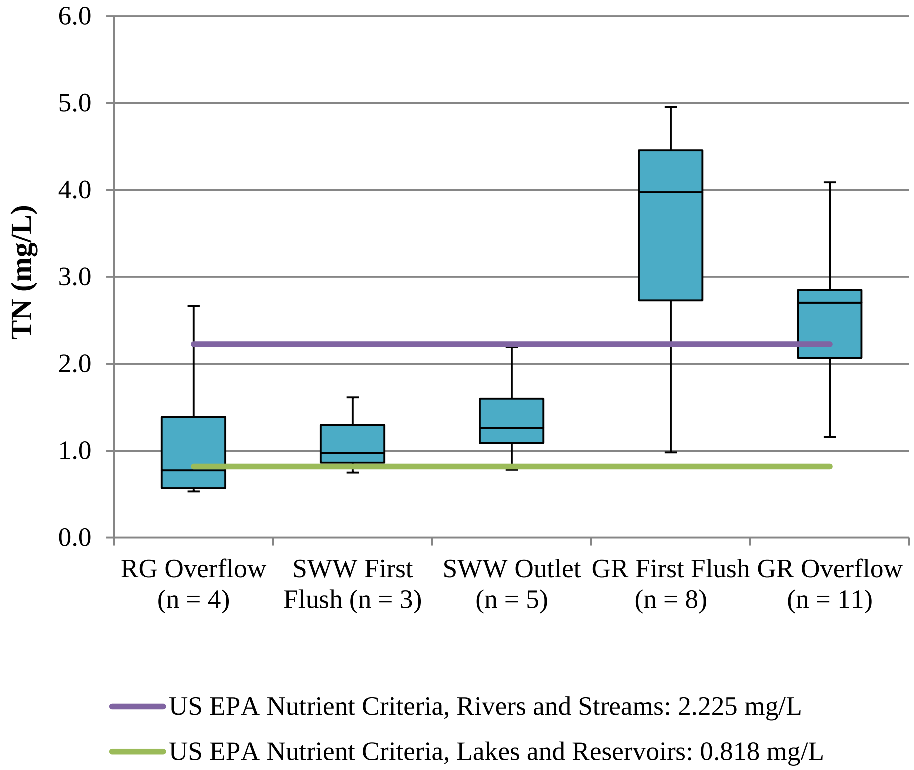


Figure 34: Comparison of green roof performance to rain garden and wetland for Total Nitrogen, with reference values as reported by the EPA (section 4.1)

Another interesting observation is the accuracy of the first flush and event mean concentrations. The wetland and green roof outflows were both analyzed for first flushes and event mean concentrations, however when looking for the hypothesized first flush phenomenon there is a very different story for the green roof effluent versus wetland effluent. In all nitrogen parameters, the green roof first flush had higher medians than green roof event mean concentration. Although these differences were not found to be statistically significant for nitrogen parameters (see section 5.1), they were visually evident in the graphs. However, the wetland had higher medians for all nitrogen parameters save NO_2 in its event mean concentrations than for its first flush samples. This would suggest that the first flush phenomenon does not exist for the wetland effluent. Influent concentrations at the wetland, while not evaluated for this study, has been studied in some detail by others (Neptune 2015a). A first flush has been observed for storm events where samples could be automatically separated. However due to the effects of mixing, any first flush effects would be dampened as the flow makes its way through the system from the inlet through the meanders and to the outlet. One of the benefits of constructed stormwater wetlands is that they mitigate high effluent concentrations that would be otherwise harmful to downstream habitats, via the processes of mixing and dilution. That said, the wetland first flush data pool was very small (n=3) and therefore it can be difficult to draw any conclusions based on these sample sets.

4.4.2 Phosphorus

As in Land Use Comparison I, acceptable orthophosphate levels should be inferred from the graph for TKP/TP. Scales for the phosphorus comparisons are graphed in semi-log axes to provide better resolution for exceedingly small concentrations. Orthophosphate concentrations for the green roof were between 0.393 and 4.01 mg/L for the first flush, and a high median of 1.281 mg/L was observed for the event mean concentration (Figure 35). Total phosphorus concentrations for the green roof were between 0.387 and 6.822 mg/L for the first flush; a median concentration of 1.355 mg/L was observed for the event mean concentration (Figure 36). All green roof overflows had higher phosphorus concentrations than either the wetland or the rain garden in all storm events tested, and were far above recommended EPA recommended criteria. The rain garden and wetland performed much better than the green roof, although still did not always meet the strict criteria. However, it should be noted that the recommended criteria are below laboratory detection limits (0.05 mg/L for 2014) and that some of the wetland data was below detection.

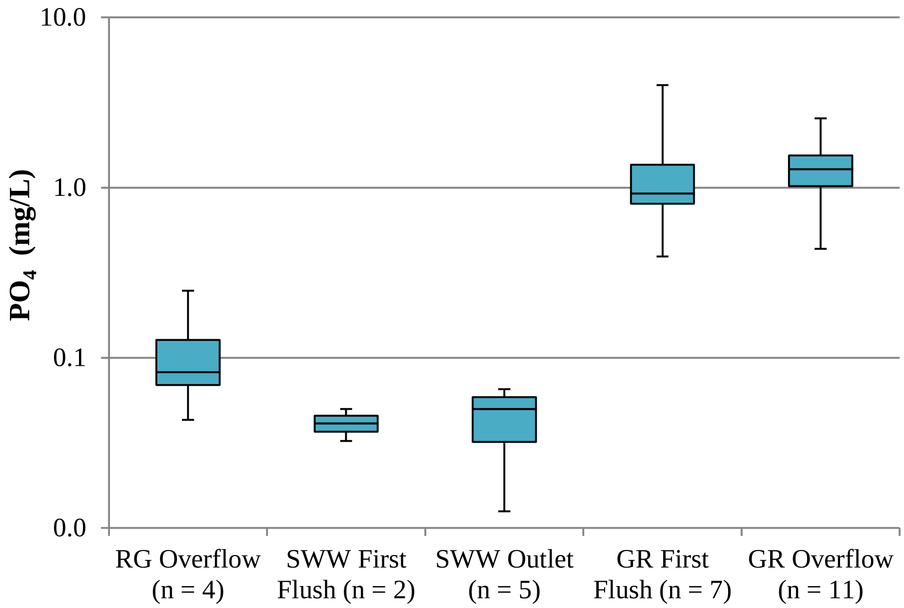


Figure 35: Comparison of green roof performance to rain garden and wetland for orthophosphate

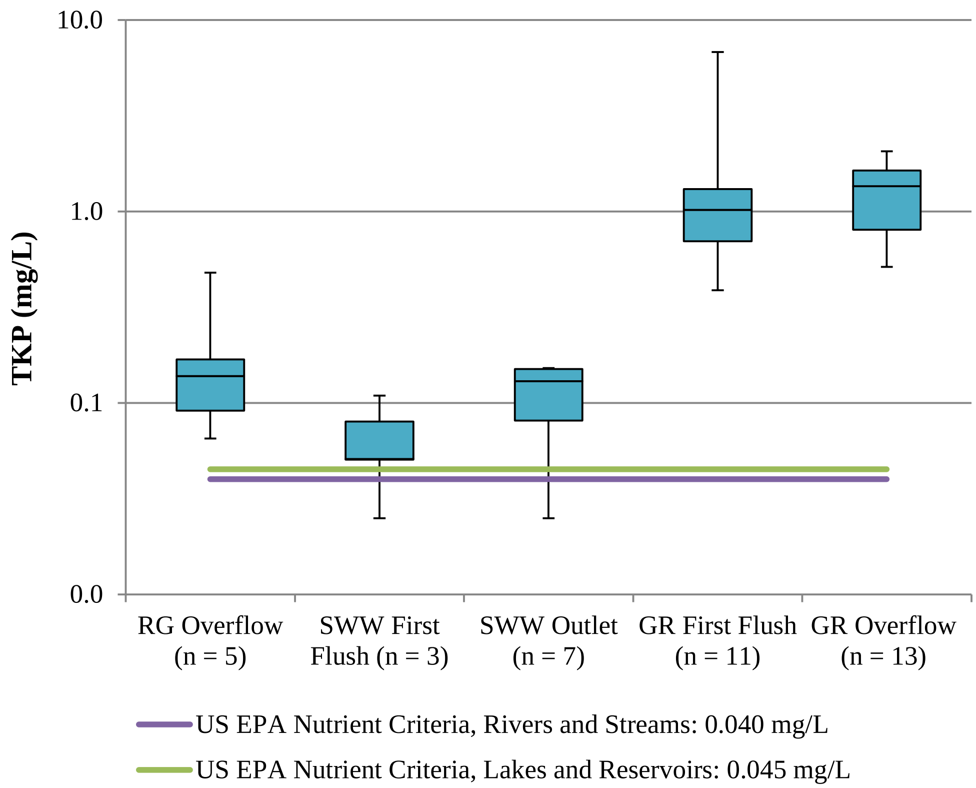


Figure 36: Comparison of green roof performance to rain garden and wetland for Total Kjeldahl Phosphorus

4.4.3 Chlorides, TDS, and TSS

Unlike in the sample groupings for Land Use Comparison I, scales for chlorides, TSS, and TDS are given in standard format because logarithmic was not necessary to visualize the comparison (Figure 37 – Figure 39). All SCMs tested for chloride generally met the acute concentration limit of 250 mg/L for PA surface waters (Figure 37). The wetland had occasionally greater concentrations which may be attributed to salt in the runoff from roadway applications within the campus watershed during winter months.

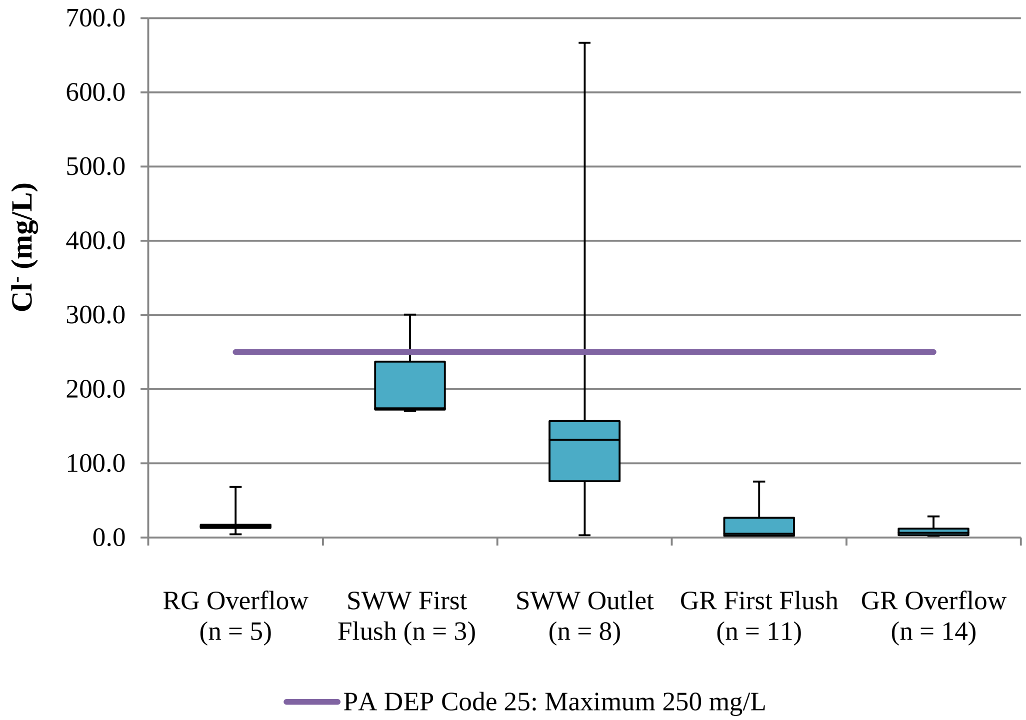


Figure 37: Comparison of green roof performance to rain garden and wetland for chlorides

In addition, all SCMs met the criteria for acute and monthly TDS concentrations of 750 and 500 mg/L respectively (Figure 38). The wetland again had occasionally higher readings, a factor which may again be attributed to seasonal runoff contaminates from roadways and from lawn and garden fertilizers. The green roof TDS may be attributed to fertilizers contributing ions in solution; from the soil media; and possibly from roofing and drainage materials.

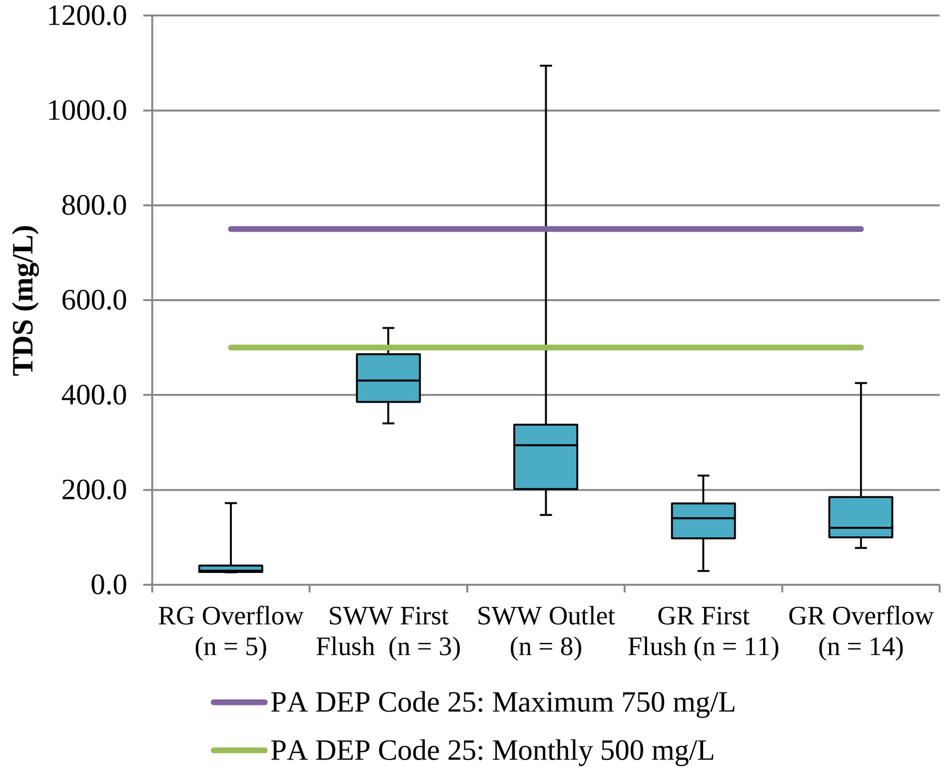


Figure 38: Comparison of green roof performance to rain garden and wetland for Total Dissolved Solids

Interestingly, the green roof, wetland, and rain garden occasionally had occasionally higher TSS readings than what may typically be found in tidal waters of the Delaware Estuary (Figure 39). Mill Creek has headwaters at the Villanova wetland and is a tributary of the Schuylkill River which empties into the Delaware River. Median values for the green roof were 19.33 mg/L for the first flush and 3.00 mg/L for the event mean concentration. Looking at the green roof, wetland, and rain garden outlets as point sources for total suspended solids, it may be said that these SCMs do not contribute concentrations outside the range that is typical for Delaware Estuary tidal waters.

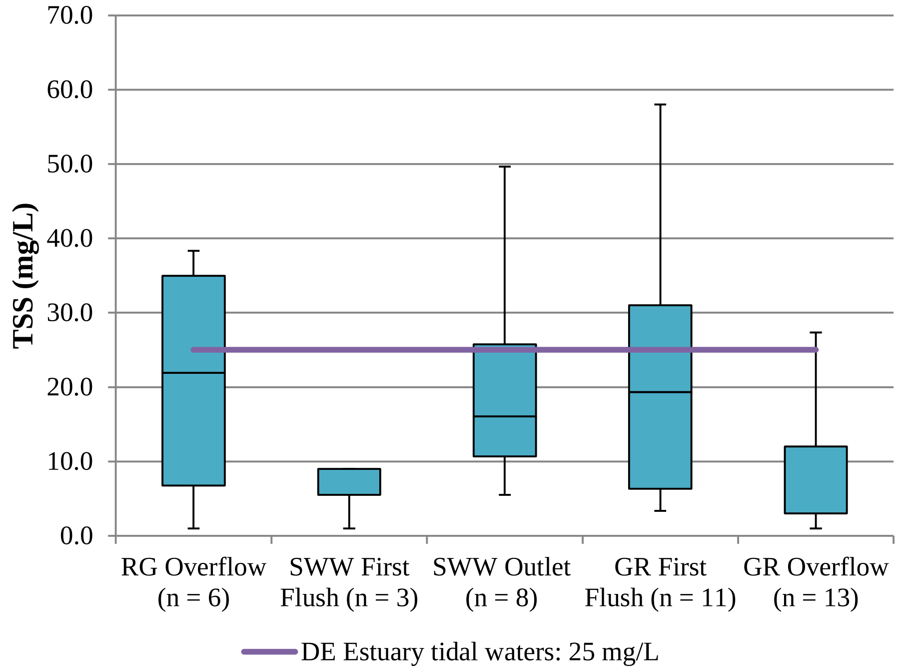


Figure 39: Comparison of green roof performance to rain garden and wetland for Total Suspended Solids

Overall, a wider range of concentrations was typically observed for green roof effluent samples as compared to that of the rain garden and the wetland, however median concentrations from the green roof were generally similar to those of the other two SCMs for some nitrogen species including NO_2, NO_3, and NO_X. However, green roof median effluent concentrations were higher than either the rain garden or the wetland for TKN, total nitrogen, and for phosphorus species. Median effluent chloride and TDS concentrations were lower for the green roof than the wetland, but higher than the rain garden, while median TSS effluent concentrations for all SCMs were generally comparable. Superior performance of the rain garden and wetland in terms of effluent quality may be expected: the design aspects for wetlands and rain gardens allow for nutrient absorption, removal, settling, and retention, and the performance of these systems has been previously documented (Komlos and Traver 2012, Heasom et al. 2006, Wadzuk et al. 2010).

Against EPA recommended criteria, median effluent concentrations for all SCMs fall at or below the levels recommended for NO_X in rivers and streams. Median concentrations for TKN were not within recommended limits for any SCMs, and it may be noted that TKN criteria were close to lower detection limits for quality testing. Total nitrogen median concentrations for the rain garden and wetland usually met with EPA criteria while those of the green roof did not. Recommended criteria for total phosphorus were below laboratory detection limits, therefore it would appear that no SCMs met with these criteria, however in general the wetland and rain garden performed far better than the green roof.

Clearly the green roof's performance is partly dependent on the water quality parameter in question, but in terms of total nitrogen, total phosphorus, and orthophosphate concentrations there is room for improvement in either system design, maintenance practices, or both before the system can be expected to meet EPA recommended criteria. The green roof media, being so shallow, may not allow for adequate retention of nitrogen due to the shallowness of the media column, the higher percentage of void space, and the occasional flushing effects of especially heavy rainfall events. Fertilizer applications may not be necessary and may contribute to unnecessary nutrient export. However, current design has shown to be very effective at storm volume retention, therefore the question of how much nitrogen or phosphorus mass the green roof exports is addressed in the following section. Mass estimates are contrasted with nitrogen and phosphorus fertilizer mass applications.

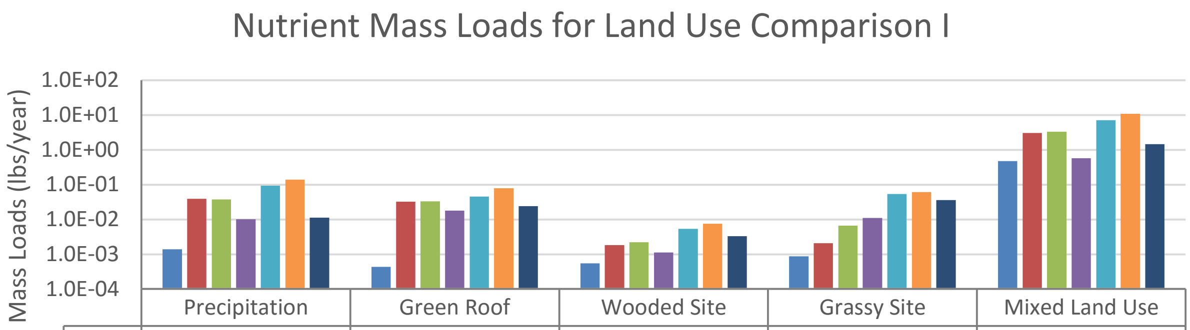
4.5 Pollutant Mass Balance

Concentration comparisons alone do not provide a complete picture of the impact of a bioretention system on surface water runoff quality. Therefore, the concentration data were also used to calculate a pollutant mass balance, providing a more complete picture of the green roof's nutrient export performance. Under the context that the green roof performs well hydrologically, the question remained if the effects of the observed effluent concentrations were mitigated by virtue of its volume retention performance. Concentration data from the previous land use comparisons were used to calculate estimates of mass input, export, and wash-off from the green roof and comparison sites. As with the concentration comparisons, where concentrations were reported at the lower detection limit, these data were replaced with half the value of the detection limit.

Mass inputs and exports were calculated as averages for a single storm event and as annual loadings, based on the assumption that there was no correlation between storm size and sample concentration (see section **Error! Reference source not found.**). Average loading is alculated by taking the volume for an event and multiplying it by the concentration for that event; the average mass per storm event is thus derived. Annual loadings may be calculated using various methods. Berghage (2009) took the annual average rainfall amount for the study's location (44 in.) and multiplied it by a coefficient which was calculated based on the retention of the green roof systems for that study. The product was then multiplied by the average concentration, and ranges for those estimates were based on the standard deviations of concentrations.

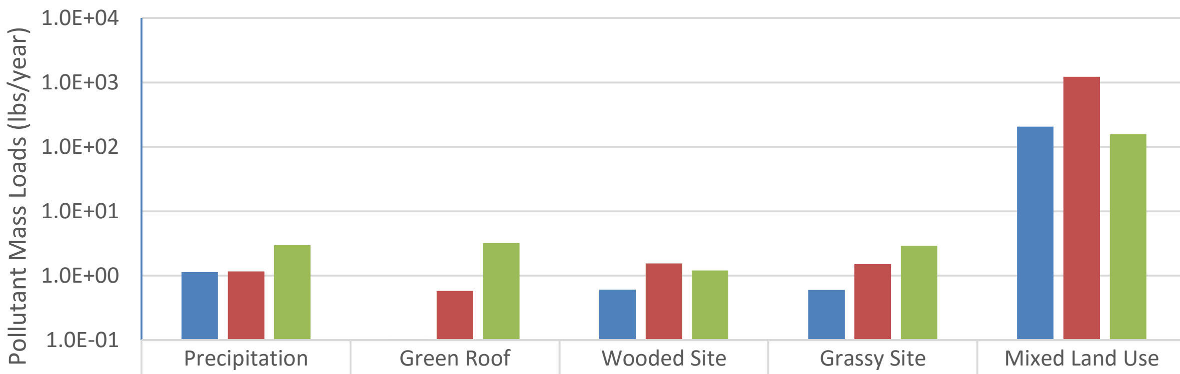
Mass load estimates for annual performance are typically complicated by the challenge of limited outflow and/or overflow quality data from a well-designed SCM. This is a desirable problem to have because limited outflow or overflow shows that the system is meeting its intended design standards for stormwater volume control. Still, due to the wide range of storm sizes which may occur in a given region, SCMs will inevitably produce overflow or outflow and pollutants will be released. For this study, various methods to estimate the mass loads produced each year were explored. The graphs in Figure 40 - Figure 43 report annual mass loads which are based on average loads and have been extrapolated out to a year as described in the following subsections.

Annual mass estimates for nutrients, that is, nitrogen and phosphorus species, are given in Figure 40 for the green roof and the various vegetated land uses included in Land Use Comparison I. Annual mass estimates for other pollutants including chlorides, TSS, and TDS are provided in Figure 41. Data tables with respective values (in lbs) are provided below the graphs, which are semi-logarithmic due to the wide range of estimates. The wooded area had the lowest nutrient loading, which may be attributed to the high storage ratio for the site. Indeed, runoff could not be collected for every storm testing event from this site due to vegetation interception, surface storage, and soil infiltration. The green roof itself had higher estimates for some parameters than either the grassy or wooded sites, although the nutrient loads do not come close to the estimated total nutrient input which accounts for both wet deposition and fertilizer (see the following subsection). The mixed use site had the highest mass export estimates although these values are very conservative because runoff was calculated based on impervious surface characteristics. It is possible that the numbers reported in Figure 40 and Figure 41 may be lower in reality because the pervious portion of the mixed use site should account for some infiltration and storage.



	Precipitation	Green Roof	Wooded Site	Grassy Site	Mixed Land Use
NO2	0.001	0.0004	0.0005	0.001	0.475
NO3	0.039	0.0326	0.0018	0.002	3.087
NOx	0.038	0.0331	0.0022	0.007	3.340
PO4	0.010	0.0178	0.0011	0.011	0.572
TKN	0.094	0.0453	0.0054	0.054	7.098
TN	0.139	0.0783	0.0075	0.061	10.81
TKP	0.011	0.0240	0.0033	0.036	1.453

Figure 40: Nutrient Mass Loads for Land Use Comparison I

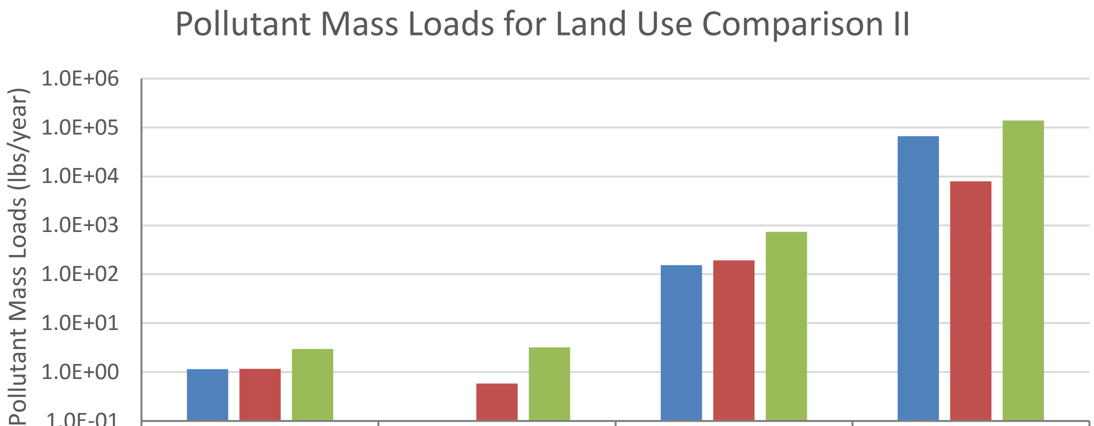


	Precipitation	Green Roof	Wooded Site	Grassy Site	Mixed Land Use
Cl-	1.140	0.104	0.607	0.604	205.7
TSS	1.166	0.584	1.545	1.518	1216
TDS	2.981	3.217	1.201	2.901	155.8

Figure 41: TSS, TDS and Chloride Mass Loads for Land Use Comparison I

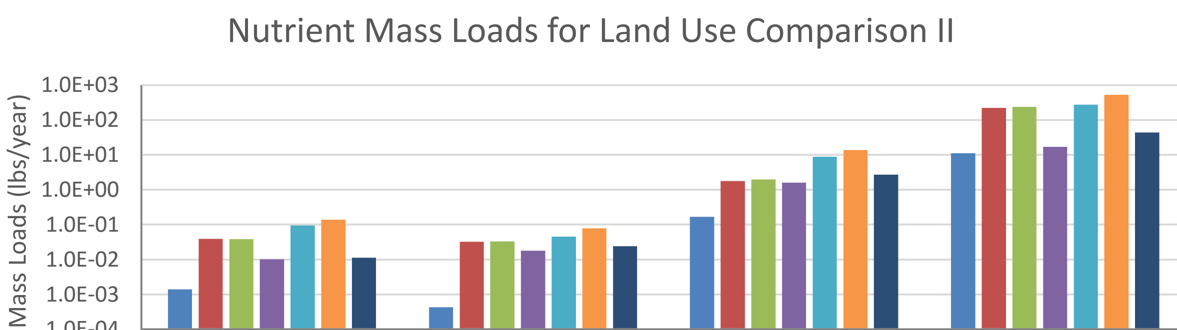
Similarly, annual nutrient and pollutant mass loadings for the stormwater control measures included in Land Use Comparison II are given in Figure 42 and Figure 43. Again, vertical scales are logarithmic due to the wide range of estimates, particularly in the case of the constructed stormwater wetland which handles pollutant quantities on a much large scale than either the green roof or the rain garden because of its large drainage area (42 acres treated by the wetland as opposed to 575 square feet for the green roof and 1 acre treated by the rain garden).

Pollutant reductions for the rain garden and the wetland are dealt with in literature (Komlos and Traver 2012; Wadzuk et al. 2010)



	Precipitation	Green Roof	Rain Garden	Wetland
Cl-	1.140	0.104	152.5	66811
TSS	1.166	0.584	191.9	7887
TDS	2.981	3.217	730.6	139141

Figure 42: Nutrient Mass Loads for Land Use Comparison II



	Precipitation	Green Roof	Rain Garden	Wetland
NO2	0.001	0.0004	0.168	11.13
NO3	0.039	0.0326	1.783	225.1
NOx	0.038	0.0331	1.980	235.8
PO4	0.010	0.0178	1.601	16.87
TKN	0.094	0.0453	8.892	273.2
TN	0.139	0.0783	13.74	533.9
TKP	0.011	0.0240	2.738	43.72

Figure 43: TSS, TDS and Chloride Mass Loads for land Use Comparison II

Wet deposition mass estimates based on annual average cumulative rainfall (see section 4.5.1) for Philadelphia are reported for the green roof mass balance. Ultimately, the quantity contributed by precipitation was miniscule compared to the quantity contributed by fertilizer (see Table 10). Mass estimates both into and out of the green roof for TN, TP, and TSS are depicted in Figure 44 below. Mass of TSS in is based on deposits from precipitation plus the 4 lbs of total fertilizer applied annually. The overall mass balance suggests that the green roof does not export as much as the nutrient input: the export quantities are less than 10% of the amounts that are input. Most of the nitrogen and phosphorus that goes into the system is taken up in plant growth.

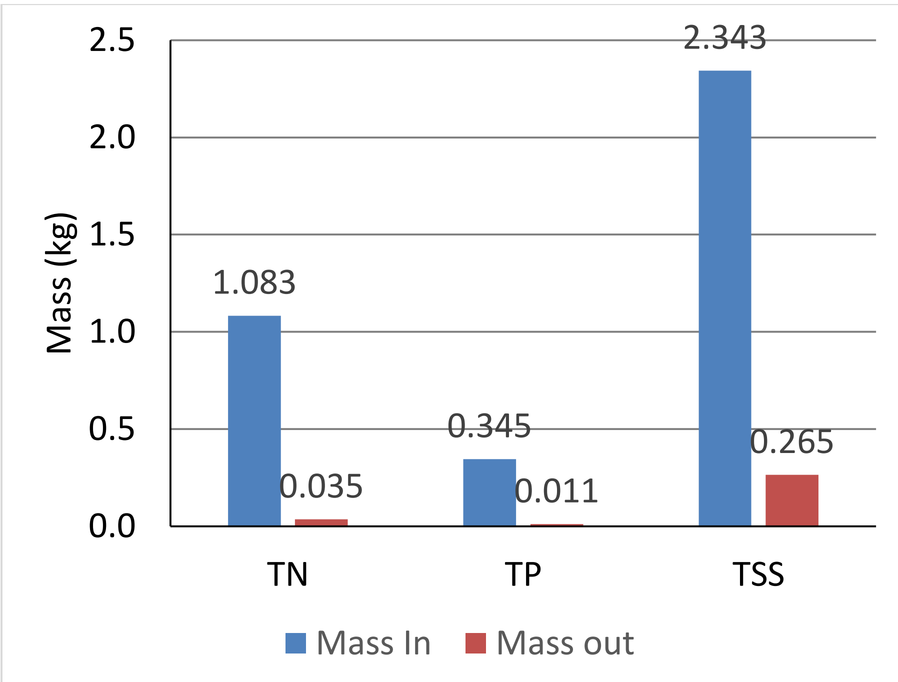


Figure 44: Green roof mass balance for TN, TP, and TSS

4.5.1 Green Roof Mass Input

Pollutant and nutrient mass input to the green roof was taken as the sum of the amounts contributed during precipitation events, plus contributions from fertilizer applications. Table 10 lists the mass input for total nitrogen and total phosphorus to the green roof, including both precipitation and fertilizer-sourced quantities (see section 3.0 Methodology).

Table 10: Nutrient input to the green roof from wet deposition and from fertilizer.

	Total N from Rain (lbs)	N from Fertilizer (lbs)	Mass of N Input (lbs)	Total P from Rain (lbs)	P from Fertilizer (lbs)	Mass of P Input (lbs)
Method 1	0.859	2.25	3.109	0.013	0.75	0.763
Method 2	0.139	2.25	2.389	0.011	0.75	0.761

Atmospheric deposition during dry weather was not measured within the scope of this study, which focused only rain event sampling, and therefore not reported; although it is possible that some dry deposition may contribute to the actual pollutant mass balance. Studies conducted in France and in California reported widely-varied annual quantities of atmospheric nitrogen deposition. For instance, Blanchoud et al. (2002) reported a range of 470-670 mg/m^2 in France, while Bytnerowicz et al. (2015) reported 0.2 – 1.4 kg/ha (20 – 140 mg/m^2) of NO_2 for the summer of 2006 in the San Bernadino Mountains in California. Fenn et al. (2008) developed empirical critical loads for atmospheric nitrogen deposition based on lichen indicator health in California, and determined that for much of the western Sierra Nevada range, these critical loads are exceeded. Bytnerowicz et al. also evaluated critical loads of nitrogen for sensitive ecosystems, which at conservative levels were 1.6 kg/ha (160 mg/m^2) for the summer months (June 1 – Sept. 30), and 3.1 kg/ha (310 mg/m^2) for a year. Estimates of dry atmospheric deposition alone typically did not exceed those critical loads, although critical loads were often exceeded when other sources were included, and numerous reasons for uncertainty in the reported estimates were described. Lequy et al. (2014) reported atmospheric phosphorus dissolved deposition in the range of 0.5 – 1.0 kg/ha/year (50 – 100 mg/m^2/year), based on samples taken in an open field in France.

Annual input attributed to precipitation was calculated using two different methods; both methods were subjected to a student's t-test for statistically significant difference between mean estimates of pollutant inputs. Calculations using Method 1 were based on average loading (Berghage et al. 2009). In Method 1, rainfall volumes were calculated for each storm using the rainfall depth recorded at the green roof, multiplied by the total area of the green roof (575 square feet). Each rainfall volume was multiplied by the concentrations of the various water quality parameters to obtain the mass export value of each parameter, specific to the testing event. The mean export value of each parameter was then multiplied by the average number of rain events per year for Philadelphia, to obtain an estimated annual total in deposition from rainfall. The average number of rain events per year for Philadelphia was an estimated 93, based on 113 years' worth of recorded rainfall data for the Philadelphia region. Rainfall depths were recorded at the Philadelphia International Airport by the National Weather Service.

In Method 2, annual loading estimates were calculated using average concentrations for each parameter which were multiplied by the average annual rainfall volume in Philadelphia of 41.5 inches per year (Miller et al. 2014) over the green roof area. It was assumed that no correlation existed between sample sizes and concentrations. A paired t-test of the two methods used (with two tails, 9 degrees of freedom, and a t-value of 2.588) yielded a p-value of 0.1714 for a confidence level of over 95 percent in the null hypothesis, meaning no significant difference could be observed in the amount of mass input as a result of using different calculation methods. Figure 63 and Figure 64 in Appendix B: Mass Estimates for Individual Sites depict the estimated mass deposition of each pollutant category, with corresponding values reported using the two methods.

4.5.2 Green Roof Mass Export

Estimates of nutrient mass export indicate that the majority of the fertilizer applied to the Villanova green roof as part of a regular maintenance routine is taken up and used by the plant life (Figure 44). The Villanova green roof vegetation was lush and well-established throughout the quality study period. Of the estimated 2.39 lbs/year total nitrogen input to the green roof (1.083 kg/year), about 0.077 lbs (0.035 kg) are not used by the plants, but exported with the overflow. Of the estimated 0.761 lbs/year total phosphorus input (0.345 kg/year), about 0.024 lbs/year (0.011 kg/year) are exported. Fertilizer applications are generally not recommended for maintaining green roofs long-term, due to the implications for nutrient loading in receiving waterways. Some fertilization is necessary immediately following installation, to help the plants mature to a point where they can self-propagate. However, once the vegetation has become established, fertilizers should be used sparingly, if at all, and proper judgement should be made in the application so that excess nutrients are not released. Routine nutrient testing of the soil media is a useful approach for informed decisions regarding fertilizing.

Mass export from the green roof was calculated first as an average loading, and then as an annual loading. Mass loadings associated with the green roof first flush were calculated using first flush concentration data and multiplying by the volume used to trigger the autosampler to collect the first flush sample (GR OUT 1) by the CR1000, which was 0.75 gallons. Mass loading associated with the remaining runoff not considered a contribution to the first flush (GR OUT 2) was calculated in the same manner. The main difference for this second outflow sample is the volume used to obtain event-specific loadings. The volume for GR OUT 2 was calculated based on the total overflow for a storm event, minus the volume attributed to the first flush.

Average total mass export loadings for the green roof were calculated by adding the mass export amounts for GR OUT 1 and GR OUT 2 for each event. Since the number of sampled storms is less than the number of storms in a year that produce overflow, annual total mass export amounts had to be estimated and were calculated using two different methods. The first method was predictive, based on the rainfall event frequency data for Philadelphia described previously. A conservative estimate of the typical rainfall-overflow threshold of the CEER green roof was 2.0 cm (0.75 - 0.80 inches), based on observation (Zaremba et al. 2016). The average occurrence per year for Philadelphia of storms with rainfall amounts equal to or greater than the observed capture volume of the CEER green roof is approximately 18 storms. Annual mass loadings were calculated using this estimated average overflow frequency value, multiplying it by each pollutant's average mass loading.

The second is based on an observed annual overflow frequency for the CEER green roof. Overflow volumes were recorded between April 2012 and June 2015 for storm events, which were defined from the start time of rainfall that was recorded until a lapse of two hours with no tipping bucket tips recorded. Overflow data were filtered to eliminate negligible flows (i.e. at detection limit) and equipment calibration errors. Since short-term overflow performance may be considerably affected by antecedent soil media moisture conditions, the data were also filtered to eliminate all rainfall events that would theoretically not produce overflow. Only events with rainfall equal to or greater than 2.0 cm (0.8 in) were considered; this produced a total of 46 events over a period of 3.25 years, yielding an estimated overflow frequency of 14 times per year. The inclusion of both methods provides different perspectives on estimating the mass export loadings, and illustrates two ways to predict expected performance. A second t-test was conducted to compare the two methods, where for a two-tailed analysis with 9 degrees of freedom and a t-value of 1.378, a p-value of 0.2234 was produced. Given that $p > \alpha$ where $\alpha =$ 0.05, this indicates that no significant difference could be observed in the amount of mass export as a result of using these two overflow frequency estimates.

Despite the statistically insignificant difference between the two methods, it remains that the method for estimating the green roof mass load is currently based on rainfall frequency estimates which are in the process of being improved. As these frequency estimates do improve, and as more storms are tested, it will become easier extrapolate the mass loading out to an annual rate. The observed retention threshold of 2.0 cm (0.80 in) for the Villanova green roof indicates that the system performs well in terms of volume retention but this presents a constraint for quality sampling due to the infrequency of sampling events. This constraint may be overcome using improved overflow frequency estimates that are rainfall-based, for predictive quality performance of the SCM.

The challenge of estimating mass loads actually strengthens the case for long-term continuous monitoring of stormwater control measures such as green roofs, and also makes a case for better rainfall analysis, which may not only help predict SCM performance but also be used to improve SCM design. Given the number of variables which currently impact green roof quality sampling, and given the challenges in calculating mass loads, it is proposed that a confidence interval be developed for each mass load. Refer to section 5.2 which explains the development of green roof mass load confidence intervals in more detail.

For reporting purposes, green roof mass load estimates based on overflow frequency estimates from observed overflows are used in Figure 40 - Figure 43. Green roof pollutant mass loads as calculated using both estimated and observed overflow frequencies are depicted in Figure 65 - Figure 68 of Appendix B. Fertilizer manufacturer ratios of N, P, and K were used to calculate the nitrogen and phosphorus portions of annual applications, and these quantities are included in the graphs.

To provide some context for the green roof's volume retention performance over the testing period, percent runoff reductions were calculated for the sampled storm events. Overflow volumes, summed from the volumes measured by the tipping bucket and at the overflow weir, were subtracted from rainfall volumes for each event to yield the volume retained, which was then divided by total rainfall for that event to arrive at percent reduction. Rainfall and overflow volumes are plotted by storm date in Figure 45; percent reductions and the volumes retained for each event are plotted in Figure 46.

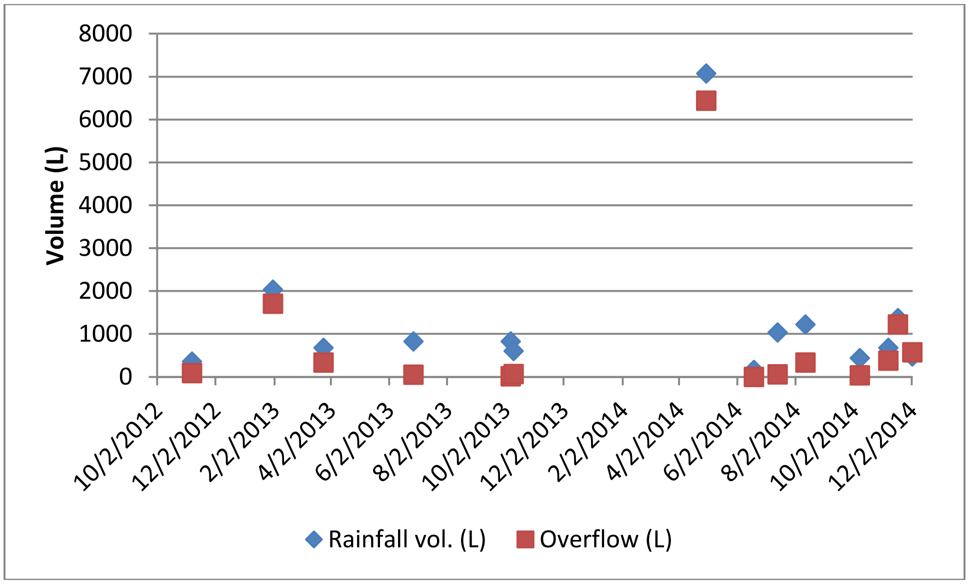


Figure 45: Rainfall received and overflow volumes generated for green roof storm testing events.

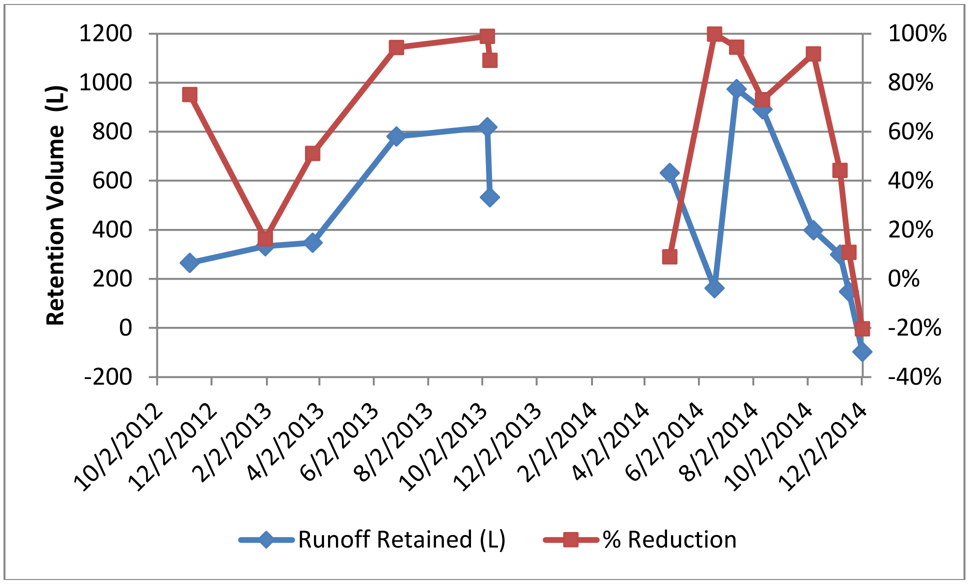


Figure 46: Percent runoff reductions and volumes retained for green roof storm testing events

The data collected thus far may be analyzed to determine if there is in fact any statistically significant difference between GR OUT 1 and GR OUT 2. A paired t-test was conducted for each water quality parameter, first assuming normal distribution and then using log-transformed data. An alpha value of 0.05 was assumed. The results of the two-tailed analysis indicated that in most cases, no significant difference could be observed between the concentrations for GR OUT 1 and GR OUT 2. A significant difference was observed for TSS under analysis as both a normally and non-normally distributed data set. A significant difference was observed for total nitrogen only if the data were assumed to be normally distributed. Test results are reported in Table 11 and Table 12.

Table 11: Paired t-test results for significant difference between first flush and EMC, assuming normal distribution

	NO2	NO3	NOX	TKN	TN
P (2-tail)	0.8318	0.1543	0.1669	0.4235	0.0356
T-value	-0.2304	1.6394	1.5852	0.9085	2.7766
n =	10	10	10	8	8
d.f.	9	9	9	7	7
P < 0.05?	NO	NO	NO	NO	YES
	PO4	TKP	Cl-	TSS	TDS
P (2-tail)	0.5444	0.4732	0.0997	0.0180	0.9081
T-value	0.7120	0.7983	1.9741	3.2855	0.1280
n =	6	9	9	8	8
d.f.	5	8	8	7	7
P < 0.05?	NO	NO	NO	YES	NO

Table 12: Paired t-test results for significant difference between first flush and EMC, using log-transformed data and assuming non-normal distribution

	NO2	NO3	NOX	TKN	TN
P (2-tail)	0.9094	0.0944	0.0986	0.7227	0.0773
T-value	-0.1234	1.9702	1.9415	-0.3950	2.2121
n =	10	10	10	8	8
d.f.	9	9	9	7	7
P < 0.05?	NO	NO	NO	NO	NO
	PO4	TKP	Cl-	TSS	TDS
P (2-tail)	0.6198	0.7119	0.1712	0.0005	0.7951
T-value	0.5790	0.4059	1.5942	6.4944	0.2884
n =	6	9	9	8	8
d.f.	5	8	8	7	7
P < 0.05?	NO	NO	NO	YES	NO

A limited amount of overflow quality data is characteristic of green roof systems with good retention; in this case n ≤ 18. Because it cannot be assumed that the data follow a normal distribution due to the limited amount of data points, more advanced statistical (non-parametric) methods are suggested to verify these results, unless it can be proven that the data are indeed normally distributed.

4.5.3 Background Site Mass Loading

Annual pollutant and nutrient wash off quantities for the background sites, reported in Figure 40 - Figure 41, were calculated by multiplying the average mass loading by the number of times that a site was expected to produce wash-off per year. Frequency of runoff was determined by estimating the number of storms for the Philadelphia area that had cumulative rainfall depths greater than the depth of initial abstractions for the site. Frequency estimates were developed using the same Philadelphia rainfall data as with the precipitation and green roof estimates described above. The wooded area was expected to produce wash-off a total of seven times per year, while the grassy area was estimated to produce wash-off 14 times per year. The annual wash-off frequency estimate for the mixed use area was determined based on the initial abstraction value associated with the impervious portion of the drainage area, which was 0.041 inches. However, this depth was below the minimum resolution of the MATLAB program used to calculate these frequencies; therefore the minimum resolution depth of 0.25 cm (0.1 in) of rainfall was used, for an estimated 63 events per year that produced wash-off (Lewellyn 2015, personal communication). The pervious portion of the mixed use area had a higher initial abstraction depth of 1.3 cm (0.5 in) and would have yielded a much lower estimate of runoff frequency—closer to that of the site that was all grass.

Overall the green roof's total nitrogen and total phosphorus mass export (0.078 lbs TN/year and 0.020 lbs TP/year) was comparable to that of the grassy area (0.061 lbs TN/year and 0.036 lbs TP/year), and both were about an order of magnitude greater than the mass export associated with the wooded site (0.0075 lbs TN/year and 0.0033 lbs TP/year). The mixed use area had the most of any sites (10.8 lbs TN/year and 1.45 lbs TP/year), although it should be noted that this is a heavy estimate for reasons described above. The green roof's TSS output

(0.58 lbs/year) was less than background sites (1.55 lbs/year for the wooded area, 1.52 lbs/year for the grassy area, and 1220 lbs/year of the mixed use area). TDS output for the green roof (3.22 lbs/year) was similar to the wooded (1.20 lbs/year) and grassy (2.90 lbs/year) sites. TDS output from the mixed use site was again the highest at 156 lbs/year, due also to its having the largest drainage area. These estimates, based on CN runoff calculations, are to be interpreted for qualitative comparison between land uses. Runoff calculations for the three background sites are shown in Figure 47, Figure 48, and Figure 49.

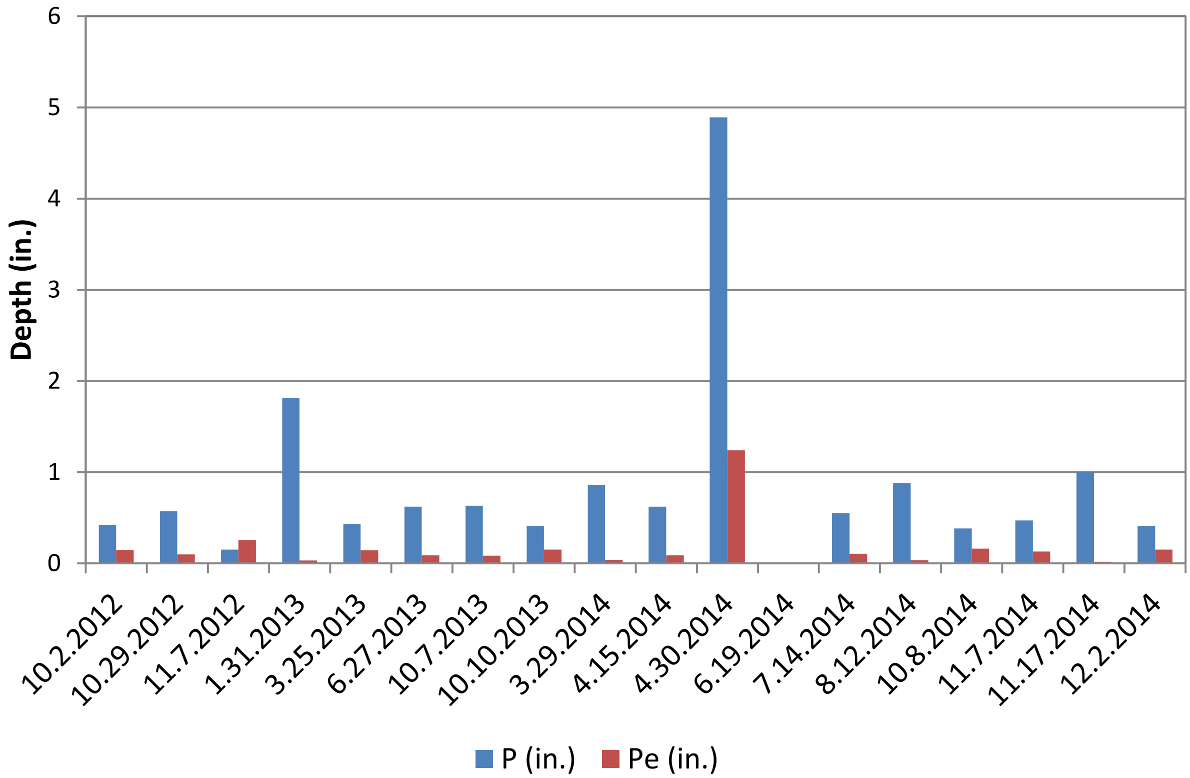


Figure 47: Rainfall and runoff for sampling events at wooded area location

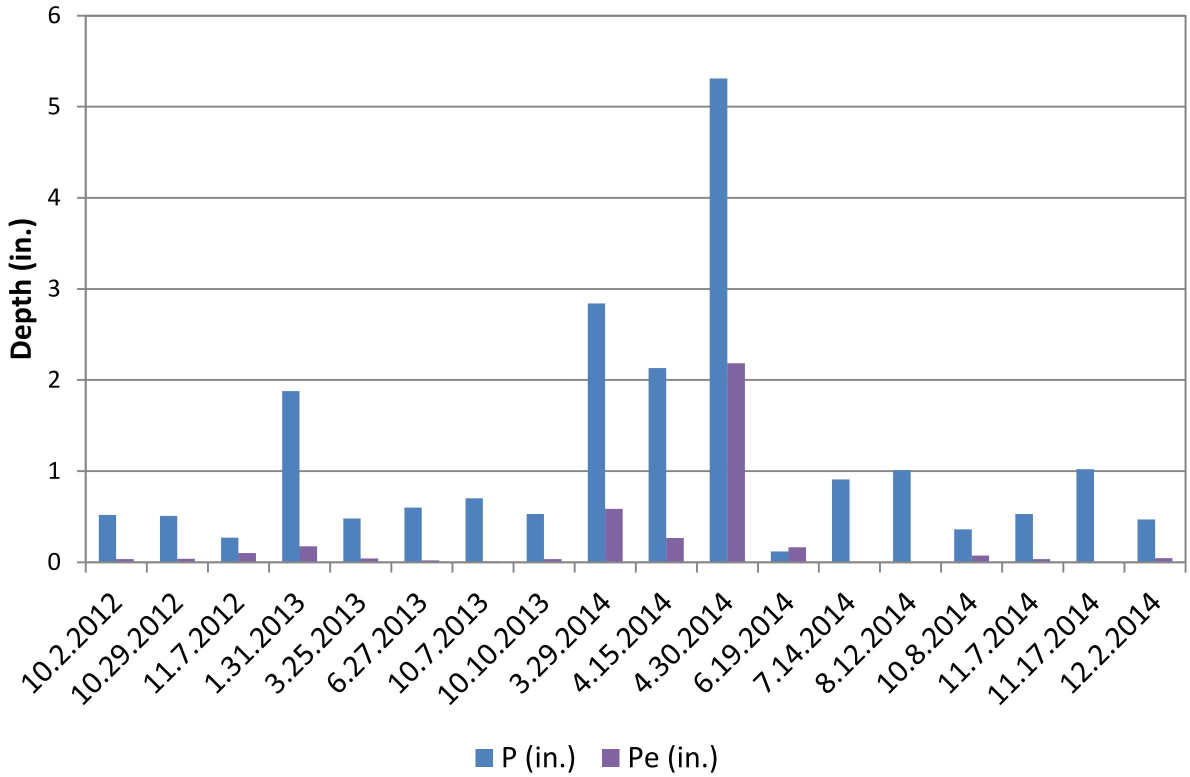


Figure 48: Rainfall and runoff for sampling events at grassy area location

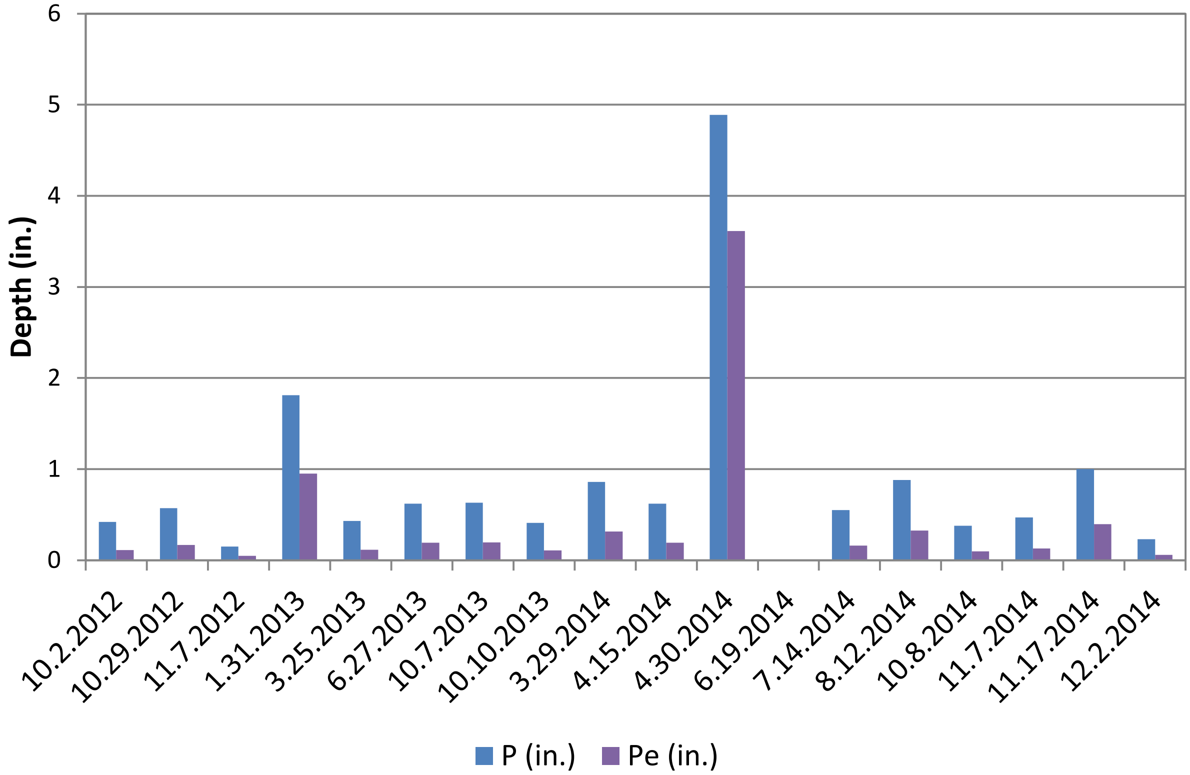


Figure 49: Rainfall and runoff for sampling events at the mixed use area location

Table 13: Rainfall and Runoff for Background Sites

	Wooded, FFW		Grassy, FFG		Mixed Use, FF02	
Date	P (in.)	P_e (in.)	P (in.)	P_e (in.)	P (in.)	P_e (in.)
10/2/2012	0.42	0.145	0.52	0.035	0.42	0.11
10/29/2012	0.57	0.099	0.51	0.037	0.57	0.17
11/7/2012	0.15	0.255	0.27	0.102	0.15	0.05
1/31/2013	1.81	0.032	1.88	0.176	1.81	0.95
3/25/2013	0.43	0.142	0.48	0.043	0.43	0.11
6/27/2013	0.62	0.085	0.6	0.021	0.62	0.19
10/7/2013	0.63	0.083	0.7	0.009	0.63	0.20
10/10/2013	0.41	0.148	0.53	0.033	0.41	0.11
3/29/2014	0.86	0.036	2.84	0.586	0.86	0.31
4/15/2014	0.62	0.085	2.13	0.265	0.62	0.19
4/30/2014	4.89	1.237	5.31	2.186	4.89	3.61
6/19/2014	--	--	0.12	0.163	--	--
7/14/2014	0.55	0.104	0.91	0.000	0.55	0.16
8/12/2014	0.88	0.033	1.01	0.003	0.88	0.33
10/8/2014	0.38	0.159	0.36	0.073	0.38	0.10
11/7/2014	0.47	0.128	0.53	0.033	0.47	0.13
11/17/2014	1.00	0.018	1.02	0.003	1.00	0.39
12/2/2014	0.41	0.148	0.47	0.045	0.23	0.06

4.5.4 Rain Garden and Wetland Mass Export

Estimates of pollutant mass export loading for the rain garden were determined for the two years that the rain garden and the green roof were tested simultaneously. Outflow pollutant concentrations were multiplied by the modeled outflow volume for the same testing event. For example, NO_2 export for the storm dated 4/30/2014 was calculated thus:

$$NO_2(g) = O_{modeled}(cf) * \frac{28.3168\ L}{cf} * NO_2\left(\frac{mg}{L}\right) * \frac{1g}{1000\ mg}$$

$$NO_2(g) = 13806\ cf * \frac{28.3168\ L}{cf} * 0.028\ mg/L \quad * \frac{1g}{1000\ mg} = 10.902\ g\ NO_2$$

where $O_{modeled}$ = outflow volume as modeled from the rain garden. Average mass exports per storm were multiplied by the estimated number of times that the rain garden was expected to overflow each year. Rain garden overflow was tested only six times simultaneously with the green roof throughout the duration of the two-year quality testing period, with rain garden volume data available for four of those six events. This number of overflow events was too small to get an accurate estimate of its storm volume retention performance, therefore data was drawn from additional years of overflow monitoring in order to get a more accurate estimate. Overflow volumes for the bioinfiltration rain garden were calculated using the basin model discussed in the Methods section and in Heasom et al. (2006). Based on an observation period of twelve years, the rain garden was expected to overflow 18 times per year on average. Refer to Figure 42 - Figure 43 for mass loads from the rain garden. These are also reported in Figure 75 - Figure 76 of Appendix B.

Due to the limited number of storm events where quality testing of the constructed stormwater wetland overlapped with green roof testing, concentration data used to calculate mass export from the wetland was taken from the pool of discrete samples as well as autosampler-averaged samples. Outflow volumes from the wetland were modeled using EPA SWMM, as described in the Methods section and in Pittman (2011). Outlet average pollutant concentrations were multiplied by the modeled outflow volume for the corresponding testing event. For example, NO_2 export for the storm dated 4/30/2014 was calculated as follows:

$$NO_2\ (kg) = Out_{modeled}(cf) * \frac{28.3168\ L}{cf} * \ NO_2\left(\frac{mg}{L}\right) * \frac{1\ g}{1000\ mg} * \frac{1\ kg}{1000\ g}$$

$$NO_2\ (kg) = 460{,}362\ cf * \frac{28.3168\ L}{cf} * \ 0.047\frac{mg}{L} * \frac{1\ g}{1000\ mg} * \frac{1\ kg}{1000\ g} = 0.606\ kg$$

Annual pollutant loadings could be estimated using average mass loads multiplied by the number of times per year that a rain event would occur and produce stormflow conditions at the wetland outlet. Difficulties were encountered in assigning this frequency estimate, partly in separating rain-induced stormflow conditions from other stormflow conditions not produced by rainfall (i.e. from pavement cleanings by campus maintenance and from snowmelts), and partly due to programming errors from the data-logging systems. Since such a value was not available for the stormwater wetland, an arbitrarily assigned number of 24 rain event-induced occurrences of stormflow conditions annually was used to produce a rough estimate.

A more general calculation for wetland annual mass loads involves multiplying the average concentration by the average depth of rainfall in a year (41.5 inches) over the wetland drainage area which is 41 acres (Wadzuk et al. 2010). Mass loads, as estimated using annual storm volumes for Philadelphia, are reported for the wetland in Figure 40 - Figure 43. These estimates as well as estimates using assigned frequency of stormflow conditions are depicted in Figure 77 - Figure 80 of Appendix B, with values reported in pounds.

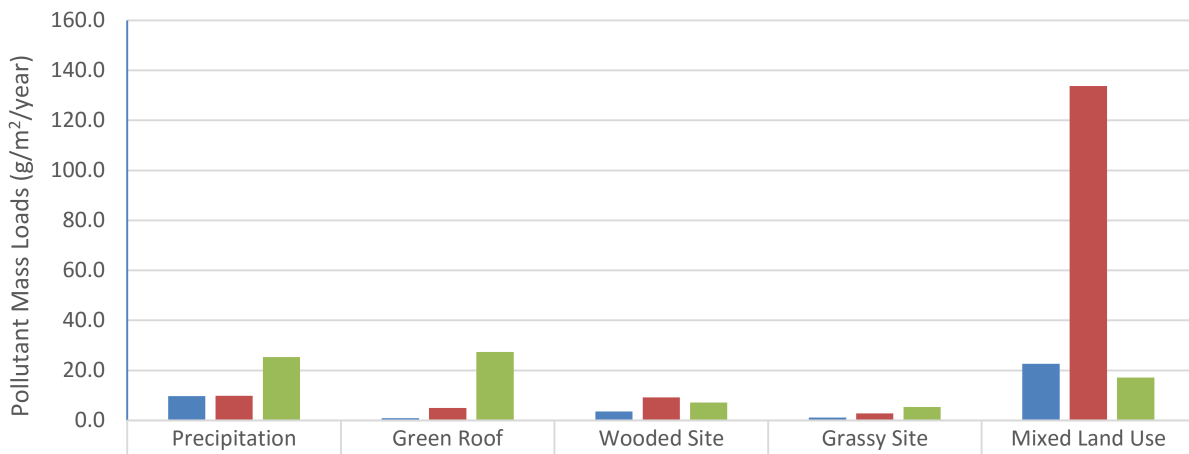
Because the wetland was only evaluated for the quality of stormflows in this study, the wetland's mass loading at its outlet is representative of storm conditions only. It should be kept in mind that water quality during baseflow conditions would also have to be considered in order to have a full assessment of the wetland's performance, but for the scope of this study only storm conditions for all three SCMs were considered. The wetland is in a somewhat different class than the rain garden and green roof, which are both bioretention systems and do not have continuous outflows. Differences in design goals should be kept in mind when comparing the performance of different SCM designs, however many insights may still be drawn from the comparison of treatment versus non-treatment SCMs.

4.5.5 Scaled Mass Estimates

The green roof surface area and the drainage areas for the background sites are differently sized, as are the treatment area ratios for the SCMs (see Table 14). To account for this drainage area scale difference, annual mass export quantities are converted and scaled to g/m^2/year (Figure 50 and Figure 51). Note that the seemingly high quantities reported for precipitation are based on the best estimate of rainfall quality criteria taken from one sample atop the green roof, and for the purposes of this study it was assumed that rainfall quality was more or less consistent for the various other sampling sites. The goal of green infrastructure is to increase the storage potential in a watershed closer to that of pre-development conditions, and in this case the wooded site is the closest indicator of what that goal may look like for a suburban watershed. From a land-use management perspective, the case can also be made for the preservation and management of green spaces within urban and suburban watersheds for the stormwater quality and volume control that they may provide.

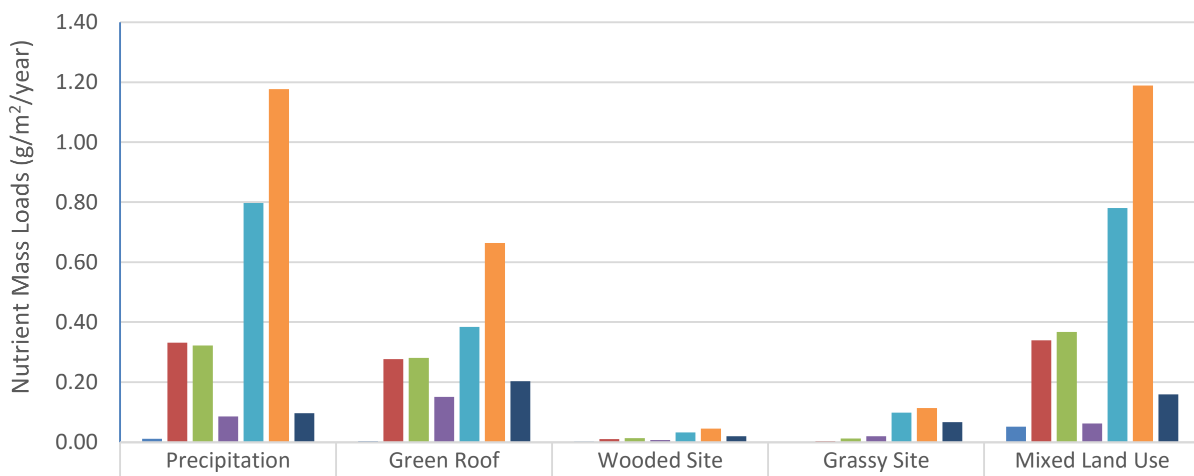
Table 14: Land use drainage areas

Land Use	**Drainage Area (ft^2)**	**Drainage Area (m^2)**	**Ratio of DA to treatment area**
Green roof	575	53.42	1:1
Wooded area	817	75.90	N/A
Grassy area	2,632	244.5	N/A
Mixed-use area	44,398 (1.02 acres)	4,125	N/A
Rain garden	44,398	4,125	10:1
Wetland*	42 acres	165,921	50:1



	Precipitation	Green Roof	Wooded Site	Grassy Site	Mixed Land Use
Cl-	9.677	0.879	3.626	1.120	22.620
TSS	9.897	4.955	9.233	2.815	133.731
TDS	25.313	27.320	7.177	5.382	17.133

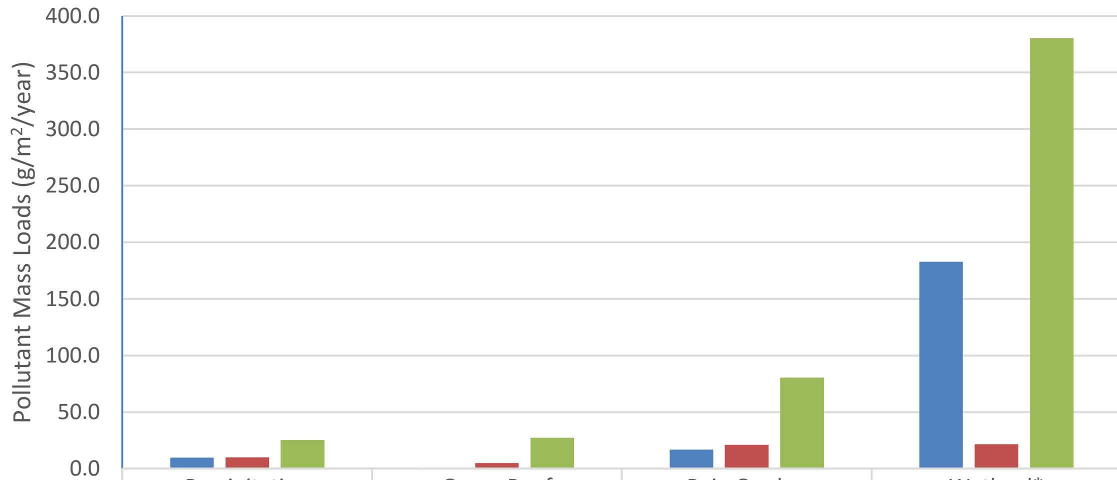
Figure 50: Scaled pollutant loads for Land Use Comparison I



	Precipitation	Green Roof	Wooded Site	Grassy Site	Mixed Land Use
NO2	0.012	0.004	0.003	0.002	0.052
NO3	0.333	0.277	0.011	0.004	0.339
NOx	0.322	0.281	0.013	0.012	0.367
PO4	0.086	0.152	0.007	0.020	0.063
TKN	0.798	0.385	0.032	0.099	0.781
TN	1.177	0.665	0.045	0.114	1.189
TKP	0.097	0.203	0.020	0.067	0.160

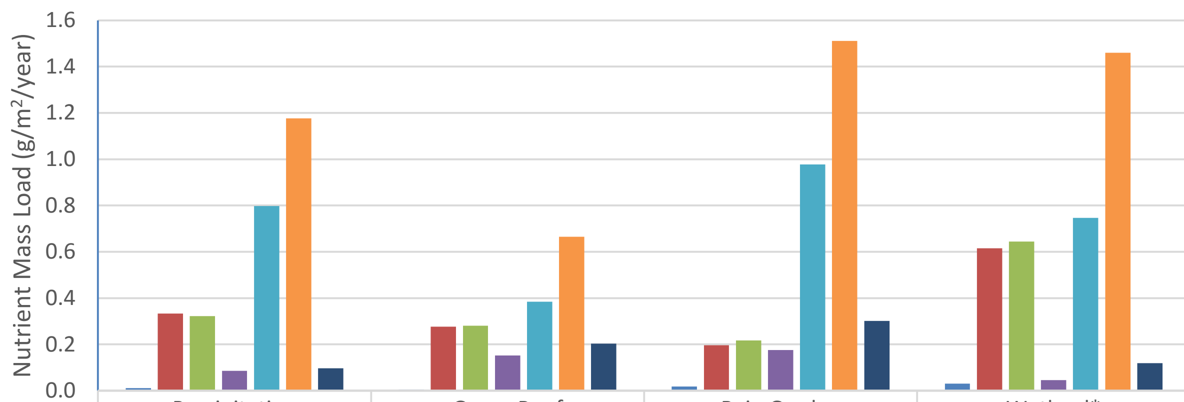
Figure 51: Scaled nutrient loads for Land Use Comparison I

Mass pollutant and nutrient retention for SCMs is dependent on the size of the drainage area, soil type and vegetation cover, percent of impervious cover, amount of site disturbance and adjacent land usage. The scales of the drainage areas for the SCMs included in this study vary widely, from the 575 square foot green roof drainage area with 1:1 ratio of SCM coverage to drainage area, to the 42-acre drainage area of the wetland which at 0.78 acres itself represents only a 1:54 ratio of SCM area to drainage area (Rinker 2013). Annual export quantities are reported in Figure 52 and Figure 53; they have been converted and scaled to grams per square meter.



	Precipitation	Green Roof	Rain Garden	Wetland*
Cl-	9.677	0.879	16.767	182.648
TSS	9.897	4.955	21.100	21.561
TDS	25.313	27.320	80.349	380.385

Figure 52: Pollutant mass loads for Land Use Comparison II



	Precipitation	Green Roof	Rain Garden	Wetland*
NO2	0.012	0.004	0.018	0.030
NO3	0.333	0.277	0.196	0.615
NOx	0.322	0.281	0.218	0.645
PO4	0.086	0.152	0.176	0.046
TKN	0.798	0.385	0.978	0.747
TN	1.177	0.665	1.511	1.460
TKP	0.097	0.203	0.301	0.120

Figure 53: Nutrient mass loads for Land Use Comparison II

It would appear that the green roof exports more nutrients per square meter on an annual basis than a wooded lot or grassy lawn. While it would be wise to keep in mind both the potential for considerable error associated with a mass estimate, and the inaccuracy of curve numbers in estimating storage potential for various land uses, still these results can indicate a lot about the value of preserved green space for stormwater pollution control in urbanized areas. Examining mass estimates for differing SCMs reveals the dependency of SCM performance on drainage are characteristics: SCMs which treat larger drainage areas will inevitably export more nutrients in the long run. From a mass perspective, the green roof has the advantage of having a 1:1 SCM surface area to drainage area ratio, therefore it is only producing nutrients associated with system components. The wetland and rain garden, on the other hand, have drainage areas that are much larger than their own surface area, and those drainage areas contribute considerably more non-point source pollution conveyed by runoff. From a concentration-based perspective, the wetland and rain garden really stand out for good performance because their effluent concentrations are more dilute than the green roof. It is the concentration value that has the greatest ecological impact: biological organisms exhibit physiological stress and even higher death rates as a result of higher pollutant concentrations.

In rain gardens, nutrients such as phosphate as well as metals can sorb to the soil particles as stormwater infiltrates through the media layers. Due to their temporary ponding capability, rain gardens are also very useful for capturing suspended solids and allowing them to settle out of solution. Stormwater wetlands are very useful for nutrient uptake by plants, settling of solids, treatment via biological nitrogen fixation, and geophysical phosphorus sorption (Vacca and Wadzuk 2012, Wadzuk et al. 2010). However, extensive green roof soil media is too porous and shallow to allow nutrients to sorb to particle surfaces (noted in the literature). While their design does not lend to hydraulic retention, extensive green roof media has considerable storage potential. If the plants are healthy and well-established, they will utilize available nutrients for growth. Input of suspended solids is not a typical concern when the only input comes from precipitation, and with appropriately selected geotextiles in the drainage layer, export of suspended solids may be held in check. However, the gravity-driven system is not known for biological nitrogen treatment.

5.0 Additional Discussion and Further Research

This research was the result of the work of several students over the course of the study period, including Burlotos (2013) and Brown (2014). There is potential to learn more about the impact of green roofs on surface water quality through improvements of the sampling process and data analysis. The remainder of this chapter discusses some of the additional factors which impact the quality of sampling and mass load estimates during the study. Recommendations for improvements are made; suggestions for stronger data analysis are discussed; and avenues for future research are explained.

5.1 Analysis of the First Flush Volume

For all storm events, there is an antecedent dry period during which pollutants such as dust and other airborne particles are allowed to build up on a surface. Once rainfall begins, runoff from a drainage area will be generated once the storage potential of that area has been maxed out. In many cases, the pollutant concentrations will be highest in runoff in the beginning, meaning the majority of the pollutant mass will be washed away by a small volume of runoff, relative to the total storm runoff produced for that event (Lee et al. 2002). This phenomenon is called the first flush, and may also be expressed as a percentage ratio of mass to storm volume, or M/V. However, the volume associated with the first flush varies depending on drainage area size as well as characteristics such as slope, storage potential, and soil type; duration of time for antecedent buildup; antecedent soil moisture; and even the type of pollutant in question (Bertrand-Krajewski et al. 1998).

This is reflected in literature where a wide range of M/V ratios are reported for sizing the first flush. The unifying characteristic for these ratios is that the percentage pollutant mass washed off at time *t* is equal to or greater than the percentage runoff volume that has removed that buildup in the same amount of time. For municipal sewer systems, ratios of 80/74 for separate sewers and 80/79 for combined sewers have been characterized, with applications for the design of treatment facilities (Bertrand-Krajewski et al. 1998). However, treating a much smaller percentage of pollutant mass may be practical depending on the first flush characteristic of the drainage area being treated. Indeed, a first flush ratio as low as 20/20 was observed for small asphalt drainage areas (Deletic 1998). For green infrastructure design purposes, it is common for the first flush to be associated with a certain rainfall depth, which facilitates proper SCM design in order to capture and treat the majority of pollutants from a drainage area.

First flush effects are particularly evident for sloped roofs with no stormwater control where the M/V ratio becomes highly efficient as it requires little runoff to wash away the initial pollutant buildup (Doyle 2008). However, for the Villanova green roof it is possible that the first flush effects may be dampened because the roof is quite flat, and has drainage layers, soil media and vegetation. The autosampler system is programmed to collect a first flush and an event mean concentration which are differentiated by the volumetric flow rate as monitored by the tipping bucket. The flow volume used to trigger the collection of the first flush is based on a cumulative rainfall depth of 0.25 inches, or after 2000 mLs have passed through the tipping bucket. This volume is assumed to contain the highest concentration of pollutants flushed off the green roof once the soil media reaches field capacity. The M/V ratio of the Villanova green roof was unknown when the sampling equipment was installed. Now with three years of recorded overflow monitoring, sufficient data exists to determine this ratio and verify whether a first flush exists or not.

It is predicted that the M/V ratio will be rather low, due to the green roof's peak flow mitigation and retention performance. Research recently concluded on the Villanova green roof stormwater retention performance indicates that the green roof can retain up to the first 0.8 inches of rain on average, before overflow is produced (Zaremba et al. 2016). This would indicate that the 0.25 inch threshold, which the autosampling program is based on, is an underestimate of the system performance. Going back to the mass estimates for GR OUT 1 and GR OUT 2, it may be possible to determine the M/V ratio of the current system by evaluating the volume data. The percentage of total overflow that the first flush represents for each storm may thus be determined; concentrations may be used to calculate the mass export for each storm event. This would produce several storm M/V ratios, from which a statistical average or median M/V ratio may be taken. This would provide a better characterization of the difference between the first flush sample and the event mean concentration sample than the statistical comparison in section 4.5.2 which discusses green roof mass export.

5.2 Correlation Tests and Confidence Intervals for Mass Loads

The mass load estimates presented in Results and Discussion were constructed based on the assumption that no correlation exists between sample concentration and rainfall volume for any given sampling event. More specifically, it was assumed that neither an increase nor decrease in the concentration would be observed based on the depth of rainfall recorded. This assumption was made because the data were too sporadic to determine if concentrations for any of the parameters followed a normal distribution. As such, it was also assumed that heavier rainfall events (such as the 4/30/2014 event with a cumulative rainfall depth of 5.21 inches measured at the green roof) would not weight the volume-based mass estimates, despite the likelihood that heavier rainfall events would produce very large outflow volumes. If any dilution effects on the sampled concentrations did occur for increasingly larger storms, that would signify a correlation between concentration and event size, however the data counts in many cases were too low (i.e. n=4 for the rain garden EMC) to indicate evidence of a normal or non-normal distribution.

The implications of the type of data distribution could affect study results, especially for the task of estimating annual mass exports from the SCMs and other study sites. Estimates based on average concentration were made for the green roof, background sites, rain garden, and wetland. It is possible that the averages that were taken may have been skewed by a particularly high reading which, had a larger data set been achievable, might actually be discarded as an outlier. Also, small data counts for SCM overflow require more careful consideration because the storm events that may be sampled are already filtered based on rainfall depth. That is, it is much easier to obtain samples for storms with 2.0 cm (0.8 inches) of cumulative rainfall than 0.64 cm (0.25 inches). Furthermore, annual mass load estimates for the green roof had to be extrapolated based on data that did not represent a full annual storm count, because not every storm that produced a substantial amount of overflow could be sampled for water quality due to laboratory testing workloads, human resources, and availability of equipment.

It may be possible to test event size and sample concentrations for evidence of correlation, and an attempt is made in this section. There are different ways of doing this, the simplest method being a correlation test in Excel. An example is given here for PO_4 at the green roof and at the various other sampling locations (Figure 54 – Figure 61). Orthophosphate is a laboratory test with a lower EasyChem success rate, therefore the data counts may be quite low which make it even more challenging to make assumptions about the data distribution. Correlation coefficients as calculated in Excel are included in the graph headings to indicate the degree of influence of one variable on the other. Rainfall in inches is plotted on the horizontal axis and PO_4 concentration (mg/L) on the vertical. A quick visual inspection of the trend lines will suggest that as rainfall volume increases, concentration tends to decrease, however the observed correlations are not very strong in most cases ($R^2 > 0.5$). The correlation model for the wetland event mean concentration (compiled from autosampler averages and discrete sampling) was the only sample category that had a positive value, indicating that a better model is needed to evaluate all other sampling locations.

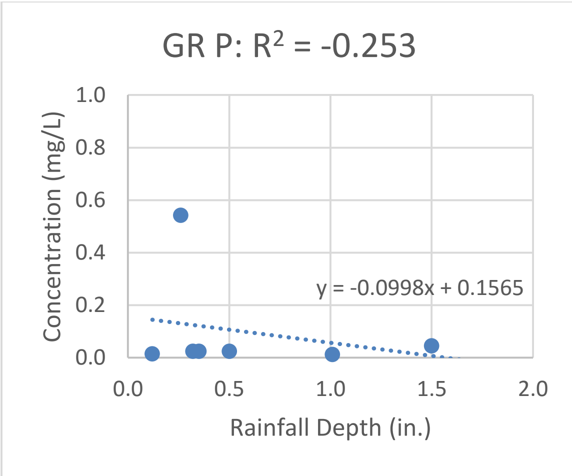


Figure 54: Correlation of GR P to rainfall depth for PO_4

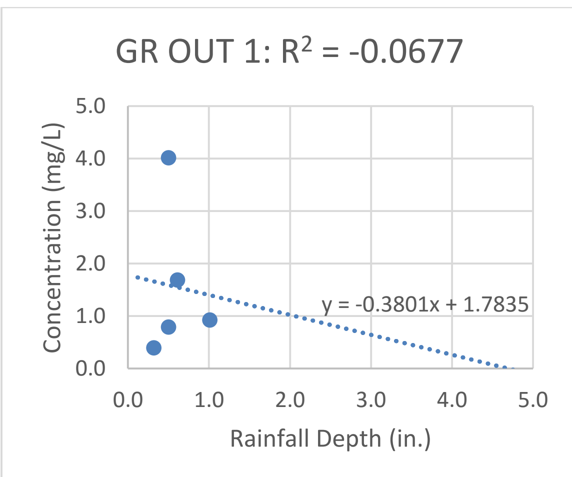


Figure 55: Correlation of GR OUT 1 to rainfall depth for PO_4

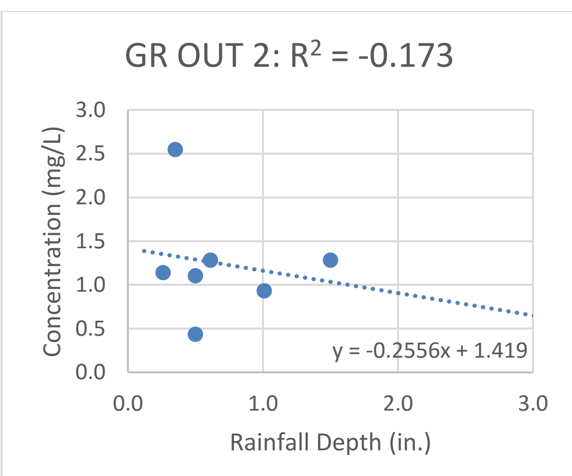


Figure 56: Correlation of GR OUT 2 to rainfall depth for PO_4

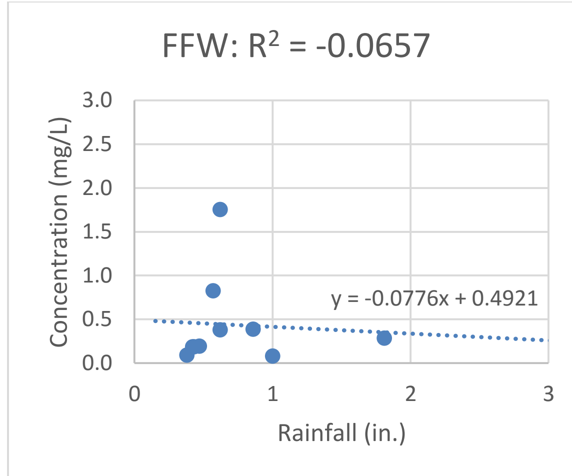


Figure 57: Correlation of FFW to rainfall depth for PO_4

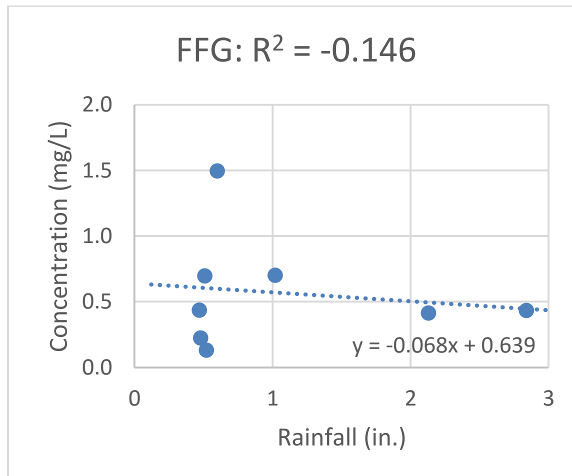


Figure 58: Correlation of FFG to rainfall depth for PO_4

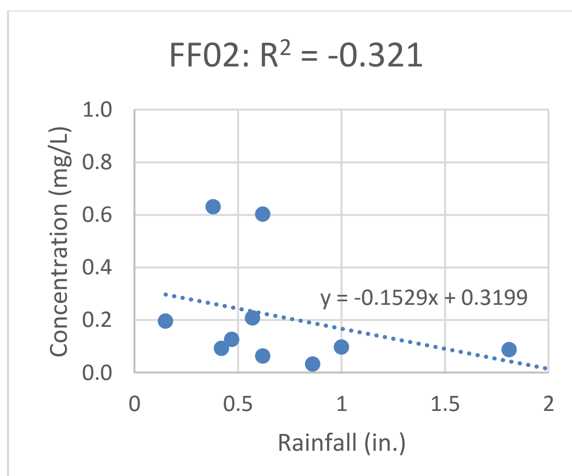


Figure 59: Correlation of FF02 to rainfall depth for PO_4

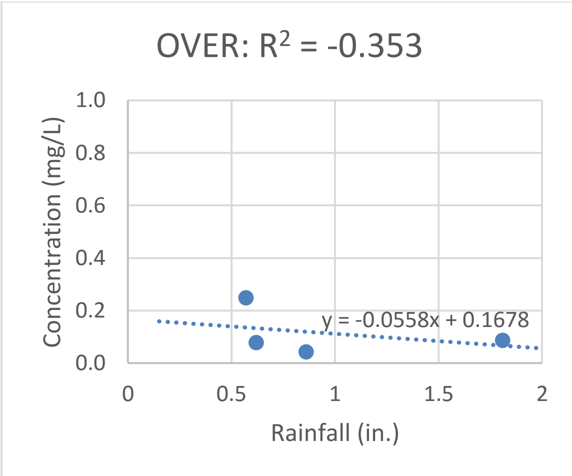


Figure 60: Correlation of OVER to rainfall depth for PO_4

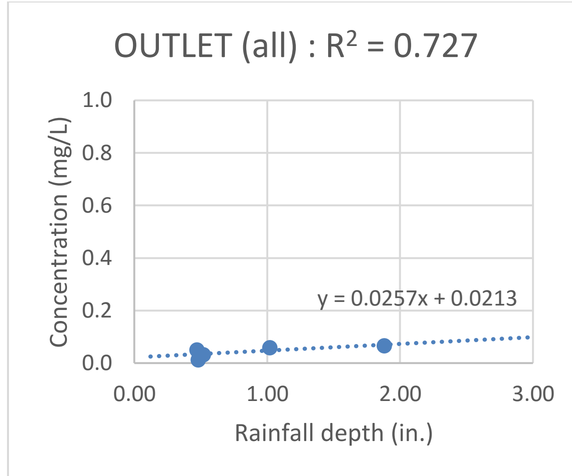


Figure 61: Correlation of all wetland sample data to rainfall depth for PO_4

Considering the number of pollutants that the green roof is tested for, as well as the number of samples from other vegetated sites and SCMs which the green roof can be compared to, the process of testing for correlation in Excel can become very laborious: there are as many as 13 water quality parameters which are currently tested for in the laboratory, and the location sampling for this study is based on at least a dozen different laboratory samples. Software packages for statistical analysis such as MiniTab or SPSS are recommended; alternatively a program may be written for efficient replication of the correlation tests, such as can be generated in MATLAB.

If no correlation can be found, or if no evidence for correlation can be found, annual mass loads for volume-monitored sites including the green roof, rain garden, and wetland, may be estimated more efficiently using the average pollutant concentration and the average annual overflow volume, predicted using recorded cumulative rainfall measurements for a year multiplied over the drainage area. It is also possible to use the summation of recorded overflow volumes over a year for each SCM. Note that due to missing data, annual rainfall amounts or overflow volumes may need to be adjusted to account for missing data. Annual mass loads for sites that cannot be monitored for runoff volume, such as FFW, FFG, and FF02 must be calculated using volumes calculated using the curve number method. Rainfall analysis must be used to determine an expected annual wash-off volume which can be multiplied by an averaged pollutant concentration for each site.

For this study, it was necessary to assume normal data distributions with no correlation because of good percent captures for the SCMs, and also due to EasyChem test failures and equipment malfunctions. The lack of rain garden data speaks very well for the rain garden's performance in terms of both volume control and mass loading, despite associated challenges in mass load analysis. A more complete picture of rain garden and wetland sample correlation to rainfall could potentially be achieved by widening the number of wetland sampling events, however further analysis should be reserved for another study concerned chiefly on the wetland.

Given the inclusion of rain garden overflow data from only four storms between late 2012 and the end of 2014, it is virtually impossible to get a reasonable estimate of annual overflow volumes. This low data count can be partly attributed to the reconstruction of the outflow weir for the rain garden in early 2014, which greatly improved the retention capability of the system and reduced the frequency of overflows. Such system improvements are the goal of green infrastructure design.

A similar set of challenges exists for the wetland, with low data counts for some pollutants and a lower frequency of storm tests that were included in the study. Estimating the annual outflow volume involves the added challenge of separating storm flow from baseflow. In reality, storm flow conditions may occur due to a variety of other factors including snowmelts and parking surface cleaning. For the sake of fairer comparison to the green roof and rain garden, this study focused solely on storm events; a more complete picture of wetland mass loads for all flow conditions is described in Wadzuk et al. (2010). Mass loads for storm events may be better estimated by more in-depth analysis of wetland flow conditions.

Due to the various sources of error which may affect a mass load estimate, it is recommended that confidence intervals be developed for the mass loads. This will better quantify the differences observed between the sites. Using estimates generated from expected overflow or outflow volumes and from expected average concentrations, confidence intervals for mass load estimates should be constructed for each pollutant at each vegetated site and for each SCM. When constructing these confidence intervals it is suggested that the data not be assumed to follow a normal distribution due to the low data counts for many of the sampling sites. Instead, quantification of the differences may be approached using non-parametric methods. Data simulations may be run based off the data that are available, to increase the data count for construction of appropriate confidence intervals. Again, statistical software packages such as MiniTab may be very useful to generate confidence intervals.

It is possible that the confidence intervals for each site's pollutant mass load may overlap, which may make difficult to determine the precise difference in performance between sites. It is likely that little to no overlap may be observed for some comparisons, such as green roof mass loads versus mixed use area mass loads, or wooded site mass loads versus precipitation input. However, overlap could occur for other comparisons, such as the green roof mass load versus grassy area or wooded area mass loads, as predicted by their concentration comparisons and estimated mass load comparisons described in the Results and Discussion section.

5.3 Redesign of Green Roof Sampling

The green roof sampling process is currently complicated by the fact that samples must be extracted from a small container within the High Sierra tipping bucket housing (see the sketch in Figure 81). The sample container from which the sample is drawn should ideally be cleaned and acid-washed between sampling events. However, the current configuration requires disconnecting the tipping bucket in order to reach inside the housing to clean the container, or risk unnecessary noise in the overflow data. In addition, there is potential for algal growth inside the sample container which may spike nutrient data.

Firstly, baseline sampling of the overflow pipe and sampling equipment is recommended to provide a better understanding of the effects that the overflow pipe interior and sample feed lines have on the sample quality. Baseline testing is conducted by trickling distilled water directly down the overflow pipe without allowing it to pass through the soil media. A gallon of distilled water, trickled at a rate slow enough to be registered by the tipping bucket, is sufficient to allow the tipping bucket to trigger the autosampler to collect the first flush (GR OUT 1), based on 2015 programming. A baseline test conducted on the system before cleaning/acidwashing the sample cup yielded the following results:

Table 15: Results of green roof baseline sampling test from November 2015

Nutrient Parameter	**NO_2 (mg/L)**	**NO_x (mg/L)**	**TKN (mg/L)**	**TKP (mg/L)**	**PO_4 (mg/L)**
Concentration	0.029	N/A	7.672	N/A	0.433
Detection Limit	0.011	N/A	N/A	N/A	0.030
Quality Parameter	**Cl- (mg/L)**	**TSS (mg/L)**	**TDS (mg/L)**	**pH**	**Cond. (µS/cm)**
Concentration	8.35	22.7	6.7	6.52	87.8
Detection Limit	2.200	2.0	6.0	--	--

These initial results may have been heavily impacted by site disturbance due to the installation of the new irrigation system; by seasonal timing of the baseline test when vegetation was beginning to die off; and by recent emptying of the Opti-controlled cistern via the overflow pipe. Additional baseline tests are recommended to get a more complete picture of the impact of the overflow pipelines and feed tubing.

The overflow lines should be considered as part of the entire green roof system when accounting for water quality contribution to surface water pollution. However, it is not necessary or advisable that algae be allowed to grow in the sampling equipment for obvious reasons. Some suggestions for improving the sampling process are outlined as follows. The sample may be drawn instead from a removable 400 to 500 ml container which can be attached to the overflow pipe below the tipping bucket and before the weir box. By cutting the horizontal pipe section, a t-section may be fitted which would allow for the connection of a sample container below; the sample container may be made of PVC pipe and have two spigots at the bottom which would allow for the attachment of the feed tubes for GR OUT 1 and GR OUT 2. The proposed location for the new sampling container is shown in Figure 82. Ideally, the sample container could be removed between sampling events and acid-washed (replaced by a seal for the t-section when not in use). A conceptual sketch of the new apparatus is provided in Figure 83.

In addition, with the installation of the Opti control system for smart programming of grey roof stormwater distribution in the fall of 2015, the green roof autosampler can no longer be regulated by the GR rain gage. Instead, the coding has been redesigned to allow for regulation of the Autosampler by the CEER roof rain gage. The necessary .CR1 file with new programming for the Campbell Scientific data logger to recognize the CEER rain gage as the autosampler regulator may be found at the following location on the WREE drive (Figure 62).

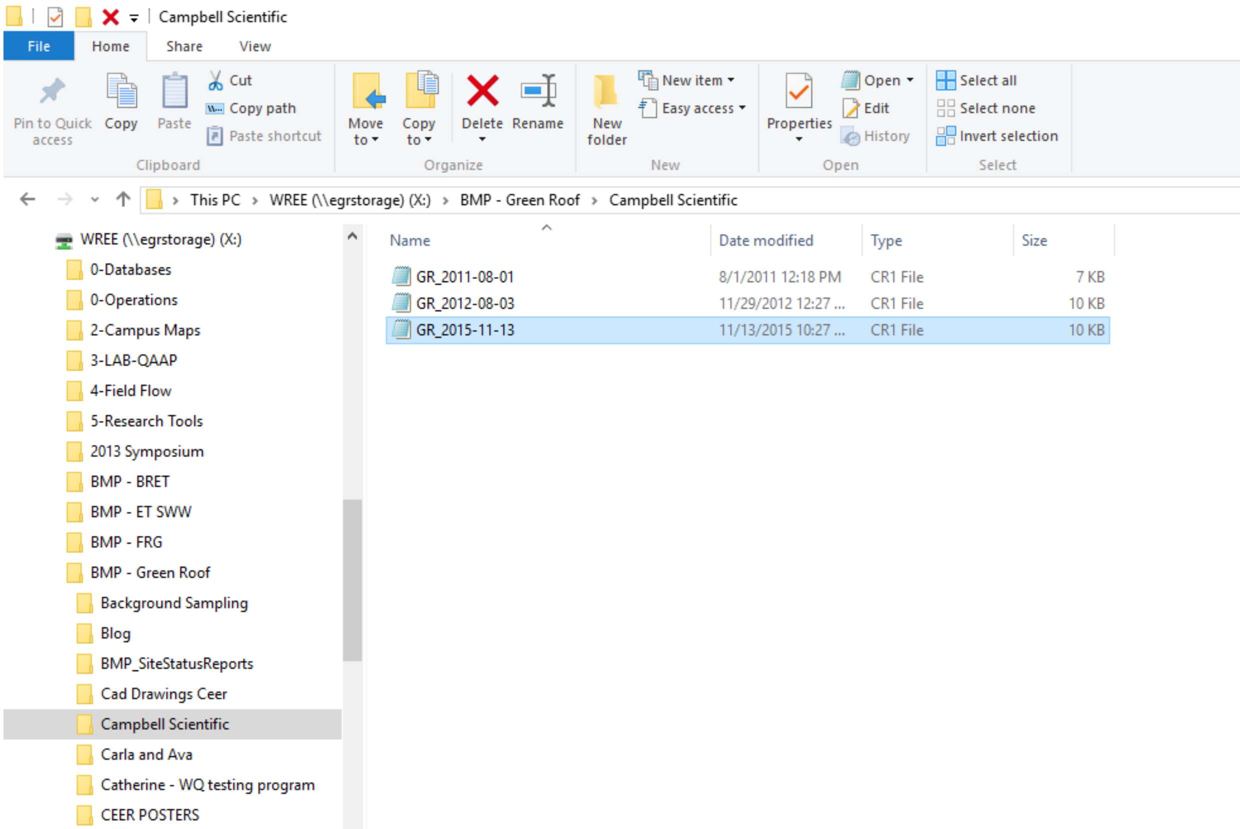


Figure 62: <WREE\BMP - Green Roof\Campbell Scientific\GR_2015-11-13.CR1>

5.4 Acid Rainfall Mitigation

Neutralization of acid rainfall in densely urban areas is a benefit which is sometimes attributed to green roofs (Berndtsson et al. 2009). The green roof has been tested for pH, as well as conductivity (data available in the green roof quality database on the WREE drive). However, these data have not been extensively analyzed, being outside the scope of the current study. Paired t-tests may be used, however it may be necessary to log-transform the data first since normal distribution of the data can at best be only assumed. Among the factors affecting pH values are temperatures, for which some data has been documented and is available through the Water Resources Laboratory.

5.5 Nutrients in Soil Media

As with any biological system, conditions in the green roof soil are constantly being changed by organisms and weather conditions. More informed administering of fertilizers may help balance plant health with runoff quality (Clark and Zheng 2013). A simple procedure was established to characterize nutrient content in the media. Experimental soil testing was begun in the summer of 2015 using a simple RapiTest soil test kit with digital test meter. The RapiTest kit can be used to test for total nitrogen, total phosphorus, and total potassium, as well as soil pH, and it is recommended that the soil be tested prior to considering fertilizer applications. In addition, soil testing may help augment overflow quality testing by providing context for nutrient buildup, storage in the media, and plant uptake. The instructions for green roof soil testing, information on the RapiTest kit, and preliminary data files are available on the WREE drive.

6.0 Conclusions and Recommendations

Sustainable stormwater management for urbanized areas involves innovate strategies to reduce stormwater runoff volumes and the associated pollution caused by stormwater. By managing stormwater volume from impervious rooftops, extensive green roofs have become an established green infrastructure option because they have been shown to provide hydrological benefits for stormwater management (Wadzuk et al. 2013, Carson et al. 2013, Fassman-Beck et al. 2013, Berghage et al. 2009). While German *Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau* (FLL) Guidelines for the Planning, Execution and Upkeep of Green-Roof Sites do not account for stormwater quality treatment, findings from the present study suggest that when properly designed, green roofs can limit their own potential contribution to downstream stormwater pollution by virtue of their volume reduction. Green roofs that effectively retain rooftop runoff can limit both nutrient and pollutant mass loadings, although overall pollutant retention behavior is dependent on additional factors such as the ratio of organics in the substrate, materials used for waterproofing and drainage, the age of the system, and atmospheric pollutant deposition. Due to the inconsistent source versus sink behavior of these living systems, green roof design guidelines must take water quality into account by achieving a nutrient balance based on minimum requirements for plant growth.

The Villanova green roof generally was not a source for nitrogen, however it was a source for phosphorus. The green roof was fertilized during the testing period and the vegetation was well-established. In comparison to other vegetated urban land uses, it performed similarly or slightly better, depending on the particular water quality parameter being evaluated. When compared to other stormwater control measures, it became clear that the green roof could not be counted on for water quality treatment as an added benefit, which was reasonable considering the shallowness of the green roof media; the rain garden and constructed stormwater wetland are effective for overall nutrient removal. Comparisons of effluent quality to EPA recommended criteria showed that nutrient concentrations from the green roof are higher than recommended for healthy waterways.

Limiting fertilizer applications may be an obvious solution in situations where green roofs are exporting large quantities of nutrient mass. Green roofs that have not been fertilized do not export large quantities of nutrients. Fertilizer should only be applied where it is necessary for plant growth to achieve reasonable evapotranspiration rates, and in ratios which balance plant health with the minimum required quantity. Instead, other soil amendments, such as biochar, may promote plant growth while reducing nutrient export quantities. Beck et al. (2011) found that an addition of seven percent biochar to sedum-planted roofs resulted in a 20% reduction of phosphorus export. Alternatively, the effluent for the green roof could be treated or amended in some way prior to discharge into surface waters.

Treatment of the excess runoff prior to its leaving an overflow pipe or storm drain is not always practical due to design constraints for the roofing system. However, there are various other options for treatment. Where there exists opportunities for additional stormwater management, green roofs should be implemented as part of a series of stormwater control measures. Green roof overflow can be directed to SCMs designed for stormwater treatment, such as rain gardens, vegetative swales, and stormwater wetlands. Where such space is not available, effluent may be collected in rain barrels for distribution in garden plots or planter boxes, thus repurposing the nutrient-rich wash-off. Green roofs are a more popular green infrastructure option in densely urbanized areas, as are planter boxes, pervious pavements, and tree trenches, all of which can serve as a sink for green roof nutrient export. Green roof effluent may also be repurposed for grey water uses such as landscape irrigation and toilet flushing (Beecham and Razzaghmanesh 2015).

Improving the green roof's runoff storage potential can also limit the amount of wash-off for nutrients and other contaminants. In the fall of 2015, the Villanova green roof's overflow system will be upgraded to increase the volume of runoff that may be retained from a previous 0.8 inches to approximately 1.05 inches, thus reducing the overflow event frequency and thereby reducing overall nutrient mass export. Soil amendments such as biochar not only help green roofs retain nutrients but actually increase the green roof's runoff retention (Beck et al. 2011). Studies have also suggested that plant selection plays a role in the ability of the green roof to retain and store nutrients (Beecham and Razzaghmanesh 2015). Depending on their nutrient requirements, some species may be more effective at removing phosphorus and nitrogen from the growing media, however further investigation is needed to qualify the effects of plant selection on green roof nutrient cycling.

From a broad perspective these findings also support the incorporation of green space into urban planning and land use. Natural woodlands, meadows, and well-established lawns offer similar advantages to green infrastructure through runoff reduction, erosion management, and retention of nutrients, total dissolved solids, and total suspended solids. Where even more space is available, preserving or creating more naturalized patches can help municipalities to maintain the health of their associated watersheds. Of course in more densely urbanized areas, the efficient sizing of stormwater control measures makes them a much more practical solution, however comparisons of engineered SCMs and pre-existing green spaces suggest similar benefits for urban watersheds.

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Appendix

A: Descriptive Statistics

Summary and descriptive statistics which were used to construct the graphs for Land Use Comparisons I and II are reported in the tables below.

Land Use Comparison I: Comparing Vegetated Land Uses

Table 16: Summary Statistics for Nitrites

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	16	12	15	13	11	15
Mean	0.014	0.042	0.026	0.172	0.114	0.059
Standard deviation	0.008	0.047	0.043	0.104	0.153	0.054
Standard error*	0.002	0.014	0.011	0.029	0.046	0.014

Table 17: Graphing Constituents for Nitrites

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Lower Detection	0.010	0.010	0.010	0.010	0.010	0.010
Minimum	0.005	0.005	0.005	0.018	0.018	0.005
Q1	0.010	0.010	0.010	0.090	0.035	0.023
Median	0.010	0.016	0.014	0.157	0.044	0.045
Q3	0.013	0.058	0.019	0.240	0.071	0.077
Maximum	0.033	0.157	0.184	0.367	0.514	0.220

Table 18: Summary Statistics for Nitrates

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	13	11	14	11	10	13
Mean	0.316	2.156	1.098	0.439	0.320	0.383
Standard deviation	0.197	1.994	1.585	0.579	0.377	0.259
Standard error*	0.055	0.601	0.424	0.174	0.119	0.072

Table 19: Graphing Constituents for Nitrates

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Lower Detection	0.050	0.050	0.050	0.050	0.050	0.050
Minimum	0.062	0.228	0.110	0.025	0.025	0.025
Q1	0.186	0.714	0.253	0.086	0.063	0.188
Median	0.252	1.078	0.564	0.194	0.130	0.304
Q3	0.383	3.605	1.085	0.470	0.468	0.546
Maximum	0.810	6.317	6.372	1.972	1.325	0.872

Table 20: Summary Statistics for Nitrites plus Nitrates

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	14	11	14	12	11	14
Mean	0.309	2.185	1.123	0.533	0.340	0.424
Standard deviation	0.201	2.025	1.629	0.585	0.374	0.293
Standard error*	0.054	0.610	0.435	0.169	0.113	0.078

Table 21: Graphing Constituents for Nitrites plus Nitrates

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Lower Detection	0.050	0.050	0.050	0.050	0.050	0.050
Minimum	0.067	0.233	0.115	0.089	0.025	0.095
Q1	0.186	0.719	0.258	0.182	0.103	0.146
Median	0.248	1.095	0.580	0.299	0.147	0.315
Q3	0.386	3.632	1.096	0.533	0.498	0.694
Maximum	0.823	6.410	6.557	2.129	1.369	0.991

Table 22: Summary Statistics for Total Kjeldahl Nitrogen

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	11	8	12	10	9	12
Mean	0.771	2.010	1.717	4.070	1.380	0.935
Standard deviation	0.891	1.054	0.680	7.800	1.602	0.613
Standard error*	0.269	0.373	0.196	2.467	0.534	0.177

Table 23: Graphing Constituents for Total Kjeldahl Nitrogen

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Lower Detection	0.100	0.100	0.100	0.100	0.100	0.100
Minimum	0.244	0.050	0.651	0.345	0.261	0.197
Q1	0.349	1.266	1.032	0.912	0.552	0.321
Median	0.532	2.395	1.701	1.793	0.717	0.871
Q3	0.685	2.871	2.350	2.322	1.268	1.309
Maximum	3.528	3.201	2.793	8.000	5.710	2.049

Table 24: Summary Statistics for Total Nitrogen

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	10	8	11	9	9	11
Mean	1.117	3.486	2.581	4.701	1.728	1.435
Standard deviation	0.941	1.329	0.786	8.168	1.527	0.898
Standard error*	0.298	0.470	0.237	2.723	0.509	0.271

Table 25: Graphing Constituents for Total Nitrogen

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Minimum	0.311	0.980	1.156	0.435	0.732	0.346
Q1	0.596	2.730	2.065	0.836	0.842	0.487
Median	0.850	3.972	2.703	2.314	1.118	1.470
Q3	1.220	4.455	2.852	2.827	1.697	2.301
Maximum	3.720	4.951	4.089	8.000	5.857	2.815

Table 26: Summary Statistics for Phosphates

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	9	7	11	11	8	11
Mean	0.096	1.380	1.292	0.431	0.566	0.209
Standard deviation	0.158	1.132	0.543	0.462	0.397	0.199
Standard error*	0.053	0.428	0.164	0.139	0.141	0.060

Table 27: Graphing Constituents for Phosphates

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Lower Detection	0.030	0.030	0.030	0.030	0.030	0.030
Minimum	0.012	0.393	0.436	0.080	0.131	0.034
Q1	0.030	0.806	1.018	0.186	0.367	0.091
Median	0.050	0.923	1.281	0.284	0.434	0.127
Q3	0.050	1.362	1.542	0.384	0.697	0.203
Maximum	0.542	4.009	2.548	1.753	1.496	0.632

Table 28: Summary Statistics for Total Kjeldahl Phosphorus

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	14	11	13	12	10	14
Mean	0.115	1.544	1.260	1.063	1.725	0.257
Standard deviation	0.189	1.730	0.510	1.602	2.574	0.260
Standard error*	0.050	0.522	0.141	0.463	0.814	0.070

Table 29: Graphing Constituents for Total Kjeldahl Phosphorus

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Lower Detection	0.050	0.050	0.050	0.050	0.050	0.050
Minimum	0.025	0.387	0.513	0.100	0.355	0.053
Q1	0.050	0.698	0.804	0.332	0.496	0.107
Median	0.050	1.020	1.355	0.430	1.017	0.181
Q3	0.088	1.308	1.638	0.840	1.370	0.214
Maximum	0.790	6.822	2.064	6.091	9.350	0.952

Table 30: Summary Statistics for Chlorides

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	15	11	14	13	11	14
Mean	9.480	20.919	10.094	193.054	28.776	16.158
Standard deviation	6.126	26.875	8.919	403.223	33.225	18.587
Standard error*	1.582	8.103	2.384	111.834	10.018	4.968

Table 31: Graphing Constituents for Chlorides

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Lower Detection	2.000	2.000	2.000	2.000	2.000	2.000
Minimum	1.000	1.000	1.000	1.000	1.000	1.000
Q1	5.062	2.386	3.100	6.721	5.253	2.708
Median	8.402	5.111	6.618	21.807	20.763	6.945
Q3	12.582	26.875	12.043	51.337	33.403	25.237
Maximum	22.033	75.622	28.591	1395.210	121.324	68.786

Table 32: Summary Statistics for Total Suspended Solids

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	16	11	13	13	12	15
Mean	9.889	22.231	8.462	581.858	109.227	134.383
Standard deviation	10.536	17.119	8.680	776.871	140.366	226.292
Standard error*	2.634	5.162	2.407	215.465	40.520	58.428

Table 33: Graphing Constituents for Total Suspended Solids

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Lower Detection	2.000	2.000	2.000	2.000	2.000	2.000
Minimum	1.000	3.333	1.000	23.000	11.333	1.000
Q1	2.000	6.333	3.000	126.000	26.000	22.833
Median	3.722	19.333	3.000	244.000	35.833	50.286
Q3	14.333	31.000	12.000	442.667	106.167	117.500
Maximum	36.667	58.000	27.333	2443.333	443.056	913.300

Table 34: Summary Statistics for Total Dissolved Solids

Summary Statistic	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
N	12	11	14	11	12	14
Mean	25.847	137.378	157.929	279.196	127.833	53.464
Standard deviation	30.312	55.199	88.692	469.466	106.153	34.590
Standard error*	8.750	16.643	23.703	141.549	30.643	9.244

Table 35: Graphing Constituents for Total Dissolved Solids

Graph Constituent	Precipitation (GR P)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)	Wooded (FFW)	Grassy (FFG)	Mixed Use (FF02)
Lower Detection	6.000	6.000	6.000	6.000	6.000	6.000
Minimum	3.000	28.667	77.333	43.000	32.667	10.000
Q1	6.000	97.667	100.083	85.000	59.583	33.036
Median	10.000	140.000	120.333	142.000	76.000	53.800
Q3	29.000	171.077	185.000	189.067	144.500	64.643
Maximum	90.833	230.000	425.333	1750.000	376.000	150.357

Land Use Comparison II: Comparing Stormwater Control Measures

Table 36: Summary Statistics for Nitrites

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	6	3	8	12	15
Mean	0.023	0.025	0.029	0.042	0.026
Standard deviation	0.00657	0.01731	0.01296	0.04683	0.04271
Standard error*	0.00268	0.00999	0.00458	0.01352	0.01103

Table 37: Graphing Constituents for Nitrites

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	0.010	0.010	0.010	0.010	0.010
Minimum	0.011	0.005	0.005	0.005	0.005
Q1	0.019	0.013	0.018	0.010	0.010
Median	0.024	0.015	0.029	0.016	0.014
Q3	0.028	0.032	0.039	0.058	0.019
Maximum	0.030	0.049	0.047	0.157	0.184

Table 38: Summary Statistics for Nitrates

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	5	3	6	11	14
Mean	0.143	0.663	0.584	2.156	1.098
Standard deviation	0.04748	0.22929	0.26576	1.99393	1.58485
Standard error*	0.02123	0.13238	0.10850	0.60119	0.42357

Table 39: Graphing Constituents for Nitrates

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	---	---	---	---	---
Minimum	0.076	0.372	0.145	0.228	0.110
Q1	0.108	0.528	0.448	0.714	0.253
Median	0.146	0.683	0.576	1.078	0.564
Q3	0.179	0.808	0.783	3.605	1.085
Maximum	0.207	0.932	0.949	6.317	6.372

Table 40: Summary Statistics for Nitrites plus Nitrates

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	5	3	6	11	14
Mean	0.163	0.686	0.612	2.185	1.123
Standard deviation	0.05090	0.24696	0.27611	2.02459	1.62860
Standard error*	0.02276	0.14258	0.11272	0.61044	0.43526

Table 41: Graphing Constituents for Nitrites plus Nitrates

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	0.050	0.050	0.050	0.050	0.050
Minimum	0.087	0.377	0.150	0.233	0.115
Q1	0.138	0.538	0.484	0.719	0.258
Median	0.156	0.699	0.596	1.095	0.580
Q3	0.198	0.840	0.813	3.632	1.096
Maximum	0.235	0.981	0.995	6.410	6.557

Table 42: Summary Statistics for Total Kjeldahl Nitrogen

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	5	3	6	8	12
Mean	0.843	0.427	0.709	2.010	1.717
Standard deviation	0.86079	0.14993	0.29031	1.05401	0.67991
Standard error*	0.38496	0.08656	0.11852	0.37265	0.19627

Table 43: Graphing Constituents for Total Kjeldahl Nitrogen

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	0.100	0.100	0.100	0.100	0.100
Minimum	0.200	0.279	0.335	0.050	0.651
Q1	0.294	0.324	0.473	1.266	1.032
Median	0.384	0.369	0.762	2.395	1.701
Q3	0.827	0.501	0.802	2.871	2.350
Maximum	2.510	0.633	1.201	3.201	2.793

Table 44: Summary Statistics for Total Nitrogen

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	4	3	5	8	11
Mean	1.186	1.113	1.385	3.486	2.581
Standard deviation	0.87111	0.36688	0.48484	1.32923	0.78607
Standard error*	0.43556	0.21182	0.21683	0.46995	0.23701

Table 45: Graphing Constituents for Total Nitrogen

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	---	---	---	---	---
Minimum	0.529	0.746	0.779	0.980	1.156
Q1	0.569	0.862	1.086	2.730	2.065
Median	0.774	0.978	1.264	3.972	2.703
Q3	1.390	1.296	1.598	4.455	2.852
Maximum	2.666	1.614	2.197	4.951	4.089

Table 46: Summary Statistics for Orthophosphate

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	4	2	5	7	11
Mean	0.114	0.041	0.044	1.380	1.292
Standard deviation	0.07909	0.00879	0.01925	1.13167	0.54262
Standard error*	0.03955	0.00622	0.00861	0.42773	0.16361

Table 47: Graphing Constituents for Orthophosphate

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	0.030	0.030	0.030	0.030	0.030
Minimum	0.043	0.032	0.013	0.393	0.436
Q1	0.069	0.037	0.032	0.806	1.018
Median	0.082	0.041	0.050	0.923	1.281
Q3	0.127	0.046	0.059	1.362	1.542
Maximum	0.248	0.050	0.066	4.009	2.548

Table 48: Summary Statistics for Total (Kjeldahl) Phosphorus

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	5	3	7	11	13
Mean	0.189	0.070	0.113	1.544	1.260
Standard deviation	0.15006	0.02758	0.04028	1.73026	0.50975
Standard error*	0.06711	0.01592	0.01522	0.52169	0.14138

Table 49: Graphing Constituents for Total (Kjeldahl) Phosphorus

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	0.050	0.050	0.050	0.050	0.050
Minimum	0.065	0.025	0.025	0.387	0.513
Q1	0.091	0.051	0.081	0.698	0.804
Median	0.138	0.051	0.130	1.020	1.355
Q3	0.169	0.080	0.150	1.308	1.638
Maximum	0.480	0.109	0.152	6.822	2.064

Table 50: Summary Statistics for Chlorides

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	5	3	8	11	14
Mean	23.752	215.194	173.274	20.919	10.094
Standard deviation	22.75245	60.39662	194.25846	26.87515	8.91929
Standard error*	10.17521	34.87000	68.68074	8.10316	2.38378

Table 51: Graphing Constituents for Chlorides

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	2.000	2.000	2.000	2.000	2.000
Minimum	4.408	170.856	3.029	1.000	1.000
Q1	13.185	172.498	76.027	2.386	3.100
Median	15.235	174.140	131.945	5.111	6.618
Q3	17.553	237.364	157.171	26.875	12.043
Maximum	68.379	300.587	666.654	75.622	28.591

Table 52: Summary Statistics for Total Suspended Solids

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	6	3	8	11	13
Mean	20.856	6.667	20.454	22.231	8.462
Standard deviation	14.85063	3.29983	13.64036	17.11920	8.68001
Standard error*	6.06275	1.90516	4.82259	5.16163	2.40740

Table 53: Graphing Constituents for Total Suspended Solids

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	2.000	2.000	2.000	2.000	2.000
Minimum	1.000	1.000	5.500	3.333	1.000
Q1	6.750	5.500	10.667	6.333	3.000
Median	21.900	9.000	16.067	19.333	3.000
Q3	34.950	9.000	25.750	31.000	12.000
Maximum	38.333	9.000	49.667	58.000	27.333

Table 54: Summary Statistics for Total Dissolved Solids

Summary Statistic	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
N	5	3	8	11	14
Mean	59.102	437.278	360.863	137.378	157.929
Standard deviation	56.74396	82.06189	285.81894	55.19989	88.69210
Standard error*	25.37667	47.37846	101.05225	16.64339	23.70396

Table 55: Graphing Constituents for Total Dissolved Solids

Graph Constituent	Rain Garden Overflow (OVER)	Stormwater Wetland First Flush (AS-OUTLET 1)	SWW Outlet (OUTLET samples)	Green Roof First Flush (GR OUT 1)	GR Overflow (GR OUT 2)
Lower Detection	6.000	6.000	6.000	6.000	6.000
Minimum	26.300	340.333	147.167	28.667	77.333
Q1	27.143	385.417	201.833	97.667	100.083
Median	29.565	430.500	293.917	140.000	120.333
Q3	40.357	485.750	337.258	171.077	185.000
Maximum	172.143	541.000	1094.000	230.000	425.333

B: Mass Estimates for Individual Sites

Mass load estimates for annual precipitation as calculated using two different methods are provided below.

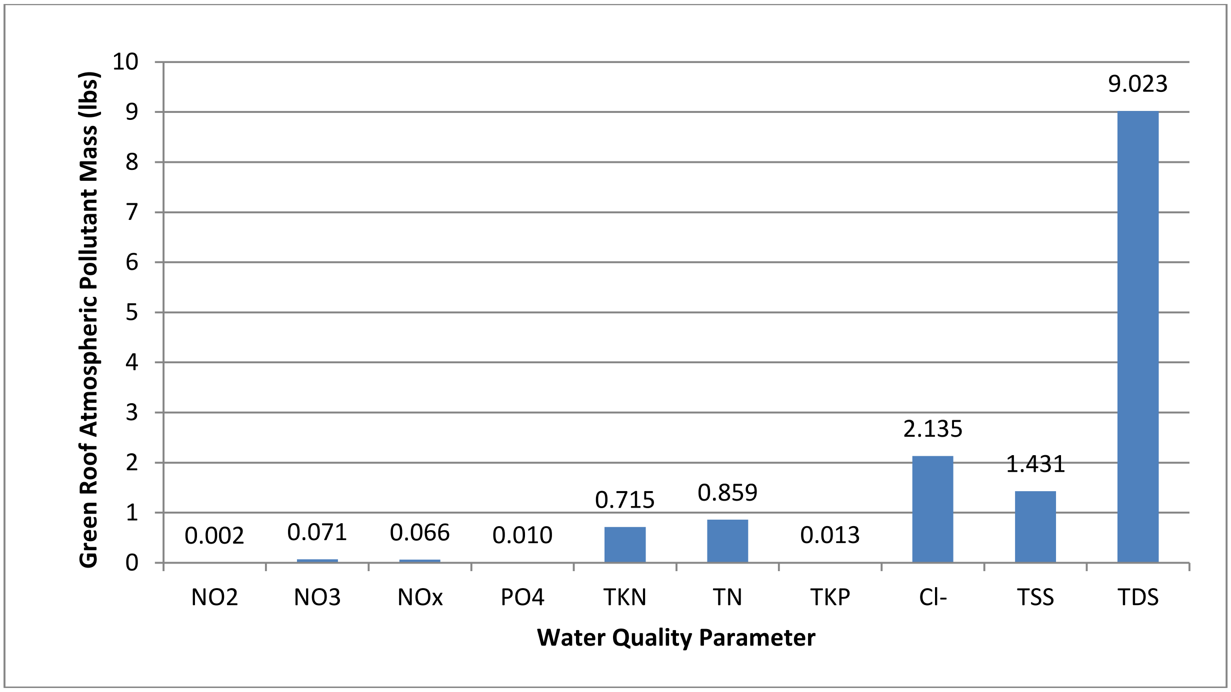

Figure 63: Annual atmospheric deposition of various pollutants for the green roof, calculated using average mass load per storm event multiplied by frequency of rainfall events for Philadelphia.

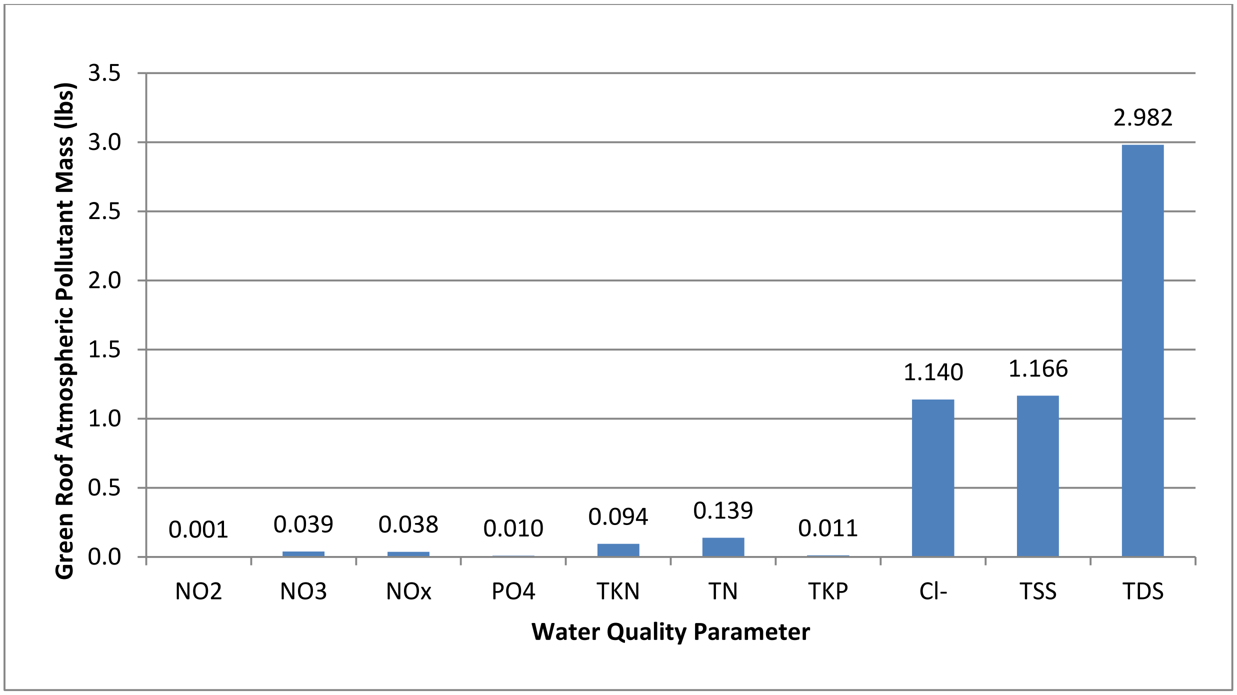

Figure 64: Annual atmospheric deposition of various pollutants for the green roof, calculated using average concentration multiplied by annual rainfall volume for Philadelphia.

Annual Mass load estimates for the green roof using two different calculation methods are provided below.

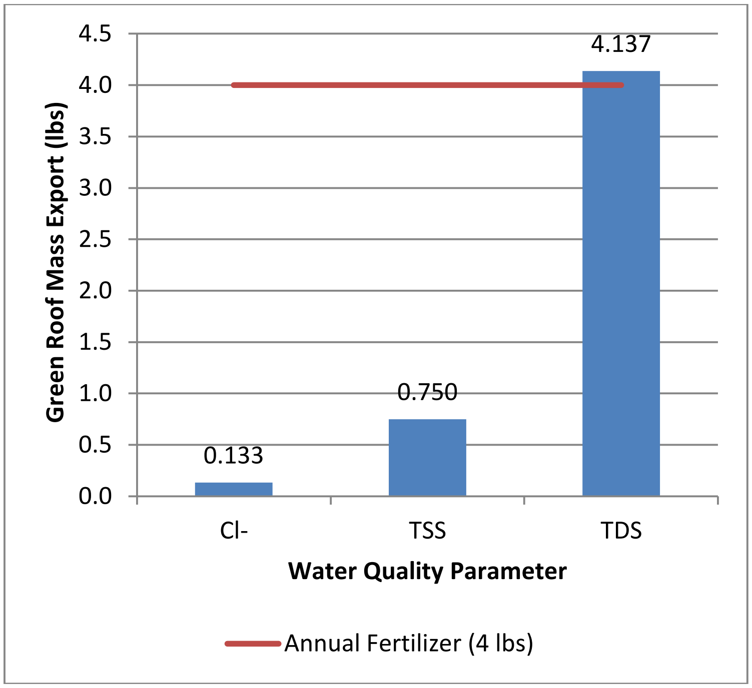

Figure 65: Green roof pollutant mass exports as calculated using estimated overflow frequencies

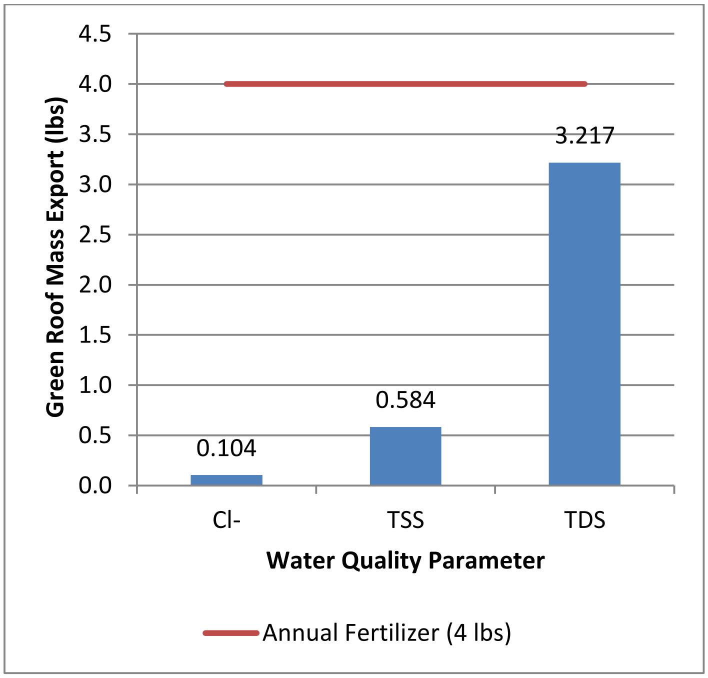

Figure 66: Green roof pollutant mass exports as calculated using measured or observed overflow frequencies

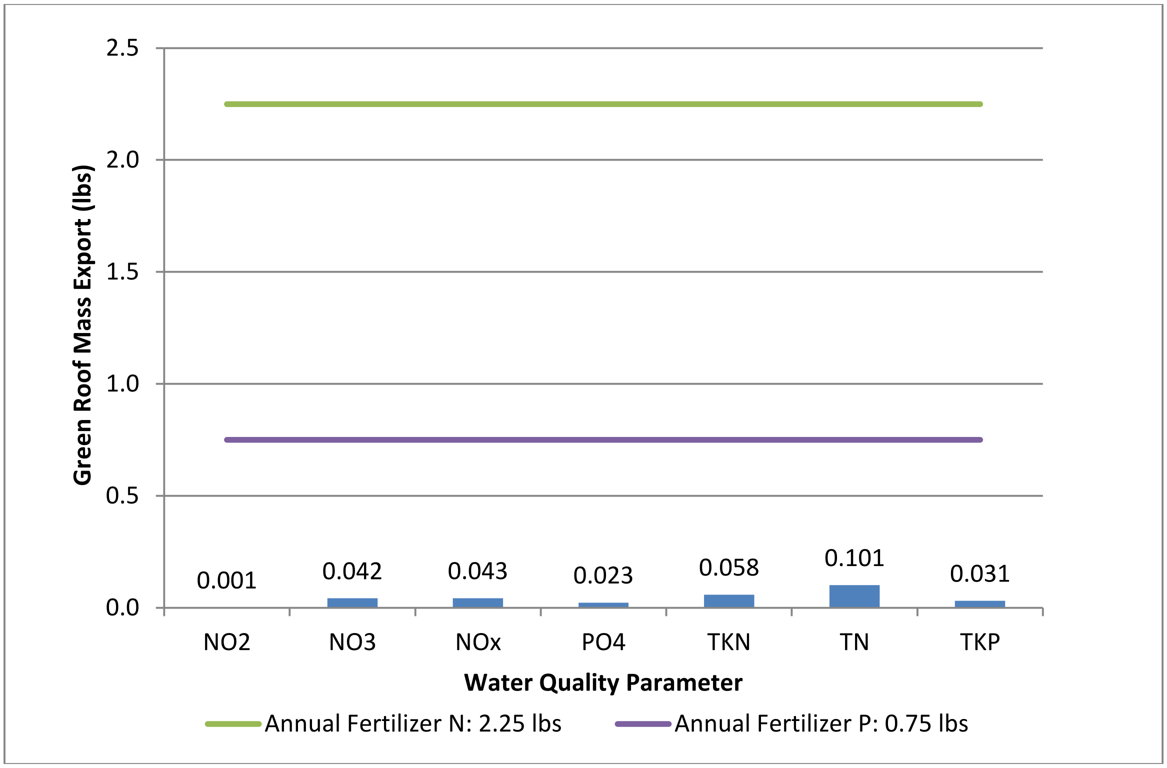

Figure 67: Green roof nutrient mass exports using estimated overflow frequencies

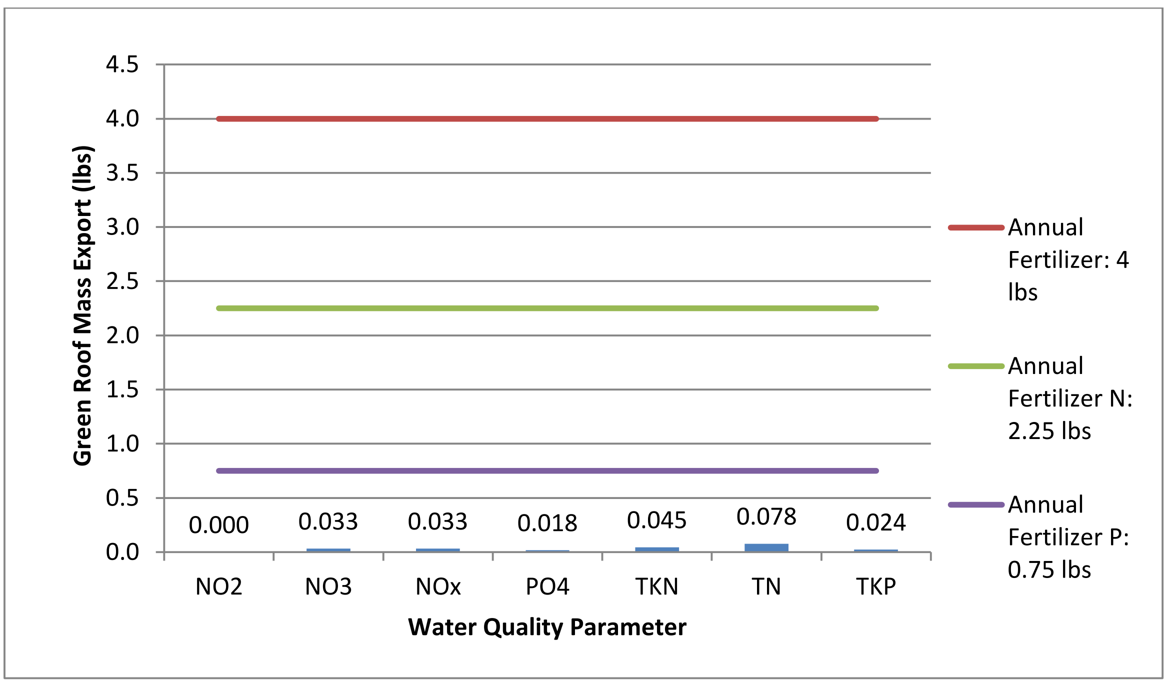

Figure 68: Green roof nutrient mass exports using measured or observed overflow frequencies

Estimated mass loads for vegetated land uses are provided in the following graphs.

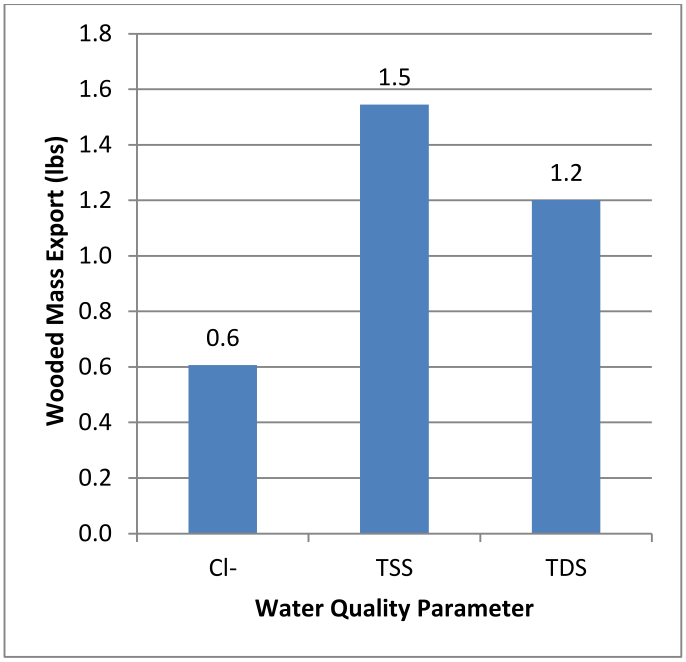

Figure 69: Pollutant wash-off for a first flush from a wooded area

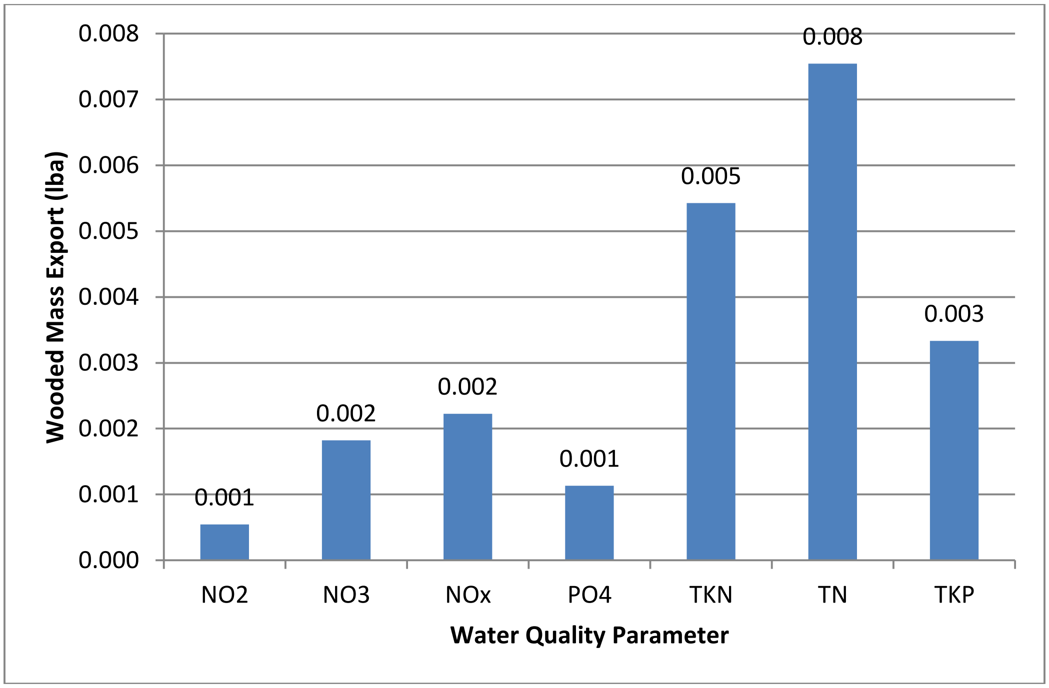

Figure 70: First flush nutrient wash-off from a wooded area

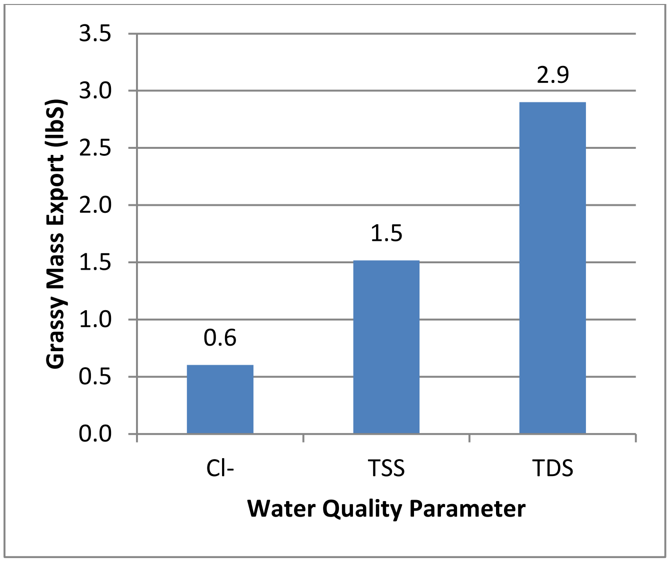

Figure 71: First flush pollutant wash-off from a grassy area

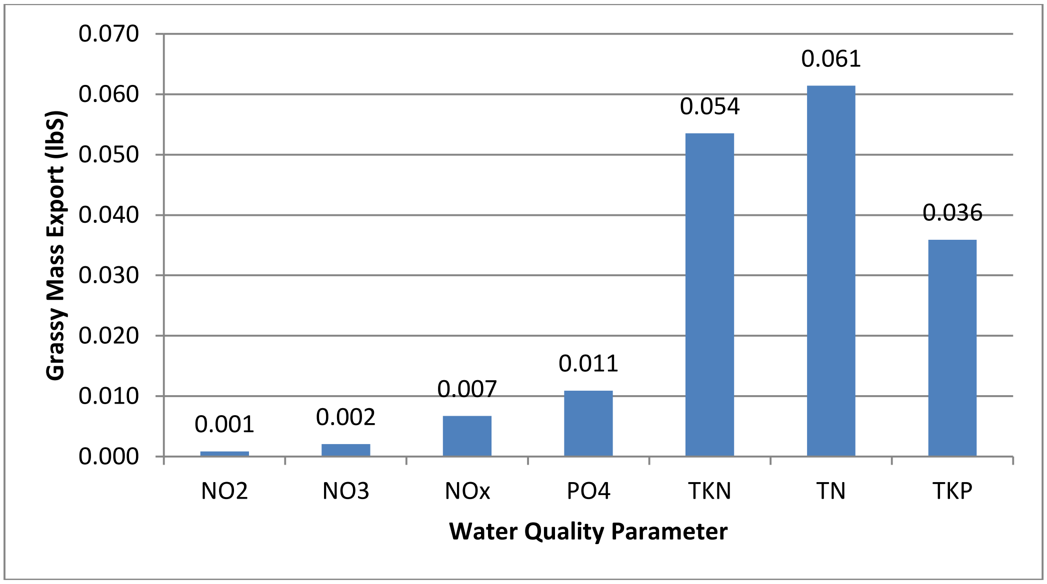

Figure 72: First flush nutrient wash-off from a grassy area

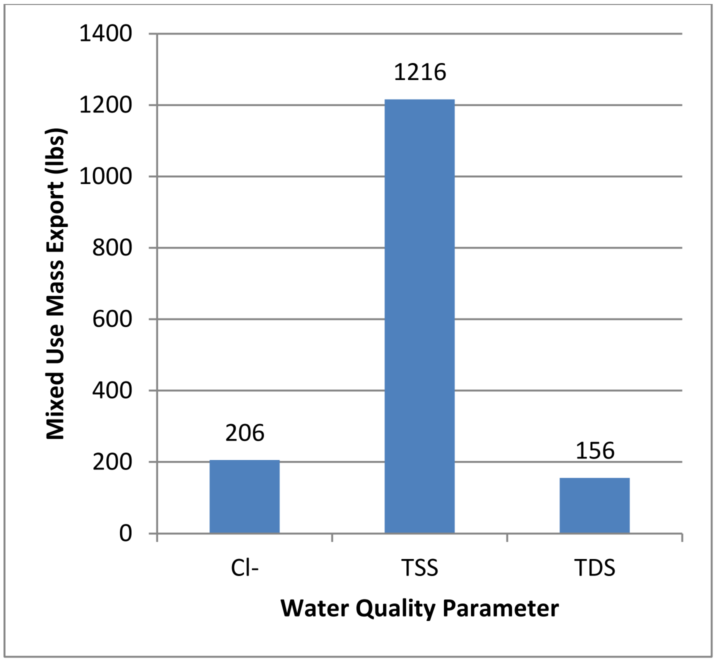

Figure 73: First flush pollutant wash-off from a mixed-use area

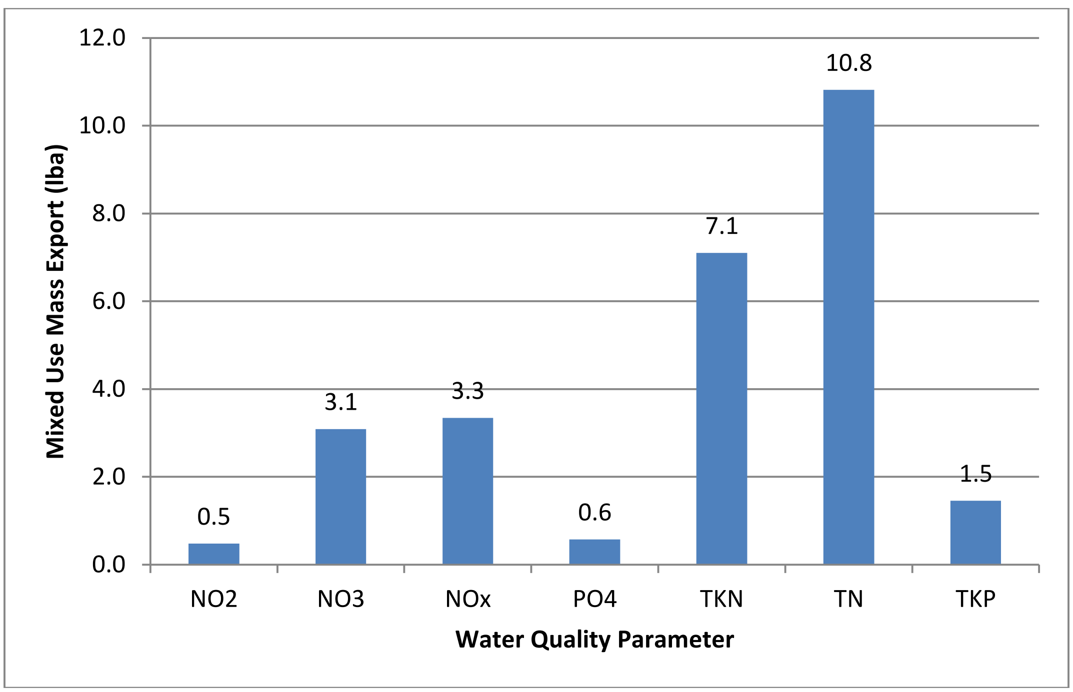

Figure 74: First flush nutrient wash-off from a mixed-use area

Mass loads for the rain garden and wetland are given in the following graphs.

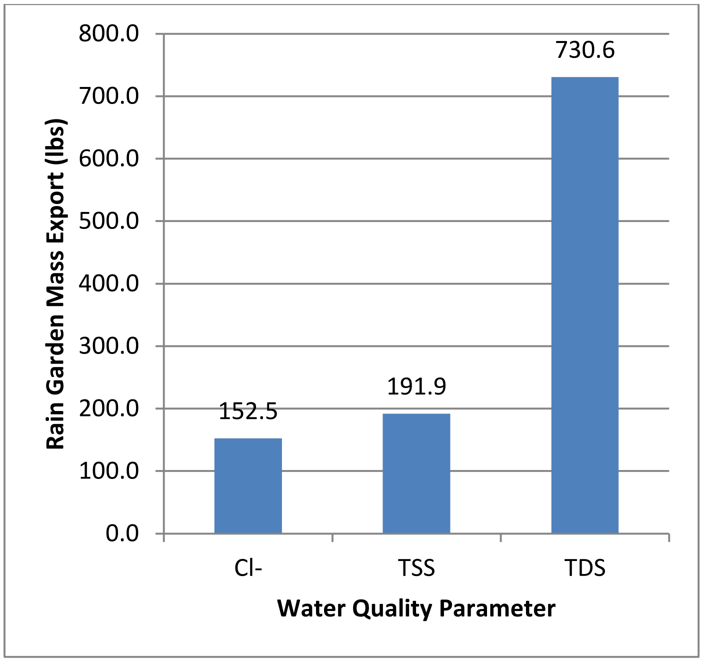

Figure 75: Annual pollutant mass export at the bioinfiltration rain garden

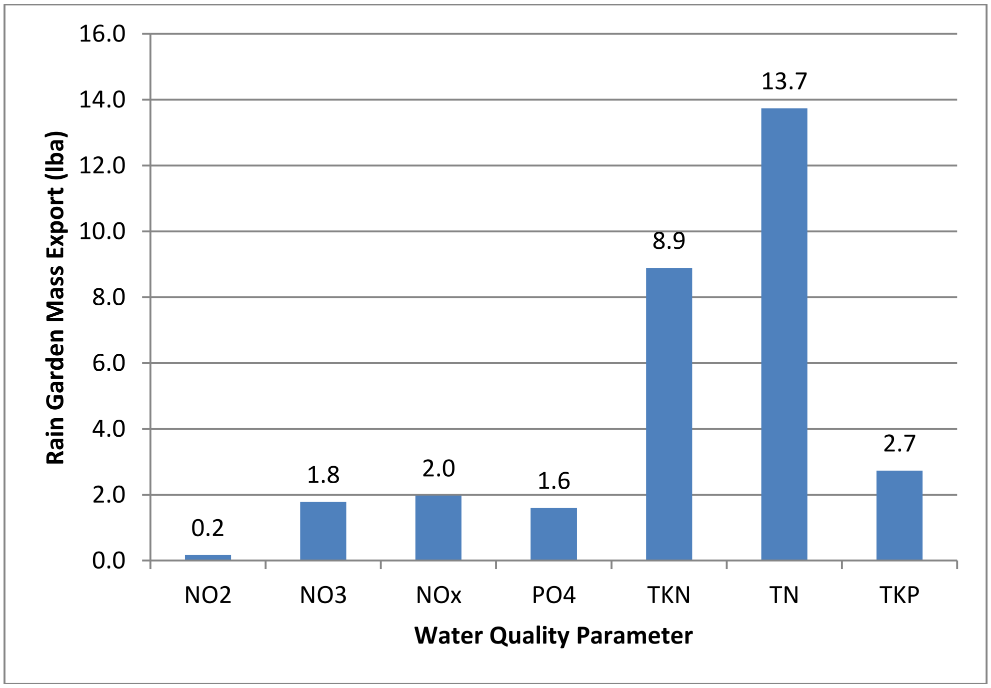

Figure 76: Annual nutrient mass export at the bioinfiltration rain garden

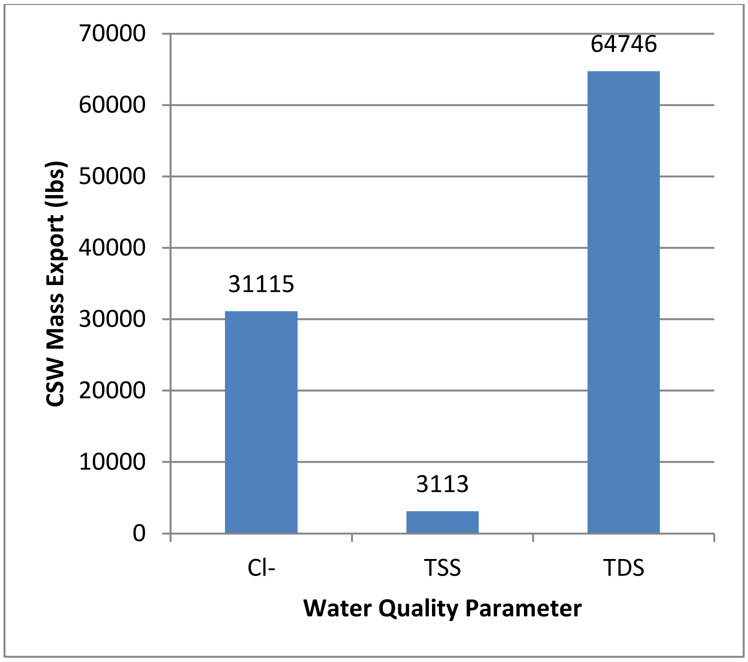

Figure 77: Annual pollutant mass export from the constructed stormwater wetland, as calculated using assigned frequency of stormflow conditions

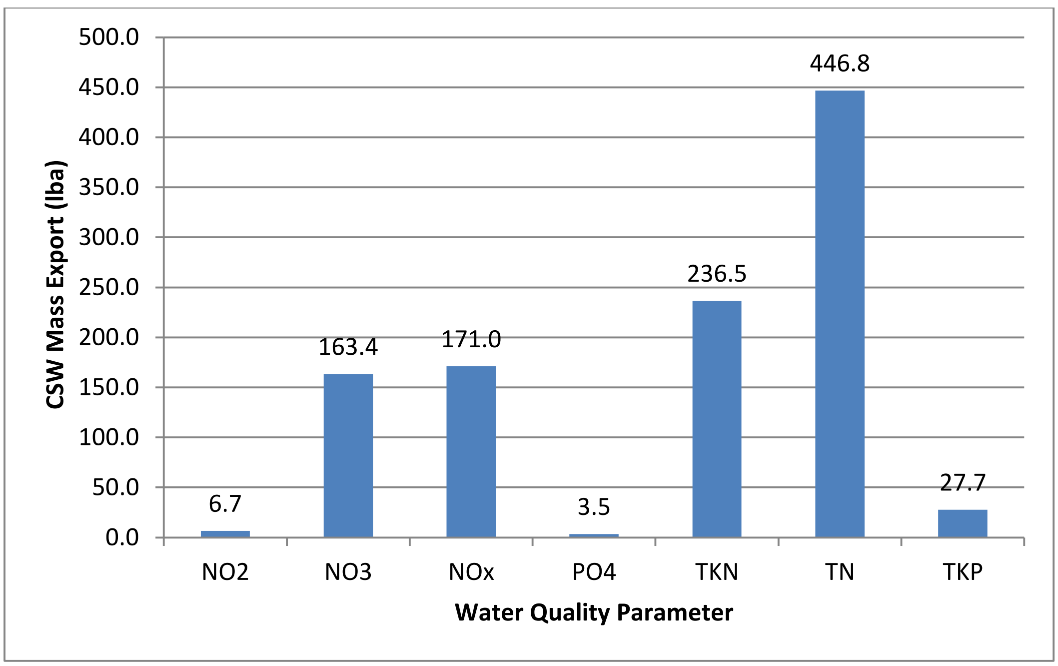

Figure 78: Annual nutrient mass export from the constructed stormwater wetland, as calculated using assigned frequency of stormflow conditions

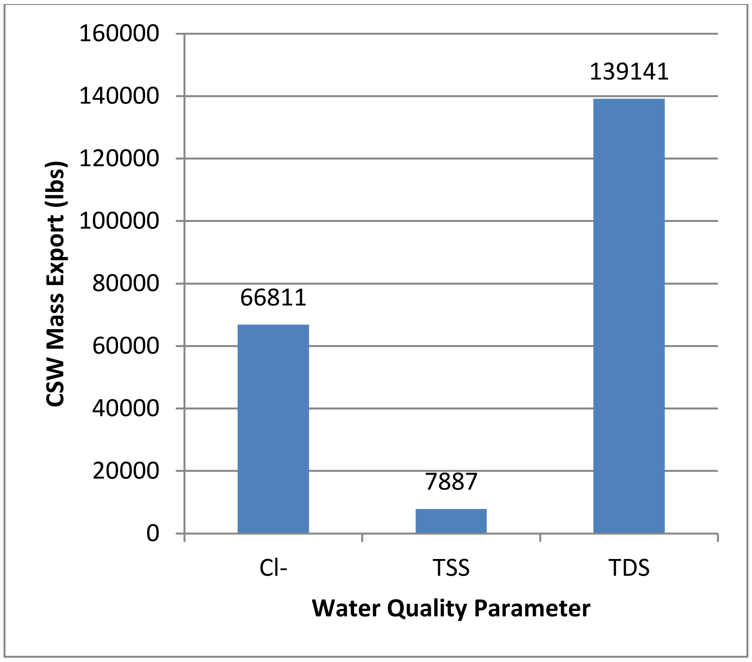

Figure 79: Annual pollutant mass load from constructed stormwater wetland, as calculated using the annual storm volume for Philadelphia

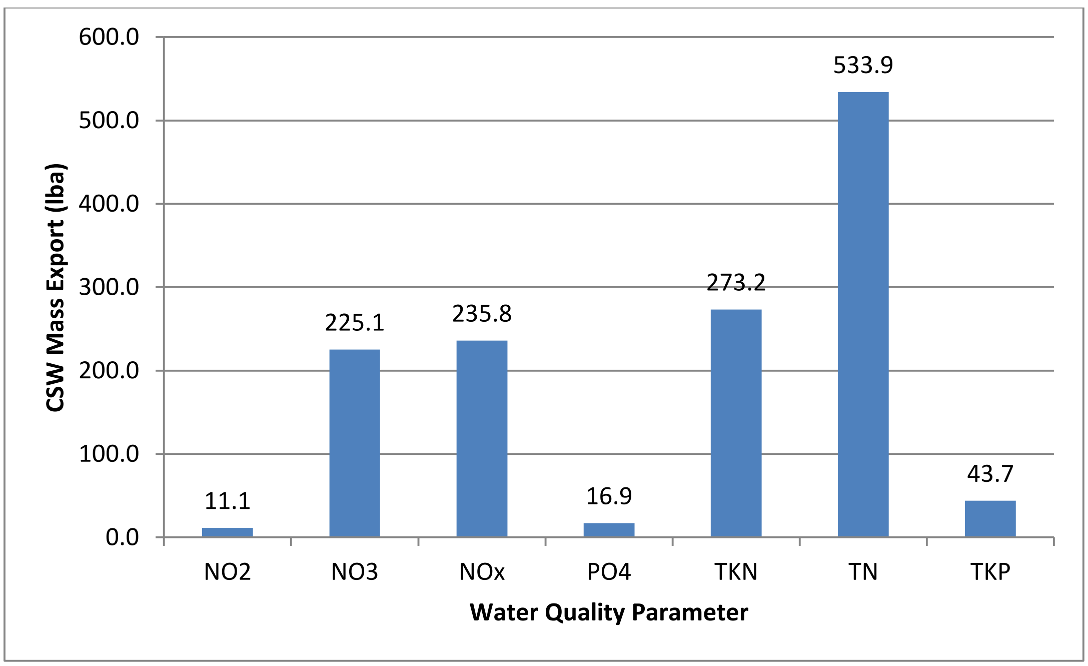

Figure 80: Annual nutrient mass export for constructed stormwater wetland, as calculated using the annual storm volume for Philadelphia.

C: Sampling Redesign

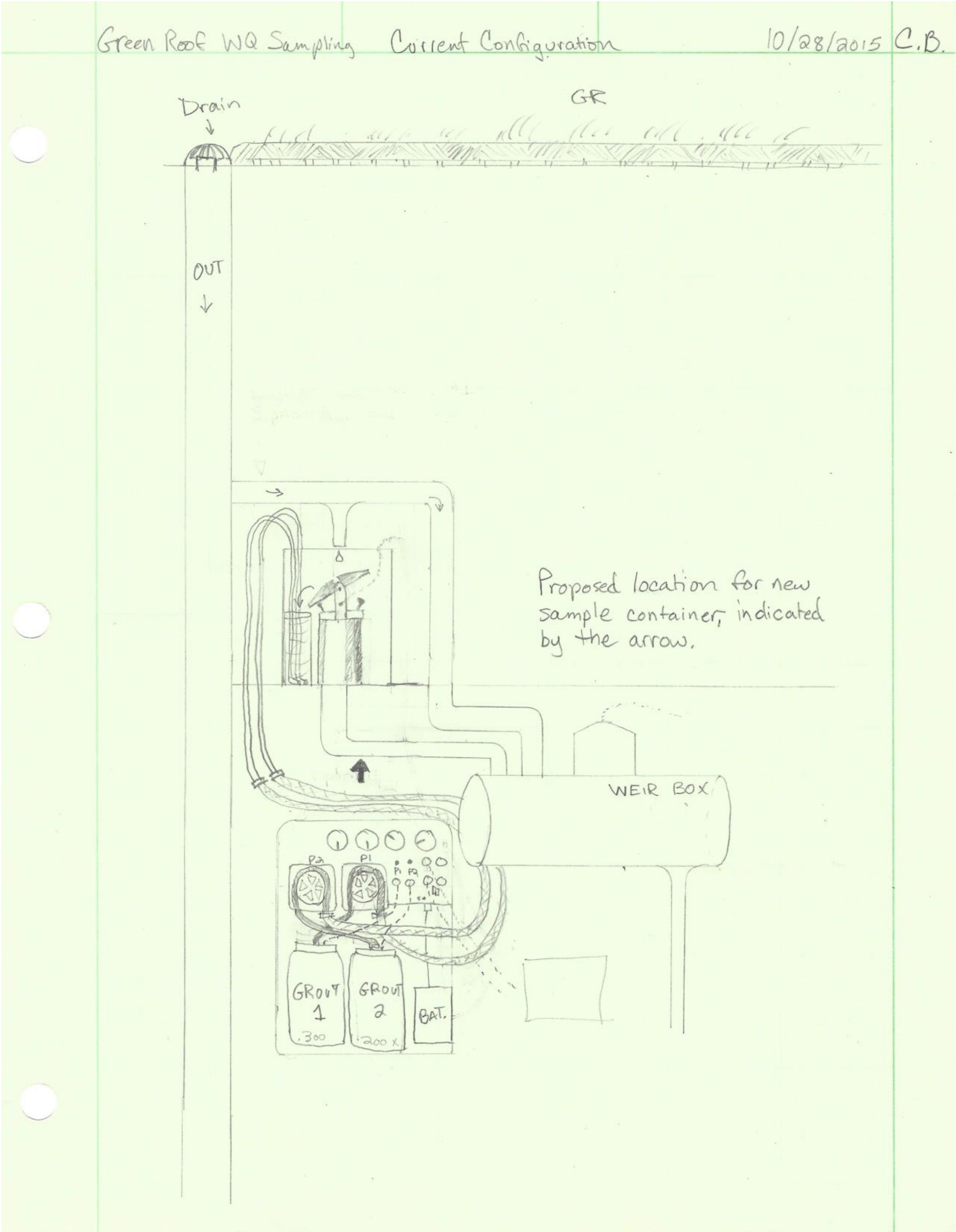

Figure 81: Current sampling configuration with sample collected inside tipping bucket housing

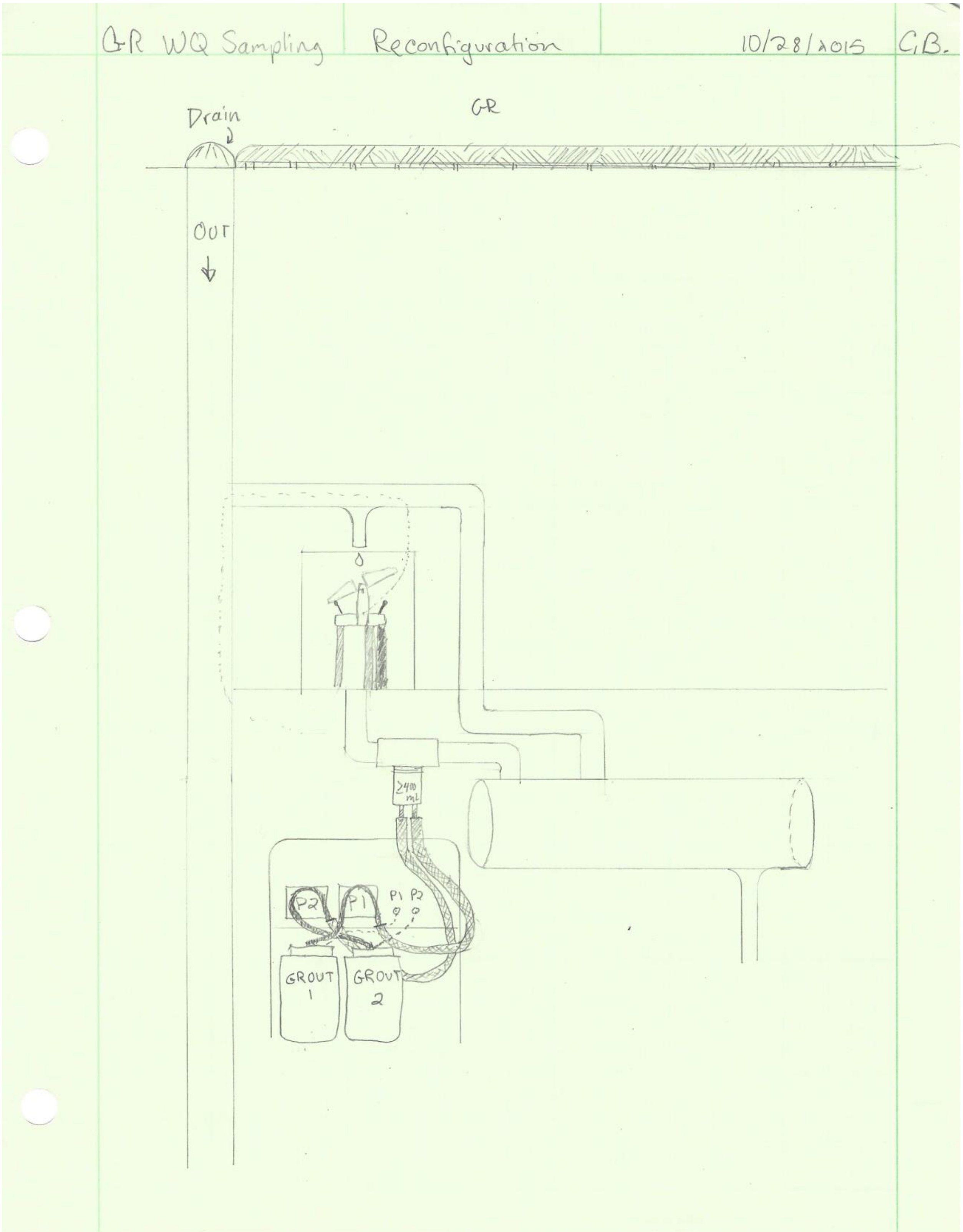

Figure 82: Proposed reconfiguration of sample collection and autosampler feed lines

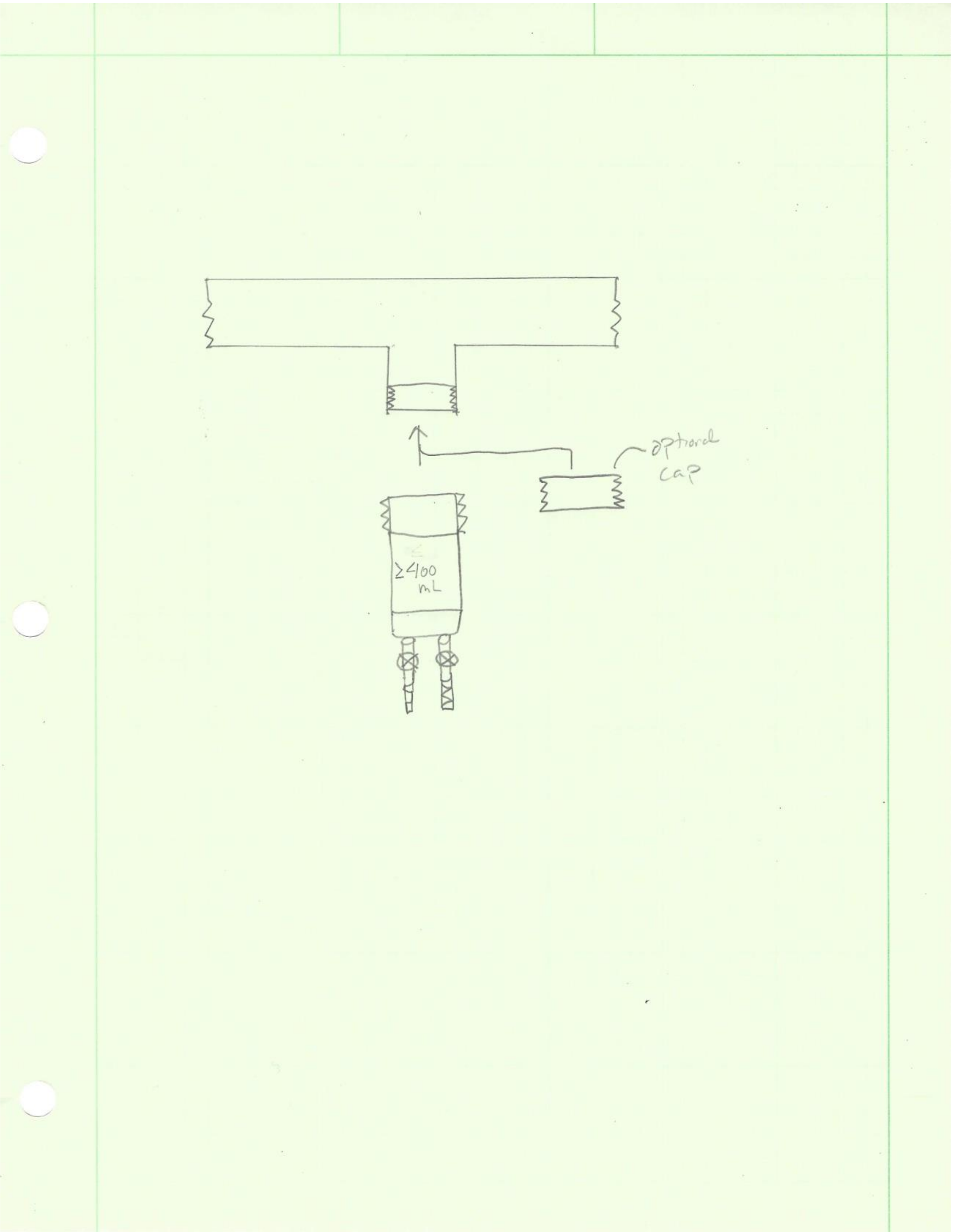

Figure 83: Conceptual sketch of proposed t-section to collect sample (courtesy of Gerald Zaremba)