EFFECTS OF GREEN ROOF PLANT SELECTION ON ENHANCING STORMWATER QUALITY UNDER STEEP SLOPED ROOF CONDITIONS

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ABSTRACT

EFFECTS OF GREEN ROOF PLANT SELECTION ON ENHANCING STORMWATER QUALITY UNDER STEEP SLOPED ROOF CONDITIONS

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Green roofs utilize surfaces on a building to grow vegetation in some type of soil substrate. This practice is not new, but most recently, it has been used to mitigate some of the negative effects of urbanization (e.g., stormwater runoff -- quality and quantity). Green roofs have been proven to reduce the total amount of stormwater runoff from roof surfaces while increasing the duration of time that runoff occurs, thus reducing peak flow for rivers in a watershed. Also, green roofs have proven to affect stormwater runoff quality, both positively and negatively. While some studies have shown that green roofs can act as a sink with respect to some pollutants in stormwater runoff, others suggest that green roofs can act as a source for other types of pollutants.

In this study, experimental sloped green roof plots were constructed to monitor green roof runoff water quality versus the runoff from conventional shingle and steel roofing surfaces. As a part of the study, two green roof vegetative types (*Sedum* & native grass) were compared to bare media only and evaluated for storm water runoff quality. From this study, it was determined that the green roofs with vegetation will uptake more nutrients than non-vegetated roofs but few differences could be determined between vegetation types with respect to water quality runoff. Runoff from green roofs proved to be higher for both nutrients and turbidity than roofs with conventional roofing materials; it also was found that green roofs increase pH when compared to roofs with conventional roofing materials.

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INTRODUCTION

This thesis contains a study performed to evaluate the effect of vegetation selection on green roof design, it is aimed at enhancing the performance capabilities of these roofing systems to mitigate the negative stormwater runoff quality characteristics of green roof systems. Some of these undesirable stormwater quality characteristics include increases in nutrient levels and excess sediment (turbidity) in runoff. These two types of contaminants can affect both the chemical and physical characteristics of receiving water bodies to the point where severe damage can be done to aquatic environments.

Water runoff samples were collected from simulated sloped green roof installations and analyzed for specific water quality properties including various nutrients (Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and Phosphate-Phosphorous (PO_4-P)), turbidity, and pH levels. Two different types of vegetation coverage including conventionally used *Sedum* species (*Sedum acre, S. album, S. ellacombianum, S. kamsatchatkum,* and *S. reflexum*) and more unconventional native grass species (*Buchloe dactyloides* and *Bouteloua gracilis*) were monitored and compared to three types of non-vegetated surfaces (bare green roof media, asphalt shingles, and steel roofing). Roof platforms designed to represent actual green roof installations were built in 2009 using these five roofing types. Each platform was constructed with a 30° slope to mimic conventional 4:12 housing pitch found on the majority of Midwestern homes. Green roof stormwater runoff produced from natural rain events was collected during the growing seasons of 2010, 2011 and 2012.

LITERATURE REVIEW

Effects of Urbanization on the Environment

Human influence on the natural environment is an inevitable part of man's existence on earth, but the extent to which mankind alters our environment is under constant debate. As human populations have grown, so has our footprint. Today, 30-50% of the earth's surface is now estimated to have been transformed (Vitousek et al., 1997). Transformations of the earth include deforestation, urbanization, and agricultural practices that directly and indirectly influence the natural processes of the previously undisturbed land. As a result of these changes in the earth's land cover, other natural resources like air, water, soil, vegetation, and wildlife have been altered. Vital natural processes such as the hydrologic cycle and regular climate events have been impacted to a degree that humans have been forced to address these issues in certain ways, some more unconventional than others. We now try to manage certain components of these natural cycles in attempt to reverse negative effects that have been caused by poor land use choices.

Green infrastructure has the ability to reduce the negative hydrological and climatic effects of urbanization, facilitate more ecosystem services within the urban environment by supporting biodiversity, and provide new business opportunities in green technology through green roof design, installation, maintenance, plant propagation, and material manufacturing.

The most influential component of urbanized areas having the greatest effects on the hydrologic cycle is the total amount of impervious area (TIA). Impervious or "hardened" surfaces such as roadways, parking lots, sidewalks and rooftops do not allow precipitation to infiltrate the ground to naturally replenish stream, river and groundwater reservoirs and/or encourage evapotranspiration (Figure 1). Infiltration of water into the soil profile and evapotranspiration from photosynthesizing plants are both key forces in the hydrologic cycle. In the United States, Ferguson (1998) estimates that 11-39% of residential areas and 71-95% of industrial, commercial, and shopping districts are comprised of impervious surfaces.

Because of urbanization, replacement of vegetation with impervious or hardened surfaces has caused significant changes in water runoff, evapotranspiration, and water infiltration components of the hydrologic cycle. As the percent of impervious surfaces increases, the area of land available for infiltration and evapotranspiration of precipitation is reduced. The amount of stormwater available for direct surface runoff also becomes greater, leading to increased frequency and severity of flooding and sediment erosion (National Research Council, 2009). As little as 10% impervious surface in watersheds can affect downstream water bodies to the point where aquatic habitats can be altered (Shaver et al., 1995). These habitat alterations can include reduced available oxygen in water, increased water temperature and increased vegetation growth; such factors, for example, can lead to a reduction of invertebrate and fish species population and diversity. Excess runoff can also inhibit water filtration facilities from functioning properly, and in some cases increases, the occurrence of combined sewer overflows (CSOs). In combined sewer systems, wastewater and stormwater are not separated from one another. High volumes of stormwater runoff overwhelm the systems and cause CSOs, allowing wastewater and stormwater to be directly released into receiving streams, lakes or oceans (Figure 2). As of 2004, 746 communities in the United States were still operating with combined sewer systems with nearly half of the communities being located in the New England and Great Lakes regions (USEPA, 2008a).

Large amounts of time and money have been spent on infrastructure upgrades to address the negative effects of CSOs in the United States. In 1987, the Clean Water State Revolving

Fund (CWSRF), a national program, was established under the federal Clean Water Act as a means to partially fund water quality projects. As of 2002, state and local expenditures reported under the CWSRF reached $0.44 billion per year. This does not account for communities with projects that are only partially funded or choose not to participate in the program at all (USEPA, 2004).

Since the mid-1990s, a growing number of municipalities have been implementing stormwater utility fee programs that affect individual residential, commercial, and industrial property owners. The utility fee is determined by the percentage impervious surface area of each individual property. In 80% of all stormwater utility fee assessment programs, the equivalent residential unit method (ERU) is used to determine the fee owed for each parcel. Regardless of the parcel's total area, the ERU method bills property owners for an amount proportional to the impervious area on a parcel using a typical single-family home's impervious footprint as the basis of measurement. The revenue from these programs is mainly used to provide support for annual stormwater facility operational costs by funding construction projects like facility upgrades and CSO programs. In the case of South Burlington, Vermont, a stormwater utility established in 2006, generates more than $1 million annually (USEPA, 2009a).

Increased stormwater runoff not only affects the *quantity* of water entering aquatic systems, but also alters the water *quality* of these aquatic systems in several ways. During precipitation events, stormwater runoff from impervious surfaces can pick up pollutants such as oils, metals, soil particles, salts, animal wastes and fertilizers. The pollution load from urban area runoff is significantly higher than from secondary domestic sewage effluent and is considered to be second in significance only to runoff from agricultural lands (Deletic and Maskimovic, 1998). Increased pollutants in water systems can increase the biological activity of aquatic vegetation such as algae; this process is known as eutrophication, which increases biological oxygen demand and reduces dissolved oxygen levels (Figure 3). This process proves harmful to aquatic ecosystems and can reduce or eliminate certain aquatic species. Water temperature also is an important factor of stormwater runoff that can influence the water quality of receiving water bodies. Urban runoff is typically higher in temperature than natural runoff or groundwater supplies. This can have a significant effect on aquatic biota because as water temperatures increase, dissolved oxygen in the water decreases (Schueler, 1987).

Much research had been done with respect to water quality beginning in the mid-to-late 1900s due in part to the formation of the Federal Water Pollution Control Act, or Clean Water Act in 1972. This law was originally established in 1948. In 1972 it underwent complete revisions, most notably revisions that called for ambitious programs aimed at enhancing surface water quality. This act, which governs many aspects of human interaction and influence on the land, has since been expanded and continues to be a major influence in environmental protection.

The majority of the Clean Water Act is comprised of two parts. One part frames the authorization of government financial assistance to fund municipal infrastructure projects such as sewage treatment plant construction or combined sewer system separation (i.e. the Clean Water State Revolving Fund). The other part sets regulatory requirements to be followed by municipal and industrial dischargers. These requirements originally focused on point source pollution which is described as pollution being discharged from a single identifiable source such as pipes and outfalls. Amendments in 1987 specifically identified and authorized measures to address the issue of non-point source pollutants such as stormwater runoff from farm lands, forests, construction sites, and urban areas. These non-point source pollutants are now estimated to represent more than 50% of the nation's remaining water pollution sources (Copeland, 2010).

Removal of natural vegetation to permit urbanization can greatly impact the immediate climate in urban areas (Figure 4). The differences in the thermal characteristics of surface materials that overlie urban areas versus those that overlie natural areas have profound implications not only for microclimates, but also for stream and watershed health (Barnes et al., 2001). Vegetated areas naturally shade surface materials and cool the air through evapotranspiration. Large amounts of unshaded surfaces, like those found in urban areas, can absorb heat from the sun and serve as a heat "sink", increasing their own temperature and the temperature of the surrounding areas. Also, since impervious surfaces make up the majority of the urban landscape, water is not allowed to infiltrate into the soil to be evaporated or transpired by plants. Evaporation of moisture serves to lower surface temperatures since the energy used in evaporation is not available for sensible heating (heat exchanged by a body that creates a change of temperature) of the surrounding area (Barnes et al., 2001).

The urban heat island effect, along with increased *albedo* (a coefficient that describes the reflectiveness of a surface) of the urban area, cause greater internal building temperatures, and in turn increases demand for summertime cooling, and increased energy expenses. For every 0.06° C (1° F) increase in summertime temperature, peak utility loads in medium and large cities increase by an estimated 1.5 – 2.0 percent (USEPA, 2003). In the United States, about one sixth ($40 billion/year) of all electricity generated, is used to air condition buildings. Of the $40 billion/year, about half is used in cities classified as "heat islands", where the air conditioning demand has risen 10% within the last 40 years (Rosenfeld et al., 1998).

Increased temperatures due to the urban heat island effect also increase the formation of ground level ozone through the combination of volatile organic compounds and nitrogen oxides. Ground level ozone is a public health hazard that can cause respiratory and cardiovascular illness

(Lo and Quattrochi, 2003). Also, the increased temperature in urban areas contributes to about 1,800 deaths per year in select metropolitan cities with excessive heat events; this phenomenon has the greatest impact on the Northeast and Midwest regions (USEPA, 2006). Other than mortality, increased daytime surface temperatures, reduced nighttime cooling, and higher air pollution levels associated with urban heat islands can affect human health by contributing to general discomfort, respiratory difficulties, heat cramps, exhaustion, and non-fatal heat stroke (USEPA, 2008b).

Green Roof History

Green roofs have not always looked or served the same functions as we know them to do today. Ornamental roof gardens seem to have originated in the 7th and 8th century B.C in the Tigris and Euphrates River valleys, purported to produce one of the most well-known rooftop gardens, the hanging gardens of Babylon (Dunnett and Kingsbury, 2008) (Figure 5). Rooftop gardens also were seen in 16^{th} -17^{th} century Mexico and 17^{th} century Russia. Canada claims several Viking and French examples of sod roofs, exported to Newfoundland and Nova Scotia by early Norse or French explorers, respectively (Peck et al., 1999). Sod roofs have been traditionally used in the colder climates of Scandinavia, Canada, and Iceland where seven or more layers of birch bark serve as a waterproof membrane and local soil is used to weigh the birch bark down. This practice ensures that the birch bark stays in place. The soil protects the birch bark and acts as insulation for the structure below. Local soil seed banks would germinate and spread to cover the roof in native vegetation.

Rooftops in Germany around 1900 consisted of wood construction overlaid with tar-board. To prevent fires, the tar-board was covered with a layer of sand and gravel which attracted a layer of unintentional vegetation (Werthmann, 2007). This vegetation process intrigued several people and led to modern green roof systems that originated at the beginning of the 20th century in Germany. Green roofs also were studied and used at that time as a way to combat the damaging influence of solar radiation on building rooftops. An example of one such demonstration project is the Moos Lake Water Filtration plant in Zurich, Switzerland, whose green roof construction in 1914 led to its registration in the new millennium as a world wildflower preserve due to the indigenous orchid seeds that came with the soil media.

Due primarily to urbanization, growing environmental concerns that arose in the 1970's created opportunities for the introduction of more progressive problem solving solutions in green roof design. Green roofs were accepted because of the multiple environmental benefits documented in the first volume of green roof technical guidelines published in 1982 by the German Landscape, Research, Development and Construction Society, an interdisciplinary research team (Oberndorfer et al. 2007; FLL, 1995). Since then, green roofs have been installed across Europe and have gained a foothold in America, steadily increasing in numbers over the past decade. Research continues in both Europe and North America as universities work to document the impact of green roofs on the environment, economy, and energy resources (Wark and Wark, 2003)

Today, modern green roofs can be categorized as intensive (having deeper substrate, a wide variety of plant species, and typically accommodating public foot travel) or extensive (having minimal maintenance requirements, shallower media depth, possible sloped applications, and typically not tolerant of public foot travel) (Getter and Rowe, 2006). Green roofs have been proven to mitigate the negative hydrologic and climatic effects of urbanization. Through their structural substrate, vegetative, and water holding components, green roof systems are shown in studies to absorb 75% of precipitation that falls on them, which translates to an immediate discharge reduction of 25% of normal levels (Peck et al., 1999). Green roof albedo (ranging from 0.7 – 0.85) has also been found to be equivalent to other high-albedo, energy efficient roofs, such as white roofs, which have an albedo of approximately 0.8 (Gaffin et al., 2005). Lower indoor air temperatures were also measured in buildings with green roofs, and estimated heating and cooling loads were lower compared to buildings with traditional roofing systems (Gaffin et al., 2005).

Benefits of Green Roofs

Green roofs are best known for their impact on the volume of stormwater released as roof runoff. Green roof systems have the capacity to retain large amounts of water because of their substrate (soil media), vegetation and water retention components (i.e. fleece fabric mats and a plastic reservoir layer). Water can be held in the porous growing media of green roofs and evaporated into the atmosphere or used for evapotranspiration by the vegetation. Due to these and other components of the overall system, green roofs have been shown to retain anywhere from 39-85% of received rainwater (VanWoert et al., 2005a; Teemusk and Mander, 2007; Monterusso et al., 2004; Cronk, 2012). These retention rates differ significantly compared to conventional flat roofs which have a typical slope of about 2% and can consist of stone ballast, tar, steel or shingle roofing material. These conventional roofing systems are shown to retain approximately only 4% of fallen rainwater (Mantens et al., 2006), which is probably due to evaporation. A study done by Carpenter (2011) compared three types of roofs; all roofs were full-scale and included green (vegetated), stone ballast roof, and asphalt roofing materials. A total of 21 storm events were observed. It was found that the green roof had an overall retention rate of 68.25% while the stone ballast roof had a retention rate of 57.75%. The study showed that conventional roofing materials had much lower stormwater retention capabilities, with the asphalt roof retaining only 10.45%.

Green roofs first evolved using vegetation from native soil seed banks to weigh down and protect layers of birch bark for waterproofing. More recently, green roof design has evolved to allow the facilitation of a larger plant palette ranging from the widely used *Sedum* spp. to larger plants or grasses and even trees. When looking at some of the more commonly used plants used in these systems, (Dunnett and Kingsburry, 2008) found that vegetation does in fact influence the amount of runoff from green roof systems. When comparing three different vegetation types (grass species, forb species, and *Sedum* species), it was found that grass species were the most effective for reducing runoff, followed by forbs, and then *Sedums*. Plant attributes such as height, density, leaf shape and orientation, and evapotranspiration rates affect the amount of runoff released. This information is important to further green roof design and maximize the potential for green roofs to mitigate stormwater issues in urban areas.

Roof slope also has an effect on stormwater retention capabilities of green roofs which can be attributed to the influence of gravity on the movement of water through the green roof system. Getter (2007a) used experimental green roof platforms at four different slopes to investigate the water retention rate differences under these conditions. All of the green roof platforms were designed in the same fashion, allowing the change in slope to be the only variable. The platforms were set at slopes of 2%, 7%, 15%, and 25% were found to have overall rainwater retention of values of 85.2%, 82.2%, 78.0%, and 75.3% respectively. This shows a direct correlation between roof slope and rainwater retention capabilities with flat roofs retaining more stormwater in the system.

Several investigations have found that green roofs can be an effective stormwater management tool due to their retention and evapotranspiration properties. Traditional roofing installations that may use shingle, tar, or metal materials, for example, act as impervious surfaces and will create higher stormwater runoff. This fact has been noticed by policy makers and government entities to the point that green roofs have been advocated and encouraged to help manage stormwater problems in urban areas. In situations where governments impose a stormwater runoff utility fee, green roofed areas are considered a porous surface and will not be included in a property's overall impervious footprint. This can be a great financial benefit to landowners as pointed out by Clark (2008) who compared traditional roofing practices versus green roof installations with respect to assessed stormwater utility fees in Ann Arbor, MI. The city of Ann Arbor assesses individual properties based on the overall square foot for residential use and square acre for industrial use of their impervious surface area, which includes rooftops with traditional roofing materials. Clark calculated that a conventional roof of 2000 m^2 (21,527 ft^2) would be assessed \$520 per year, whereas a green roof of the same size would be assessed \$0 per year. This is an example of how green roofs provide a financial incentive for installation in addition to their documented environmental benefits.

The urban heat island effect is a phenomenon that describes the increased ambient air temperature in urban areas due to the increase of mechanical operations, reduced albedo of road and building surfaces, and reduction of vegetation that creates shade and cools the air through the process of evapotranspiration. This occurrence has been considered a contributor to many issues including increased building energy consumption for cooling and increased adverse health effects due to extreme summer temperatures in urban areas. Much of the urban landscape consists of densely located buildings where the rooftop represents the footprint of each building.

Therefore, green roofs have a potentially positive impact on the surrounding temperature due to several factors.

Traditionally constructed rooftops, especially on office or industrial buildings, use materials that have a low albedo (low reflective, high absorptive heat properties). These materials include, but are not limited to, tar roofs and darker colored asphalt shingles both of which will absorb more solar energy. This increases air temperature immediately above the roof when compared to vegetated surfaces.

Atmospheric air quality has been an issue of concern due to the increased burning of fossil fuels and the subsequent release of airborne pollutants into the atmosphere. This issue is of greatest concern in and around urban areas where there is a higher concentration of industrial activity and increased transportation operations such as the use of fossil-fuel burning automobiles. Green roofs have been identified as a way to reduce problems caused by airborne pollutants, namely the reduction of nitrogen oxides, carbon dioxide, polycyclic aromatic hydrocarbons (PAHs), and heavy metals in the environment. Rowe (2011) has summarized several studies that have addressed this issue as well as discussed the importance of green roofs as a tool for remediating environmental pollution on many levels.

Clark (2008), analyzing the many benefits of green roofs, estimated that a 2000 m^2 green roof could take up approximately 530 kg_{no2}/year (variance: 700 $kg^2_{no2}/year^2$) . This translates into \$890 (variance: 2.0E6 $\$^2$) -\$3390 (variance: 2.8E7 $\$^2$) of public health benefits per person. This data was derived from studies done by the United States Environmental Protection Agency (USEPA) that placed economic values on NO_x removal with respect to its influence on premature death and cases of chronic bronchitis. In addition to the potential NO_x removal by green roofs, their ability to sequester carbon also has been investigated. Getter (2009a) looked at green roofs planted with primarily *Sedum* species and analyzed the amount carbon content over a 2 year period. She found that after two years, the twenty experimental plots examined (13.06 m^2 in total area), sequestered 375 g $C \cdot M^{-2}$ by means of above and below ground biomass and substrate organic matter. This shows that green roofs can be a significant air pollutant removal tool, especially when applied on a larger, city-wide scale.

Green Roofs and Stormwater Runoff Quality

As previously mentioned, green roofs are best known for their positive impact on stormwater runoff issues. This is particularly true in urbanized areas with large amounts of impervious surfaces. In addition to the research conducted on stormwater quantity, there also have been investigations of green roofs with regards to the *quality* of the stormwater runoff.

In most instances, natural rainwater falls and lands on the ground or on rooftops constructed out of traditional roofing materials. This rainwater then runs off the surface quickly, and makes its way to a roof gutter, storm sewer system, or natural body of water. This is the same with runoff released from green roofs, but unlike roofs with traditional roofing materials, this rainwater must first pass through the several layers contained in a green roof system. This introduces new variables in the equation. It has been found that stormwater released from green roof systems is significantly different in its physical and chemical properties than natural rainwater or rainwater runoff from roofs with traditional roofing materials. Even though water quality has not been as thoroughly investigated as water quantity, there are studies that have attempted to analyze this issue. The main investigation in researching green roof runoff water quality is whether or not green roofs can improve stormwater runoff quality (compared to runoff from roofs using conventional roofing materials or uninhibited natural rainwater) or if they introduce or increase additional pollutants otherwise non-existent in natural rainwater or traditional runoff.

Rowe (2011) summarized the majority of research studies pertaining to water quality of green roof runoff, and it was found that there exists wide variation in the findings (Alsup et al., 2010; Bliss et al., 2009; Carpenter and Kaluvakolanu, 2011; Bernstsson, 2010; Berndtsson at al., 2009; Berndtsson at al., 2006; Emilsson et al., 2007; Gregorie and Clausen, 2011; Hathaway et al., 2008; Monterusso et al., 2004; Retzlaff et al., 2008; Teemusk and Mander, 2007; Toland et al., 2012; USEPA, 2009; Vijayaraghavan et al., 2012). Among water quality characteristics that have been investigated are various nutrients (K, Na, NO_3-N, NO_2-N, NH_4-N, PO_4-P, Total N, Total P and SO_4), metals (Cd, Cr, Cu, Fe, Mg, Mn, Ni, Pb, Zn), polycyclic aromatic hydrocarbons (PAHs), chemical oxygen demand (COD), biological oxygen demand (BOD), electric conductivity (EC), turbidity, color, and pH. All of these variables affecting water quality can come from different sources, whether from the natural environment or anthropogenically introduced, and all play significant roles in the natural balance of our earth's many ecosystems. This study focuses on the concentration levels of different forms of nitrogen and phosphorous in stormwater emanating from two types of green roofs, a brown roof (no vegetation), and two types of conventional roofing (stell and fiberglass shingle). It also includes investigations of turbidly and pH levels from these roof types.

When examining the roll of nutrients in the natural environment, it is known that nitrogen and phosphorous are important in plant growth and establishment. Their use as fertilizers in crop production and their detrimental effects when introduced into the environment in above average levels is well established in the literature. Several forms of nitrogen are readily available in the environment including the forms of nitrate (NO_3^-), nitrite (NO_2^-) and ammonia (NH_3). These three forms are part of the nitrogen cycle and are products of nitrogen fixation and nitrification processes. NH_3 occurs when dinitrogen gas (N_2), the most abundant and unusable form of N in the biosphere, is fixated by bacteria in the soil to create ammonia (NH_3). NH_3 can appear as a gas, moving freely throughout the soil, or dissolved in water. When dissolved in water, the NH_3 can be transported much more easily throughout the water column and into the groundwater supply. This natural production and movement of NH_3 within the hydrologic cycle tends to produce very minimal negative effects on aquatic species when transported to rivers, streams and water bodies of varying sizes. Higher levels of NH_3 and subsequent pollution of natural waters tends to come from other man made practices such as fertilization and the use of organic compost in farming practices. These larger amounts of NH_3 can be detrimental to aquatic organisms such as fish species, especially in waters of higher temperature and lower pH levels. It has been shown that high concentrations of NH_3 in water reduces hatching success and growth rate in fish, including morphological development. It also leads to pathological changes in the cell tissues of gills, liver, and kidneys. Exposure to higher concentrations of NH_3 (ranging from 0.304 mg/L – 1.2 mg/L of NH_3 in this study, uncorrected for pH) also causes loss of equilibrium, hyperexcitibility, and increases in breathing, cardiac output and oxygen uptake. Fish have displayed convulsions, coma and death (USEPA, 1985) under ammonia poisoning. In humans, this phenomenon is very rare and can only occur when introduced in extremely high levels.

The formation of nitrite (NO_2^-) is a product of the nitrification process within the larger nitrogen cycle. Bacteria play a role in this process. Ammonium (NH_4^+, an ionized form of NH_3) is converted into NO_2^-. From this, NO_2^- is transformed into nitrate (NO_3^-) by denitrifying bacteria (Robertson and Groffman, 2007). Due to the ease of this transformation process, NO_3^-, the end product of nitrification, is generally in greater abundance than NO_2^-. Since nitrite and nitrate act similarly within the environment and produce many of the same effects, the two are often combined and categorized together under the term *nitrates*. These nitrates, much like ammonia, occur naturally in the environment and are vital to many ecological and biological processes. Naturally occurring, these highly soluble nitrates generally produce no harmful side effects when they are transported through the soil column and into the groundwater supply or to natural water bodies. The problem arises when increased levels of nitrates are introduced through the use of agricultural or home use fertilizers or as byproducts of untreated animal waste. This makes areas around home and agricultural lands of great importance due to the increased incidence of nitrates; these forms of nitrates are able to reach drinking water sources through soil infiltration to the water table or by overland flow to streams, rivers and lakes.

Human exposure to above average levels of nitrates can be, at times, very detrimental to one's health. When overexposed, infants and children can develop what is called "blue-baby syndrome" which is seen most often when infants are exposed to nitrates from drinking water used to make formula. Adults diagnosed with chronic abstractive pulmonary disease also are susceptible to impaired oxygen delivery to vital organs due to nitrate affinity for hemoglobin (Westphal, 2014). This syndrome is named for the blue coloration of the skin caused by impaired oxygen delivery to tissues due to the nitrate's interruption of regular hemoglobin function. Increased nitrate exposure also can increase the incidence of brain tumors, leukemia, nose and throat tumors in children and cancer in adults (USEPA, 2007).

In addition to the negative human health effects of nitrates, NO_2^-, NO_3^- and NH_3 also alter natural ecosystems and can cause significant, unwanted outcomes. These same environmental effects also are apparent when there is an increase of the nutrient phosphorous (P) into the environment. Phosphorous is not found often as a free element, P, in the environment because of its high reactivity with other elements like hydrogen and oxygen. When phosphorous goes through its natural oxidation process, the final product is orthophosphate (PO_4); this ion is taken up by virtually every plant and used in almost every metabolic process including respiration and photosynthesis. Though it is an important nutrient involved in many plant functions, it is often the least available nutrient in a great number of aquatic and terrestrial ecosystems. Therefore, it is often the limiting component to complete various environmental processes, both good and bad. This means that a small amount of phosphorous allows many processes to be completed (e.g. algae blooms) that eventually devoid water systems of oxygen. A large source of phosphorous introduced into the environment comes from the use of fertilizers for crop production that supplement soils that are naturally deficient of orthophosphates, the main form of phosphorous taken up by plants. Introduction of phosphorous into the environment is evident by the fact that 90% of mineral orthophosphate used worldwide is derived from fertilizers (McDonald et al., 2001).

Phosphate and nitrogen are essential to many plant functions but also are drivers of several unwanted environmental outcomes when introduced at higher than average levels to the environment. As discussed previously, anthropogenic introduction of these nutrients into the environment can be directly linked to agriculture practices such as the application of fertilizers or livestock grazing that produces untreated livestock waste. Though a large contributor, agriculture practices are not the only source of nitrogen and phosphorous in the environment. Residential, commercial and municipal landscape application of fertilizers, leaky septic tanks, combined sewer overflows, atmospheric deposition, and as by-products of mining practices also contribute these nutrients to groundwater supplies by overland runoff or by infiltrating through the soil column into the water table. This transport of nutrients to various water bodies can lead to eutrophication, the ecosystem's response to the addition of artificial and natural substances.

Eutrophication of aquatic systems increases the growth of aquatic plant and animal species, such as blue-green algae, creating elevated biomass levels. These plants and organisms will eventually die and decompose. The process of decomposition uses oxygen, and therefore, the more plant and organism biomass that decomposes, the less oxygen is available for all other processes within that aquatic environment. These lower oxygen levels (low dissolved oxygen content) can create numerous negative environmental effects including shifts in aquatic plant and organism species abundance and composition, reduced water clarity, decreased aesthetic value, changes in water taste and odor, water supply filtration problems, elevated pH, shifts in fish species composition towards less desirable species, and probability of fish kills (Smith et al., 1999).

The issues of increased nutrient introduction into the environment are well documented and are of obvious concern when examining aquatic systems and groundwater supply near and around agricultural land. Although these areas are of great concern, there also are concerns that arise near and around urbanized areas. In urban areas, stormwater that runs off of a landscape comprised of impervious surfaces is channeled directly into stormwater sewer systems in many cases. Some of these systems are connected to water treatment plants that try to filter as many pollutants picked up by the stormwater as possible. In many instances though, the stormwater is drained directly to receiving rivers, streams, lakes or other water systems. This means that all pollutants, including nutrients such as nitrates and phosphates, are picked up during the stormwater's travels and are directly introduced in greater than normal levels into these aquatic systems. In high enough concentrations and under certain circumstances, these pollutants can cause detrimental effects to these aquatic systems and their connected environments.

Green roofs can provide many environmental benefits including increased avian and insect habitat (Eaken 2012; Monsma, 2012), increased energy savings due to added building insulation, and cooler surrounding temperatures due to their increased albedo and evapotranspiration properties. Although these are well documented motives to install green roofs on new and existing structures, the ability to manage stormwater is probably the greatest benefit when considering a green roof in areas with high impervious surfaces, such as urban areas. The ability to retain large amounts of rainfall and prolong the release of any runoff makes green roofs a useful tool to reduce the impact on urban stormwater systems. While stormwater quantity has been heavily researched, fewer studies have examined the quality of stormwater that runs off of these green roof systems.

Green roof systems can vary in several ways; for example, they can be a built-up system (soil placed directly on roofing components and planted) or a modular system (pre-grown green roof cells or trays). These different systems have different structural materials (e.g., plastic trays or drainage layers, rubber for roofing membranes, fabric water retention layers, etc.) and can use growing media comprised of different mixes. Each variation in structure supports an array of plant species adapted to survive the extreme climate found on rooftops. As stormwater falls on these green roof systems, it travels through and makes contact with these different materials; it picks up pollutants and particles along the way. The unnatural additions found in the subsequent stormwater runoff can alter the physical and chemical properties of the released water and in many cases, are characterized as pollutants to the surrounding environment. This water, especially in urban environments, can make its way directly to receiving aquatic systems with minimal, or no filtration at all. This makes examining the quality of stormwater runoff from green roofs an increased environmental concern as it can have direct implications on the health of receiving rivers, streams, lakes and other water bodies.

Pollutants such as metals have been examined in green roof runoff as well. Alsup et al. (2010) concluded that different growing substrates (soils) and different vegetation forms can influence the level and type of metal pollutants contained in green roof runoff. She found that none of the green roofs treated with different substrates were significant sources of Chromium (Cr), Copper (Cu), Iron (Fe), Nickel (Ni), or Zinc (Zn). There was evidence, however, that one substrate, Lassenite, was the only substrate tested that could be considered a source of Magnesium (Mn). This occurrence did show Mn in greater concentrations than what is recommended by USEPA water quality criteria, but in non-toxic amounts that only affect the taste of drinking water and the possibility of staining of cloth when washed with water containing Lassenite. The work of Alsup, et. al (2010) performed on substrates in planting plots with and without vegetation, found that leachate from 45.4% of the examined plots exceeded USEPA standard with regard to lead (Pb) concentrations.

Berndtssson et al. (2006) examined stormwater runoff from full scale green roofs of different ages with respect to concentrations of cadmium (Cd), chromium (Cr), copper (Cu), Iron (Fe), potassium (K), magnesium (Mn), lead (Pb), zinc (Zn), nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), total nitrogen (Tot-N), phosphate-phosphorous (PO_4-P) and total phosphorous (PO_4-P). It was found that the examined green roofs acted as a source of these nutrients in green roof runoff when compared to natural rainwater with an exception to NO_3-N. The authors found that nitrate-nitrogen was retained by the green roofs, either by their vegetation, growing media, or both. In addition, Phosphate-phosphorous was found to be released in greater amounts from green roofs that were newer in establishment. The oldest green roof performed better with respect to phosphate-phosphorous release which leads one to believe that phosphate-phosphorous levels in green roof runoff can decrease over time as a green roof system matures.

In an experiment conducted by Bliss et al. (2009), the authors compared an extensive green roof to a conventional ballast roof to examine water retention capabilities and quality of stormwater runoff with respect to sulfate (SO_4), phosphorous (P), chemical oxygen demand (COD), Tot-N, Pb, Zn, and Cd. While the green roof reduced runoff volumes by up to 70%, it was found that stormwater runoff from the observed green roof had higher concentrations of phosphorous and elevated levels of COD when compared to the conventional ballast roof. Like Bliss et al. (2009), Teemusk and Mander (2007) found that green roofs increase pH (less acidity) of stormwater runoff from green roofs. They also found that the green roofs performed better than the observed runoff from the studied bituminous roof with respect to pollutant concentrations in stormwater runoff during light and moderate rains. During heavy rains though, green roofs demonstrated higher pollutant concentrations in stormwater runoff due to the accumulation of the pollutants in the green roof system that were eventually flushed out during heavy rain events.

Berghage and his co-authors, in a study reported by the USEPA (2009b), examined smaller green roof installations and their stormwater runoff properties with respect to pH, electric conductivity (EC), turbidity, color, nitrate, P, K, Ca, Fe, Mg, Mn, Na, Zn, and Sulfur (S). The green roofs proved to release stormwater with higher concentrations of nutrients (K and P) as well as demonstrating greater hardness with higher levels of Ca and Mg. Though there showed greater release of some pollutants, green roofs appeared beneficial in removing atmospheric nitrate in this study. They also examined the concept of pollutant loading in green roof; this concept compares minimal runoff with higher pollutant concentrations from green roofs to higher runoff volumes with lower pollutant concentrations from conventional roofs. They found that when factoring in the total volumes of stormwater with respect to pollutant concentration levels, that green roofs acted similarly to conventional roofs with respect to pollutant loads in stormwater runoff.

At a study performed at the Michigan State University campus, Monterusso et al. (2004) compared four commercially available green roof systems. Each system was planted with *Sedum* spp. and native grass species. The research monitored the stormwater runoff quantity and quality with respect to various systems and vegetation coverage types. The authors examined stormwater runoff quality with respects to NO_3-N and Tot-P. There appeared to be no correlation of phosphorous concentrations in stormwater runoff and green roof system type. However, it was found though that green roofs planted with *Sedum* spp. and with shallower substrate released greater amounts of nitrate in stormwater runoff. This may indicate that green roofs with native grass vegetation may produce different results than green roofs planted with *Sedum* spp. when looking at pollutant concentrations in stormwater runoff.

Furthering research on the subject, Hathaway et al. (2008) collected rainfall runoff from an extensive green roof in North Carolina planted with predominately *Sedum* species. The rainfall runoff was examined for levels of TKN (Total Kjeldahl nitrogen), $NO_3 + NO_2$, NH_3, Total Nitrogen (TN) and Total Phosphorous (TP). During the course of this study, it was observed that this green roof consistently released greater amounts of TN and TP in its stormwater runoff when compared to rainfall and runoff from the adjacent gravel ballast roof.

Emillson et al. (2007) also looked at different forms of nitrogen and phosphorous in relation to fertilization treatments of green roof and subsequent levels in stormwater runoff.

Traditional and controlled release fertilizers (CRFs) were applied to experimental green roof plots in attempts to determine overall nutrient levels, nutrient level decline over time, and influence of vegetation composition on nutrients in stormwater runoff. In the controlled greenhouse experiment, experimental plots with three coverage types, including shoot-grown vegetation (*S. album*, *S. acre*, and *Phedimus spurius*), established pre-grown vegetated mats (2 years old at time of study) and plots with no vegetation (growing media only) were satisfied. It was found that traditional fertilizer applications released greater amounts of nutrients in runoff when compared to applications using CRFs. With respect to vegetation coverage type, it was found that plots with vegetated coverage generally released runoff with lower levels of nitrogen compounds. This also was true with respect to phosphorous; the un-vegetated plots released greater amounts of phosphorous in runoff. This demonstrates that vegetation coverage does have an influence on nutrient concentrations in stormwater runoff.

A study performed in Southeast Michigan by Carpenter and Kaluvakolanu (2011) compared green roof, gravel ballast and asphalt roofing applications with respect to stormwater retention and stormwater runoff quality. Unlike the majority of other studies that examined nutrient runoff from green and traditional roofs, this experiment showed that total phosphorous runoff from green roofs was less than that of the gravel ballast and asphalt roofs. Nitrate concentrations were highest from the stone roof with the green roof and asphalt roof releasing similar levels in stormwater runoff. Although the phosphorous levels in runoff from green roofs were uncharacteristically lower than the traditional roofing materials, the green roof showed statistically greater amounts of total solids in runoff, which is congruent with the majority of research performed on green roof systems.

In examining the past research performed on green roofs with respect to water quality of stormwater runoff, it is evident that there are many factors that can influence the concentration of metals and nutrients in released stormwater. Substrate composition, system materials, maintenance practices, roof age, vegetation composition, and location are just some of the factors that can influence green roof runoff quality. With respect to nutrient, metal and sediment loads in stormwater runoff, it has been shown that green roofs can perform both better or worse than systems using traditional roofing materials. This study aims to reduce as many influencing factors as possible and focus on green roof vegetation composition and its influence on the quality of green roof runoff.

HYPOTHESIS

This study compares green roof systems of the same construction, materials, and slope with vegetation type being the only differentiating factor (ie., *Sedum*, native grass, and media only). The goal is to compare the quality of stormwater runoff from these green roof systems in attempt to determine the best green roof vegetation selection to improve stormwater runoff quality.

Null Hypothesis 1

There is no relationship between green roof vegetation treatment and concentration levels of Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N) and Phosphate-Phosphorous (PO_4-P) in stormwater runoff from these systems.

Hypothesis 1a:

There is a significant ($p \geq 0.05$) relationship between green roof vegetation treatments and concentration of the nutrients Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and/or Phosphate-Phosphorous (PO_4-P) in stormwater runoff with the native grass roofing treatment releasing runoff with lower concentrations of these nutrients than the *Sedum* roofing treatment.

Hypothesis 1b

There is a significant ($p \geq 0.05$) relationship between green roof vegetation treatments and concentration of the nutrients Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and/or Phosphate-Phosphorous (PO_4-P) in stormwater runoff with the native grass roofing treatment releasing runoff with lower concentrations of these nutrients than the media-only roofing treatment.

Hypothesis 1c

There is a significant ($p \geq 0.05$) relationship between green roof vegetation treatments and concentration of the nutrients Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and/or Phosphate-Phosphorous (PO_4-P) in stormwater runoff with the *Sedum* roofing treatment releasing runoff with lower concentrations of these nutrients than the media-only roofing treatment.

Null Hypothesis 2

There is no significant ($p \geq 0.05$) relationship between green roof and traditional (steel and shingle) roofing treatments with respect to concentration of the nutrients Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and Phosphate-Phosphorous (PO_4-P) in stormwater runoff from these systems.

Hypothesis 2a

There is a significant ($p \geq 0.05$) relationship between green roof and traditional (steel and shingle) roofing treatments with respect to concentration of the nutrients Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and/or Phosphate-Phosphorous (PO_4-P) in stormwater runoff with all green roof treatments (sedum, grasses or media only) releasing stormwater runoff with higher concentrations of these nutrients than both traditional steel and shingle roofing treatments.

Null Hypothesis 3

There is no significant ($p \geq 0.05$) relationship between green roof and traditional roofing treatments with respect to pH levels in stormwater runoff from these systems.

Hypothesis 3a

There is a significant ($p \geq 0.05$) relationship between green roof and traditional roofing treatments with respect to pH levels in stormwater runoff with all green roof treatments releasing stormwater runoff with higher pH levels (less acidic) than both traditional steel and shingle roofing treatments.

Null Hypothesis 4

There is no significant ($p \geq 0.05$) relationship between green roof and traditional roofing treatments with respect to turbidity (NTU) levels in stormwater runoff from these systems.

Hypothesis 4a

There is a significant ($p \geq 0.05$) relationship between green roof and traditional roofing treatments with respect to turbidity (NTU) levels in stormwater runoff with all green roof treatments releasing stormwater runoff with higher turbidity levels than both traditional steel and shingle roofing treatments.

MATERIALS AND METHODS

Green Roof Testing Platforms

In the summer of 2009 five roof testing platforms were built at the Michigan State University Landscape Architecture Alumni Research Site on the Old Mission Peninsula in Traverse City, MI (Lat. 44.8822°N, Lon. 85.5059°W, Elev. 210 m (689 ft.)) (Figure 6). Each platform was constructed using a 1.22 m x 2.44 m (4.0 ft. x 8.0 ft.) sheet of plywood that acted as roof sheeting. Trusses were built to hold the platforms at a 4:12 pitch (33.33% slope); this pitch represents the range of typical slopes found on single family structures in Michigan. Each of the platforms were raised from the ground an average of 1.22 m (4.0 ft) to facilitate stormwater runoff collection; the platforms were located in an open field away from any obstructions to rainfall. Platforms were partitioned into three sections, each section having the dimensions of 0.81 m (2.66 ft, width) x 1.22 m (4.0 ft, run) creating a roof area of 0.93 m^2 (10 ft^2). Each section was lined with 0.045 mm EPDM rubber membrane that acted as the roof waterproofing protection layer (Figure 7). Partition front, back and side boards were 15.2 cm (6 in.) high to hold the green roof components and a 2.54 cm (1 in.) drain was cut at the bottom end to allow each partition to drain separately. A 0.75 cm (.26 in) thick water retention fabric (Xeroflor XF158, Xeroflor America, LLC, Durham, NC) was placed over the EPDM membrane in each section and covered the drainage outlet. No drainage layer was incorporated into the partitions containing the green roofs.

Five different roofing treatments were included in this experiment, and each treatment was replicated three times (5 platforms with 3 partitions each = 15 partitions) (Figure 8). The roofing treatments were green roof with *Sedum* species, green roof with native grass species, green roof with no vegetation (media only), conventional roof with fiberglass shingle roofing material, and conventional roof with steel roofing material. All green roof sections were filled to a depth of 15.2 cm (6 in.) with engineered growing media composed of 80% heat-expanded slate (Permatill, Stalite, Salisbury, NC), 15% USDA grade course sand, and 5%compost from municipal yard waste. Proportions were mixed on a volume basis. *Sedum* species selected for planting were *S. acre, S. album, S. ellacombianum, S. kamtschaticum,* and *S. reflexum* and sowed into growing media at a rate of 0.9 kg (2 lbs.) per square meter. Native grasses included *Buchloe dactyloides* and *Bouteloua gracilis* and were planted as plugs [7.62 cm (3 in.)] at 10.16 cm (4 in.) on center (Figure 9). The vegetated green roof partitions were irrigated twice daily during the first three weeks for establishment; no fertilizers were used in this study. The third green roof treatment with no vegetation contained only growing media of the same consistency and depth as the planted partitions. The two conventional roofing treatments used were three-dimensional (30 year) fiberglass shingles and galvanized steel roofing; these two treatments represent typical residential roofing materials found in the region.

Water Collection

Stormwater runoff from each individual partition was collected via a plastic gutter system that drained into a TB-4 tipping bucket (Campbell Scientific Inc.) for quantity measurements. An additional tipping bucket was located on site to record rainfall (2011 and 2012 seasons only). Outflow from the tipping buckets was directed into 18.93 L (5 gal.) plastic carboys by polypropylene tubing. Growing media moisture content was recorded throughout the study using CS616 water content reflectometers (Campbell Scientific Inc., Logan, UT). Each green roof partition was monitored for moisture using two reflectometers: one located 0.30 m below the top of the partition and one located .030 m above the drainage outlet at the bottom and inserted 10.16 cm (4 in.) deep into the green roof media. All electronic data was recorded using a CR-1000 datalogger (Campbell Scientific, Inc.) programmed to collect data values every minute and totaling them every 5 minutes, 24 hours a day during the study.

Water quality samples were collected for individual rain events that occurred during the growing seasons of 2010 (3 rain events), 2011 (6 rain events) and 2012 (8 rain events). No data was collected during the winter after the onset of freezing temperatures. Rainfall event categorizations were guided by a previous study done by Getter et al. (2007a) and were determined as precipitation events that were preceded, at minimum, by 6 hours of no rainfall. After rainfall had commenced, a 6 hour waiting period occurred before samples were taken to allow for adequate stormwater runoff. If precipitation began again during the 6 hour waiting period, the rain events were combined. Representative samples from the collection carboys were taken in 500 ml polypropylene sample containers within 24 hours of the rain event ending. These samples were frozen on-site until transportation to East Lansing could occur for analysis.

Samples were analyzed using various methods to determine levels of the monitored water quality characteristics. Year 2010 samples tests were conducted at Michigan State University's Environmental Engineering Laboratories, East Lansing, MI. All nutrient concentrations (mg/L) were determined using Vacu-vial ampoules supplied by CHEMetrics, Inc., USA (Samples tested for: Ammonia-Nitrogen, Salicylate Method; Nitrite-Nitrogen, Azo Dye Formation Method; Nitrate-Nitrogen, Cadmium Reduction Method; Phosphate-Phosphorous, Stannous Chloride Method). Turbidity was determined using a Hach 2100N Turbidimeter (NTU) (Hach Company, Loveland, CO), and pH was determined using an Orion 720A pH Meter (Thermo Fisher Scientific, Waltham, MA). For year 2011 and 2012, nutrient levels were determined using a DR/890 Colorimeter supplied by Hach Co., USA (Sample tested for: Ammonia-Nitrogen, Salicylate Method; Nitrite-Nitrogen, Diazotization Method; Nitrate-Nitrogen, Cadmium

Reduction Method; Phosphate-Phosphorous, Ascorbic Acid Method). Sample pH was determined using a remote reading pH meter supplied by McMaster-Carr, USA.

Data Analysis

Data were analyzed as mean nutrient, pH, and turbidity concentration levels in stormwater runoff using a One-Way ANOVA model with roof treatments as the independent variable. For each of the water quality characteristics, significant differences between roof treatments were determined using post-hoc analysis for multiple comparisons with Tukey HSD adjustments. All statistics were run using IBM SPSS 20.0 statistical software (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp).

RESULTS

During the study (22 July, 2010 – 24 September, 2012) there were a total of 17 sampled rain events. During this data collection period, daily precipitation totals ranged from 0.25 mm to 58.32 mm for the individual rain events (Figure 10). Daily low temperatures ranged from -18.2°C to 23.3°C and daily high temperatures ranged from -12.2°C to 35.3°C (Figure 11). Through analysis of the collected data, there are several statistical similarities and differences between roof treatment types with respect to each individually tested water quality parameter.

Results of the One-Way ANOVA model are shown in Table 1. The Tukey's HSD Model of Multiple Comparisons showed significant similarities between different roof treatments, both green and conventional, when looking at the individually tested water quality parameters (Tables 2-7). Continuing to divide the data, the Homogenous Subsets further illustrate the similarities of the different roof treatments with respect to the individually monitored water quality characteristics (Tables 8-13).

Nutrients

With respect to the observed average Nitrate-Nitrogen (NO_3-N) levels, concentrations in stormwater runoff ranged from 0.07-.93 mg/L for green roof with *Sedum*, 0.15-1.20 mg/L for green roof with grasses, 0.43-5.10 mg/L for green roof with media only, 0.10-.97 mg/L for conventional roof with metal, 0 .02-.53 mg/L for conventional roof with shingle, and 0.20-.80 mg/L for rainwater (Figure 12). Media only roof (no vegetation cover) produced the highest concentration of NO_3-N on 2 August, 2012 at 5.10 mg/L while the conventional shingle roof produced the lowest concentration of NO_3-N on 14 August, 2010 at .02 mg/L.

Observed average Nitrite-Nitrogen (NO_2-N) levels for concentrations in stormwater runoff ranged from 0.003-0.148 mg/L for green roof with *Sedum,* 0.002-0.148 mg/L for green roof with grasses, 0.003-0.149 mg/L for green roof with media only, 0.003-0.037 mg/L for conventional roof with metal, 0.003-0.036 mg/L for conventional roof with shingle, 0.001-0.017 mg/L and 0.003-0.036 mg/L for rainwater (Figure 13). Media only roofs produced the highest concentration of NO_2-N on 2 August, 2012 at 0.149 mg/L while green roofs with grasses produced the lowest concentration of NO_2-N on 24 September, 2012 at 0.002 mg/L.

With respect to the observed average Ammonia-Nitrogen (NH_3-N) levels, concentrations in stormwater runoff ranged from .01-2.00 mg/L for green roof with *Sedum*, .01-1.67 mg/L for green roof with grasses, .00-.70 mg/L for green roof with media only, .02-1.16 mg/L for conventional roof with metal, .00-1.00 mg/L for conventional roof with shingle, and .03-1.00 mg/L for rainwater (Figure 14). Green roofs with *Sedum* produced the highest concentration of NH_3-N on 3 August, 2011 at 2.00 mg/L while green roofs with media only and conventional roofs with shingle both produced the lowest concentration of NH_3-N on 24 September, 2012 and 20 October, 2011, respectively, at .00 mg/L.

Looking at the observed average Phosphate-Phosphorous (PO_4-P) levels, concentrations in stormwater runoff ranged from 0.11-5.39 mg/L for green roof with *Sedum*, 0.12-3.31 mg/L for green roof with grasses, 0.12-3.73 mg/L for green roof with media only, 0.01-1.71 mg/L for conventional roof with metal, 0.01-1.66 mg/L for conventional roof with shingle, and 0.09-2.10 mg/L for rainwater (Figure 15). Green roofs with *Sedum* produced the highest concentration of PO_4-P on 3 August, 2011 at 5.39 mg/L while conventional roof with metal and conventional roof with shingle both produced the lowest concentration of PO_4-P together on 2 July, 2010, August 14, 2010, and 19 August, 2010 at 0.01 mg/L.

When comparing the different green roof treatments, it was found that there is a significant ($p \geq 0.05$) relationship between green roof vegetative treatments and concentration of the nutrients Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and Phosphate-Phosphorous (PO_4-P) in stormwater runoff with the native grass roofing treatment releasing runoff with lower concentrations of these nutrients than the *Sedum* roofing treatment (Hypothesis 1a: Accepted). This relationship was found due to the fact that *Sedum* planted green roofs produced runoff that contained significantly higher levels of Phosphate-Phosphorous (PO_4-P) than green roofs planted with native grass. There were no significant differences between *Sedum* and grass covered green roofs with respect to NO_3-N, NO_2-N and NH_3-N.

In addition, it was found that here is a significant ($p \geq 0.05$) relationship between green roof vegetative treatments and concentration of the nutrients Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and Phosphate-Phosphorous (PO_4-P) in stormwater runoff with the native grass roofing treatment releasing runoff with lower concentrations of these nutrients than the media-only roofing treatment (Hypothesis 1b: Accepted). This relationship was found due to the fact that the media only green roofs produced runoff that contained significantly higher levels of Nitrate-Nitrogen (NO_3-N) than green roofs planted with native grass. There were no significant differences between media only and grass covered green roofs with respect to NO_2-N, NH_3-N and PO_4-P.

Furthermore, it was found that there is a significant ($p \geq 0.05$) relationship between green roof vegetative treatments and concentration of the nutrients Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and Phosphate-Phosphorous (PO_4-P) in stormwater runoff with the *Sedum* roofing treatment releasing runoff with lower concentrations of these nutrients than the media-only roofing treatment (Hypothesis 1c: Accepted). This relationship was found due to the fact that the media only green roofs produced runoff that contained significantly higher levels of Nitrate-Nitrogen (NO_3-N) than *Sedum* planted green roofs. In addition to the previously stated, it was shown that *Sedum* planted green roofs produced higher levels of Phosphate-Phosphorous (PO_4-P) than the green roofs with media only. There were no significant differences between *Sedum* and media only green roofs with respect to NO_2-N and NH_3-N.

When comparing green roof treatments to traditional roofing treatments, it was found that there is a significant ($p \geq 0.05$) relationship between green roof and traditional (steel and shingle) roofing treatments with respect to concentration of the nutrients Nitrate-Nitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonia-Nitrogen (NH_3-N), and Phosphate-Phosphorous (PO_4-P) in stormwater runoff with all green roof treatments releasing stormwater runoff with higher concentrations of these nutrients than both traditional steel and shingle roofing treatments (Hypothesis 2a: Accepted).

pH.

Average pH levels in stormwater runoff ranged from 6.53-8.94 pH for green roof with *Sedum*, 6.66-9.71 pH for green roof with grasses, 6.57-9.38 pH for green roof with media only, 5.55-7.05 pH conventional roof with metal, 6.06-6.75 pH for conventional roof with shingle, and 6.16-6.93 pH for rainwater (Figure 17). Green roofs with grasses produced the highest pH levels on 14 August, 2010 at 9.7 pH while conventional roof with metal produced the lowest pH levels on 19 August, 2010 at 5.55 pH.

When comparing green roof treatments to traditional roofing treatments, it was found that there is a significant ($p \geq 0.05$) relationship between green roof and traditional roofing treatments with respect to pH levels in stormwater runoff with all green roof treatments releasing stormwater runoff with higher pH levels than both traditional steel and shingle roofing treatments (Hypothesis 3a: Accepted).

Turbidity

With respect to the observed average Turbidity, levels in stormwater runoff ranged from 0.507-4.085 NTU for green roof with *Sedum*, 0.626-7.484 NTU for green roof with grasses, 0.603-5.093 NTU for green roof with media only, 0.112-3.063 NTU for conventional roof with metal, 0.096-4.227 NTU for conventional roof with shingle, and 0.070-2.730 NTU for rainwater (Figure 16). Green roofs with grasses produced the highest levels of turbidity on 3 August, 2011 at 7.484 NTU while conventional roof with shingle produced the lowest levels of turbidity on 25 September, 2011 at 0.096 NTU.

When comparing green roof treatments to traditional roofing treatments, it was found that there is a significant ($p \geq 0.05$) relationship between green roof and traditional roofing treatments with respect to turbidity (NTU) levels in stormwater runoff with all green roof treatments releasing stormwater runoff with higher turbidity levels than both traditional steel and shingle roofing treatments (Hypothesis 4a: Accepted)

DISCUSSION

Significant relationships between green roof treatments themselves, as well as differences between green roof and conventional roofing treatments allow for comparison of different roofing treatments and the subsequent outcomes of stormwater runoff quality released from these systems. It was originally assumed that the green roofs with native grass species would absorb the most, and release the least amount of nutrients in observed stormwater runoff. This has proven to not always be the case. It was also assumed that green roofs, of all vegetative types, would produce stormwater runoff with significantly different levels of turbidity and pH when compared to traditional roofing materials. This was proven to be true with green roofs, or all roofing treatments producing stormwater runoff with higher levels of pH and turbidity than the tested traditional roofing treatments.

There was no significant difference in pH concentrations between green roof treatments, but the study did show that green roof planted with media only did produce significantly higher levels of turbidity then green roof treatment of *Sedum* and Grasses.

The strongest and most consistent outcome when comparing green roof planting treatments with respect to nutrient levels in stormwater runoff was the fact that green roofs with media only (no vegetation) released more NO_3-N than grass and *Sedum* planted roofs for this specified green roof system. This leads to believe that green roofs with vegetation, whether grass or *Sedum* planted, are absorbing more NO_3-N due to the vegetation uptake of this major nitrogen component in observed green roof systems. Berghage in USEPA (2009b) suggested similar relationships from observed green roof installments and speculated that new roofs without full plant cover may contribute to nitrate runoff as opposed to fully established green roofs, which may not. NO_3-N is probably the most important nitrogen compound in natural systems as it makes up the majority of TKN (total Kjeldahl nitrogen). TKN defines the total nitrogen in a system by combining the components of nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen, and organic nitrogen. When looking at the vegetated green roofs, *Sedum* planted roofs released higher amounts of PO_4-P than green roofs planted with native grasses. This would lead one to believe that native grass green roofs uptake more phosphorous-phosphate than *Sedum* planted green roofs. This could guide designers to use native grasses as a means of controlling PO_4-P runoff from green roofs. Since phosphorous is usually the *limiting nutrient* in natural systems, this finding is more important than relations regarding to nitrogen concentrations when focusing on nutrient availability and aquatic plant growth.

It was initially thought that between the green roof treatments (i.e. *Sedum* versus Grasses), roofs planted with grasses would uptake more, and release fewer nutrients in stormwater runoff. The reasoning for this was that the grasses have more above ground biomass that would require more nutrients to support growth. Also, grasses have a more extensive and dense rooting system that would allow for the uptake of larger amounts of available nutrients. This fact was not distinguishable between the grass and *Sedum* planted roofs as there was not enough significance to say that the grasses performed better at absorbing nutrients than the *Sedum* species with respect to all observed nutrients. The vegetated green roofs, though, performed better than media only green roofs most consistently with respect to nitrate-nitrogen. This leads one to believe that the plants on green roofs are taking up more available nitrate-nitrogen in the system. No conclusion could be made between vegetated and non-vegetated roofs with respect to NO_2-N, NH_3-N and PO_4-P. If this is correct, a case can be made to maximize the health and density of vegetation on a green roof as it would uptake more and release fewer nutrients than roofs with large areas of bare soil. This fact could influence maintenance and watering regimes in attempts to achieve the greatest green roof plant coverage as possible.

Though this study did not address the issue, decomposition of above ground plant material and soil organics can (and may have) contribute to overall available nutrients, and pH in a system and could potentially increase the nutrient levels, pH, and turbidity in stormwater runoff of green roofs with vegetation. Also, seeing as the plants were still early in their establishment, total vegetation coverage and root mass also could have affected the amount of nutrients uptake of these different green roof systems as observed in this study. Ideally, studies should continue, or be re-administered as the experimental roofs develop over a 10-20 year period.

Until now, no green roof studies have been performed to quantify and categorize the results of green roof stormwater runoff quality with these exact system parameters. Previous research dealing with green roof runoff water quality has been difficult to compare to this study because of the comparative inconsistencies in the materials and methods of the tested green roof systems (i.e. individually observed water quality characteristics, media depth and composition, plant coverage, root mass ratio to above ground biomass, roof age, geographic location, maintenance and fertilization practices, etc.). A significant influence on stormwater runoff quality can be brought about by these characteristics and individual studies cannot be compared unless all independent variables are consistent when comparing green roofs with different vegetation types.

Testable hypothesis H2a was accepted due to the fact that all green roof treatments (grass, *Sedum*, and media only) were found to release more NO_3-N, NO_2-N, NH_3-N, and PO_4-P than both the steel and shingle roof treatments. This corresponds to the findings of Berghage in USEPA (2009b) and is generally contributed to the stormwater interaction with the vegetative materials and growing media organics. Berndtsson et al. (2006), when researching existing green roofs of different sizes, component design, vegetation treatments and age, found multiple studied green roofs to be a "sink" of NO_3-N in which stormwater runoff from these roofs contained less Nitrate-Nitrogen than collected rainwater. Alternatively, he did find green roofs to be a source of PO_4-P from all observed green roofs. Gregorie and Clausen (2011) found similar results from an existing 248 m² green roof consisting of extensive modules planted with *Sedum spp.* when compared to a conventional bituminous tar roof with the green roofs proving to be a sink for NO_3-N and a source of PO_4-P. Opposite of these findings, Toland et al. (2012) was not able to distinguish a significant difference between conventional and green roofs with respect to NO_3-N, NO_2-N and NH4-N in stormwater runoff.

The highest Phosphate-Phosphorous (PO_4-P) concentration of all observed green roof treatments came on August 3, 2011 from *Sedum* planted green roofs at a level of 5.39 mg/L in runoff. This is well above the Michigan Department of Environmental Quality standard for point source discharges of 1.0 mg/L (MDEQ, 2012), but can be attributed to the fact that this study collected mainly the "first flush" of green roof runoff. This first flush is the highest in nutrient concentration but is then combined with the remainder of cleaner, less polluted green roof runoff, which would dilute the water and reduce the overall concentrations of pollutants at that scale (Berndtsson et al., 2008). More research can be done to determine the effect of mass loading of pollutants on a larger, more applicable scale.

The highest Nitrate-Nitrogen (NO_3-N) concentration of all observed green roof treatments came on August 2, 2012 from media only green roofs at a level of 5.10 mg/L. This is well below the guidelines for drinking water standards set by the U.S. EPA at 10.0 mg/L (USEPA, 2012a), but is above other Great Lake Region state standards like Minnesota who limits NO_3-N concentrations to 0.012 mg/L for lakes with trout and 0.09 mg/L for shallow lakes and reservoirs in Minnesota. (USEPA, 2012b). Again, this could be contributed to the fact that this study collected mostly first flush runoff of these smaller-scaled, representative green roof installations. These reductions of Nitrate-Nitrogen and Phosphate-Phosphorous over time were also observed in Berndtsson (2010), Berndtsson et al. (2006), Hathaway et al. (2008) and Van Seters et al. (2009).

Testable hypothesis H3a was accepted due to the fact that all green roof treatments were found to release stormwater runoff with a higher pH level than both conventional steel and shingle roofs. This corresponds to findings of Berndtsson at al. (2009), Retzlaff et al. (2008), and Berghage in USEPA (2009b) that also found green roofs releasing stormwater with higher pH levels. Higher pH levels indicate less acidic, and more alkaline, water properties. This is generally good for the environment as it is a combatant to the dwindling occurrences of "acid" rains found downwind of industrialized as well as urbanized areas.

Testable hypothesis H4a was accepted due to the fact that all green roof treatments produced stormwater runoff with higher turbidity levels than both conventional steel and shingle roofs. This contradicts findings from Bliss (2009) in which green roofs were found to produce less turbid runoff than runoff from a conventional ballasted membrane roof. However, green roofs still produced higher turbidity levels than what was found in collected rainwater. Due to the presence of granular growing media and the media's proximity to the roof's drainage outlet, solids are allowed to release from the system at different amounts depending on the system's filtration system.

Though the influences of roof age on runoff water quality of green roofs was not a focus of this study, nor were statistical comparisons made to compare these two variables, it is clear that the age of the green roof affected both turbidity as well as pH levels in green roof runoff. Throughout the 3 year sampling period, it was observed that pH and turbidity levels of green roof treatments leveled off and became more consistent with runoff from the conventional roofing treatments. Berghage in USEPA (2009b) found similar results and stated that over time, a green roofs pH buffering capacity (mainly a product of the growing media make-up) would decline over time, much like older European roofs, and acidification of stormwater runoff would occur. In this study, the decline in observed turbidity in green roof runoff was attributed to the establishments, construction methods, maintenance and filtering components of these roofs. Essentially, loose media that was present from initial construction was believed to be washed out over the first season and turbidity levels in stormwater runoff continued to decline over the course of this study. A more complex and thorough runoff filtration system could be used to reduce the initial levels of turbidity in stormwater runoff of the observed green roofs and lower levels to what was typically seen from conventional roof runoff.

Though a roof slope of 33.33% was a consistent factor across all green roof and traditional roofing treatments, it is believed that roof slope has minimal effect on the concentrations of observed runoff quality characteristics in stormwater runoff. Additional studies with roof slope being the only variable could be performed to determine if it truly has an effect on water quality of stormwater runoff from green and conventional roofing treatments.

CONCLUSION

In conclusion, this study focused on steep sloped green, media and conventional roofing types under steep slope (33.33%) conditions, though roof slope was thought to have no effect on the outcomes of this study. It focused on runoff water *quality* characteristics among these five roofing materials. In regards, the data corroborated earlier studies on the quality of runoff water emanating from different roof treatments. For example, some green roof vegetation treatments performed better than others with respect to individual water quality characteristics. It also solidifies findings of past research that green roofs can be a less than 100% successful treatment with respect to the *quality* of any water released from these systems. Given the study design, more research could be done with fully established large scale green roofs to provide quantifiable information that could be applied on city or region wide models to predict the impact of green roofs on stormwater runoff quality in an area.

Green roof component design, including media composition, construction materials and methods could also be tailored to increase the water quality of green roof runoff. Green roof growing media amendments, such as biochar with a high exchange capacity, can increase the retention of nutrients in green roof systems, releasing less in stormwater runoff and making the nutrients more available for plant uptake (Beck et al., 2012)

When looking at building and site systems as a whole, green roofs can be a legitimate mean of stormwater *quantity* management as shown by Cronk (2012) but may require further on-site treatment of runoff to address increased nutrient, pH and turbidity levels. Additional on-site measures can be taken to address these water quality issues in the form of recycling green roof stormwater runoff to a rooftop before costly in ground bioretention and infiltration systems are used. Addressing this issue on-site, before any site runoff can occur, will combat one of the few negative aspects of green roofs and continue to hold green roofs as a viable tool in stormwater management.

APPENDIX

Table 1: One-way ANOVA table for respective water quality characteristics in stormwater runoff from five roof platform treatments replicated three times. Study was completed over 3 growing seasons (22 July, 2010 – 24 September, 2012). Levels of pollutants in stormwater runoff are the dependent variables. Roof treatments are the independent variables.

One-Way ANOVA for Study Sample						
	Type of Variance	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F-Statistic**	**P-Statistic**
Mean NO_3-N (mg/L)	Between Groups (All Treatments)	5.877	4	1.469	38.529	0.000
	Within Groups (Individual Treatments)	0.381	10	0.038		
	Total	6.258	14			
Mean NO_2-N (mg/L)	Between Groups (All Treatments)	0.002	4	0.000	10.238	0.001
	Within Groups (Individual Treatments)	0.000	10	0.000		
	Total	0.002	14			
Mean NH_3-N (mg/L)	Between Groups (All Treatments)	0.074	4	0.019	8.689	0.003
	Within Groups (Individual Treatments)	0.021	10	0.002		
	Total	0.095	14			
Mean PO_4-P (mg/L)	Between Groups (All Treatments)	6.921	4	1.730	342.491	0.000
	Within Groups (Individual Treatments)	0.051	10	0.005		
	Total	6.972	14			
Mean NTU	Between Groups (All Treatments)	7.606	4	1.902	71.519	0.000
	Within Groups (Individual Treatments)	0.266	10	0.027		
	Total	7.872	14			
Mean pH	Between Groups (All Treatments)	5.606	4	1.402	133.514	0.000
	Within Groups (Individual Treatments)	0.105	10	0.010		
	Total	5.711	14			

Table 2: Tukey's HSD test for multiple comparisons of Nitrate-Nitrogen (NO_3-N) for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Multiple Comparisons - Tukey's HSD							
Dependent Variable	**Treatment (I)**	**Treatment (J)**	**Mean Difference (I-J)**	**Standard Error**	**Significance**	**95% - Lower Bound**	**95% - Upper Bound**
Mean NO_3-N	G	S	0.18941	0.15944	0.758	-0.3353	0.7141
		M	-1.3449*	0.15944	0	-1.8696	-0.8202
		CM	0.28	0.15944	0.446	-0.2447	0.8047
		CS	0.31431	0.15944	0.344	-0.2104	0.839
	S	G	-0.18941	0.15944	0.758	-0.7141	0.3353
		M	-1.53431*	0.15944	0	-2.059	-1.0096
		CM	0.09059	0.15944	0.977	-0.4341	0.6153
		CS	0.1249	0.15944	0.93	-0.3998	0.6496
	M	G	1.3449*	0.15944	0	0.8202	1.8696
		S	1.53431*	0.15944	0	1.0096	2.059
		CM	1.6249*	0.15944	0	1.1002	2.1496
		CS	1.65922*	0.15944	0	1.1345	2.1839
	CM	G	-0.28	0.15944	0.446	-0.8047	0.2447
		S	-0.09059	0.15944	0.977	-0.6153	0.4341
		M	-1.6249*	0.15944	0	-2.1496	-1.1002
		CS	0.03431	0.15944	0.999	0.4904	0.559
	CS	G	-0.31431	0.15944	0.344	-0.839	0.2104
		S	-0.1249	0.15944	0.93	-0.6496	0.3998
		M	-1.65922*	0.15944	0	-2.1839	-1.1345
		CM	-0.03431	0.15944	0.999	-0.559	0.4904

Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing).
All roof treatments were replicated three times.

Mean differences denoted with "*" are significant at a level ≥ 0.05

Table 3: Tukey's HSD test for multiple comparisons of Nitrite-Nitrogen (NO_2-N) for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Multiple Comparisons - Tukey's HSD							
Dependent Variable	**Treatment (I)**	**Treatment (J)**	**Mean Difference (I-J)**	**Standard Error**	**Significance**	**95% - Lower Bound**	**95% - Upper Bound**
Mean NO_2-N	G	S	0.00688	0.00566	-0.0118	-0.0118	0.0255
		M	-0.00729	0.00566	-0.0259	-0.0259	0.0113
		CM	0.01808	0.00566	-0.0006	-0.0006	0.0367
		CS	0.02402*	0.00566	0.0054	0.0054	0.0427
	S	G	-0.00688	0.00566	0.0255	-0.0255	0.0118
		M	-0.01418	0.00566	-0.0328	-0.0328	0.0045
		CM	0.0112	0.00566	-0.0074	-0.0074	0.0298
		CS	0.01714	0.00566	-0.0015	-0.0015	0.0358
	M	G	0.00729	0.00566	-0.0113	-0.0113	0.0259
		S	0.01418	0.00566	-0.0045	-0.0045	0.0328
		CM	0.02537*	0.00566	0.0067	0.0067	0.044
		CS	0.03131*	0.00566	0.0127	0.0127	0.05
	CM	G	-0.01808	0.00566	-0.0367	-0.0367	0.0006
		S	-0.0112	0.00566	-0.0298	-0.0298	0.0074
		M	-0.02537*	0.00566	-0.044	-0.044	-0.0067
		CS	0.00594	0.00566	-0.0127	-0.0127	0.0246
	CS	G	-0.02402*	0.00566	0.012	-0.0427	-0.0054
		S	-0.01714	0.00566	0.075	-0.0358	0.0015
		M	-0.03131*	0.00566	0.002	-0.05	-0.0127
		CM	-0.00594	0.00566	0.827	-0.0246	0.0127

Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing).
All roof treatments were replicated three times.

Mean differences denoted with "*" are significant at a level ≥ 0.05

Table 4: Tukey's HSD test for multiple comparisons of Ammonia-Nitrogen (NH_3-N) for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Multiple Comparisons - Tukey's HSD							
Dependent Variable	**Treatment (I)**	**Treatment (J)**	**Mean Difference (I-J)**	**Standard Error**	**Significance**	**95% - Lower Bound**	**95% - Upper Bound**
Mean NH_3-N	G	S	0.00863	0.03768	0.999	-0.1154	0.1327
		M	0.09216	0.03768	0.18	-0.0319	0.2162
		CM	0.10251	0.03768	0.12	-0.0215	0.2265
		CS	0.19196*	0.03768	0.003	0.0679	0.316
	S	G	-0.00863	0.03768	0.999	-0.1327	0.1154
		M	0.08353	0.03768	0.249	-0.0405	0.0276
		CM	0.09388	0.03768	0.169	-0.0301	0.2179
		CS	0.18333*	0.03768	0.005	0.0593	0.3074
	M	G	-0.09216	0.03768	0.18	-0.2162	0.0319
		S	-0.08353	0.03768	0.249	-0.2076	0.0405
		CM	0.01035	0.03768	0.999	-0.1137	0.1344
		CS	0.0998	0.03768	0.134	-0.0242	0.2238
	CM	G	-0.10251	0.03768	0.12	-0.2265	0.0215
		S	-0.09388	0.03768	0.169	-0.2179	0.0301
		M	-0.01035	0.03768	0.999	-0.1344	0.1137
		CS	0.08945	0.03768	0.2	-0.0346	0.2135
	CS	G	-0.19196*	0.03768	0.003	-0.316	-0.0679
		S	-0.18333*	0.03768	0.005	-0.3074	-0.0593
		M	-0.0998	0.03768	0.134	-0.2238	0.0242
		CM	-0.08945	0.03768	0.2	-0.2135	0.0346

Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing).
All roof treatments were replicated three times.

Mean differences denoted with "*" are significant at a level ≥ 0.05

Table 5: Tukey's HSD test for multiple comparisons of Phosphate-Phosphorous (PO_4-P) for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Multiple Comparisons - Tukey's HSD							
Dependent Variable	**Treatment (I)**	**Treatment (J)**	**Mean Difference (I-J)**	**Standard Error**	**Significance**	**95% - Lower Bound**	**95% - Upper Bound**
Mean PO_4-P	G	S	-0.45098*	0.05804	0	-0.642	-0.26
		M	-0.0902	0.05804	0.554	-0.2851	0.1008
		CM	1.16196*	0.05804	0	0.971	1.353
		CS	1.18098*	0.05804	0	0.99	1.372
	S	G	0.45098*	0.05804	0	0.26	0.642
		M	0.36078*	0.05804	0.001	0.1698	0.5518
		CM	1.61294*	0.05804	0	1.4219	1.8039
		CS	1.63196*	0.05804	0	1.441	1.823
	M	G	0.0902	0.05804	0.554	-0.1008	0.2812
		S	-0.36078*	0.05804	0.001	-0.5518	-0.1698
		CM	1.25216*	0.05804	0	1.0612	1.4432
		CS	1.27118*	0.05804	0	1.0802	1.4622
	CM	G	-1.16196*	0.05804	0	-1.353	-9710
		S	-1.61294*	0.05804	0	-1.8039	-1.4219
		M	-1.25216*	0.05804	0	-1.4432	-1.0612
		CS	0.01902	0.05804	0.997	-0.172	0.21
	CS	G	-1.18098*	0.05804	0	-1.372	-0.99
		S	-1.63196*	0.05804	0	-1.823	-1.441
		M	-1.27118*	0.05804	0	-1.4622	-1.0802
		CM	-0.01902	0.05804	0.997	-0.21	0.172

Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing).
All roof treatments were replicated three times.

Mean differences denoted with "*" are significant at a level ≥ 0.05

Table 6: Tukey's HSD test for multiple comparisons of Turbidity (NTU) for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Multiple Comparisons - Tukey's HSD							
Dependent Variable	**Treatment (I)**	**Treatment (J)**	**Mean Difference (I-J)**	**Standard Error**	**Significance**	**95% - Lower Bound**	**95% - Upper Bound**
Mean NTU	G	S	0.09747	0.13314	0.944	-0.3407	0.5356
		M	0.63599*	0.13314	0.005	0.1978	1.0742
		CM	1.79093*	0.13314	0	1.3528	2.2291
		CS	1.42728*	0.13314	0	0.9891	1.8654
	S	G	-0.09747	0.13314	0.944	-0.5356	0.3407
		M	0.53852*	0.13314	0.016	0.1003	0.9767
		CM	1.69346*	0.13314	0	1.2553	2.1316
		CS	1.32981*	0.13314	0	0.8916	1.768
	M	G	-0.63599*	0.13314	0.005	-1.0742	-0.1978
		S	-0.53852*	0.13314	0.016	-0.9767	-0.1003
		CM	1.15495*	0.13314	0	0.7168	1.5931
		CS	0.7913*	0.13314	0.001	0.3531	1.2295
	CM	G	-1.79093*	0.13314	0	-2.2291	-1.3528
		S	-1.69346*	0.13314	0	-2.1316	-1.2553
		M	-1.15495*	0.13314	0	-1.5931	-0.7168
		CS	-0.36365	0.13314	0.118	-0.8018	0.0745
	CS	G	-1.42728*	0.13314	0	-1.8654	-0.9891
		S	-1.32981*	0.13314	0	-1.768	-0.8916
		M	-0.7913*	0.13314	0.001	-1.2295	-0.3531
		CM	0.36365	0.13314	0.118	-0.0745	0.8081

Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing).
All roof treatments were replicated three times.

Mean differences denoted with "*" are significant at a level ≥ 0.05

Table 7: Tukey's HSD test for multiple comparisons of pH for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Multiple Comparisons - Tukey's HSD							
Dependent Variable	**Treatment (I)**	**Treatment (J)**	**Mean Difference (I-J)**	**Standard Error**	**Significance**	**95% - Lower Bound**	**95% - Upper Bound**
Mean pH	G	S	0.18667	0.08366	0.244	-0.0886	0.462
		M	0.11353	0.08366	0.665	-0.1618	0.3888
		CM	1.30118*	0.08366	0	1.0259	1.5765
		CS	1.38078*	0.08366	0	1.1055	1.6561
	S	G	-0.18667	0.08366	0.244	-0.462	0.0886
		M	-0.07314	0.08366	0.9	-0.3485	0.2022
		CM	1.11451*	0.08366	0	0.8392	1.3898
		CS	1.19412*	0.08366	0	0.9188	1.4694
	M	G	-0.11353	0.08366	0.665	-0.3888	0.1618
		S	0.07314	0.08366	0.9	-0.2022	0.3485
		CM	1.18765*	0.08366	0	0.9123	1.463
		CS	1.26725*	0.08366	0	0.9919	1.5426
	CM	G	-1.30118*	0.08366	0	-1.5765	-1.0259
		S	-1.11451*	0.08366	0	-1.3898	-0.8392
		M	-1.18765*	0.08366	0	-1.463	-0.9123
		CS	0.07961	0.08366	0.87	-0.1957	0.3549
	CS	G	-1.38078*	0.08366	0	-1.6561	-1.1055
		S	-1.19412*	0.08366	0	-1.4694	-0.9188
		M	-1.26725*	0.08366	0	-1.5426	-0.9919
		CM	-0.07961	0.08366	0.87	-0.3549	0.1957

Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing).
All roof treatments were replicated three times.

Mean differences denoted with "*" are significant at a level ≥ 0.05

Table 8: Homogenous subset of recorded NO_3-N data for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Mean NO_3-N			
		Subsets for Alpla = 0.05	
Treatment	N	1	2
CS	3	0.2682	
CM	3	0.3025	
S	3	0.3931	
G	3	0.5825	
M	3		1.9275
Significance		0.344	1.000

Table 9: Homogenous subset of recorded NO_2-N data for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Mean NO_2-N				
		Subsets for Alpla = 0.05		
Treatment	N	1	2	3
CS	3	0.0108		
CM	3	0.0167	0.0167	
S	3	0.0279	0.0279	0.0279
G	3		0.0348	0.0348
M	3			0.0421
Significance		0.075	0.058	0.166

Table 10: Homogenous subset of recorded NH_3-N data for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Mean NH_3-N			
		Subsets for Alpla = 0.05	
Treatment	N	1	2
CS	3	0.2294	
CM	3	0.3189	0.3189
M	3	0.3292	0.3292
S	3		0.4127
G	3		0.4214
Significance		0.134	0.120

Table 11: Homogenous subset of recorded PO_4-P data for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012)..

Mean PO4-P				
		Subsets for Alpla = 0.05		
Treatment	N	1	2	3
CS	3	0.3043		
CM	3	0.3233		
G	3		1.4853	
M	3		1.5755	
S	3			1.9363
Significance		0.997	0.554	1.000

Table 12: Homogenous subset of recorded NTU data for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Mean NTU				
		Subsets for Alpla = 0.05		
Treatment	N	1	2	3
CM	3	0.9586		
CS	3	1.3222		
M	3		2.1135	
S	3			2.6520
G	3			2.7495
Significance		0.118	1.000	0.940

Table 13: Homogenous subset of recorded pH data for all roof treatments during the study's 3 growing seasons (22 July, 2010 – 24 September, 2012).

Mean pH			
		Subsets for Alpla = 0.05	
Treatment	N	1	2
CS	3	6.4196	
CM	3	6.4992	
S	3		7.6137
M	3		7.6869
G	3		7.8004
Significance		0.870	0.244

Table 14: Data from rain event 22 July, 2010. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: July 22, 2010						
Treatment	**Nitrate-Nitrogen (NO_3-N)**	**Nitrite-Nitrogen (NO_2-N)**	**Ammonia-Nitrogen (NH_3-N)**	**Phosphate-Phosphorous (PO_4-P)**	**Turbidity (NTUs)**	**pH**
G1	0.32	0.064	0.21	0.20	4.43	9.01
G2	0.23	0.077	0.31	0.23	3.38	8.66
G3	0.40	0.064	0.45	0.21	2.65	8.04
G Average	0.32	0.069	0.33	0.21	3.49	8.57
M1	2.06	0.058	0.69	0.20	3.49	8.83
M2	1.97	0.053	0.31	0.20	2.69	7.79
M3	2.11	0.078	0.67	0.24	3.28	7.33
M Average	2.05	0.063	0.56	0.22	3.15	7.98
S1	0.17	0.048	0.45	0.15	3.48	7.99
S2	0.10	0.082	1.17	0.18	5.19	8.69
S3	0.15	0.096	1.53	0.36	9.86	8.78
S Average	0.14	0.075	1.05	0.23	6.18	8.49
CM1	0.09	0.038	0.07	0.01	4.56	6.98
CM2	0.15	0.032	0.06	0.01	0.94	6.49
CM3	0.11	0.041	0.07	0.01	0.85	6.33
CM Average	0.11	0.037	0.07	0.01	2.12	6.60
CS1	0.21	0.039	0.12	0.01	2.32	6.14
CS2	0.18	0.037	0.12	0.01	2.05	6.14
CS3	0.09	0.037	0.05	0.01	1.49	6.36
CS Average	0.16	0.037	0.10	0.01	1.95	6.21
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 15: Data from rain event 14 August, 2010. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: August 14, 2010						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
G1	0.20	0.046	0.11	0.09	5.41	10.28
G2	0.68	0.080	0.48	0.16	3.14	9.32
G3	0.64	0.062	0.12	0.13	3.83	9.53
G Average	0.50	0.063	0.24	0.13	4.13	9.71
M1	1.99	0.128	0.14	0.13	3.97	9.38
M2	1.98	0.097	0.09	0.09	4.72	9.73
M3	2.00	0.159	0.19	0.18	3.22	9.02
M Average	1.99	0.128	0.14	0.13	3.97	9.38
S1	0.18	0.057	0.20	0.17	4.09	9.15
S2	0.20	0.054	0.08	0.14	5.12	9.20
S3	0.15	0.061	0.33	0.19	3.05	9.09
S Average	0.18	0.057	0.20	0.17	4.09	9.15
CM1	0.02	0.023	0.03	0.01	1.07	7.30
CM2	0.27	0.011	0.07	0.01	1.73	6.44
CM3	0.10	0.012	0.09	0.01	1.85	6.75
CM Average	0.13	0.016	0.06	0.01	1.55	6.83
CS1	0.01	0.013	0.02	0.01	1.29	6.75
CS2	0.03	0.018	0.05	0.01	0.98	5.61
CS3	0.01	0.021	0.01	0.01	0.55	5.83
CS Average	0.02	0.018	0.03	0.01	0.94	6.06
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 16: Data from rain event 19 August, 2010. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: August 19, 2010						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
G1	0.06	0.037	0.14	0.12	5.32	9.30
G2	0.15	0.061	0.22	0.11	5.51	9.97
G3	0.32	0.037	0.20	0.13	4.56	9.52
G Average	0.18	0.045	0.19	0.12	5.13	9.60
M1	0.86	0.035	0.21	0.08	6.56	9.56
M2	0.57	0.034	0.20	0.11	5.10	8.80
M3	1.96	0.035	0.26	0.17	3.62	8.44
M Average	1.13	0.034	0.22	0.12	5.09	8.93
S1	0.06	0.025	0.26	0.08	5.91	8.21
S2	0.08	0.027	0.15	0.13	5.44	9.55
S3	0.06	0.030	0.29	0.13	5.29	9.05
S Average	0.07	0.027	0.23	0.11	5.55	8.94
CM1	0.09	0.016	0.21	0.01	3.10	5.72
CM2	0.15	0.010	0.35	0.01	3.07	5.32
CM3	0.15	0.010	0.39	0.01	1.94	5.61
CM Average	0.13	0.012	0.32	0.01	2.70	5.55
CS1	0.12	0.020	0.32	0.01	3.73	6.26
CS2	0.25	0.019	0.45	0.01	2.24	6.02
CS3	0.08	0.014	0.24	0.01	2.85	6.10
CS Average	0.15	0.018	0.34	0.01	2.94	6.13
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 17: Data from rain event 3 August, 2011. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: August 3, 2011						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
G1	0.9	0.023	2.00	2.66	5.87	8.92
G2	1.5	0.010	1.00	2.62	6.94	8.21
G3	1.2	0.037	1.00	3.20	9.64	8.34
G Average	1.2	0.023	1.33	2.83	7.48	8.49
M1	4.6	0.020	1.00	2.75	3.22	7.92
M2	4.2	0.044	1.00	2.57	3.74	7.83
M3	5.5	0.018	0.00	2.46	4.77	7.69
M Average	4.8	0.027	0.67	2.59	3.91	7.81
S1	0.7	0.011	2.00	5.17	5.81	8.01
S2	0.4	0.014	2.00	5.50	6.18	7.81
S3	0.1	0.003	2.00	5.50	5.20	7.87
S Average	0.4	0.009	2.00	5.39	5.73	7.90
CM1	0.6	0.005	0.62	0.19	0.22	6.65
CM2	0.2	0.005	0.41	0.20	0.37	6.69
CM3	0.4	0.010	0.55	0.51	0.71	6.40
CM Average	0.4	0.007	0.53	0.30	0.43	6.58
CS1	0.2	0.010	0.28	0.22	1.79	6.31
CS2	0.5	0.006	0.11	0.10	1.72	6.35
CS3	0.6	0.006	0.16	0.16	1.38	6.41
CS Average	0.4	0.007	0.18	0.16	1.63	6.36
Rainwater	0.3	0.005	0.16	0.16	0.63	6.61
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 18: Data from rain event 19 September, 2011. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: September 19, 2011						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
G1	1.3	0.032	0.59	2.66	5.87	7.41
G2	1.0	0.025	0.46	1.72	5.55	7.61
G3	0.5	0.024	0.33	1.92	5.57	7.97
G Average	0.9	0.027	0.46	2.10	5.66	7.66
M1	1.7	0.006	0.52	2.75	3.46	7.53
M2	0.5	0.012	0.67	2.15	4.89	7.55
M3	2.3	0.017	0.27	2.46	4.19	7.93
M Average	1.5	0.012	0.49	2.45	4.18	7.67
S1	0.5	0.002	0.50	2.40	4.34	7.90
S2	0.3	0.012	0.45	2.27	5.89	7.60
S3	0.9	0.019	0.55	2.09	5.19	7.61
S Average	0.6	0.011	0.50	2.25	5.14	7.70
CM1	0.2	0.001	0.18	0.12	0.94	6.31
CM2	0.2	0.003	0.30	0.22	0.85	6.85
CM3	0.2	0.004	0.51	0.30	1.32	6.63
CM Average	0.2	0.003	0.33	0.21	1.03	6.60
CS1	0.2	0.005	0.26	0.22	2.44	6.48
CS2	0.3	0.004	0.28	0.17	2.26	6.55
CS3	0.3	0.002	0.16	0.06	1.32	6.57
CS Average	0.27	0.004	0.23	0.15	2.01	6.53
Rainwater	0.2	0.004	0.17	0.15	1.88	6.52
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 19: Data from rain event 25 September, 2011. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: September 25, 2011						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
G1	0.4	0.022	0.42	1.12	3.63	7.55
G2	0.4	0.016	0.63	1.39	3.86	7.99
G3	0.3	0.025	0.36	1.40	3.99	7.64
G Average	0.4	0.021	0.47	1.30	3.82	7.73
M1	0.6	0.012	0.35	1.70	1.88	7.63
M2	0.5	0.017	0.59	1.05	1.58	7.47
M3	0.2	0.017	0.47	1.71	1.92	7.57
M Average	0.4	0.015	0.47	1.49	1.79	7.56
S1	0.2	0.014	0.31	1.67	2.07	7.62
S2	0.3	0.004	0.41	1.53	2.84	7.58
S3	0.4	0.010	0.49	1.73	2.56	7.64
S Average	0.3	0.009	0.40	1.64	2.49	7.61
CM1	0.0	0.006	0.22	0.12	0.08	6.97
CM2	0.1	0.003	0.10	0.09	0.12	6.74
CM3	0.2	0.001	0.15	0.13	0.14	6.61
CM Average	0.1	0.003	0.16	0.11	0.11	6.77
CS1	0.1	0.004	0.19	0.28	0.08	6.46
CS2	0.2	0.001	0.24	0.23	0.06	6.59
CS3	0.3	0.005	0.11	0.19	0.15	6.60
CS Average	0.2	0.003	0.18	0.23	0.10	6.55
Rainwater	0.2	0.006	0.23	0.23	0.07	6.50
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 20: Data from rain event 27 September, 2011. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: September 27, 2011						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
G1	0.3	0.015	0.27	1.31	3.48	7.69
G2	0.6	0.007	0.16	1.20	4.27	7.79
G3	0.2	0.021	0.20	1.23	3.97	7.83
G Average	0.4	0.014	0.21	1.25	3.91	7.77
M1	0.6	0.013	0.29	1.17	2.37	8.00
M2	0.8	0.011	0.21	1.29	2.14	7.37
M3	0.1	0.027	0.17	1.66	2.84	7.81
M Average	0.5	0.017	0.22	1.37	2.45	7.73
S1	0.2	0.020	0.25	1.68	2.51	7.79
S2	0.3	0.010	0.18	1.67	3.09	7.60
S3	0.7	0.014	0.27	1.72	2.59	7.54
S Average	0.4	0.015	0.23	1.69	2.73	7.64
CM1	0.2	0.003	0.07	0.14	0.08	6.29
CM2	0.1	0.004	0.15	0.06	0.21	6.39
CM3	0.2	0.009	0.20	0.13	0.13	6.53
CM Average	0.2	0.005	0.14	0.11	0.14	6.40
CS1	0.2	0.005	0.23	0.49	0.10	6.55
CS2	0.2	0.003	0.15	0.12	0.19	6.60
CS3	0.2	0.003	0.10	0.06	0.03	6.64
CS Average	0.2	0.004	0.16	0.22	0.11	6.60
Rainwater	0.2	0.001	0.17	0.17	0.13	6.59
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 21: Data from rain event 14 October, 2011. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: October 14, 2011						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
G1	0.6	0.009	0.10	1.48	3.43	7.96
G2	0.7	0.010	0.17	1.44	4.21	7.79
G3	0.5	0.015	0.05	1.22	4.01	7.83
G Average	0.6	0.011	0.11	1.38	3.88	7.86
M1	0.9	0.013	0.09	1.29	2.36	8.00
M2	0.3	0.008	0.17	1.00	2.14	9.37
M3	1.0	0.019	0.14	2.06	3.36	7.81
M Average	0.7	0.013	0.13	1.45	2.62	8.39
S1	0.6	0.020	0.09	1.45	2.78	7.79
S2	0.6	0.014	0.05	1.67	3.05	7.60
S3	0.9	0.010	0.15	1.72	2.35	7.54
S Average	0.7	0.015	0.10	1.61	2.73	7.64
CM1	0.4	0.006	0.09	0.14	0.09	6.29
CM2	0.4	0.006	0.07	0.06	0.07	6.39
CM3	0.4	0.007	0.06	0.13	0.23	6.53
CM Average	0.4	0.006	0.07	0.11	0.13	6.40
CS1	0.3	0.004	0.05	0.49	0.39	6.55
CS2	0.1	0.008	0.06	0.12	0.18	6.60
CS3	0.4	0.007	0.04	0.06	0.24	6.64
CS Average	0.3	0.006	0.05	0.22	0.27	6.60
Rainwater	0.4	0.007	0.05	0.09	0.11	6.67
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 22: Data from rain event 20 October, 2011. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: October 20, 2011						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
G1	0.6	0.005	0.06	1.38	2.47	7.49
G2	0.5	0.004	0.05	1.53	1.82	7.51
G3	0.4	0.010	0.04	1.43	2.42	7.95
G Average	0.5	0.006	0.05	1.45	2.24	7.65
M1	0.4	0.010	0.04	1.31	0.82	7.49
M2	0.3	0.011	0.04	1.07	1.37	7.50
M3	1.0	0.007	0.02	1.41	1.06	7.53
M Average	0.6	0.009	0.03	1.26	1.08	7.51
S1	0.2	0.009	0.03	2.49	1.33	7.53
S2	0.2	0.004	0.03	1.87	1.57	7.33
S3	0.2	0.005	0.04	1.79	1.84	7.10
S Average	0.2	0.006	0.03	2.05	1.58	7.32
CM1	0.2	0.002	0.01	0.22	0.77	7.83
CM2	0.3	0.003	0.01	0.13	0.81	7.29
CM3	0.1	0.004	0.00	0.28	0.74	7.05
CM Average	0.2	0.003	0.01	0.21	0.77	7.39
CS1	0.2	0.002	0.02	0.16	0.65	6.75
CS2	0.2	0.003	0.01	0.07	0.79	6.71
CS3	0.1	0.004	0.00	0.10	0.60	6.69
CS Average	0.2	0.003	0.01	0.11	0.68	6.72
Rainwater	0.2	0.004	0.03	0.24	0.37	6.39
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 23: Data from rain event 28 May, 2012. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: May 28, 2012						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
S1	0.200	0.006	0.170	3.380	2.240	6.55
S2	0.200	0.003	0.140	3.050	1.810	6.75
S3	0.000	0.003	0.080	4.100	3.570	6.55
S Average	0.133	0.004	0.130	3.510	2.540	6.62
G1	1.300	0.019	0.230	2.420	0.891	6.99
G2	0.700	0.063	0.120	3.850	1.200	7.04
G3	0.300	0.000	0.170	3.670	0.981	6.77
G Average	0.767	0.027	0.173	3.313	1.024	6.93
M1	2.000	0.011	0.200	4.120	0.945	7.06
M2	1.700	0.071	0.160	3.220	0.431	7.09
M3	3.800	0.012	0.160	3.850	0.434	7.00
M Average	2.500	0.031	0.173	3.730	0.603	7.05
CM1	0.400	0.004	0.600	1.440	3.110	6.26
CM2	0.500	0.004	0.730	2.260	2.690	6.32
CM3	0.500	0.010	0.710	1.420	3.390	6.44
CM Average	0.467	0.006	0.680	1.707	3.063	6.34
CS1	0.500	0.003	0.030	2.000	2.470	6.57
CS2	0.500	0.010	0.050	1.800	4.050	6.78
CS3	0.600	0.007	0.030	1.170	6.160	6.89
CS Average	0.533	0.007	0.037	1.657	4.227	6.75
Rain	0.800	0.006	0.030	2.100	2.730	6.86
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 24: Data from rain event 2 June, 2012. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: June 2, 2012						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
S1	0.400	0.002	0.020	1.170	1.240	7.44
S2	0.600	0.002	0.020	1.640	0.707	8.76
S3	0.300	0.000	0.000	1.190	0.974	7.96
S Average	0.267	0.035	0.013	1.557	1.553	6.53
G1	0.400	0.002	0.020	1.170	1.240	7.44
G2	0.600	0.002	0.020	1.640	0.707	8.76
G3	0.300	0.000	0.000	1.190	0.974	7.96
G Average	0.433	0.001	0.013	1.333	0.974	8.05
M1	1.900	0.004	0.000	1.620	1.320	7.80
M2	1.500	0.002	0.000	2.300	0.448	8.22
M3	3.300	0.004	0.070	1.820	0.593	7.60
M Average	2.233	0.003	0.023	1.913	0.787	7.87
CM1	0.200	0.004	0.490	0.410	0.748	6.09
CM2	0.200	0.003	0.130	0.250	2.030	6.14
CM3	0.300	0.004	0.010	0.060	0.555	6.33
CM Average	0.233	0.004	0.210	0.240	1.111	6.19
CS1	0.400	0.003	0.020	0.220	1.160	6.34
CS2	0.200	0.003	0.440	0.670	1.460	6.23
CS3	0.400	0.005	0.290	0.400	2.440	6.30
CS Average	0.333	0.004	0.250	0.430	1.687	6.29
Rain	0.300	0.003	0.070	0.210	0.421	6.31
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 25: Data from rain event 19 June, 2012. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: June 19, 2012						
Treatment	**Nitrate-Nitrogen (NO_3-N)**	**Nitrite-Nitrogen (NO_2-N)**	**Ammonia-Nitrogen (NH_3-N)**	**Phosphate-Phosphorous (PO_4-P)**	**Turbidity (NTUs)**	**pH**
S1	0.300	0.008	0.220	2.000	0.680	6.54
S2	0.300	0.008	0.070	2.020	1.210	6.81
S3	0.100	0.003	0.100	1.650	0.987	6.93
S Average	0.233	0.006	0.130	1.890	0.959	6.76
G1	0.400	0.019	0.240	1.810	0.734	6.94
G2	0.600	0.016	0.070	1.520	0.816	7.14
G3	0.300	0.006	0.260	1.320	0.447	7.04
G Average	0.433	0.014	0.190	1.550	0.666	7.04
M1	2.800	0.030	0.240	2.040	1.330	7.16
M2	1.300	0.009	0.040	1.530	0.595	7.17
M3	4.300	0.015	0.070	2.160	2.810	7.39
M Average	2.800	0.018	0.117	1.910	1.578	7.24
CM1	0.500	0.016	1.000	0.220	0.348	6.58
CM2	0.200	0.007	1.000	0.510	0.562	6.48
CM3	0.400	0.015	1.000	0.240	0.538	6.53
CM Average	0.367	0.013	1.000	0.323	0.483	6.53
CS1	0.400	0.015	0.000	0.370	0.318	6.36
CS2	0.400	0.012	1.000	0.210	0.467	6.43
CS3	0.300	0.019	1.000	0.120	6.160	6.46
CS Average	0.367	0.015	0.667	0.233	2.315	6.42
Rain	0.500	0.010	1.000	0.370	2.730	6.37
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 26: Data from rain event 2 August, 2012. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: August 2, 2012						
Treatment	**Nitrate-Nitrogen (NO_3-N)**	**Nitrite-Nitrogen (NO_2-N)**	**Ammonia-Nitrogen (NH_3-N)**	**Phosphate-Phosphorous (PO_4-P)**	**Turbidity (NTUs)**	**pH**
S1	0.200	0.001	0.180	4.910	0.625	8.67
S2	1.000	0.020	0.320	3.670	1.240	7.21
S3	0.100	0.011	0.230	4.020	1.920	6.98
S Average	0.433	0.011	0.243	4.200	1.262	7.62
G1	0.400	0.016	0.340	2.750	0.939	7.49
G2	0.900	0.022	0.190	2.470	0.765	7.83
G3	1.100	0.026	0.390	3.430	1.310	8.56
G Average	0.800	0.021	0.307	2.883	1.005	7.96
M1	5.200	0.076	0.470	3.730	1.560	8.66
M2	5.100	0.322	0.690	2.490	1.470	7.71
M3	5.000	0.049	0.360	2.170	0.557	7.12
M Average	5.100	0.149	0.507	2.797	1.196	7.83
CM1	0.600	0.049	0.100	0.100	0.419	6.52
CM2	0.100	0.066	0.700	1.980	0.760	6.26
CM3	0.500	0.060	0.610	0.460	0.829	5.56
CM Average	0.400	0.058	0.470	0.847	0.669	6.11
CS1	0.300	0.003	0.590	0.360	0.769	6.45
CS2	0.300	0.004	0.160	0.580	0.713	6.53
CS3	0.200	0.002	0.060	0.320	1.020	6.55
CS Average	0.267	0.003	0.270	0.420	0.834	6.51
Rain	0.300	0.002	0.730	0.490	0.614	6.16
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 27: Data from rain event 20 August, 2012. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: August 20, 2012						
Treatment	**Nitrate-Nitrogen (NO_3-N)**	**Nitrite-Nitrogen (NO_2-N)**	**Ammonia-Nitrogen (NH_3-N)**	**Phosphate-Phosphorous (PO_4-P)**	**Turbidity (NTUs)**	**pH**
S1	0.100	0.060	1.000	3.790	0.580	7.21
S2	1.000	0.375	0.010	4.120	1.000	6.93
S3	0.300	0.008	0.470	3.110	1.040	7.11
S Average	0.467	0.148	0.493	3.673	0.873	7.08
G1	0.800	0.077	1.000	1.390	0.951	6.25
G2	1.400	0.227	2.000	2.470	1.640	6.95
G3	0.700	0.100	2.000	1.950	0.623	6.78
G Average	0.967	0.135	1.667	1.937	1.071	6.66
M1	1.200	0.086	1.000	2.170	0.582	7.13
M2	4.900	0.073	0.280	3.470	1.010	7.26
M3	5.200	0.046	0.580	2.050	0.748	6.45
M Average	3.767	0.068	0.620	2.563	0.780	6.95
CM1	0.800	0.103	0.490	0.230	0.671	7.12
CM2	0.800	0.042	1.000	0.350	0.572	6.54
CM3	1.300	0.076	2.000	1.180	0.648	6.21
CM Average	0.967	0.074	1.163	0.587	0.630	6.62
CS1	0.300	0.002	1.000	1.250	1.210	6.32
CS2	0.300	0.010	1.000	0.500	0.429	6.47
CS3	0.400	0.010	1.000	0.230	0.570	6.11
CS Average	0.333	0.007	1.000	0.660	0.736	6.30
Rain	0.600	0.010	1.000	1.140	0.949	6.38
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 28: Data from rain event 8 September, 2012. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: September 8, 2012						
Treatment	**Nitrate-Nitrogen (NO_3-N)**	**Nitrite-Nitrogen (NO_2-N)**	**Ammonia-Nitrogen (NH_3-N)**	**Phosphate-Phosphorous (PO_4-P)**	**Turbidity (NTUs)**	**pH**
S1	0.700	0.040	0.670	0.970	0.981	7.04
S2	1.300	0.032	1.000	1.360	1.310	6.63
S3	0.500	0.057	0.700	1.210	1.070	6.87
S Average	0.833	0.043	0.790	1.180	1.120	6.85
G1	0.600	0.082	0.530	2.210	0.821	6.93
G2	0.600	0.041	1.000	1.410	0.679	7.10
G3	0.900	0.067	0.590	1.010	1.183	6.91
G Average	0.700	0.063	0.707	1.543	0.894	6.98
M1	1.000	0.061	0.660	0.430	0.873	6.68
M2	0.800	0.066	0.410	0.710	1.228	6.87
M3	1.100	0.071	0.490	0.330	0.764	7.19
M Average	0.967	0.066	0.520	0.490	0.955	6.57
CM1	0.300	0.032	0.310	0.120	0.839	6.43
CM2	0.400	0.011	0.200	0.270	0.437	6.21
CM3	0.200	0.008	0.220	0.240	0.521	6.54
CM Average	0.300	0.017	0.243	0.210	0.599	6.39
CS1	0.600	0.016	0.100	0.430	0.771	6.38
CS2	0.400	0.031	0.080	0.190	0.682	6.44
CS3	0.300	0.014	0.350	0.290	0.811	6.21
CS Average	0.433	0.020	0.177	0.303	0.755	6.34
Rain	0.300	0.017	0.110	0.200	0.693	6.32
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 29: Data from rain event 19 September, 2012. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: September 19, 2012						
Treatment	**Nitrate-Nitrogen (NO3-N)**	**Nitrite-Nitrogen (NO2-N)**	**Ammonia-Nitrogen (NH3-N)**	**Phosphate-Phosphorous (PO4-P)**	**Turbidity (NTUs)**	**pH**
S1	0.900	0.023	0.310	1.140	0.643	6.97
S2	1.200	0.037	0.470	0.970	0.702	7.34
S3	0.700	0.044	0.590	1.030	0.579	7.21
S Average	0.933	0.035	0.457	1.047	0.641	7.17
G1	0.600	0.036	0.520	1.090	0.489	6.61
G2	0.600	0.041	1.000	1.680	0.721	6.88
G3	0.500	0.067	0.630	0.820	0.667	7.04
G Average	0.567	0.048	0.717	1.197	0.626	6.84
M1	1.300	0.081	0.430	0.930	0.812	6.68
M2	0.600	0.033	0.670	2.110	0.935	6.83
M3	0.800	0.046	1.000	1.200	0.741	6.75
M Average	0.900	0.053	0.700	1.413	0.829	6.57
CM1	0.400	0.015	0.170	0.330	0.692	6.94
CM2	0.200	0.014	0.220	0.210	0.437	6.41
CM3	0.100	0.023	0.040	0.430	0.497	6.37
CM Average	0.233	0.017	0.143	0.323	0.542	6.57
CS1	0.100	0.019	0.150	0.370	0.881	6.59
CS2	0.300	0.044	0.160	0.220	0.643	6.21
CS3	0.200	0.009	0.270	0.100	0.410	6.18
CS Average	0.200	0.024	0.193	0.230	0.645	6.33
Rain	0.200	0.013	0.190	0.190	0.693	6.37
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Table 30: Data from rain event 24 September, 2012. All concentrations except pH and turbidity are in milligrams per litre (mg/L) and/or parts per million (PPM).

Rain Event: September 24, 2012						
Treatment	**Nitrate-Nitrogen (NO_3-N)**	**Nitrite-Nitrogen (NO_2-N)**	**Ammonia-Nitrogen (NH_3-N)**	**Phosphate-Phosphorous (PO_4-P)**	**Turbidity (NTUs)**	**pH**
S1	0.300	0.002	0.010	1.230	0.621	6.73
S2	0.300	0.002	0.000	0.930	0.357	6.81
S3	0.200	0.001	0.010	0.640	0.543	7.13
S Average	0.267	0.002	0.007	0.933	0.507	6.89
G1	0.300	0.003	0.020	0.430	0.473	7.32
G2	0.200	0.002	0.000	0.840	0.921	7.01
G3	0.300	0.002	0.020	0.920	0.833	6.97
G Average	0.267	0.002	0.013	0.730	0.742	7.10
M1	0.900	0.004	0.010	1.040	0.721	7.32
M2	0.400	0.004	0.000	0.720	1.370	6.89
M3	1.200	0.011	0.000	0.880	0.739	7.12
M Average	0.833	0.006	0.003	0.880	0.943	6.57
CM1	0.300	0.004	0.000	0.210	0.461	7.12
CM2	0.300	0.003	0.010	0.110	0.323	6.32
CM3	0.400	0.004	0.040	0.200	0.679	6.36
CM Average	0.333	0.004	0.017	0.173	0.488	6.60
CS1	0.200	0.001	0.080	0.100	0.831	6.61
CS2	0.300	0.004	0.010	0.120	0.611	6.52
CS3	0.200	0.003	0.000	0.110	0.528	6.21
CS Average	0.233	0.003	0.030	0.110	0.657	6.45
Rain	0.400	0.004	0.050	0.190	0.799	6.35
Treatment Index: G (Green Roof w/ Grass Species), S (Green Roof w/ Sedum Species), M (Media Only Roof Treatment), CM (Conventional Metal Roofing) & CS (Conventional Shingle Roofing)						

Figure 1: Graphic representations of land cover change and its subsequent effect on stormwater runoff. (Source: http://www.fairfaxcounty.gov/nvswcd/images/drainageproblem/runoff.jpg)

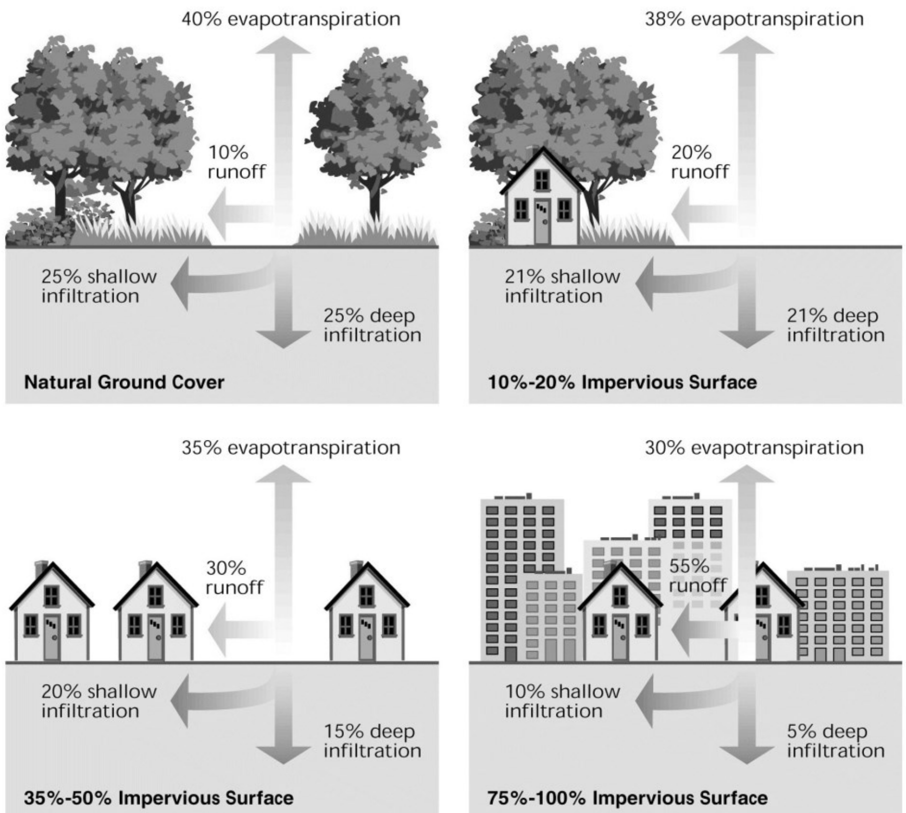


Figure 2: Graphic representations of urban stormwater runoff catchment area and transport through stormwater utility systems. (Source: http://www2.cincinnati.com/blogs/ gardening/ 2011/11/28/ rain/)

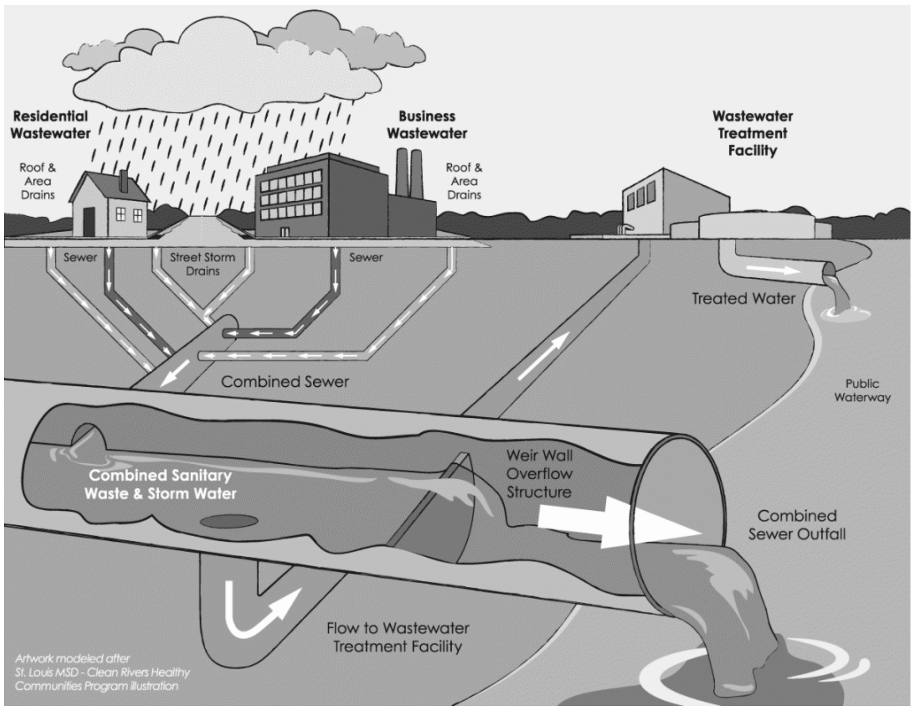


Figure 3: Image showing the impacts of excessive nutrient runoff to receiving water bodies. (Source: http://www.lakeforest.edu/academics/programs/environmental/courses/seniorseminar/springbreak/students/newcomer.php)

Figure 4: Graphic representation of land type and use and its effect on air temperature. (Source: http://indymedia.org.au/2013/06/02/cities-to-get-much-hotter-as-heatwaves-amplify-urban-heat-island-effect)

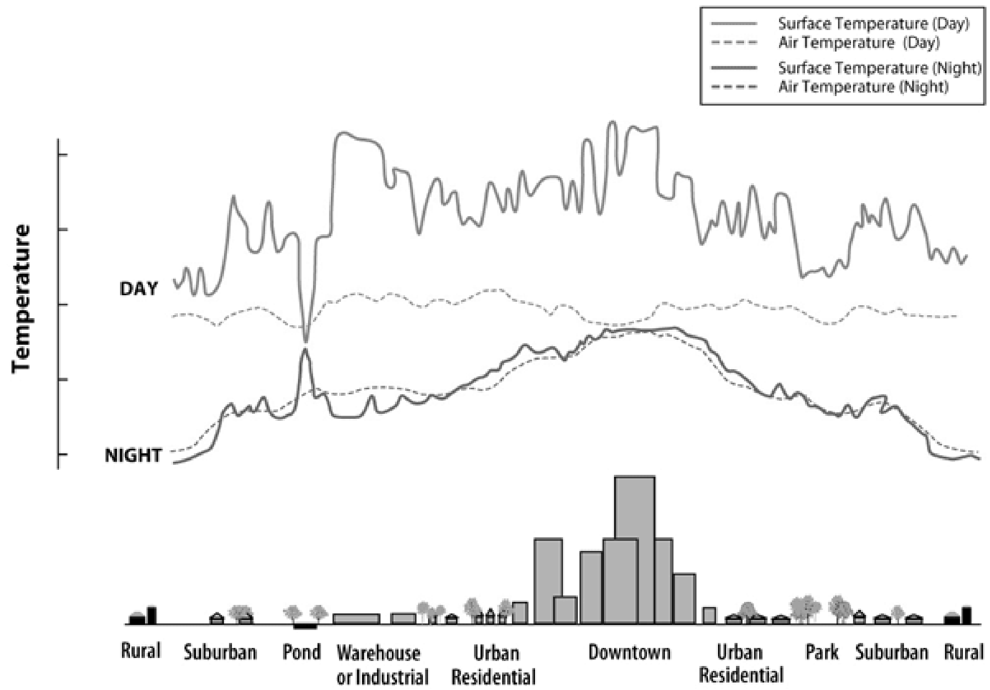


Figure 5: Artist's illustration of the Hanging Gardens of Babylon. (Source: http://batkya.deviantart.com/art/Hanging-Gardens-of-Babylon-203309919)

Figure 6: Project location map. Study was performed at the Michigan State University Landscape Architecture Alumni Research Site, Old Mission, MI (Krogulecki, 2014).

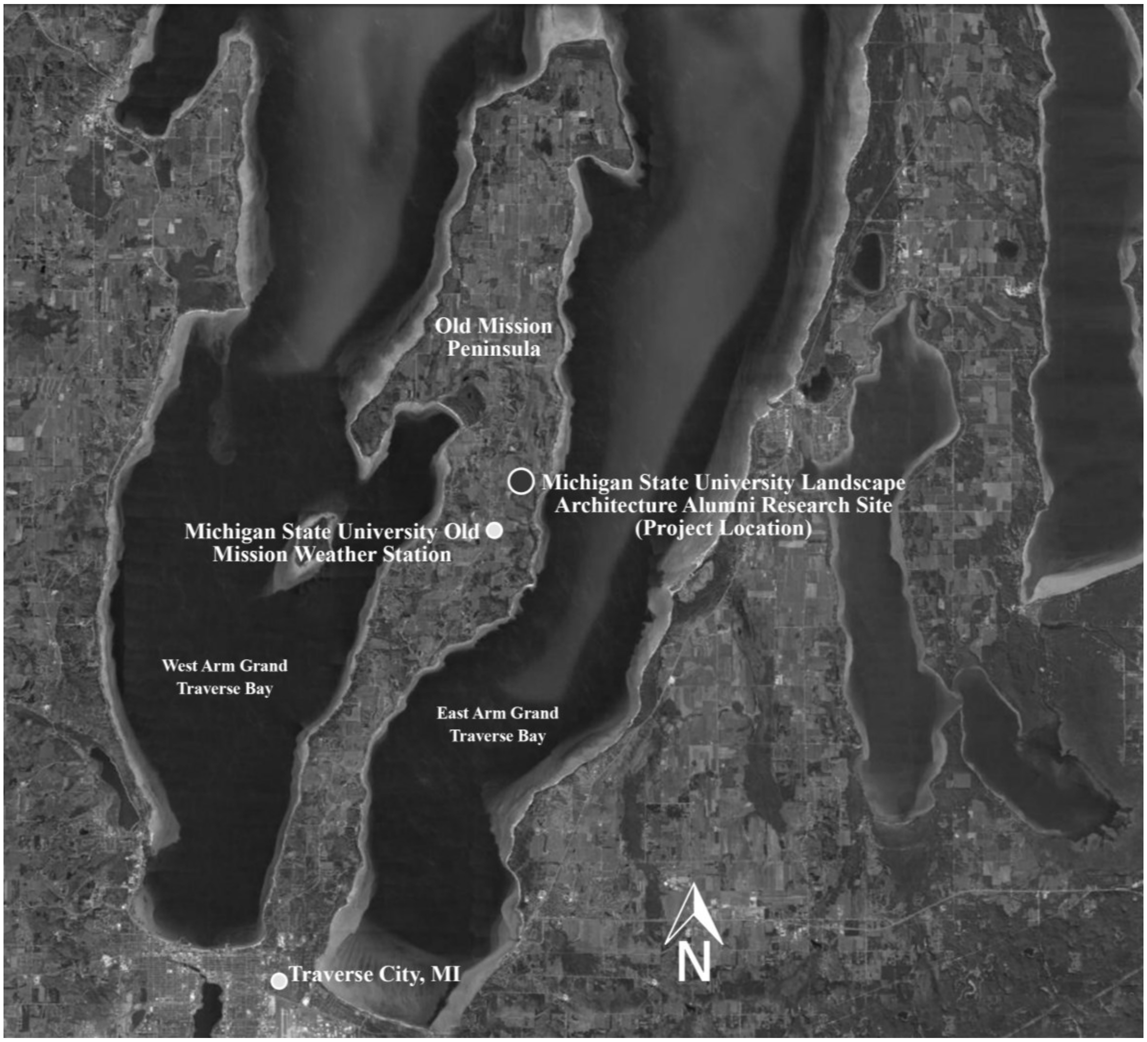


Figure 7: Picture taken during construction illustrating the use of .045 mm EPMD rubber waterproof membrane (Krogulecki, 2009).

Figure 8: Plan view detail of plot dimensions and randomized treatment layout (Krogulecki, 2014).

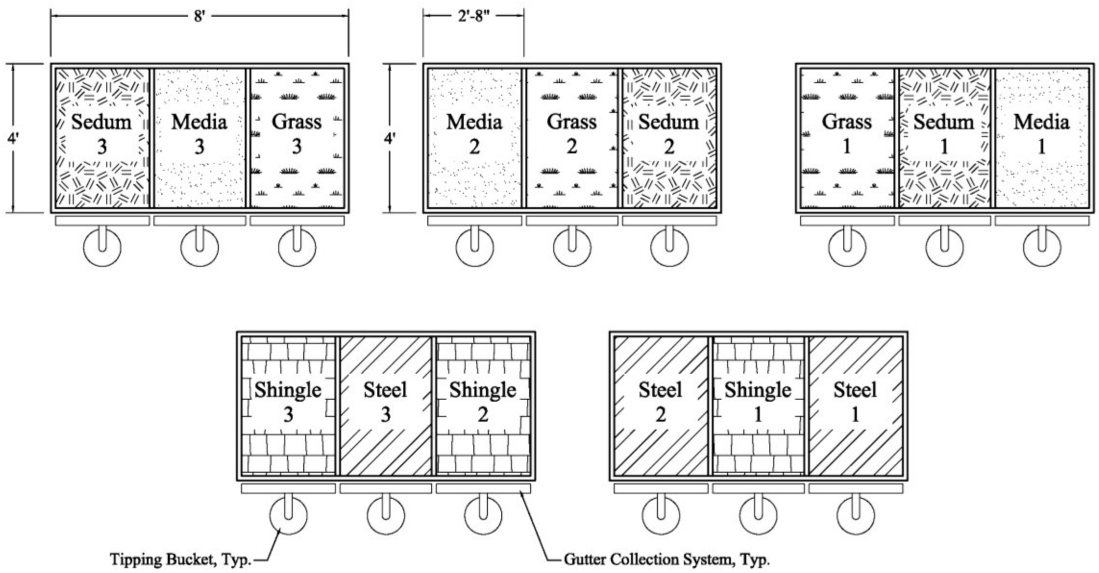


Figure 9: Picture showing the three green roof vegetation treatments after planting (Krogulecki, 2009).

Figure 10: Daily precipitation totals (inches) during the study (22 July 2010 – 24 September 2012). Data collected from the Michigan State University Old Mission weather station. (Source: http://www.agweather.geo.msu.edu/mawn/ station.asp?id=old&rt=24)

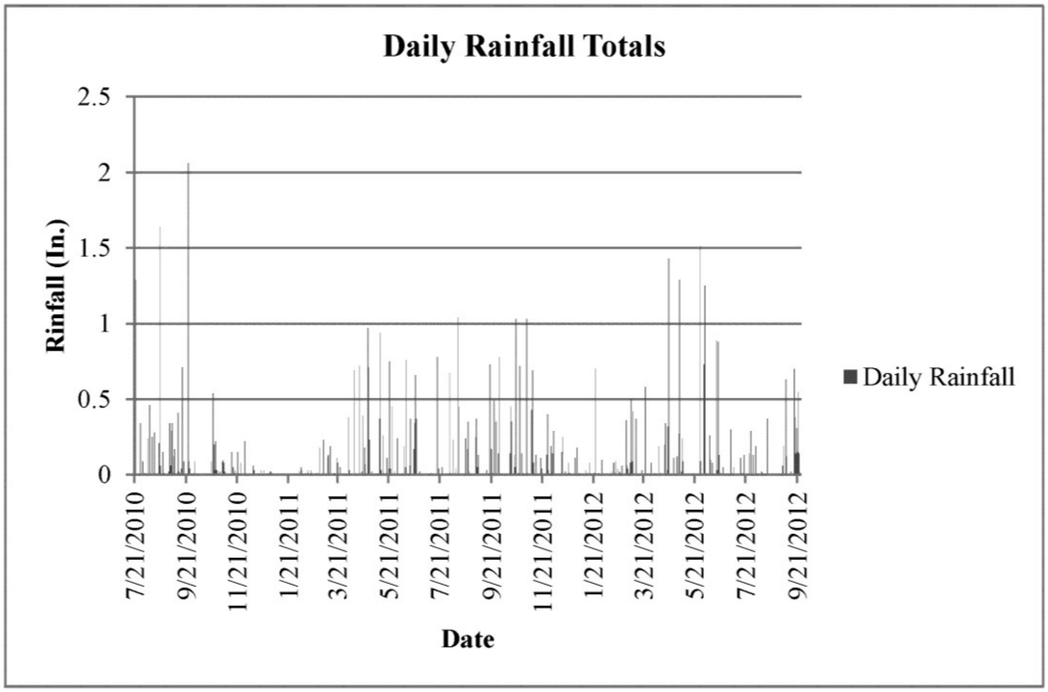


Figure 11: Daily maximum and minimum temperatures (°F) during the study (22 July 2010 – 24 September 2012). Data collected from the Michigan State University Old Mission weather station. (Source: http://www.agweather.geo.msu.edu/mawn/station.asp?id=old&rt=24)

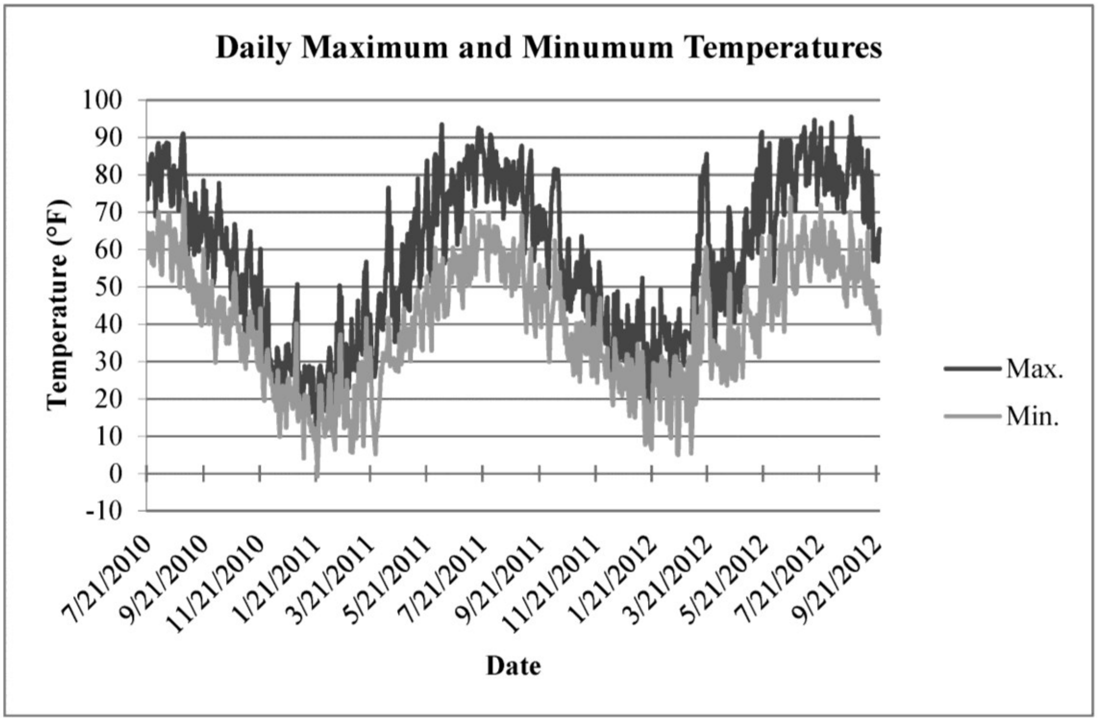


Figure 12: Mean concentration of Nitrate-Nitrogen (NO_3-N) in collected runoff samples for each individual roofing treatment during the study period (22 July 2010 – 24 September 2012).

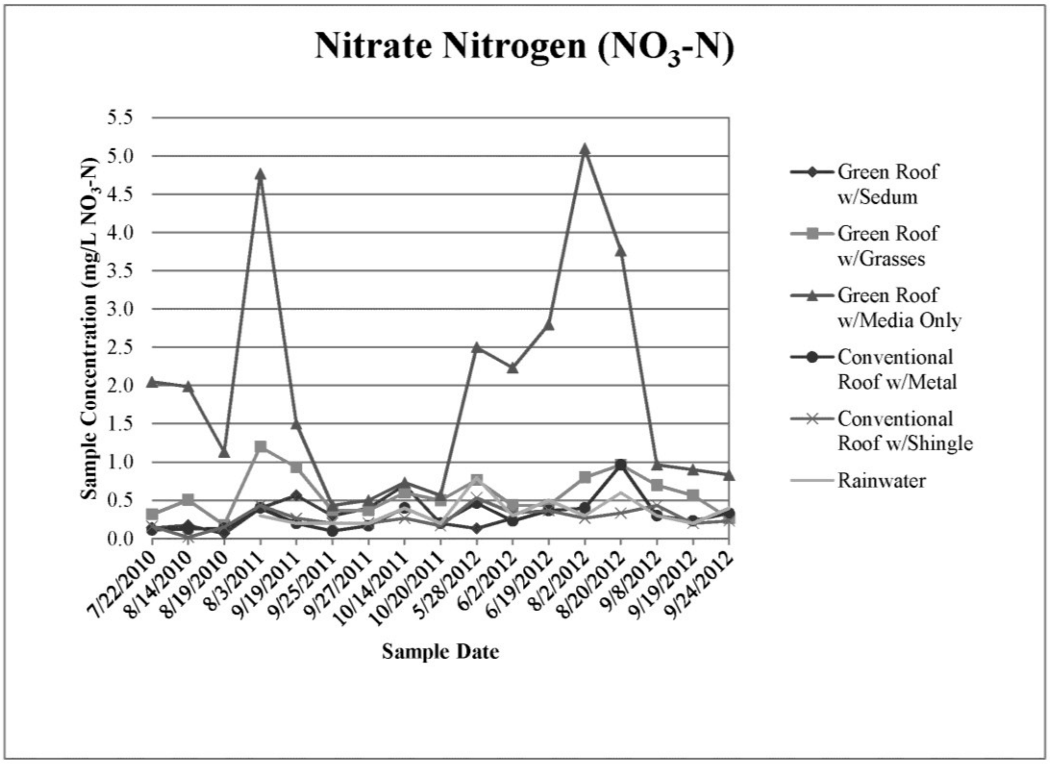


Figure 13: Mean concentration of Nitrite-Nitrogen (NO_2-N) in collected runoff samples for each individual roofing treatment during the study period (22 July 2010 – 24 September 2012).

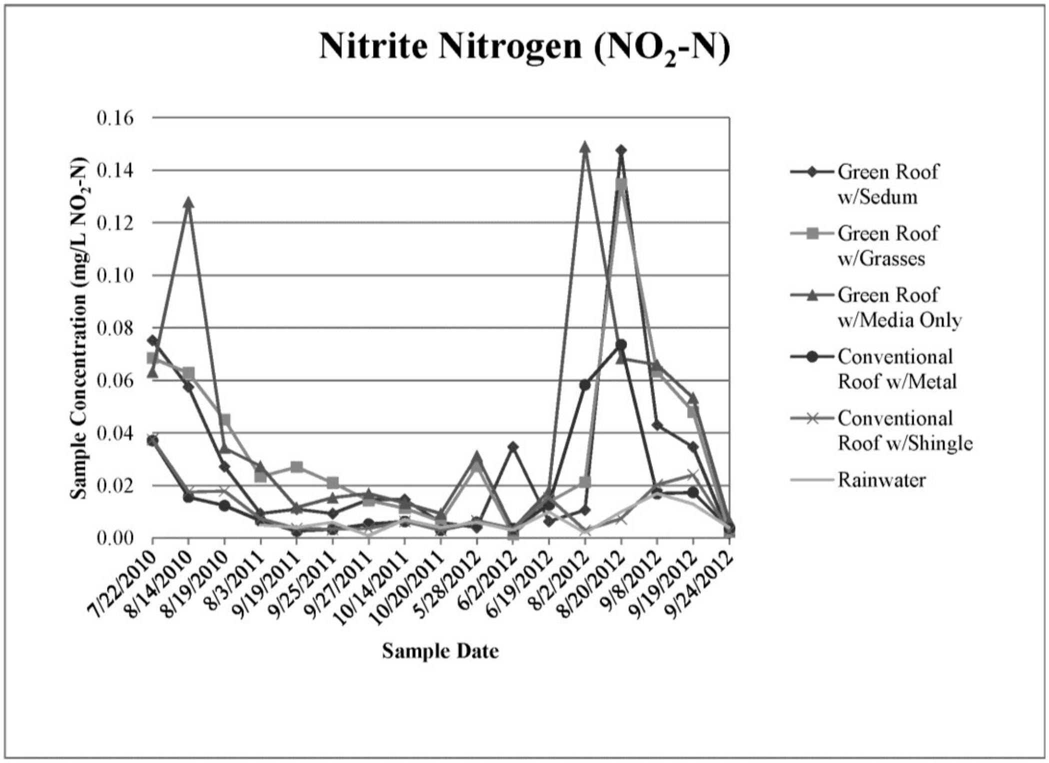


Figure 14: Mean concentration of Ammonia-Nitrogen (NH_3-N) in collected runoff samples for each individual roofing treatment during the study period (22 July 2010 – 24 September 2012).

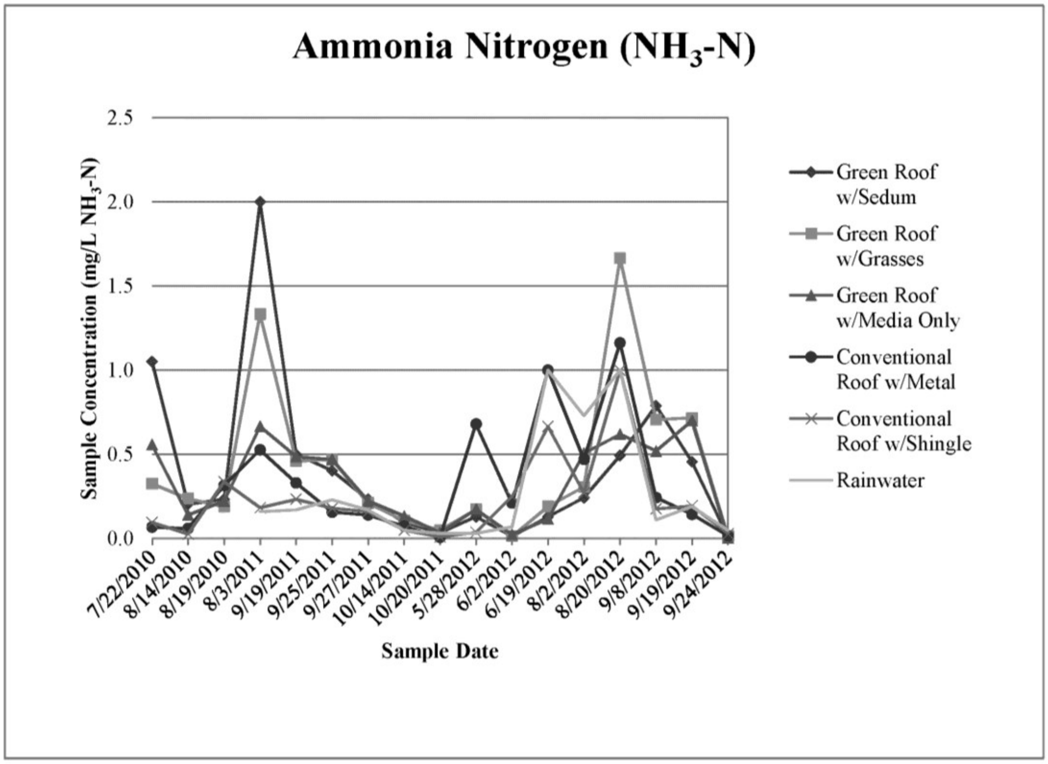


Figure 15: Mean concentration of Phosphate-Phosphorous (PO_4-P) in collected runoff samples for each individual roofing treatment during the study period (22 July 2010 – 24 September 2012).

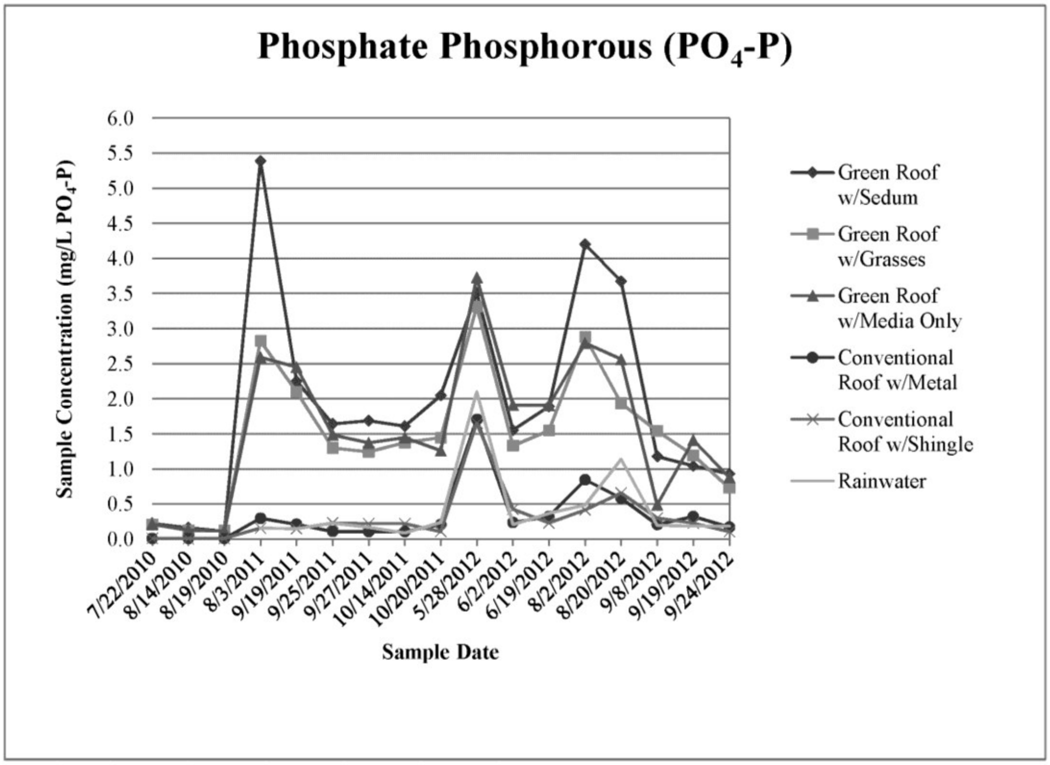


Figure 16: Mean Turbidity (NTU) levels in collected runoff samples for each individual roofing treatment during the study period (22 July 2010 – 24 September 2012).

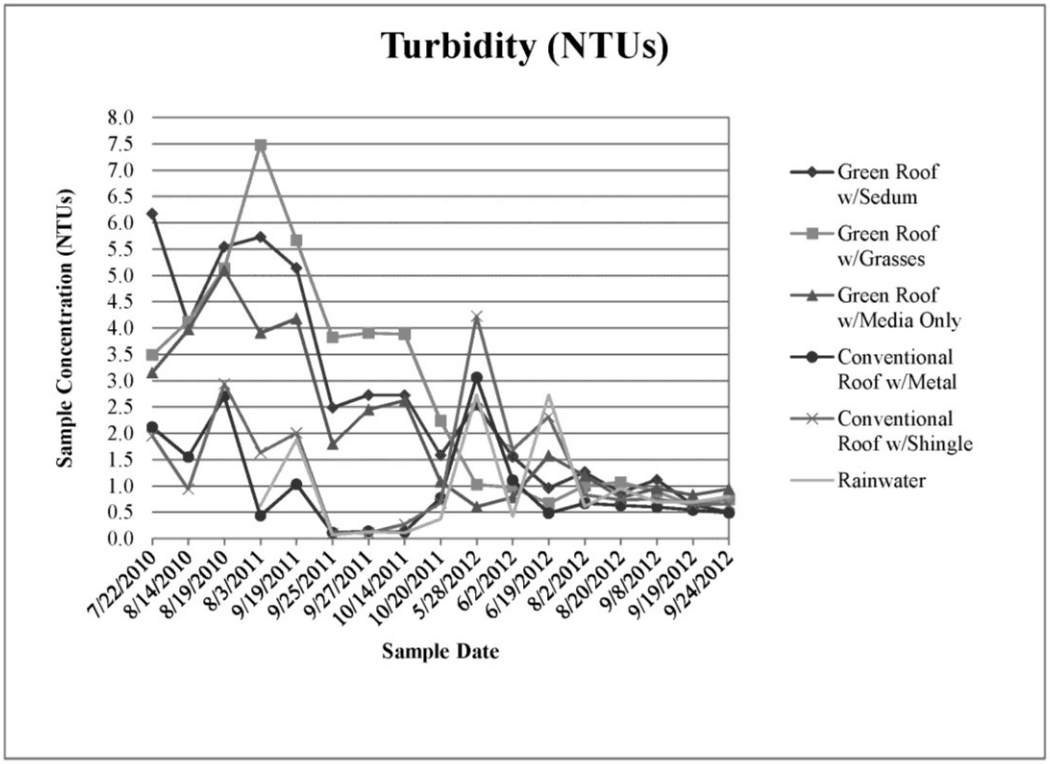
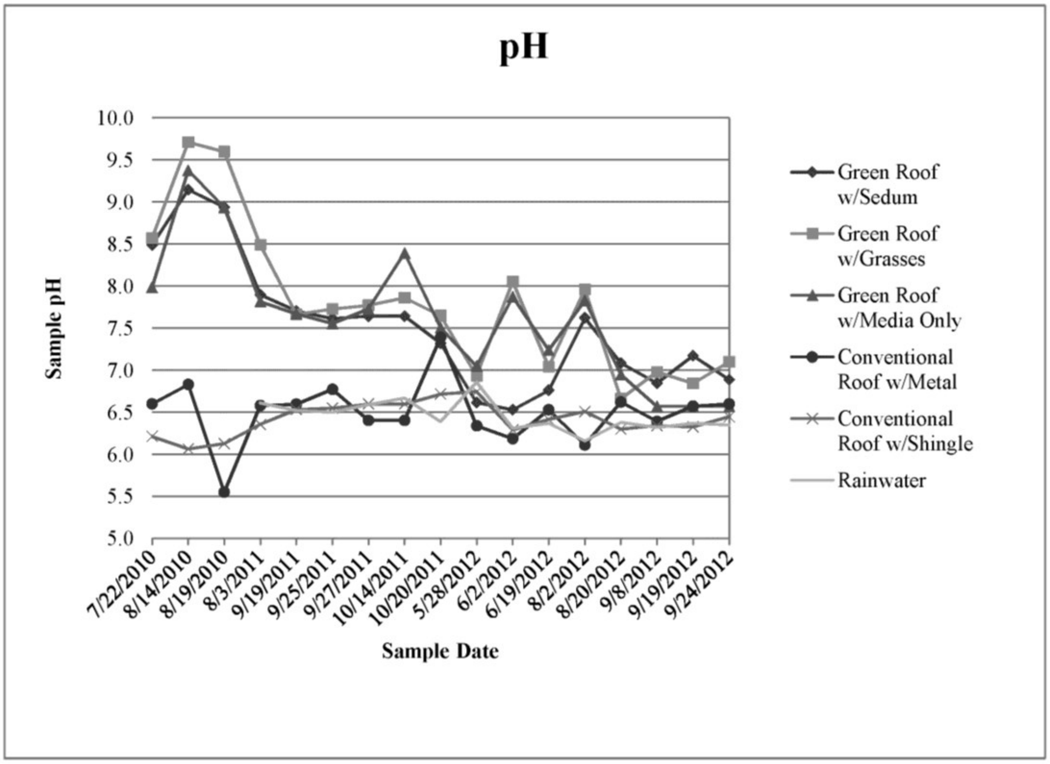


Figure 17: Mean pH levels in collected runoff samples for each individual roofing treatment during the study period (22 July 2010 – 24 September 2012).



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