STORMWATER RUNOFF MITIGATION AND WATER QUALITY IMPROVEMENTS THROUGH THE USE OF A GREEN ROOF IN PITTSBURGH, PA

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A green roof was constructed in Pittsburgh, PA to help reduce combined sewer overflows (CSOs) events. They occur because the sewer infrastructure of Pittsburgh, and many older cities, is inadequately designed to handle the large amounts of stormwater runoff created by the sprawling areas of impervious surfaces in today's modern cities. Raw sewage is frequently dumped into Pittsburgh's three rivers when the sewer system becomes overloaded.

A 12, 300 square foot extensive green roof was constructed at a commercial and residential site in Pittsburgh to measure the stormwater benefits. The green roof sits atop the new portion of an expanded supermarket, with a 21,000 square foot conventionally ballasted roof covering the existing portion. The green roof consists of a 5 1/2 inch thick layer of soilless mix and a plant layer consisting mainly of sedum varieties. Using the conventional roof as a control, an extensive monitoring system was constructed to measure parameters including rainwater, soil moisture and runoff.

The absorption of rainwater by the substrate and plants reduces the total volume of runoff that reaches the sewer system by between 5 and 70 percent. At least a 20 percent reduction occurs for a rain storm of 0.6 inches or less. Storm duration, total rainfall amount and soil moisture prior to the storm affect performance. The peak flow rate of runoff leaving the roof is also significantly reduced, by 5 to 70 percent. The flow rate is lower at all stages of storm. The

green roof also delayed the start of runoff and, at times, the peak flow. At the conclusion of a storm, runoff would continue to flow from the green roof for up to several hours longer than the control roof at a very low rate.

Water quality tests on runoff and rainfall samples indicate that a first flush effect is not present in the green roof runoff. The concentration of phosphorus was elevated in the green roof runoff, likely from the use of fertilizers. COD was also elevated, while turbidity levels were lower than the control roof. Runoff from both roofs neutralized the slightly acidic rainwater.

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1.0 INTRODUCTION

Many older cities throughout North America suffer from inadequate sewer systems that are unable to compensate with the rapidly increasing amounts of impervious surfaces created by the ever expanding urban sprawl. Excess stormwater runoff causes the systems to become overwhelmed, with large amounts of untreated, raw sewage spilling into lakes, streams and rivers.

These unsafe, and often illegal, conditions are not easy to fix. The old and undersized sewer systems are difficult to replace. Water treatment plants can not be quickly expanded. Changes like this can be enormously expensive and they do not get to the root of the problem: that too much stormwater runoff is being produced. The system is simply expanded to deal with the load.

Green roofs seek to help to solve this problem from a different angle. By putting soil and plants onto roofs, natural surfaces that can absorb rain instead of shedding it are reintroduced into urban areas. These layered roofing systems absorb water that otherwise would have become runoff and entered the sewer system, reduce runoff flow rates, delay peak flows and improve the water quality of runoff.

Pittsburgh is one of the many cities affected by sewer overflow problems. As part of a multi-front attack on the problem, a large extensive green roof was installed on a supermarket in the eastern part of the city. Through extensive monitoring, this project aims to show the positive effects a green roof can have on stormwater with practical results. The results presented here can be used to not only improve the situation in Pittsburgh, but in any other city experiencing the same problems.

1.1 MOTIVATION AND OBJECTIVES

The goal of the Shadyside Giant Eagle green roof project was to construct and test a green roof in Pittsburgh to evaluate the benefits in this particular location. The affect of green roofs were divided into two areas: water and temperature.

Pittsburgh has a significant combined sewer overflow (CSO) problem. CSOs are systems designed to carry both the stormwater runoff and wastewater from homes and businesses to a central wastewater treatment plant. The system in Pittsburgh is decades old, deteriorated and undersized for the current wet weather stormwater runoff. While adequate during dry weather, very little stormwater runoff is needed to cause an overflow event. The average depth of rainfall for a storm in Pittsburgh is approximately one-quarter of an inch, yet only one-tenth of an inch of rain can cause overflows of the combined sewer system. Raw sewage is frequently deposited into the city's three rivers as a result of rain events.

The water retention properties of green roofs are potentially part of the solution to the sewer overflow problem, so this is an area of prime interest for the project. A number of parameters were monitored to create a water balance, allowing the impact of green roofs on stormwater runoff to be measured. The water quality of runoff is also an important factor to consider in CSOs. Tests were carried out on runoff from both the control and green roofs to measure the effect green roofs have on purifying water.

The Shadyside Giant Eagle green roof was also measured for numerous temperature and weather conditions. These measurements included temperature profiles from below the roof deck to one meter above the roof, soil and surface temperatures, wind speed and direction, net solar radiation and relative humidity. The thermal performance (insulation value) of the green roof and changes to the urban heat island effect were determined from this data. This thesis will not go into the details of these results, but the companion thesis by Kosareo (2007) looks into these areas of the project extensively.

2.0 GREEN ROOF BACKGROUND

Green roofs are an emerging technology that is being used with increasing frequency on green construction projects. It is a back to basics approach. With their roots tracing back to ancient civilizations, the roofs bring green spaces back into today's cities. While the basic principle is the same, modern green roofs are far more advanced than their ancient counterparts. Made up of many layers, the roofs form a complex system that maximizes performance.

As urban sprawl has turned urban areas into sprawling masses of concrete, asphalt and steel, problems have arisen. The large surface area of impervious materials shed massive amounts of water into sewer systems. Most systems are decades old and their design capacities are far exceeded. Pollution pours into rivers, streams and lakes as a result. The health of humans, animals and ecosystems can be devastated. The cities become hot and humid as the man made materials trap heat. As urban areas expand and population grows, the problem only gets worse.

Green roofs can help reverse the negative effects of urban sprawl by reintroducing green space into the concrete expanse. By absorbing and detaining water during rain storms, green roofs reduce the flow of stormwater into sewer systems. With less sewer overflows, the water ways are less polluted. Additionally, green roofs can filter various pollutants out of the runoff before it enters the sewer system. The plants on a green roof can also cool the air above a roof. With a significant surface area, the overall temperature of a city can be reduced.

2.1 TYPES OF GREEN ROOFS

Green roofs generally fall into two broad categories: intensive and extensive. The use, plant types and soil depth are the main factors that differentiate the two. There are several other types of green roofs, but their use is far less wide spread.

Intensive green roofs are akin to rooftop parks. They are usually found to be covered with trees, shrubbery and other large plants. At times, intensive green roofs may be planted with sod to create open fields (Scholz-Barth 2001). The substrate is usually at least six inches thick, but it can often be well over a foot. This depth of soil is required to give the roots of the large plants room to grow (Dunnett 2004). Intensive green roofs do not just look like a rooftop park, they often act as one. In these cases, the roof is designed to handle the load of groups of people walking around on the roof (Scholz-Barth 2001). Pavers are often added as a pathway on the roof.

There are a number of drawbacks to intensive green roofs. The most significant is the costly and time consuming maintenance required to keep up the roof. If sod is installed on the roof, mowing will be required frequently. The large trees and shrubs that make up the bulk of plantings on many intensive green roofs need to be trimmed and maintained on a regular basis. Irrigation also becomes an issue. With plants this large, significant amounts of water are required and an extensive irrigation system must be installed to keep the plants healthy. Installing such a system on a roof can be a complicated matter (Scholz-Barth 2001).

A second issue arises out of the weight of the roof itself. There is around a foot of soil covering a typical intensive green roof. The shear volume of soil is a strain on the roof, even if a lightweight substrate is used. The trees and shrubs themselves are also quite heavy. Most intensive green roofs are designed to be interacted with by large groups of people. This results in an additional live load to consider. Summing the live and dead loads of the green roof along with those associated with a typical roof results in a significant burden (Scholz-Barth 2001). A typical intensive green roof weighs between 300 and 1000 kg/m^2 (61 to 205 psf) (Dunnett 2004). More complex roofs, with thicker soil layers, may weigh as much as 1220 to 1465 kg/m^2 (250 to 300 psf) (Osmundson 1999). While most structures are designed with some excess dead load capacity, the added load from an intensive green roof would exceed that in most instances. Live load requirements would vary from building to building, but many roofs are not designed to carry the weight of large numbers of people on the roof on a frequent basis. In older buildings, these loads may be too high to make an intensive green roof a plausible option. Even in new construction, where the weight could be accounted for in the design stages, an intensive green roof is likely to result in an increase of materials to support the weight of the roof. This can again make choosing an intensive green roof a difficult option.

Extensive green roofs are the focus of this study and provide a much more practical option. Extensive green roofs only have a few inches of soil. Depth depends on the types of plants used, but the substrate is rarely greater than six inches thick. Unlike the rooftop parks created by their intensive counterparts, extensive green roof are more similar to a rooftop garden (Scholz-Barth 2001). In fact, extensive green roofs are not intended for much interaction with people. At times, they may even be placed out of sight. Here, the goal is not for a public space, but to reap the environmental benefits of a green roof (Dunnett 2004). Instead of the large trees and shrubs seen on intensive roofs, extensive roofs are planted with low lying, drought resistant plants designed to be ground cover. The types of plants chosen for each roof are done so specifically for the site. They are picked for the climate in the area and should be able to survive solely on the natural rainfall that reaches the roof, reducing the need for watering. In many cases, however, an irrigation system is installed as a safeguard. It is helpful to water the plants in the early stages of development to help establish the plants and cases of extreme drought are always a possibility. Extensive green roofs are not meant to be walked on, except for infrequent maintenance. Generally speaking, maintenance is limited to a few instances a year for things like weeding, but it varies depending on the types of plants used in the roof. Occasionally, extensive green roofs will have sod that requires more frequent maintenance, but this is the exception, not the rule (Scholz-Barth 2001).

With smaller plants, a thinner soil substrate and a significantly reduced live load to consider, the structural strain added to a building by an extensive green roof is much more manageable than that of an intensive green roof. Provided they are structurally stable, many existing buildings will be able to support the load of an extensive green roof. A typical extensive green roof with a depth of 2 to 6 inches (5 to 15 cm) will weigh approximately 70 to 170 kg/m^2 (14 to 35 psf). The additional weight is within acceptable limits for many roofs. In the case of thinner extensive green roofs, the weight of the roofing system is often on par with conventional roof covering. A 1.5 inch thick green roof, for example, weighs roughly the same as a 4 inch thick gravel ballasted roof (Dunnett 2004). Without the hurdles of high maintenance cost or structural design, extensive green roofs are a practical addition to a building.

The majority of green roofs are classified as either intensive or extensive. They are sometimes referred to with different terms, however. The term “eco-roof” can be used to describe extensive green roofs. This is used most commonly in Portland, Oregon. The roofs are only green for a short period of time each year because of the frequently cold weather, hence the name. Though rare, there are also other variations of green roofs. While not nearly as common as intensive or extensive green roofs, brown roofs are simply made up of a substrate that is left unplanted. Often, rubble from brick and concrete is used as as a substrate, though soil may also be used. It is possible that the roofs can become spontaneously planted as animals track material onto the roof. While not intended to be green roofs, brown roofs often take this appearance with time. The term "semi-extensive" green roof is sometimes used to describe a green roof that is designed with the environmental benefits of an extensive green roof in mind, but has slightly larger plants and a slightly thicker substrate (up to about eight inches) (Dunnett 2004).

2.2 COMPONENTS OF A GREEN ROOF

Visually, green roofs appear to be nothing more than plants growing in a layer of soil on a rooftop. But in reality, they are far more complicated. A green roof is made up of many layers. Between the structural roofing deck and the substrate, waterproofing membranes keep moisture out of the structure, root barriers prevent plants from breaking the waterproof seal, a drainage layer carries away excess water and a filter fabric prevents soil particles from washing away in the rain. Basically, the different layers allow the structural roof and building to remain dry while providing space for the moisture the plants need to survive. There are many green roof systems available. Some manufacturers lay each component as a separate membrane, while others combine several in a single piece. Systems are even available where all components are combined in a modular system. Even though they take different approaches to the manufacturing process, the basic components remain the same.

2.2.1 Waterproofing Membrane

Moisture is one of the most important factors in green roof design. The plants and soil on the green roof will absorb water. Yet it is essential that the structural roof remains dry and isolated from the moisture. The waterproofing membrane provides a durable seal that makes green roofs feasible. It is very important that the membrane is installed properly to prevent leaks in the future, which are very difficult to repair.

The most common type of waterproofing membrane used on green roofs is built-up roofs. They are made up of layers of asphalt roofing felt placed between asphaltic bitumen. Bitumen is simply asphalt mixed with tar. The asphalt and bitumen are the materials that actually waterproof the roof, while the felt adds strength (Osmundson 1999). A drawback of this type of waterproofing is its limited life span of 15 to 20 years on a standard roof. This primarily due to temperature, humidity and ultraviolet radiation, this can cause cracks and leaks when the material is exposed to sunlight. With a layer of soil and plants shielding the waterproofing membrane in a green roof, the lifespan is extended (Dunnett 2004). Since bitumen is an organic material, plant roots may try to feed on it. To avoid this, a root barrier has become an important part of green roof systems, as will be discussed in detail below (Osmundson 1999).

Another type of waterproofing membrane used with green roofs is single-ply roof membranes. Inorganic plastic or synthetic rubber is laid across the roof in sheets. Joints are overlapped and either heat or an adhesive is used to bond the joints (Osmundson 1999). At times, they are installed as tiles instead of sheets (Dunnett 2004). Single-ply membranes have some advantages over built-up roofs. All the material is inorganic, so there is less chance of root penetration. The material is installed at one time, as opposed to in several layers. There are far fewer joints in this type of roof, where leaks are most likely to occur (Osmundson 1999). On the other hand, the seams and bonds are susceptible to leaks if not installed properly, especially around drainage pipes. Also, if the membranes are made of PVC or butyl rubber, they can still degrade from UV radiation (Dunnett 2004).

Fluid applied membranes are sometimes used in strangely shaped areas where the other types of membranes would be difficult to install. Either a hot or cold liquid is sprayed or painted onto the surface of the roof. This creates a seal without any seams (Osmundson 1999).

There are a few other components related to the water proofing membrane that are included in some projects. Protection boards made of polystyrene or PVC is often placed over the membranes during construction to protect against damage. A layer of insulation is sometimes added just above or below the waterproofing membrane (Dunnett 2004).

There are several different choices of water proofing methods available for green roofs. What is ultimately important, though, is that the membranes are installed properly. As long as the membranes are free of leaks and provide a water tight seal, the green roof will have a solid base.

2.2.2 Root Barrier

The root barrier layer is placed directly above the waterproofing membrane and is vitally important in protecting the structural roof. This layer is needed in roofs where there is a built up roof or any other that type contains asphalt, bitumen or other organic materials that may attract roots. It provides a layer of separation between the plants and the membrane. The barrier is usually made of PVC, a long lasting material that is not prone to leaks. It is laid out in sheets, similar to the single ply water proofing membranes. The joints are welded together. Otherwise, plants could find their way through gaps. The root barrier is extended up the side of the perimeter of the green roof and around any protrusions, such as vents or skylights to provide a more complete seal (Dunnett 2004).

2.2.3 Drainage Layer

The health of the plants and the effectiveness of a green roof depend in large part on proper drainage. The drainage system on a green roof is made up of two parts: a drainage layer within the roof itself and the drains that carry excess water into the sewer system. The drainage layer of a green roof must tie into the roof drains, but the drains themselves are identical to those found on any roof.

Precipitation that falls on a green roof can head in several different directions. Some water will be evaporated into the atmosphere; some will be transpired by the plants (absorbed through the roots and released through the leaves); some will be absorbed by the substrate. All other water must have a path to exit the roof. This is the role of the drainage layer. While it is important for the plants to be adequately watered, too much can be damaging. Plants can begin to rot if they are in saturated soil for extended periods of time, retarding growth. Similarly, the roof membrane can deteriorate more quickly if it is in constant contact with water, which can lead to leaks. The roof is also far less effective in insulating the building when saturated (Dunnett 2004).

When the substrate is saturated, the excess water will enter the drainage layer and is eventually carried off the roof through the drainpipes. While the convention used in this paper and most others is to call this water 'runoff', it is actually 'underflow' because it first filters through the substrate (Dunnett 2004). During some rainfall events, the substrate may be able to absorb all of the water. During other storms, depending on the saturation ratio of the substrate, the intensity and duration of the storm, there may be some amount of runoff.

The drainage layer itself can be made of several different types of materials. Granular materials like gravel, broken rocks or clinker are traditional building materials that can be incorporated into a green roof. They have large pore spaces, which allows for good drainage (Dunnett 2004). Most pre-World War II green roofs and many built up through the 1950s and 1960s used broken rocks. While heavy, they were effective (Osmundson 1999). Today, the lighter materials like pumice and broken clay tiles are often used. A thin layer usually weighs less than the substrate and protects the plants from standing water in the soil. As a side benefit, this layer can offer some extra root space for the plants (Dunnett 2004).

In the 1970s, grass cells were sometimes used on intensive green roofs. These were a plastic honeycomb structure molded in interlocking squares that was designed to grow grass in high traffic areas. By turning it over, an effective drainage system for green roofs was created (Osmundson 1999).

Porous mats made of recycled materials can be incorporated into green roofs. They act like sponges and absorb water. Unfortunately, they can absorb excessive amounts of water and deprive the plants (Dunnett 2004).

One of the most common types of drainage mediums used on green roofs is a plastic or polystyrene drainage layer. Their appearance can vary, but many are in an egg crate shape with holes throughout the structure to allow movement of excess water. Depending upon the structure, the layer itself may be able to retain water. Some layers are filled with granular material, but it is not common (Dunnett 2004).

2.2.4 Filter Fabric

As the water flows through the soil, it can pick up particles from both the plants and soil. The drains and drainage layers could become clogged with these, so a filter fabric is often used to capture this material. The fabric is commonly made of polypropylene fibers and was adapted from materials used to prevent erosion. Physically, the filter fabric resembles felt (Osmundson 1999).

2.2.5 Substrate

The next to last layer of a green roof is the substrate. This layer of soil obviously provides the plants with room to grow, but also serves important roles in drainage and water retention.

The most important factors to consider when choosing a soil for a green roof is that it is able to retain water for the plants, yet still allows for drainage. This is often obtained with a mix of a granular material. Those with pour spaces are the main ingredient with smaller particles that will absorb water included in the mix (Dunnett 2004). Many times, the substrate is actually a soilless mix that is high in nutrient content.

On the ground, topsoil is usually used to grow plants. While this may be perfectly acceptable for the exact same set of plants in a park, it is not suitable for green roofs. Topsoil contains many fine silt particles which can easily clog pores and prevent drainage. In addition to silt, it is made up of clay and sand. If there is too much clay, the soil will retain excess water. Large amounts of sand will result in a substrate that drains too quickly and loses many of its nutrients. Topsoil has little organic material to begin with and these are especially important on a roof environment. Weight is also an issue; as topsoil is very heavy when wet (Osmundson 1999).

Organic materials have a tendency to oxidize and decompose over time, resulting in a volume reduction. Some green roof systems therefore use a soilless mix that has no organic materials. They use minerals that can retain water, resulting in the same effect as organic material. In most cases, though, this type of soil is used with a low amount of organic material to give nutrients for the plants. (Dunnett 2004) Two of the main components in many soilless mixes are perlite and vermiculite. Perlite is a volcanic material that provides good drainage. Courser material has a higher porosity. Perlite's irregular surfaces trap some water and air. It also does not change the pH or nutrient quality of the mix because it is chemically inert. Vermiculite is a mica material. It is expanded by heat, creating large pour spaces to retain water (Clothier 2006). Small amounts of minerals and fertilizers are often added as well (Answers.com 2006). The depth of the soil has a significant impact on the moisture retention of the roof, with thicker layers retaining more water (Dunnett 2004).

It is important to note that while there are general conventions for green roof substrates, the final decision is really a function of the plants chosen for a particular project. The type of soil must be appropriate to promote growth and proper drainage. It must also retain enough water to sustain the roof without damaging the plants and roof. The thickness of the soil layer should be thin enough to be structurally feasible, yet thick enough for adequate water retention and to support the plants.

2.3 HISTORY OF GREEN ROOFS

While green building techniques and scientific research into green roofs have only come about in recent decades, green roofs are far from a new technology. Green roofs actually date back thousands of years to some of the first known civilizations. The basic principles formed in ancient times have been expanded and refined with the benefits of research and modern building materials.

Not unlike their different structures and uses, intensive and extensive green roofs have developed along separate paths. Generally, intensive green roofs have been constructed by the wealthy and influential for decoration and leisure. Conversely, extensive green roofs have served practical purposes with little regard for appearance.

2.3.1 Intensive Green Roofs

The ancient Mesopotamian civilization was centered on the area between the Tigris and Euphrates Rivers in western Asia. Today, the nations of Iraq, Turkey and Syria occupy the area. Often called the "cradle of civilization", Mesopotamia was one of the world's first civilizations. One of the earliest forms of writing was developed here and many of the oldest surviving writings come from this area (Wikipedia 2006b).

Starting in about 4000 BC, the Mesopotamians built religious structures called ziggurats. These were stepped pyramids constructed of stone. The buildings were encircled with spiral stairways to reach the various levels. Most major cities contained ziggurats within temples. Archeological excavations of ziggurats have uncovered evidence that plants were grown on level surfaces, probably to protect against the heat. These are the earliest known green roofs (Osmundson 1999).

Two of the most famous structures in history were built with green roofs during this time period. The first references to green roofs in literature are in the Old Testament of the Bible. The book of Genesis tells the story of the Tower of Babel, in which people tried to build a tower to heaven (Wikipedia 2006c). Some believe that the story may refer to the most famous Mesopotamian ziggurat, Etemenanki. It was built around 600 BC by Nebuchadrezzar II in the city of Babylon (in modern day Iraq) and destroyed during revolts in 462 BC.

It is believed that the Hanging Gardens of Babylon, one of the Seven Wonders of the Ancient world, were also constructed by Nebuchadrezzar and destroyed during this same revolt. However, there are no accounts of the Gardens until several hundred years after its destruction. Many Greek and Roman writers describe the Gardens as containing several different levels planted with very large trees in topsoil. The roof was supported by vaults and was layered with lead as a sealant. It is also described as having of an irrigation system to carry water onto the roof. According to an account by Greek historian Diodorus Siculus around 100 AD, the Gardens were 100 feet by 100 feet and stood 70 feet tall.

Unfortunately, no evidence of either green roof has surfaced. Other Mesopotamian green roofs have been uncovered, however. The oldest is the ziggurat of Nanna built around 2100 BC in the city of Ur (now Muqaiyir, Iraq). It was remodeled as late as 550 BC (Osmundson 1999).

Green roofs were known to be popular throughout the Mediterranean during the time of the Roman Empire, but little information regarding them has survived. In the excavation of the Roman city of Pompeii, which was covered under volcanic ash by the eruption of Mount Vesuvius in AD 79, three very large villas have been uncovered. The Villa of Mysteries had a terrace around three side of the building that was covered with a green roof. The volcanic ash preserved the city exactly as it was at the time of the eruption to the point that the types of plants used on the green roof have even been determined (Osmundson 1999).

In the middle ages, much of the wealth in Europe laid with the Roman Catholic Church. Religious buildings were generally the most significant structures built during this time. A Benedictine Abbey, Mont-Saint-Michel in France, has one of the surviving green roofs of the Middle Ages. According to the regulations at the time, the Abbeys were required to be enclosed. In order to let in light and provide the monks with a planting area, a green roof was built at the center of the top floor (Osmundson 1999).

Pope Pius II reigned from 1458 to 1464 and was responsible for one the earliest surviving green roofs of the Italian Renaissance. Pius built a summer palace in his hometown of Pienza, Italy and he used the green roof to hold audiences. The palace was built on a hill, with the front of the building downhill. The green roof was constructed on the back of the building, making it appear that it was at ground level (Osmundson 1999). Several wealthy Italian families also built green roofs in the Renaissance, including the Medicis.

Green roofs were very popular with the Russian nobility in the seventeenth and eighteenth centuries. A massive two-tier hanging garden was built on one of the palaces in the Kremlin, near the Moscow River. The upper most level was constructed first and was 10 acres in area with a one thousand square foot pond, including a fountain. The roof was level with the main rooms of the mansion and was easily accessible. The lower level of the roof was built in 1681 and was quite large itself, at 6 acres, and also contained a pond. Peter the Great played in the pond as child and may have developed his fondness for sailing here. Water was pumped from the river to fill the ponds and fountains. Waterproofing was accomplished with lead sheets and the plants were placed in boxes on the roof. The palace was replaced in 1773, but other Russian green roofs do exist. Catherine II, the czar of Russia from 1729 to 1796, built the Hermitage in Saint Petersburg to house her art collection. There is a green roof with four identical flowerbeds, a pool and fountain, with a walkway dividing the space (Osmundson 1999).

Royalty in other European countries were also fond of green roofs. The King of Bavaria, Ludwig II, built a green roof in Munich. It was something of a green house roof, as it included a glass enclosure. The building was short lived, however. The copper platting used for waterproofing failed miserably and the building was eventually demolished (Osmundson 1999).

Around the turn of the twentieth century, intensive green roofs began to be built in more public spaces, although they were still mostly associated with the upper crust of society.

Perhaps the most popular use for green roofs became as a theater space. Rudolph Aronson was a musician who wanted to build theaters inside gardens in New York City like the ones he saw on a trip to Paris. The land costs were prohibitive, so he turned to green roofs. With the backing of wealthy New Yorkers, he built the Casino Theater in 1880 and added a green roof two years later. There was a stage built on the roof and theater performances were often held there during the summer months. There was a sliding glass roof that covered part of the green roof in the event of rain. Others had built garden theaters, but they all had to be placed outside of the city limits to obtain the necessary land. With a garden stage in the heart of New York City, the Casino Theater became the premier theater for the next decade.

The success and popularity of the Casino Theater led to many others to be built with green roofs throughout the United States, particularly in New York City. One of the most famous arenas in the US today began as one of these structures. Madison Square Garden in New York City has been torn down, rebuilt and moved several times since PT Barnum opened "The

Barnum's Monster Classical and Geological Hippodrome" on the site of a railroad station in 1871. In 1876, the name was changed to "Gilmore's Garden" and it finally became Madison Square Garden in 1879 when it was purchased by William Vanderbilt (Wikipedia 2006a). Despite the name, it wasn't until the second Madison Square Garden was built on the same site in 1890 that a green roof became part of the building. One was added to the new building to host variety acts, along with a 300-foot tall bell tower at one end. The structure was the tallest in the city at the time.

Green roofs became so popular that there were nine along Broadway in New York City. Five were completely open air while the other four had partial glass roofs. It proved to be only a fad and their popularity waned by the end of the 1890s. Between 1900 and 1920, all the roofs were demolished (Osmundson 1999). Madison Square Garden was replaced by a new building in 1925, which did not contain a green roof (Wikipedia 2006a).

As the popularity of theater gardens declined, many hotels, restaurants and apartment buildings began to install intensive green roofs. These roofs had a longer life span, remaining popular from about 1920 through World War II. In New York City, green roofs were status symbol on the most expensive apartment complexes. Two of the most prestigious hotels in the city, the Waldorf-Astoria and the Astor, had green roofs installed at this time (Osmundson 1999).

During this same period from the turn of the century to World War II, architects Frank Lloyd Wright and Le Corbusier incorporated intensive green roofs into their designs, to a degree. Both advocated utilizing roofs as functional space. Each designed several buildings with roof plantings, although neither recommended the practice. Wright's Midway Gardens in Chicago, Larkin Building in Buffalo and the Imperial Hotel in Tokyo along with Le Corbusier Villa

Savoye outside Paris, Domino Houses and the Unite d'Habitation all contained plantings on roof terraces (Osmundson 1999).

Modern day intensive green roofs are heavily influenced in both style and function by a few designs completed just prior to World War II. The Derry and Toms gardens in London and the five green roofs installed at Rockefeller Center in New York City have become the basis for the design of many intensive green roofs built today. Perhaps the most influential is Union Square in San Francisco. This is a public space and was the first green roof installed on top of an underground parking garage. From the 1950s through today, intensive green roofs are increasingly public spaces; with underground parking garages being one of the most frequently used locations (Osmundson 1999).

2.3.2 Extensive Green Roofs

Like its intensive counterpart, the origins of extensive green roofs stretches back many centuries. Kurdistan and Scandinavia simultaneously developed extensive green roof technology.

Today, Kurdistan is largely contained in portions of Turkey, Iraq and Iran. One of the traditional building materials of the area was mud. The development of green roofs was accidental. Seeds deposited on the flat mud roofs would sprout grass, creating a green roof. The area is extremely warm in the summer and the green roofs proved to help keep the buildings cool, making them a staple of Kurdish architecture. The roofs would also help insulate the buildings in the winter (Dunnett 2004).

Extensive green roofs in Scandinavia followed a similar development, but here the main concern was keeping warm during the brutal winters (Osmundson 1999). Scandinavian green roofs became more sophisticated than their Kurdish counterparts. While they were not constructed as effectively as today's extensive green roofs, the basic components were in place. The base of the roof was made of wooden boards, which were then covered with birch bark as a sealant. This was followed by a layer of twigs that acted as a drainage layer. Finally, the roof was finished with turf grass. Instead of allowing the roof to grow naturally, as the Kurds did, the Scandinavians removed grass and soil from the ground that was already established. This layer was the insulation, but it also protected the layers beneath it. All together, the green roofs were fairly watertight and did a good job preventing water from leaking into the buildings during rainstorms. Green roofs were often installed on sloped roofs in Scandinavia, unlike the Kurds, who used flat roofs. Since the roofs were slopped, additional plants would sometimes be installed to stabilize the soil. One of the plant species used, sedums, is still one of the most popular types used in extensive green roofs today (Dunnett 2004).

The materials involved in building these extensive green roofs were very inexpensive and their use became widespread. Some early Scandinavian settlers to the United States and Canada even brought the technique with them, but the use did not spread past the settlements. They were not without drawbacks, however. The roof was primarily covered with grass, so mowing was required on a regular basis. Further maintenance was needed to remove any plants that might spontaneously grow, including trees. Flammability was a concern with a roof constructed completely out of organic materials. The roofs had a somewhat limited lifespan of about 20 years. At that point, the birch material began to break down. Once modern building materials became readily available, traditional Scandinavian extensive green roofs fell out of favor. The new materials were inexpensive and less maintenance was required. Some green roofs were still installed, but primarily for aesthetic reasons (Dunnett 2004).

The development of modern day extensive green roofs can be traced to Europe in the 1960s and 1970s, primarily in Germany. As part of the counter-culture, squatters took over blocks of many European cities. The movement looked at many different ways of living and one of the ideas was to introduce green space into cities. This was particularly strong in West Berlin where practically every available space was planted. Community gardens were popular, as was living walls created by training plants to grow up vertical surfaces. Many roofs were used to grow food and old industrial containers were used as planters wherever there was space (Dunnett 2004).

In other parts of the world, the practices of hippie squatters may have gone unnoticed by the larger public, but this was not the case in Germany. At the same time, influential people outside the movement, from writers to ecologists, were thinking of what German cities should look like in the future. They agreed that green spaces should play a large role in the modern city. The idea became somewhat popular within the environmentally conscious German public and scientific research started on green roofs. There had been some research in the 1950s on plants that spontaneously grew on flat roofs covered with gravel, but it wasn't until the 1960s that research turned to plants growing in thin substrates on roofs. By the 1970s, a clear distinction was made between extensive and intensive green roofs. Due to their practicality, research quickly focused on extensive roofs. In 1977, a green roof group was created in the German landscape research society Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL). Much of the structure of today's extensive green roofs can be attributed to research in Germany during this period. Water proofing and root penetration were problems that were grappled with into the 1980s, when breakthroughs were made. With time and increasingly severe pollution problems in Germany, the culture accepted green roofs and environmental preservation in general (Dunnett 2004).

Germany still remains the epicenter of the green roof universe today, but extensive green roof use has become increasingly widespread in recent years. Different areas are using the roofs for different reasons and with a varying degree of acceptance, but they are slowly spreading across the globe.

With an environmentally conscious society very concerned with the loss of the urban environment, green roofs have become common in Germany. Their use is so widespread that an estimated 10 percent of all flat roofs in Germany were green in 2002. The process is helped greatly by a set of laws promoting the use of green roofs. One of the first was a citywide program in Stuttgart that offered advice and subsides for materials and installation of green roofs. Other cities followed, including Berlin in 1988. Regulations there stated that if a new building took up too much ground space, a green roof is required to replace this area before construction will be allowed. Today, support for green roofs come from all levels of government, including 43 percent of all cities. Like the regulations of Berlin, many programs tie permission for construction with green roofs. This is often related to runoff levels, where the water retention of the green roofs can become very important. One of the underlying principles that have helped with the widespread acceptance of green roofs in Germany is provisions in the Federal Building Code and state and national level nature protection acts that require new developments to repair any damage to nature (Dunnett 2004).

The rest of Europe has widely varying acceptance of green roofs. Austria and Switzerland have similar programs to those in Germany and development is occurring rapidly. Norway has likewise accepted extensive green roof technology. As one of the areas that previously used the Scandinavian turf green roofs, it is seen as part of the national heritage. Great Brittan and the Netherlands have only begun to build green roofs in the last few years and it is still seen as a new technology. There has been little development in Southern Europe as well. The standard sedum heavy green roof used in Germany does not fair well in the hot, dry temperatures of the region. This part of the continent sees far less rainfall, creating less of an issue with water retention, although the thermal properties would be beneficial in the area. Despite their popularity with the Russian nobility in centuries past, green roofs have not caught on in Eastern European nations. They are occasionally used to grow food in St. Petersburg, but are otherwise absent from the landscape (Dunnett 2004).

In tropical regions of the world there are very high rainfall rates. The climate is hot and very humid as well, which leads to a high rate of evapotranspiration. Green roofs can be particularly useful in these areas. In Asia, green roofs are being installed to reduce the urban heat island effect. A number of roofs have been installed in Singapore where space is very limited. In addition to the thermal benefits, it provides green space for inhabitants of the city. Tokyo has recently undertaken perhaps the most ambitious program ever for green roofs. Starting in 2001, the government requires new buildings cover 20 percent of their roofs with vegetation if they have 10,760 square feet of floor space. By 2011, the hope is to have 1200 hectares (2965.26 acres) of green roofs and to reduce the temperature at the centre of Tokyo by 1.7 degrees Fahrenheit (1 degree Celsius). With its massive rain forests, Brazil is looking at green roofs for its water retention properties. Rainfall events in Rio de Janeiro, for instance, have yearly rainfall events that would be 100 year storms in much of the rest of the world. This puts a tremendous strain on the sewer systems. As green roofs are being developed in the area, there are concerns that the excessive rainfall may cause erosion and damage the plants. The soil would also remain saturated for long periods of time (Dunnett 2004). Researchers from Germany have begun to transfer the knowledge gained from decades of research to the Brazilian climate (Kohler et. al, 2001). Australia has a tropical climate as well, but green roofs are still considered an experimental technology. There is interest, but at this time only a few demonstration projects have been built in Melbourne (Dunnett 2004).

North America is not unlike Australia, but the development is further along. While intensive green roofs were first wide spread in the late 1800s and many cities have housed some up through the present day, it is only in the past several years that extensive green roofs have begun to be built and scientific research has been carried out. Many of the European manufacturers of green roof products have expanded into North America and have made their products available. Some cities have installed demonstration projects to look at the benefits of green roofs. One demonstration project has been installed on Chicago's city hall as part of their attempt to become the greenest city in the United States. Chicago has also instituted a policy requiring that new and replaced roofs meet a set of minimum standards of emissivity and solar reflectance, which green roofs accomplish. Toronto has installed a number of green roofs in an attempt to combat the urban heat island effect. They are also the center of Green Roofs for Healthy Cities, a group that promotes green roofs. The largest green roof in the world was recently built by the Ford Motor Company in Dearborn, Michigan. Green roofs are also being used to combat storm water overflow problems, which occur in many older North American cities where combined sewer systems exist. Portland was one of the first to look at green roofs as a solution in this direction. There are several green roofs around the city that are under study that are also looking at the effect of green roofs on the pollution of urban runoff. Portland has a zoning provision that allows more floor space on a project if a green roof is installed (Dunnett 2004).

2.4 WASTEWATER MANAGEMENT AND THE SEWER SYSTEM

One of the most serious problems facing older American cities today are combined sewer overflows (CSOs). Many cities have hundreds of the structures near rivers, streams and lakes. During heavy rain storms, untreated wastewater is dumped into the waterbodies. This creates pollution problems and health risks. While CSOs were originally designed as a primary method of waste disposal, treatment plants began to be added to sewer systems decades ago to keep the waterways clean. Unfortunately, CSOs are still part of sewer systems. With increasing urbanization come ever larger areas of impervious surfaces. These conditions cause large amounts of stormwater runoff to enter the sewer system, often overloading it and causing CSO events. Fixing the problem is not an easy task, but green roofs can be part of the solution.

2.4.1 The Hydrologic Cycle

In order to understand the problems involved with combined sewer overflows and the role green roofs can have on improving the situation, it is important to first have a complete view of the Earth's hydrologic atmosphere.

Although the amount of water on Earth and in the atmosphere is constant, the distribution of the water is constantly changing. The majority of the water is contained in the oceans, with large amounts held in other water bodies like lakes and rivers. Some of this water evaporates into the atmosphere, where it stays until it becomes precipitation and falls to the Earth's surface. Plants will absorb a portion of the precipitation, while some will infiltrate into the soil. Part of this water will recharge the groundwater held in the soil deep below the surface. Overland flow of water may occur when the soil is saturated. Also, some of the infiltrated water can become subsurface flow. Water that is discharged into water bodies becomes surface runoff. Evaporation occurs during all of these processes as well. This hydrological cycle is constantly moving the approximately 366 quintillion (3.66 x 10^{20} or 366 million trillion) gallons of water on Earth (Chow 1988).

2.4.2 Wastewater

Wastewater or sewage is basically any liquid waste that is discharged from domestic, commercial and industrial sources. The majority of wastewater is domestic, which includes homes and institutions. The waste from toilets is the most important component of sewage. While each flush does not use a high volume of water compared to other activities, toilets are used frequently. A large part of the pollution in wastewater is human excreta, with toilet paper contributing significantly as well. Water from washing and laundry also contribute to the waste stream. In particular, the soap in the water accounts for about half of the phosphorous in wastewater.

Commercial buildings are offices, hotels, shops and other types of businesses. Typically, about half of the wastewater generated here is from toilet flushing due to the large concentrations of people. Washing and drinking also contribute. Industrial sites contribute very little of their total wastewater discharge from these same activities, with processing, cleaning and cooling being the largest contributors.

It is important to note that the majority of the potable water drawn from the system is returned as wastewater. Only forty percent is actually consumed in the United States, with the other sixty percent discharged back into the system. In the United Kingdom, the split is even more severe, with 95 percent returned and only 5 percent consumed.

Various factors contribute to the amount of wastewater discharged. There are fluctuations at different times of day, increasing when people are preparing for work and school, but dropping dramatically when most people are asleep. Water usage changes from season to season, with increases in the summer months due to activities like watering gardens (Butler 2004).

There is also a contribution from sources that were not intended to be part of the waste stream. Infiltration can add significant amounts of water to the sewer system. Cracked pipes, poorly sealed joints and other defects in the system allow groundwater and stormwater to enter the pipes. Stormwater can also enter the sewer system through inflows, where illegal connections have been made to the system. One example is illegally connecting a downspout of a home to the sewer (Butler 2004).

2.4.3 Stormwater

The other component of the sewer system is stormwater. When it rains in urban areas, much of the water ends up entering the sewer system through storm grates after running off impervious surfaces.

The hydrologic cycle and several other factors interact with the water between the time it hits the ground and enters the sewers. Even in large cities, there are some green areas, with plants. The plants will absorb some of the water in a process called interception (Butler 2004).

As runoff flows over impervious surfaces, it can become trapped in depressions like potholes or ruts in the wheel paths of roadways. Eventually, this water will evaporate or infiltrate into the substrate (Butler 2004). As the intensity of a storm increases, the effect of these storage mediums decreases rapidly. There are processes that occur during the course of a storm, however. Evapotranspiration can occur at any point during a storm, but the effect is very minimal. Water can also infiltrate soil and fill its pores. Dry soil can absorb significant amounts of water, but the effect decreases rapidly as the soil reaches saturation. The significance of this process is highly dependant on the porosity of the soil, its depth and the surface area covered by plants and soil (Butler 2004). Any runoff that has not been absorbed or detained will become overland flow until it enters the sewer system through an opening (Butler 2004).

While the discussion up to this point has focused on stormwater and runoff at the ground level, it is essentially the same process at the roof level. Conventional roofs are constructed completely out of impervious surfaces. Some rainwater may be trapped in depressions or evaporated, but the majority will typically become runoff and exit the roof through roof drains or downspouts. The runoff can then enter the sewer system through these connections.

2.4.4 Combined Sewer Systems and Combined Sewer Overflows

As the name suggests, combined sewer systems carry both wastewater and stormwater in one pipe. Cesspools and backyard privies were typically used for wastewater disposal before the advent of combined sewer systems. Privies are areas under an outhouse where waste accumulates. Surface privies accumulate the waste on the ground surface, while pit privies collect waste in a hole dug in the ground. In both cases, liquids were allowed to leach away.

Drop privies were sometimes used to discharge waste directly into streams or rivers (Gilbert et. al 2005). Cesspools are holes filled with large pieces of granular material, typically stone or building material, that allow waste to filter through them. They are not sealed, as a modern septic tank would be, so the waste can leach into the soil untreated (Gilbert et. al 2005). Sewer systems were a significant improvement, as the smell and other unsanitary aspects of waste disposal were moved away from population centers. Originally, the systems carried the wastewater and stormwater to streams and rivers, where it was discharged. By combining the two water sources together, the systems had a way to move the waste and provide dilution (Moffa 1997). The original thought process was that running water would purify itself and that large bodies of water would dilute the sewage (Gilbert et. al 2005).

Wastewater treatment plants were eventually added to the sewer systems to treat water before discharging it into waterways. During dry weather, the sewer only carries wastewater. When it begins to rain, stormwater also flows in the pipes. The stormwater usually dominates the flow, even after only a short rainfall (Butler 2004). The older systems, constructed before treatment plants were included, were typically designed to carry only a small portion of the stormwater flow. The pipes were often designed to carry either small storms (one-year storms) or as a multiple of the dry weather flow (typically two to four times) (Moffa 1997). In today's modern cities, it is not uncommon for the wet weather flow to be 50 or 100 times the dry weather flow (Butler 18). Since the sewer pipes carry just the dry water flows the majority of the time, it would be very expensive to size the pipes to carry the full flow over the full length of the system. In order to deal with the excess flow, combined sewer overflows (CSOs) were installed along the system. Once the flow reached a certain level, it would be diverted into the overflow and released into a waterway (Butler 2004). In the early systems, the waste was eventually emptied into a large body of water at the end of the system anyway. The more modern systems had wastewater treatment plants as the final destination, yet CSOs were still included as part of these systems. Designing the plants to treat the peak flow was still cost prohibitive, so the CSOs were either left in the system or continued to be built (Butler 2004).

The CSOs act as a flow divider for the mix of stormwater and wastewater. The continuation flow is the part that passes through and continues to the wastewater treatment plant and the spill flow is the portion that is released into the adjacent waterway (Butler 2004). There are many different designs for CSOs, often varying by region (Moffa 1997). Normally, though, a weir is used. If the flow passes below the crest of the weir, it will simply flow through the CSO and continue through the system. Once the flow reaches the crest, some water will continue to the treatment plant and some will be discharged by the CSO. The spill flow increases with the flow rate. The ideal situation would be for all of the wastewater to reach the treatment plant while only stormwater was discharged. Even in the best designed CSOs, however, this is not possible. While many designs do very well with retaining the largest solids, some wastewater is inevitably dissolved in the stormwater and smaller particles are discharged (Butler 2004).

2.4.5 Separate Sewer Systems and Sanitary Sewer Overflows

The other type of sewer system used to dispose of waste is the separate sewer system. Here, two sets of pipes are used to deal with liquid waste. The storm sewer pipes carry stormwater until it can be discharged into a water body. The other set of pipes are called sanitary sewers and usually run alongside the storm sewer carrying the wastewater to the treatment plant. The storm sewer is the larger of the two, often about the same size as a combined sewer pipe. The wastewater pipe is considerably smaller.

Despite different pipes, it is difficult to achieve true separation of the flows. Rainwater can still find its way into the wastewater pipes through infiltration or direct inflow from illegal connections, just as with combined systems. It is also nearly impossible to be certain that the stormwater being discharged is clean. As will be discussed in detail later, stormwater is often polluted from a number of sources (Butler 2004).

Today, sanitary sewers are not designed to have overflows into waterways like the combined sewers. But, since stormwater does find its way into these sewer pipes, they can become overloaded. When this is the case, Sanitary Sewer Overflows (SSO) do occur. Without an outlet to discharge the water, SSOs can happen at cracks or damaged points in pipes (potentially causing groundwater contamination), manholes or back up into basements. Some separate sewers systems may connect to combined sewers at some point or are treated at a plant where combined sewer systems are also served. In these cases, raw sanitary sewage may be allowed to overflow if the capacity of the treatment plant is exceeded. There are some instances of SSOs as part of earlier sewer systems, but they are now illegal (Gilbert et. al 2005).

2.4.6 Water Quality

Regardless of the source, any water that is part of the sewer system is polluted to some degree. As discussed earlier, wastewater is polluted by its very nature. While it may appear clean, stormwater is also contaminated. CSOs are designed to only discharge stormwater, but in reality they discharge a mix of stormwater and wastewater. It is therefore important to understand the make up of the untreated water that is discharged from sewer systems.

The pollution of stormwater begins before the rainwater even reaches the ground. As the rain falls through the atmosphere it can pick up pollutants suspended in the air from vehicle exhaust, heating and cooling or industry. These same materials can settle on the ground and be transferred as the water runs off. Nitrogen, phosphorus, lead, zinc and cadmium are commonly introduced to stormwater in this way. Amounts vary, but the majority of these pollutants are often transferred in this way (Butler 2004).

The vehicle exhaust that contributes to atmospheric pollution contains lead, hydrocarbon losses and volatile solids. Vehicles contribute pollution from other sources as well. Tires release zinc and hydrocarbons as they break down. Metals (copper and nickel) are released as break lining and other parts of the car wear (Butler 2004).

Essentially anything that can be found on the ground in an urban area can pollute stormwater, particularly things found on roads. Any wastes left by animals contribute bacteria pollution to the stormwater. Litter or leaves and yard waste near streets can wash into the sewers. Similarly, motor oil on the roads or cleaners dumped into storm drains degrades the water quality. Salts used to clear streets in the winter substantially increase the chloride levels in stormwater. Even the roadways themselves can contribute to pollution. As they decay, pieces can enter the sewer and act as suspended solids. Metal objects along the road can also contribute chromium as they corrode (Butler 2004).

While roof runoff is usually considered clean, some recent studies have shown this assumption to be false. Copper, lead and zinc levels in runoff were found to be high, with zinc levels the most severe. Many of the runoff samples had metal contents higher than from other urban sources and zinc levels were at times high enough to be toxic to aquatic life. Galvanized roofing materials appear to cause the increased levels of zinc, while the copper and lead in the runoff come from roof coatings and other roofing materials, especially copper flashing. Studies showed that while there was a first flush effect, the levels stayed elevated well into the storm (Schueler 2000). Rainwater recycling is often a component of green building projects. The recycled water is often used to flush toilets or similar grey water tasks. In these instances, water quality may not be a major concern. But recycled rainwater is also used as drinking water in many places, where water quality is vitally important.

When a CSO discharges water, there is a mix of stormwater and wastewater released. There is a first flush effect, where the initial rush of water to exit the CSO has a high concentration of sewage. As the stormwater moves through the pipes for the first time, it washes the wastewater off the walls (Gilbert et. al 2005). Additionally, the stormwater moves faster than the wastewater already in the sewer, so it creates a wave as it moves, picking up increasing amounts of sewage. Organic materials are often concentrated at the top layer of wastewater. The initial flow of stormwater will absorb some of this material. Any build up of pollutants from catchment surfaces since the last rainfall would also be mixed in during this first flush (Butler 2004). During the first flush, levels of suspended solids and BOD can even be higher than in raw sewage (Gilbert et. al 2005). BOD stands for biochemical oxygen demand and it is a measure of the amount of oxygen consumed when microorganisms oxidize an organic material they are using as a food source into carbon dioxide and water. The COD or chemical oxygen demand is similar, but it is a measure of the amount of oxygen required for oxidization using a chemical oxidizing agent (Davis 1998).

A first flush can typically last up to a half hour after the initial discharge, but this will vary greatly depending on the conditions of the storm. The levels of pollutants are elevated during this period of peak flow and are very important in diagnosing the effect of the CSOs on water quality (Moffa 1997). After this point, discharges from CSOs are composed of larger concentrations of stormwater. The wastewater is diluted, but still present. The concentrations of pollutants decline as a result of the dilution (Gilbert et. al 2005).

When looking at water quality and CSOs, there are a few indicators that are frequently studied. Bacteria are of prime importance. As will be discussed later, this is the main source of public health problems associated with CSOs and is therefore a vital topic. Organic materials and metals can also be discharged by CSOs in large amounts. Dissolved oxygen levels can decrease. The visually obvious pollutants discharged from CSOs are solids, in the form of debris and waste (Moffa 1997).

The effect of CSOs is usually measured by changes in water quality in the discharged water body. A decrease in dissolved oxygen is one of the more common effects. This is caused by BOD deoxygenation and ammonia nitrification in the waste discharged from the CSO. The exact effect of these processes is inconclusive up to this point, but some studies have shown that organisms in the water may die or that it effects growth and reproduction when there is a dissolved oxygen depression (Moffa 1997). The added nitrogen and phosphorous from the discharge can increase algae and weed growth in the water body. This process can affect drinking water use or could cause a decrease in dissolved oxygen. Faster moving rivers and streams are less affected by this process because the nutrients are typically washed away before they can cause too much harm (Moffa 1997). CSO discharges are often high in suspended solids, which can settle as sediment at the bottom of waterways. High levels of metals and biologic oxidation in the sediment can lead to high sediment oxygen demands (SOD) (Moffa 1997). SOD measures the dissolved oxygen that is removed by biological material in sediment (Moffa 1997). Any sort of toxic materials that work their way into the sewer system, including ammonia and dissolved trace metals, can be discharged. These can kill wildlife and be harmful to humans as well (Moffa 1997).

2.4.7 History of Pittsburgh's Sewer System

Pittsburgh sits in Southwestern Pennsylvania at the convergence of the Allegheny, Monongahela and Ohio Rivers. As the largest inland port in the United States, the three rivers have played an important role in Pittsburgh's history from the time of the French and Indian war, through the region's time as the world's biggest steel producer and to the present day.

Pollution was an all too familiar problem in Pittsburgh during its steel producing heyday. The air pollution problems were obvious. At times, the smoke and smog in the air made the noon time sunlight completely indistinguishable from the darkest nights. With the collapse of the steel industries in the late 1970s and early 1980s, these drastic air pollution problems have subsided. Though soot still stains many buildings, the air is clean.

The water pollution problems in Pittsburgh have often been forgotten. Industry polluted Pittsburgh's rivers along with its air, but the rivers have not received the same amount of attention. While industrial water pollution may have been reduced in the region, sewer overflows still pose an ongoing and serious pollution problem.

From the time that Europeans first settled in the Pittsburgh area in the mid eighteenth century, drinking water was supplied by wells and ponds. The decision was made to construct public waterworks in 1826, which were completed in 1828. Water was drawn from the Allegheny River and distributed throughout the city from a reservoir by gravity. As the city expanded and became heavily industrialized, the system grew. The system was not efficient, with many leaks (Gilbert et. al 2005).

Pittsburgh relied on cesspools and privy vaults for waste disposal through the 1800s. There were concerns with the smell and pollution, especially in the rivers. Fines were levied and attempts were made to clean up the waste. The problems still persisted, however, and the city realized it was a health issue by 1875. It wasn't until running water became widely used in the last quarter of the nineteenth century that planning began to take place to install a proper sewer system. In a wide majority of homes, the wastewater from the new appliances was disposed of in the same privy vaults and cesspools. This aggravated the pollution problem (Gilbert et. al 2005).

The commercial district of Pittsburgh did have a sewer system for runoff by 1866. It was underground and was installed mainly to prevent flooding. It grew to 25 miles in length by 1875, but the system was poorly designed. It was not sized correctly for much of its run and clogged frequently (Gilbert et. al 2005).

The first proper sewer system in Pittsburgh was constructed between 1889 and 1912. It was almost completely a combined sewer system and ran 412 miles long. There was intense debate for a time on whether a separate or combined sewer was best for the city. The separate sewer side argued that the wastewater and harmful gasses should be carried away separately before they decomposed and were exposed to people. Stormwater was not considered important. The case for combined sewers focused on the reduced cost of installing a single set of pipes. This argument, along with the more balanced plan to dispose of both types of water, won the decision for combined sewers. As was typical for the time, the combined system contained CSOs for times when rainfall would overwhelm the system (Gilbert et. al 2005).

While the new sewer system was at least in part installed to improve public health, problems still persisted. The sewer pipes drained directly into the Allegheny River. This was the same river that the drinking water for the city of Pittsburgh was drawn. To exacerbate the situation, 75 other communities discharged waste into this same river, upstream of the city. Typhoid fever rates were high in the city as a result of the pollution. The death rates for the disease were nearly three times the national average and were the highest among major cities (Gilbert et. al 2005). The illness is spread by bacteria that can be passed along by diseased persons or in their feces (CDC 2005). The filthy rivers undoubtedly contributed to this problem.

As early as 1905, Pennsylvania acted on the pollution problems associated with discharging raw sewage into rivers by passing the Purity of Waters Act. While it was no longer allowed, municipalities that were already discharging untreated waste could continue to do so. Permits were also available if one of the existing systems was to be expanded. In late 1907, the city did take a positive step forward and began filtering its water. Typhoid rates began to drop (Gilbert et. al 2005).

In 1910, Pittsburgh applied for a permit to expand its existing sewer system. The Pennsylvania Department of Health (PADOH) required a comprehensive plan for the city to collect and dispose of its waste before granting the extension and suggested changing from a combined to a separate sewer system. The city hired engineers to come up with a plan. They argued that the dilution from disposing the waste in the rivers was enough to prevent any problems. The PADOH had also suggested a treatment plant for wastewater. The engineer's report stated that the downstream communities would not benefit from improved water quality downstream, because waste was discharged upstream of Pittsburgh as well. These cities would still need to filter their drinking water. Likewise, Pittsburgh would not receive any direct benefits from the improvements. Perhaps most importantly, the cost of converting to a separate sewer system was prohibitive. In 1913, the PADOH granted Pittsburgh its permit to extend its sewer system and to continue discharging it into the rivers (Gilbert et. al 2005).

Throughout the 1920s and 1930s, there was some movement towards treating sewage, but the vast majority of waste in the Pittsburgh region was still discharged into rivers. A Sanitary Water Board was created in 1923. They classified Pittsburgh's rivers as so polluted they could not be used for drinking water or recreation unless treated, effectively allowing sewage to continue to be dumped into the rivers. Drinking water was drawn from the rivers, though, and taste and odor problems persisted. Diarrhea and enteritis still caused deaths, even after filtration and chlorination had reduced typhoid fatalities (Gilbert et. al 2005).

The wheels were set in motion for finally cleaning up the polluted rivers in 1937, when the Sanitary Water Board was given control over waste treatment by the Clean Streams Act. They ordered all municipalities to treat their sewage to a primary degree, but World War II delayed any action from occurring until 1945. At this point, the discharge of untreated waste into waterways was officially banned. Deciding to tackle the waste treatment on a county wide level, the Allegheny County Sanitary Authority (ALCOSAN) was formed in March of 1946. ALCOSAN studied the various options for treatment, including number, type and location for the plants. The decision was made to install a central treatment plant on the bank of the Ohio River, just north of Pittsburgh. Part of the system was a network of interceptor sewers to connect the various sewer lines running throughout the county and to carry the waste to the treatment plant. ALCOSAN would be in charge of these pipes, while local municipalities would be responsible for their own sewer systems. Sewer charges were determined by water usage (Gilbert et. al 2005).

The existing sewer system was mainly combined systems, but several separate sewers were also tied into the system. For both combined and separate sewers, it was necessary to provide overflow relief because the flow to the ALCOSAN treatment plant needed to be regulated (Gilbert et. al 2005). There are a total of 317 overflow structures in ALCOSAN's system, 265 CSOs and 52 SSOs (3RWWDP 2006b). Statewide, Pennsylvania has the highest number of CSOs of any state (Gilbert et. al 2005).

2.4.8 Impervious Surfaces

As discussed earlier, the hydrologic cycle determines where rainwater will go once it falls to the ground. Some rainwater will become runoff, some will infiltrate the ground surface and become groundwater and some will be absorbed by the process of evapotranspiration. Urban areas introduce vast amounts of impervious surfaces that do not absorb water and change the water balance.

In an undeveloped area, surface runoff will find its way to rivers fairly quickly. The portion that becomes groundwater will eventually join the river as well, but this occurs gradually and is not tied to any particular rainfall. In urban areas, water is not absorbed by the impervious surfaces created by roads, rooftops and other structures. The amount of surface runoff is therefore greatly increased while less infiltration occurs. This results in far more runoff reaching rivers during and just after storms. Additionally, water travels faster off impervious surfaces and through sewer pipes than over natural surfaces, so the runoff reaches rivers more quickly. Often times, the additional runoff entering sewers will overload the system. This causes CSOs and SSOs to overflow, dumping large amounts of raw sewage into rivers and creating pollution problems (Butler 2004).

As cities expand, the amounts of imperious surfaces rapidly increase. More and more stormwater is introduced into the sewer system with each rainfall, while the sewer systems remain the same size. Urbanization places stress on sewer systems and increases the likelihood of overflow events and pollution.

2.4.9 Pittsburgh's Sewer Problems

The city of Pittsburgh has changed significantly since the ALCOSAN treatment plant was first added to the sewer system in the 1940s. Pittsburgh was heavily industrialized, with the steel industry leading the way. In the late 1970s and early 1980s, the steel industry collapsed and the population has been in a state of decline ever since. From 1970 to 2000, there was a population drop from 520,000 to 335,000 (35.7 percent) in the city of Pittsburgh. Likewise, the metropolitan area population declined from 2.5 million people to 2.3 million (7.7 percent). This follows a common trend for large American cities: large numbers of people moving from the city centers to the suburbs (Gilbert et. al 2005). What is uncommon, however, was the amount of sprawl relative to its population decline. Between 1982 and 1997, the urbanized area of the Pittsburgh metropolitan area grew by 42.6 percent while the population declined by 8 percent. This works out to a decline in population density of 35.5 percent, the fourth largest among northeastern US cities during this time. Additionally, Pittsburgh grew in developed land area by 43 percent during this same 15 year period. This puts the city among the 20 largest land consuming metropolitan areas in the country, yet it is the only one to lose population during this time (Gilbert et. al 2005).

In its present state, Pittsburgh has the infrastructure (including the sewer system) for a city much larger than its present population (Gilbert et. al 2005). Much of this infrastructure is old and in disrepair. The sewer system is no exception (Gilbert et. al 2005). Fifty to sixty percent of the inflow and infiltration is from leaky pipes or illegally connected roof drains. Even during dry weather, forty percent of the water ALCOSAN treats can be from these sources (3RWWDP 2002). As Pittsburgh and its suburbs have expanded, the amount of impervious surfaces has increased similarly. More impervious surfaces result in more runoff during each rainfall. All of this water must be handled by a sewer system designed decades ago for a much more compact city. As a result, sewer overflows are a common occurrence in Pittsburgh.

The average rainfall depth in Pittsburgh is approximately 0.25 inches, yet a rainfall of only one tenth of an inch can cause the sewer system to dump raw sewage into the rivers (3RWWDP 2006a). The average depth number is obtained by dividing the total precipitation for an average year (about 36 inches) by the total number of wet weather days in an average year (about 150). The average number of wet weather days is defined as when at least 0.01 inches of precipitation accumulated during a 24 hour period (BBC 2007). The overflows therefore occur quite frequently, after most rainstorms. The Allegheny County Health Department, for instance, typically issues warnings on 30 to 50 days during the May through December recreation season. These warnings tell boaters to avoid bodily contact with the river water (Gilbert et. al 2005). While disrupting fishing and swimming may seem insignificant, it is a good gauge of the overall water quality. Indicator organisms are measured to test if water is fit for human contact. If it is considered unsafe, the levels of E. coli and Enterococci bacteria in the water are too high (Gilbert et. al 2005). E. coli is a bacterium that causes gastroenteritis. Outbreaks are normally associated with contaminated meat (usually ground meat or undercooked beef), but waterborne outbreaks have also occurred when sewers pollute water bodies. Enterococci are used to indicate the levels of fecal bacteria in the water. This can be used to estimate the amount of feces and fecal pathogens in the water. Many types of bacteria and viruses can be present in contaminated water, but these are used to gauge the overall water quality (Gilbert et. al 2005).

To the present day, ninety percent of Allegheny County draws its water from one of Pittsburgh's three rivers. All together, approximately 16 billion gallons of stormwater and sewage overflows into the rivers each year (3RWWDP 2002). As such, the water quality of the rivers is vitally important to the health of the city. Rates of waterborne illness are high for the state, indicating that there is a pollution problem. A full 19 percent of waterborne disease outbreaks and 26 percent of waterborne illnesses in the United States occurred in Pennsylvania between 1971 and 1985. From 1986 to 1992, Pennsylvania also ranked near the top of all states in cases of waterborne disease outbreaks (Gilbert et. al 2005).

There are numerous studies that show water quality problems in the Pittsburgh area. Some drinking water treatment plants test the water prior to treatment. Indicator pathogens are present on a regular basis. 3 Rivers 2nd Nature also conducted a study in 2000 to compare river water quality during dry and wet weather. Using E. coli and fecal coliform as indicator pathogens, the study found that the levels were within acceptable limits during dry weather, but they increased after rainstorms. The levels stayed elevated for several days after the storms. Also, the highest concentrations of contamination occur at the edges of the river, where the discharges take place. A second study in 2002 again showed elevated fecal coliform levels in wet weather. After storms, the highest concentrations of pollution were found near CSOs. Similar results were found in studies by a number of other organizations (Gilbert et. al 2005). These factors clearly indicate that sewer overflows are a leading cause of pollution in the Pittsburgh watershed.

The sewer overflow problems facing Pittsburgh are not simply hazardous. They also are illegal, as they violate the Clean Water Act (Gilbert et. al 2005). ALCOSAN is facing enforcement action from many different organizations, including the Environmental Protection Agency (EPA), Pennsylvania Department of Environmental Protection (PADEP) and Allegheny County Health Department (ACHD) (Gilbert et. al 2005). With these pressures, there is a plan in place to improve the situation.

When constructing a Long-Term Control Plan (LTCP) for CSOs, there are two approaches that may be taken: presumption and demonstration. The presumption approach essentially assumes that reducing the amount of overflow events will be sufficient to improve water quality levels to an acceptable point. Extensive water quality testing is not required to prove effectiveness. This plan can be met by either limiting the overflow events to an average of four to six per year or by eliminating or treating 85 percent of the combined sewage in the system each year. The demonstrative approach, on the other hand, is based on using monitoring to show that the controls put in place have improved the water quality to an acceptable degree (Moffa 1997).

ALCOSAN choose to go with the presumption approach, although there are third party reviews that question whether it is possible to gain satisfactory results in this way (Gilbert et. al 2005). They stated, "Clearly the most cost-effective investment in wet-weather overflow prevention will be the construction of treatment plant improvements to maximize the treatment of the current CSOs. These improvements will result in an immediate reduction of overflows and will reduce costs…" The first stages of the project were started in 1996, which included expanding the treatment plant from 200 million gallons per day (mgd) to 250 mgd (ALCOSAN, 1996). The main parts of the overall plan are an expansion of the ALCOSAN waste water treatment plant to a wet weather capacity of 875 mgd. This will take place over a 20-year period. They will also reduce the amount of water overflowed into the rivers and increase the amount treated by updating the infrastructure of the interceptor sewers. The interceptor sewers that run along the three main rivers would be conveyed to the main plant for flow regulation and primary treatment. Those that run along tributary rivers would be upgraded, have peak flow storage and would undergo some treatment. All together, ALCOSAN believes this plan will reduce CSO overflows by 85 percent. Also included as part of this plan are extensive rehabilitation and reconstruction of the sewer system. This can run into complications for systems that ALCOSAN does not control, yet treats its water. The plan is estimated to cost approximately three billion dollars. Over the approximately 50 years it will take to complete the project, this works out to $9000 per customer (Gilbert et. al 2005).

There are a number of other typically suggested solutions to CSO problems. Sewer flushing during dry weather to wash out sludge, regulators to restrict flow and create a backup and storage and vortex separators to regulate flow and remove suspended solids are commonly used. Storage areas to hold water from peak wet weather flows are considered necessary to control CSOs in most cases. Storage can be inline, where it is connected in series to the sewer pipe and is created by letting the inflow volume surpass the outflow volume, or offline, where the storage is parallel to the sewer system and only accessed during high flows (Moffa 1997).

All of the methods for treating sewer overflows discussed so far, both in general and specifically for Allegheny County, have dealt with controlling flow. Through treatment or storage, the large flow created during wet weather events is contained within the system. The pollution associated with sewer overflows can be can be reduced in this manner, but it does not get the root of the problem: there is too much stormwater runoff being produced when it rains.

As will be discussed in detail in the next section, green roofs reduce runoff by replacing impervious surfaces on rooftops with porous natural surfaces that absorb water. Technologies like green roofs and sewer controls can be put to use in concert to tackle the overflow problems facing Pittsburgh.

2.4.10 Contaminants of Interest

Many topics regarding water quality issues were discussed in the previous sections. To actually measure any affect green roofs can have on water quality, it is necessary to choose several key parameters. Using these parameters, it would be possible to detect differences in water quality. This section will provide background information on each contaminant. The test procedures used to monitor each parameter is discussed in section 4.3.

2.4.10.1 Nitrogen

Nitrogen is the largest constitute of the atmosphere, with Nitrogen gas (N_2) accounting for 78.1 percent by volume. During the hydrologic cycle, rainwater passes through the atmosphere and can equilibrate with the gases present. During combustion, nitrogen oxides (NO_x) are produced and introduced into the atmosphere (Snoeyink 1980). Industrial processes that use hydrogen as a reducing agent can reduce the atmospheric nitrogen to ammonia (NH_3) (Boyd 2000).

The nitrogen cycle encompasses the main forms of nitrogen. Atmospheric nitrogen is absorbed by plants and then transferred to animals as they eat the plants. When the plants and animals die and decompose, ammonia is released. This also occurs with animal excrement. The ammonia can react with hydrogen ions to form ammonium (NH_4^+). Bacteria oxidation can transform ammonia to nitrite (NO_2^-) and then further to nitrate (NO_3^-). Some bacteria can also reduce nitrate to nitrogen gas, nitrate or ammonia. Fertilizer production is another source of ammonia and nitrate (Snoeyink 1980).

Nitrogen is vital to aquatic ecosystems and its quantity in the water can control the ecosystem's productivity. Nitrogen is a nutrient to many organisms and an overabundance of any nutrient can cause excess plant growth and an oxygen deficit, depriving larger animals. In particular, nitrogen is necessary for algae growth. Ammonium is deposited in soil from wastewater. When this is transformed to nitrate in the nitrogen cycle, it can seep into the ground water. This is potentially dangerous. If nitrate is further transformed into nitrogen gas, it can cause elevated nitrogen levels in drinking water. This can cause an oxygen deficiency in infants, the so called "blue baby" syndrome (Chin 2006).

2.4.10.2 Phosphorus

While phosphorus is not a toxic pollutant in water, it does play an important role for plants, both in water and on the ground. Phosphorous is mainly found in soil deposits as part of minerals like iron and aluminum. These concentrations are typically low, but there are several locations around the world with high levels of calcium phosphates. No significant sources of phosphorus exist in the atmosphere. In unpolluted water, the sediment is the primary source of phosphorous.

There is not a global cycle for phosphorus like there is for nitrogen, but there is a similar process in aquatic ecosystems. Phosphorous can enter the water from a number of sources, including the atmosphere, runoff, plant debris and pollution. Fertilizer is a common source. Plants absorb phosphorous from the water and it becomes part of their biomass, which is then becomes food for animals. When both plants and animals die, phosphorous mineralizes and is released. During these processes, any remaining phosphorous that plants do not use is absorbed by the sediment. Rooted plants in the water can utilize this phosphorous. There is normally equilibrium between the phosphorous in the water and that in the sediment, but with far greater concentrations in the soil. Phosphorous leaves the system through outflows, human use and the harvesting of aquatic species (Boyd 2000). Orthophosphate (H_3PO_4) is the only significant form of phosphorous for plants and algae (Chin 2006).

The main negative effective of phosphorous additions to water runoff, pollution and similar sources is the rapid growth of phytoplankton. These organisms absorb phosphorous from the water quickly, including storing extra for future use. When there is an influx of phosphorous, the phytoplankton grows rapidly, increasing the turbidity and changing the color of the water. This can restrict light, which can harm or kill many species that live in the water (Boyd 2000). Phosphorous can also have a similar effect on algae growing in lakes, where it is similarly the limiting factor controlling growth (Chin 2006).

2.4.10.3 Sulfur

Sulfur is an important element to the aquatic ecosystem, plants and animals. Very little sulfur exists in the atmosphere, with 0.0001 percent of SO_2 (sulfur dioxide) by volume (Snoeyink 1980). Along with hydrogen sulfide, H_2S, it is introduced into the atmosphere through volcanic eruptions. Hydrogen sulfide is also created by the decomposition of organic material (Boyd 2000). The oceans contain a large amount of sulfate (SO_4^{2-}), with a concentration of 2700 ppm (Snoeyink 1980). This is the type of sulfur usually used by plants. Sulfate can be introduced into the atmosphere as sea water evaporates. Combustion of fuels releases sulfur dioxide into the air at a rate of approximately 100 million metric tons (102.3 million tons) of sulfur per year.

This is believed to be more than from natural sources, although the exact amounts of naturally occurring sulfur in the air are not know precisely (Boyd 2000).

Despite pollution, levels of sulfur in the air are typically low because reduced forms of sulfur oxidize to sulfate and other sulfur compounds are absorbed by rain as it moves through the atmosphere. The sulfur absorbed by rainwater oxidizes to form sulfuric acid, which results in acid rain. This can be toxic to animals, but some can reduce it to sulfide and use it to make amino acids as part of the sulfur cycle. Sulfate, however, is usually used by plants as a sulfur source. Sulfur is passed on to animals as they eat plants, which can then be used by bacteria from excrement and as the animals die and decay. Some bacteria can transform sulfate into other forms of sulfur. Gypsum and other sources of sulfur are mined and used in industrial processes. Concerns over sulfur levels in water fall into two areas. High levels of magnesium or sodium sulfate in drinking water gives it a bitter taste and it can act as a laxative. For aquatic ecosystems, excessive hydrogen sulfide is toxic to animals (Boyd 2000).

2.4.10.4 Chemical Oxygen Demand

Aquatic organisms depend on dissolved oxygen in the water for survival. Therefore, the levels in a water source are important for the health of an ecosystem. Unlike other substances discussed in previous sections, it is the lower limit of concentration that is important. This is a limiting factor in the amount of life an aquatic ecosystem can support (De Zuane 1990).

One parameter that is measured to gauge the health of a water source is Biochemical Oxygen Demand (BOD). This is the amount of oxygen needed to biochemically oxidizes the organic matter in water. Wastewater typically contains materials with high BOD levels that consume large amounts of dissolved oxygen which can harm organisms and deprive them of oxygen when it is discharged into a waterway (Chin 2006).

Testing for BOD is a lengthy process. Results are normally reported as a five day BOD (BOD_5) because 70 to 80 percent of the dissolved oxygen is consumed during the first five days (De Zuane 1990). In short, a water sample is diluted and inoculated with microorganisms. It is then left to incubate in the dark for five days at a constant temperature (20°C). The dissolved oxygen concentration is measured at the start and end of the test, with the difference the BOD (typically reported in mg/L or ppm) (Davis 1998). Due to time required to complete BOD tests, a related, but quicker test is often carried out (as is the case with this project).

Standard Methods (1992) defines Chemical Oxygen Demand (COD) as "a measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant." The COD is larger than the BOD because many organic substances that are oxidized by the COD test are not immediately available as food to microorganisms. Typically, the COD of wastewater is twice its BOD_5. By itself, COD gives an indication of overall quality of water and potential damage to aquatic organisms. With additional occasional BOD tests, the ratio can be monitored to gauge the level of biodegradable waste in the water. A ratio approaching one indicates a high level, while a ratio approaching zero would indicate poorly biodegradable material (Chin 2006).

2.4.10.5 Metals

In urban areas, the major source of heavy metal pollution is vehicle traffic. This is true for not just lead (Pb), but also zinc (Zn) and cadmium (Cd). Vehicle exhaust is the main source of this pollution, but tire wear, lubrication fluids and wear and tear of parts also contribute. Also of note is that asphalt paved roads contribute approximately 80 percent more pollution than concrete paved roads. Obviously, more traffic creates more pollution (Chin 2006).

In the case of lead, the gasoline and batteries in cars are the sources of pollution (Chin 2006). Approximately 90 percent of the lead that humans take in from the atmosphere is from leaded gasoline. Lead builds up cumulatively in the blood of humans. When levels become too high, lead poisoning can have severe consequences. Children are particularly susceptible. Death may occur if levels become too high, but severe mental retardation can also occur at lower levels of concentrations in the blood stream (De Zuane 1990). Other effects of lead poisoning include kidney damage, high blood pressure, anemia and nervous system damage (with retardation as the most extreme case). Lead may also be a carcinogen (Chin 2006).

Runoff, particularly from industrial and mining sources, can contribute to increased levels of lead in water. In the case of lead poisoning, however, corroded lead pipes delivering drinking water or the ingestion of products such as lead paint are typically the cause (De Zuane 1980).

Like lead, zinc pollution is caused by traffic. In particular, tire wear and corrosion of metal are the sources. Also, zinc comes from the salt used to deice roads that is picked and carried by the tires. Pennsylvania is one of the leading states in salt use (Chin 2006).

Zinc levels are normally low in natural waters (only trace amounts), but pollution can result in a concentration as high as 50 mg/L. Industrial pollution and zinc mining are significant contributors. There are no reported ill effects of zinc by the USEPA. In drinking water, up to 20 mg/L has been consumed safely, although concentrations of 5 to 30 mg/L produce a hazy appearance and has an unpleasant taste (De Zuane 1990).

Cadmium is an element which is used in metal plating and batteries and as an alloy with several other metals. Corrosion releases cadmium. It often enters water distribution systems as this process effects pipes. Urban air has increased levels of cadmium and it can be harmful to humans. Each person can intake approximately 0.5 mg per week safely from dietary sources. Levels in the body of about 0.05 mg/L are safe. Nausea can occur at 15 mg/L. Ingestion of cadmium can be fatal in severe cases (De Zuane 1990). Typical side effects of high concentrations are kidney damage and high blood pressure. Cadmium may be carcinogenic (Chin 2006).

2.4.10.6 pH

pH is an important water quality parameter to monitor because it is related to acid rain. Acid rain is a solution of mild sulfuric and nitric acids formed by the reaction of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) with water and oxygen in the air. The SO_2 and NO_x in the atmosphere primarily come from fossil fuel combustion emissions (USEPA 2007). pH of water can range from 0 to 14. At a pH of 7, a solution is neutral. Lower values correspond to an acidic solution, while higher values result in basic solutions. Because pH is a logarithmic function, a change of one unit would correspond to a ten times increase or decease in the acidity of a solution (De Zuane 1990). Non-acid rain typically has a pH of about 5.6 due to dissolved carbon dioxide in the atmosphere. Acid rain, particularly prevalent in the Northeastern United States and Canada, can have pH levels of between 4 and 5 (Chin 2006). Raw water normally has a pH greater than 7 due to reactions that occur with carbonates and bicarbonates as the water comes into contact with rocks. The addition of acid rain, though, can reduce the overall pH of water below 7 (De Zuane 1990). The addition of significant amounts of stormwater runoff can have the same effect if it too is acidic.

Aquatic organisms can be harmed by the acidification of natural water. Some species of fish, for example, may be unable to live in the transformed environment (Chin 2006). There is no direct harm to humans pH in drinking water and many food and processed beverages are acidic. Low pH can increase corrosion, however, which can be a potential health risk when lead pipes are present (De Zuane 1990).

2.4.10.7 Turbidity

Turbidity measures the suspended particles in water. As such, it provides a good general indication of water quality. The suspended particles can be many different materials, including microscopic organisms, organic or inorganic particles or soil (clay and silt) (*Standard Methods* 1992). Although typically associated with drinking water, there are a few other causes of turbidity. Precipitate of calcium carbonate can cause turbidity in hard water, aluminum hydrate can cause it in treated waters and iron oxide precipitate is a cause in corrosive waters (De Zuane 1990).

A high turbidity is not necessarily dangerous. For instance, inert suspended particles (i.e. clay) in drinking water may be safe, even if it is ascetically unpleasant (Davis 1998). Generally, though, a higher turbidity means a lower quality of water. Particularly for runoff samples, harmful contaminants may be present.

2.5 BENEFITS OF GREEN ROOFS

Green roofs offer advantages over conventional roofing materials in three main areas: water, thermal and cost. This study is focused on the water issues, which include both quality and quantity benefits.

As impervious surfaces are becoming more common in today's modern cities, the additional stormwater they create is causing sewer systems to become overloaded during rainstorms. This causes sewer overflows and untreated raw sewage pours into rivers and lakes, resulting in sever pollution problems. By reintroducing porous natural surfaces that can absorb water into cities, green roofs reduce the total amount of runoff that reaches the sewer systems. The growing media, the roof membranes and the plants each contribute. Eventually, the substrate will become saturated and the rest of the roof will reach its retention capacity. At this point, runoff will leave the roof. But the time that it takes for the soil to become saturated and for the water to filter through the green roof delays the runoff significantly. On a normal roof, runoff will begin to flow very shortly after the rain begins to fall. Green roofs can delay runoff by hours, depending upon the water content of the substrate and the intensity of rain. Additionally, this delay will often push the peak green roof runoff flow rate to a time when the demand on the sewer system is lessened. Conventional roofs will have peak flow rates when the rainfall is falling hardest. Since this occurs on all conventional roofs, the peak flow from every roof hits the sewer system at approximately the same time, exacerbating the problem.

Water quality can also be improved by green roofs. Rainfall can contain many pollutants itself and many more can be added as water flows over a conventional roof. In a green roof, water must filter through the substrate and roof membranes before leaving the roof. Green roofs have been shown to absorb and retain many of the pollutants in normal runoff as well as neutralizing acid rain. The plants play a large part in this process and the effect usually increases as the plants grow and mature.

From a thermal standpoint, green roofs offer insulation benefits and can reduce the urban heat island effect. The green roof layers, namely, the roofing membranes, growing medium, and the plants, act as a layer of insulation, potentially reducing the heating costs in the winter and cooling costs in the summer. Due to the large amounts of materials like asphalt and concrete in today's cities, they are typically a few degrees warmer than the countryside. This urban heat island effect occurs because concrete and similar materials absorb heat during the day and release it at night. The release of heat throughout the evening prevents cities from cooling down. Green roofs are covered with natural plant materials that break this cycle. Compared to a conventional roof, the air above a green roof is typically cooler.

In addition to the heating and cooling cost savings mentioned earlier, green roofs also save money on materials. While initially more expensive than conventional roofs due to greater amounts of material and labor, green roofs are less expensive in the long run. Sunlight and ultraviolet radiation are two of the leading causes of roofing deterioration. Because the roof membranes are shielded by soil and plants, they get far less exposure thereby lasting longer. Green roofs may last two or three times longer than conventional roofs, greatly reducing costs over the life of a roof.

The thermal and cost benefits of green roofs are not the focus of this thesis, but the same project was used to study water benefits also examined these issues in detail. (Kosareo 2007) covers the temperature and cost issues in detail.

2.5.1 Stormwater

With sewer overflow problems plaguing many cities, green roof have been shown to be an effective way to reduce stormwater runoff. Reducing the amount and rate of runoff makes green roofs a good addition to a sewer rehabilitation program.

The National Research Council of Canada built a Field Roof Facility in Ottawa in 2000 to study the benefits of green roofs. Dr. Karen Liu (2003) discusses the results of the two year study, which looked at an 800 square foot roof area divided into equally sized green and control roofs. The green roof section was an extensive green roof and the control was a standard bituminous roof, similar to those commonly found in Canada. The green roof was planted with a wild flower meadow in the first year and with sod in the second. The substrate was six inches of soil both years.

The green roof was found to reduce the runoff volume and peak runoff rate, while also delaying stormwater runoff. The data shows that from April to September of 2002, the green roof reduced runoff by 54 percent. It is noted that two important factors in effect for a particular storm are the intensity and duration of the storm and the moisture content of the soil. Generally speaking, the lower the intensity and duration of a storm, the greater the reduction in runoff and the longer the delay. The rainiest month of the study was June and this was also when the green roof was least effective. With frequent rainfall, the soil moisture content was high and allowed little room for water to be absorbed.

Bard Bass and Bas Baskaran (2003) produced a study at the same site in Ottawa. Their results present more detailed information about two earlier storms, from the fall of 2001. The first storm dropped 1.3 inches of rain on the roof. All of the rainfall that fell on the control roof became runoff, but the green roof retained 0.3 inches, or approximately 23 percent, of the rainfall. The runoff flow rate was also reduced for the duration of the storm.

The second storm actually consisted of three rain events in one evening. During all three events, the runoff curve from the control roof followed the rainfall curve closely. Most, but not all of the rainfall became runoff. The authors hypothesized that the remaining water was either absorbed by the roof membrane or evaporated. During the first event, the green roof had a significantly reduced runoff volume and runoff was delayed for 45 minutes after the rain started. The second time it rained, the runoff rate from the green roof was only slightly lower than the control roof. The first rainfall had likely brought the soil close to saturation. The overall flow volume was still much lower, however. Runoff continued to flow off the green roof after the second phase of the storm ended, while it stopped on the control roof shortly after the rainfall ended. The runoff rates were nearly identical during the final rainfall, indicating that the soil was all most certainly saturated by this point. Over the course of this entire second storm, the green roof retained 45 percent of the runoff volume (4.5 of 10 mm or approximately 0.2 of 0.4 inches). The initial 0.08 inches of rainfall were absorbed by the roof, resulting in the 45 minute delay of runoff. The runoff flow rate was reduced by approximately 80 percent compared to the rainfall rate (which was nearly identical to the control roof runoff flow rate) over the first four hours of the storm. This encompasses most of the first two rainfall events.

This same study created a hydrology model for green roofs. There are models for both rainfall and snow melt, which is important to consider in the cold Canadian climate. The rainfall model incorporated processes for interception, runoff, infiltration, percolation, evaporation and evapotranspiration. Two simulations were run on historical data. The first used an extensive green roof with about six inches of soil depth and historical data from one of the wettest periods on record. In this simulation, the green roof absorbed 43 percent of the rainfall, with no excess runoff. A second simulation was run using hurricane conditions and an intensive green with about one foot of soil. As drainage, the green roof absorbed 29 percent of the rainfall. In this case, there was excess runoff at the end of the storm after the soil became saturated. The authors note that these results show that green roofs can be helpful in even extreme cases. This instance could contribute to flood prevention. In both simulations, an initial degree of moisture was assumed. The simulation was not run with any actual data from the project, but the results are in line with the measurements obtained in the field.

Several studies related to green solutions for stormwater control have been conducted in Portland. Liptan (2000) and Hutchinson (2003) have published the results of the research group. This includes projects with green roofs, as well as similar projects involving landscape infiltration gardens. While not exactly a green roof, they perform the same water retention and filtering process. The structure is similar, but infiltration gardens are normally placed at grade. The projects in Portland included one surrounding the perimeter of a building and another around a parking lot.

Initial tests on infiltration gardens were conducted using test swales approximately four foot long. Top soil was used as the substrate. One swale was planted with native grasses that were allowed to grow throughout all tests. The other was planted with turf grasses that were mowed regularity. Stormwater runoff from a nearby urban area was pumped onto the swales in equal volumes and the runoff from the swales was measured. It was found that up to 41 percent of the water was retained by the native vegetation swale, while 27 percent was retained by the turf grass. It was hypothesized that this was because there was more organic material in the unmowed natural material. While there is significant stormwater retention by both swales, this study shows the importance of utilizing low maintenance native plants.

The Buckman Terrace Apartments are a 150 unit complex built in Portland in 1999. The site combines the apartments with commercial space and underground parking. Landscaping swales and stormwater planters are installed around the site to help with stormwater reduction. Portions of the conventional roof drain into these areas by downspouts. More importantly, however, are the ecoroofs (the term used to describe extensive green roofs in Portland) installed on the site. The entire building is designed to support an ecoroof, but they were only installed over small portions as a test. The full roof area is 25,000 square feet. The front entrance is covered with a 200 square foot green roof with a 25 square foot standard roof area draining into it from above. The main green roof is a 1500 square foot area over the commercial space. An additional 750 square foot of conventional roofing drains here as well. There is a four inch deep substrate covering the roofs, with plantings consisting mainly of sedums. American Hydrotech green roofing membranes were used.

Extensive monitoring was not carried out on this project, but the roofs were observed carefully. The roofs retained most of the rainfall and additional runoff from the adjacent roofs during the summer months, when runoff from the green roofs was rare. In the winter, runoff occurred more frequently, but the water was detained. It should be noted that the only maintenance carried out on the roofs was one watering. The plants survived, but it was recommended that at least the grasses should be mowed the following year.

After the first round of testing was found to be promising, the same group in Portland moved forward and constructed a full sized ecoroof on the Hamilton Apartments in late 1999. The building is a ten-story apartment complex with two sections of green roofs. The east side of the building has a 2520 square foot green roof with three inches of substrate. Conversely, the western ecoroof is 2620 square foot in size with a five inch thick substrate. The substrates used on the two sides of the roof have different compositions. Due to wind erosion, approximately one inch of substrate was lost across both sides of the roof. There is an irrigation system present at the site. It was used after the initial plantings, but the goal is to reduce the amount of water applied to the roof through irrigation overtime until the roof is completely self sufficient.

While both green roofs were monitored, there was a penthouse containing mechanical equipment with a conventional roof on site. It has its own drainage system, but during heavy rainfalls water sometimes flows onto the east side of the roof, negating these results. Over the course of the study period, January 2002 to April 2003, the western ecoroof retained 69 percent of the rainfall. It also appears that the retention rates are increasing with time, as a significantly higher percentage was retained during the first few months of 2003 when compared to 2002, despite similar amounts of rainfall. The most likely culprit is the differences in rainfall pattern. In 2002, the rainfall was relatively evenly distributed while the 2003 rainfall included several long periods without rain. The researchers hypothesized that these periods allow for more evapotranspiration and therefore less runoff. The average temperature is also a factor that affects evapotranspiration. It was higher in 2003, which could again account for the increased runoff reduction.

Runoff rate reduction is another important area where green roofs are helpful. The Portland study found that the green roof reduced the peak runoff in all instances, even when the substrate was saturated. While the rainfall events had sharp peaks, the green roof runoff would taper off gradually after reaching the peak. The rate itself is also substantially lower than the rainfall rate, at reaching only 1/16 of the peak.

Similar to the project in Portland, rainwater infiltration gardens were studied in Burnsville, Minnesota on a larger scale. For four years, 17 infiltration gardens were monitored along one street in a residential neighborhood. An adjacent neighborhood was the control. Each of the gardens consists of layers of mulch and sod followed by a layer of compost and topsoil. Below this is the natural sandy subsoil, which helps with drainage. The gardens are enclosed with a limestone retaining wall and there are curb cuts that allow water to flow into the gardens. The plants were chosen individually by each homeowner from a list. They include low maintenance plants and shrubs along with some perennials that require care. To prevent fine soil particles from building up in the garden, easily replaceable sod strips are placed between the curb and the garden. During the course of the study, the infiltration gardens have reduced the runoff volume by 90 percent. The design allows the first 0.9 inches of rainfall to be captured by the gardens. With this proven effectiveness and the ability to incorporate the gardens into existing areas, there are plans to expand the program to other parts of the watershed. The program was originally proposed to reduce levels of phosphorus from leaching into a nearby lake. Due to problems with sampling, tests could not be completed on the runoff. However, the reduced volume of runoff would reduce the overall levels (Trimbath, 2006).

The city of Chicago (MHW 2004) saw an increase in green roof interest after installing an intensive green roof on city hall. To capitalize on the attention, the city set up a test plot program to study the benefits of green roofs. The project included nine six foot by six foot by three and a half foot test plots built on the roof of the Chicago Center for Green Technology. Six of the plots were extensive green roofs, each designed by a different manufacturer, and three were made of conventional roofing material. All three conventional roofs were used in the study of thermal benefits, but only one (covered with a white reflective paint) was used for water comparisons.

During the study, which took place in the summer of 2003, all six green roofs behaved similarly. Therefore, the results were averaged and compared to the control roof for analysis. The green roofs proved to very effective in reducing stormwater runoff. They generally produced less than half the runoff generated by the control roof. This study considered small storms to be any in which less than 1/2 inch of rain fell. The green roofs absorbed most of the rainfall in these instances. Runoff rate was also delayed significantly by the green roof and the peak flow was reduced. The conventional roof would begin to show runoff almost immediately after rain began to fall and would level off immediately after it stopped. It would also follow the same pattern as the rainfall, peaking at the same point. The green roof delayed the start of runoff by as much as several hours, depending on the duration and intensity of the storm. At times, runoff would begin to flow after the conclusion of the storm. This delay means that the runoff contributed by the green roof would typically enter the sewer system after the runoff from conventional roofs had already reached its peak. This could greatly reduce the stain on the sewer system.

Two green roofs in North Carolina (Moran 2004a, 2004b) also looked at studying the benefits of extensive green roofs in their particular climate. The fist site was built in May of 2002 at the Wayne Community College (WCC) in Goldsboro, NC. A three inch thick substrate covered the roughly 750 square foot green roof. The other half of the roof remained covered with traditional roofing materials and became the control. The other green roof was constructed at the Neuseway Nature Center in Kinston, NC in April of 2002. Built over a 290 square addition to the Center, the existing 1820 square foot roof was used as a control. This roof had four inches of substrate, but the same set of sedum plants were used at both site. The drainage layers in each roof were manufactured by two different companies, however.

The WCC site was monitored for nine months from April to December of 2003, while the Center roof was only monitored for four non-consecutive months over that same period. Rainwater retention was significant at both sites. The WCC roof retained 62 percent of all rainfall, while the Center roof retained 63 percent. Even more substantial was the reduction in the peak flow rate. The reduction at the WWC site was 78 percent, from an average of 1.5 inches per hour as the peak rate of rainfall to 0.3 inches per hour for the runoff. Similarly, the Center roof reduced runoff by 87 percent, from 1.7 inches per hour to 0.2 inches per hour. Over the course of the study, the green roofs retained an average of the first 0.6 inches of rainfall.

Penn State University conducted a pilot project by constructing six small buildings with 48 square feet of roof space. The building dimensions were 6 foot by 8 foot by 8 foot. Three of the roofs were green, with identical membranes, soil and sedum plants. The study looked at the thermal and stormwater benefits of by comparing these three green roofs with three roofs covered with traditional roofing materials.

Seven storm events were recorded in October and November of 2002. The green roofs retained between 18 and 100 percent of the rainfall during these storms, which ranged in duration from 8 to 20 hours and in intensity from 3 to 40 millimeters. The average retention was 40 percent. This study did not find a strong connection between the retention and rainfall amount or between rainfall detention and the time between events (DeNardo 2003).

Manfred Kohler and Marco Schmidt (2004) led a team in Germany that conducted several green roof studies. Two small test plot projects were started in the mid-1980s. The first, Englische Straβe in Berlin-Charlottenburg, measured the runoff from one-meter square plots. The weekly runoff was compared to the precipitation. A similar project at the Institute of Landscape Development used two-meter square test plots and took more detailed measurements. For the two test plot tests, the annual retention rate (over three years) was 75 percent of the precipitation. Additionally, two full scale green roofs were constructed and studied. The cultural centre at UFA-Fabrik in Berlin Tempelhof and a building at the University of Neubrandenburg were both covered with a 360 square meter green roof. The full sized roofs preformed better than the test plot results. Runoff from the large green roofs was only 10 percent of the precipitation during some storms.

The results discussed so far have only dealt with project specific stormwater reductions. There are estimates through models and calculations that predict widespread use throughout a city. In Toronto, it is estimated that 3.6 million cubic meters (127 million cubic feet) of stormwater will be retained if 6 percent of the total roof area in Toronto is covered with green roofs (6.5 million square meters or 70 million square feet) (Gutteridge 2003).

2.5.2 Water Quality

The other water related area where green roofs provide benefits is water quality. By acting as a filter, the runoff that exits a green roof can be significantly cleaner than runoff from a conventional roof. Kohler and Schmidt (2003) describe the process. “On one hand, green roofs retain and bind contaminants which are introduced either as dry dust particles or suspended and dissolved in rain water. On the other hand, contaminants can be leached out of the substrate used in the green roof’s construction, which can complicate the reuse of the runoff water”

Green roofs became an accepted technology in Germany much earlier than anywhere else in the world. This gives Germany a head start on scientific research and allows long established green roofs to be included in studies.

Kohler and Schmidt present the combined results of two studies conducted in Germany that outline many of the positive aspects of pollutant control in green roofs.

One study at the Technical University of Berlin showed a significant retention of heavy metals and phosphorus. As a percentage of influx, 94.7 percent of lead, 87.6 percent of cadmium, 80.2 percent of Nitrate and 67.5 percent of phosphate were retained. It also showed that retention of pollutants can increase over time. In the first year after construction, only 26.1 percent of phosphorous was retained, but this increased to 79.9 percent by year four.

A second study for the project, “DEBIS am Potsdamer”, looked at the contaminant discharge of several different substrates. Test plots two square meters in size were used for each of the three substrates.

To measure the amount of dissolved solids, electrical conductivity tests were completed. Higher conductivity indicates a greater amount of inorganic material in the runoff. A first flush was evident, with a decrease in conductivity as the storm wears on. On average, over the six month study period, the inorganic compounds were higher in the green roof runoff than in both the rainfall and control roof. There was a steady decline in the amount present in the green roofs, however. There was a more than 50 percent reduction over the course of the study to the point that the levels were only slightly higher than those of the rainfall and control roofs. Similarly, mature green roofs were found to have a low organic content. The green roofs were extremely effective at neutralizing Berlin’s acid rain. In all instances, the green roof runoff had a higher pH than the rainfall. A pH scale runs from 1 to 14. A pH of 7 is a neutral solution, while a pH below 7 is acidic and a pH above 7 is basic. For longer storms the effect was lessened because of the reduced detention times. On average, conventional roofs were actually detrimental, lowering the pH and making it even more acidic.

When comparing turbidity levels, which give an overview of the amounts of contaminates discharged, the results were similar. The control bituminous roof had the highest turbidity by far, at more than double the rainfall. Two of the three materials used as substrate significantly reduced the turbidity. The third contained pumice stone, which was washed away, increasing the turbidity. Again, the performance of improved over time. By the end of the six month study period, the average green roof turbidity had reduced by over 80 percent.

Total nitrogen (NO_3-N and NH_4-N (ammonium)) was reduced, on average, by between 50 percent and about 90 percent, depending on the materials in the substrate. Pumice contains high amounts of nitrogen, so it was higher than most, for instance. While there is some variation over time, the general trend is a significant reduction in nitrogen levels by slightly less than 90 percent.

Unlike the other materials and the previous study, phosphate levels do not show any apparent change over time. There is still a reduction of about two-thirds by the green roofs. Phosphate retention is limited by plant growth, so long established roofs do show increased retention, just at a much slower rate than with other pollutants.

One additional conclusion that can be reached from these results is that the composition of the soil affects the runoff characteristics. Pumice, for instance, will increase discharges from agricultural sources.

The two North Carolina green roof projects also included water quality testing for many of the same pollutants, although the focus was on nitrogen and phosphorous. In the area, both are regulated in stormwater. Unlike the German study, no water quality improvement was found during the nine month study period when the green roof is compared to the control roof and rainfall. There was no significant difference in total nitrogen levels between the green and control roofs or the rainfall. Total phosphorous levels in the green roof, on the other hand, were actually significantly higher than both the rainfall and control roofs. The conclusion reached by the research team was that nitrogen and phosphorous were most likely leaking from the soil, which contained a fair amount of compost (15 percent). A side study indicated that both substances will leech from the soil in greater amounts as more compost is present in the soil mix.

The short time period of the study did not allow for conclusive evidence, but it appears that the nitrogen levels were beginning to decrease with time (Moran 2004b).

The Portland Hamilton Apartment project included some water quality testing, although only the green roof runoff was measured. While this doesn't allow for direct comparisons, the information still highlights important points. The east and west halves of the green roof used different substrates and a detailed breakdown of the components of each is available. The western roof contained 2.6 and 3.3 times the total phosphorous and extractable ortho-phosphate phosphorous, respectively, than that of the eastern roof. During four of the seven monitored events, the western roof had significantly higher levels of both phosphorous and ortho-phosphate. The levels were roughly equal in the other three cases. This supports the North Carolina study, which also showed that phosphorous appeared to leech from the soil and is dependant on the composition of the soil. The levels also decreased over the course of the two year study period, until the last three events. It should be noted that the lower levels occurred during the warmer months, when there is reduced flow and loadings. The other material tested for in this study was dissolved copper. Again, the western roof had copper in the soil and generally had higher levels than the eastern roof. The roofing materials used on site are a likely cause of the high copper levels, from the treated lumber used in landscaping (Hutchinson 2003). In any project, the surrounding materials are important to consider when testing water quality.

Also in Portland, the test swale study provides some insight into water quality and green roofs. The native and turf swales were monitored for pollutant removal for an extensive list of materials. With the exception of phosphorous and conductivity, which increased, the swales retained significant amounts. In general, the native swale retained more material than the mowed turf grass swale, perhaps because there was more organic material in the former. The results range from 16 percent and 8 percent for the native and turf swales, respectively, to 81 percent and 69 percent for total suspended solids. The majority of the tests showed fifty percent or greater retention (Liptan 2002).

3.0 3 RIVERS WET WEATHER DEMONSTRATION PROGRAM

The sewer overflow problem and the water quality issues associated with it present complex issues without a quick solution. The 3 Rivers Wet Weather Demonstration Program (3RWWDP) is one of the organizations currently attempting to remedy the situation in Allegheny County. It is a non-profit organization that is looking at sustainable and cost effective ways to improve Pittsburgh's water quality long into the future. While other organizations, such as ALCOSAN, focus on improving the sewer system itself and other conventional techniques, 3 Rivers Wet Weather (3RWW) looks at more innovative approaches and educates the public. The lessons learned in Pittsburgh will be shared with other cities facing the same issues.

ALCOSAN and the Allegheny County Health Department (ACHD) became partners and formed the 3 Rivers Wet Weather Development Program in 1998. They were faced with $275 million in fines and litigation from the Environmental Protection Agency (EPA) and U.S. Department of Justice for violations of the Clean Water Act. As stated on their website, "[t]he organization's ultimate goal is to improve Allegheny County's water resources by helping municipalities find a long-term, cost-effective sustainable solution to the region's problems." ("How the Program Operates," 2006)

Much of the funding for the 3RWWDP comes from EPA grants, with the main source the State and Tribal Assistance Grants. Matching funds are required for 45 percent of the money received from the EPA. ALCOSAN, the ACHD and the Commonwealth of Pennsylvania are the largest contributors of these funds, but municipalities and private foundations also donate money.

The majority of 3RWW's budget goes to municipalities that are rehabilitating their sewer systems. They use a variety of innovative approaches that can then be used as models for other communities. In accordance with EPA grant guidelines, 3RWW can fund 55 percent of sewer project with the municipality making up the other 45 percent, similar to the 3RWWDP's own funding structure. All together, $6.8 million have been used to fund 33 different sewer projects in the ALCOSAN service area. Additional money is used for technical projects, public education and operating expenses.

3.1 THE GREEN ROOF DEMONSTRATION PROJECT

Stormwater management and the sewer overflow problem are two of the main areas 3RWW is looking to solve. It is doing this through funding Stormwater Best Management Practice (BMP) demonstration projects, specifically Low-Impact Development (LID) projects. The ultimate goal of widespread LID use is to have a landscape that has predevelopment hydrologic conditions. This is done by retaining, infiltrating and evaporating rainwater, reducing the stormwater runoff volumes and transferring less pollution to waterways. Also, uses for runoff that keep it out of the sewer system are encouraged. Projects in the region focus on runoff volume reduction that does not include infiltration, which is difficult to consider with the topography and soil in the area.

Much of the runoff created in cities comes from rooftops. Roofs are an estimated 15 percent of the surface area in residential neighborhoods. In commercial areas this figure is 26 percent (City of Olympia 1994). The total impervious surface area for residential land use is between 20 and 65 percent, depending on the average lot size. With the dense packing of houses in urban areas, 40 to 65 percent is typical. In commercial and business districts, about 85 percent of the surface area is impervious and about 72 percent of industrial areas are impervious (Chow 1988). With its stormwater control qualities, green roofs are a natural fit for a city looking to reduce runoff. With the Green Roof Demonstration Project, the 3RWWDP provided funding for three green roof projects to be built and studied in Pittsburgh. Each project contains a green roof and some type of conventional roof. Monitoring equipment will be installed on each section of roof, with the conventional roof serving as a control. While the primary concern of 3RWW is stormwater, monitoring will be carried out for the temperature benefits of green roofs as well. The results will be used to determine the performance of the green roof when compared to the conventional roof at each site, and the results from each site will be compared.

The largest of the three projects in terms of area is the Shadyside Giant Eagle green roof. This is the subject of this thesis and will be discussed in detail in the following chapters. It is located in the Shadyside neighborhood of Pittsburgh on a site consisting of an expanded grocery store and condominiums. The monitoring of this extensive green roof is being carried out by the University of Pittsburgh. Construction of the roof was completed in July 2006. The second green roof sits on top of Hammerschlag Hall on the campus of Carnegie Mellon University, built in the spring of 2005. An extensive green roof was added as part of a renovation and monitoring will be carried out by Carnegie Mellon. The University of Pittsburgh will be monitoring the final building, an extensive green roof to be installed on an existing residential and commercial building in Homestead, along the main thoroughfare for the neighborhood. While much smaller than the Giant Eagle project, with 2200 square feet each of green and control roof area, a similar monitoring plan will be carried out for this project. A fourth green roof was scheduled to be built in Pittsburgh's South Side on an early twentieth century industrial site. One of the two main buildings would have had an extensive green roof installed. However, construction on this project was never initiated.

3.2 OTHER PROGRAMS AND PROJECTS

The 3 Rivers Wet Weather Demonstration Program also includes a rain barrel program. As with green roofs, the main function is to keep runoff out of the sewer system. A barrel is connected to a house's downspout and collects runoff. It can later be used to water plants or grass, eventually reaching the groundwater table. 3RWW makes the rain barrels available to all residents of Allegheny County for $130 to $150. It also worked with the Nine Mile Run Watershed Association to install 500 barrels to demonstrate their effectiveness.

To help with the repair and rehabilitation of sewer systems, 3RWW is taking part in a Geographic Information System (GIS) project. GIS is essentially a computerized map that can store specific information, in this case about the sewer system. Old paper maps outlining 4000 sewer lines in 83 communities were first imputed into the system. A second phase will expand the information, including details such as manhole locations and size of sewer pipes.

The calibrated rainfall data project provides accurate rainfall data for Allegheny County by combining data from 33 rain gauges and radar. The county is divided into 2276 one kilometer squares areas with real time data available for each. With this system, very specific data is available for any point in the county. This project provides accurate and up to date rainfall data that is important for sewer rehabilitation projects.

4.0 THE SHADYSIDE GIANT EAGLE GREEN ROOF PROJECT

This study focuses on the Shadyside Giant Eagle supermarket green roof. It is located in a neighborhood on the eastern side of Pittsburgh, close to the University of Pittsburgh campus.

The site originally contained the supermarket, several commercial buildings, a parking garage, several houses and an apartment building. The new site extensively renovated and expanded the Shadyside Giant Eagle and demolished the other structures. The store itself was more than doubled in size. In addition, a two-storey parking garage was built beneath the structure and seventy-eight condos occupy five-stories built above the rear of the supermarket. Figure 1 shows the original structure (on the left of the picture) and Figures 2 and 3 show the expanded portions of the store during construction.

Approximately 12,300 square feet of the newly constructed store is covered with a five and half inch thick extensive green roof. The roof uses a Garland system for its filter fabric and drainage layers. The substrate used on the roof is a soilless mix, made primarily of expanded shale, perlite and coir (coconut husks). Nutrients are incorporated into the mix to sustain the plants for three months. Table 1 summarizes the soil properties. There is a mix of plants, mainly focusing on different varieties of sedum. The remaining 21,000 square feet of the Giant Eagle roof are conventionally roofed and gravel ballasted, separated from the green roof by a parapet wall. This was the control for all tests.

Figures 4 through 10 depict the green and control roofs at various stages of construction. Figure 4 shows the green roof area early in the construction process. The black surface visible in the photograph is the waterproofing layer. The control at the same point in time is shown in Figure 5. The root barrier and drainage and filter layer are shown in Figure 6, just after they were applied above the waterproofing layer. The substrate was then installed on top of these layers (Figure 7). The green roof is picture just after the installation of the plants in Figure 8. Figure 9 shows the control at this time. Prior to the completion of the green roof, several skylights were installed on both roofs. They are visible in the last few photographs. Finally, Figure 10 shows the green roof near the end of the first growing season.

Table 1 - Shadyside Green Roof Soilless Mix Properties

Soil Property	Value
Void Ratio at container capacity	> 15% (vol)
Moisture content at container capacity	> 15% (vol)
Maximum water capacity	> 45% (vol)
Density at maximum water capacity	27.63 psf
Saturate hydraulic conductivity	> 0.75 in/hr and < 8.0 in/hr
pH	5.5 to 6.5
Soluble salts (EC)	< 0.33 mmhos/cm (1:20 dilution)

Figure 1 - Shadyside Giant Eagle – Existing Structure

Figure 2 - Shadyside Giant Eagle - New Construction (Front)

Figure 3 - Shadyside Giant Eagle - New Construction (Rear)

Figure 4 - Giant Eagle Green Roof - Early in the Construction Process

Figure 5 - Giant Eagle Control Roof - Early in the Construction Process

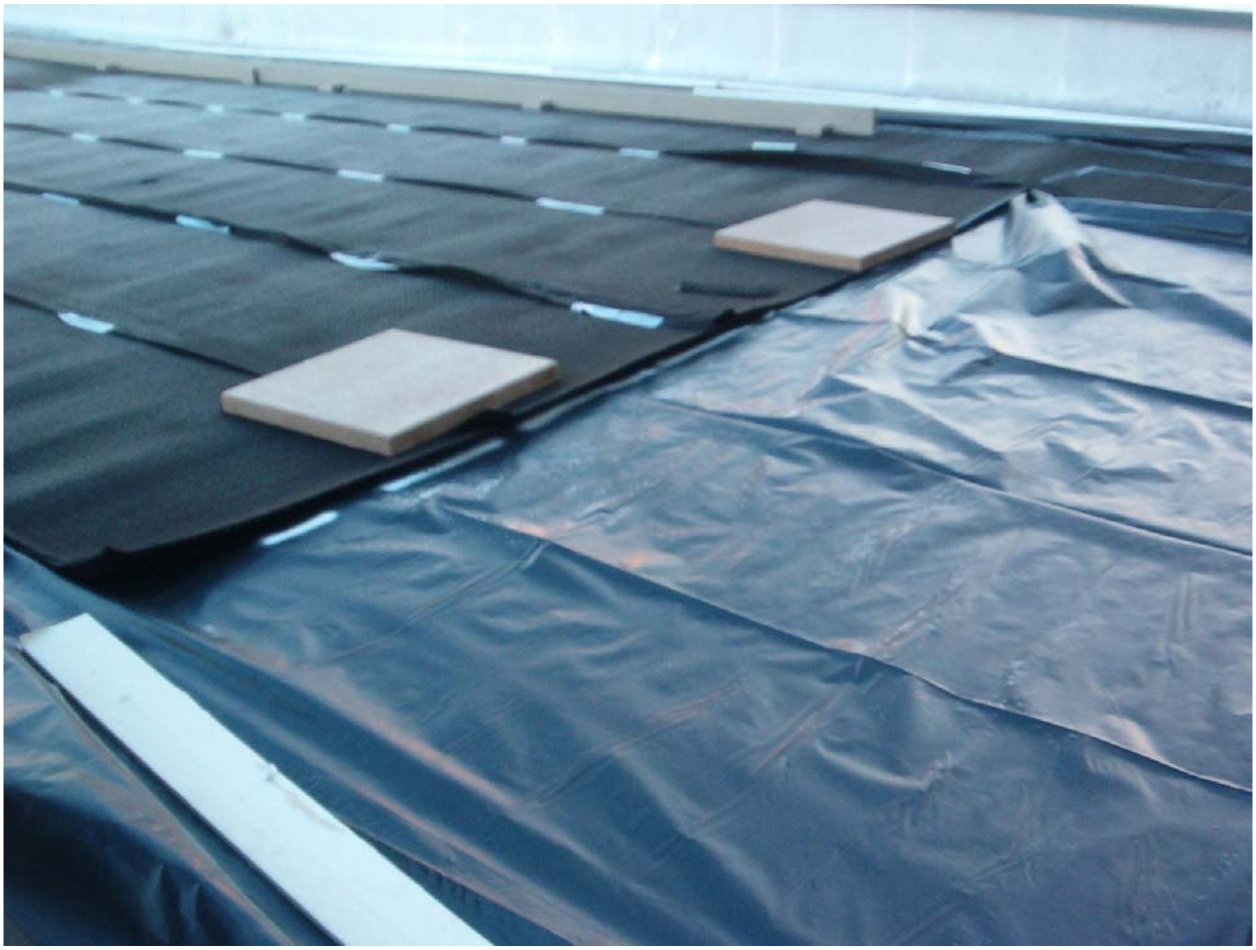

Figure 6 - Green Roof Detail During Installation

Figure 7 - Giant Eagle Green Roof as Soil is Installed

Figure 8 - Giant Eagle Green Roof Just After Installation of Plants

Figure 9 - Giant Eagle Control Roof after Green Roof Installation

Figure 10 - Green Roof After One Growing Season

4.1 WATER QUANTITY PROTOCOL

In order to quantity the changes in stormwater runoff generated by a green roof compared to a standard roof, it is necessary to account for all the water involved in the cycle from the time rain falls on the roof surface until it exits as runoff.

The first step is to determine an accurate measure of the rainfall reaching the rooftop. To accomplish this, a Hydrologic Services RG703 8 inch Tipping Bucket Rain Gauge (Figure 11) was used. A siphon mechanism allows the gauge to measure all rainfall intensities. After each one hundredth of an inch of rain falls, the bucket tips and sends a reading to the datalogging system, which will be discussed in detail later. The rain gauge not only takes a measurement on the rainfall volume that falls on the roof, but also rate of rainfall. The rainfall data was used to calculate both the total volume of water that reaches the roof and the rate. Along with runoff data, this will show the affect the green roof has on reducing runoff. Similarly, the rainfall rate will show the delay in runoff accumulation from each roof.

Figure 11 - Rain Gauge Installed on the Green Roof

To measure the runoff created by each roof, two important pieces of equipment are required: Tracom 60-degree Extra Large Trapezoidal Flumes (Figures 12 and 13) and Greyline Instruments LIT25 (Level Indicating Transmitter) Ultrasonic sensors (Figures 14 and 15). The flumes are essentially open pipes. There is a known shape, in this case a trapezoid, on the upstream side of the flume. If the depth of water is measured at this point, the volume of water in the flume at that instant can be calculated due to the known dimensions. Since the green roof and control roof have different surface areas (12,300 and 21,000 square feet, respectively), it was not feasible to measure all the runoff that is created by each roof. Therefore, one roof drain on each roof was chosen to measure. Each drain has approximately 3530 square feet of roof sloping towards the drain, allowing measurements to be equalized. The drain from each roof has a flume installed in line before the water is deposited into the sewer system. They are at ground level, near the back of the building. An ultrasonic sensor is suspended eight inches above the top of each flume, at the measurement point. These sensors send a sound wave into the flume, which then bounces back. The time that the wave takes to return allows the equipment to measure the depth of water in the flume at that point. From the depth of water, the flow rate and cumulative volume of runoff are calculated.

Figure 12 – Flumes

Figure 13 - Flumes (Opposite Angle)

Figure 14 - Ultrasonic Sensor

Figure 15 - Ultrasonic Sensor in the Field

Soil moisture is an important parameter that affects stormwater runoff. During a rainstorm, the pours of the soil absorb water. As the storm progresses, the soil becomes saturated and reaches its maximum storage point. After this time, the green roof will act similarly to a conventional roof in regards to runoff quantity, although there will still be a runoff delay as the water filters through the soil. Because of this process, it is important to monitor the moisture content of the soil both before and during a storm. The dryer the soil is when a storm begins, the greater the amount of runoff reduction. In order to monitor this process, two Campbell Scientific SM616 Soil Water Content Sensors (Figure 16) were installed on the green roof. Electric pulses are sent out of the two metal probes that penetrate the soil. By measuring the dielectric permittivity of the soil, the sensors calculate the water content of the soil. Water has a high dielectric permittivity, while soil does not, so any changes in the quantity are a result of a change in water content. The volume of soil on the roof is known, so the amount of water within the soil at each point in time can be determined with simple multiplication. The rate of absorption can be calculated by dividing the volumetric water content by the time in between readings.

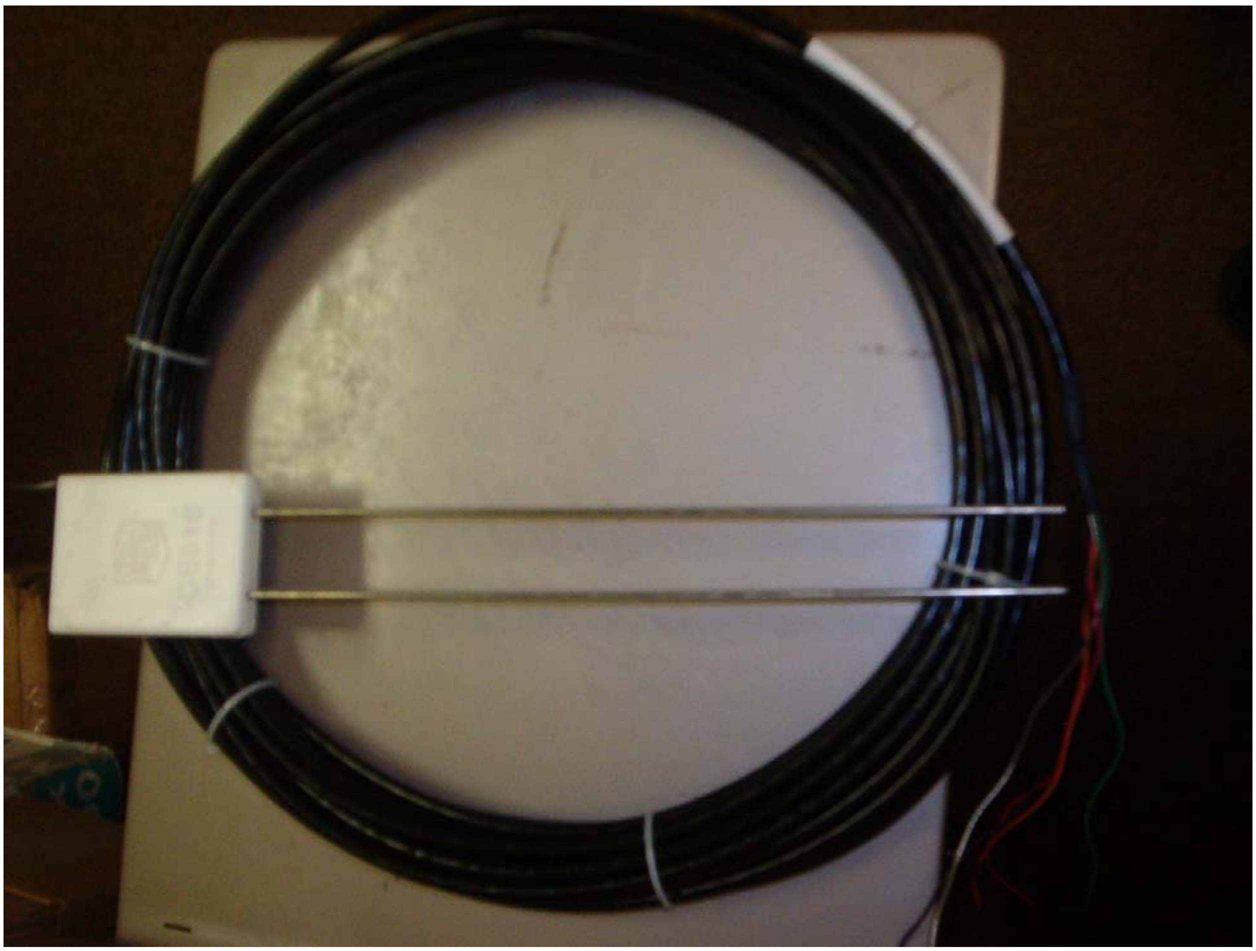

Figure 16 - Soil Moisture Sensor

4.2 WATER QUALITY PROTOCOL

In addition to water quantity monitoring and data collection, two additional components are necessary to measure the affect of green roofs on water quality: a collection system at the site and the water quality tests themselves, both in the laboratory and the field.

An automated collection system allows samples to be collected at very specific pre-programmed points in a storm. Collection of samples at the same point over numerous storms permits direct comparisons between storms. Sampling at numerous points during a storm allows the first flush effect to be studied.

Once the samples are collected, laboratory analysis was conducted. The water quality analysis was structured in two levels: on set of criteria were measured for all storms, and an additional set of analyses were undertaken for selected storms. The water samples were subject to the full range of analyses for selected storms. The chosen storms were from a wide range of intensities and durations, giving a cross-sectional view of water quality.

4.2.1 The Collection System

Runoff samples were collected by a system constructed on site. Water must be collected after it passes through the flumes, so as not to affect runoff rate and volume measurements. It also must be collected while the green and control roof drainage pipes are still separate and before they enter the sewer system. To accomplish this, a “T” was connected to the straight run of pipe just past the end of the flumes. Some of the runoff is diverted through a run of pipe for collection before joining back to the drainpipe, just as the water enters the sewer system. Each flume has its own run of collection pipe with six solenoid valves attached. Figure 17 shows the collection system connected to the green roof flume. These solenoid valves are normally closed and are opened when energized. Each of the valves is connected to a 500 mL low density polyethylene sample bottle (Figure 18). The valves are wired to the datalogger located on the roof, which controls when the valves are opened. Each of the six valves are programmed to open at a set value of cumulative runoff. Since runoff can start at different times and flow at different rates on the green and control roofs, this allows the samples to be matched from both roofs. Additionally, the series of valves allows for samples to be taken at six different points during a storm. With samples taken in this manner, the first flush effect can be studied. Less specifically, it lets the changes in water quality throughout the storm be measured. The 500 mL of sample provided enough water to complete the series of water quality tests in the protocol. The valves were programmed to stay open for as short a time as possible to allow the sample bottles to fill while minimizing overflows.

Figure 17 - Solenoid Valve Sampling Manifold

Figure 18 - Solenoid Valves and Sample Bottles

4.2.2 General Water Testing Notes

Before discussing the individual test procedures, there are several notes about sample preparation and storage that apply to all tests.

At the site, the samples are collected in 500 mL LDPE (low density polyethylene) plastic bottles. Once the samples are brought back to the University of Pittsburgh's Environmental Engineering laboratories, the first step is to filter half of the sample, which is then stored in a separate LDPE bottle.

Vacuum filtering was carried out using 0.45 μm (nominal pore size) cellulose membrane filters. As discussed by Hunt (1986), this type and size of filter is the most commonly used. Many test procedures utilize it and it is considered the standard by many organizations.

The pH and turbidity tests do not utilize the filtered samples. In the case of the pH, this is because the test is preformed on site, shortly after the storm. The turbidity measures the amount of suspended particles in water and filtering would remove many of these. Similarly, the metal tests only use the filtered samples because filtering is one of the necessary steps in sample preparation when conducting atomic absorption tests.

For all other experiments, both the filtered and unfiltered samples were tested. In these cases, the filtered samples represent the levels of dissolved contaminant, while the unfiltered samples represent the nondissolved portion.

After the samples are collected and the pH and turbidity tests are completed, the samples are stored in a refrigerator for preservation before the other tests are completed.

4.2.3 Spectrophotometry

Approximately half of the substances tested for rely on spectrophotometry. The concentration of a substance is measured by its absorption of light at a particular wavelength. Each sample of water is prepared with a number of chemical reactions, as laid out in the *HACH Water Analysis Handbook* (2003).

In these tests, a prepared sample is placed in a sample cell. Light is shone through a filter or monochromator, which then allows light of only the selected wavelength (visible or ultra violet light) to pass through the water sample. A photoelectric detector then reads the absorbance and it is displayed on the unit (Hunt 1986).

Once the water samples have been prepared and are ready for testing, the first step in the testing procedure is set the spectrometer to the appropriate wavelength to test for the pollutant in question. Next, a clean test tube containing deionized water is placed into the sample cell. The transmittance of light is then set to 100 percent, which corresponds to an absorbance of zero, per Beer's Law.

Beer's Law describes the logarithmic relationship between the transmittance and absorbance of light. Before a light is shone through a sample, it has a power, P_0. After the light passes through a sample, it has a power, P. P will be less than P_0 if any light is absorbed by the sample. Transmittance is defined as the ratio between these two values.

$$T = \frac{P_0}{P}$$

If only deionized water is present in the sample cell, all of the light will be transmitted through the sample. This results in a maximum transmittance of 1 (or 100 percent). Transmittance can drop as low as zero if no light is able to pass through the sample (Ball 2001). The absorbance of light, A, has a logarithmic relation to the transmittance.

$$A = \log_{10} T = \log_{10}\left(\frac{P_0}{P}\right)$$

Therefore, while transmittance ranges from 1 to 0, absorbance ranges from 0 to infinity (Hunt 1986). A second definition of absorbance relates to the concentration of the contaminant in the water.

$$A = a \cdot b \cdot c$$

Where, a = Absoptivity constant

b = Sample length

c = Concentration

Using these equations, the concentration of a contaminant in a sample can be determined (Ball 2001).

Instead of using the absorbance equation to determine the concentration, samples of a known concentration are used to create a calibration curve. To do this, the samples with a known concentration of the material in question are prepared in the same manner as the other water samples and are placed in the spectrometer first. The absorbance of these samples is recorded. A standard curve is formed from this data that provides a relation between absorbance and concentration. When the prepared water samples themselves are placed in the machine, the absorbance is recorded. The concentration of the pollutant in the sample is calculated using the equation obtained from the standard curve.

Initially, a blank and five other samples of known concentrations are used to create the standard curve. On subsequent tests, three standards are run with the water samples. The same standard curve can be used with each set of tests, provided these standards are approximately equal to the original values.

At the conclusion of each set of tests, the standards for that session are run through the spectrometer again to see if the calibration has fallen off. Each water sample is tested in duplicate for each parameter.

4.2.3.1 Total Nitrogen

In order to measure the amount of total nitrogen in the water samples from the green roof project, method 10071 from the HACH Water Analysis Handbook (2003) was followed. The procedure converts all forms of nitrogen to nitrate and can detect concentrations in the range of 0.5 to 25.0 mg/L. At the conclusion of testing, absorbance is measured at a wavelength of 410 nm.

For each sample tested, the first step in the procedure is to perform an alkaline persulfate digestion. This is the process that converts each form of nitrogen to nitrate. This is accomplished by first placing a Total Nitrogen Persulfate Reagent Powder Pillow (basically, a premixed and premeasured packet of the appropriate chemical) into a Total Nitrogen (TN) Hydroxide Reagent vial. After adding 2 mL of sample to the vial, they are shaken for 30 seconds. A thirty minute digestion period follows, where the samples are heated at 105 degrees Celsius. After the digestion, the samples are allowed to cool and sodium metabisulfate is added to remove interferences from halogen oxides. To do this, TN Reagent A and TN Reagent B Powder Pillows are added to the digested vial separately. After each addition, the vials are mixed by shaking and there is a several minute long reaction period. The addition of Reagent B causes the sample to turn yellow. 2 mL of the prepared samples are then added to TN Reagent C vials. Mixing by inversion causes the samples to become warm and turn yellow in color. There is a short reaction period next. At this point, the samples are ready for testing.

4.2.3.2 Phosphorus

Phosphorus testing follows Method 8048 from the HACH Water Analysis Handbook, which is equivalent to both USEPA Method 365.2 and Standard Method 4500-P from the Standard Methods for the Examination of Water and Wastewater.

The HACH procedure detects levels of reactive phosphorus (from 0.06 to 5.00 mg/L PO_4^{3-}), which consists of orthophosphate and a small portion of condensed phosphate that may be hydrolyzed during the testing. To detect other forms of phosphorous, pretreatment would be required. As discussed in USEPA Method 365.2 (1983), samples that are filtered through a 0.45

μm membrane filter show the levels of dissolved orthophosphate, while unfiltered samples show the levels of total orthophosphate.

To begin the HACH test procedure, 5 mL of sample are added to a Reactive Phosphorus Test 'N Tube Dilution vial. After mixing, a PhosVer 3 Phosphate Powder Pillow is added to the vial and mixed again. The Powder Pillow contains all the reagents necessary for the ascorbic acid method. These chemicals produced a two step reaction. First, the orthophosphate reacts with molybdate in acid solution to form a yellow phosphomolybdate complex. This is then reduced by ascorbic acid to a molybdenum blue species. The level of blue color is proportional to the level of phosphorus in the sample and can be determined by measuring the absorbance in a spectrometer at a wavelength of 880 nm (in the ultraviolet light range).

4.2.3.3 Sulfate

Testing for sulfate in water samples followed HACH Water Analysis Handbook (2003) Method 8051 and can detect levels from 2 to 70 mg/L. This turbidimetric procedure is equivalent to USEPA Method 375.4.

The procedure converts sulfate to a barium sulfate suspension. The turbidity of the suspension can then be measured with a nephelometer, filter photometer or spectrophotometer. The turbidity is proportional to the concentration (USEPA 1983). To complete the HACH (2003) procedure, 10 mL of sample is added to a sample cell. A SulfaVer 4 Reagent Powder Pillow is added to the sample and it is swirled to mix. After a five minute reaction period, the sample is ready for measurement. For all test procedures for this project, the absorbance was measured using a spectrometer at a wavelength of 450 nm. The SulfaVer 4 Powder Pillow contains the barium (Ba^{2+}) necessary to react with the sulfate to form barium sulfate ($BaSO_4$).

4.2.3.4 Chemical Oxygen Demand

Clocking in at several hours instead of several days, the HACH Water Analysis Handbook (2003) Method 8000 for COD is a more convenient test for oxygen levels in water than BOD tests. Two detection ranges were used for the project. Primarily, the ultra low range (0.7 to 40.0 mg/L) tests were used, but some low range tests (3 to 150 mg/L) were run as well. The steps to prepare the samples are identical regardless of the range, but absorbance is measured at different wave lengths (365 nm for the ultra low range; 420 nm for the low rang).

The HACH COD test "measures the oxygen equivalent of the amount of organic matter oxidizable by potassium dichromate in a 50% sulfuric acid solution." To begin, 100 mL of sample is homogenized in a blender for 30 seconds and 2 mL of the mixed sample is pipeted into a COD Digestion Reagent Vials held at a 45 degree angle. Besides the sulfuric acid and potassium dichromate, the vials also contain a silver compound to help oxidize organic material and a mercuric compound to reduce interference from the oxidation of chloride by the dichromate. After a washing of the outside of the vials with deionized water and mixing by inversion (during which the samples become warm), the vials are placed in a reactor preheated to 150 degrees Celsius for two hours. During this process, most of the carbon in the sample is converted to carbon dioxide and hydrogen is converted to water. The samples are allowed to cool in the reactor for twenty minutes and are then removed, inverted several times to mix and allowed to cool to room temperature. Once they have cooled, the vials are cleaned and the absorbance is measured in the spectrometer. During the initial chemical reaction, when the vials are first mixed, the solution turns a yellow color. During the digestion process, the solution turns a blue-green color. The absorbance measurement at the end of the test is measuring the remaining yellow chromium (Cr^{6+}) in the sample, which is then related to COD.

4.2.4 Atomic Absorption Spectrometry

In order to test for metals, Atomic Absorption Spectrometry (AAS) was used. Lead (Pb), zinc (Zn) and Cadmium (Cd) were each determined following the procedures outlined in Section 3111 of *Standard Methods* (1992).

The basis of the testing is that "determinand atoms in a non-emitting ground state will absorb light of a characteristic resonance wavelength." Greater numbers of atoms results in higher rates of absorption (Hunt 1986). To accomplish this, a water sample is sucked through a tube, aspirated into an air-acetylene flame and atomized. A light is passed through the flame, into a monochromator and detector. The amount of light absorbed in the flame is then measured (Standard Methods 1992). The light source in AAS tests is a hallow-cathode lamp (HCL). HCLs only emit light at a specific wavelength that corresponds to a given element (Hunt 1986). Typically, a different lamp is required for element, although multi-element lamps are available in instances where several elements require light of a similar wavelength. They provide lower sensitivity, however (Standard Methods 1992).

The AAS tests follow the same basic procedure as the spectrophotometer tests discussed in the previous section. For each element, a set of standards at various known concentrations is created before testing begins. Along with a blank of deionized water, the absorbance of each standard is measured to create a standard curve. Each water sample is then tested. The absorbance is recorded and the concentration is determined after testing using the equation of the standard curve. In between each reading of a standard or water sample, a reading is taken with deionized water. This is to ensure that there are no residual metals in the tubing. At the conclusion of testing, the set of standards is run through the machine one final time to check for any deterioration of the standard curve.

The testing procedure is identical for the three metals of interest: lead (Pb), zinc (Zn) and cadmium (Cd). The only difference is that each element uses a separate HCL to generate light at the appropriate wavelength.

4.2.5 Other Test Procedures

Several test procedures do not fall into the two broad categories discussed previously: pH, turbidity and solids. Testing for each of these parameters is unique. In the case of pH and turbidity, the tests are relatively simple in comparison to the others. For this reason, they were conducted more frequently. Solids testing is more complex and time consuming, so this analysis was preformed only when the full range of tests was completed.

4.2.5.1 pH

To perform the pH tests, a small handheld Oakton pHTestr 30 was used. The device provides a digital readout of the pH to a hundredth of a unit along with the water temperature. pH is time sensitive, so the readings were taken at the site, shortly after the conclusion of a storm as often as conditions would allow. In some instances, readings were recorded at the University of Pittsburgh's Environmental Engineering laboratories immediately after collection from the site, but these results are not included in the final analysis.

4.2.5.2 Turbidity

Turbidity tests are carried out frequently, with each storm. Along with pH, the tests can be preformed quickly and efficiently and provide a good first indication of water quality that can be used as a basis for further testing. First flush effects can also be seen from sequential sampling.

To test for turbidity, the nephelometric method (2130 B) from *Standard Methods* (1992) was followed. A turbidimeter (or nephelometer) is used in testing. A HACH Model 2100A Turbidimeter (Figure 19) was used for this study. A water sample is placed in a chamber and light is shown through it. A photoelectric detector measures the intensity of light scattered at a 90 degree path to the incident light. As more particles are present in a sample, more light is scattered. This higher intensity of scattered light corresponds to a higher turbidity, measured in nephelometric turbidity units (NTU).

Figure 19 - Turbidimeter

It is necessary to allow the turbidimeter to warm up for a few minutes before beginning testing. The turbidimeter used for this project (and most models) contain several ranges. For instance, 0 to 0.02 NTU, 0 to 10 NTU, 0 to 100 NTU and 0 to 1000 NTU. A standard is required for each range. As with all samples, it is necessary to clean the outside of the standard sample before placing it in the turbidimeter. Once it is in the chamber, an opaque cylinder is placed over the portion of the cell that protrudes from the chamber. The turbidimeter is then set to the turbidity of the standard and testing can begin. Each water sample to be tested must be shaken, poured into a clean and dry sample cell and have the outside of the cell whipped clean before it is placed in the cylinder for a reading. If a sample has a turbidity near the top or bottom of the range, a reading would also be taken for the next higher or lower range to ensure accuracy. The turbidimeter used on this project frequently falls out of calibration. Therefore, it is recalibrated after every other sample.

4.3 DATALOGGING

A National Instruments Fieldpoint datalogging system was used to record data for the project and operate all the equipment. Located inside a six foot long weatherproof metal enclosure on the green roof, this is the control center for the project.

The Fieldpoint system is comprised of modular units that each accepts different types of inputs. Two banks of modules were used for this project. Both banks contained a power supply (PS-4 module) and a network module (FP-2000). The network module contains an Ethernet port that allows the bank of Fieldpoint units to communicate with computers, both directly and over the internet. They also contain a small computer, which allows simple programs to be run on the unit as well as host web pages. Through communication with the network modules, the data that is received from the other units can be stored, displayed and studied. The Fieldpoint units are connected inline, with the network module in the first position.

The first bank of modules is the largest. It receives the majority of the data from the thermocouples and controls the solenoid valves. There are five FP-TC-120 units, each accepting eight thermocouples. One FP-CTR-502 counter module records the rainfall. Each time one-hundredth of an inch of rain falls, the rain gauge tips and sends a reading to the counter module to be recorded. To control the opening and closing of the solenoid valve, they are wired to a FP-DO-401 digital output module. Each channel can be energized programmatically, opening the valve connected to that channel.

The second Fieldpoint bank contains two AI-100 analog input modules. These units acquire data for all of the equipment on the roof, with the exception of the thermocouples, rain gauge and solenoid valves. The analog input modules are able to accept both voltages and currents that are output by the equipment. This bank also includes a FP-DO-401. The majority of the equipment on this bank is able to draw its power constantly, which is done from the analog input modules. To avoid over heating, however, the 107-L temperature sensors, wind direction and soil moisture sensors can only be powered when a reading is taken. The digital output module is used to control when these pieces of equipment receive power. Finally, there is one thermocouple module for the last eight thermocouples on the roof.

Figures 20 and 21 show the datalogger prior to installation and inside the metal enclosure on the roof, respectively. For both banks of modules, the first unit on the left is the network module. The others follow in order as they were described above.

Figure 20 - National Instrument Fieldpoint Datalogger Prior to Installation

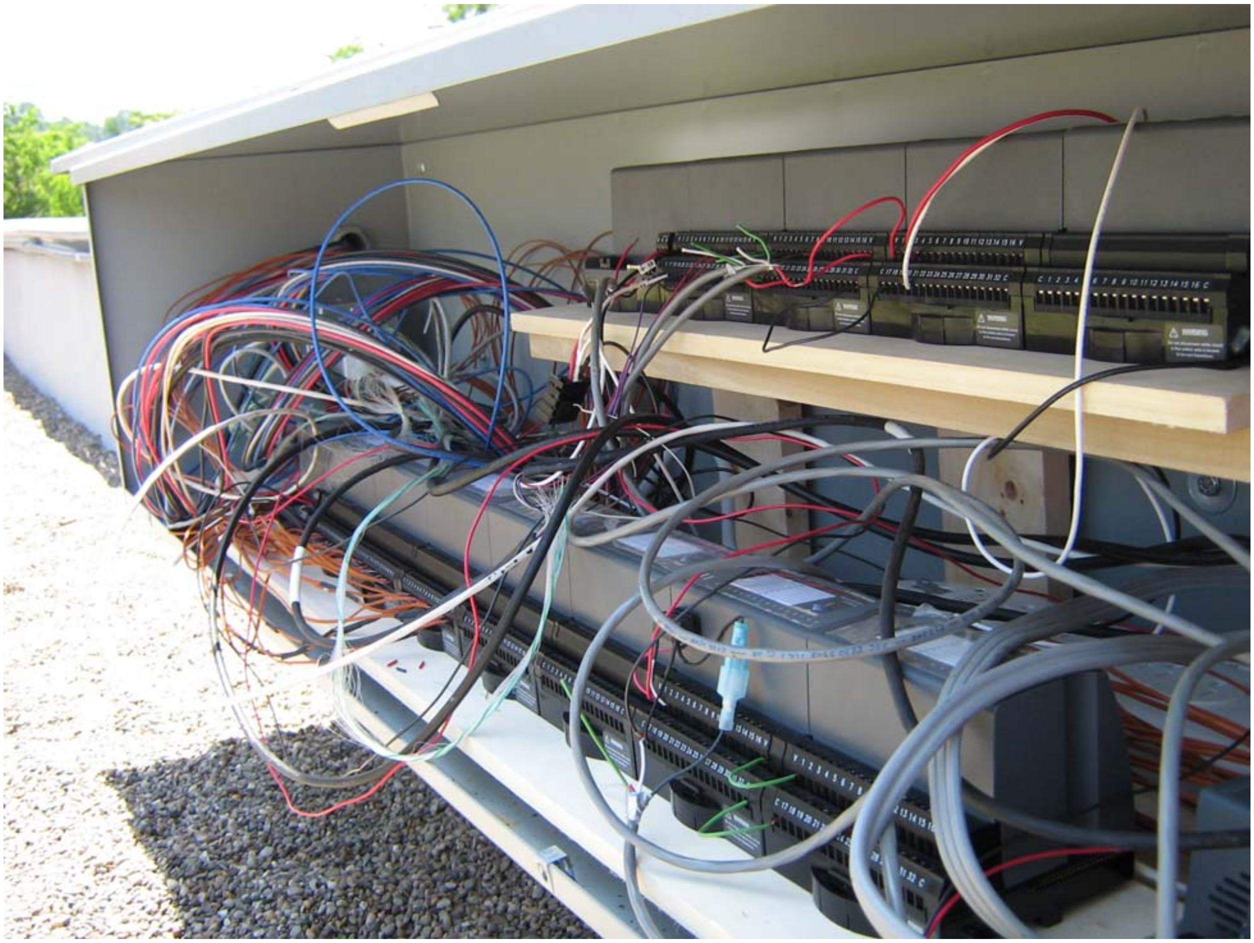

Figure 21 - National Instruments Fieldpoint Datalogger in Metal Enclosure

To control the equipment, a program was written in National Instrument's LabVIEW 8.0 programming language. First, the program acquires data from the Fieldpoint units. As most of the data is in units such as volts, it is then converted to a usable form. This data is stored on a server on the campus of the University of Pittsburgh and displayed in real time on a website hosted off the same server.

The LabVIEW program is broken up into three smaller programs to make the coding more manageable and to simply the website displays. One program is for all the thermocouple measurements, one is for the remainder of the temperature equipment and the third handles the water equipment.

The FP-2000 module can convert the thermocouple readings to temperature automatically. Once every five minutes, the program takes readings from all 48 thermocouples and writes the values to a file. The file stores the time, date and temperature. The monitoring location on the roof and vertical location are both recorded as well for each thermocouple. The current temperature and a chart of the past several hours worth of measurements are displayed for a portion of the thermocouples. Figure 22 shows several thermocouples installed on one of the two tripods placed on the control roof.

The LabVIEW program displayed is shown in two figures. Figure 23 shows the top third of the display. The thermometers show the current temperature at all four measurement locations for selected vertical points. In Figure 24, several graphs display trend data for the previous 3 and a half days. An example LabVIEW code is depicted in Figure 25. The reading from a single thermocouple is read every five minutes, stored in a data file (the temperature reading itself plus its location is recorded) and displayed. This must be done for each thermocouple measurement point. This is also the basic procedure follow in all programs, but more complex programming is required for the other pieces of equipment.

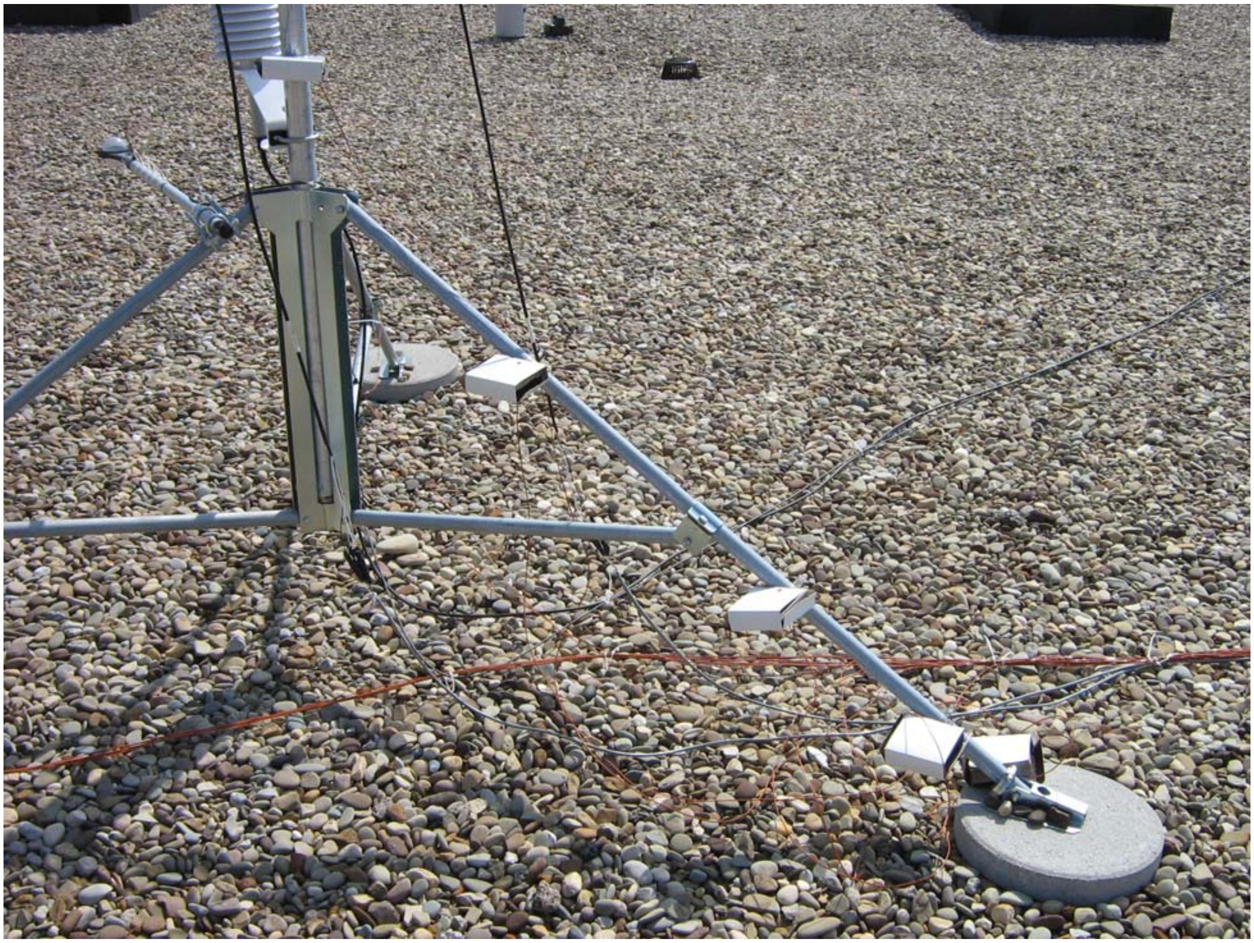

Figure 22 - Thermocouples Installed on a Control Roof Tripod

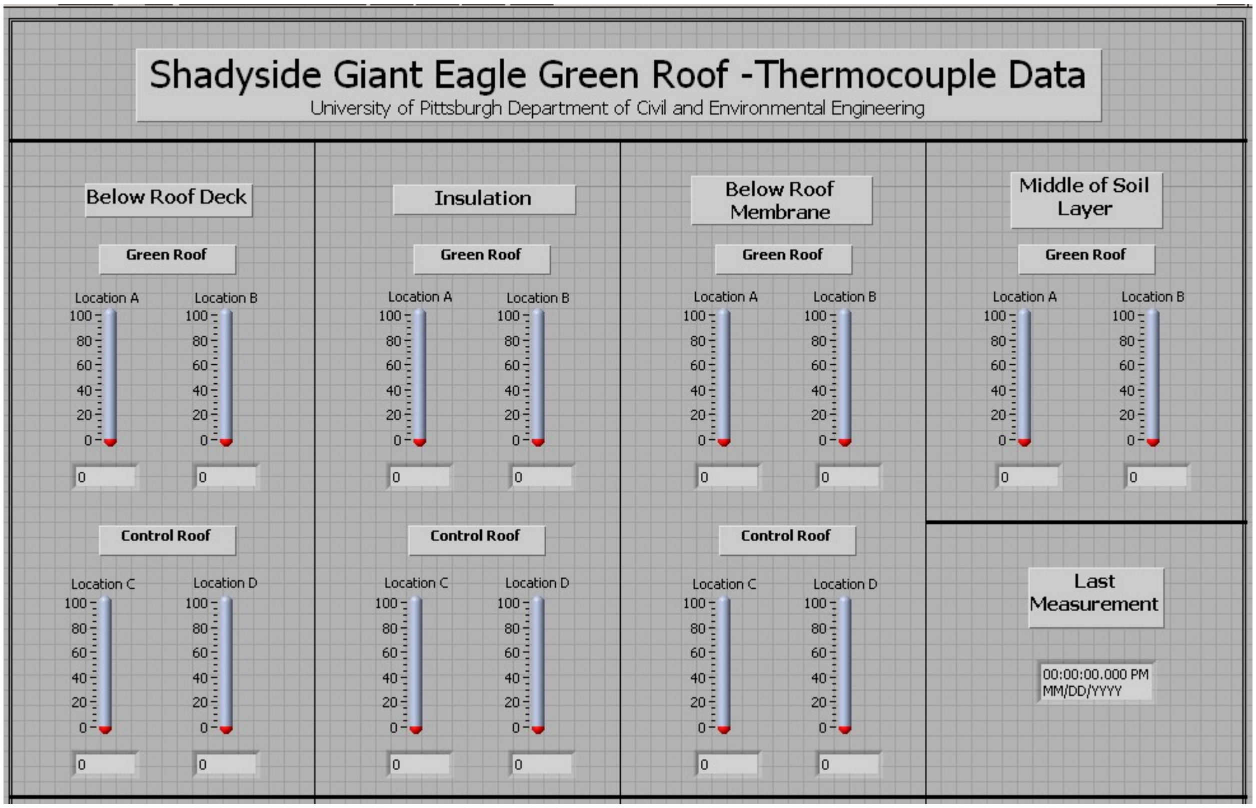

Figure 23 - Thermocouple LabVIEW Program Display - Top Half

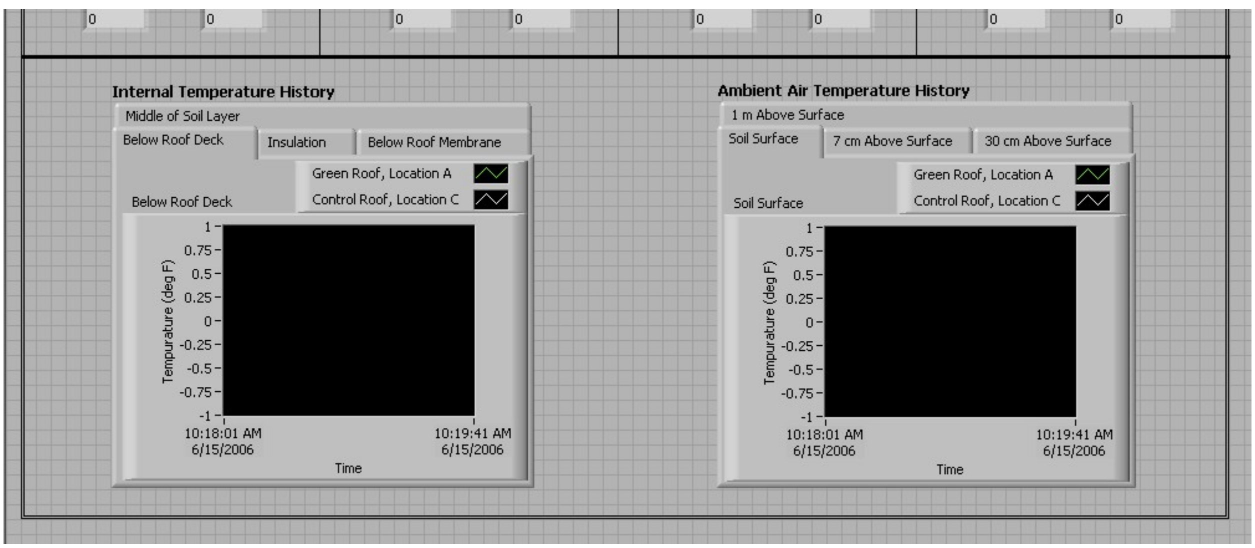

Figure 24 - Thermocouple LabVIEW Program Display - Bottom Half

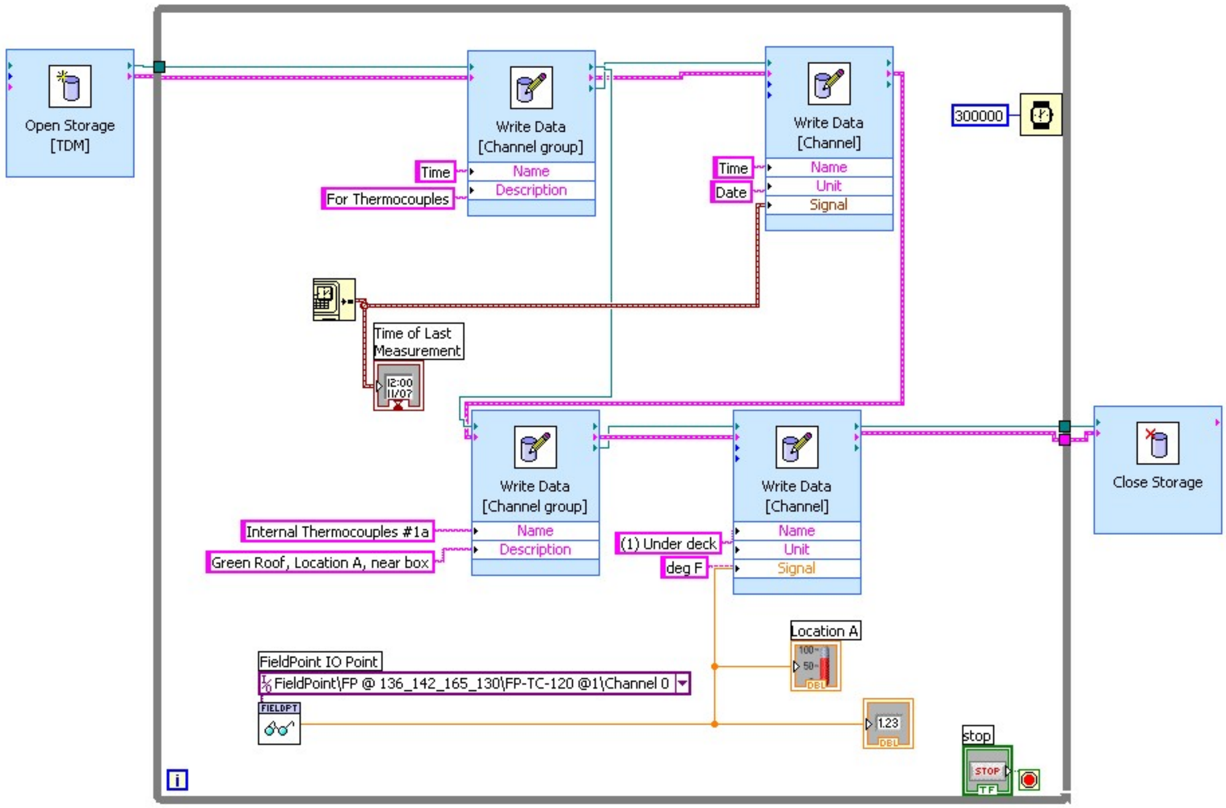

Figure 25 - Example LabVIEW Code for a Thermocouple

The program for the remaining thermal equipment is more complex. It also relies on a five minute sampling period. The temperature and relative humidity sensors (Figure 26) return readings in voltages, which are then converted in the program into degrees Fahrenheit and percent relative humidity, respectively. The temperature range of the sensor is -40 degrees to 60 degrees Celsius. The humidity range is 0 to 100 percent. In both cases, the output voltage ranges from 0 to 1 volt. A simple linear equation was derived for both measurements.

$$T_F = 180 \cdot V - 40$$

Where, T_F = Temperature in degrees Fahrenheit

V = measured voltage [volts]

$$RH = 100 \cdot V$$

Where, RH = Relative Humidity (%)

V = measured voltage [volts]

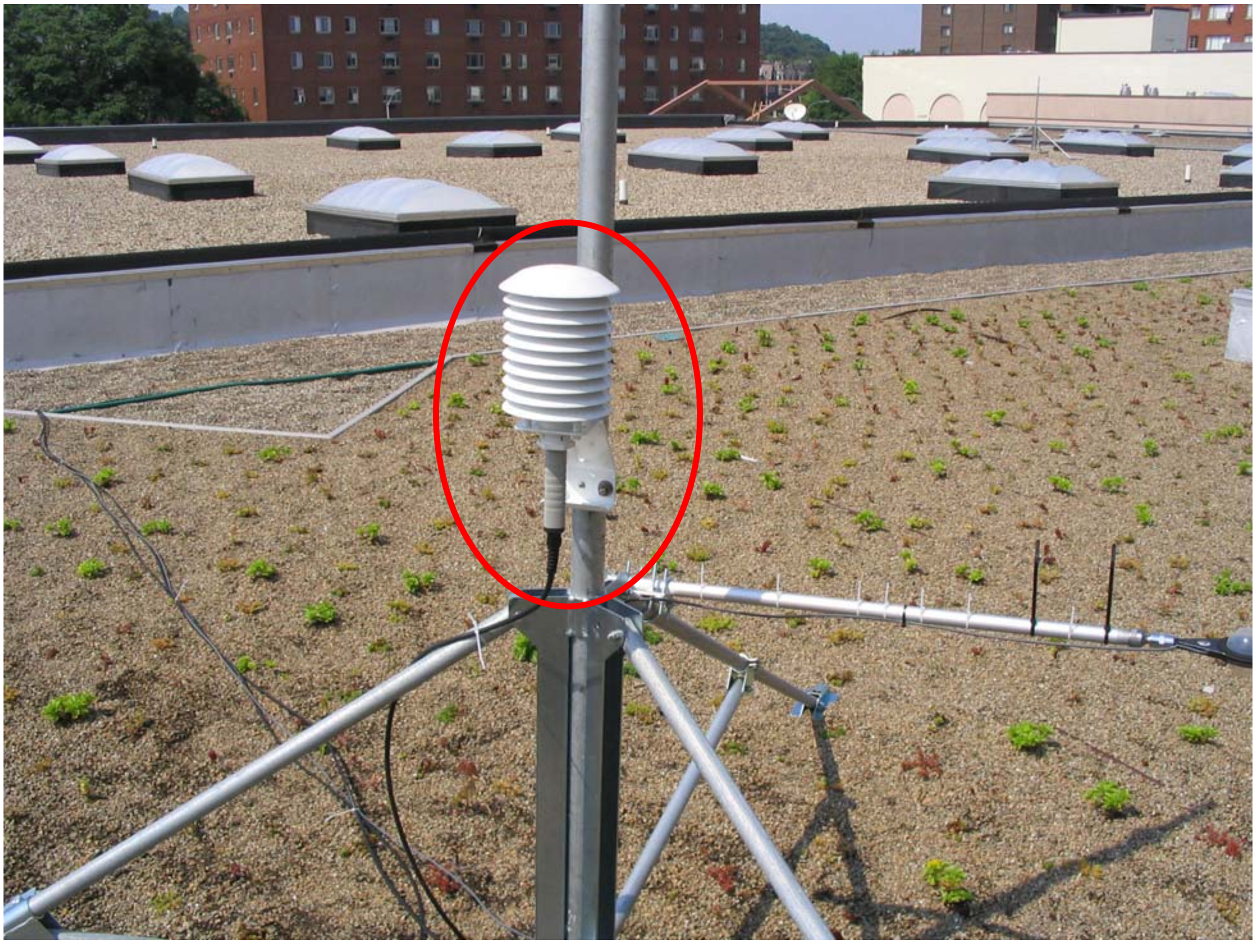

Figure 26 - Temperature/RH Sensor (Circled) Installed on a Green Roof Tripod

The net radiometers (Figure 27) follow the same process, but the results are converted to Watts per square meter. There is one equation for the conversion, but different factors are used for positive and negative readings. Each radiometer is factory calibrated and has slightly different factors.

$$\text{For } V_t > 0,\ Q^* = V_t \cdot F_p$$

$$\text{For } V_t < 0,\ Q^* = V_t \cdot F_n$$

Where, V_t = Output Voltage [mV]

F_p = Positive Calibration Factor [W/m^2 mV]

F_n = Negative Calibration Factor [W/m^2 mV]

Q* = Net Radiation Level [W/m^2]

Figure 27 - Net Radiometer Installed on Green Roof Tripod

The wind speed anemometer (Figure 28) returns a sinusoidal wave of voltage readings. The program first calculates the number of peaks in the wave during a one second period. This value is then translated to a wind speed in miles per hour.

$$W_{speed} = (1.6770 \times f) + 0.4$$

Where, W_{speed} = Wind Speed [mph]

f = Calculated frequency [Hz]

The wind vane (Figure 28) requires power only at the time of measurement, so the first step in acquiring wind direction data is to power the equipment. A voltage reading is then taken and converted to degrees.

$$W_{direction} = mult \cdot V$$

Where, $W_{direction}$ = Wind Direction [Degrees]

V = Output Voltage [Volts]

$$mult = \frac{355}{ExcitationVoltage}$$

Excitation Voltage = 12 Volts

Figure 28 - The Wind Speed Anemometer (Left) and Wind Direction Vane (Right)

The 107-L temperature sensors (Figure 29) used on the soil surface follow the same procedure, but the voltage readings are converted to degrees Fahrenheit.

$$x = 800 \cdot \left(\frac{V_s}{V_x} \right)$$

$$C = -53.46 + 90.807x - 83.257x^2 + 52.283x^3 - 16.723x^4 + 2.211x^5$$

$$F = 1.8 \cdot C + 32$$

Where, V_s = Measured Voltage

V_x = Excitation Voltage (5 V)

C = Temperature [Degrees Celsius]

F = Temperature [Degrees Fahrenheit]

Figure 29 - 107-L Temperature Sensor

Each time a piece of equipment takes a reading, it is stored and displayed. Each type of equipment has its own file, but results are combined into one webpage. Figures 30 and 31 show the display for this program.

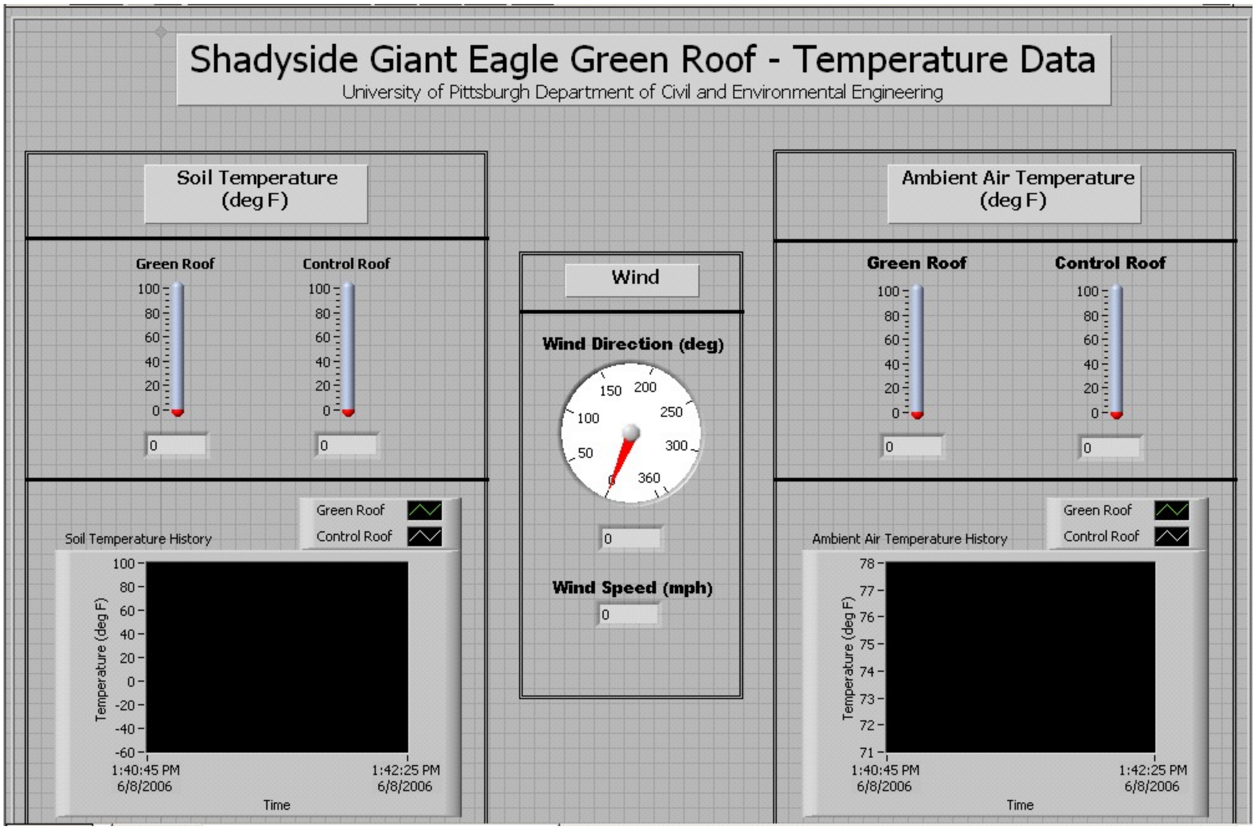

Figure 30 - Temperature LabVIEW Program Display - Top Half

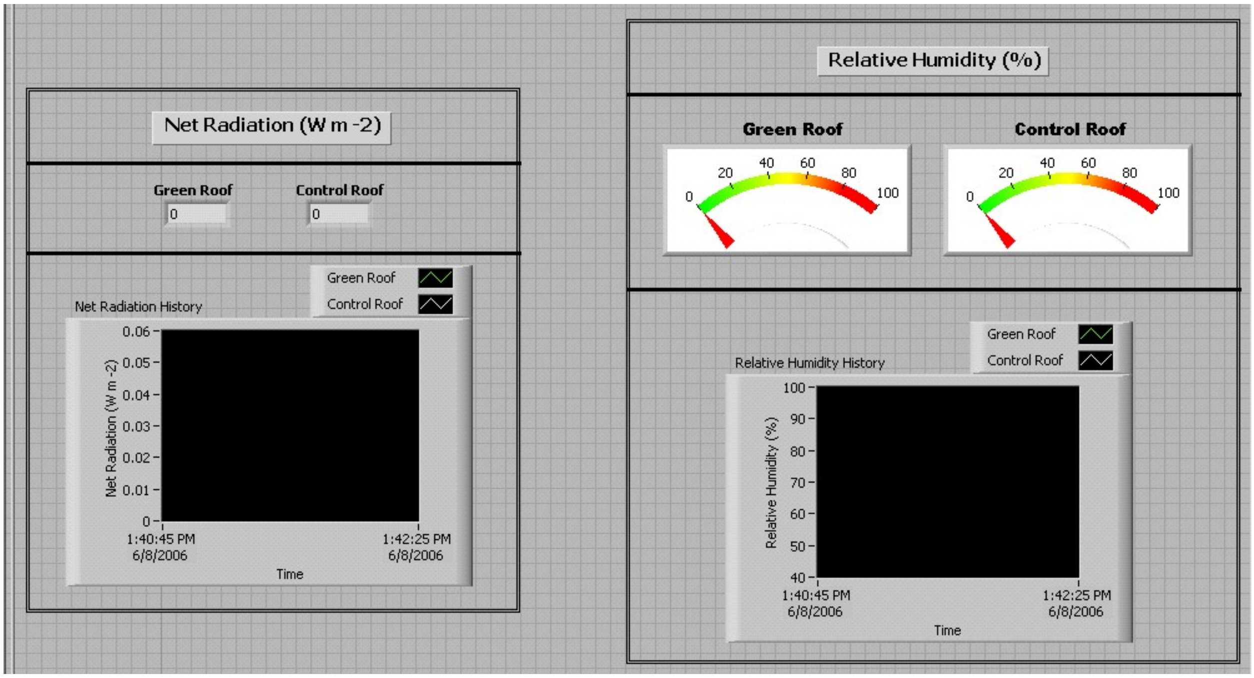

Figure 31 - Temperature LabVIEW Program Display - Bottom Half

The final program (Figure 32) controls the water equipment. Every ten seconds, the program checks the counter module to see if any rain has fallen. If the count (number of rain gauge tips) has not changed, nothing happens. If there is a change, the cumulative rainfall amount is incremented by 0.01 inch. The rainfall values are displayed and saved.

For runoff, several calculations are required. The ultrasonic sensor takes a reading every ten seconds and returns a reading, in amps, to the program. This is converted to give the depth of water in the flume at that instance. The depth is then used to calculate the flow rate, which is displayed and saved to file. From this flow rate, the amount of water that has passed through the flume during the ten seconds is calculated and added to the cumulative total for the storm. This cumulative runoff value is also shown on the website and saved. The ultrasonic sensors are calibrated with an output of 4 mA (milliamps) is equal to a measurement of 20.7 inches (no water in the flume) and 20 mA is equal to 9 inches (a full flume of 11.7 inches of water). A linear equation was derived from the calibration.

$$d_{measured} = -0.73125 \cdot i + 23.625$$

Where, $d_{measured}$ = The measured distance from the ultrasonic sensor to the flume or water level in inches

i = Outputted current [mA]

The actual depth of water is determined from the equations below.

$$d = -d_{measured} + 20.7$$

$$d = 0.73125 \cdot i - 2.925$$

Where, d = Depth of water in the flumes in inches

The flume manufacturer provides a chart that equates water depth in the flume to flow rate, in cubic feet per second. Using Excel, a quadratic equation was calculated. The cumulative flow volume is determined using this result.

$$f_r = 0.0026 \cdot d^{2.5532}$$

$$V_c = f_r \cdot s_r$$

Where, f_r = Flow rate [cfs]

V_c = Cumulative runoff volume [cf]

s_r = Sampling rate [seconds]

The valves are controlled based on the cumulative runoff value for each roof. Each valve is programmed to open once a certain amount of runoff has accumulated. The valves remain open just long enough to fill the sample bottle and are then closed. They must open in series, however, so the program does not allow a valve to open unless the previous valve has been filled (i.e. opened and closed). No data relating to the valves is recorded, but a display on the website indicates when the valves have opened, so that samples may be collected.

The final pieces of equipment are the water content sensors. These too must only be powered during measurements, so the first step in the program to energize the sensors. Like the anemometer, the water content sensors return a voltage wave, this time a square wave. In this case, it is the frequency of the wave that converted to give the water content. Unfortunately, the frequencies produced by the sensors are out of range for the Fieldpoint unit, so a frequency to voltage converter is required (Dataforth DSCA45-08 Frequency Input Signal Conditioner). The frequency that enters the converter is output as a proportional voltage that can be read by the datalogger. The voltage value is then converted to find the water content. As before, data is stored and displayed.

The water content is calculated with the equations listed below.

$$f = 10 \cdot V$$

$$T = 1000 \cdot \frac{1}{f}$$

$$VWC = 100 \cdot \left[-0.0663 - (0.0063 \cdot T) + (0.0007 \cdot T^2) \right]$$

Where, V = Signal Conditioner Output [volts]

f = Frequency [kHz]

T = Period [μs]

VWC = Volumetric Water Content [%]

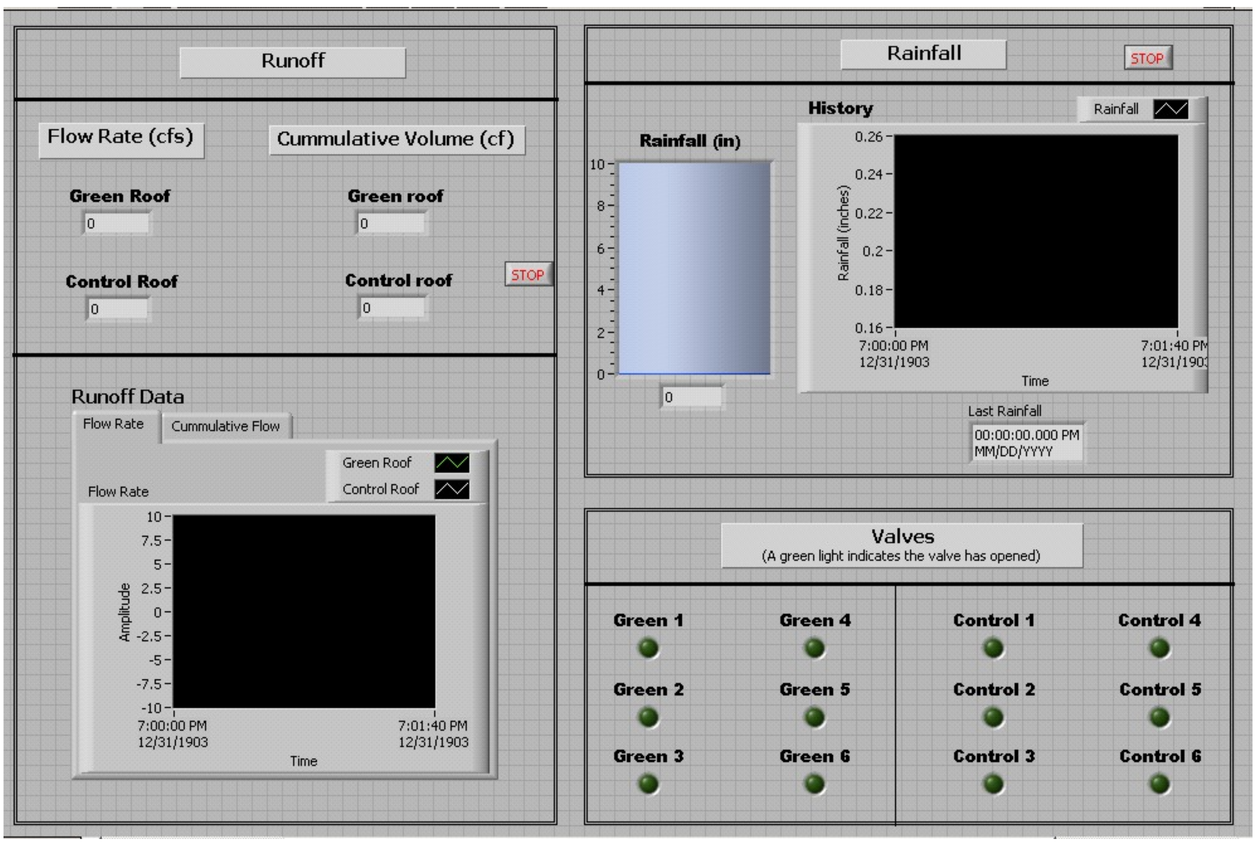

Figure 32 - Water LabVIEW Program Display

5.0 RESULTS

This chapter will present results from the Giant Eagle Shadyside green roof in addition to results obtained during a pilot study. The pilot study used simple techniques to test many of the same aspects as the full scale green roof. Selected results are presented here, with discussions of important points. The appendices list the complete water quantity and quality results for the Giant Eagle project in detail.

5.1 PILOT PROJECT RESULTS

Prior to the construction of the Shadyside Giant Eagle site, a green roof pilot project was started in the summer of 2004 as part of the Mascaro Sustainability Institute Undergraduate Research Program in Sustainable Engineering at the University of Pittsburgh. Using a set of green roof test plots, including one identical to the roof in Shadyside, a set of tests were completed that focused on the water quantity, water quality, urban heat island and insulation effects of green roofs. With the exception of the water quality tests, the experiments were considerably lower-tech than those conducted at the Giant Eagle green roof. Despite this, the tests provided a base for the performance of green roofs in Pittsburgh. The water results are presented briefly for comparison purposes.

5.1.1 Test Plots

The pilot project consisted of six green roof test plots (Figure 33). Four of the plots were two-foot by two-foot in size, while the other two were one-foot square. Two of the two-foot square test plots were intensive green roofs with twelve inches of soils, as was both of the one-foot square test plots. The other two large test plots were extensive green roofs with a five and a half inch substrate (Figure 34).

Figure 33 - Pilot Project Green Roof Test Plots

Figure 34 - Garland Extensive Green Roof Test Plot

Products from two different manufacturers were used in the project. American Hydrotech's system consisted of separate layers for a root barrier, a water retention mat, a drainage layer and a filter fabric. This system is about one and a quarter inches thick. The other system was made by Garland, and is identical to the materials used on the Giant Eagle green roof. It is made up of a root barrier and a single layer combining the functions of the drainage layer and filter fabric. It is about one quarter of an inch thick. Each manufacturer's system was used on one large intensive, one extensive and one small intensive test plot. The same soilless mix from the Shadyside project was used in all roofs. The mix of plants was also identical for all plots and is similar to the Shadyside green roof, consisting of a mix of sedum kamtschaticum, worm grass sedum and thymus x citriodorus.

5.1.2 Water Quantity Results

To monitor the amount of runoff leaving each green roof test plot, a drain pipe was placed in a corner of the plots which was then connected to a bucket (Figure 35). Actual rainfall and runoff data was collected, along with several simulated storms. After each rain storm or test, the amount of water in each bucket was recorded, along with the amount of rainfall from a simple grain gauge positioned next to the plots.

Figure 35 - Pilot Project Collection Buckets

5.1.2.1 Weather Data

During the initial summer and fall period of measurement (from July 15 to October 24, 2004), a total of 42 rain events occurred, with only 16 (38 percent) producing runoff. During this same period of time, the simulated storms were completed, though they are not included in totals.

For comparison purposes, the runoff volumes were converted to equivalent inches of rain with the equation below.

$$R = \frac{R_{vol}}{SA}$$

Where, R = Runoff (in)

R_{vol} = Runoff volume (ci)

SA = Surface Area of Test Plot (si)

The results for all rain events from July 15 to October 24, 2004 are summarized in Table 2. All together, 32.4 inches of rain fell on the green roof test plots, but only between 7.4 and 12.7 inches became runoff. This results in a retention rate of between 60.9 and 77.1 percent. The large test plots, both intensive and extensive, show a higher retention rate for the Garland materials. The opposite is true for the small intensive plots.

Table 2 - Test Plot Runoff Results - June - October 2004

Roof		Total Rainfall (in)	Runoff (in)	% Retained	% Detained
Large Int.	Garland	32.4	7.4	77.1%	22.9%
	Am. Hydrotech		8.5	73.8%	26.2%
Large Ext.	Garland		8.4	74.1%	25.9%
	Am. Hydrotech		9.4	71.1%	28.9%
Small Int.	Garland		12.7	60.9%	39.1%
	Am. Hydrotech		10.2	68.6%	31.4%

These results are not for typical storms, however. During a nine day period in early September 2004, Pittsburgh received severe rainstorms that were the remnants of hurricanes. The first storm was 7.15 inches of rain over approximately one and half days, while the second was approximately 7.7 inches of rain in about 20 hours. The storms were among the worst ever recorded and were equivalent to the 500-year storm (greatest rainfall to be expected over a 500-year period) for the Pittsburgh region. Due to the significant amounts of rainfall and the collection system of buckets, the runoff amounts recorded for these two storms is inaccurate. The runoff overwhelmed the collection buckets and much of the runoff overflowed before it could be accounted for. Table 3 lists the runoff results excluding these two storms. There is a substantial increase in effectiveness of the green roofs, with retention rates in the 71.1 to 85 percent range.

Table 3 - Test Plot Runoff Results Excluding Hurricane Storms

Roof		Total Rainfall (in)	Runoff (in)	% Retained	% Detained
Large Int.	Garland	17.6	3.1	82.4%	17.6%
	Am. Hydrotech		3.7	79.1%	20.9%
Large Ext.	Garland		4.0	77.4%	22.6%
	Am. Hydrotech		5.1	71.1%	28.9%
Small Int.	Garland		3.9	77.8%	22.2%
	Am. Hydrotech		2.6	85.0%	15.0%

The two small intensive green roofs did produce accurate results during the second storm. Due to their smaller size, the amount of runoff produced was completely contained within containers. Between the two plots, an average of 24 percent of the runoff was absorbed. By applying this number to both of the two hurricane storms, an estimate can be obtained the green roof performance during these large storms, as indicated in Table 4. Estimates could not be made for the extensive green roofs due to lack of data, but the retention would be somewhat lower due to the lesser amount of soil present. In total, the intensive green roofs retained between 51.9 and 58.9 percent of the runoff.

Table 4 - Test Plot Runoff Results with Hurricane Storm Estimate

Roof		Total Rainfall (in)	Runoff (in)	% Retained	% Detained
Large Int.	Garland	32.4	14.4	55.7%	44.3%
	Am. Hydrotech		15.0	53.9%	46.1%
Small Int.	Garland		15.6	51.9%	48.1%
	Am. Hydrotech		13.5	58.5%	41.5%

A number of conclusions can be drawn from this information. Obviously, the intensive green roofs proved to be more successful in retaining rainwater than their extensive counter parts. This can be contributed to the greater depth of soil present. The additional soil provides more pore spaces for water to be absorbed. There were a few instances over the course of the study where one of the extensive roofs would produce more runoff than one the intensive roofs, but overall, the intensive roofs retained substantially more water.

Over a long period of time, in the absence of a catastrophic rainfall event, these results show that a retention rate of approximately 70 to 78 percent can be expected from an extensive green roof and that up to 85 percent may be retained by an intensive green roof. Considering severe conditions, the retention rates can decrease significantly, to approximately 51 to 59 percent. This is still substantial, however.

One conclusion that can not be reached is which material proved more successful at retaining water. It would stand to reason that the American Hydrotech roofing system should retain more because it has a thicker drainage layer. While this does hold true for the small intensive green roofs, the Garland roofs held more overall for the large plots. For the individual storms, there are instances where both roofs out perform each other.

A simple, yet important, point can be illustrated with the runoff data: dry soil retains water, but saturated soil does not. Generally speaking, when the soil was dry, runoff did not occur. Only three of the sixteen runoff events occurred with essentially dry soil. The first was when nearly 3 inches of rain fell over a 12 hour period, while the other two instances were the hurricane storms. Light rain over long periods of time and short bursts of heavy rain with dry soil conditions failed to produce runoff. At one point, an entire month passed without runoff despite frequent and, at times, heavy rainfall. On the other hand, even relatively light rainfalls of one quarter of an inch over several hours produced runoff once the substrate was saturated. It should be noted that soil water content levels were not collected during this study.

5.1.2.2 Simulated Storms

To see the effects of green roofs specifically in regards to delaying runoff and for more detailed results, a set of storms were simulated. Using intensity-duration-frequency curves (Bell et. al, 2000), it was found that the 100-year storm was a 4.5 inches per hour intensity rainstorm lasting 20 minutes. This equated to applying the equivalent of 1.5 inches of rain covering the entire surface of the two foot by two foot roof in 20 equal increments. Two runs of the test were completed, with the amount of runoff monitored every five minutes as well as noting the time that runoff first began to flow.

As shown in Table 5, there is a delay of several minutes in all cases. With a conventional roof, the runoff would begin to flow almost immediately after it began to rain. The extensive roofs became saturated before the intensive roofs, as would be expected with their thinner substrate. The Garland products produced runoff more quickly than their American Hydrotech components. This is likely attributed to the thicker layer of materials in the American Hydrotech system, which would require a longer time for water to flow through.

Table 5 - Test Plot Runoff Delay

Roof		Runoff Delay (Minutes) 1	2
Intensive	Garland	9.9	10.3
	Am. Hydrotech	11.8	13.1
Extensive	Garland	5.8	4.0
	Am. Hydrotech	8.5	6.8

The flow volume summaries for both test runs are listed in Table 6 and Table 7, respectively. The results show that the intensive roofs retain a higher percentage of the rain water and that the American Hydrotech products retain more water than the Garland materials. In the initial test, the retention rates range from 47 to 72 percent while they decrease to 30.9 to 52.1 percent in the second. This is most likely due to the moisture levels present in the soil at the start of the tests. For the first test, it had been nearly a month since the last runoff event, although there had been several moderate rainfalls in the week leading up to the test. The second test was run just a week after the second severe hurricane rain storm.

Table 6 - Runoff Volume Results - Test 1

Roof		Total Rainfall (in)	Runoff (in)	% Retained	% Detained
Intensive	Garland	1.5	0.57	61.8%	38.2%
	Am. Hydrotech		0.42	72.0%	28.0%
Extensive	Garland		0.78	47.9%	52.1%
	Am. Hydrotech		0.71	53.0%	47.0%

Table 7 - Runoff Volume Results - Test 2

	Roof	Total Rainfall (in)	Runoff (in)	% Retained	% Detained
Intensive	Garland	1.5	0.72	52.1%	47.9%
	Am. Hydrotech		0.73	51.3%	48.7%
Extensive	Garland		1.04	30.9%	69.1%
	Am. Hydrotech		0.98	34.4%	65.6%

The first set of results is close to the real time results, not including the hurricane storms (Table 3), although with slightly lower retention values. In the test, the intensive green roofs retained approximately 10 percent less than in actual conditions, while the extensive roofs were about 20 percent less. With the exception of the hurricane storms, none of the storms on record reached the severity of the 100-year storm. This increased intensity, dropping more water on the roof more quickly than normal, would account for the reduced performance.

The results from the second run of tests are just slightly lower than the estimated totals including the hurricane storms for the intensive roofs (Table 4). The increased moisture content from the recent heavy rainfalls decreased the effectiveness of the green roofs to retain water in much the same way the hurricane rain reduced the totals over the study period. Since the values are very close for the intensive roofs, the 30.9 to 34.4 percent retention range recorded for the extensive roofs here may be close to the performance of the extensive green roofs under the hurricane storms.

Figures 36, 37, 38 and 39 show the flow rates during the both sets of experiments for each of the large green roof test plots and Table 8 shows a summary of the maximum flow rates. Several important points can be drawn from this information. The Garland roofs tended to discharge runoff more quickly than their American Hydrotech counterparts, with a high flow rate over a short period of time. The Hydrotech roofs had a slower flow rate over a longer period of time. The extensive green roofs had a higher flow rate than the intensive roofs. They also maintained a flow rate near the peak for a longer period of time than the intensive green roofs, which would spike and quickly drop off.

Table 8 - Maximum Flow Rates - Controlled Runoff Experiments

Roof		Maximum Flow Rate (ci / min)	
		1	2
Intensive	Garland	20.9	34.7
	Am. Hydrotech	12.3	28.9
Extensive	Garland	29.2	34.7
	Am. Hydrotech	20.9	37.5

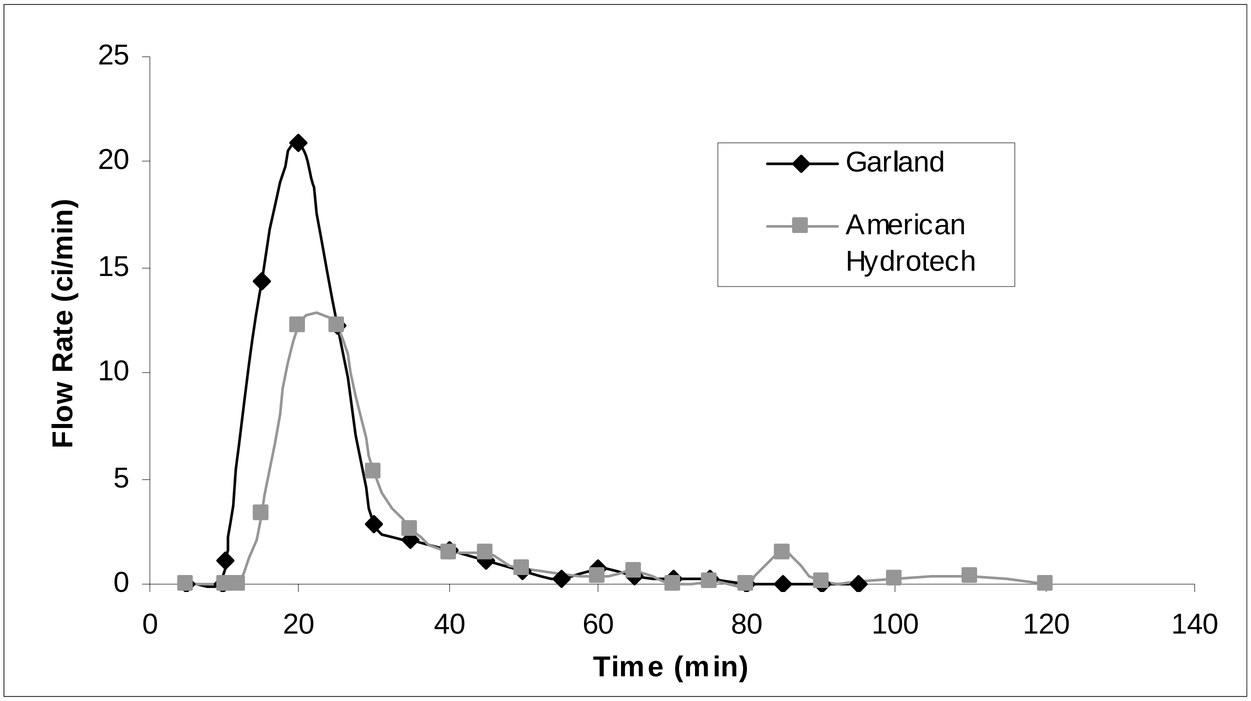

Figure 36 - Intensive Green Roof Flow Rates - Controlled Runoff Experiment 1

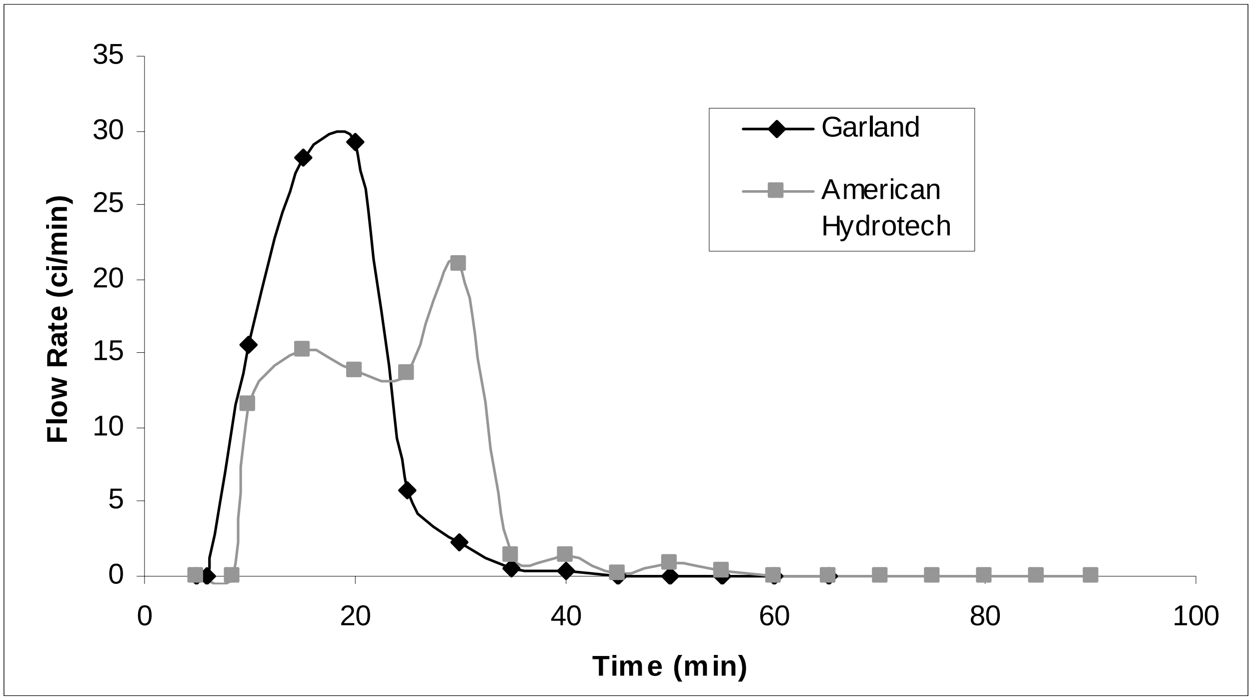

Figure 37 - Extensive Green Roof Flow Rates - Controlled Runoff Experiment 1

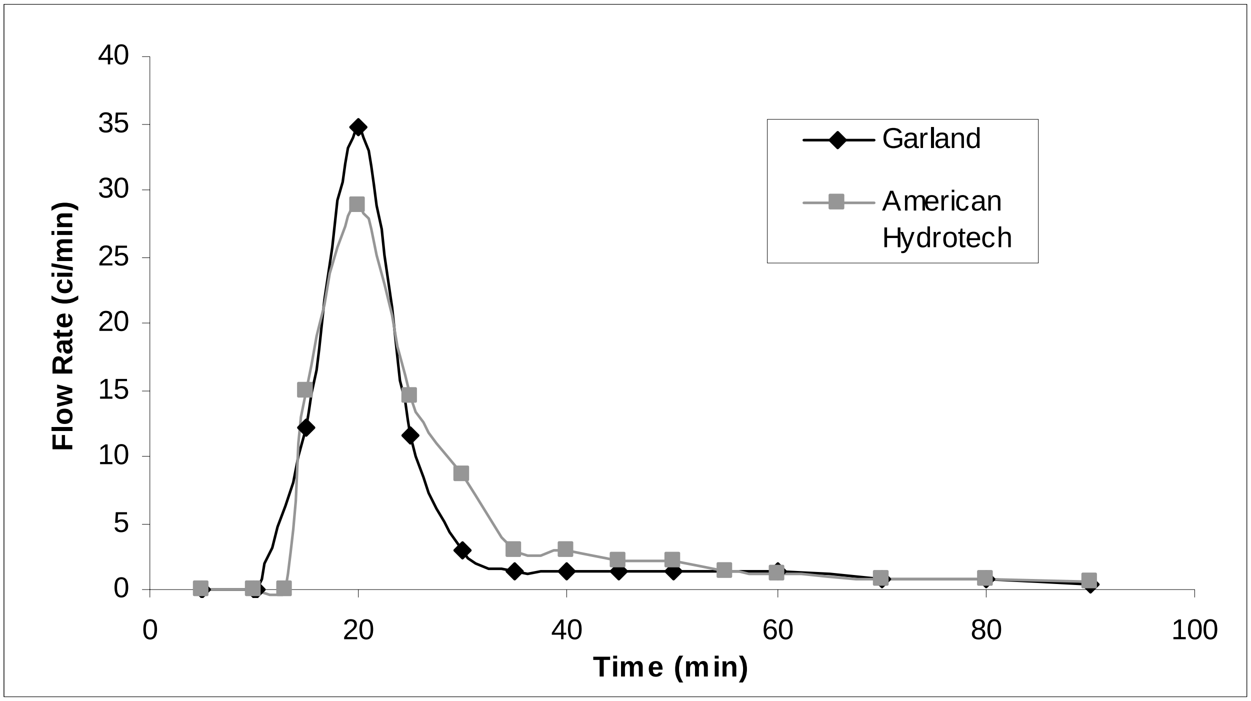

Figure 38 - Intensive Green Roof Flow Rates - Controlled Runoff Experiment 2

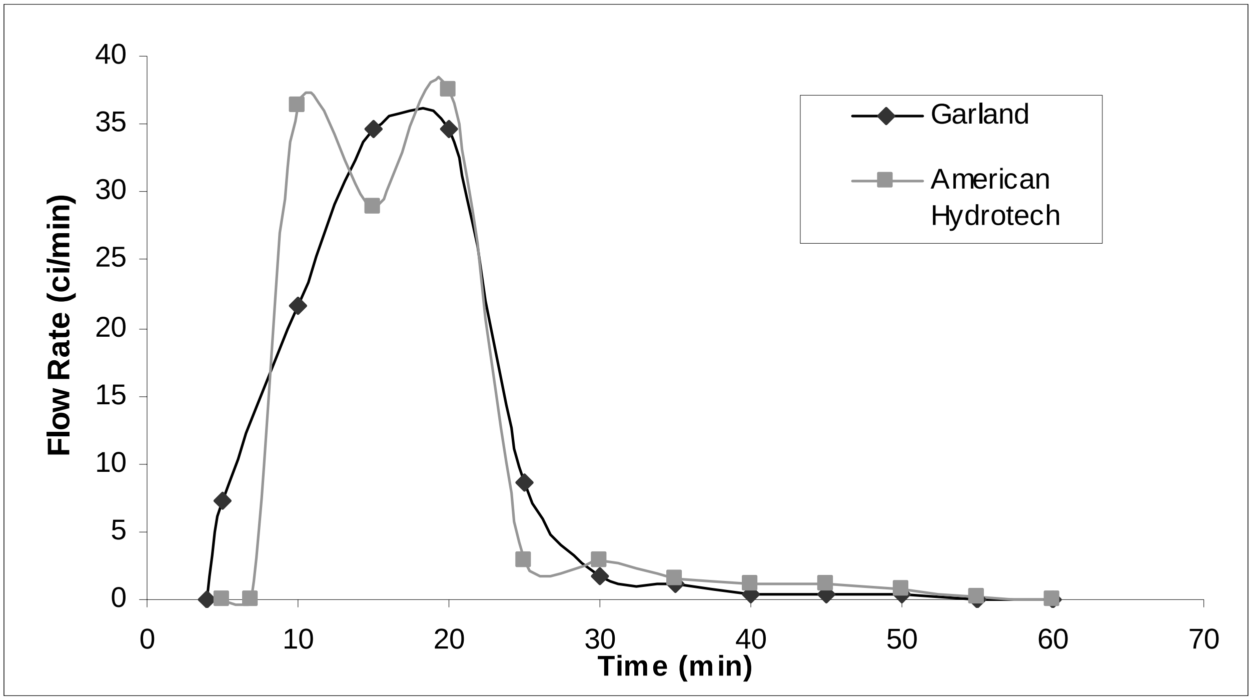

Figure 39 - Extensive Green Roof Flow Rates - Controlled Runoff Experiment 2

Also of note is that while the majority of the test plots produced a smooth and predictable curve building quickly to one peak and then gradually decreasing at a slower rate, the extensive American Hydrotech roofs preformed differently. As seen in Figure 37 and Figure 39, there are actually two peaks. The other characteristics of the flow pattern are not drastically different from those of the extensive Garland roof, but the dual peaks are evident.

5.1.3 Water Quality Results

During the course of the pilot project, the runoff from the test plots was monitored for a limited number of water quality parameters. For approximately one year, each storm that produced runoff was tested for pH and turbidity. Due to the complexity of the tests, only one storm was selected for more extensive metals and phosphorus testing. Each test was also preformed on a rainwater sample to obtain a baseline for comparison.

5.1.3.1 pH

Simple pH strips were used to test the pH of the stormwater and rainwater samples. While they did not produce the most accurate results, they were chosen so the tests could be preformed at the site shortly after the storms ended, before pH had a chance to change.

Throughout the duration of the tests, the rainwater samples maintained a very consistent pH of 5. This is slightly acidic and is in line with the acid rain that the Northeastern United States receives.

The measured values for the green roofs were fairly consistent as well. The vast majority of samples had a pH of 6. While this reading is still slightly acidic, it is more neutral than the rainwater sample. Of the approximately 250 runoff samples tested, only one sample failed to decrease the acidity of the water. During several of the early tests, pH levels were measured at 6.5 and 7 in a number of samples. The last of these samples occurred three months into monitoring period. The first three storms exhibited pH measurements in this range for most of the roofs, but these tests were carried out using pH strips with less accuracy and a smaller range than the rest of the tests. For all other measurements, each instance of a pH greater than 6 was exhibited with an intensive roof. For the large intensive roofs, there were equal instances for each brand of materials. The small American Hydrotech roof only reached this point in one third of the instances of the Garland roof.

These results indicate that green roofs are able to decrease the effect of acid rain. Intensive roofs exhibited better performance than the extensive roofs during the first quarter of the study period. There is not enough data to conclude that one brand of material affects pH significantly, but the increased soil depth of the intensive roofs do show that the soil, rather than the plants (which were identical on each roof), are decreasing the pH. Also, slighter better performance can be expected in the early life of the roof before pH measurements level off.

5.1.3.2 Turbidity

As discussed earlier, turbidity measures the amount of particles suspended in a liquid. Essentially, how 'clean' a sample is. An increased turbidity means more particles are present. Samples were transported from the test plots to the Environmental Engineering labs at the University of Pittsburgh for testing.

Throughout the testing, the pH of the rainwater averaged about 2.7 NTU (Nephlometric Turbidity Units). After the first rainstorm, the green roof runoff samples had turbidities of 20 to 38 NTU. This steadily decreased to 4.8 to 9.8 NTU by the fourth rainfall. There appeared to be an initial flushing out of the system followed by stabilization.

There was then a one month period of frequent rainfall, but without runoff. When runoff did occur from a rainstorm, the turbidities increased significantly to 25 to 56 NTU. This indicates that the runoff transferred particles into the soil, which was again flushed out of the system. The plant growth was more developed at this point and may also have played a role. After the next several storms in a few day period, turbidities decreased to 5.6 to 8.3 NTU.

After a three week break without runoff, the process was repeated again, as shown in Figure 40. Turbidities decreased from 42 to 8 NTU to 15 to 5.4 NTU in the course of two days.

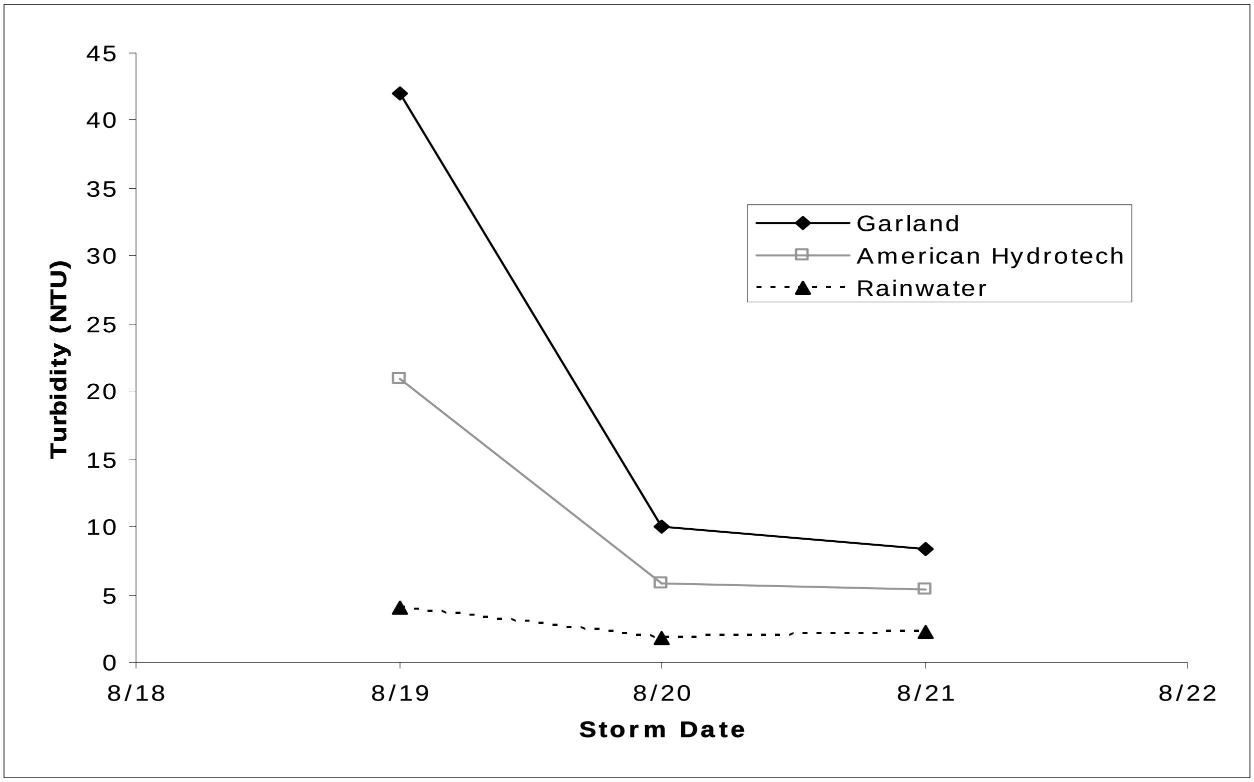

Figure 40 - Turbidity Results

After this point, three months into the year long study, the turbidity readings stabilized. There were only two instances where the turbidity was above 10 NTU over the remainder of the study. Many measurements were as low as 2 NTU, often times at approximately the same level as the rainwater. These results show that a green roof will initially discharge water containing large number of particles, most likely soil. After a period of stabilization, however, the water becomes significantly cleaner. This indicates that the roof retains more particles as the roof matures.

Before the roof stabilized, the Garland roofs produced runoff with a higher turbidity than the American Hydrotech roofs. This would seem to indicate that the American Hydrotech roof structure is better at filtering out the runoff. There was far less of a difference between the two after stabilization, however. Similarly, intensive roofs produced higher turbidity than their extensive counterparts throughout the study. Once the roofs stabilized, though, the results were much closer and there was not a discernable difference between the two in many instances.

5.1.3.3 Metals and Phosphorus

Using the same testing procedures outlined for the Giant Eagle project, additional water quality test were preformed for one rainwater sample, one runoff sample from the intensive Garland roof and two extensive Garland samples. The tests were preformed twice on each sample. Table 9 summaries the results.

Table 9 - Metals and Phosphorus Pilot Project Test Results

Sample	Pb [mg/L]	Zn [mg/L]	Cd [mg/L]	P [mg/L]
Rain	0.11	0.20	0.00	0.05
Intensive	0.10	0.93	0.00	25.60
Extensive (1)	0.13	0.68	0.00	14.90
Extensive (2)	0.12	0.73	0.00	24.70

The first metal tested for was cadmium (Cd). The rainwater was found to have a concentration of approximately zero mg/L (milligrams per liter). Cadmium was also not found in any of the runoff samples, indicating that the soil does not contain any of this metal.

Next, lead (Pb) was tested. A very small amount, 0.11 mg/L, was present in the rainwater and approximately that same level was found in the runoff, again indicating that no lead was present in the soil.

Tests were also run for the metal zinc (Zn). An average of 0.20 mg/L of zinc was found in the rainwater. The levels in the runoff samples were three to four and a half time greater. Since the intensive samples had more present, it can be concluded that there is zinc in the soil and that greater depths of soil will result in greater absorption

While not a metal, tests for phosphorous were carried out at the same time. There was very little in the rainwater, at 0.05 mg/L. The amount in the runoff increased dramatically to about 15 to 25 mg/L. Obviously, the phosphorous was absorbed as the water filtered through the soil. There is not enough evidence to conclude if the depth of soil has a connection to the levels present, however, as one of the extensive samples and the intensive sample have nearly identical amounts of phosphorous.

Because only one set of tests was completed, any changes in retention of these pollutants over time can not be determined. However, these tests were completed on samples from the first two weeks after the test plots were constructed. Previous research indicates that performance improves as the roof matures.

5.2 GIANT EAGLE WATER QUANTITY RESULTS

On site water monitoring of the Giant Eagle site began in July of 2006. The first storm data was recorded on July 28th. Through the end of January 2007, a total of 24 storm events were recorded at the site. The intensity of these storms varied significantly, from 0.07 inches through 2.2 inches. The duration of storms also covered a wide range, lasting up to several days. A subset of these storms will be discussed in this section to highlight the benefits of green roofs over a range of storms with different properties.

Several problems with the water quantity monitoring made certain data sets either incomplete or unavailable. When the equipment was initially installed onsite, in late July, the ultrasonic sensors were operational before the rain gauge. Complications with the rain gauge delayed it's installation by several days. During this time, four storms occurred. Good flow data was available, but detailed rainfall data from the site was not. Similarly, the soil moisture sensors were not installed until several months after the other pieces of equipment. This was primarily due to delays in obtaining the parts necessary to connect the sensors to the datalogger.

During the first growing season, the irrigation system installed on the green roof was used. The roof was watered each morning, past the point of saturation. Because it was over watered, runoff would flow from the green roof every morning at approximately 8 A.M. The ultrasonic sensors recorded these flows. This occurred from shortly after the installation of the green roof through early October 2006. During this time period, the soil on the green roof was at or near saturation at all times. The water retention abilities of the roof were limited at this time because of the water in the soil from the irrigation. Because the system was on timers, irrigation even occurred in the middle of rain storms. This resulted in artificial peaks in green roof flow during the storm and an increase in the total flow volume for the green roof. Fortunately, due to the regularity of irrigation runoff, the irrigation interference is easily detectible. Data sets affected in this way were adjusted to eliminate the irrigation peaks that occurred during storms. This provides a close approximation of the runoff data. These storms are included in the overall analysis, but they are not discussed in detail because the data is not as exact as the other storms. Five storms were affected in this way.

Several sets of data were made completely unusable due to computer crashes. In the LabVIEW programming language, each program must be properly shut down to view the data it stored in various files. Part of the data is stored temporarily in the computer's memory while the program is running and is only written to file at the time the program is shut down. In several instances, the computer running the program was shut down or turned off without the programs being properly shut down. Despite efforts to recover this data, it was unusable. Three or four storms were lost in this manner.

Several key parameters are used as benchmarks when discussing storms in detail: flow rate, total flow volume, runoff reduction and runoff as rainfall. The flow rate and volume are calculated and recorded by the LabVIEW programming, as discussed in section 4.4.

Runoff reduction was calculated as the total green roof runoff volume divided by the same value from the control roof at a point in time. This is used to show how the effectiveness of water retention varies as a storm progresses.

$$\%\mathrm{Re}duction = \frac{V_G}{V_C} \cdot 100$$

Where, V_G = Total Green Roof Flow Volume [cf]

V_C = Total Control Roof Flow Volume [cf]

Runoff as rainfall is a parameter used to convert the total runoff volume at a point in time to an equivalent value of rainfall depth. Essentially, this is showing the depth of rainfall that became runoff. A simple comparison can show the water retention performance of the roof. This also provides runoff data on a unit area basis. In this instance, both the green and control roofs have the same surface area sloped to each roof drain, so direct comparisons could be made even without this conversion. However, data from other roofs can more easily be compared with the data in this form.

$$D_{equiv} = \left(\frac{V}{SA}\right) \cdot 12$$

Where, D_{equiv} = Equivalent Runoff Depth [in]

V = Total Runoff Volume [cf]

SA = Surface Area [sf]

5.2.1 August 27, 2006 Storm

The August 27, 2006 storm is first storm with both flow and rainfall data available for analysis. The storm lasted for a total of 15 hours and deposited 0.59 inches of rain on the roof. The storm is actually made up of two separate phases. In the morning, 0.08 inches of rain fell in about one and half hours. No runoff occurred on either roof during this time. Nine hours later, the remaining 0.51 inches of rain fell over nearly five hours. It is during this period that runoff occurred. Figure 41 through Figure 45 show the details of the storm.

In Figure 41, the pattern of runoff is shown to closely follow the rate of rainfall, with the control roof having a higher flow rate than the green roof. Figure 42 shows a closer view of the runoff flow rates during the storm. The flow pattern is actually made up of four individual peaks, each corresponding to a period of increased rainfall. During the first peak, the maximum flow from the control roof is approximately 0.015 cubic feet per second (cfs), while the green roof flow only reaches 0.0065 cfs during this same period. This is a reduction of 57 percent over the control. At the second peak of the storm, the control roof has reached a maximum flow rate of 0.022 cfs and the green roof reaches 0.014 cfs. The gap between the two roofs is closer, but the green roof flow is still 36 percent lower. It is also still less than the first peak for the control roof. The control roof reaches a maximum flow of 0.043 cfs during the third peak and 0.047 cfs during the final peak. The values for the green roof during these same periods of time are 0.028 cfs and 0.038 cfs, respectfully. This corresponds to a reduction of flow rate of 35 and 21 percent.

These results clearly show that the green roof is capable of reducing the flow rate of runoff, but that its effectiveness decreases as the storm progresses and the soil becomes saturated. The final peak of the storm represents the maximum for both roofs.

This storm saw only a very slight delay in runoff. Runoff began to flow from the green roof only two minutes after it began on the control. There is, however, a significant extension of flow from the green roof. Runoff flowed from the green roof at an extremely low rate for just over two and a half hours longer than the control roof. There is no significant delay between the peak flows from each roof, as the peaks occur at virtually the same point.

Looking at the storm as a whole, the control roof produced 147 cubic feet (cf) of runoff compared to the green roof's 116 cf. This is shown in Figure 43. This corresponds to overall reduction of runoff by the green roof of 20 percent. Figure 44 shows how the runoff reduction changes over the course of the storm. The reduction drops quickly from 100 to about 30 percent while it is raining. There is a much more gradual drop from 30 to 20 percent. This occurs mainly during the period after the storm when only small flow rates are observed. This also includes when only the green roof was producing runoff.

Finally, Figure 45 shows the runoff as equivalent inches of rainfall. This is the same data presented in Figure 46, but in a different form. It can be seen that the rate of runoff closely follows the rainfall rate. At the end of the storm, the equivalent of 0.40 inches of runoff was produced by the green roof compared with 0.50 inches on the control. This corresponds to a 32 percent retention rate by the green roof. For the control roof, only 15 percent is retained. If only the second section of rainfall is considered, when 0.51 inches of rain fell, 98 percent of the rain became runoff on the control roof while only 2 percent was retained.

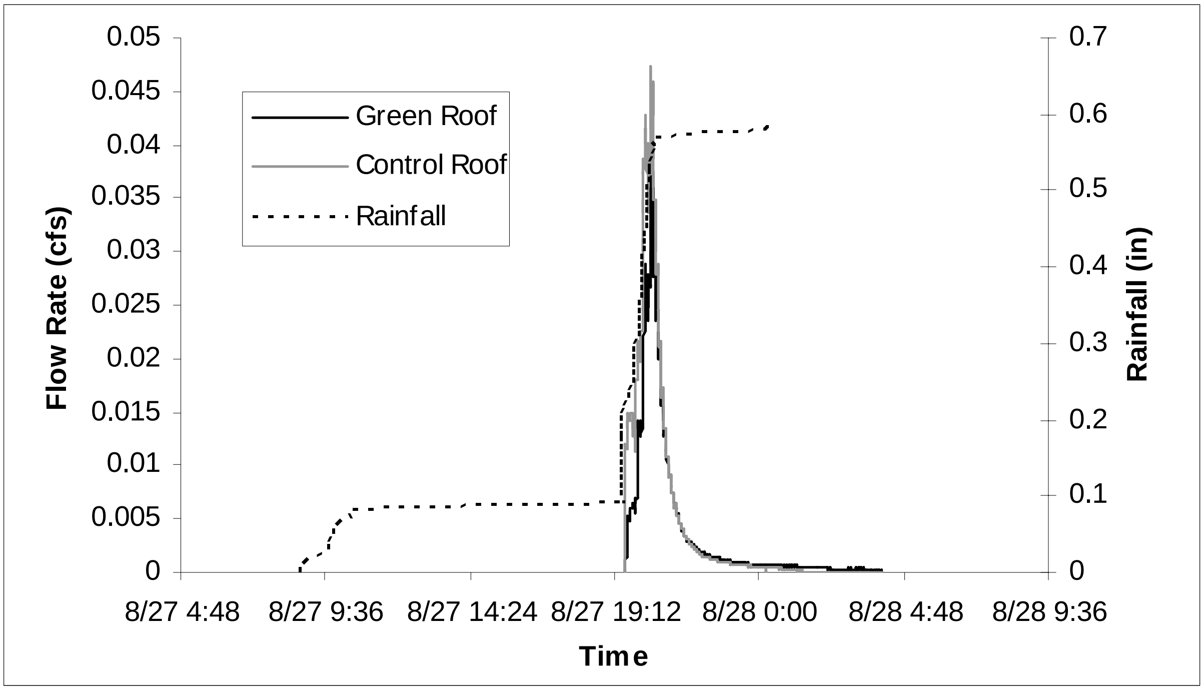

Figure 41 - Runoff Flow Rates - August 27, 2006 Storm

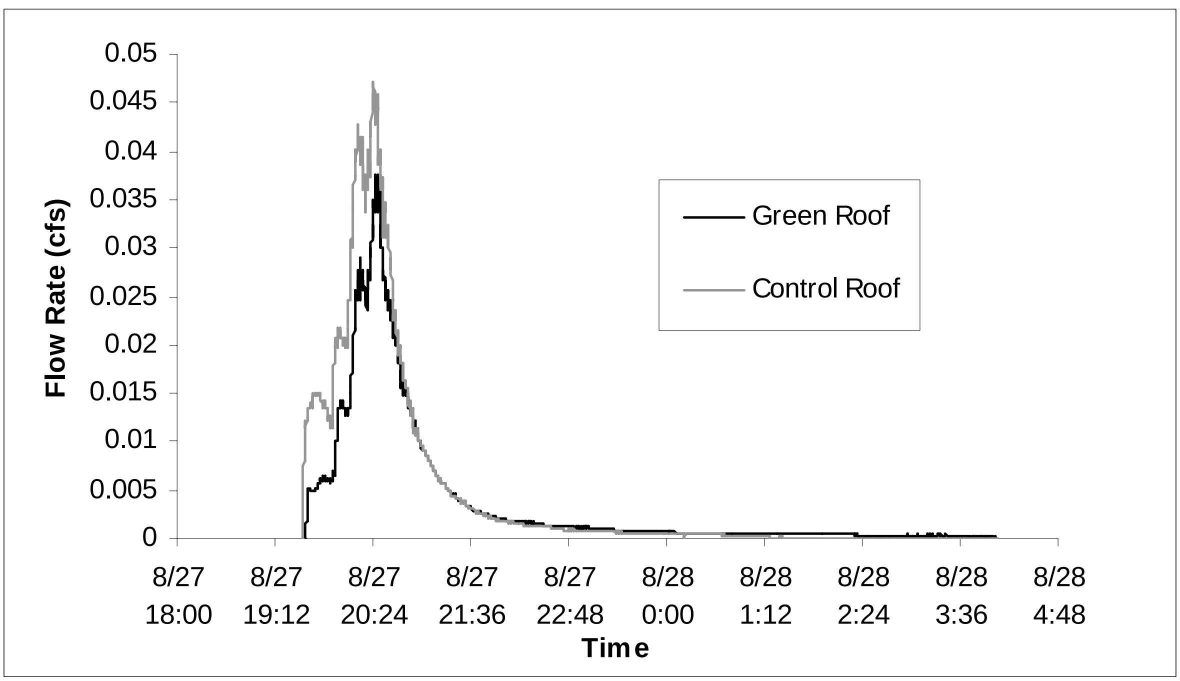

Figure 42 - Runoff Flow Rate Detail - August 27, 2006 Storm

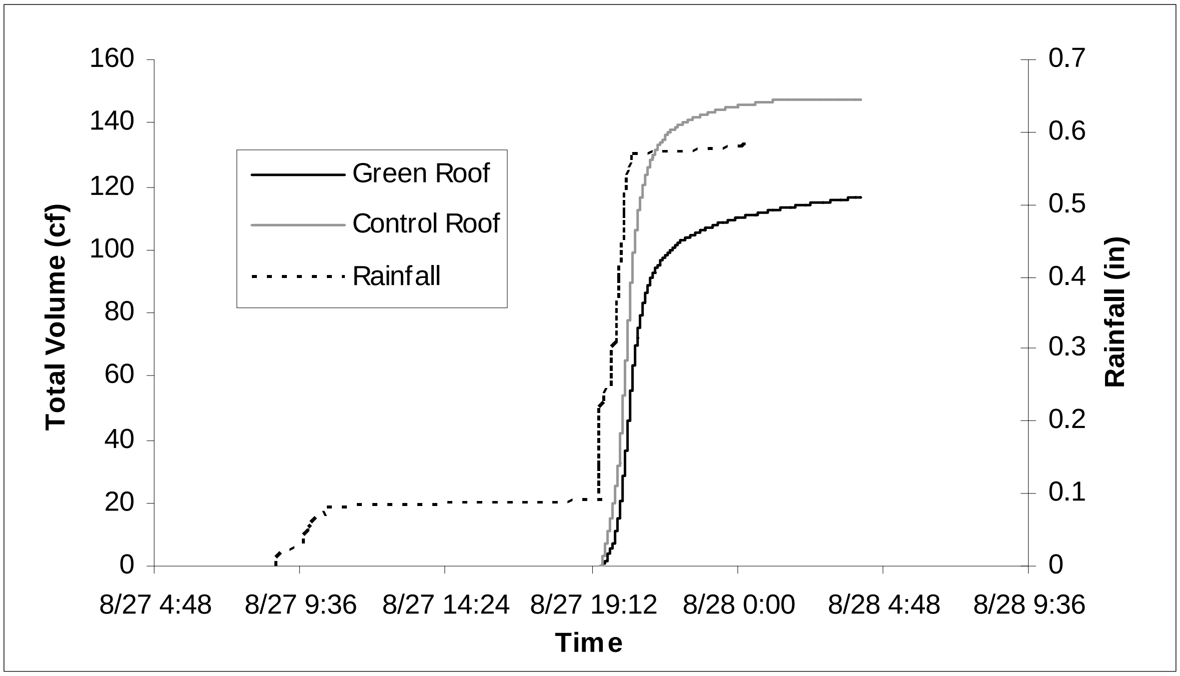

Figure 43 - Runoff Volumes - August 27, 2006 Storm

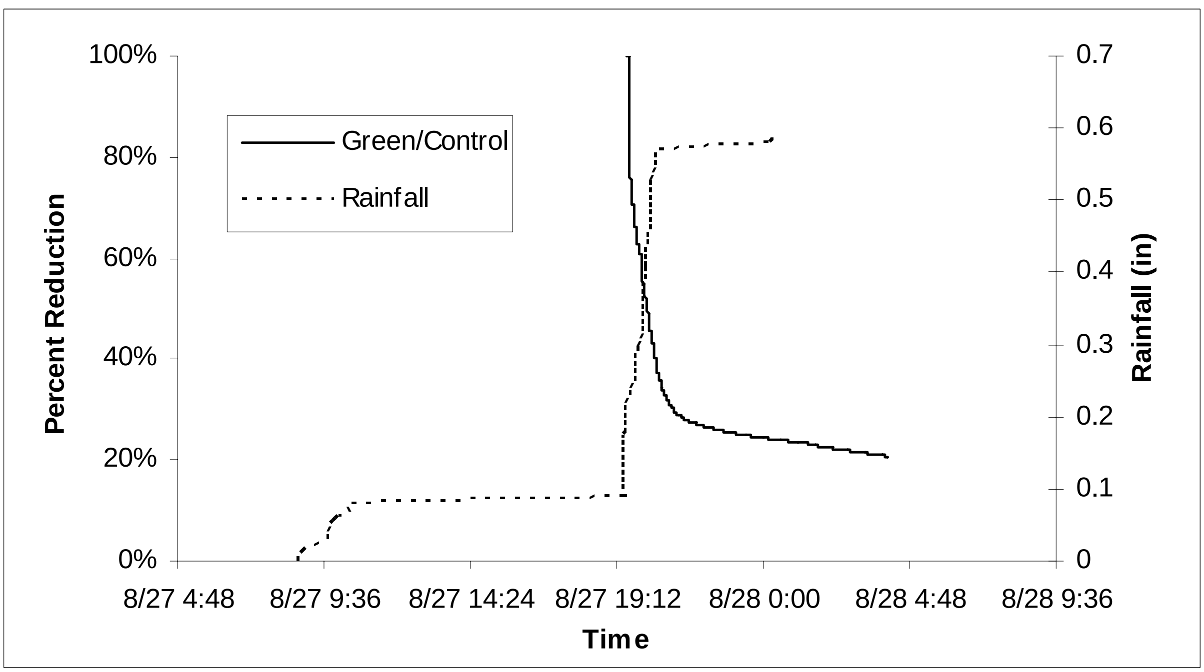

Figure 44 - Runoff Reduction - August 27, 2006 Storm

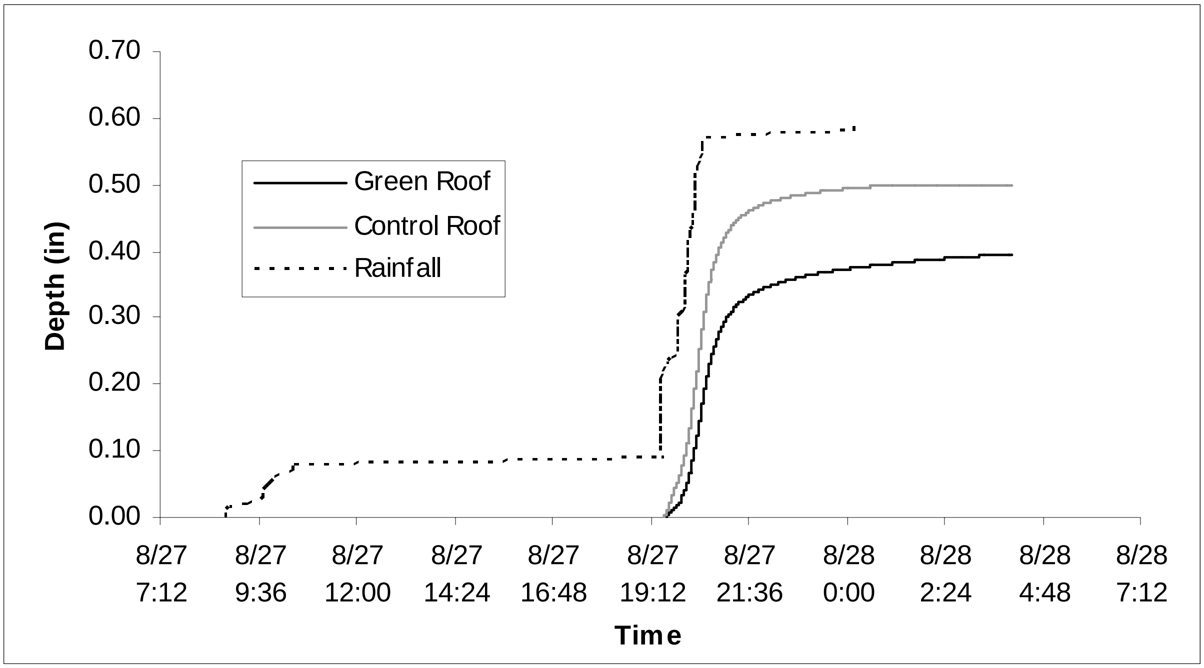

Figure 45 - Runoff as Rainfall - August 27, 2006 Storm

5.2.2 October 17, 2006 Storm

The October 17, 2006 storm was the second largest experienced during the monitoring period. 1.94 inches of rain fell over about 10 hours. The 0.19 inches per hour intensity during this portion of the storm corresponds to roughly a 5 year storm for the Pittsburgh area. This is the first storm that occurred after the irrigation system was turned off for the winter. Water content data is also available beginning with this storm.

Figure 46 shows the runoff flow rates throughout the storm for both roofs. A number of factors are evident. First, there is a 21 minute delay from the time the control roof begins to produce runoff to the time it begins to flow from the green roof. When runoff does begin to flow from the green roof, it was already raining for just over three hours. There is also an extension of flow at the conclusion of the storm. Runoff continued to flow from the green roof for four hours and forty five minutes longer than the control roof, at a very low rate.

The difference in flow rate changes during the course of the storm. Early on, there is a very significant difference. When the control roof hits its first peak, its flow rate is 0.016 cfs. At that same time, the green roof is only at 0.0019 cfs, or 88 percent less. As the soil becomes more saturated, the flow rates become much closer. By the end of the storm, they are nearly identical. For the entire storm, the maximum green roof flow rate (0.042 cfs) was 29 percent lower than the control roof (0.059 cfs). There is no significant delay between the peak flows from each roof, as the peaks occur at virtually the same point.

The total volume of runoff during the storm is shown in Figure 47. The green roof produced 414 cf of runoff compared to 514 cf for the control. This 100 cf difference results in a 19 percent reduction by the green roof. Figure 48 shows how the reduction changed during the storm. Despite being over three times greater in intensity than the August 27, 2006 storm, the runoff volume reduction by the green roof bottoms out at about 20 percent. Both storms also see a drastic decrease in the rate of reduction after the rainfall stops.

Figure 49 shows the equivalent inches of rainfall that became runoff for each roof. For the green roof, 1.41 of the 1.94 inches of rainfall became runoff. For the control roof, the figure is 1.75 of 1.94 inches.

The volumetric water content for two locations on the green roof is shown in Figure 50. Location A is situated next to the roof drain that is monitored for flow. Location B is on the opposite side of the roof. Both are located near the tripods that hold the temperature equipment. At the start of the storm, both locations have an identical water content of 16 percent by volume. These reach their maximum at 20.6 percent at location A and 19 percent at location B at about the time the green roof reaches its peak runoff flow rate. The water content began to steadily decline at the point the bulk of the rain had stopped falling, reaching values of 18 and 17 percent water by volume by the time runoff stopped flowing from the green roof.

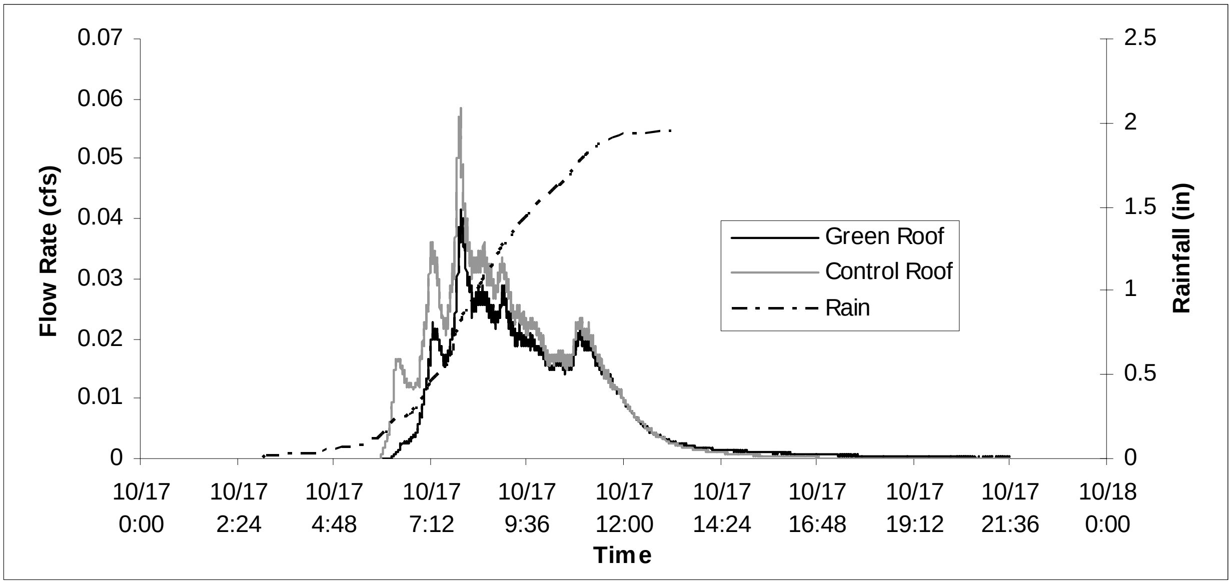

Figure 46 - Runoff Flow Rates - October 17, 2006 Storm

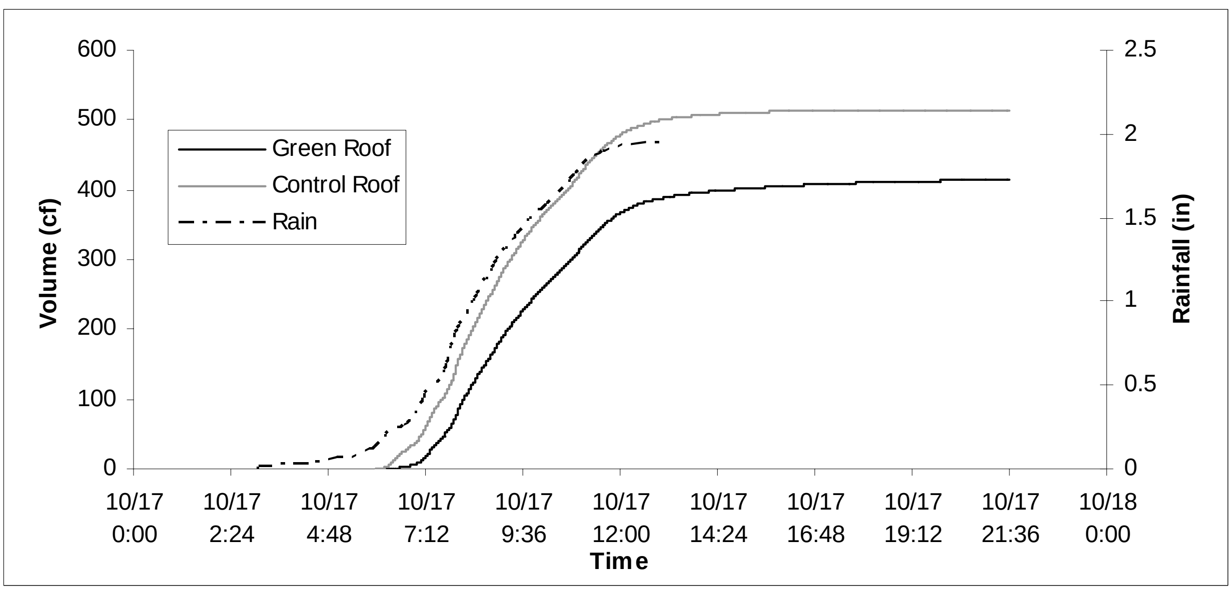

Figure 47 - Runoff Volumes - October 17, 2006 Storm

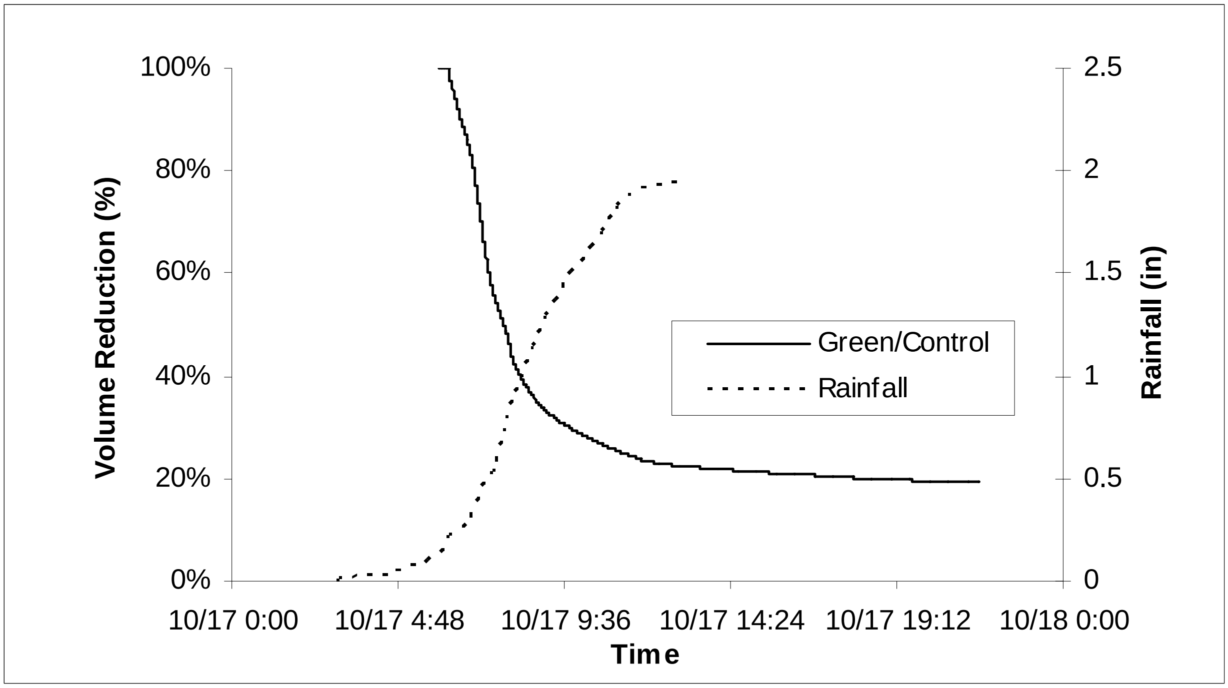

Figure 48 - Runoff Reduction - October 17, 2006 Storm

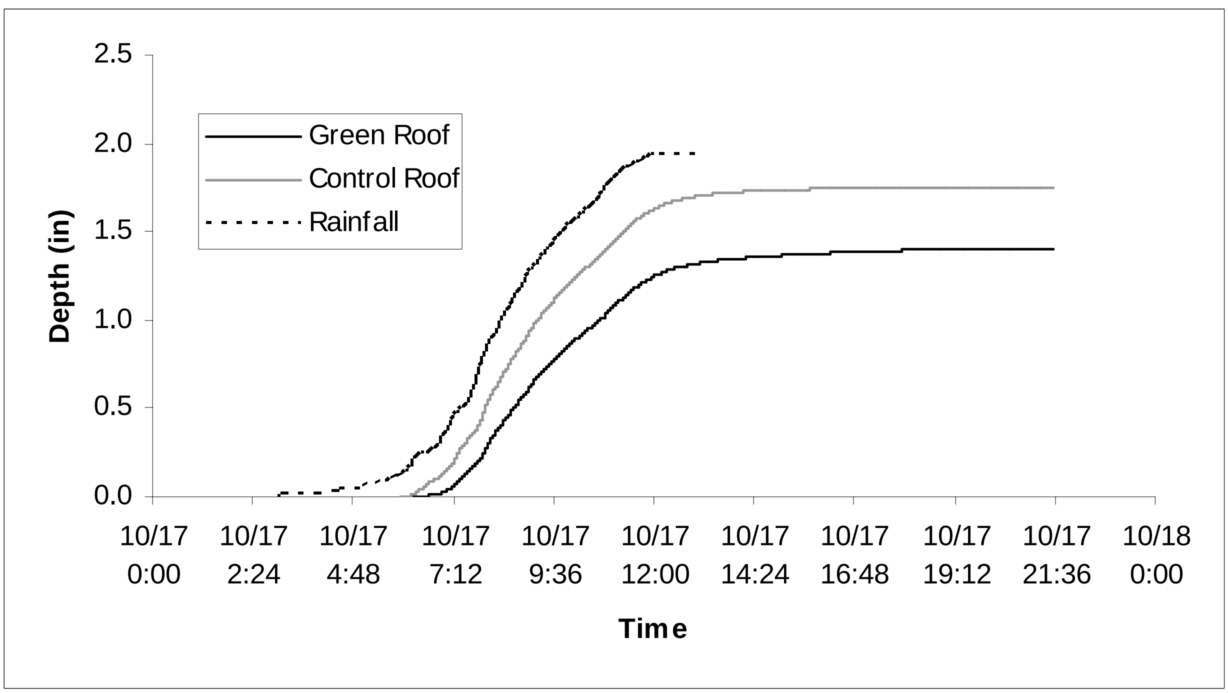

Figure 49 - Runoff as Rainfall - October 17, 2006 Storm

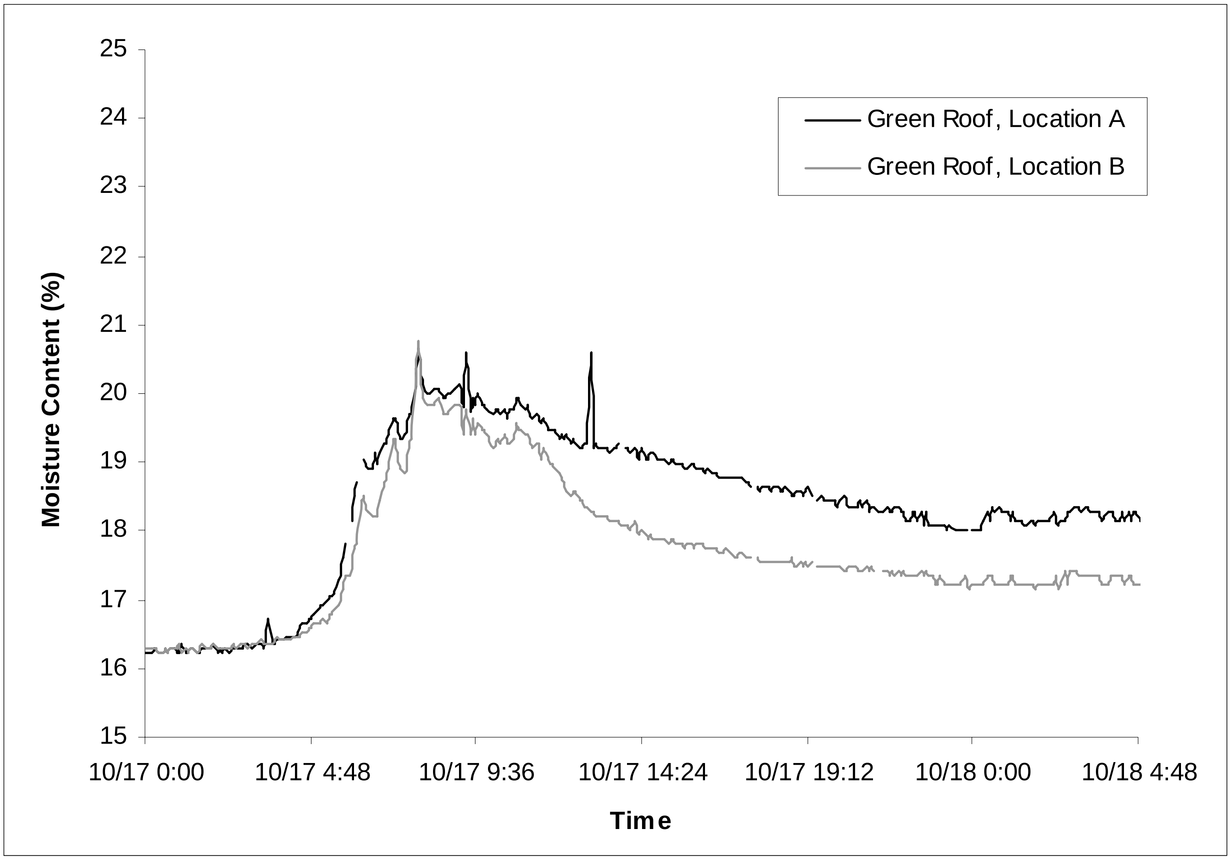

Figure 50 - Green Roof Water Content - October 17, 2006 Storm

5.2.3 October 27, 2006 Storm

The October 27, 2006 storm was also fairly large, depositing 1.2 inches of rain on the Giant Eagle roofs over a 24-hour period.

Figure 51 shows the change in runoff flow rate throughout the storm. In this case, a 30 minute delay in runoff occurred between the times the green and control roofs began producing runoff. It was a full three hours after the rain began that runoff began to flow off the green roof.

For this storm, the green roof again had a lower maximum flow rate of 0.018 cfs compared to 0.022 cfs for the control roof. This is a 16 percent reduction. Like the previous storms, the difference in flow rates is greatest at the start of the storm and the two values converge as the storm goes on. In this instance, they are nearly identical after about 0.65 inches of rain fell. There is no significant delay between the peak flows from each roof, as the peaks occur at virtually the same point.

Over the course of the storm the green and control roofs produced 281 cf and 343 cf of runoff, respectively. The green roof reduced the total volume by 18 percent, as seen in Figure 52. Figure 53 shows how the reduction in runoff volume changes over the course of the storm. Like the previous two storms, it bottoms out near 20 percent and the rate of reduction drops dramatically after the rainfall stops. The reduction drops at a slower for this storm than the others, however, likely due to a slower rate of rainfall.

In Figure 54, the runoff volumes are shown as equivalent inches of rainfall. The green roof produced 0.96 inches of runoff from 1.2 inches of rainfall, while the control roof produced 1.17 inches.

The volumetric water content of the green roof began at 15.8 percent at location A and 15.9 percent at location B, as shown in Figure 55. The values reach a peak of 20.3 and 17.8 percent before dropping to 18.2 and 17.5 percent by the time runoff ceased flowing from the green roof.

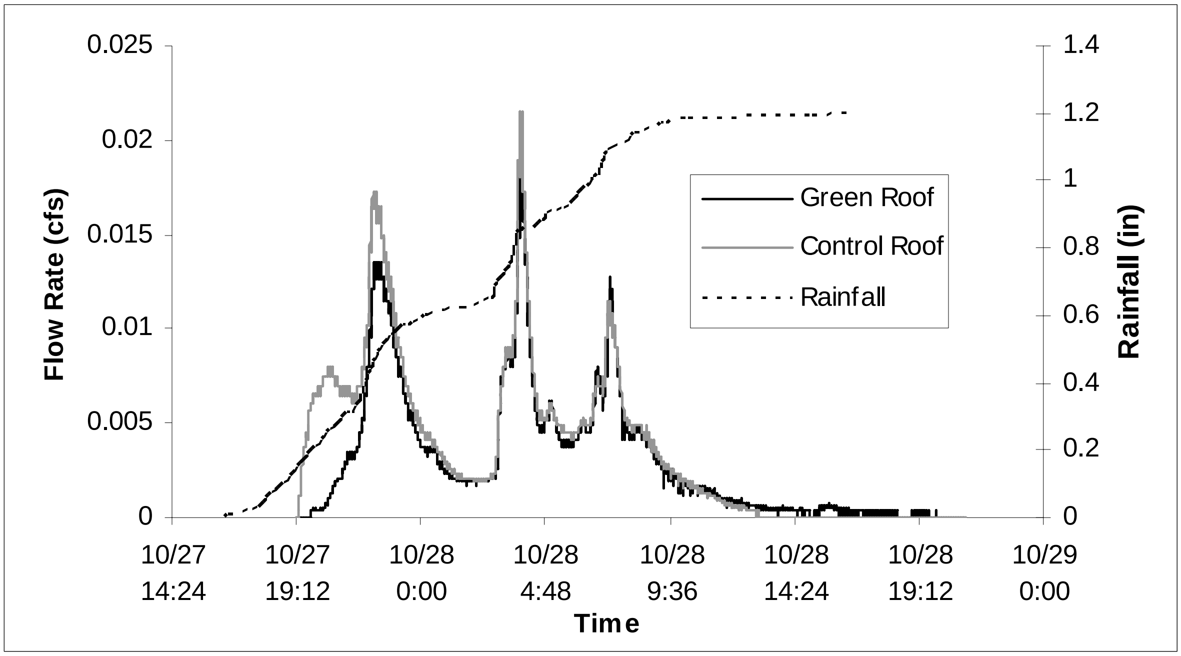

Figure 51 - Runoff Flow Rates - October 27, 2006 Storm

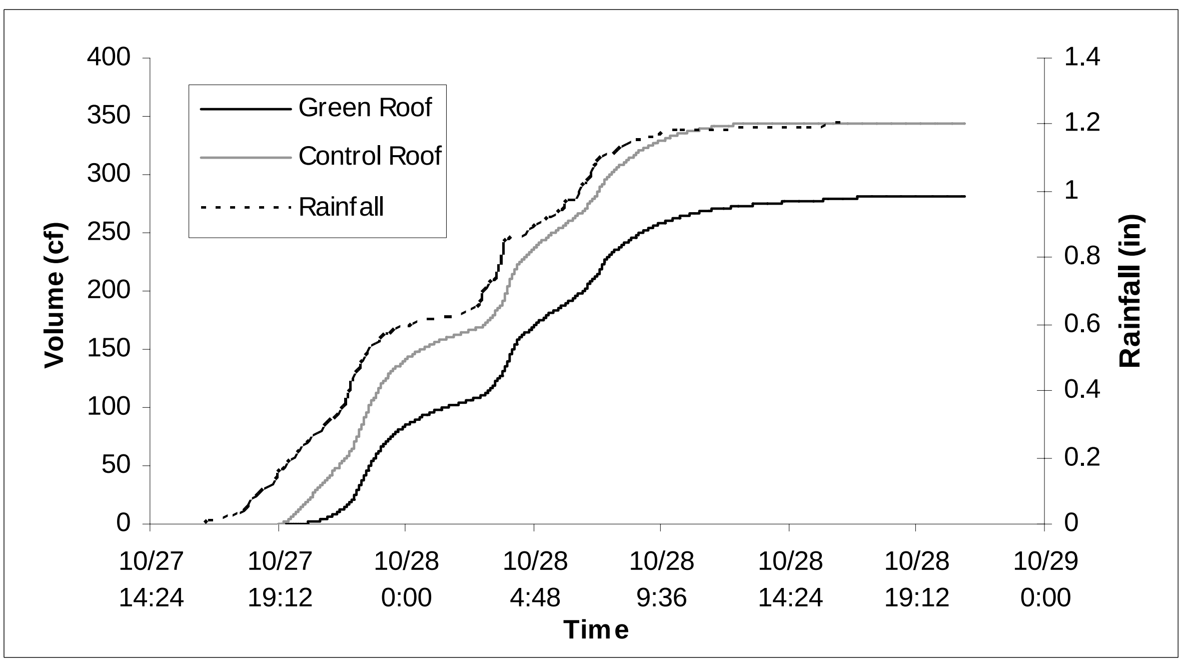

Figure 52 - Runoff Volumes - October 27, 2006 Storm

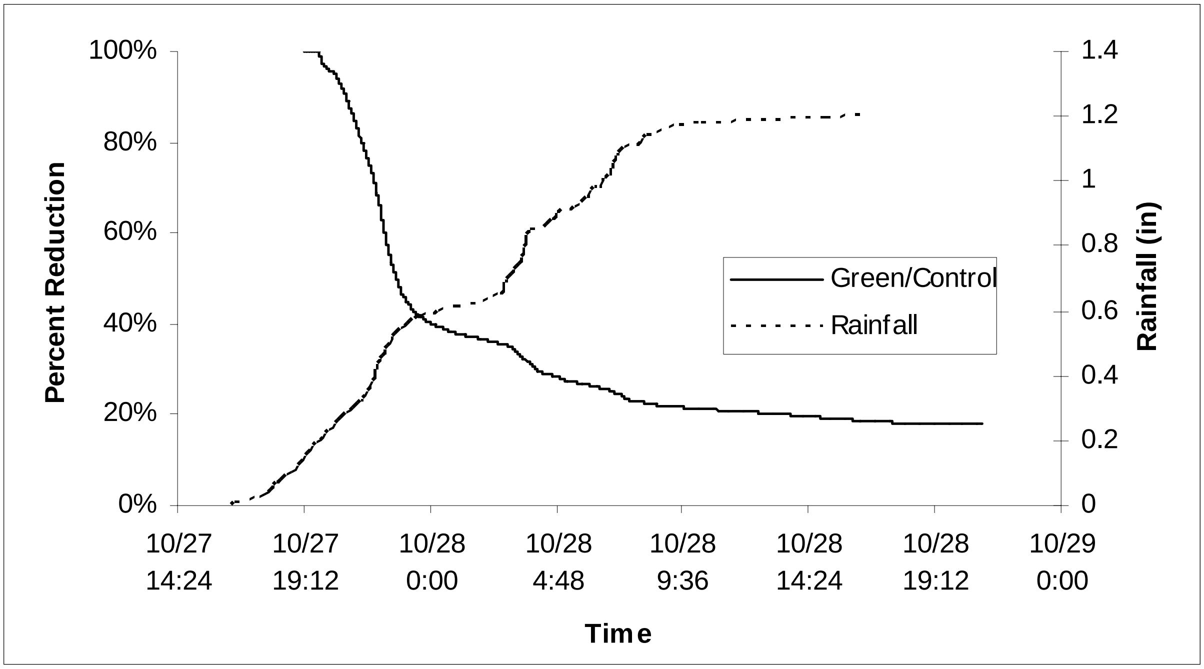

Figure 53 - Runoff Reduction - October 27, 2006 Storm

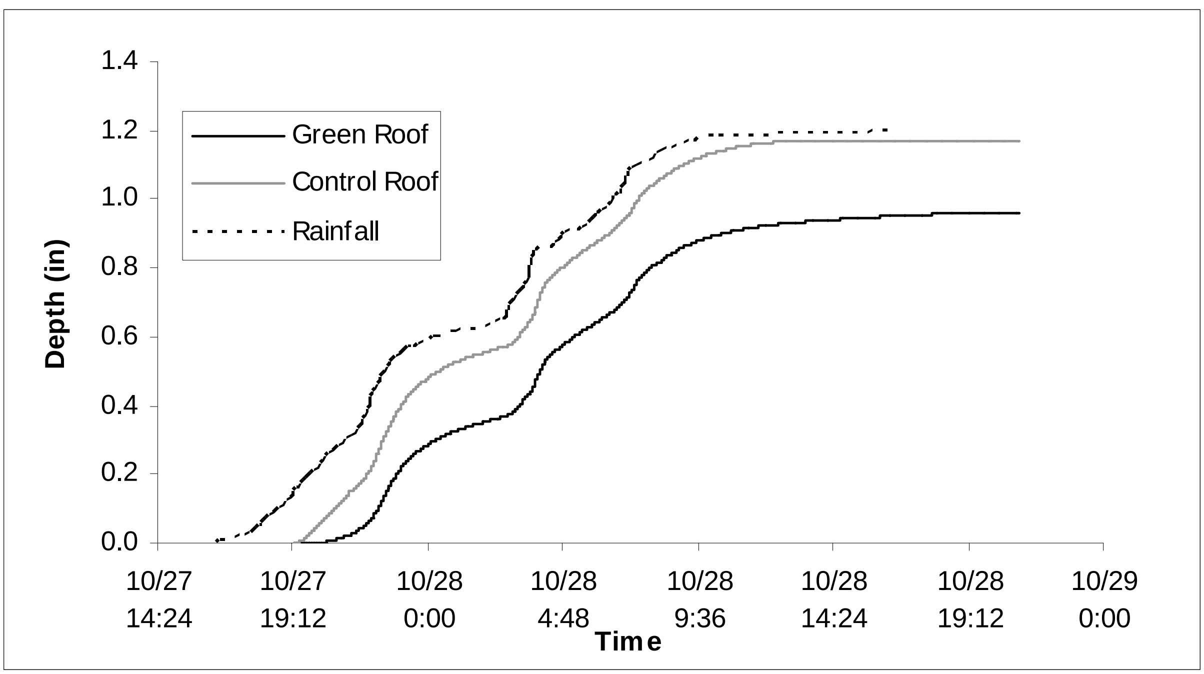

Figure 54 - Runoff as Rainfall - October 27, 2006 Storm

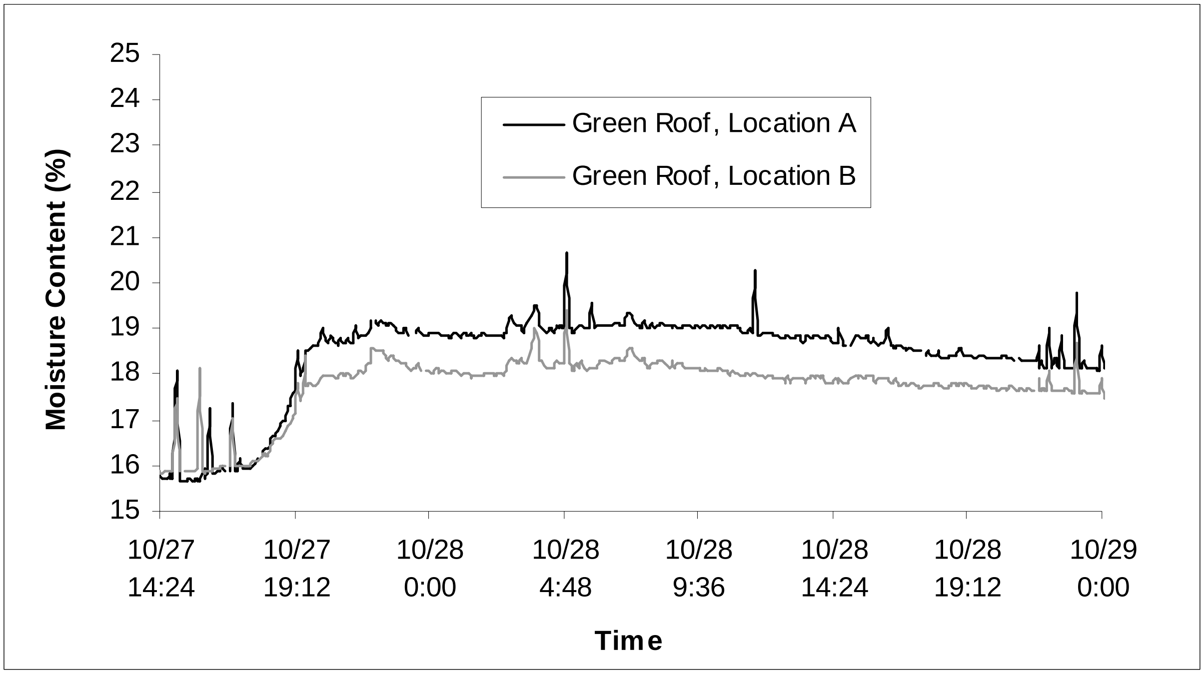

Figure 55 - Green Roof Water Content - October 27, 2006 Storm

5.2.4 October 31, 2006 Storm

The October 31, 2006 storm is the event that most closely resembles the average volume of rainfall for Pittsburgh of 0.25 inches (BBC 2007). A total of 0.19 inches of rain fell in approximately 5 and a quarter hours.

Figure 56 shows the runoff flow rates throughout the storm. There is a runoff of delay of twenty five minutes for the green roof compared to the control. This is also three hours after the rainfall started. In this instance, there is no extension of runoff. The green roof actually stops first, but the flow only continues for an additional 10 minutes on the control roof. Like the other storms, the green roof significantly reduces the flow rate. The maximum value is 0.001 cfs for the green roof, 70 percent lower than the control roof's 0.0035 cfs. The difference is still greatest at the start of the storm, but the lighter intensity of rainfall does not allow the two values to converge.

There is an approximately two hour delay from the time the control roof reaches its maximum flow rate to the time the green roof reaches its maximum. In both instances, the peak flow rate is sustained for several minutes.

The control roof produced 36 cf of runoff for the entire storm, compared to 11 cf for the green roof. This 69 percent reduction can be seen in Figure 57. The reduction only changes gradually during the course of the storm (Figure 58).

Of the 0.19 inches of rainfall, the green roof produced the equivalent of 0.04 inches of runoff and the control produced 0.12 inches. This is shown in Figure 59. For both roofs, a much lower percentage of rainfall was converted to runoff for this lower intensity storm.

Figure 60 shows the volumetric water content throughout the storm. The values start at 18.6 and 16.2 percent at locations A and B. The peak is 28.1 percent at location A and 19.27 percent at location B. By the end of the storm, levels had decreased to 24.2 percent and 17.1 percent, respectively.

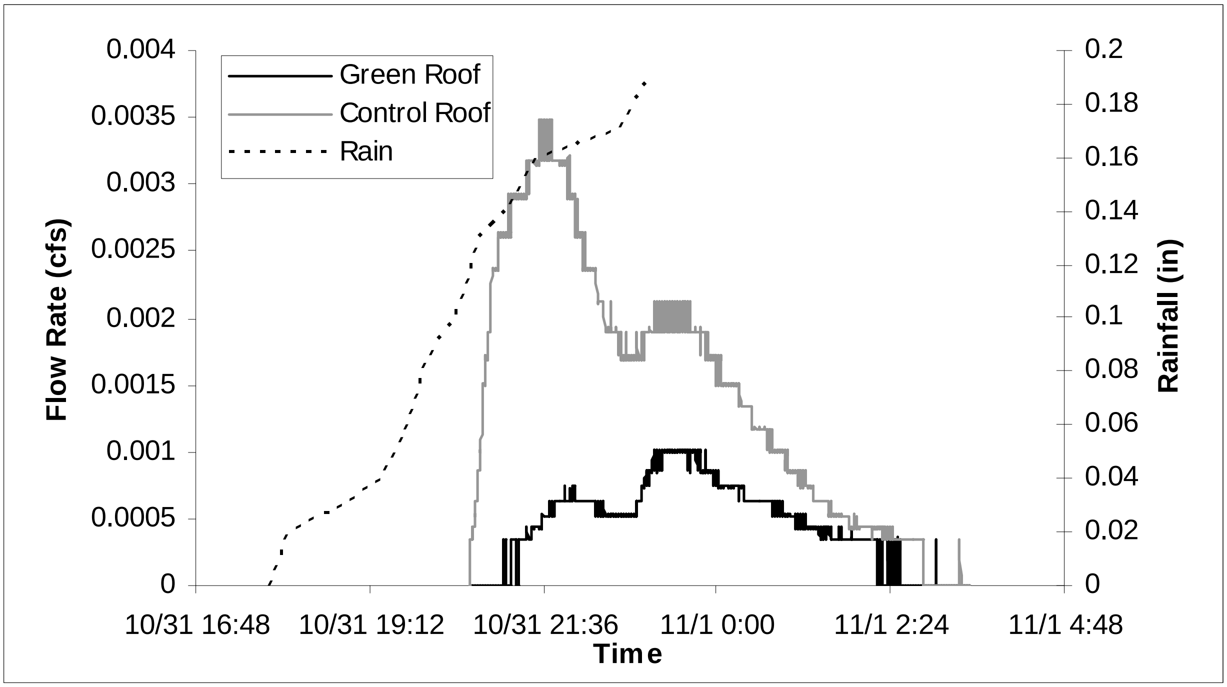

Figure 56 - Runoff Flow Rates - October 31, 2006 Storm

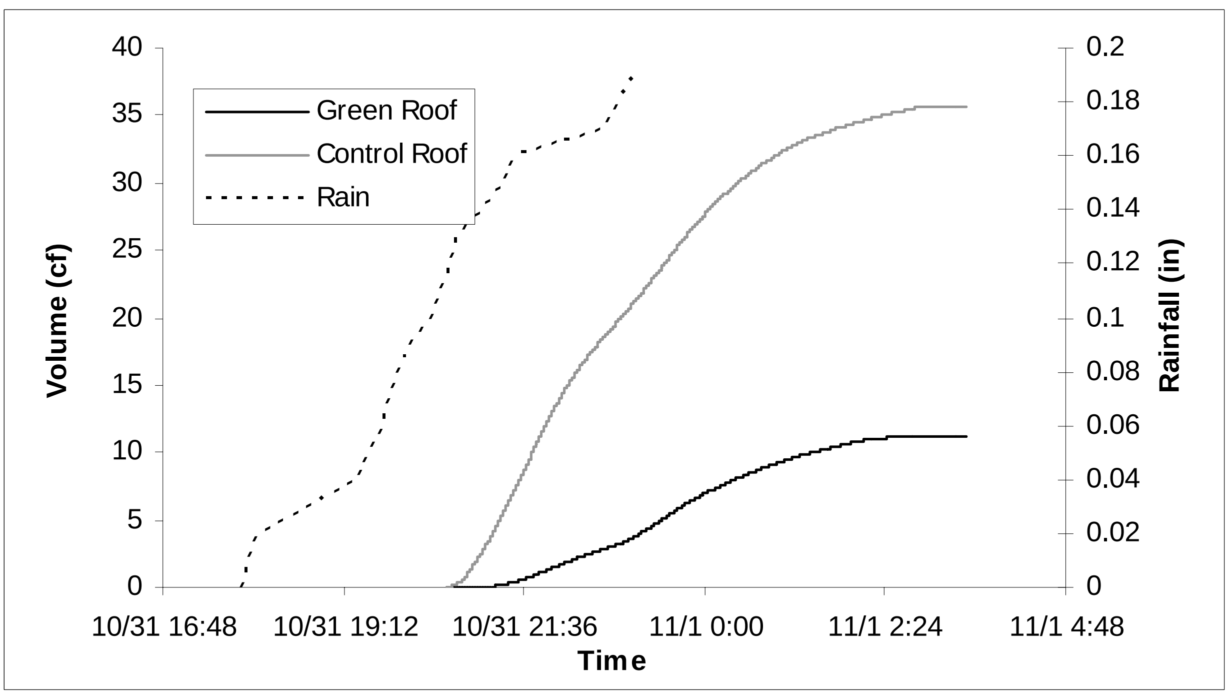

Figure 57 - Runoff Volumes - October 31, 2006 Storm

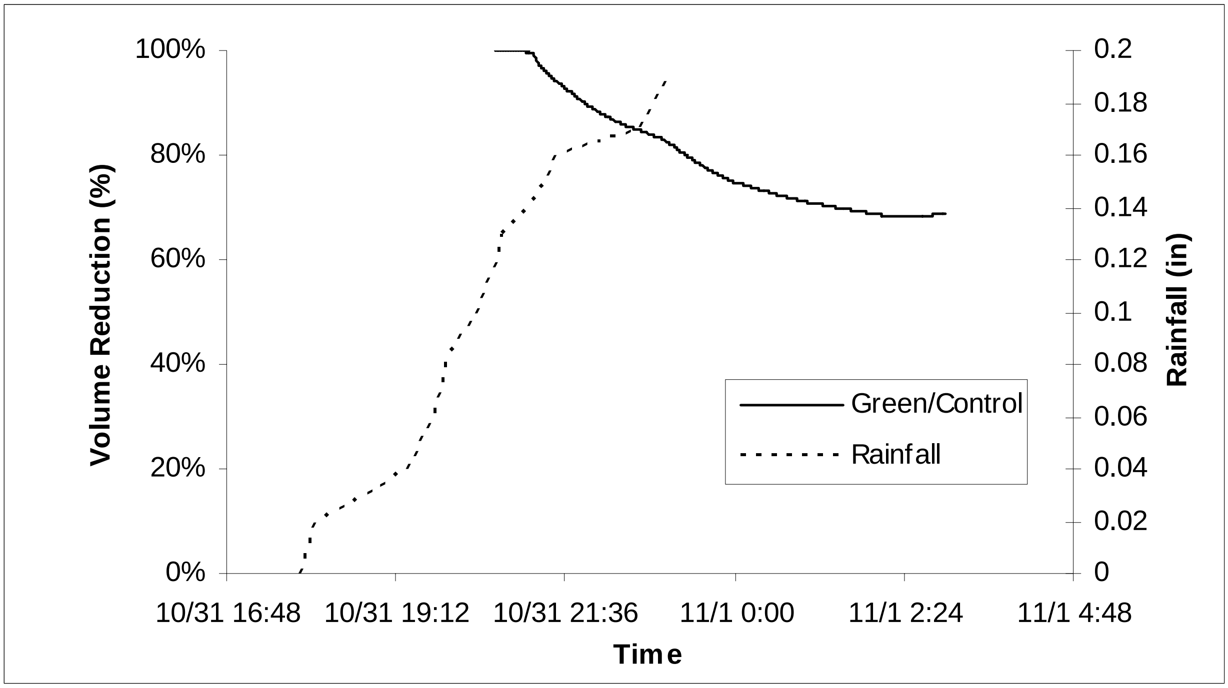

Figure 58 - Runoff Reduction - October 31, 2006 Storm

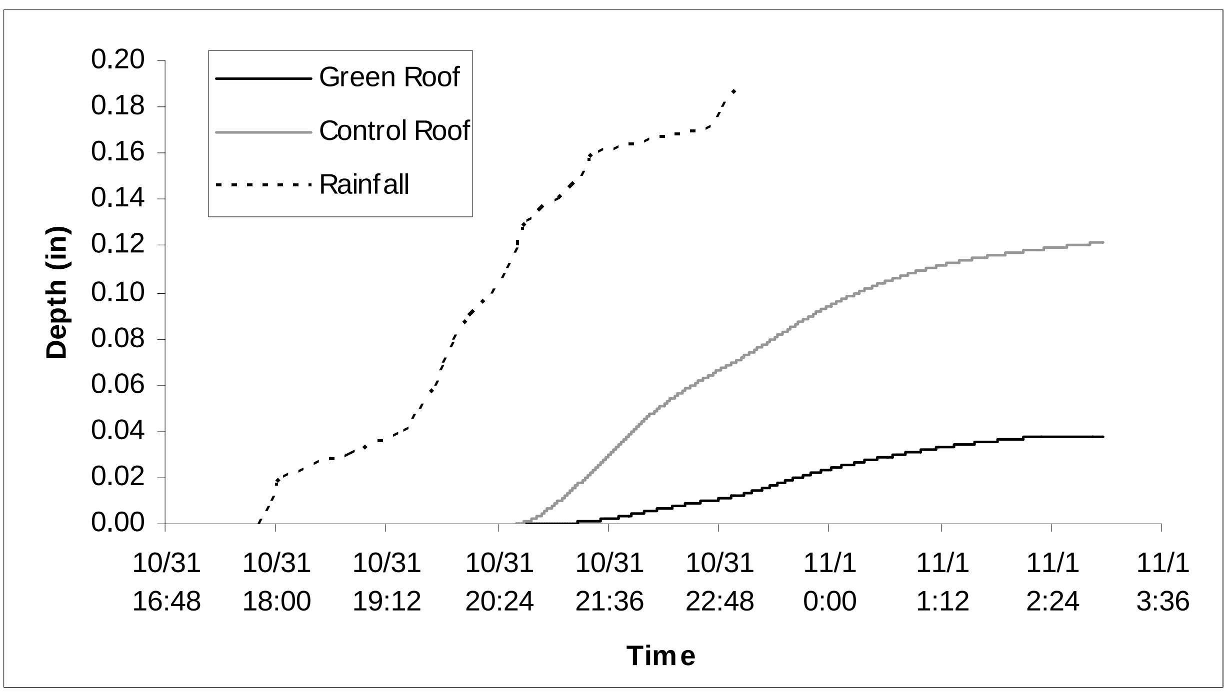

Figure 59 - Runoff as Rainfall - October 31, 2006 Storm

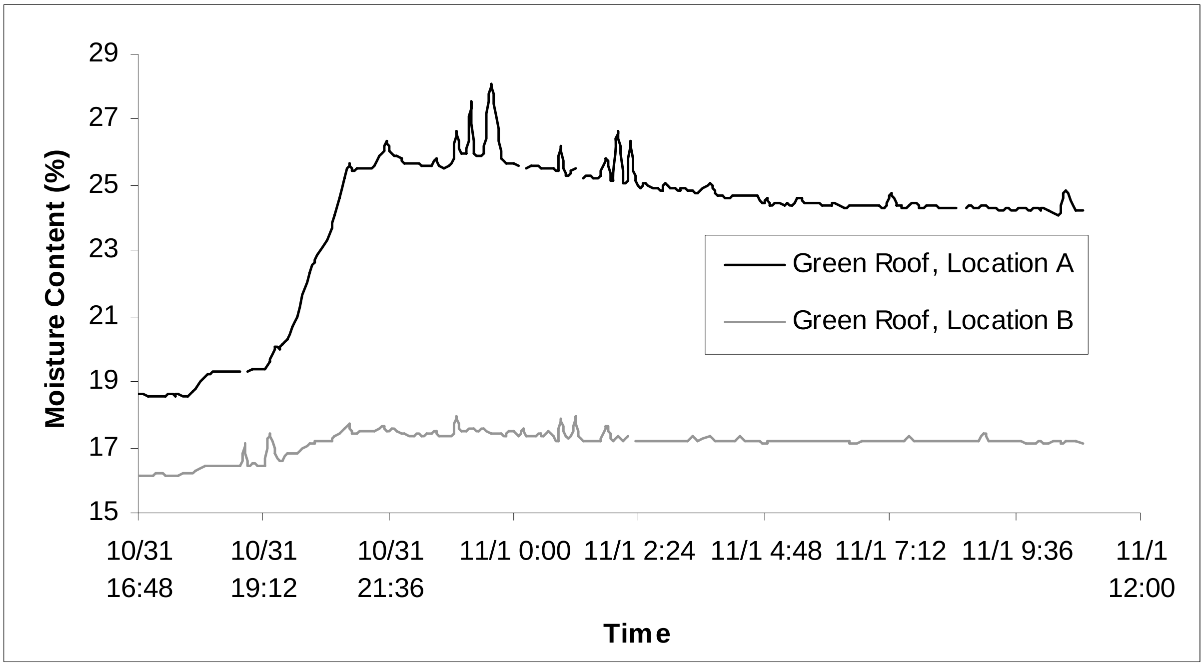

Figure 60 - Green Roof Water Content - October 31, 2006 Storm

5.2.5 November 1, 2006 Storm

The lightest intensity storm observed during the study period was the 0.07 inch storm on November 1, 2006. It was also one of the shortest duration storms, at just over two hours.

Figure 61 shows the runoff flow rates throughout the storm. Unlike the previous instances, the green roof began producing runoff first and stopped prior to the control roof. There is a 50 minute delay between the time rain began to fall and runoff began to flow off of the green roof, however. The second major difference between this storm and the previous ones is that there is a single peak in flow. The flow rates themselves are very small, with a maximum of 0.0005 cfs for the green roof and 0.0009 for the control roof. This corresponds to a 38 percent reduction by the green roof.

The green roof does not delay the peak runoff for this storm. The green roof peak actually occurs one hour and 49 minutes before the control roof, although it is still lower.

The total flow volumes are shown in Figure 62. Only small amounts of runoff were produced by either roof, but there is still a 69 percent reduction by the green roof. 10.1 cf of runoff were produced by the control roof; 3.4 cf was produced by the green. This is the largest reduction in flow volume by any observed storm. Figure 63 shows the change in reduction over the course of the storm. The green roof produced runoff first, so there is actually an increase in runoff for a time at the beginning of the storm. By the end of the storm, however, there is a clear reduction by the green roof.

Figure 64 shows the equivalent inches of runoff created by each roof. Of the 0.07 inches of rain, only 0.01 inches became runoff for the green roof. This figure is 0.03 inches for the control.

Finally, Figure 65 shows the change in volumetric water content in the green roof soil. At location A, the water content starts at a value of 23.4 percent, peaks at 28.4 percent and is at 25.0 percent by the conclusion of the storm. The corresponding values for location B are 16.9, 17.7 and 17.23 percent.

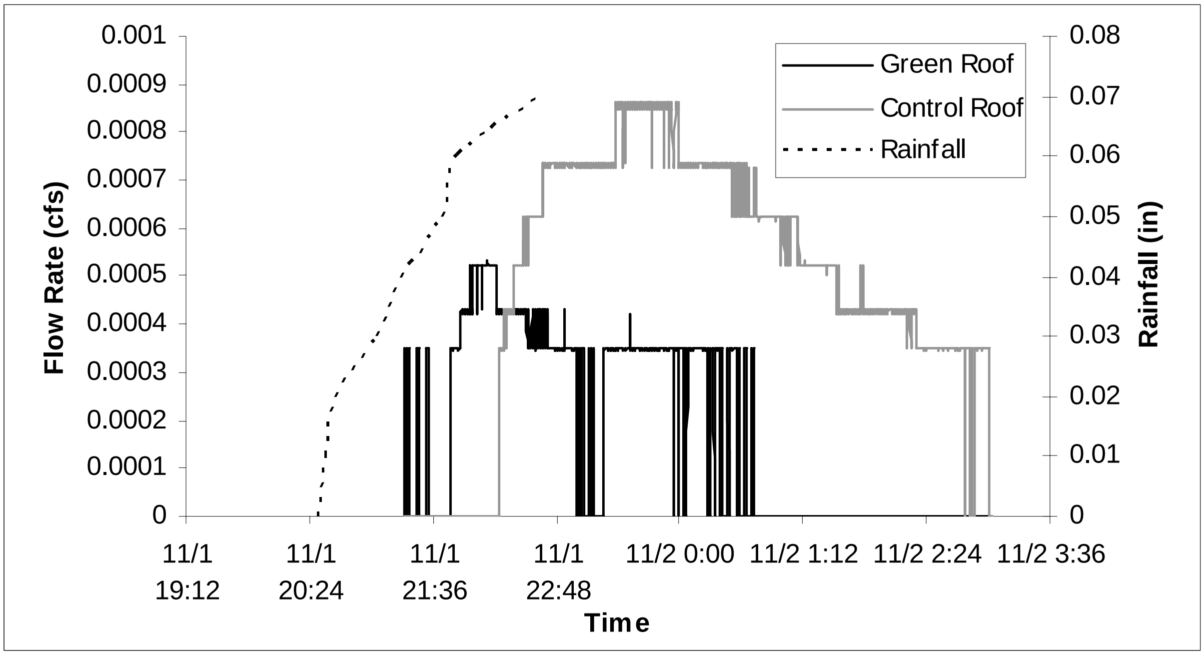

Figure 61 - Runoff Flow Rates - November 1, 2006 Storm

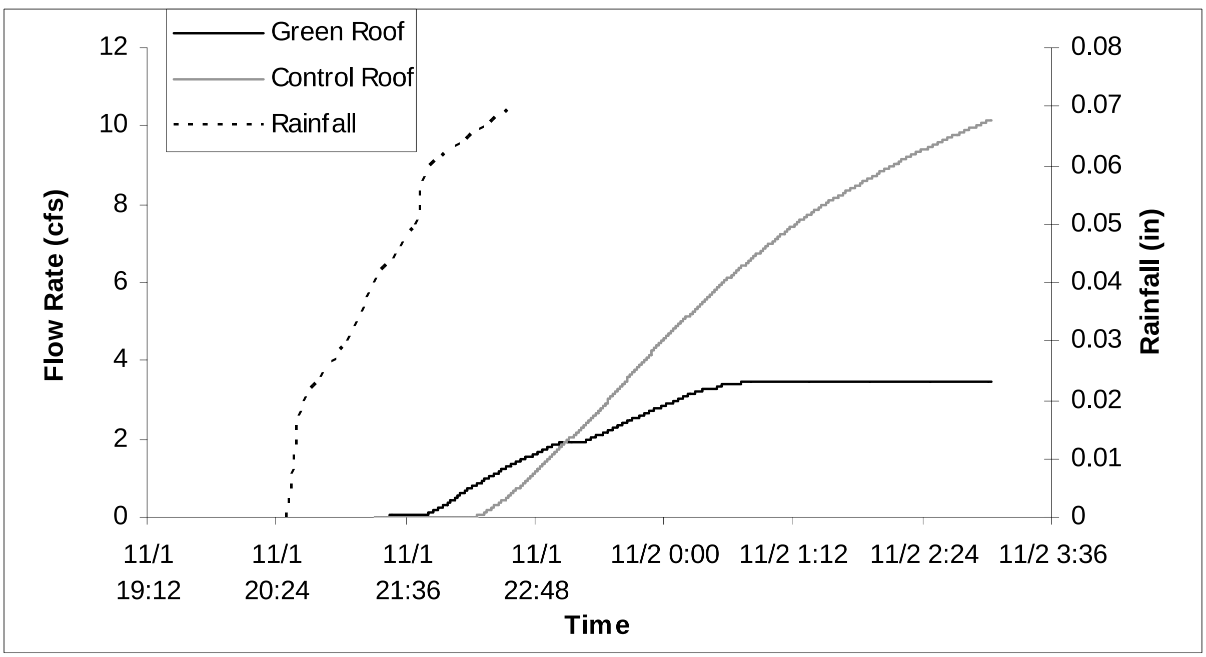

Figure 62 - Runoff Volumes - November 1, 2006 Storm

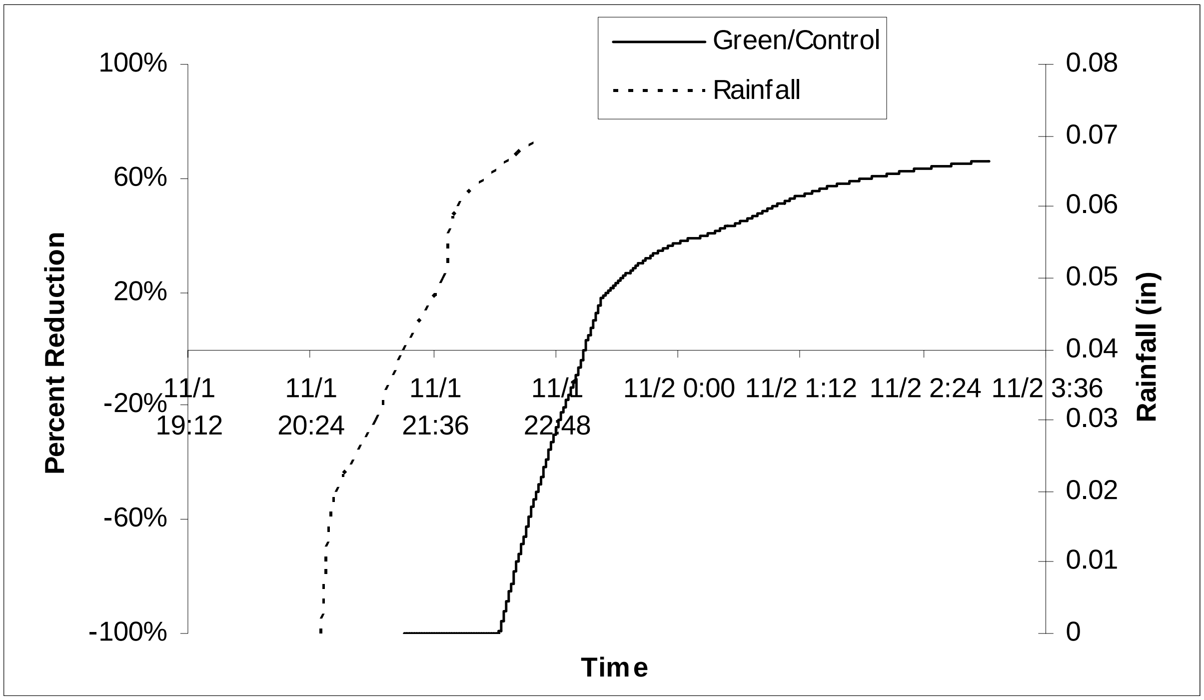

Figure 63 - Runoff Reduction - November 1, 2006 Storm

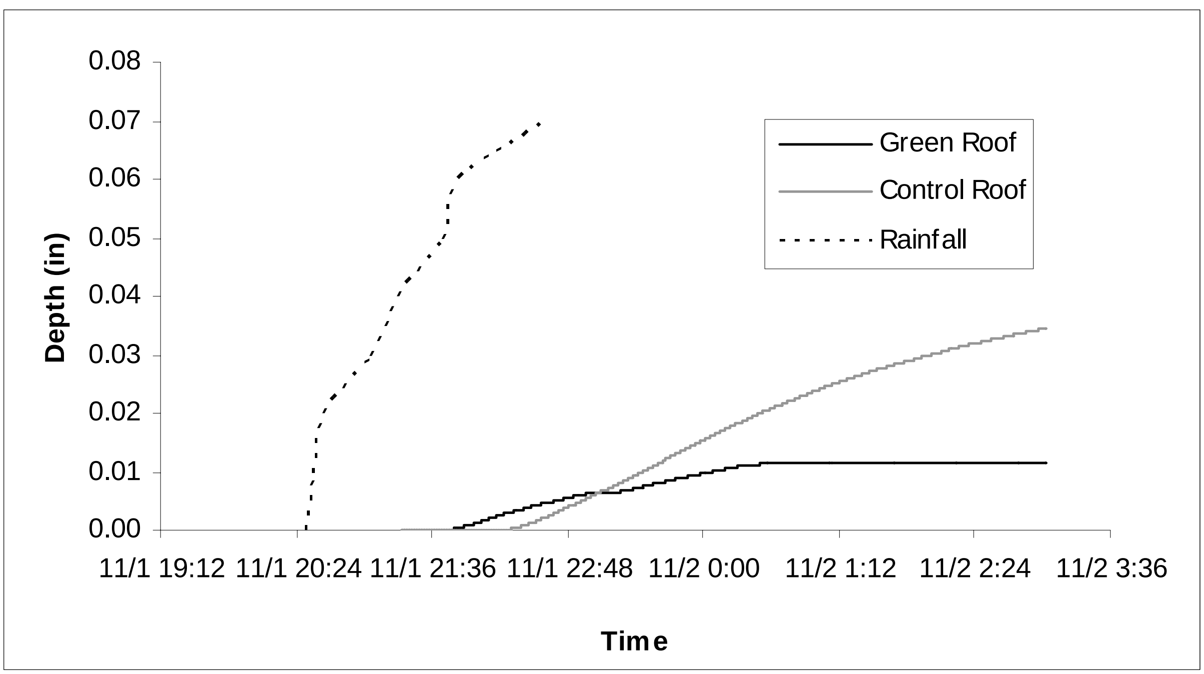

Figure 64 - Runoff as Rainfall - November 1, 2006 Storm

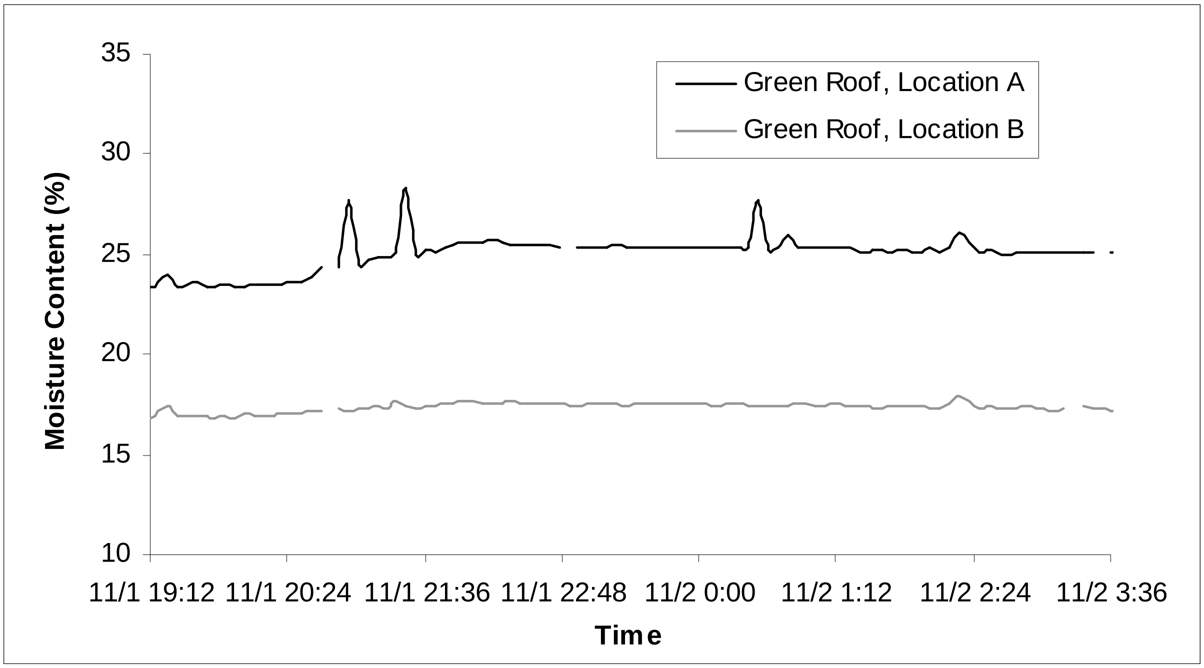

Figure 65 - Green Roof Water Content - November 1, 2006 Storm

5.2.6 November 11, 2006 Storm

The final storm shown in detail has the most significant difference between the green and control roofs in terms of flow rate. The November 11, 2006 storm resulted in 0.57 inches of rain being deposited on the Giant Eagle roof over an approximately 15-hour period. The storm was made up of three periods of heavier rain interspersed with lighter rainfall.

In Figure 66, the runoff flow volumes are shown throughout the storm. The control roof begins to produce runoff during the first period of heavier rain, about one hour and ten minutes after the rainfall begins. The green roof, however, does not begin to produce runoff until four hours and ten minutes later (nearly five and a half hours after the storm began). This is the longest delay observed during the project. There is also a very significant difference in flow rate between the two roofs when the control peaks. When the control roof reaches its storm maximum of 0.024 cfs, the green roof is only at 0.0065 cfs (a 73 percent reduction). The maximum for the green roof over the entire storm is 0.016 cfs, still 30 percent less than the control roof maximum. As with most of the other storms, the gap between the flow rates decreases as the storm progresses. By the time the green roof has reached its maximum, the flow rates for the two roofs are nearly identical. At the end of the storm, runoff continues to flow from the green roof for an additional three hours and ten minutes after it has stopped on the control roof.

There is a significant delay between the time the control roof and the green roof reach their respective peak flows. The green roof reaches its peak approximately two hours later.

At the conclusion of the storm, the control roof has produced 134 cf of runoff while the green roof has produced 94 cf. This 30 percent reduction can be seen in Figure 67. Figure 68 shows how this changes during the course of the storm. Unlike the other storms discussed, there is a long period at the start of the storm with a 100 percent reduction in flow volume. It then decreases rapidly in two stages, corresponding the later two periods of heavier rain.

The equivalent inches of rainfall can be seen in Figure 69. Of the 0.57 inches of rainfall, 0.32 inches became runoff on the green roof. For the control roof, 0.46 inches of the 0.57 inches became runoff.

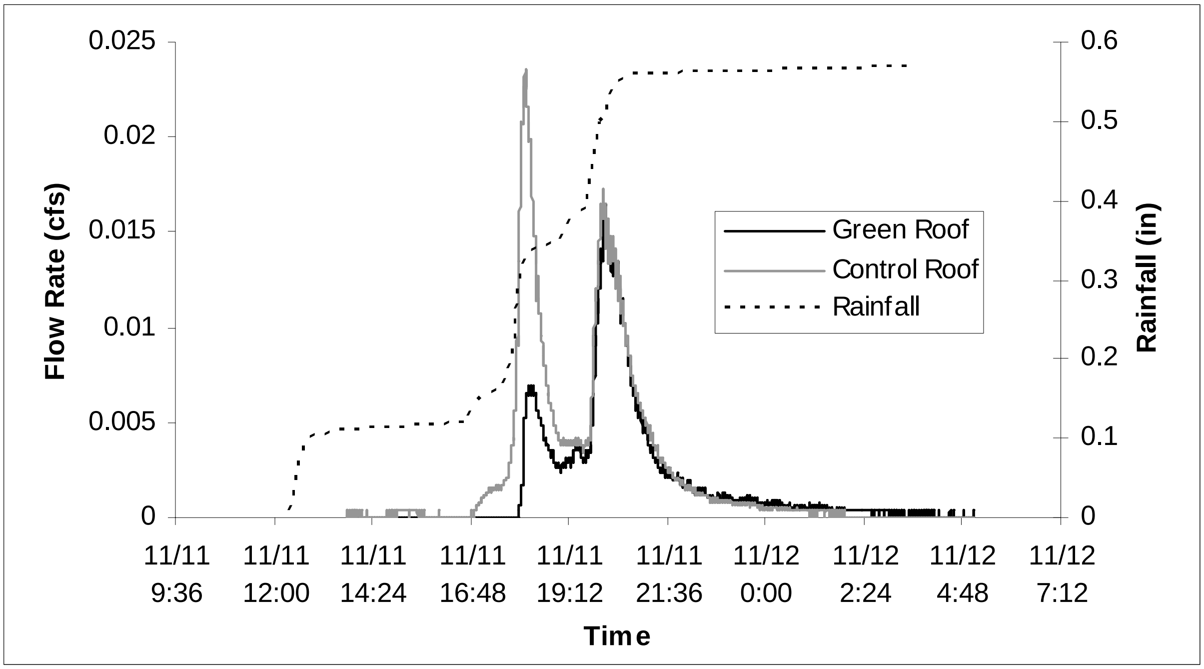

Figure 66 - Runoff Flow Rates - November 11, 2006 Storm

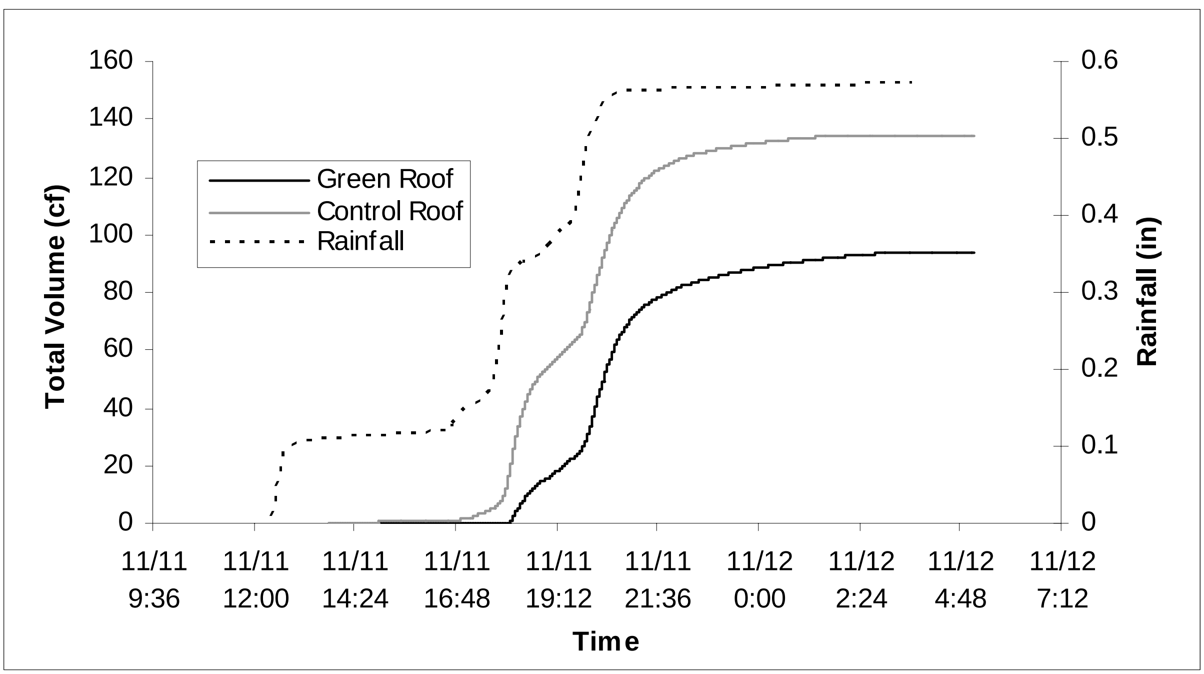

Figure 67 - Runoff Volumes - November 11, 2006 Storm

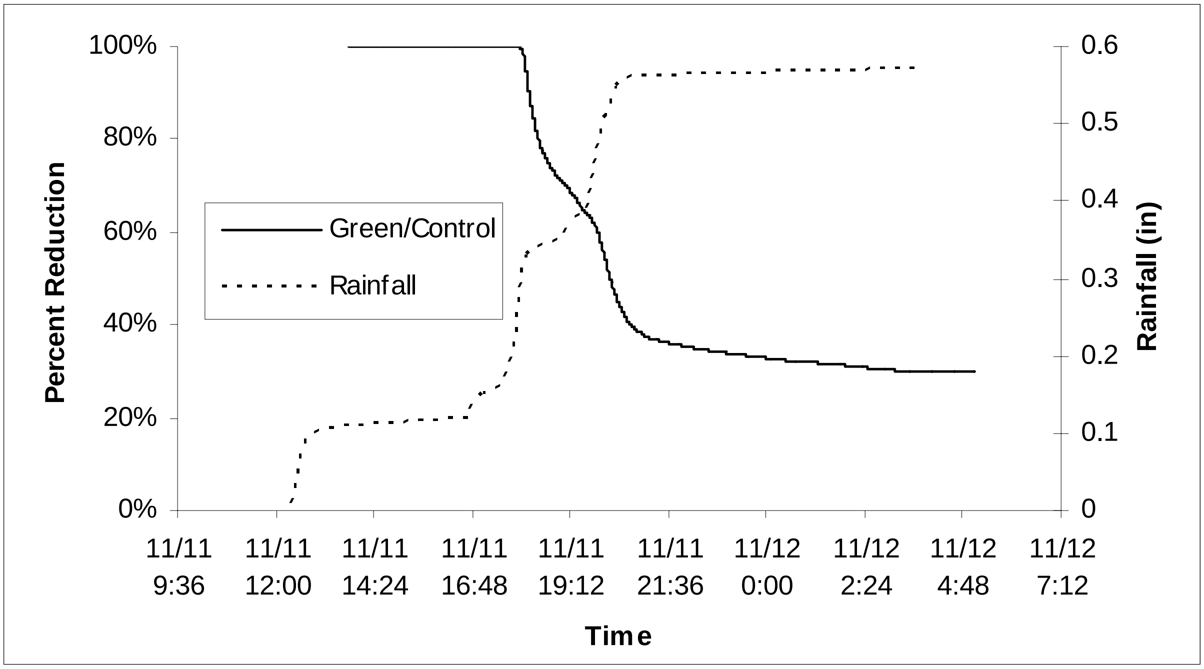

Figure 68 - Runoff Reduction - November 11, 2006 Storm

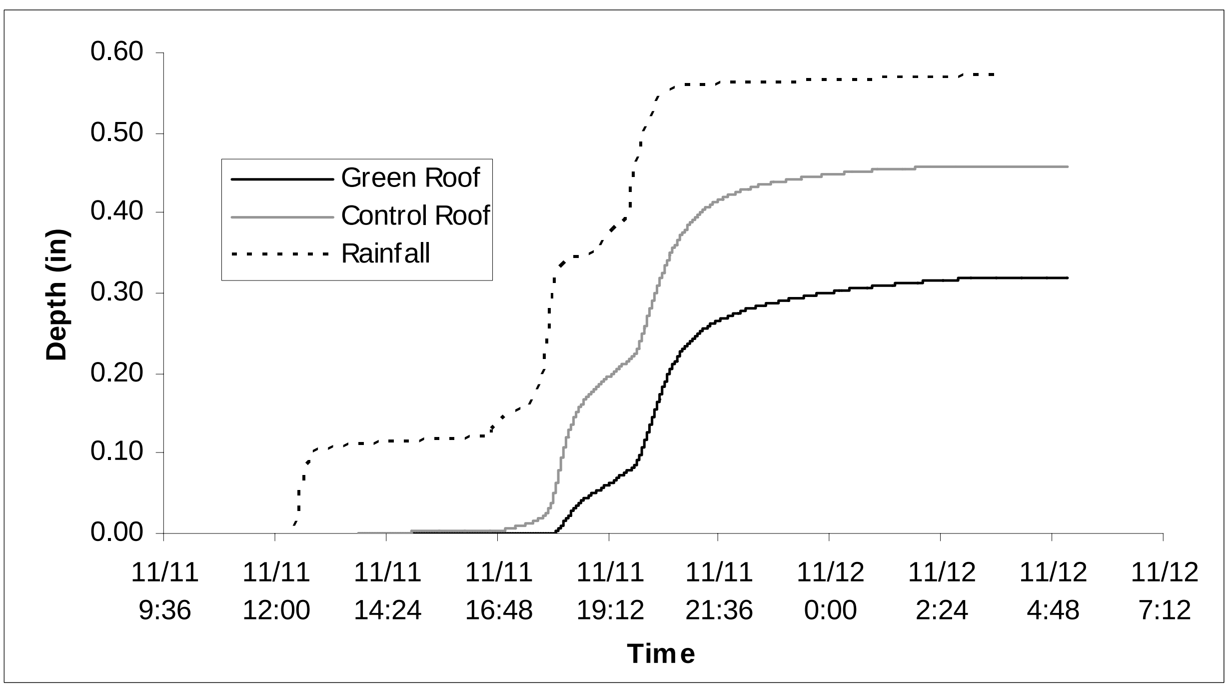

Figure 69 - Runoff as Rainfall - November 11, 2006 Storm

5.3 GIANT EAGLE WATER QUALITY RESULTS

To monitor the Giant Eagle green roof for water quality benefits, several storms were sampled and laboratory tests were conducted as described in the protocol. Samples from both the green and control roofs and rainwater were tested, and the full protocol was performed for three storms. One of these storms also included a rainwater sample and one additional storm was tested only for rainfall.

Runoff from the October 17, 2006 storm the first set tested. The storm had one of the greatest intensities during the observation period, with 1.94 inches of rain falling in approximately 10 hours. Appendix A lists the data for this storm.

The next storm tested took place on November 1, 2006. Runoff samples from both roofs were again tested. This storm was the lightest observed, with an accumulation of 0.07 inches. The duration is also short, at two hours and nine minutes. Section 5.2.5 discusses the runoff characteristics of this storm in detail.

Because the first two storms selected for testing only included runoff samples, the November 11, 2006 storm was used to test rainfall. This storm had a total rainfall of 0.57 inches and lasted for approximately 15 hours. Section 5.2.6 discusses the runoff characteristics of this storm in detail.

Finally, the samples from the rainfall and runoff were tested from the December 1, 2006 storm. This storm of 0.83 inches lasted for about six hours and 50 minutes.

While most tests were completed with both unfiltered and filtered samples, there were a few instances were only a small amount of water was available for a particular sample. In these cases, there was not enough sample to filter the sample and still have enough water to complete the full range of testing, so only unfiltered water was tested for these samples. This occurred in several instances with green roof runoff samples.

5.3.1 Turbidity

Turbidity was determined for each sample from all storms selected for complete sampling, along with several other storms where only turbidity was tested.

For several storms where control roof runoff samples were tested, some degree of a first flush effect was observed. There was no first flush detectable from any of the corresponding green roof samples.

As a base line, the turbidity of all of the rainwater samples tested for turbidity are shown in Figure 70. Each item in the turbidity bar graphs represent one test. The November 11, 2006 storm is high, with a turbidity of about 6 NTU. This is due to a large amount of debris that was deposited in the rainwater sampling container at the site. The November 16, 2006 and December 1, 2006 storms have turbidities of approximately 1.5 NTU and were free from excess debris.

The December 1, 2006 storm showed the most dramatic first flush effect. Figure 71 shows the turbidity levels on the control roof and Figure 72 shows the values for the green roof. There is a steady decline in turbidity in each successive control roof sample. The sample collected at 5 cf of runoff has a turbidity of about 70 NTU, which is the highest of any sample tested during the observation period. By the final sample (60 cf), the turbidity had dropped to about 9.5 NTU. For the green roof samples, there is no consistency. Samples range in turbidity from 4.5 to 9.2 NTU without a first flush effect.

Two other storms showed similar although less pronounced results. In the October 17, 2006 storm, the turbidity of the control roof dropped from 20 NTU for the 5 cf sample to 15

NTU for the 10 cf sample. The remaining four samples had turbidities of approximately 5.5 NTU. Again, the green roof showed no first flush effect. As with the control roof, the values are considerably lower than the December 1, 2006 storm. Turbidity ranges from about 2 to 3 NTU. The November 1, 2006 storm shows a very slight first flush effect for the control roof. The first sample has a turbidity of 4 NTU, while the remaining samples are approximately 2.5 NTU. Once again, the green roof turbidities are lower, ranging from 1.5 NTU to 2.5 NTU, and show no first flush effect.

Not all storms showed this first flush effect, however. Figures 73 and 74 show the turbidity measurements for the November 15, 2006 storm. In this case, a first flush is not evident for either roof. The control roof ranges from approximately 2 to 9.5 NTU and the green roof ranges from 4.5 to 9.5 NTU.

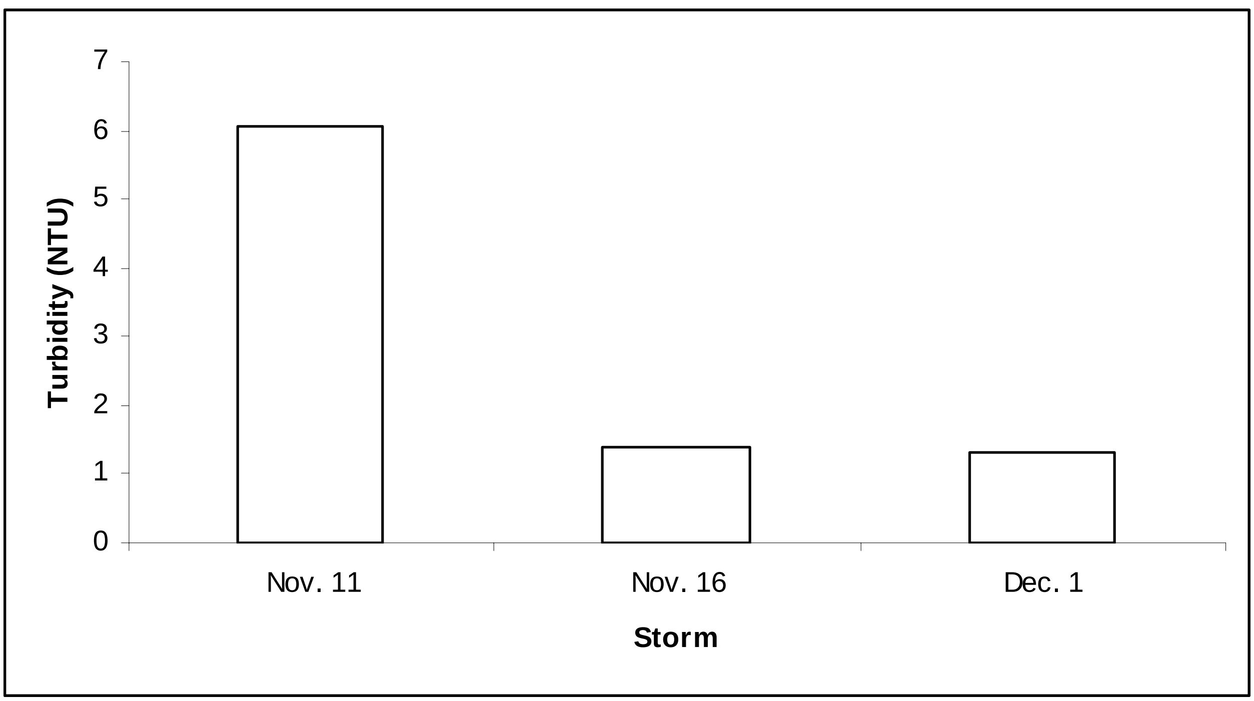

Figure 70 - Turbidity - Rainwater Samples

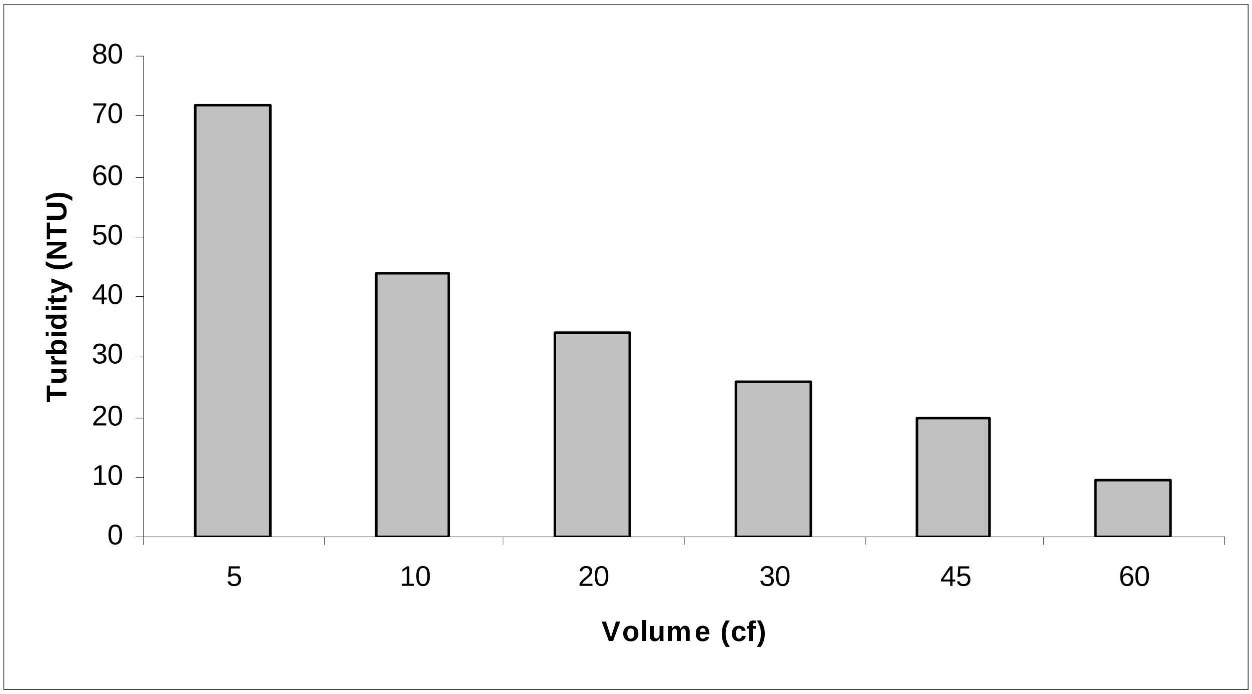

Figure 71 - Turbidity - Control Roof Samples - December 1, 2006 Storm

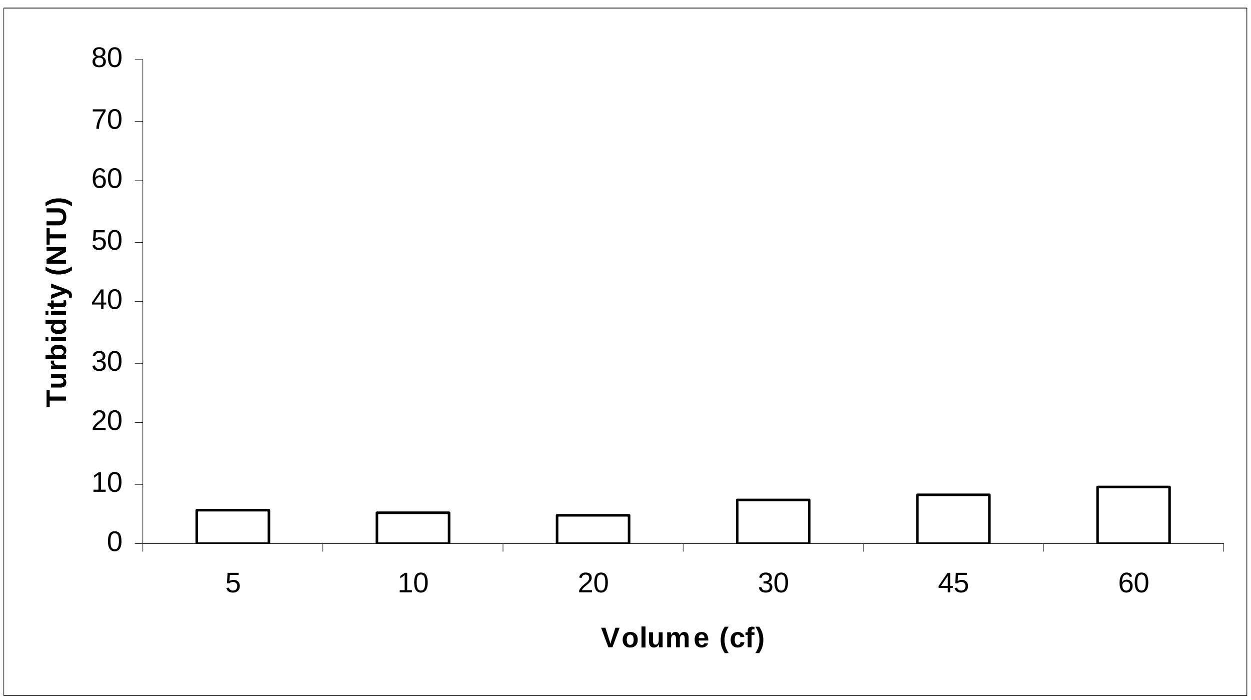

Figure 72 - Turbidity - Green Roof Samples - December 1, 2006 Storm

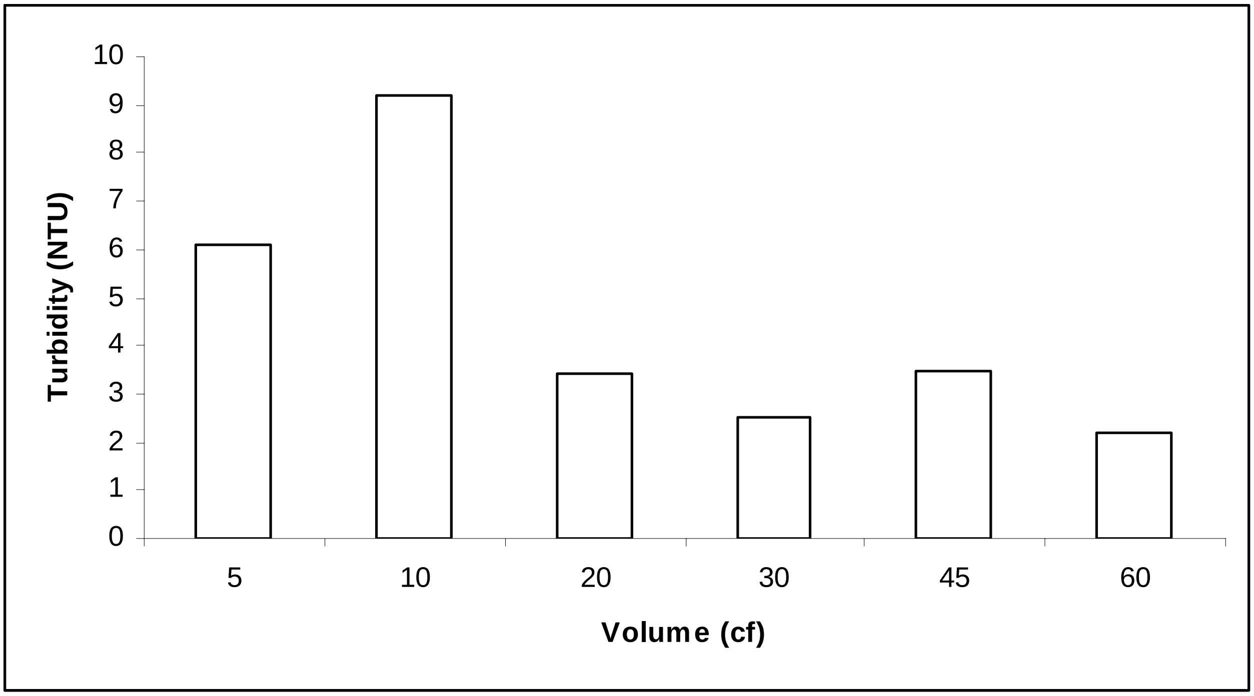

Figure 73 - Turbidity - Control Roof Samples - November 15, 2006 Storm

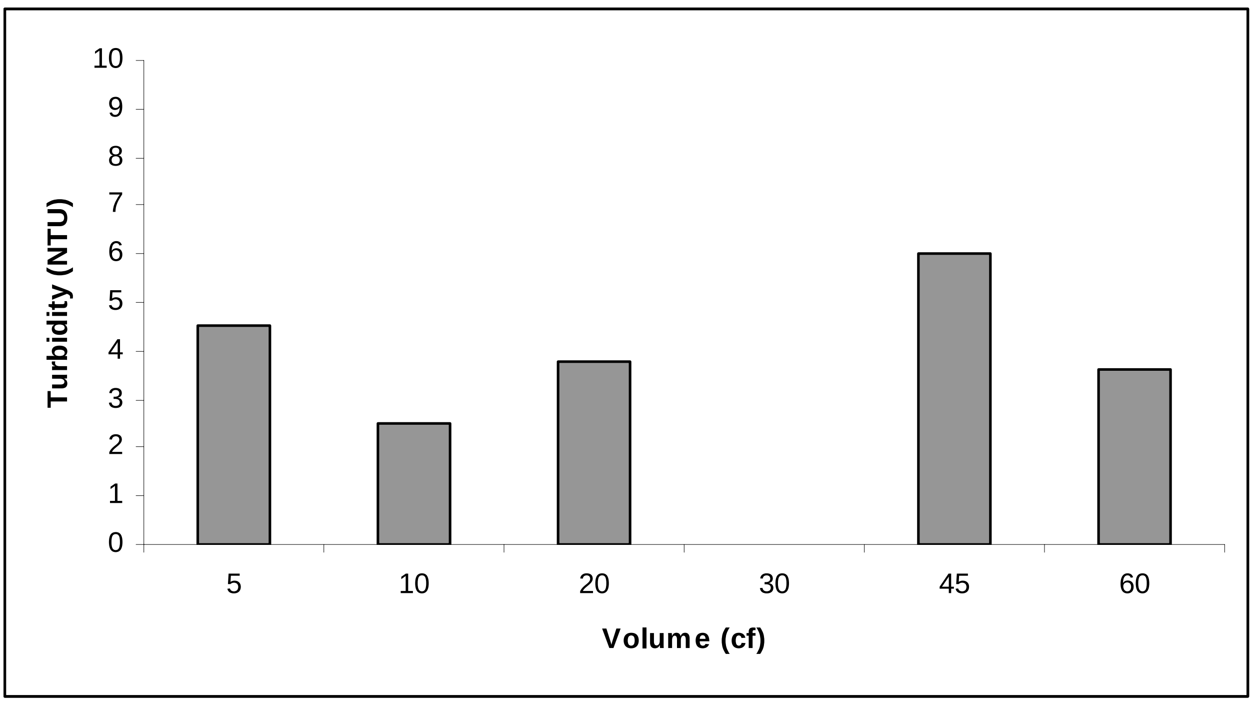

Figure 74 - Turbidity - Green Roof Samples - November 15, 2006 Storm

5.3.2 pH

pH was tested for each storm that received the full battery of tests, along with several additional storms. Throughout the testing, no discernable difference existed between the green and control roof runoff samples. The pH of samples ranged from approximately 7.5 to 8.3. No first flush effects were detected and neither of the roof's runoff samples were consistently higher or lower than the others. There was some difference between the runoff samples and the rainfall, however. The November 13, 2006 storm was sampled for rainfall, but not runoff. This rain sample had a pH of 7.9, which is within the range of the runoff samples from other storms. The November 16, 2006 and December 1, 2006 storms had both rainfall and runoff sampled. The pH of the rainfall samples were 7.0 and 6.4, respectively. In both of these cases, the rain samples are slightly more acidic than the runoff. Graphs detailing these results are in Appendix B.

5.3.3 Phosphorus

Phosphorus tests were completed for the October 17, 2006, November 1, 2006 and November 11, 2006 storms. In each instance, the results of testing were consistent.

The phosphorus levels in the rainwater samples are very low. Figure 75 shows the results from the November 11, 2006 storm. The bars in this graph (all subsequent water quality graphs) represent the mean value. The 'x's' show the minimum and maximum values for the respective samples. The unfiltered rainwater sample had a concentration of 0.04 mg/L and the filtered sample contained 0.02 mg/L. So half of the phosphorus is dissolved and half is undissolved.

The green roof runoff samples show significant levels of phosphorus. The unfiltered samples from the November 1, 2006 storm are shown in Figure 76 and the filtered samples from the same storm are shown in Figure 77. Samples at 20 and 30 cf. runoff volume were compromised. Also, only a small amount of runoff was sampled at 10 cf, so a filtered sample was not able to be tested. The phosphorus levels for the unfiltered samples are 3.0 mg/L at 5 cf, 2.3 mg/L at 10 mg/L and 2.8 mg/L at both 45 and 60 cf. This is an average value of 2.7 mg/L. The filtered phosphorus levels are nearly identical, with only the 5 cf sample dropping to 2.9 mg/L. The results are in line with those of the October 17, 2006 storm. The levels were slightly lower, at about 2 mg/L for most samples. There is again no significant difference between the filtered and unfiltered samples.

Figures 78 and 79 show the unfiltered and filtered control roof samples, respectively, for the same storm. Phosphorus was not detected in any samples and there was no difference between the filtered and unfiltered samples. In the October 17, 2006 storm, levels were again extremely low. Three of the unfiltered samples registered 0.1 mg/L of phosphorus, but all other samples had no detectable phosphorus.

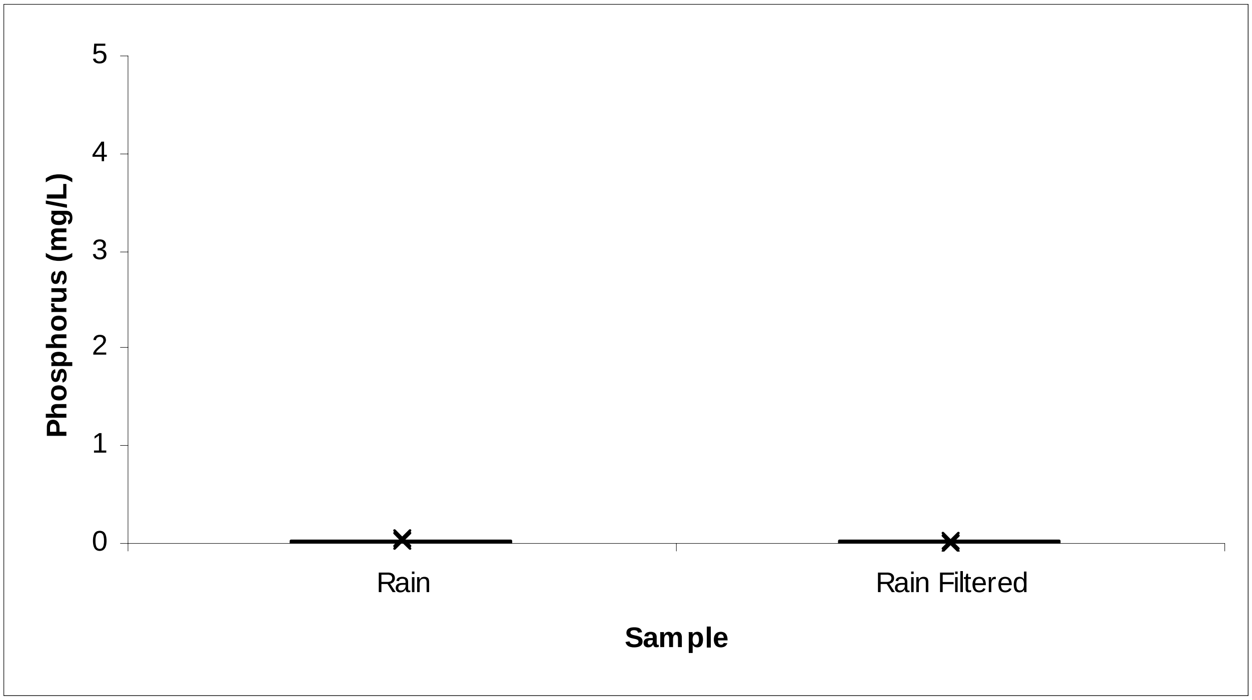

Figure 75 - Phosphorus - Rainwater Samples - November 11, 2006 Storm

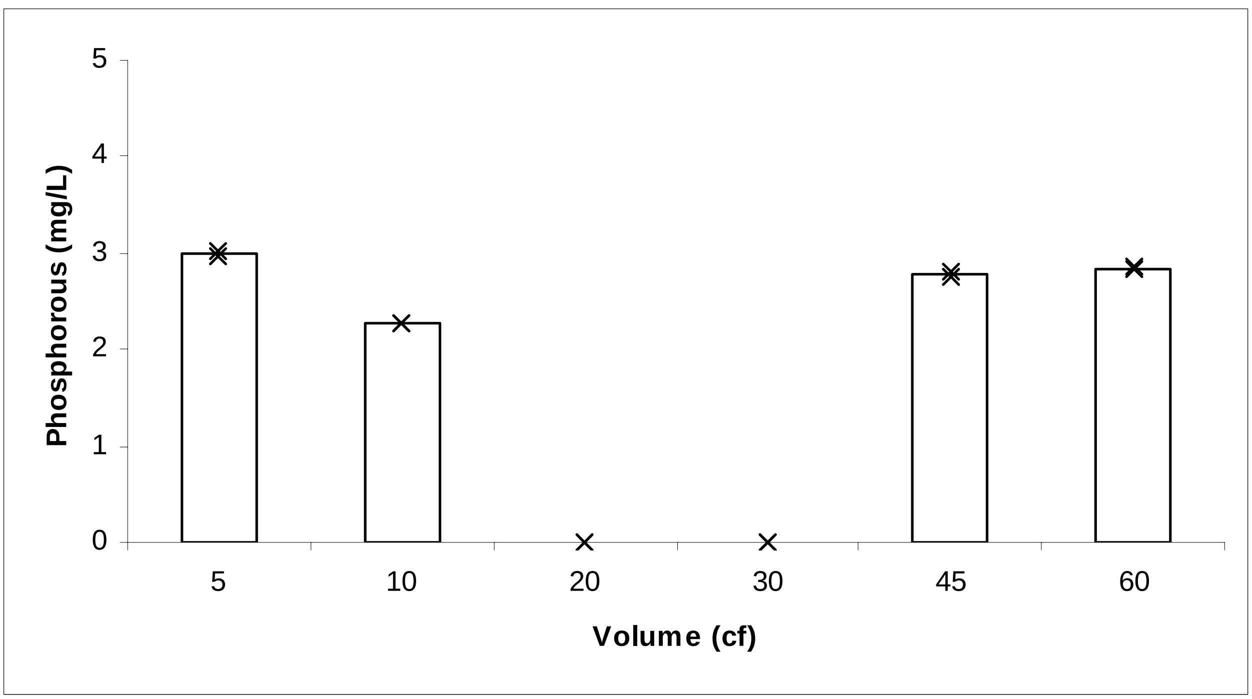

Figure 76 - Phosphorus - Unfiltered Green Roof Samples - November 1, 2006 Storm

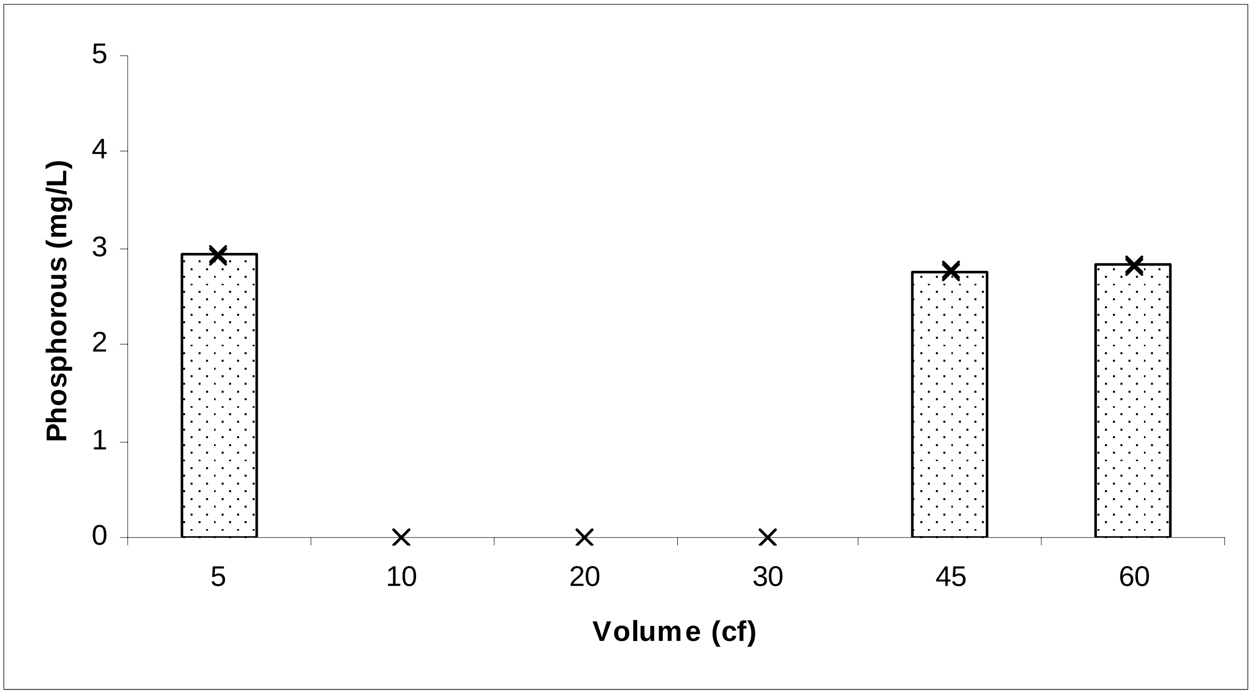

Figure 77 - Phosphorus - Filtered Green Roof Samples - November 1, 2006 Storm

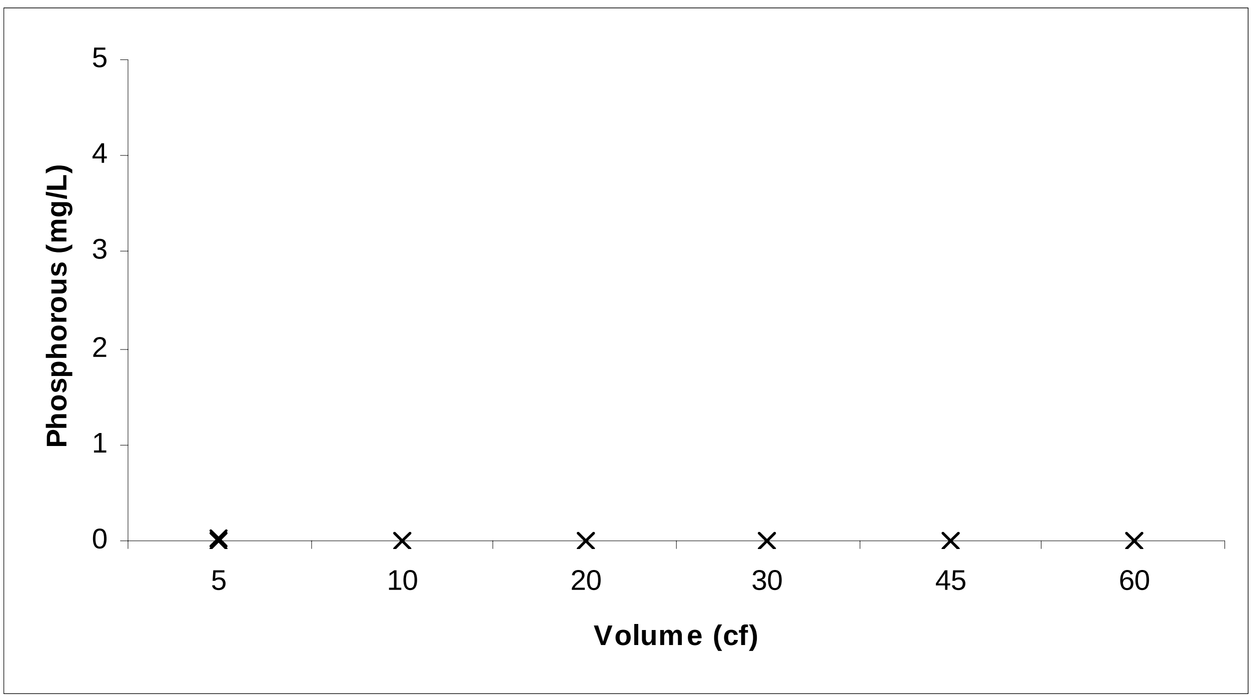

Figure 78 - Phosphorus - Unfiltered Control Roof Samples - November 1, 2006 Storm

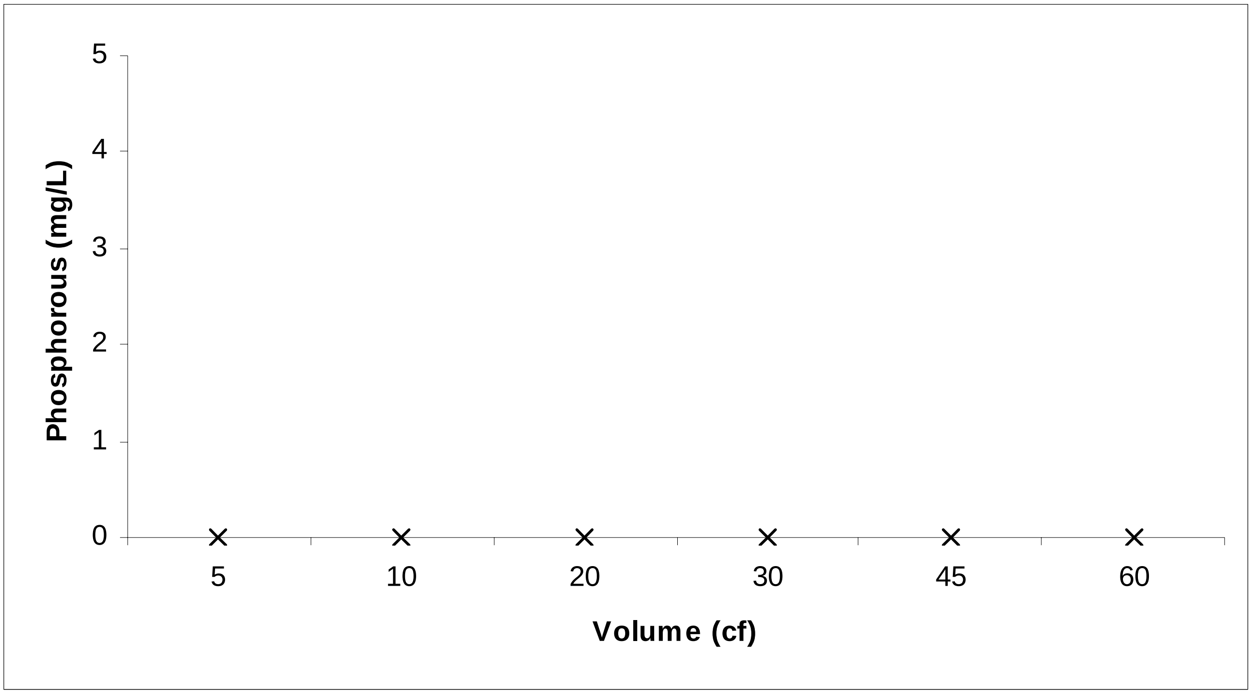

Figure 79 - Phosphorus - Filtered Control Roof Samples - November 1, 2006 Storm

5.3.4 Sulfate

For sulfate, runoff from three storms was tested: October 17, 2006, November 1, 2006 and December 1, 2006. The December 1 testing also included rainwater samples and an additional rainwater sample was tested from the November 13, 2006 storm.

The rainwater samples were somewhat inconsistent. One sample had to be disregarded, as it fell far outside the range of the test. Excluding this sample, the November 13, 2006 unfiltered sample had a concentration of 8.4 mg/L, with 12 mg/L for the filtered sample. The values for the December 1, 2006 storm were 4.2 and 8.4 mg/L, respectively. These values are all consistently lower than the runoff samples from both roofs.

For the first storm (October 17), the green roof samples have concentrations of sulfate that range from 35 to 47 mg/L, which are higher than the control roof concentrations of 16 to 25 mg/L. There is no first flush effect, although the final control roof sample (60 cf) is the lowest. The only significant difference between the filtered and unfiltered samples from both roofs is the 30 cf sample on the control roof, which sees the unfiltered sample at 30 mg/L and the filtered sample 25 mg/L.

The November 1, 2006 storm is essentially the opposite of the first storm. Again, there is no first flush effect evident and there is no significant different between the filtered and unfiltered samples on either roof. This time, however, the control roof has higher concentrations (27 to 31 mg/L) than the green roof (18 to 21 mg/L).

The December 1, 2006 storm is quite different from the previous storms. This is the storm where a first flush was evident in the turbidity reading on the control roof samples. The same results occur here, with a first flush in the unfiltered control roof samples (Figure 80). Sulfate levels drop consistently from 30 mg/L to approximately 17 mg/L. In Figure 81, the filtered control samples are shown to be fairly consistent. Each sample decreases, with a range of about 20 to 16 mg/L. This indicates that the first flush is the result of increased undissolved sulfate particles. Figures 82 and 83 show the unfiltered and filtered green roof runoff samples. With the exception of one sample, the levels are less than the control roof values and there is little difference between the filtered and unfiltered samples.

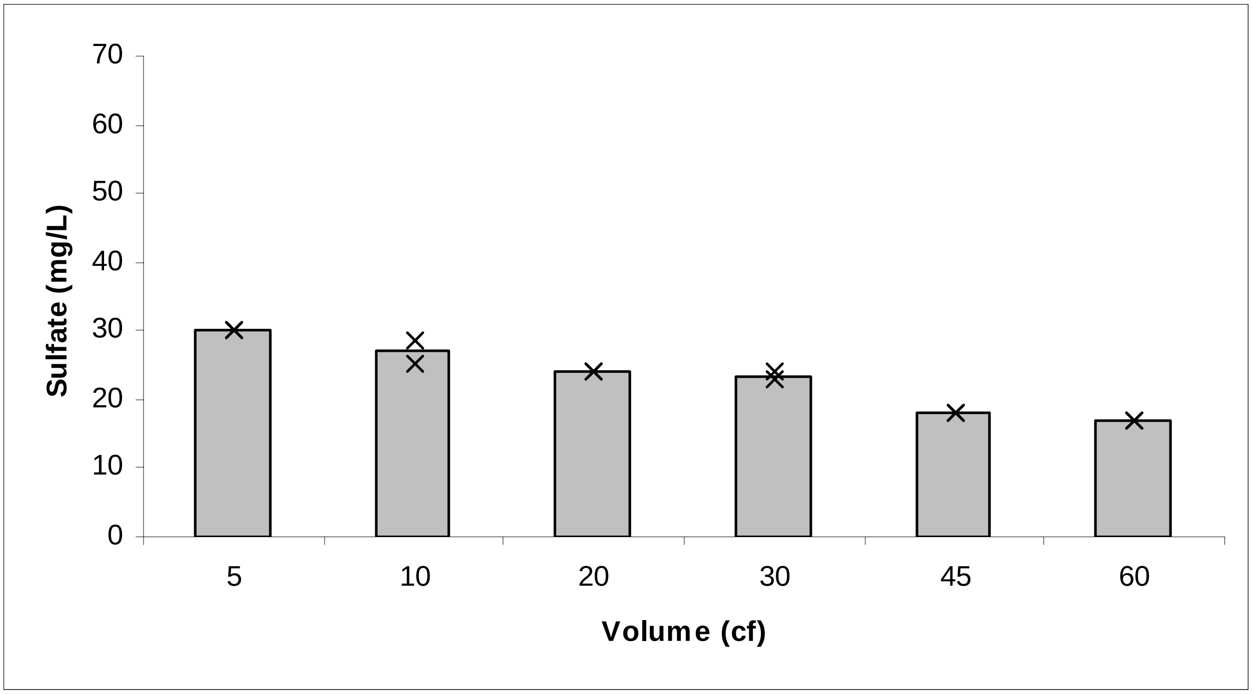

Figure 80 - Sulfate - Unfiltered Control Roof Samples - December 1, 2006 Storm

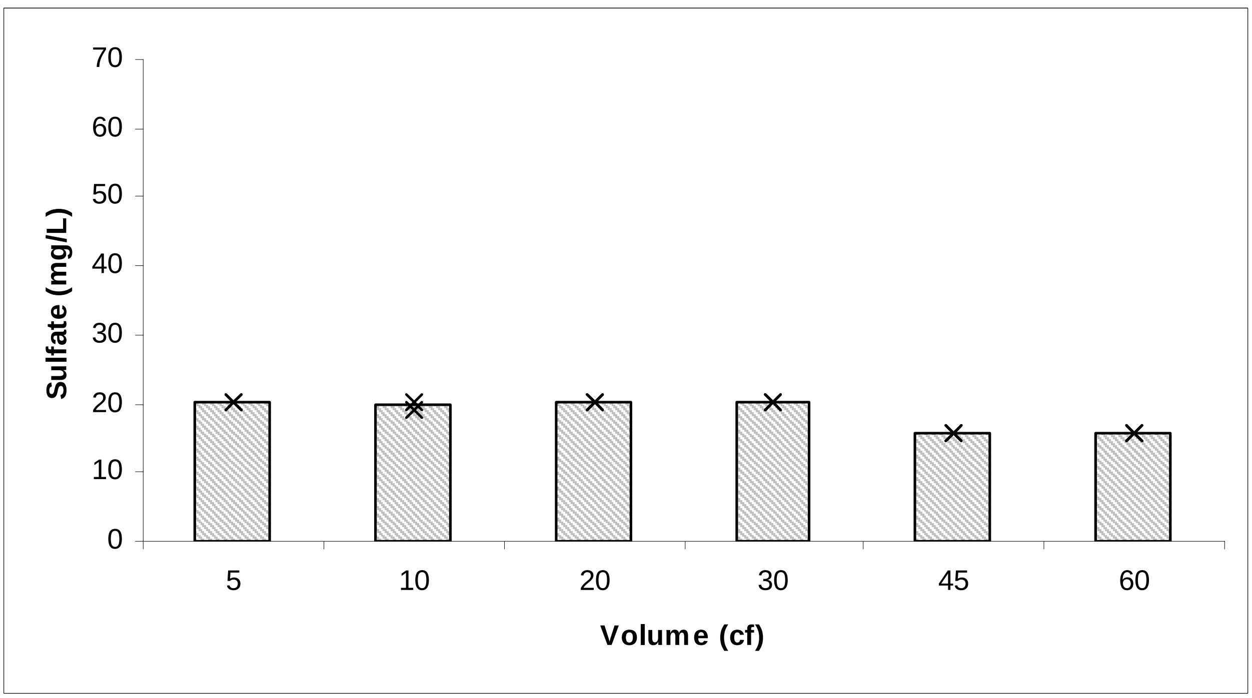

Figure 81 - Sulfate - Filtered Control Roof Samples - December 1, 2006 Storm

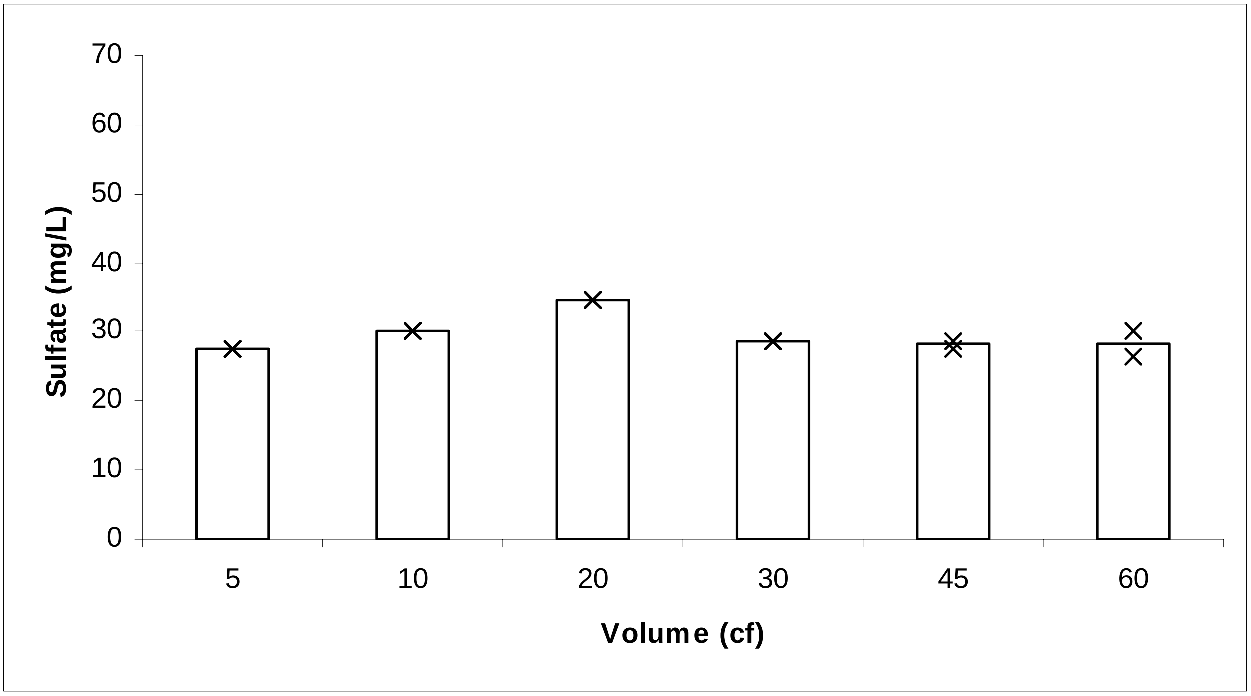

Figure 82 - Sulfate - Unfiltered Green Roof Samples - December 1, 2006 Storm

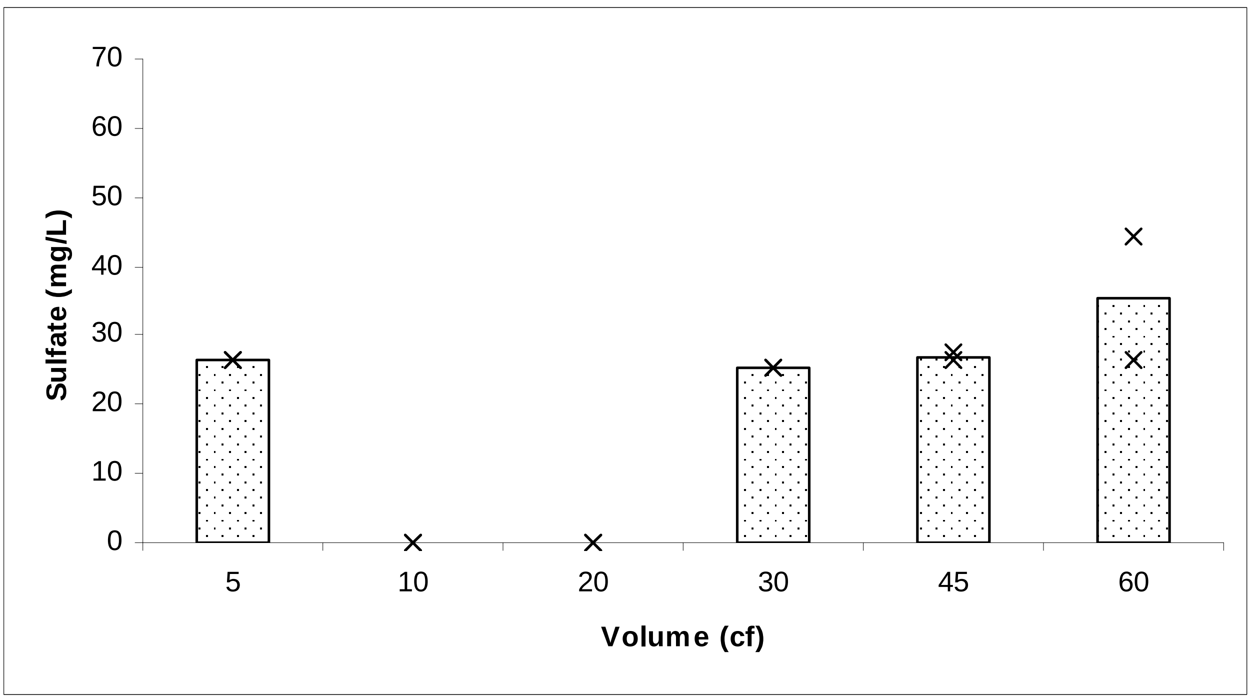

Figure 83 - Sulfate - Filtered Green Roof Samples - December 1, 2006 Storm

5.3.5 Nitrogen

Runoff samples from both roofs were tested for nitrogen after the October 17, 2006, November 1, 2006 and December 1, 2006 storms. Rainwater samples from the December 1 storm were tested as well. Appendix B extensively lists the results from these tests.

The vast majority of samples, regardless of their source, registered a nitrogen concentration of approximately zero. All together, 61 percent of the samples had no detectible levels of nitrogen. Many of the samples that did show traces of nitrogen were with very low concentrations (below 1 mg/L). The highest concentration was about 4.5 mg/L for a filtered control roof sample.

No patterns were evident when comparing the control and green roof samples or filtered and unfiltered samples.

5.3.6 COD

COD testing was completed for the October 17, 2006, November 1, 2006 and December 1, 2006 storms for the green and control roof runoff samples. Rainwater was tested after the November 13, 2006 and December 1, 2006 storms.

The December 1, 2006 storm was typical of the storm events. Figure 84 shows the COD levels for the rainwater sample. The unfiltered sample has a concentration of 12.4 mg/L, which decreases to 1.3 mg/L once the sample is filtered. The green roof samples have higher COD concentrations of COD than the control roof, with concentrations of 26 to 41 mg/L for the unfiltered samples (Figure 87). The unfiltered control roof samples (Figure 85) are between 5 and 15 mg/L. While there is often a lower concentration in the filtered green (Figure 88) and control (Figure 86) roof runoff samples, it does not happen consistently.

For the other two storms tested, the green roof also has consistently higher values than the control roof, although the overall values are generally less for both roofs during both storms.

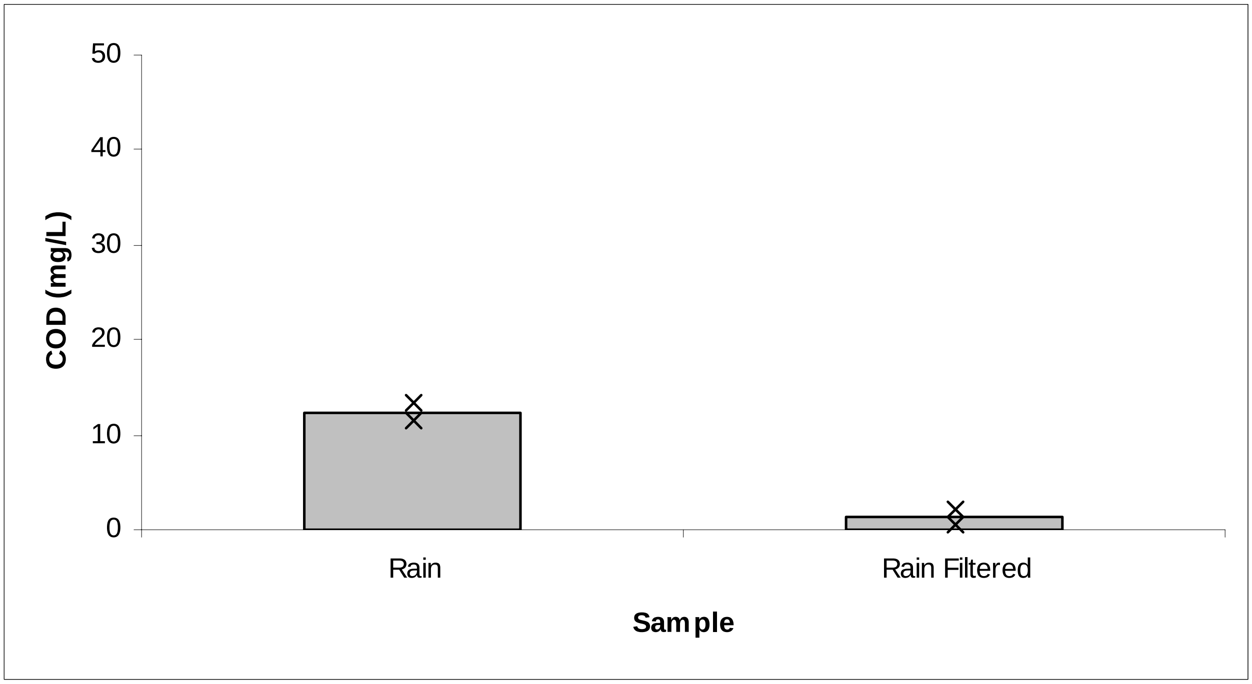

Figure 84 - COD - Rainwater Samples - December 1, 2006 Storm

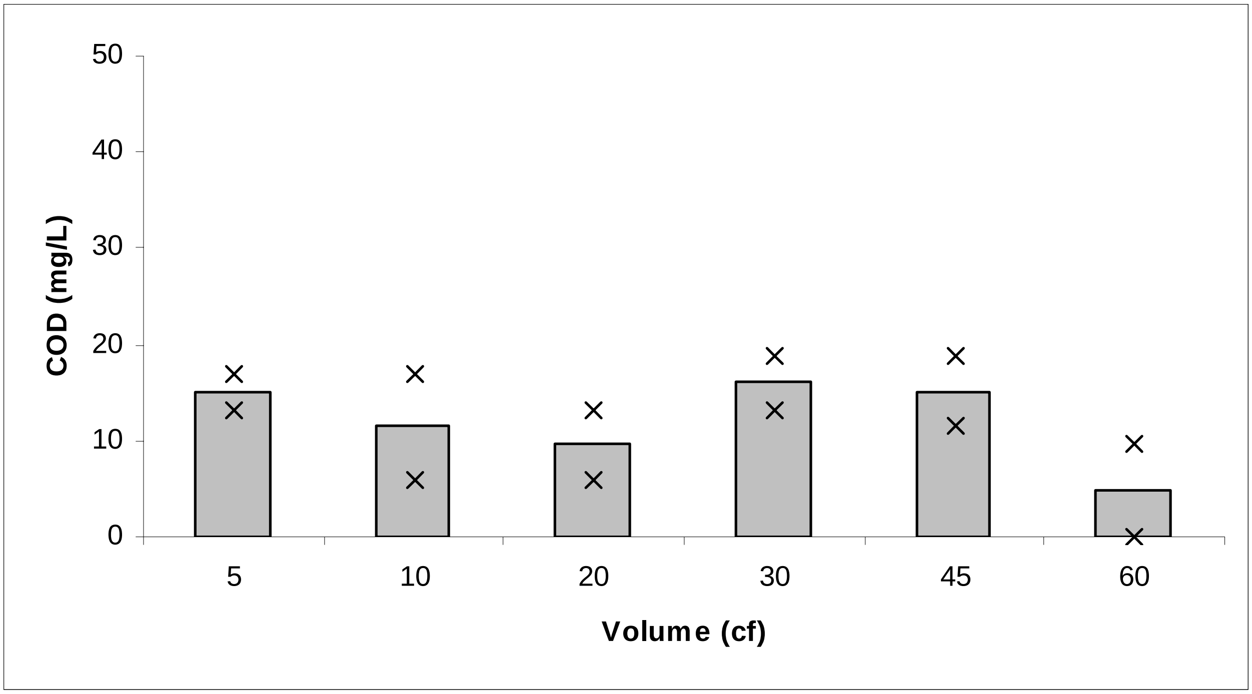

Figure 85 - COD – Unfiltered Control Roof Samples - December 1, 2006 Storm

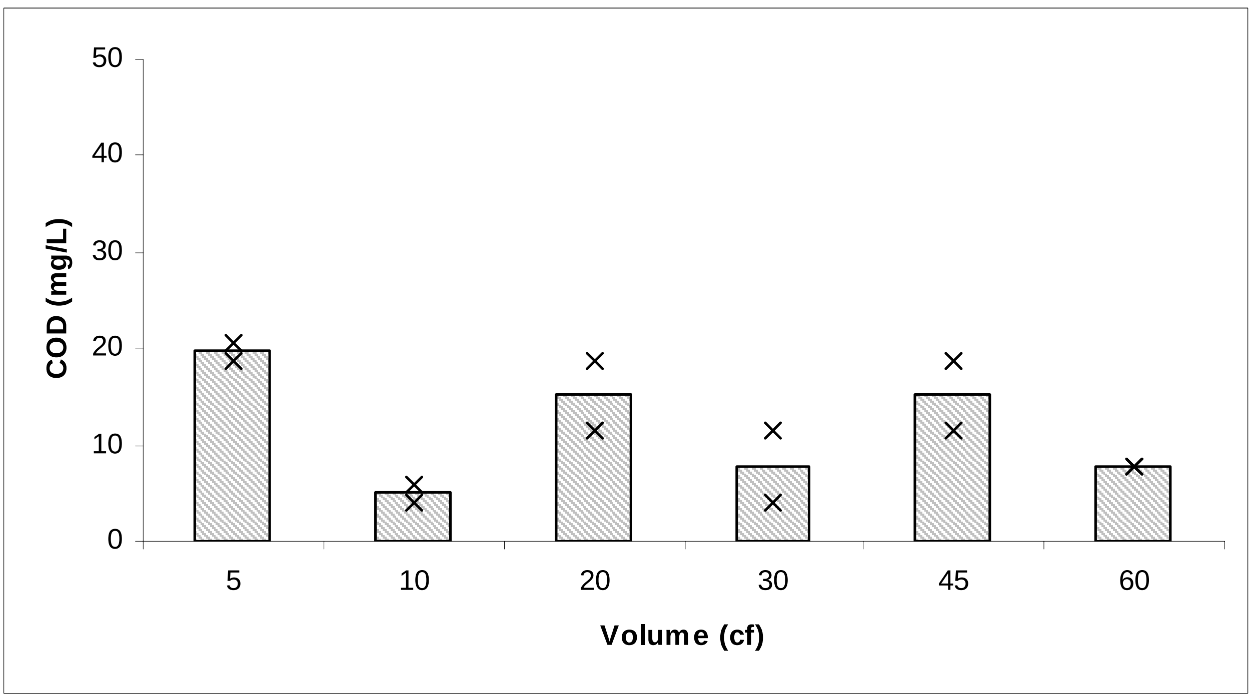

Figure 86 - COD - Filtered Control Roof Samples - December 1, 2006 Storm

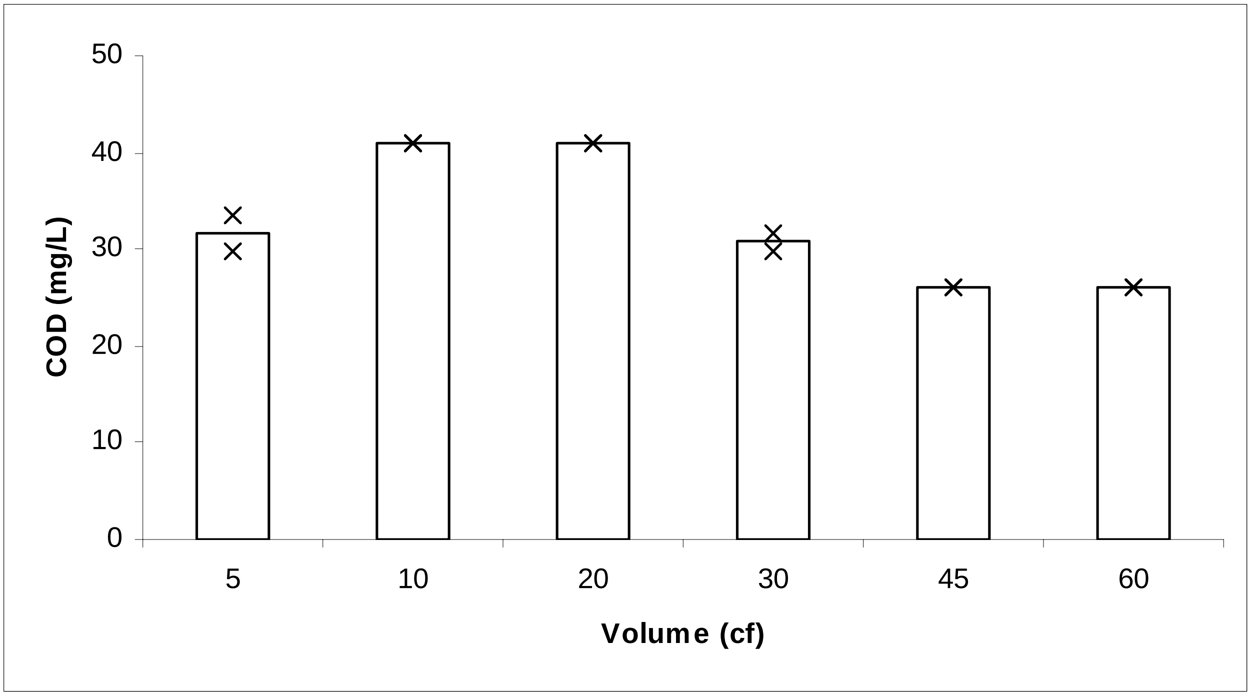

Figure 87 - COD - Unfiltered Green Roof Samples - December 1, 2006 Storm

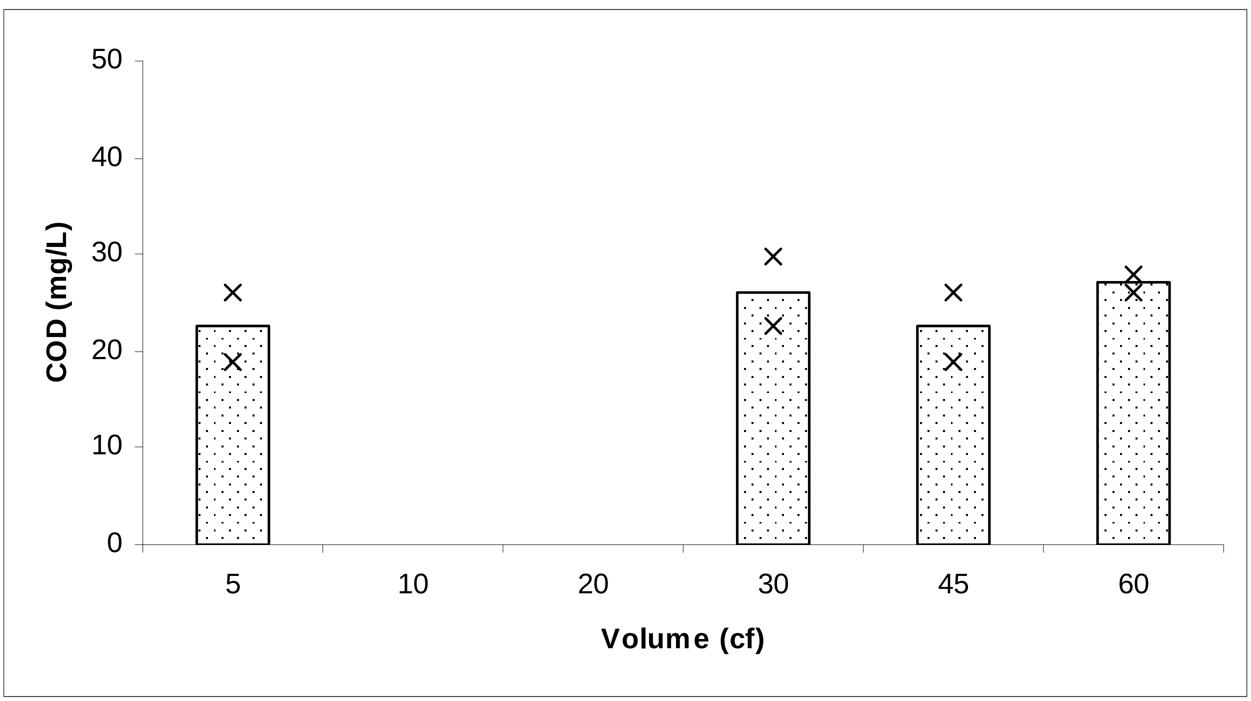

Figure 88 - COD - Filtered Runoff Samples - December 1, 2006 Storm

5.3.7 Zinc

Selected green and control roof samples were tested for zinc from the October 17, 2006 and December 1, 2006 storms. All runoff samples from the November 1, 2006 storm were tested. Rainwater from the November 13, 2006 and December 1, 2006 storms were also tested.

The results are summarized in Figure 89. The detected levels were very low, with the highest at only 0.44 mg/L of zinc. There is no consistent difference between the green and control roof samples, nor is there a first flush effect evident. The rainwater samples are also not consistently higher or lower than the runoff samples.

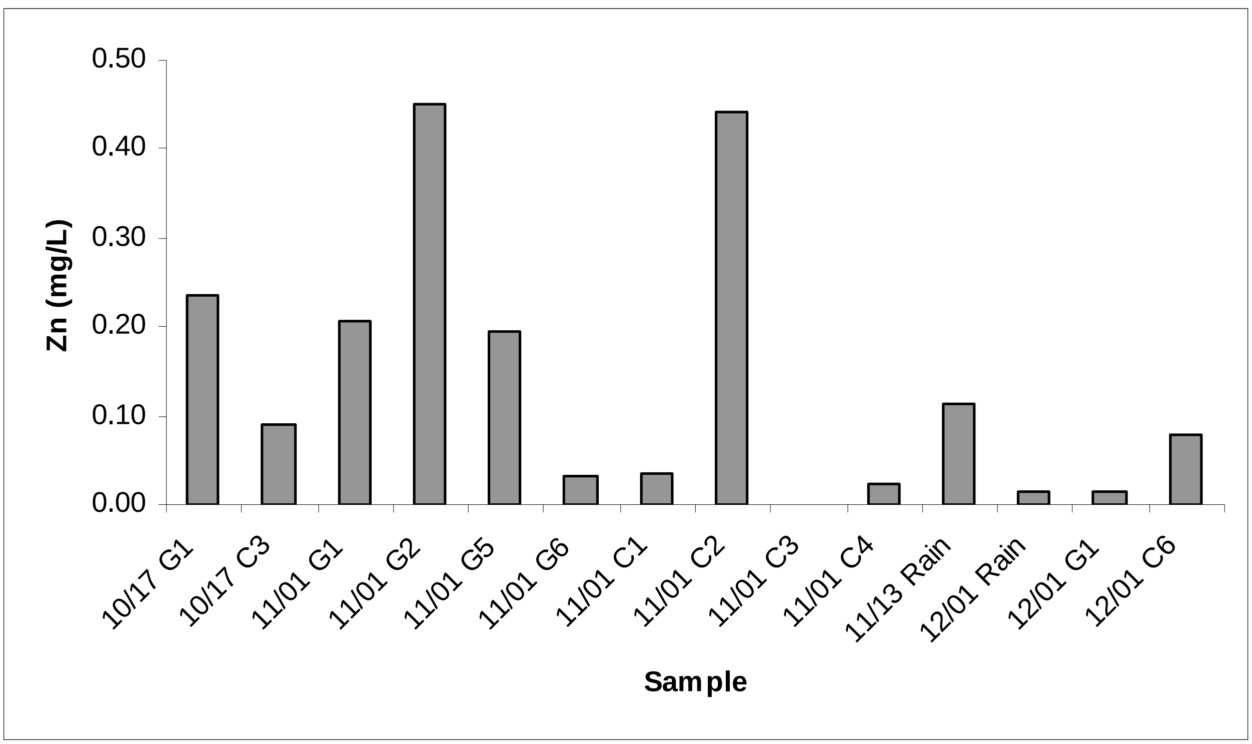

Figure 89 - Zinc - All Storms

5.3.8 Cadmium

Testing for cadmium was completed on selected green and control roof runoff samples from the October 17, 2006, November 1, 2006 and December 1, 2006 storms. Rainwater samples from the November 13, 2006 and December 1, 2006 storms were also tested. No detectible levels of cadmium were found in any of the samples.

5.3.9 Lead

Testing for lead was completed on selected green and control roof runoff samples from the October 17, 2006, November 1, 2006 and December 1, 2006 storms. Rainwater samples from the November 13, 2006 and December 1, 2006 storms were also tested.

As with the zinc testing, the levels of lead detected are low (Figure 90). The maximum concentration is 0.53 mg/L. Again, the concentration in the runoff from either roof is not consistently greater than the other. Both rainwater samples did have higher levels of lead than all but one runoff sample (the green roof sample from the October 17, 2006 storm). There is no first flush effect evident from this limited data.

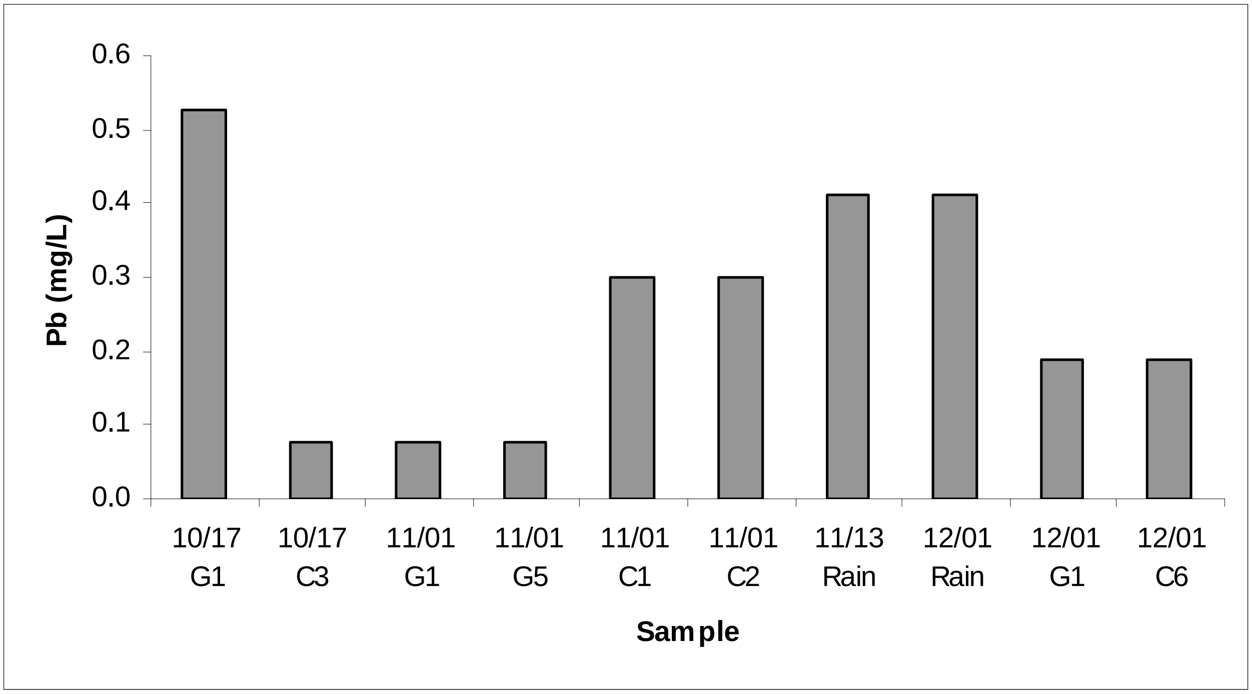

Figure 90 - Lead - All Samples

5.4 SUMMARY AND DISCUSSION

The results show very clearly that the rate of runoff from the green roof is reduced. For a typical storm, there is a large gap between the flow rates from the green and control roofs early in a storm. During the beginning of the November 11, 2006 storm, for instance, the green roof runoff flow rate was 73 percent less than the control roof runoff. As the storm progresses and the soil on the green roof becomes saturated, the flow rates converge. During the August 27, 2007 storm, each progressive peak saw the difference between the flow rates of the two roofs decrease, though the green roof was always lower. The peak flow rate for the green roof was consistently lower than the control roof, by 5 to 70 percent, depending on the storm characteristics. The two exceptions to this rule were the storms where the irrigation caused artificially inflated flow rates from the green roof and the January 12, 2007 storm. The January 12 storm was the heaviest (2.2 inches) and longest (3 days, 3 hours and 45 minutes) storm recorded. Discounting the typical periods of flow extension, the flow rate of the green roof was higher than the control roof for approximately 15 percent (about 11 ½ hours) of the storm. This did not occur until fairly late in the storm, however, after over half and inch of rain fell in about 15 and a quarter hours. The green roof flow rates are also not substantially greater than the control roof. For example, the green roof peak flow rate for the storm is higher than the control, but only by 5 percent. The rainfall intensity of 0.03 inches per hour over 76 hours corresponds to a 1-year storm, so both the storm itself and the runoff performance are atypical.

At times, there was a delay between the when the green and control roof reached their peak flow rate. During the October 31, 2006 storm, the green roof reaches its peak about two hours after the control. On November 11, 2006, there was also a delay of approximately two hours. More often than not, however, this was not the case. During most storms, the peak flows from both roofs were reached at approximately the same time, though the green roof had a lower value in all but one instance.

The green roof also consistently reduced the total volume of runoff. Overall, the reduction ranged from just under 70 percent less than the control roof for the three lightest storms to 5 percent for one of the heaviest. Many of the heavier storms still saw about a 20 percent reduction. There are a few exceptions. Irrigation skewed the results of five storms, causing the green roof to have an artificially greater runoff total. Once the excess runoff is removed, however, the green roof has a lower total than the control roof. The second and forth observed storms (on July 28, 2006 and July 30, 2006) both show a higher total flow from the green roof. In both instances, these were the second storms in a 24 hour period and the soil was saturated at the time the storms started. The runoff on July 28th was minimal, with the lowest totals for any storm. The July 30th storm produced significant runoff. It was only at the very end of the storm, with an extended low rate of flow from the green roof, that the green roof overtakes the control. Throughout the bulk of the storm, the control roof produced more runoff, though it produced 11 percent less total.

For most storms, the control roof produced runoff first, so there would initially be a 100 percent reduction in runoff volume. Once water began to flow from the green roof, the amount of reduction would begin to drop. This would usually occur at a rapid pace, similar to the rate of rainfall. Once the storm ended, there was a much more gradual decline as additional runoff flowed from the green roof after the conclusion of the storm.

Several graphs discussed previously in section 5.2 are reproduced below to illustrate several additional conclusions that can be drawn from about the total flow volume. Figure 91 shows the runoff flow rates for the October 27, 2006 storm and Figure 92 shows the runoff reduction for this same storm event. Figures 93 and 94 show the same parameters for the October 31, 2006 storm.

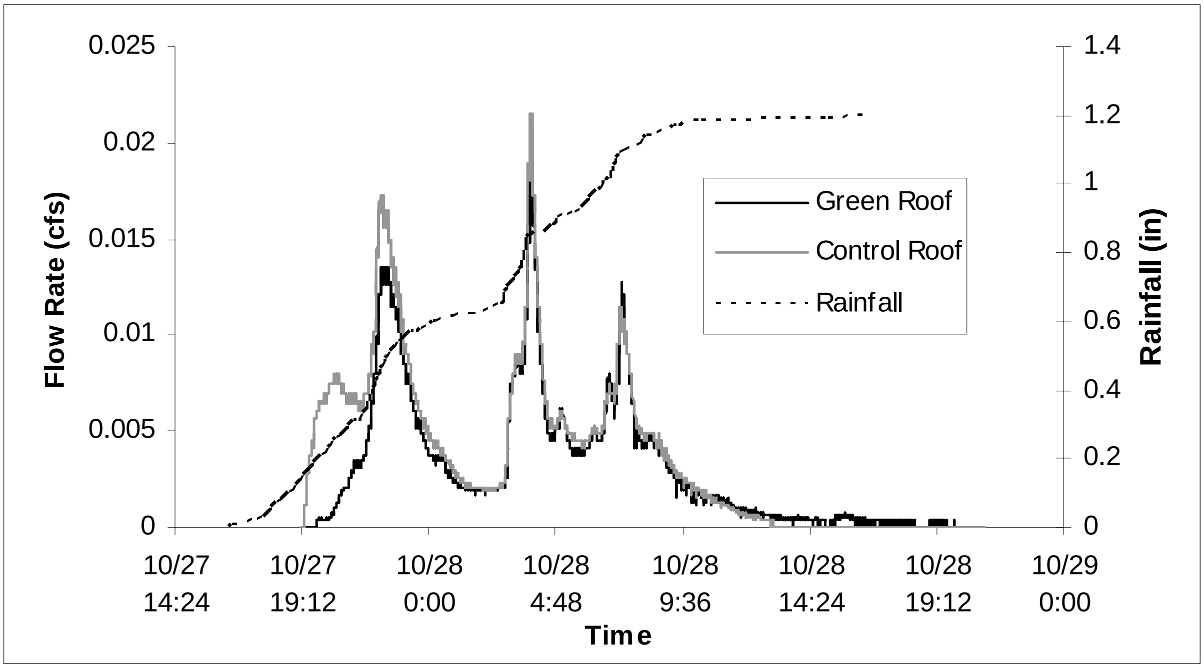

Figure 91 - Runoff Flow Rates - October 27, 2006 Storm

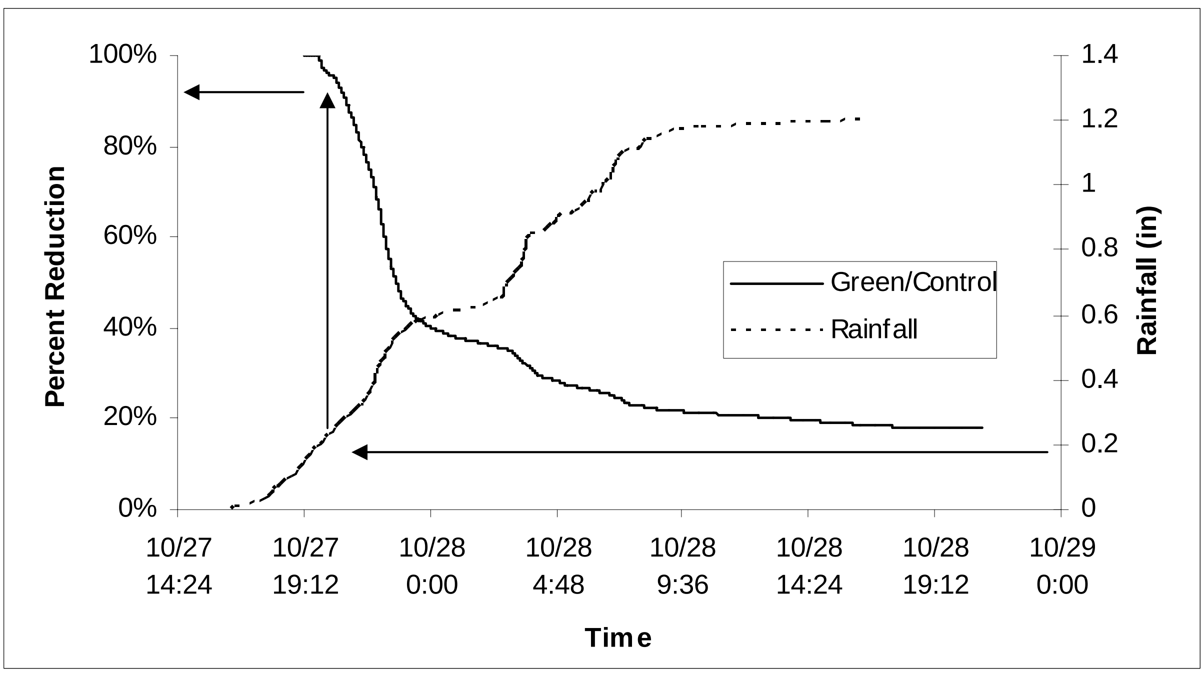

Figure 92 - Runoff Reduction - October 27, 2006 Storm

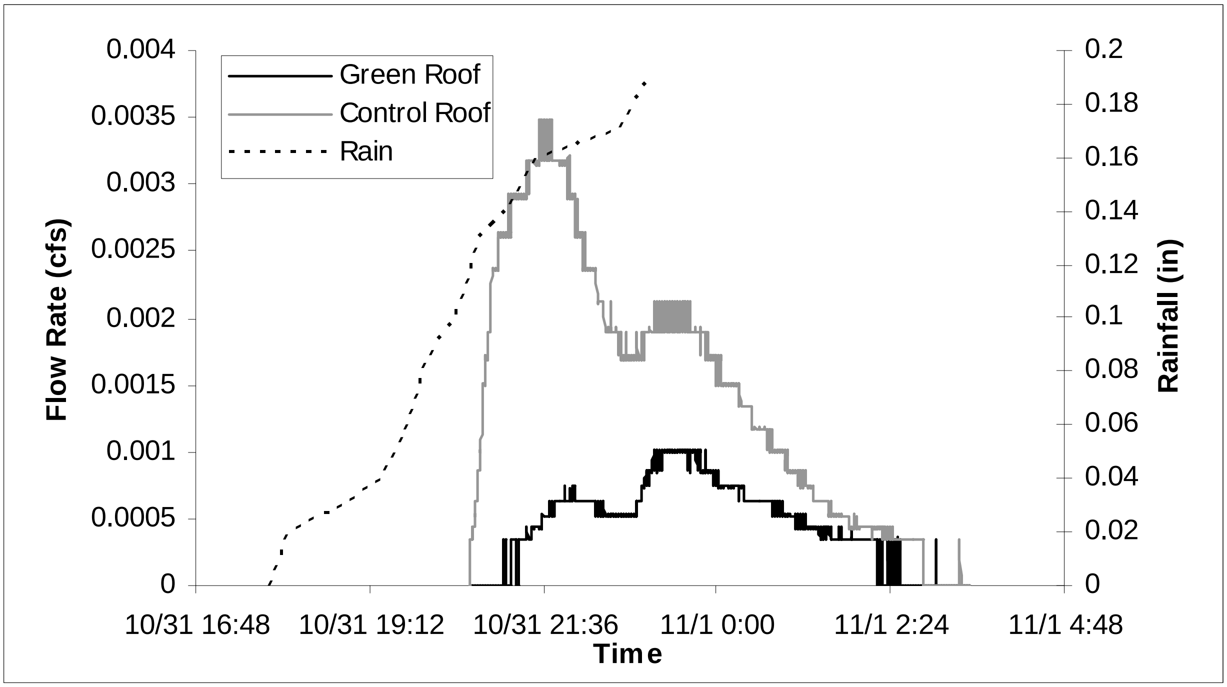

Figure 93 - Runoff Flow Rates - October 31, 2006 Storm

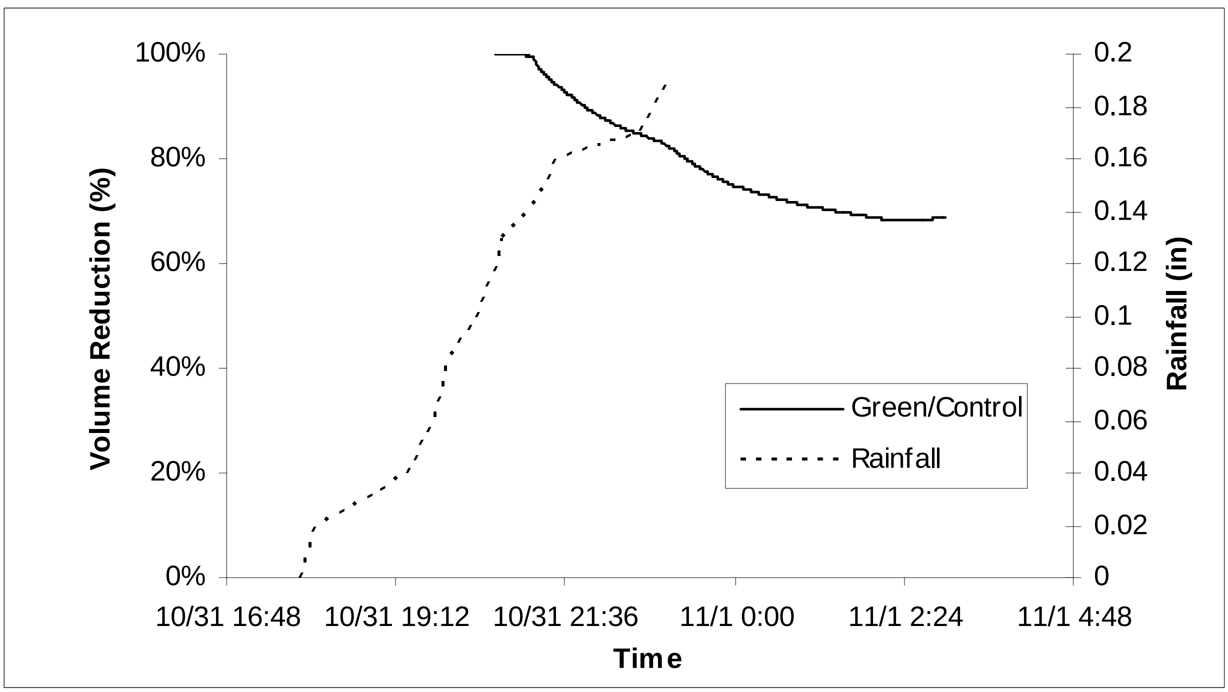

Figure 94 - Runoff Reduction - October 31, 2006 Storm

The October 31st storm is one of the most important observed storm events because at 0.19 inches it is the closest to the average volume of rainfall for Pittsburgh of 0.25 inches. Figure 84 shows a 69 percent reduction in runoff volume by the end of the storm. In Figure 88, a number of lines are drawn to show the runoff reduction after 0.19 inches of rain fell in the October 27th storm. There was an approximately 90 percent reduction at that point. Nearly one additional inch of rain fell before the end of this storm. These numbers underscore the importance of soil moisture in green roof performance. Before the October 27th storm, there was a period of eight days without rainfall. The volumetric water content was 15.8 percent at the start of the storm. There was only four days before the next storm, on October 31st. At this point, the soil moisture was at 18.6 percent. With dryer soil before the October 27th storm, there is better performance by the green roof. There was even a higher intensity for the storm on the 27th, as the first 0.19 inches of rain fell in several hours less than the October 31st storm. These two storms were chose for comparison because of their proximity. Factors such as plant growth and weather were essentially unchanged.

Delays in producing runoff were not as clear. There are many instances where the runoff from the green roof begins flowing after it has begun to flow from the control roof, at times significantly. The November 11, 2006 storm, for instance, had a 4 hour and 9 minute delay and the November 1, 2006 storm had a delay of just under an hour. In many instances, though, the delay was minimal, on the order of 1 or 2 minutes up to a half hour. There are even some cases where the green roof produced runoff first, although these are usually insignificant delays. Each instance of no delay or the green roof producing runoff first occurred in one of two conditions. Several times, irrigation flow started just before a storm, negating any potential delay. In every other instance, it occurred shortly after a previous rainfall. For instance, the November 1, 2006 storm produced runoff from the green roof about an hour before the control roof, but there was another storm that ended only 16 and a half hours earlier. The water content of the soil was about 23 percent prior to the storm, the highest recorded during the observation period. In other words, a delay in runoff from the green roof can be expected when there is a dry period prior to the storm. The soil is somewhat dry and has room to absorb moisture. When the soil is at or near saturation (shortly after a storm), a delay will be minimal and may not occur at all.

There is also delay from the time rainfall begins to fall and runoff is produced from the green roof. With one exception, there was at least a delay of 45 minutes. In many instances it was one to several hours. It was only the most severe conditions, when the first 0.3 inches of December 1, 2006 storm fell in roughly 10 minutes, that there was a brief delay of only 8 minutes. A delay is usually also experienced on the control roof, although it is often less than that of the green roof.

At the conclusion of a storm, the green roof extended flow by a significant amount of time. The flow rate from the green roof continued to flow at a very low rate after the control roof was no longer producing runoff after most storms. At times, the difference was only a few minutes, but in most cases it was several hours. The majority of storms saw an extension of one to four hours. The most significant extension was the October 27, 2006 storm when runoff flowed from the green roof for an addition 6 hours and 46 minutes. During a couple of the smallest storms, the green roof stopped producing runoff first, although runoff never continued to flow from the control roof for a significant amount of time.

There are both similarities and differences between the results obtained during the Giant Eagle project and the pilot project. The simulated storms in the pilot project had profiles very similar to those experienced on the Shadyside green roof. The same basic pattern is present in both, with a rapidly increasing peak during the rainfall that drops off just as quickly after it ends. The runoff flowed from the test plots at a low flow rate for a significant period of time after the storm, but there was no control roof to measure the extension at the end of the storm. Likewise, there was a delay between the time the simulated rain was applied to the roofs and runoff began to flow, but there is no control roof for comparison.

The major difference between the two studies is the volume of runoff retained. Storm to storm, the pattern is basically the same. There is more water retention when the soil is dry and less retention when it is wet, shortly after the previous rainfall. Over the study period, however, the extensive pilot roofs retained roughly 70 percent of all rainfall. While the Giant Eagle roof consistently reduced the runoff volume compared to the control roof, it did not retain that high a percentage of the total rainfall. It is difficult to obtain an exact figure due to the interference of the irrigation system, but at least 20 percent of the total rainfall was retained by the Giant Eagle green roof.

There are several different possibilities to explain the performance difference between the two studies. The most significant is the irrigation interference. The daily watering of the Giant Eagle green roof resulted in constantly saturated soil, reducing the water retention capabilities of the roof. The test plots were only watered on a few occasions: just after the plant installation and after a period of several weeks without rain. The Giant Eagle roof was frequently watered beyond saturatation. The most notable difference between the two data sets is that there were numerous small storms that produced no runoff during the pilot study. This did not occur during any of the available data sets for the Shadyside green roof. The August 27, 2006 storm, which occurred before the irrigation interference began and while the plants were alive, the first 0.08

inches of rainfall was retained without runoff. With more controlled irrigation in the next growing season, better performance should be expected.

Additionally, the pilot project test plots were stored at a fairly steep slope to ensure drainage. They likely had a steeper slope than the actual roof, which would contribute to more drainage.

The volumetric water content of the green roof substrate does appear to affect the overall performance of the green roof, though the data is more limited than any of the other measured parameters. Between rain storms, the water content generally stabilized to about 15 percent by volume. In January of 2007, the values dropped to as low as 10 to 12 percent. During this time, however, temperatures were often dropping below freezing. The ambient temperature on the roof was between 25 and 30 degrees in the days preceding the low water content readings. While there were warmer days (reaching the mid 50 degree range) in the week prior, night time temperatures were consistently below freezing. The water content reaches a maximum during a rainfall. Though there was one instance of a 34 percent water content by volume reading during the longest and heaviest rainfall (January 12 to 15, 2007 storm), the peak values were usually 20 to 28 percent. The Garland specifications for the soilless mix (Table 1) list a maximum water content of 45 percent by volume. The values recorded during the project are lower than this at all times. The compaction of the soil during plant and instrument installation is likely the cause. This process would reduce the volume of voids in the soil and reduce the moisture retention qualities of the substrate.

The clearest relationship between water content and runoff is water content in relation to the point when runoff begins to flow. Figure 95 shows a plot of the volumetric water content just before the start of each storm versus the depth of rainfall that fell before runoff began to flow from the green roof. Both measurement locations are shown on the graph, but location A is the most important. This measurement point is situated a few feet from the green roof drain where runoff measurements are recorded. Figure 95 shows more rainwater is retained by the green roof when the substrate is drier. Dry soil has more void spaces available to absorb water. The results presented in the graph show all storms with available data from October 17, 2006 through the end of the year. Three additional storms from January 2007 are not plotted. These storms all produced runoff after approximately 0.1 inches of rain fell, at starting volumetric water contents of 14 to 19 percent. These results do not match exactly with the earlier data. As mentioned earlier, during this time period temperatures were often below freezing, including periods of snow accumulation, which likely affected the results.

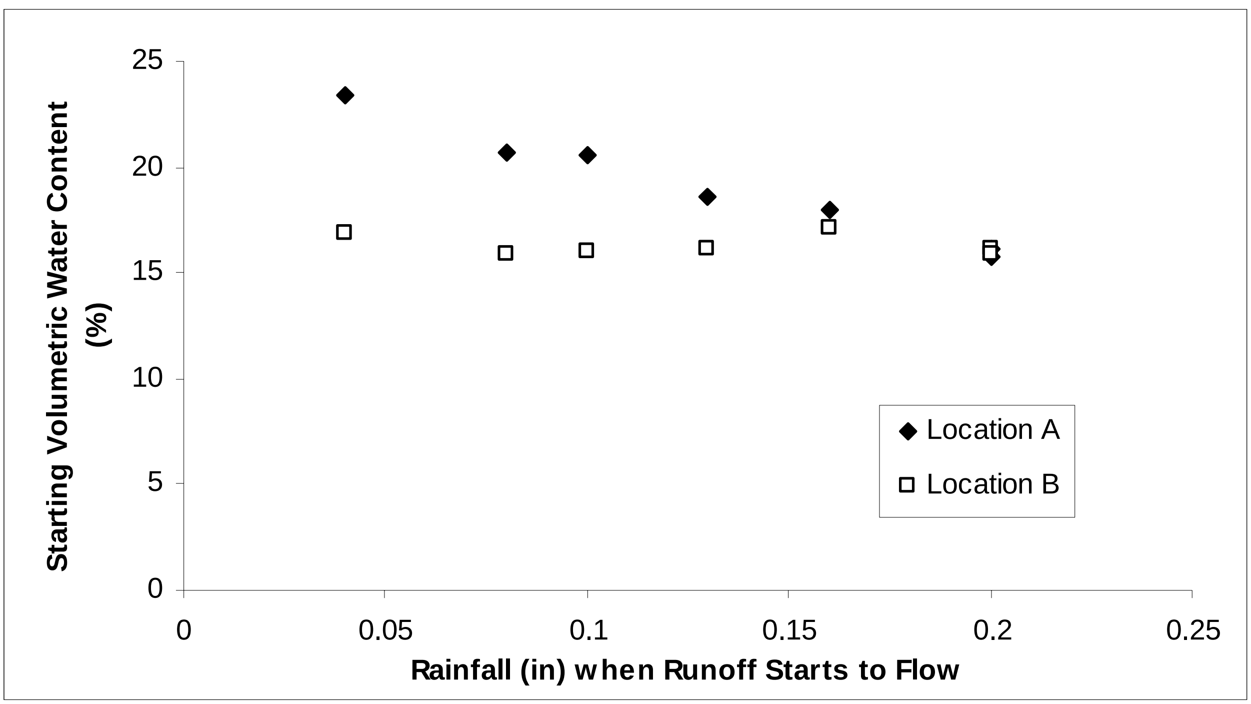

Figure 95 - Water Content versus Rainfall Depth at the Start of Runoff Flow

To further illustrate the affect of the starting volumetric water content, three consecutive storms from October 27 through November 1, 2006 will be examined in more detail. The volumetric water content is 15.8 percent at both green roof locations on October 27th, before there is any rainfall. The storm starting on October 27th had an intensity of about 0.05 inches per hour (1.2 inches of rain in 24 hours). The water content levels were elevated before the October 31st storm, to 18.6 and 16.2 percent. This storm deposited 0.19 inches of rain on the roof in 5 hours and 14 minutes (0.036 in/hr intensity). The volumetric water content levels were further increased prior to the November 1st storm at 23.4 and 16.9 percent, respectively. 0.07 inches of rain fell in about 2 hours (0.035 in/hr intensity) during the storm.

With little time for the water to transpire and evaporate between these consecutive storms, the starting volumetric water content consistently increased. This effected several characteristics of the green roof runoff. Each progressive storm had a shorter delay between the time the storm started and runoff began to flow. On October 27th, the delay was three hours and nine minutes. This was reduced to three hours and five minutes on October 31st and forty nine minutes on November 1st. While there is only a four minute difference between the delays on the 27th and 31st of October, there is a significant difference in storm intensity. The October 27th storm intensity was more than two times as great as the October 31st storm, yet there is less of a delay during the second storm. Further more, the November 1st delay is significantly shorter than both. Despite being the lightest storm recorded (0.07 inches), it is the second shortest delay during the monitoring period. The elevated water content levels at the start of this storm are the highest of any storm. Temperatures were fairly warm during this period. The ambient temperature on the roof before the October 27th storm was between 45 and 50 degrees. The temperature steadily increased to about 75 degrees on October 31st before dropping slightly to around 70 degrees on November 1st.

Similarly, the delay between the green and control roof runoff may also be affected by the starting water content. The delays of the October 27th and October 31st storms are similar, at 30 and 26 minutes, despite the significant difference in storm intensities.

The starting volumetric water content does not appear to affect the overall runoff volume or runoff flow rate characteristics. The October 27th storm is heavier than most measured storms at 1.2 inches, while the October 31st (0.19 inches) and November 1st (0.07 inches) are among the lightest. Conversely, the overall runoff volume reduction is on the low end (20 percent) for the October 27th storm, while the other storms are two of the three best in performance (about 70 percent reduction). The flow rate reduction is also the lowest for the October 27th storm.

Based on these results, the overall depth, duration and intensity of storm are the main factors affecting the runoff volume and flow rate reduction, but starting volumetric water content affects the delay in runoff when comparing the green roof to both rainfall and the control roof.

Figures 96 through 99 show several overall trends from data. First, in Figure 96, an Intensity-Duration-Frequency graph is shown with both the Giant Eagle green roof data and historical Pittsburgh weather data from NOAA (Bonnin 2004). The NOAA data shows the 1 and 5 year storms. This represents the average intensity that should be expected in a one or five year period for a given duration and frequency. The green roof data plotted along side this data shows that most measured storms are either at or below the 1 year storm level. The data recorded here, therefore, is a cross section of storms at various intensities and durations that would be experienced in a typical year. There was one exception to this, on October 17, 2006. 1.94 inches of rain fell in 10 hours, corresponding to about a 5-year storm. As noted earlier, the 0.25 inch average rainfall number used by the 3RWWDP is the average depth of rainfall calculated by dividing the total amount of rainfall during a year in Pittsburgh by the total number of days that it rains.

The relationship between runoff reduction and rainfall depth is shown in Figure 97 and runoff reduction versus duration is plotted in Figure 98. The general trend is that as the amount of rain or duration of the storm increases, the runoff reduction decreases. The three storms with the best performance have the lowest total rainfall and durations. Likewise, the two worst cases are two of the largest storms with the longest durations. In Figure 97, the area of peak performance is for storms of about 0.6 inches or less. At least a 20 percent reduction in runoff volume can be expected. This accounts for approximately 45 percent of the storms during the observation period. Figure 99 combines these two graphs into an intensity versus runoff reduction plot. A relationship is between intensity and runoff reduction is not evident.

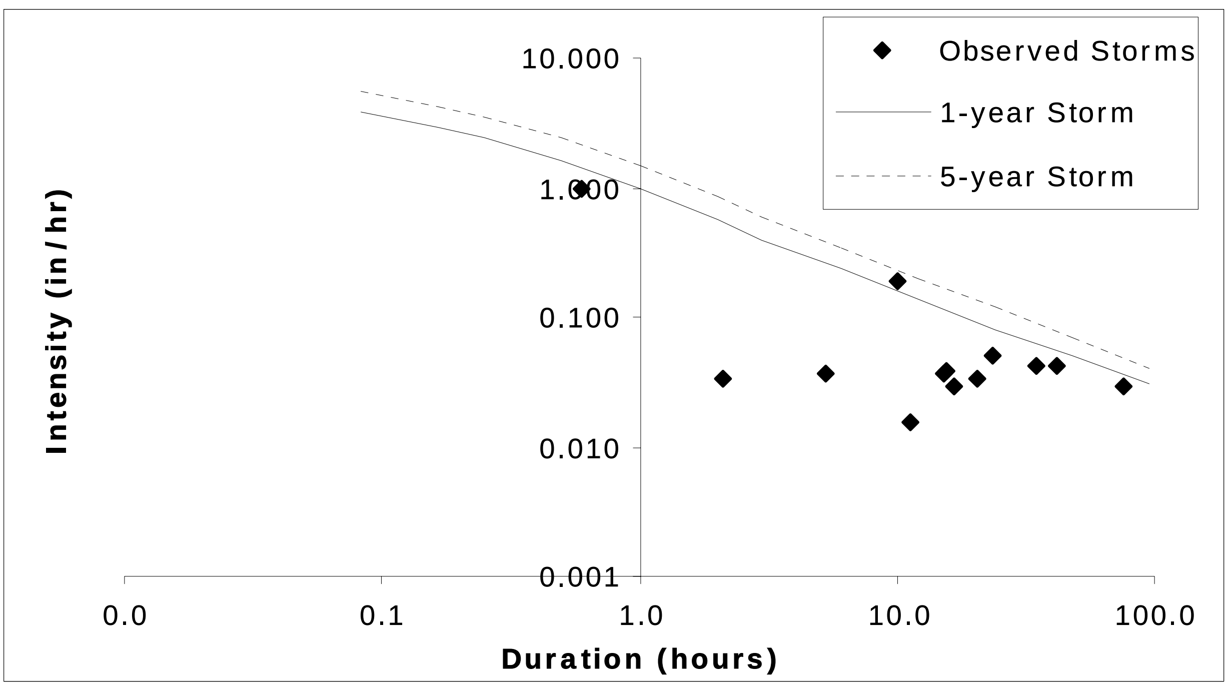

Figure 96 - Intensity-Duration-Frequency Curve - Green Roof and NOAA Data (Bonnin 2004)

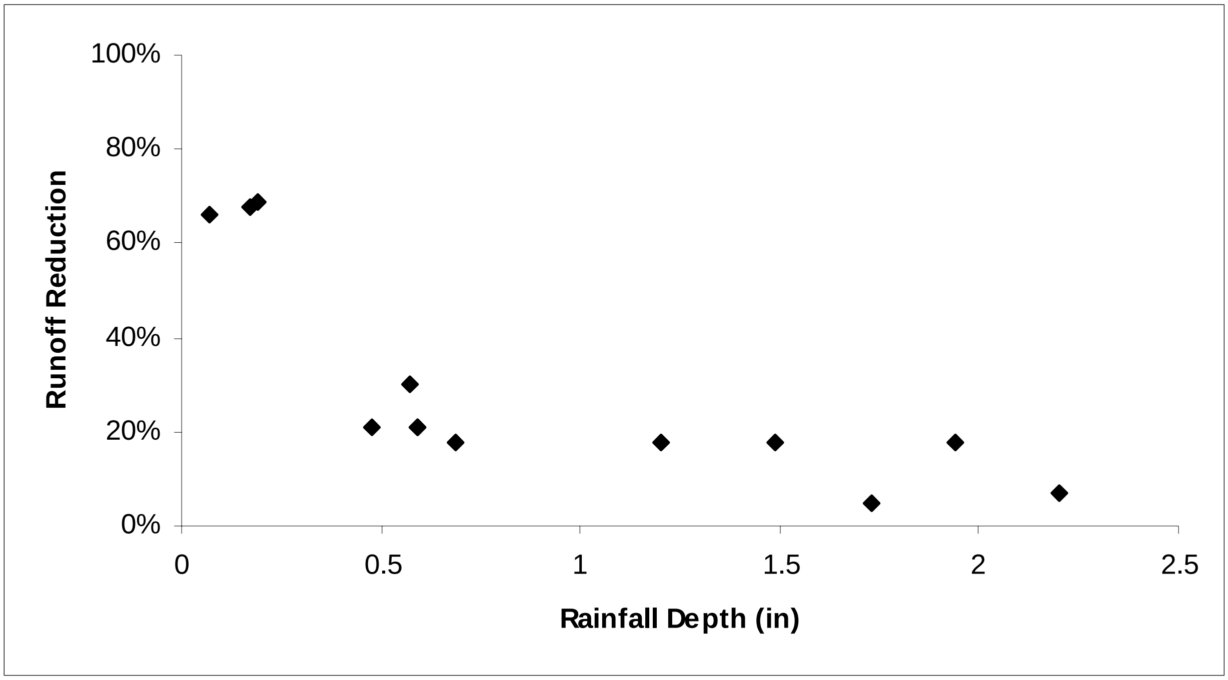

Figure 97 - Runoff Reduction versus Rainfall Depth

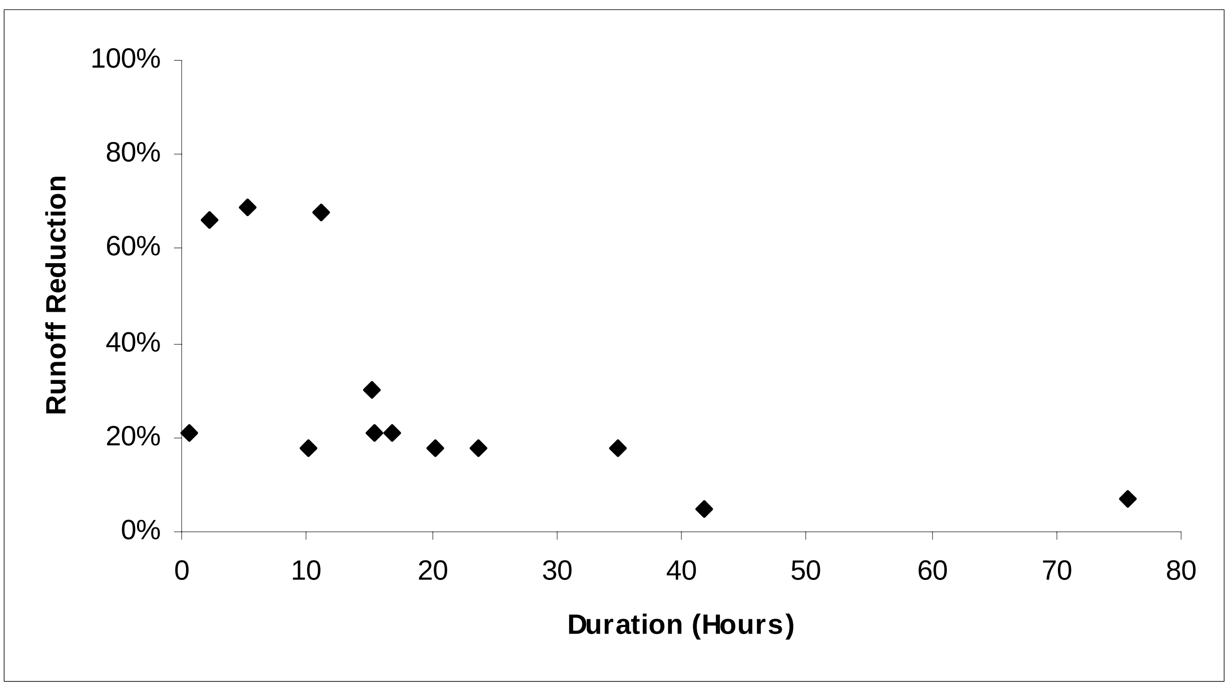

Figure 98 - Runoff Reduction versus Duration

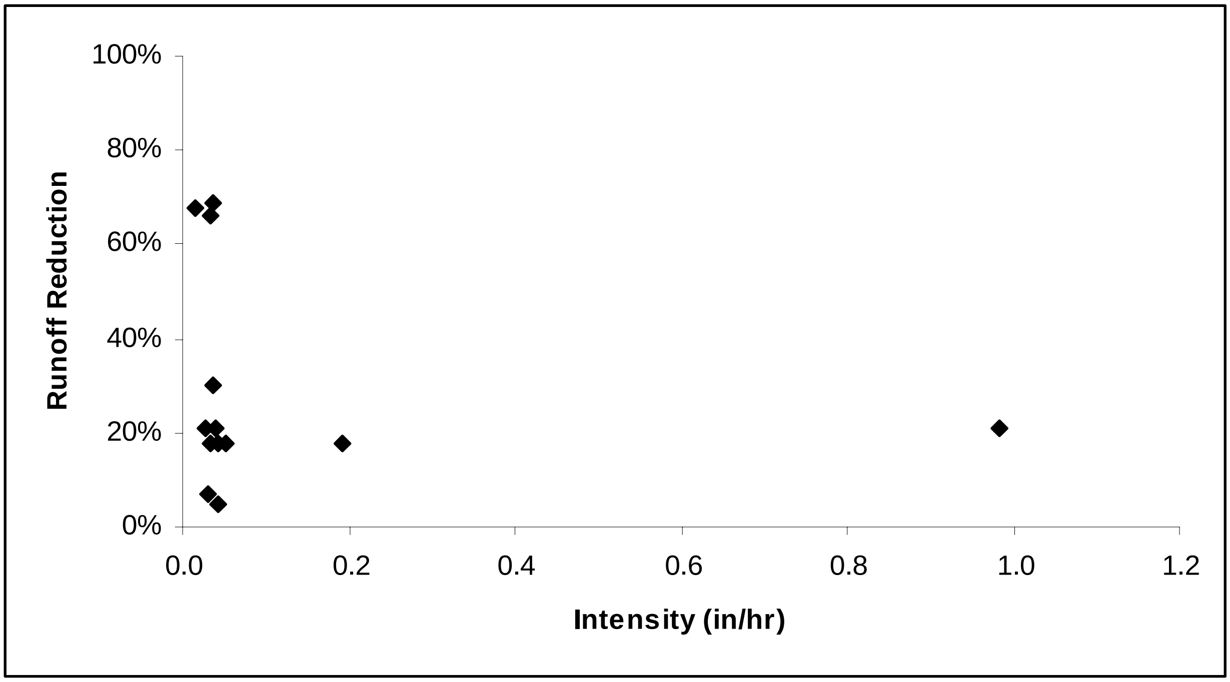

Figure 99 - Runoff Reduction versus Intensity

By using a series of six sequential valves for both the control and green roofs at the Shadyside site, the first flush effect could be studied. Based on the whole of the water quality results for the project, there does not appear to be a significant first flush effect. The green roof runoff samples did not exhibit any first flush characteristics for any parameter. The control roof runoff samples showed some first flush effects, but only on a limited basis. As discussed in Chapter 5, some storms showed a steady decrease in turbidity. In one of these instances, the same effect was observed for sulfate. Based on the test results for the storm in question, the first flush on the control roof appears to be due to an increased amount of non-dissolved sulfate. This likely built up on the roof during the dry period prior to a storm. It is likely that the prior dry period and first flush effects are correlated.

In terms of the turbidity in general, the control tended to have more turbid samples. In some of the cases where there was a first flush effect, there was a significant difference between the first control roof sample and any of those from the green roof in particular. Most instances did not see that large of a gap between the two roofs, however. While the green roof runoff could be expected to be more turbid than the results show, there are some reasons why it may be lower. First, there was usually build up of soil in the drainage pipe just before the flumes. Had these soil particles remained in the water to the sampling point, a higher turbidity may have occurred. Additionally, some green roof valves became clogged at times. This was presumably the result of soil particles becoming jammed in the valve mechanics and not making it into the sampling bottles. In the case of the pilot project, the turbidity of the green roof samples was quite high, especially early on and after dry periods. The values did eventually equalize to lower values, similar to those observed at Giant Eagle. Frequent irrigation likely decreased the period of high turbidity and samples were not collected for several months after the roof was completed, so the effect may have been missed.

Perhaps the clearest conclusion regarding water quality is that phosphorus is leaching from the green roof. The green roof runoff samples consistently had phosphorus concentrations of 2 to 3 mg/L while both the control roof runoff and rainwater contained only negligible, if any, phosphorus. Similar results were found for the pilot project. Very low levels of phosphorus were found in the rainwater and 15 to 25 mg/L were found in the green roof runoff samples. This significant increase in phosphorus concentration is likely due to the time sampling occurred. The pilot project samples were collected shortly after the construction and installation of the test plots, while the Giant Eagle samples were collected between three and four and a half months after the installation. This indicates that phosphorus leaching will decrease with time. It should also be noted that the pilot project testing was of a single storm, while the main project contained numerous samples from multiple storms.

Likewise, COD levels are consistently higher in the green roof runoff than the control or the rainwater. The green roof samples were roughly twice that of the control.

Despite the previously discussed relation to first flush and sulfate, there is not a clear difference between sulfate levels on the two roofs. Each roof produced higher concentrations than the other during at least one storm. The samples did contain at least two to three times more sulfate than the rainwater. It appears that sulfate deposited on the roof is a significant source in the runoff.

Testing has shown that nitrogen is essentially non existent from all sources. The majority of samples tested showed a concentration of zero. Most of the other samples had very low levels. No discernable pattern was evident.

The testing completed for metals was more limited than the others, but a few conclusions can be drawn. No detectible concentrations of cadmium were found in the samples tested. This is true not only of the Giant Eagle site, but also the pilot project. In all tests for metals, the Giant Eagle samples were undigested, filtered samples. Acid digestion was preformed on the pilot project samples prior to testing.

In the case of zinc, the levels were fairly low, with a maximum of 0.44 mg/L for a green roof samples. The majority of the samples are on the order of 0.1 mg/L. Runoff from one roof is not consistently higher than the other, nor is the rainfall appreciably different from the runoff samples. Results were generally higher for the pilot project, with the extensive roof samples having a concentration of 0.7 mg/L compared to 0.2 mg/L for the rainfall.

Again, no clear distinctions can be drawn from the lead testing results. In the pilot project testing, all samples had concentrations of about 0.1 mg/L. For the main project, several samples are at this level. Others, including the rainfall, are higher, at approximately 0.3 to 0.4 mg/L. Overall, these are low levels of lead and no clear pattern emerges.

pH levels from both roofs were consistently slightly basic, with pH readings in the range of 7.5 to 8.25, while the rainfall was slightly acidic. While it appears that the green roof is mitigating the acid rain, the control roof is having the same effect.

It should be noted that the water quality results presented here are preliminary. Additional tests are needed to verify the conclusions. This is especially true in the case of the metals. It is fairly clear, however, that a significant first flush effect is not occurring.

6.0 CONCLUSIONS

The Shadyside Giant Eagle green roof proved to improve the stormwater runoff characteristics at the site effectively in several different ways. A number of conclusions can be drawn from the data collected at the site.

The total volume of runoff was consistently reduced by the green roof. For a rainstorm of 0.6 inches or less, the green roof produced at least 20 percent less runoff than the control roof. The runoff volume was reduced by between 5 and 70 percent during the study period. The performance of the green roof depended on the storm duration and total amount of rainfall. Likewise, the soil water content prior to the start of storm also affected the green roof. Drier soil absorbed more rainfall before runoff began to flow from the green roof.

The green roof reduced the runoff flow rate. It was lower than the control throughout a storm, with the greatest difference occurring in the early stages. The flow rates would converge as a storm progressed, although the green roof value would continue to be lower than the control. The peak flow rates are also reduced by the green roof, by 5 to 70 percent. During several of the lighter observed storms the green roof peak flow rate was delayed, occurring up to a few hours after the peak control roof flow rate. Two other delays were also observed. It would take up to several hours after the start of a rainstorm before the green roof produced runoff. Runoff also often began to flow from the control roof before the green roof.

In terms of water quality, the test results show that a first flush is not evident in green roof runoff for any tested parameters. A first flush was observed in the control roof runoff for turbidity, which was related to a first flush of undissolved sulfate in one instance. The green roof affected water quality in three main areas. The turbidity of green roof runoff samples were consistently lower than the control roof runoff samples and both were higher than the turbidity of rainfall. Phosphorus concentrations were elevated by the green roof, likely due to the use of fertilizers. Phosphorus was not found in either the control roof runoff or rainfall. COD levels in the green roof runoff were also consistently higher than that of the control roof or rainwater. Both roofs neutralized the slightly acidic rain collected at the roof, though there was no apparent difference between the green and control roof runoff samples. Nitrogen and cadmium were not detected during testing from any source. Both lead and zinc are present in the rainfall and runoff samples from both roofs, but more extensive testing is required to determine if the green roof is affecting the concentrations.

In summary, the Shadyside Giant Eagle green roof has reduced the total volume of water entering the sewer system by retaining significant amounts of rainfall. Additionally, by reducing the runoff flow rate during the course of a storm, reducing the peak flow rate and delaying runoff flow, much of the runoff from the green roof reaches the sewer when it is not at peak demand. The green roof reduces the burden on the sewer system and makes combined sewer overflow events less likely. Growing acceptance of green roofs can contribute to cleaner rivers in Pittsburgh and around the world by reducing sewer overflow events.

APPENDIX A

STORM DATA – SHADYSIDE GIANT EAGLE GREEN ROOF

This appendix includes graphs and tables summarizing each of the 24 storms recorded during the measurement period at the Shadyside Giant Eagle green roof. All available data is included, though some storms are incomplete due to the unavailability of various pieces of equipment during the project.

In instances where irrigation interfered with the runoff measurements, graphs are included of both the raw data and adjusted data. The adjusted data removes the irrigation portion of the flow from the calculations.

A.1 JULY 28, 2006 STORM ONE

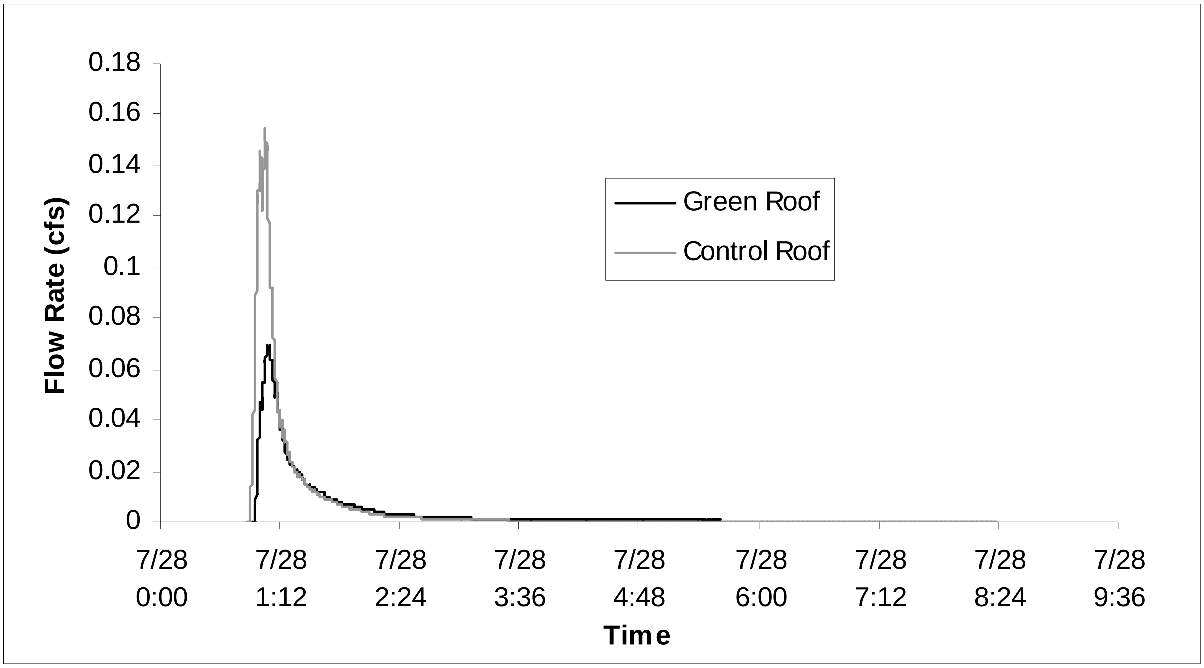

Figure 100 - Runoff Flow Rates - July 28, 2006 Storm One

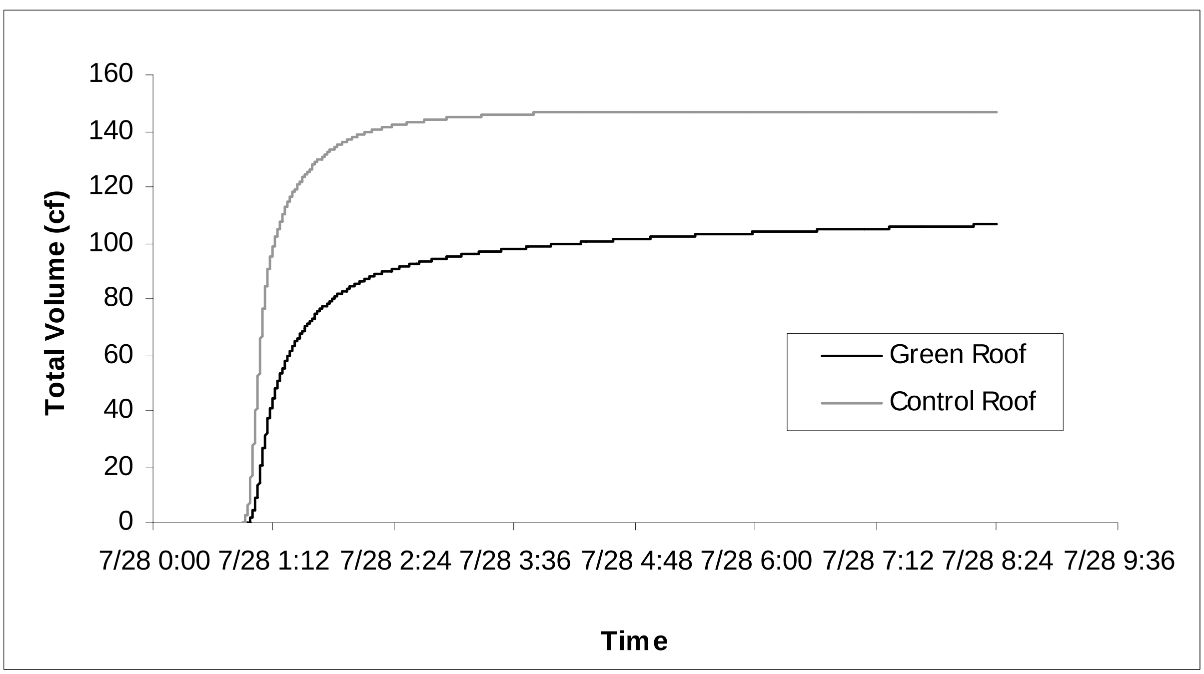

Figure 101 - Runoff Volumes - July 28, 2006 Storm One

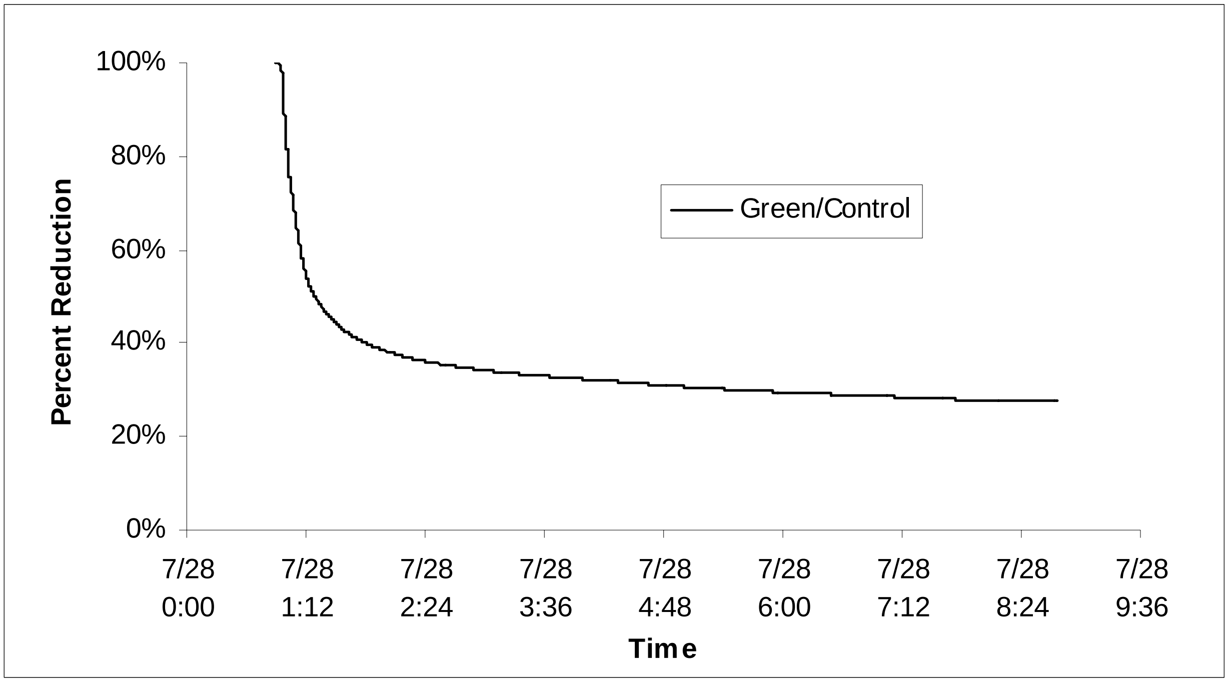

Figure 102 - Runoff Reduction - July 28, 2006 Storm One

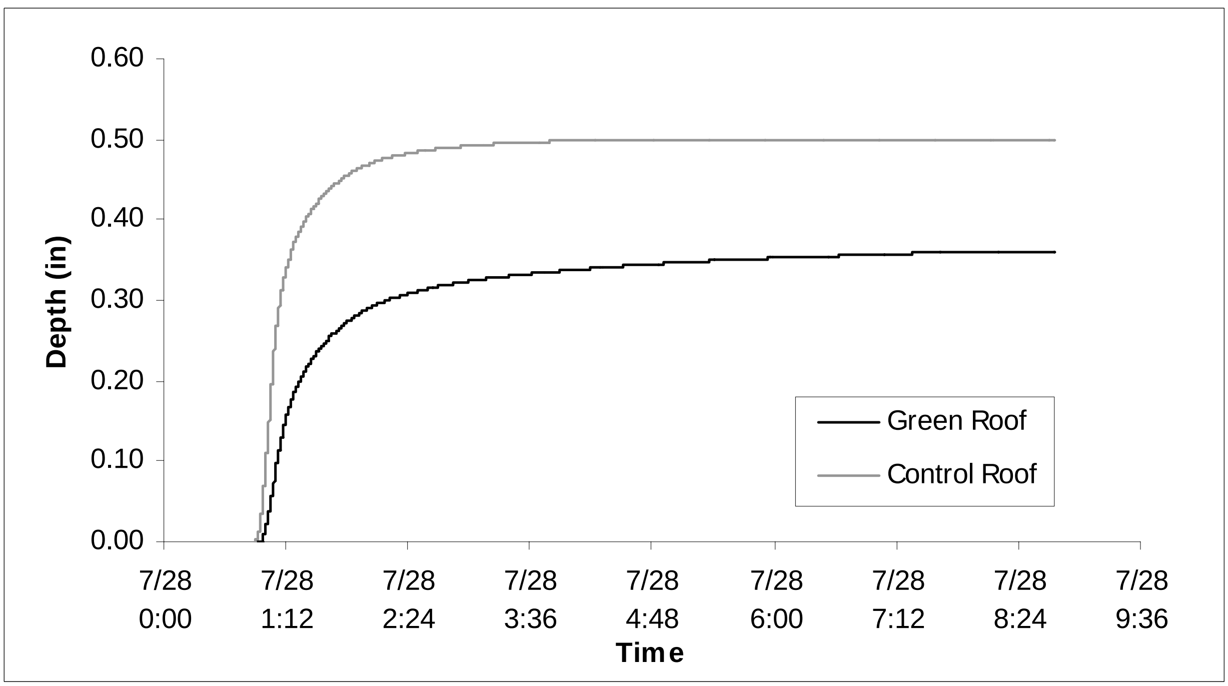

Figure 103 - Runoff as Rainfall - July 28, 2006 Storm One

Table 10 - July 28, 2006 Storm One Summary

July 28, 2006 Storm One		
Rainfall	Depth (in)	
	Length	
Runoff	Delay	0:02
	Extension	4:01
Max Flow Rate (cfs)	Green	0.0696
	Control	0.1542
	Reduction	55%
Total Volume (cf)	Green	106.29
	Control	147.01
	Reduction	28%
Equiv. in of Rain	Green	0.36
	Control	0.5

A.2 JULY 28, 2006 STORM TWO

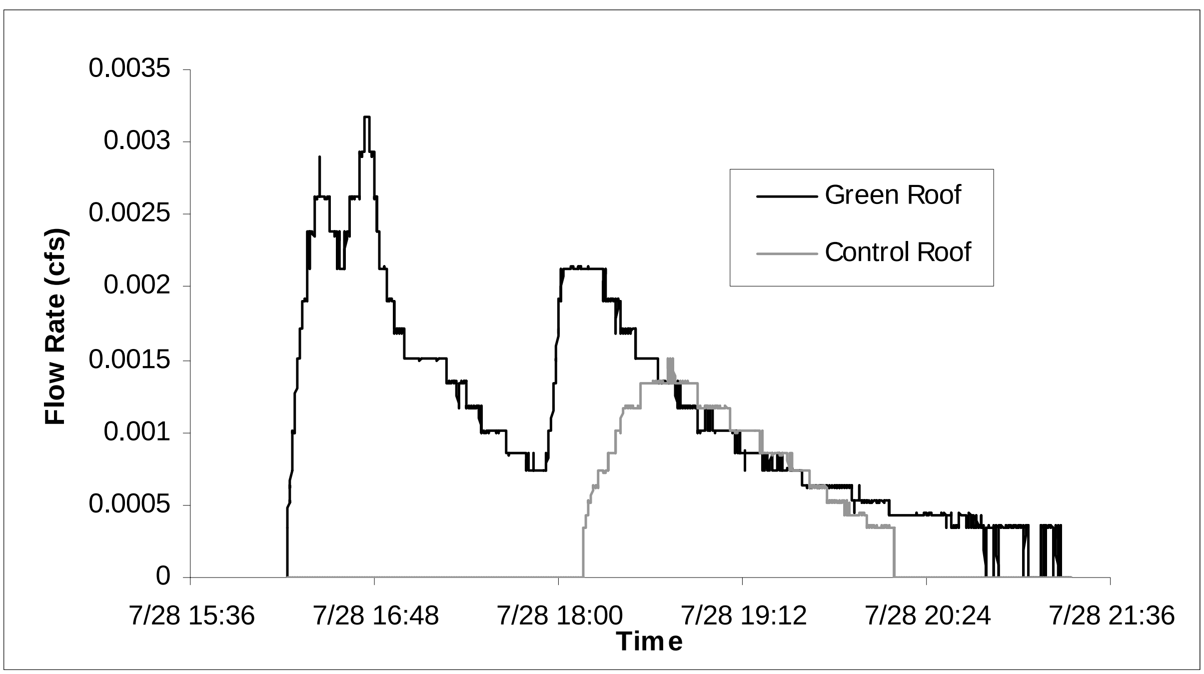

Figure 104 - Runoff Flow Rates - July 28, 2006 Storm Two

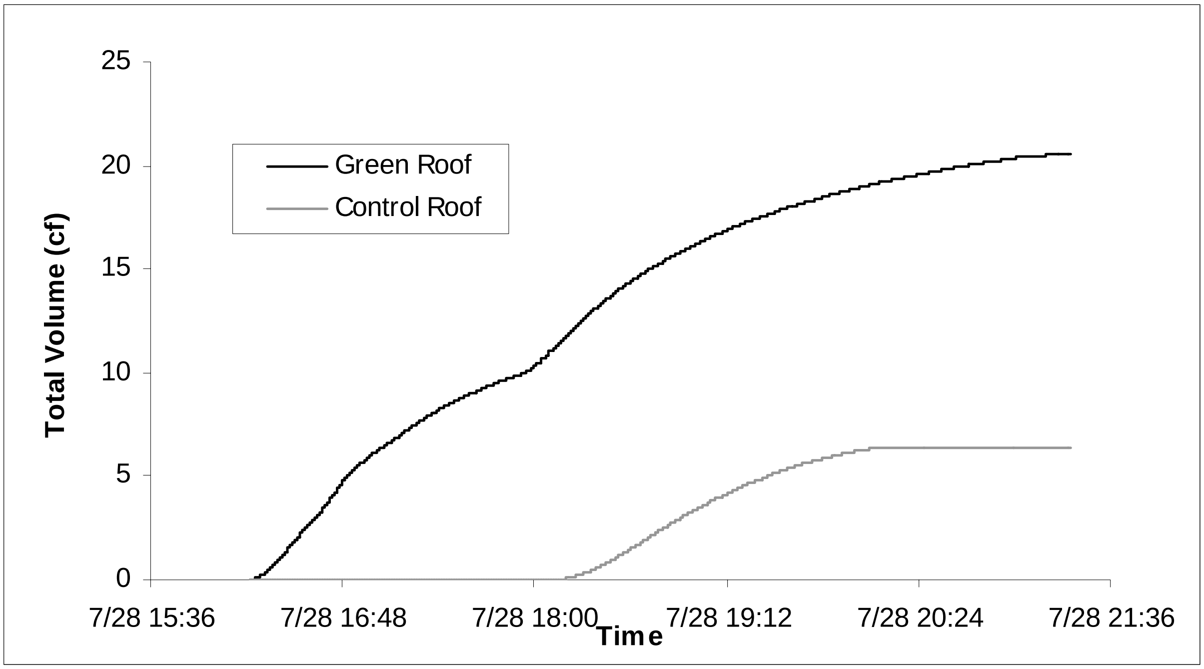

Figure 105 - Runoff Volumes - July 28, 2006 Storm Two

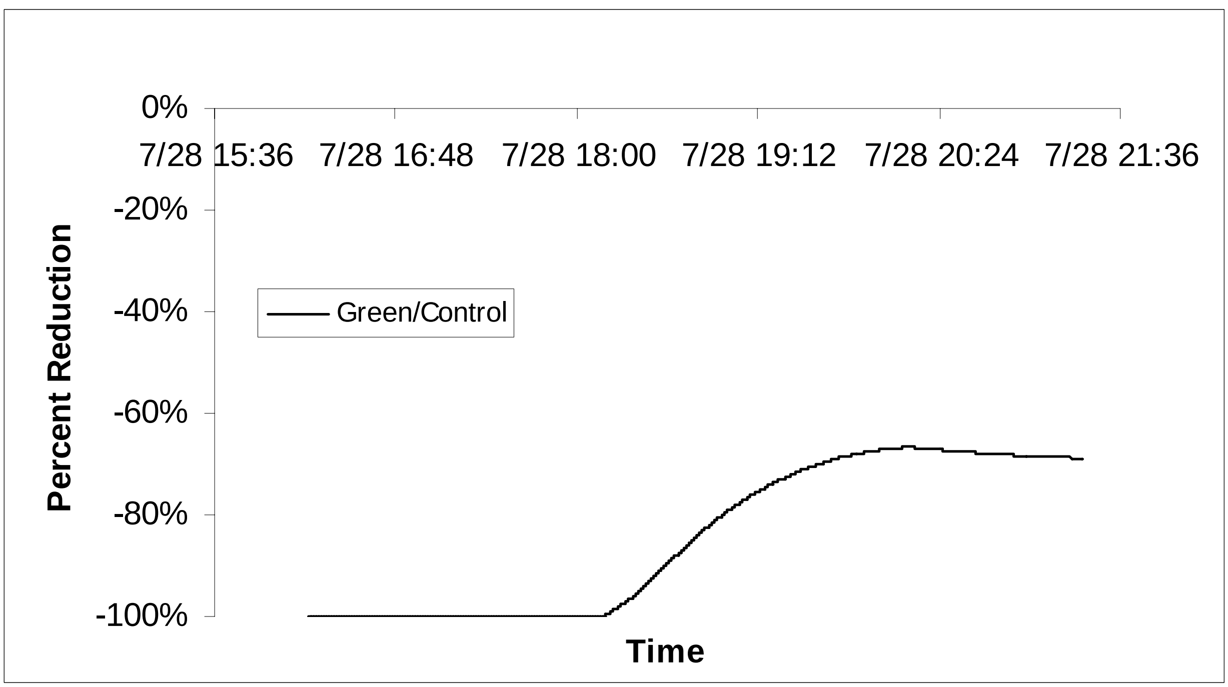

Figure 106 - Runoff Reduction - July 28, 2006 Storm Two

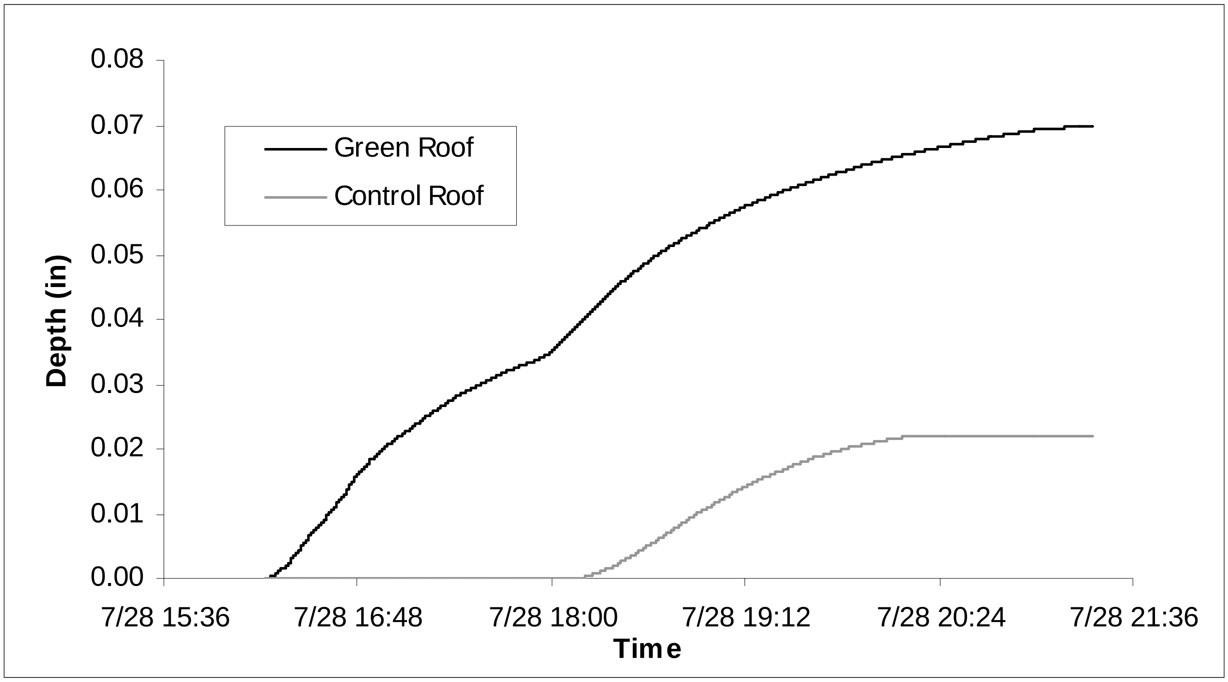

Figure 107 - Runoff as Rainfall - July 28, 2006 Storm Two

Table 11 - July 28, 2006 Storm Two Summary

July 28, 2006 Storm Two		
Rainfall	Depth (in)	
	Length	
Runoff	Delay	1:57
	Extension	1:05
Max Flow Rate (cfs)	Green	0.0032
	Control	0.0015
	Reduction	-53%
Total Volume (cf)	Green	20.55
	Control	6.42
	Reduction	-69%
Equiv. in of Rain	Green	0.07
	Control	0.02

A.3 JULY 30, 2006 STORM ONE

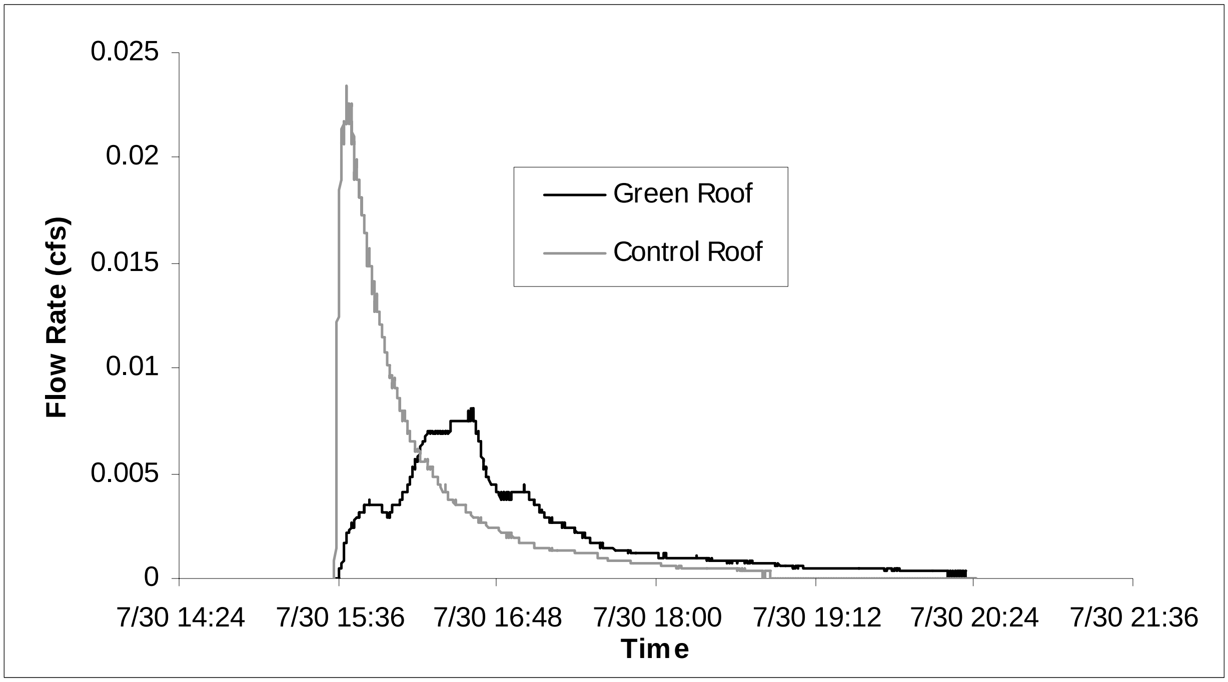

Figure 108 - Runoff Flow Rates - July 30, 2006 Storm One

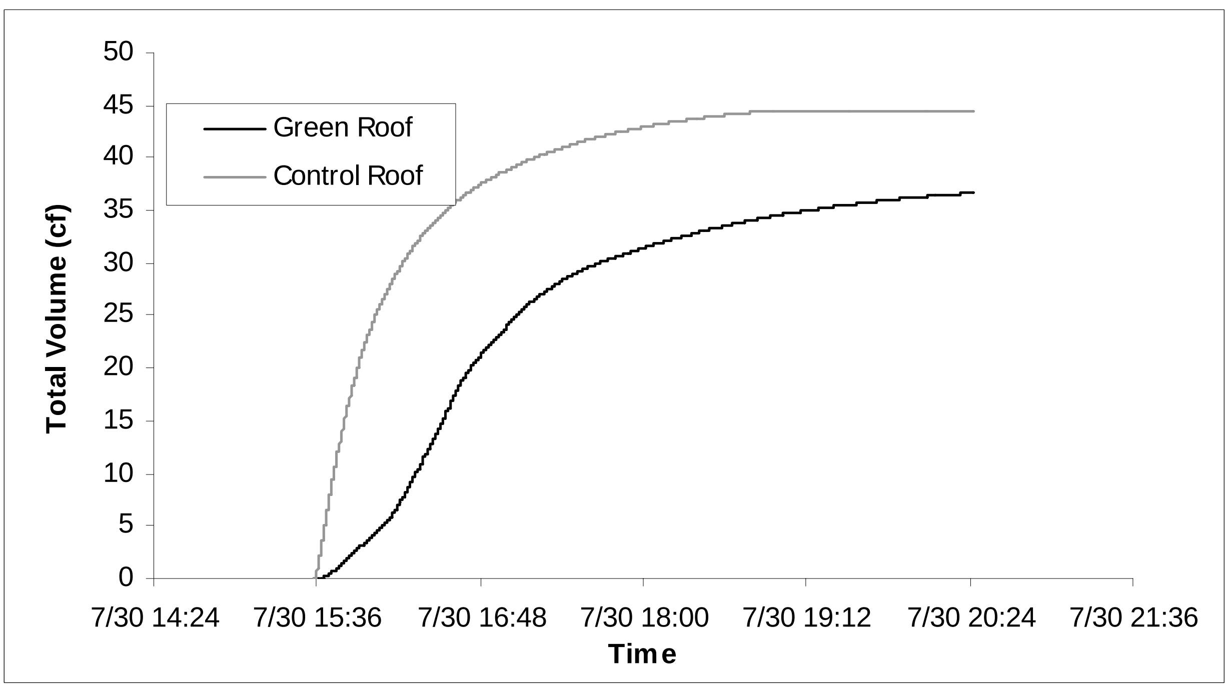

Figure 109 - Runoff Volumes - July 30, 2006 Storm One

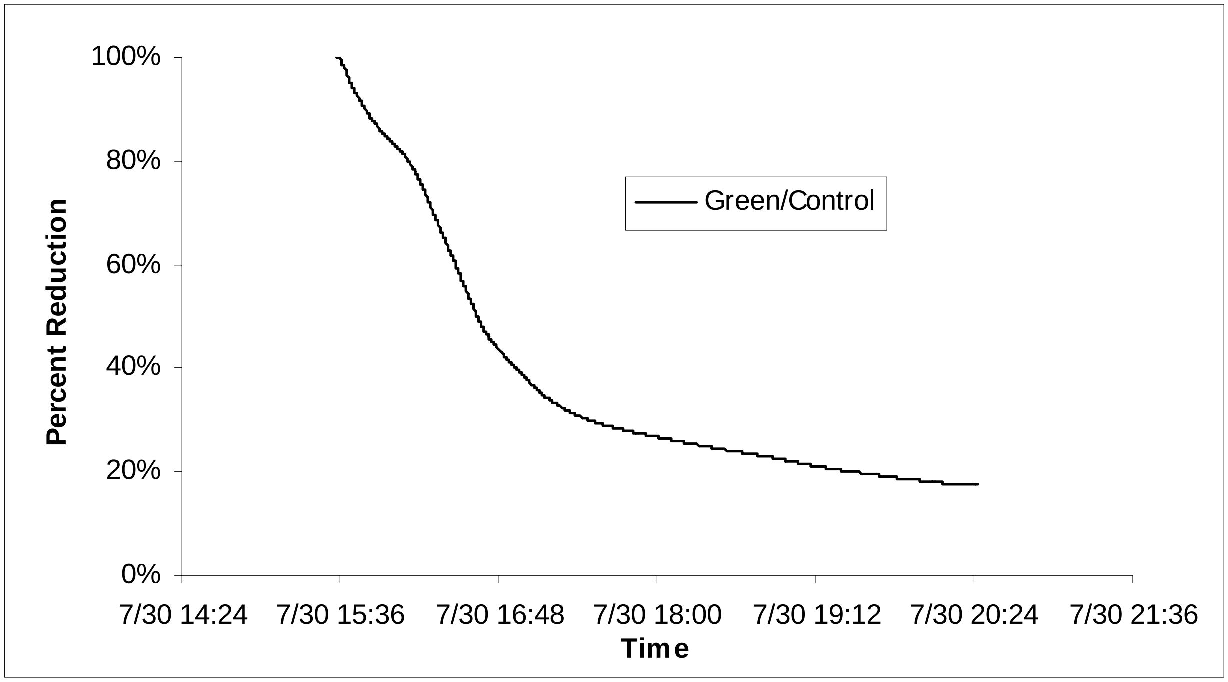

Figure 110 - Runoff Reduction - July 30, 2006 Storm One

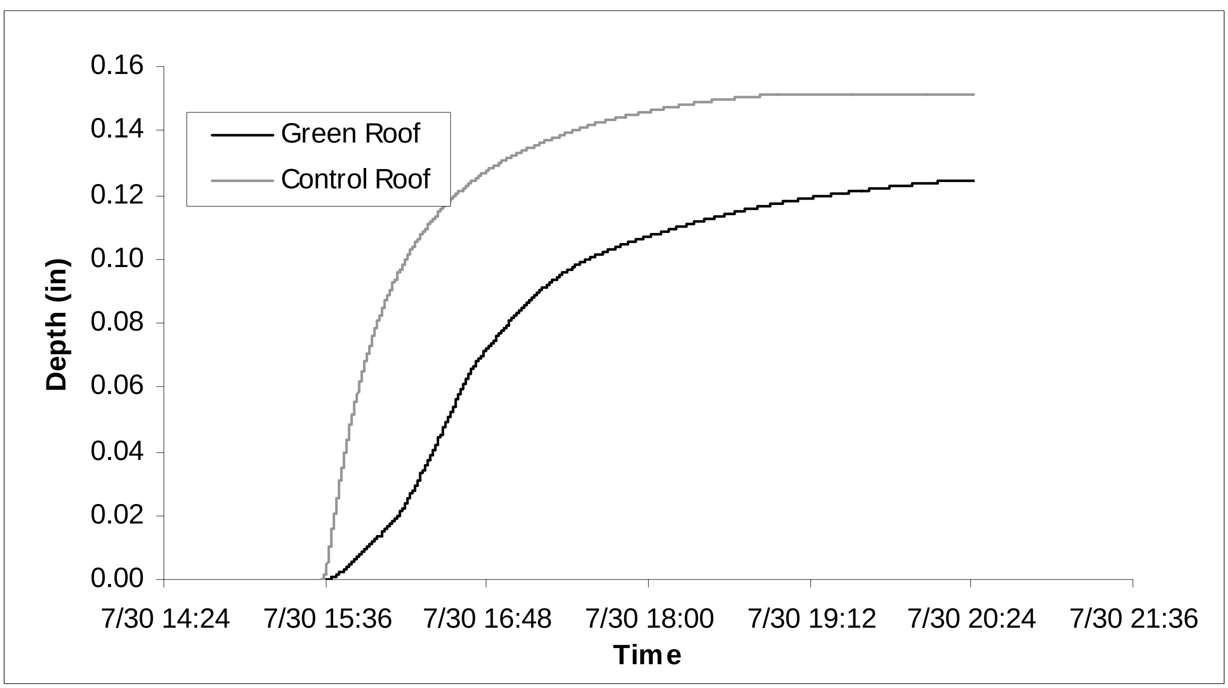

Figure 111 - Runoff as Rainfall - July 30, 2006 Storm One

Table 12 - July 30, 2006 Storm One Summary

July 30, 2006 Storm One		
Rainfall	Depth (in)	
	Length	
Runoff	Delay	0:01
	Extension	1:29
Max Flow Rate (cfs)	Green	0.0081
	Control	0.235
	Reduction	66%
Total Volume (cf)	Green	36.6
	Control	44.4
	Reduction	18%
Equiv. in of Rain	Green	0.12
	Control	0.15

A.4 JULY 30, 2006 STORM TWO

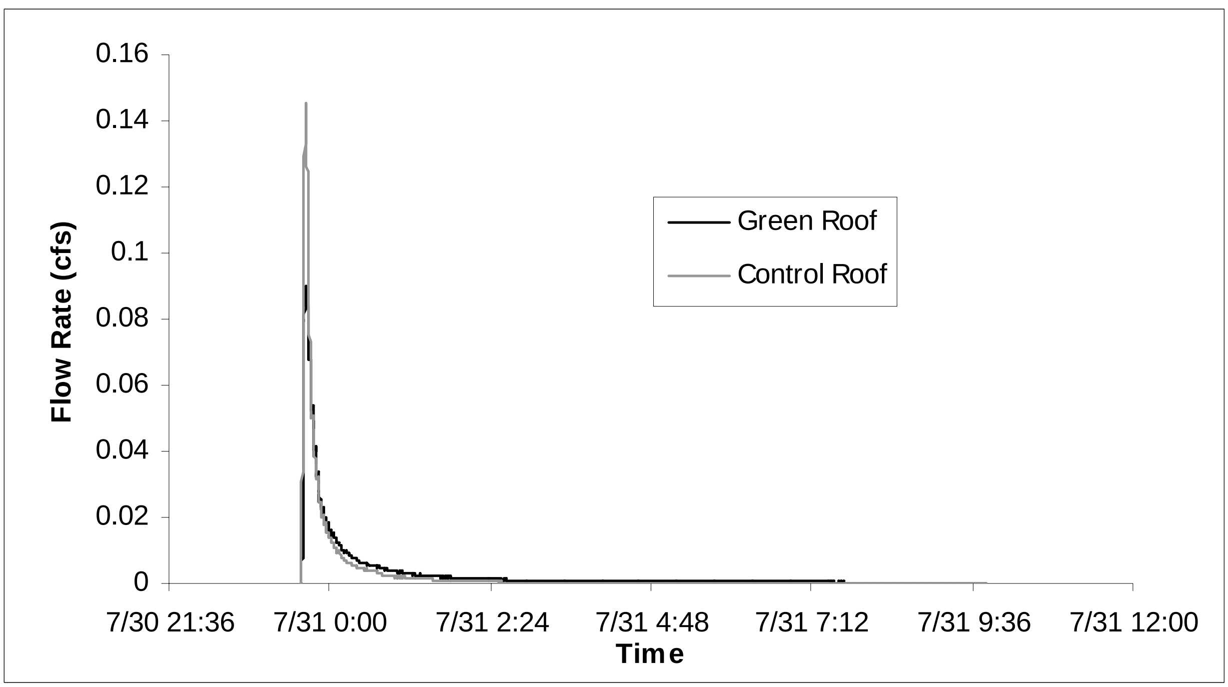

Figure 112 - Runoff Flow Rates - July 30, 2006 Storm Two

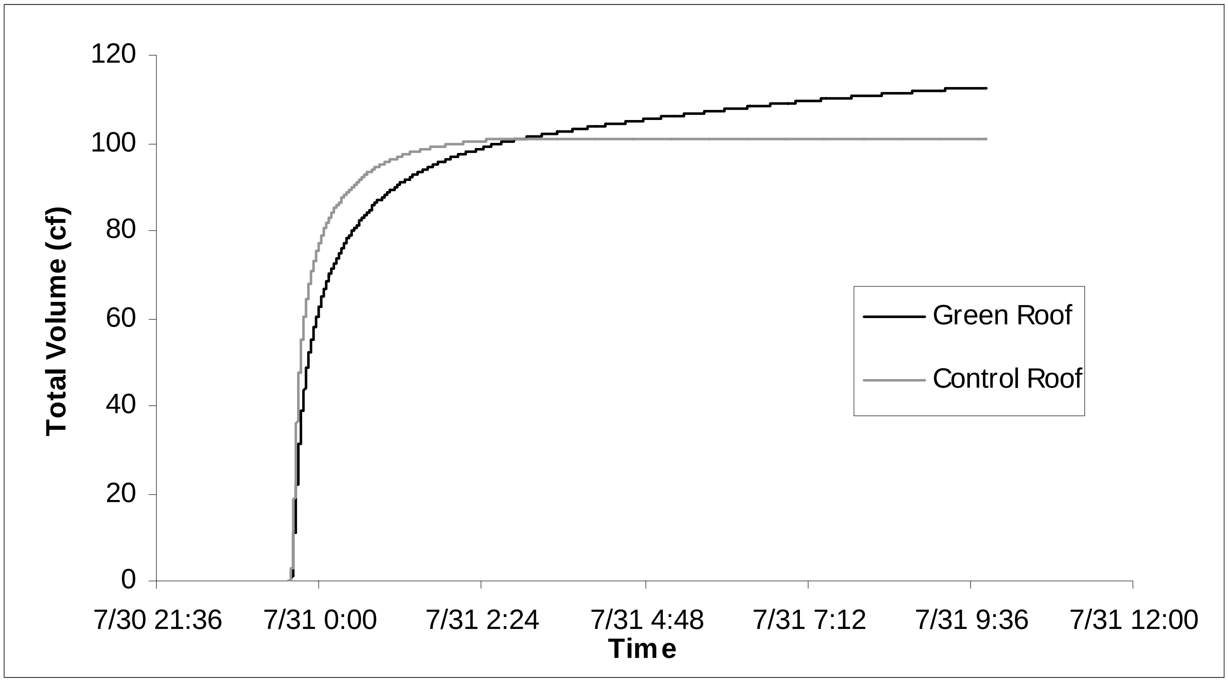

Figure 113 - Runoff Volumes - July 30, 2006 Storm Two

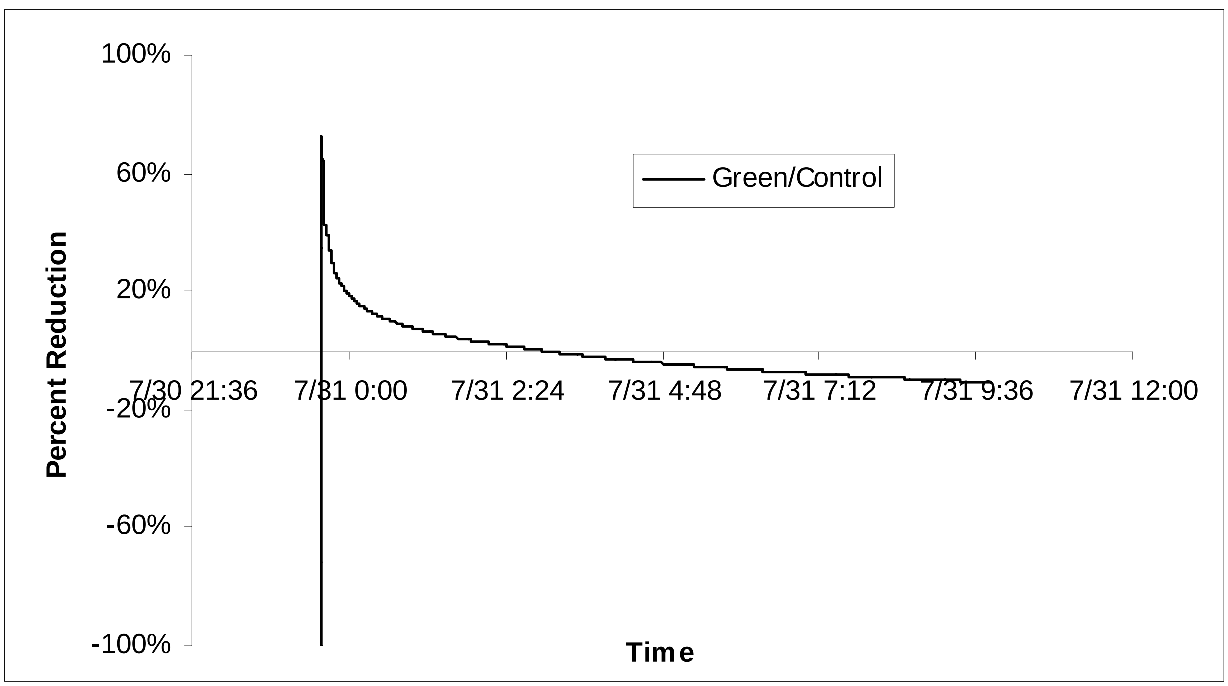

Figure 114 - Runoff Reduction - July 30, 2006 Storm Two

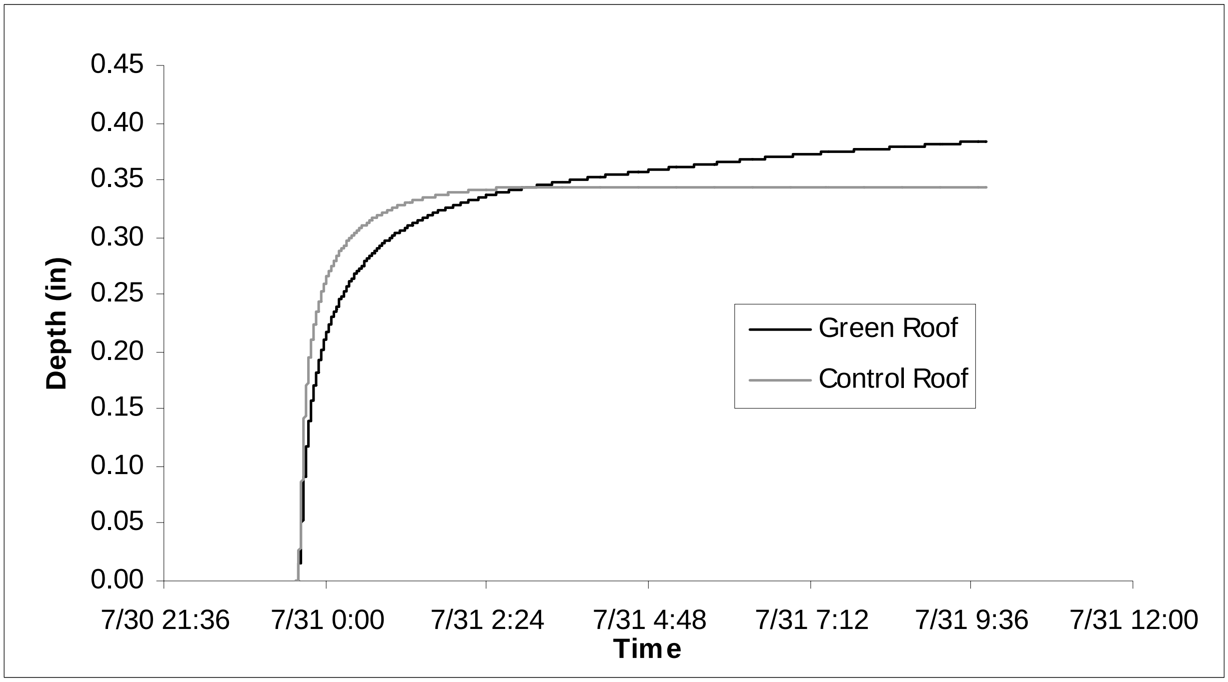

Figure 115 - Runoff as Rainfall - July 30, 2006 Storm Two

Table 13 - July 30, 2006 Storm Two Summary

July 30, 2006 Storm Two		
Rainfall	Depth (in)	
	Length	
Runoff	Delay	0:00
	Extension	- 1:14
Max Flow Rate (cfs)	Green	0.0903
	Control	0.1455
	Reduction	38%
Total Volume (cf)	Green	112.58
	Control	100.76
	Reduction	-11%
Equiv. in of Rain	Green	0.38
	Control	0.34

A.5 AUGUST 27, 2006 STORM

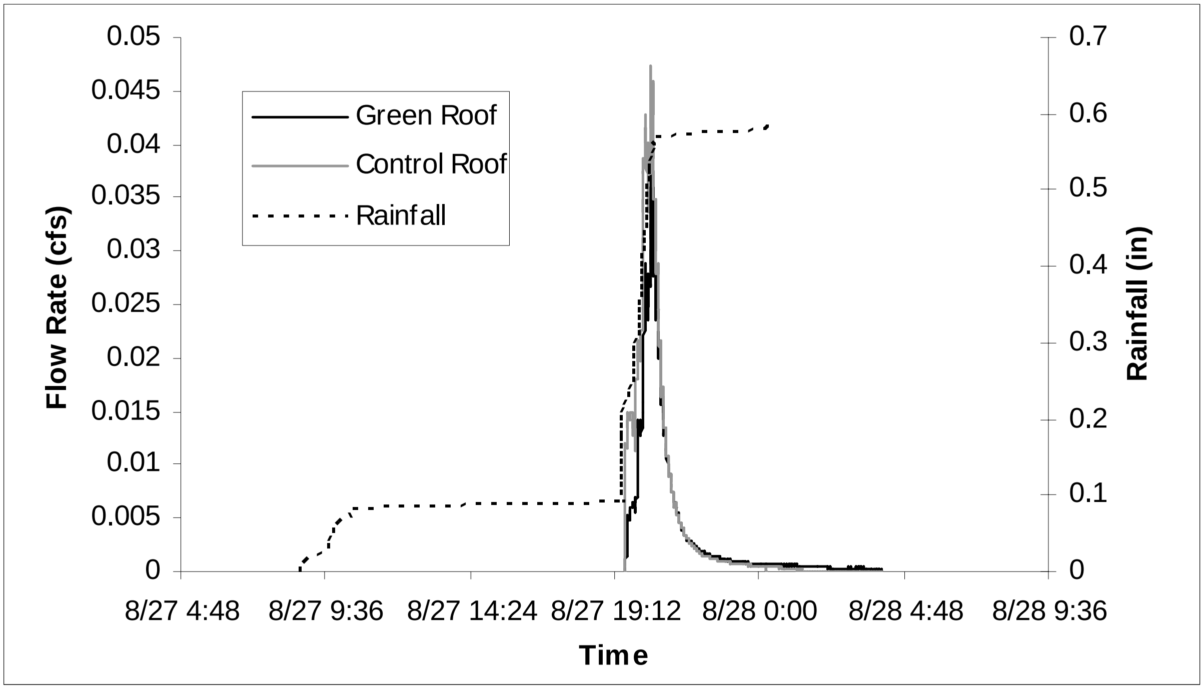

Figure 116 - Runoff Flow Rates - August 27, 2006 Storm

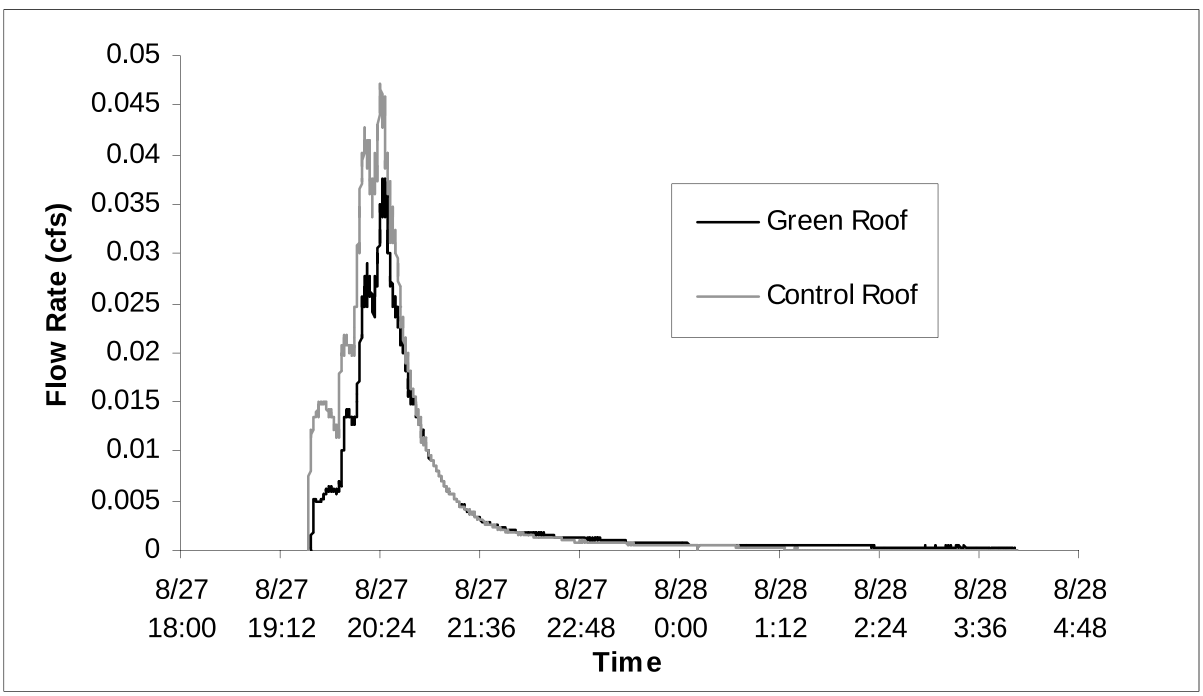

Figure 117 - Runoff Flow Rate Detail - August 27, 2006 Storm

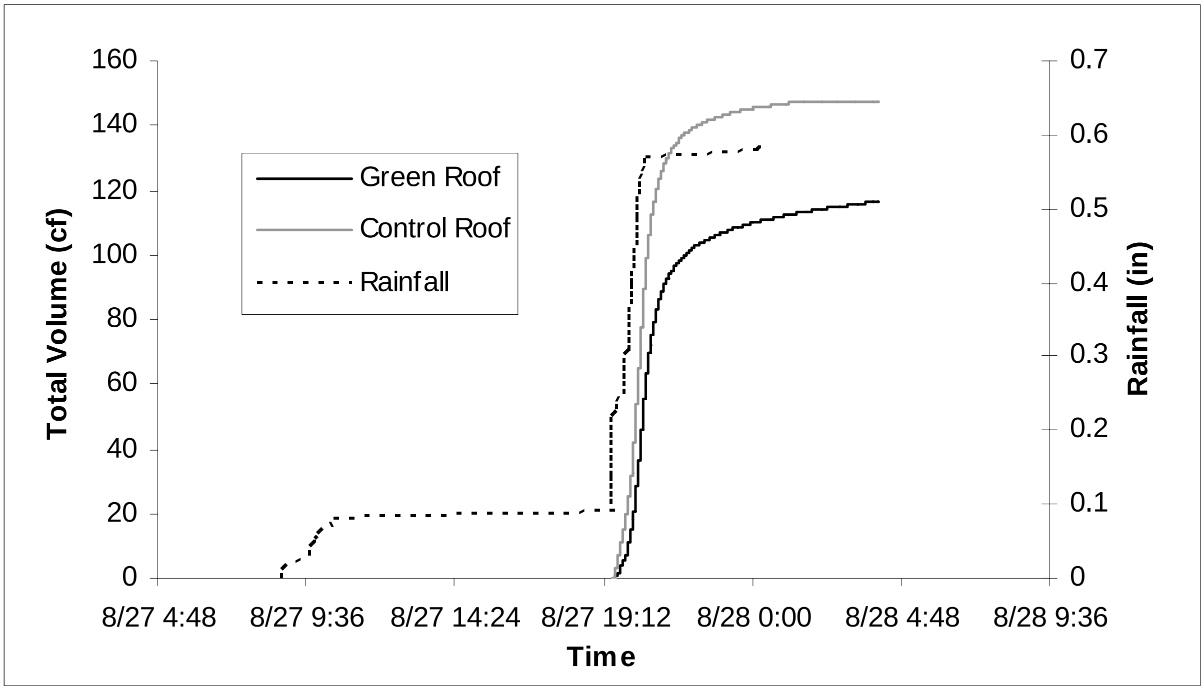

Figure 118 - Runoff Volume - August 27, 2006 Storm

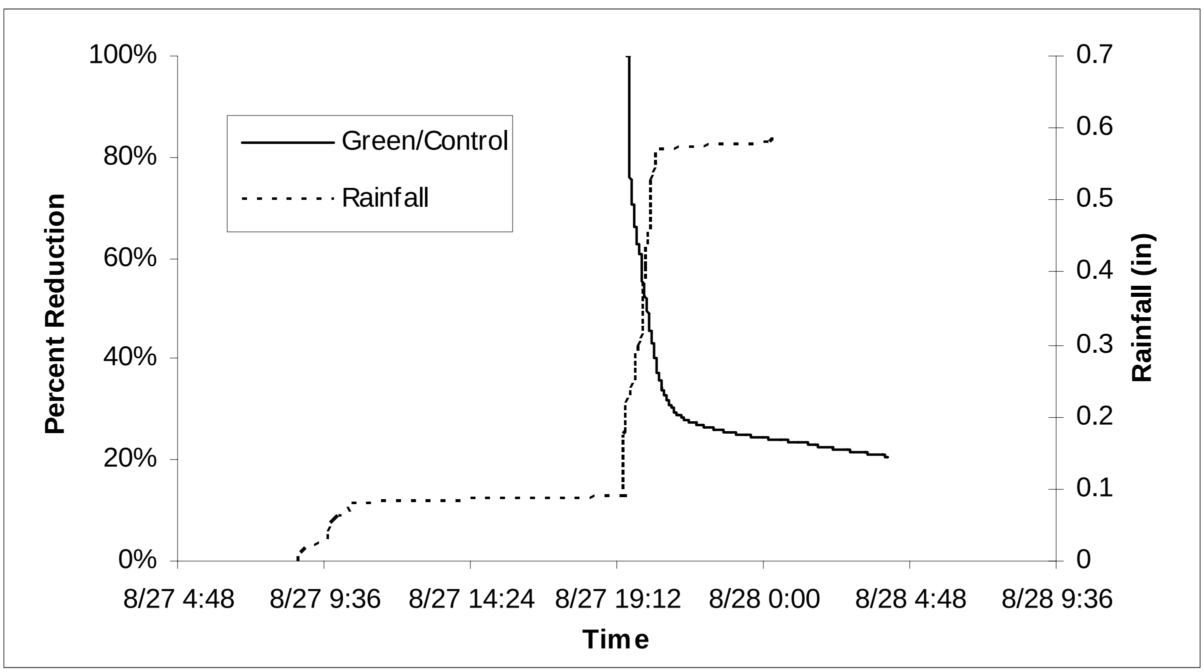

Figure 119 - Runoff Reduction - August 27, 2006 Storm

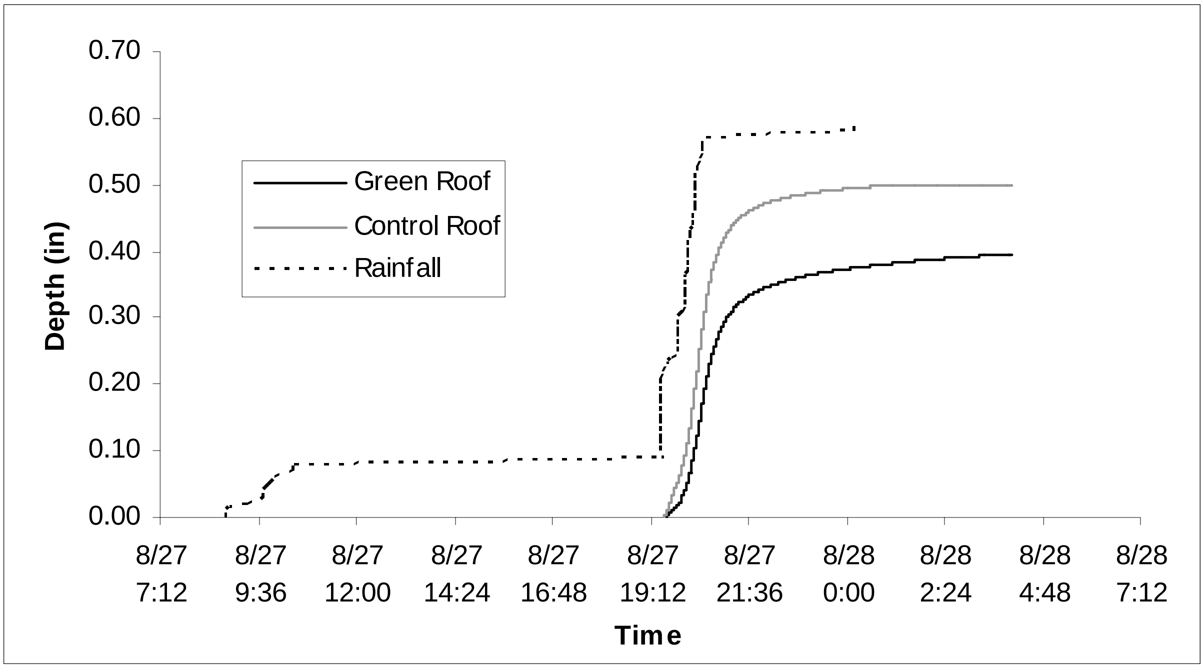

Figure 120 - Runoff as Rainfall - August 27, 2006 Storm

Table 14 - August 27, 2006 Storm Summary

August 27, 2006 Storm		
Rainfall	Depth (in)	0.59
	Length	15:25
Runoff	Delay	0:02
	Extension	2:36
Max Flow Rate (cfs)	Green	0.0375
	Control	0.0472
	Reduction	21%
Total Volume (cf)	Green	116.45
	Control	147.08
	Reduction	21%
Equiv. in of Rain	Green	0.4
	Control	0.5

A.6 AUGUST 28, 2006 STORM

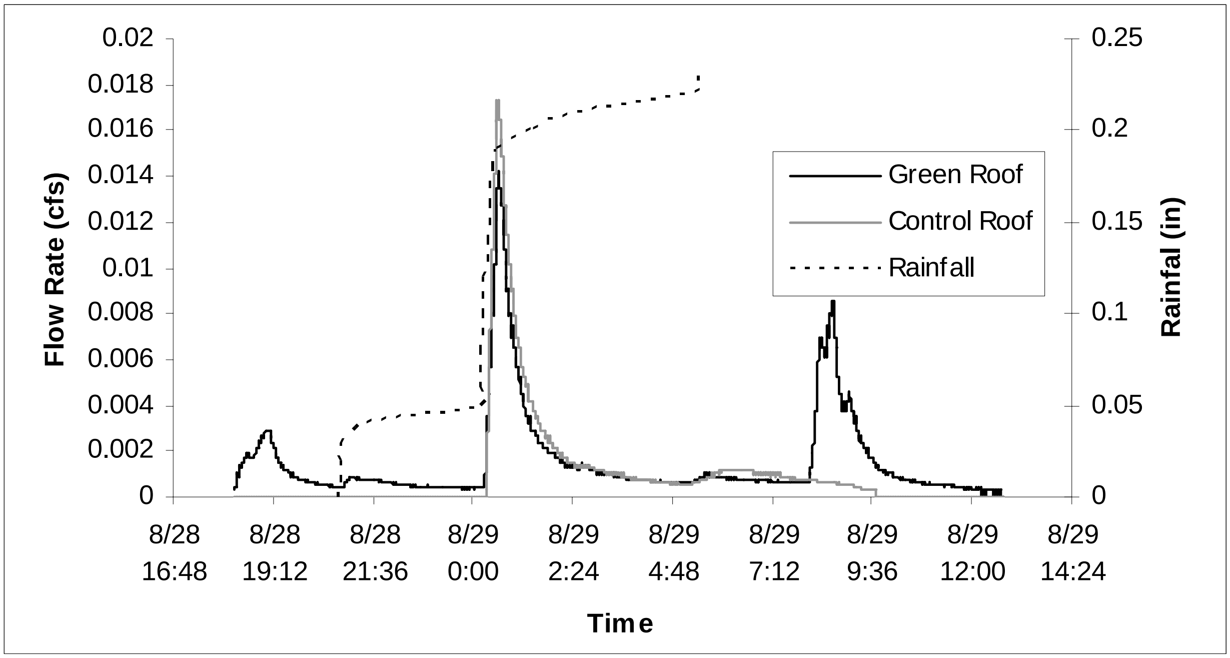

Figure 121 - Runoff Flow Rates - August 28, 2006 Storm

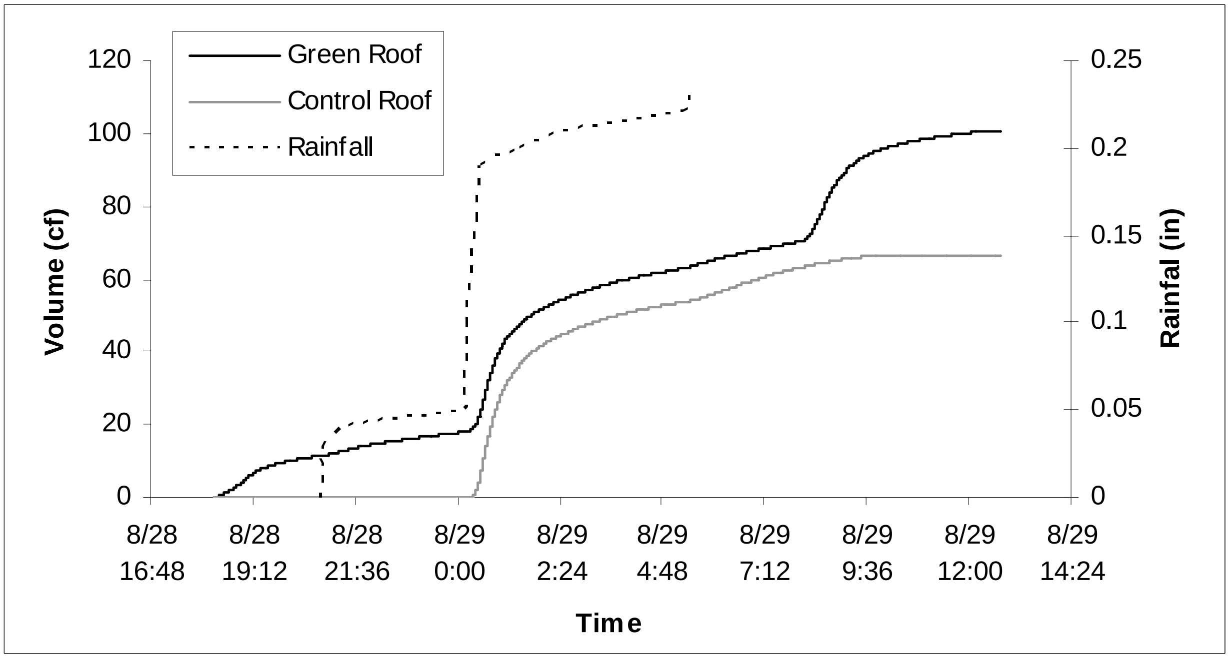

Figure 122 - Runoff Volumes - August 28, 2006 Storm

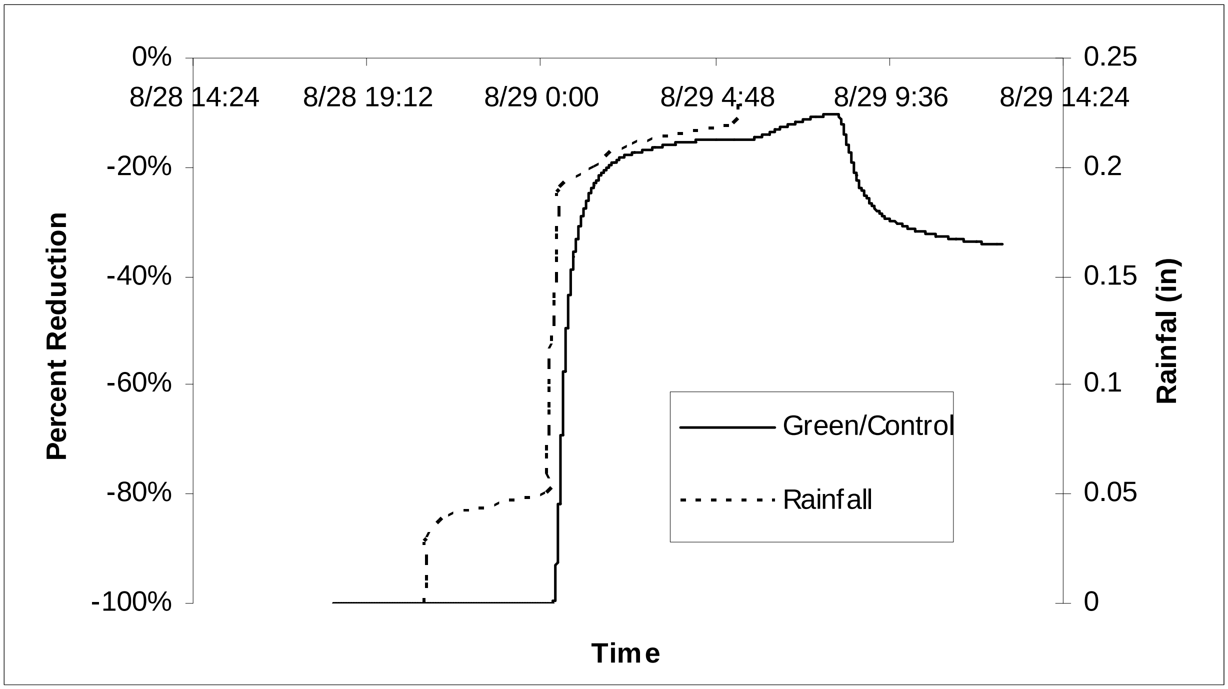

Figure 123 - Runoff Reduction - August 28, 2006 Storm

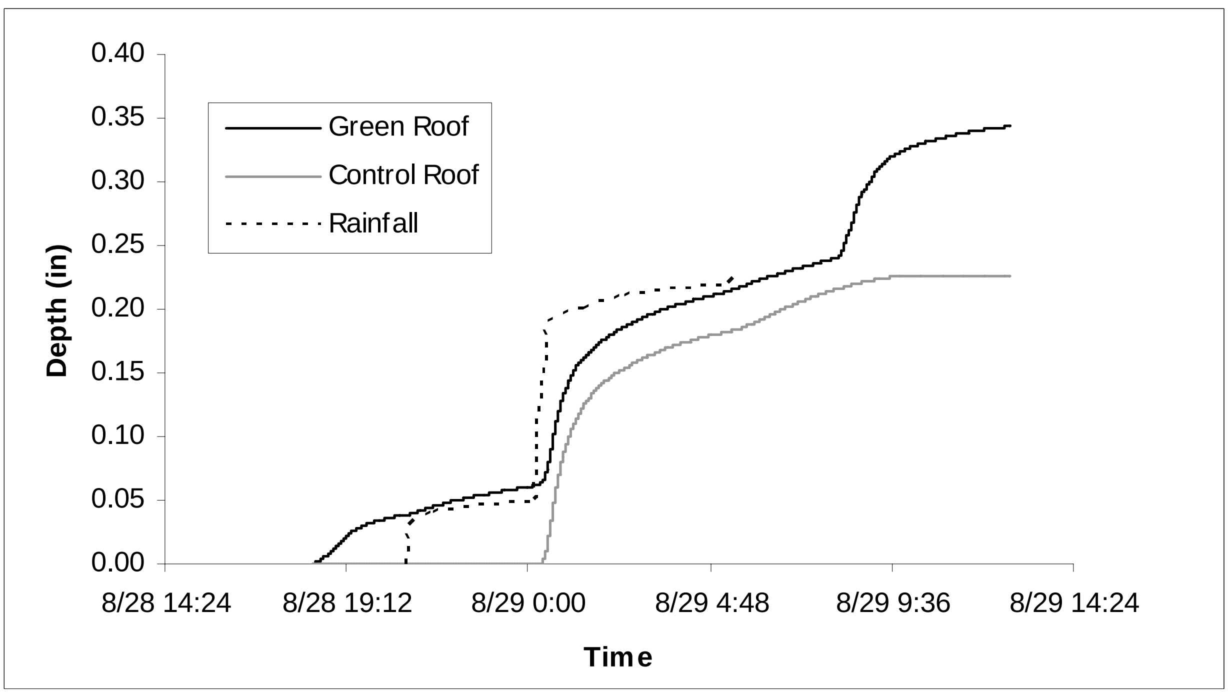

Figure 124 - Runoff as Rainfall - August 28, 2006 Storm

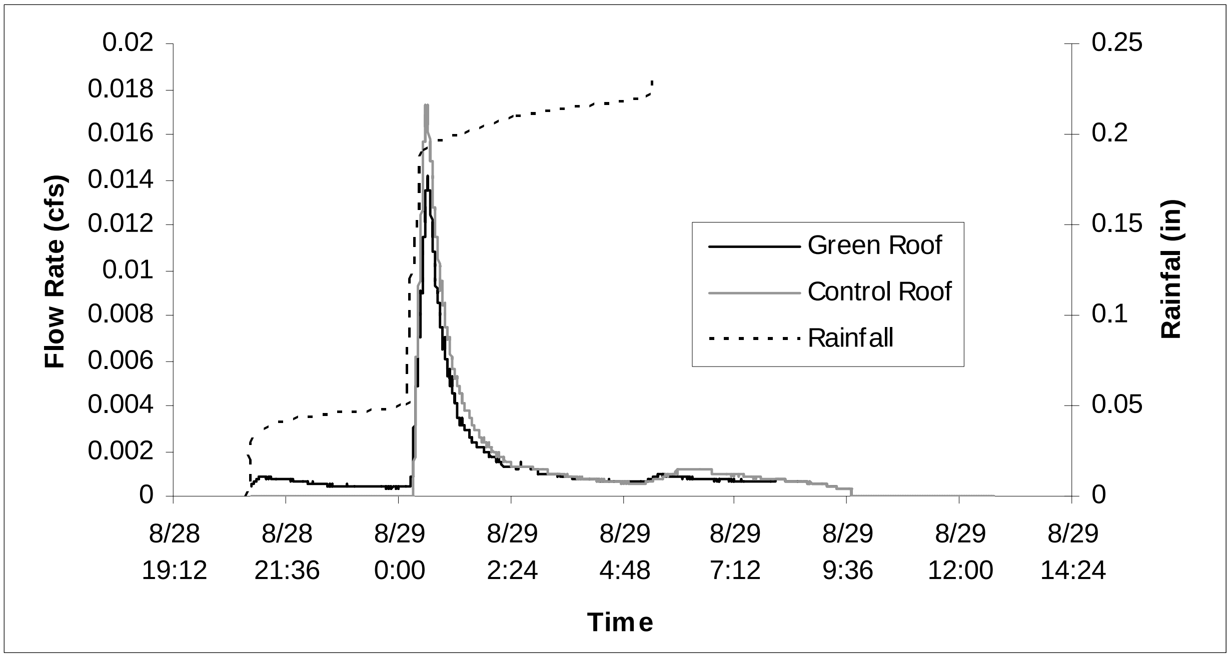

Figure 125 - Adjusted Runoff Flow Rates - August 28, 2006 Storm

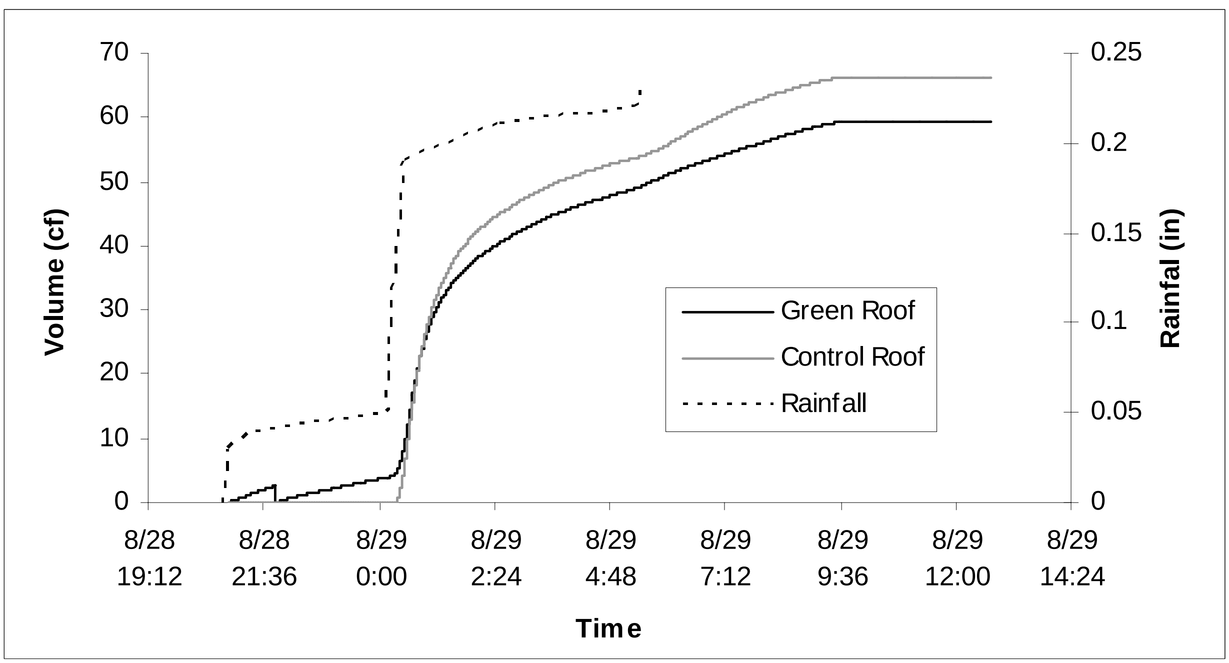

Figure 126 - Adjusted Runoff Volumes - August 28, 2006 Storm

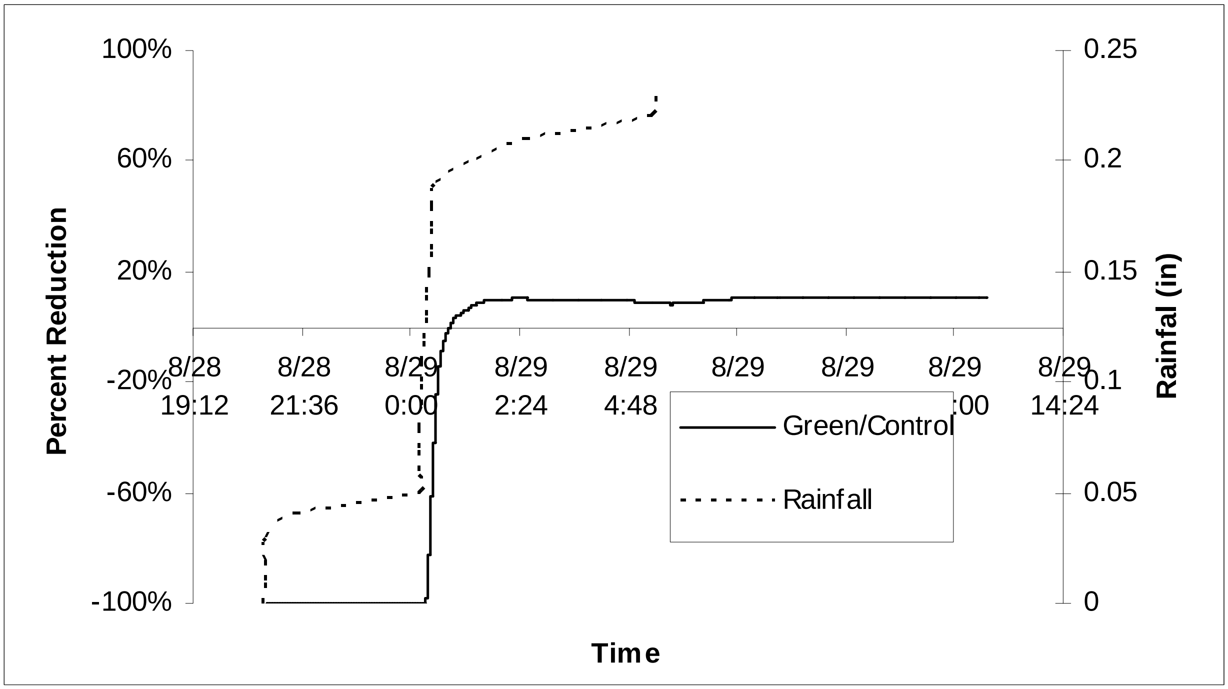

Figure 127 - Adjusted Runoff Reduction - August 28, 2006 Storm

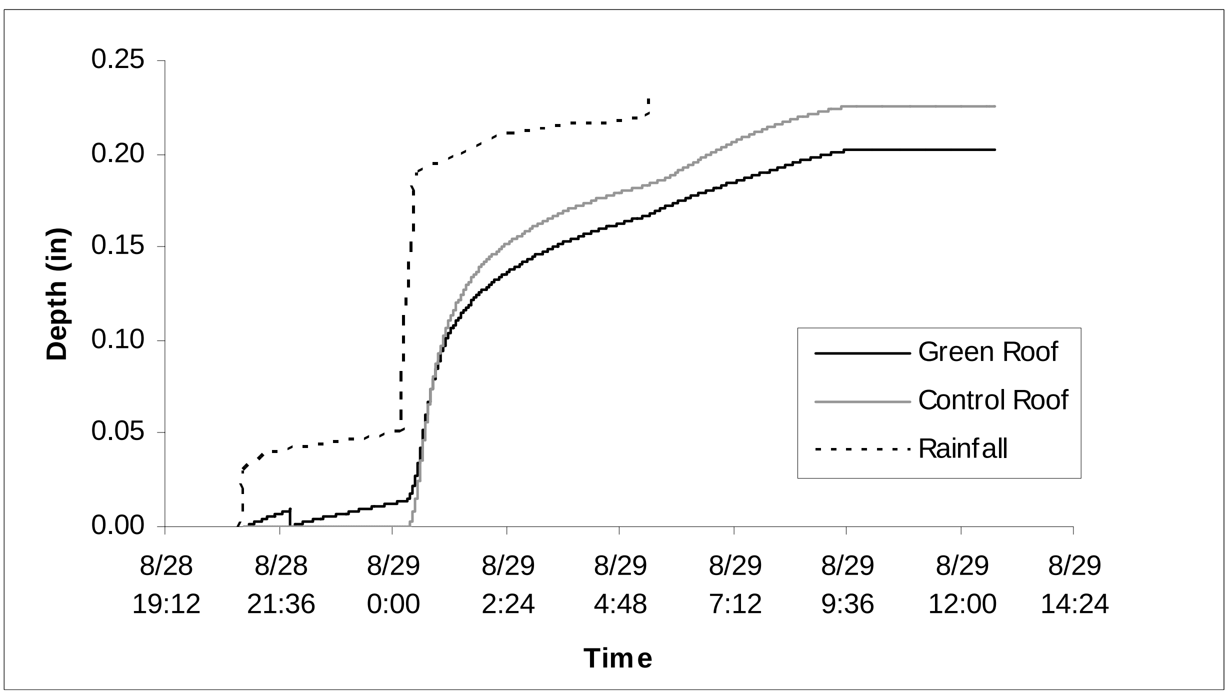

Figure 128 - Adjusted Runoff as Rainfall - August 28, 2006 Storm

Table 15 - August 28, 2006 Storm Summary

August 28, 2006 Storm			
Rainfall	Depth (in)	0.23	**Adjusted Values**
	Length	8:39	
Runoff	Delay	6:03	
	Extension	3:00	
Max Flow Rate (cfs)	Green	0.0142	
	Control	0.0173	
	Reduction	18%	
Total Volume (cf)	Green	100.92	59.43
	Control	66.36	
	Reduction	-34%	10%
Equiv. in of Rain	Green	0.32	0.2
	Control	0.23	

A.7 SEPTEMBER 2, 2006 STORM

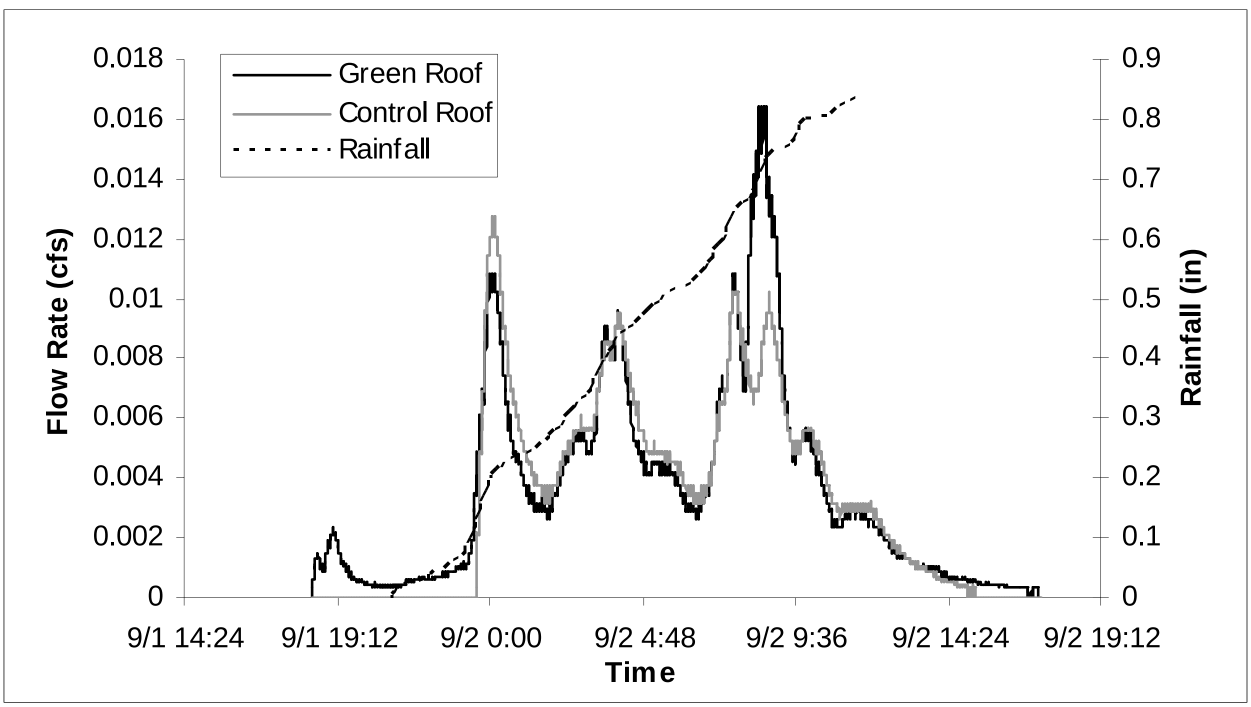

Figure 129 - Runoff Flow Rates - September 2, 2006 Storm

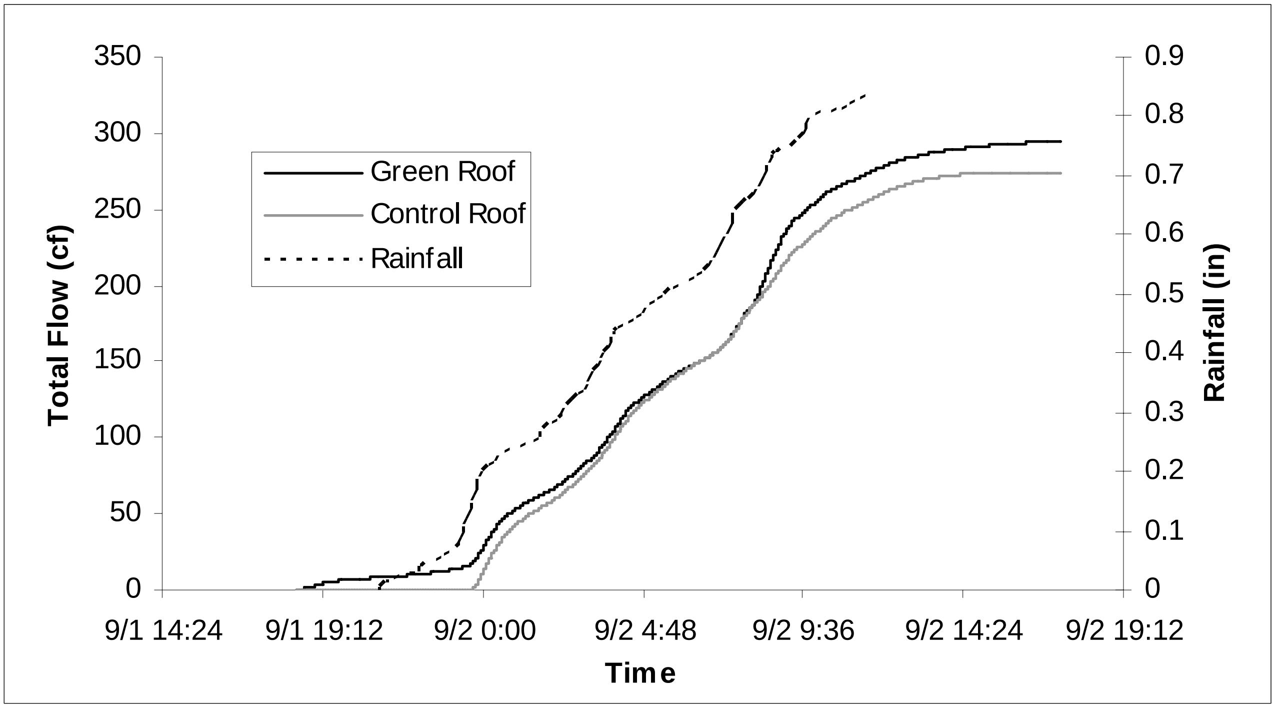

Figure 130 - Runoff Volume - September 2, 2006 Storm

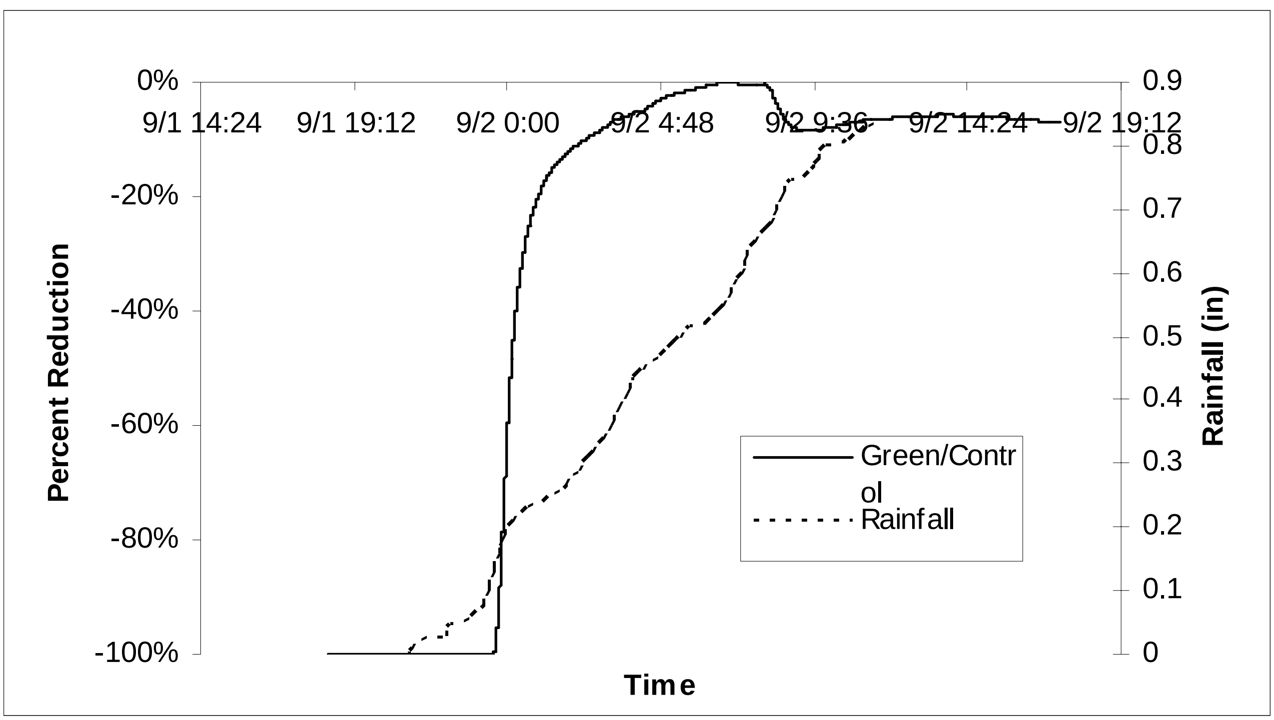

Figure 131 - Runoff Reduction - September 2, 2006 Storm

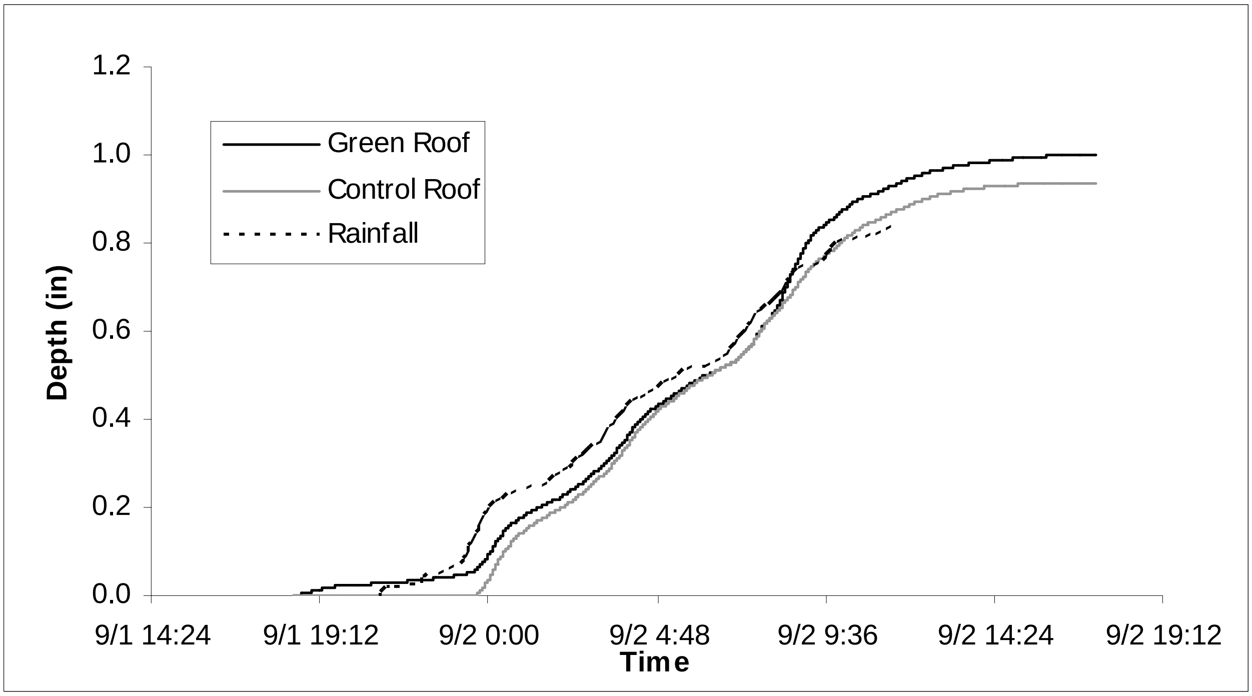

Figure 132 - Runoff as Rainfall - September 2, 2006 Storm

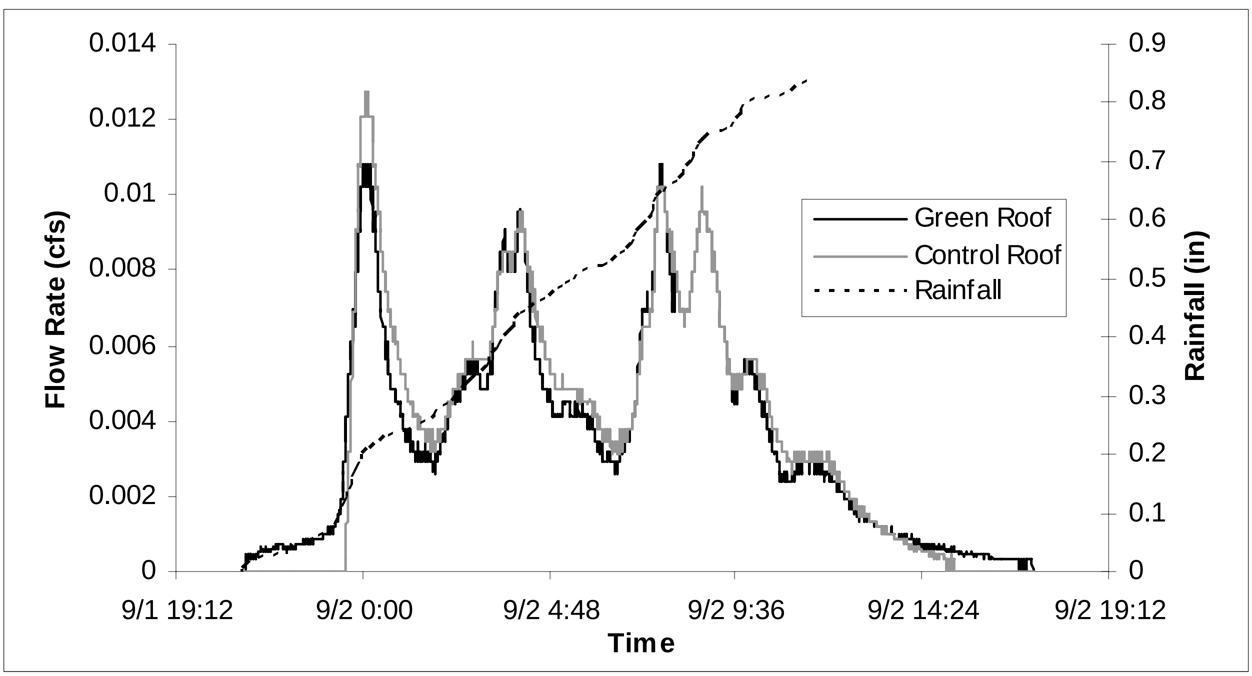

Figure 133 - Adjusted Runoff Flow Rates - September 2, 2006 Storm

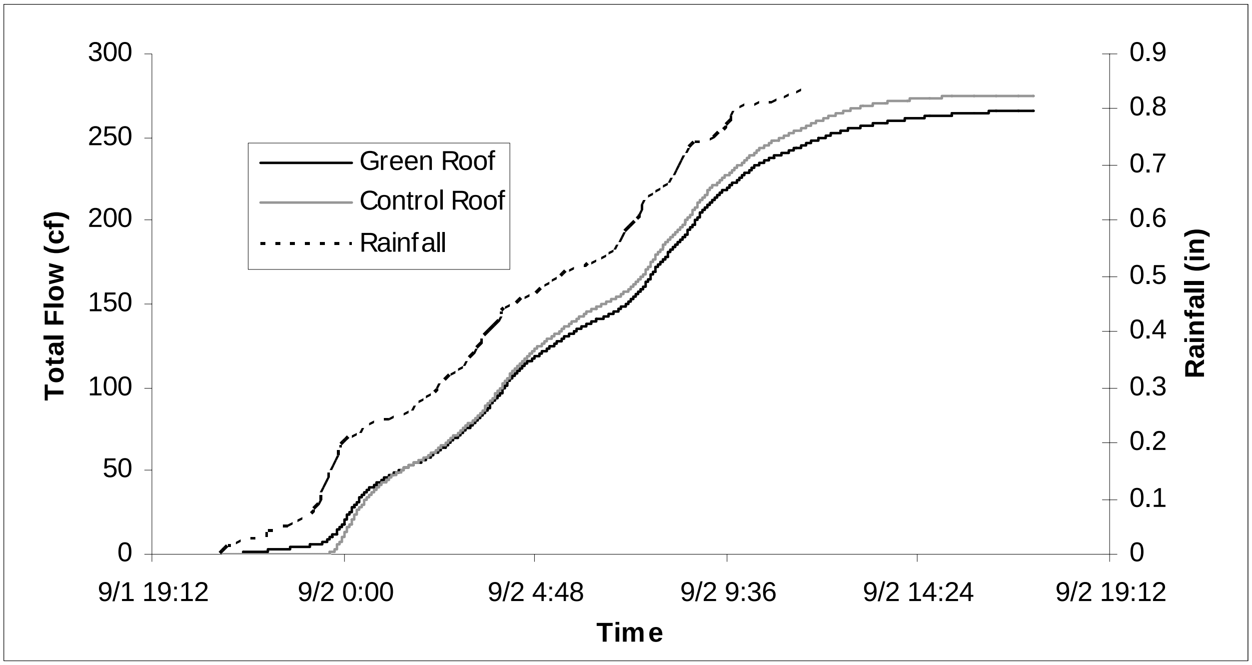

Figure 134 - Adjusted Runoff Volume - September 2, 2006 Storm

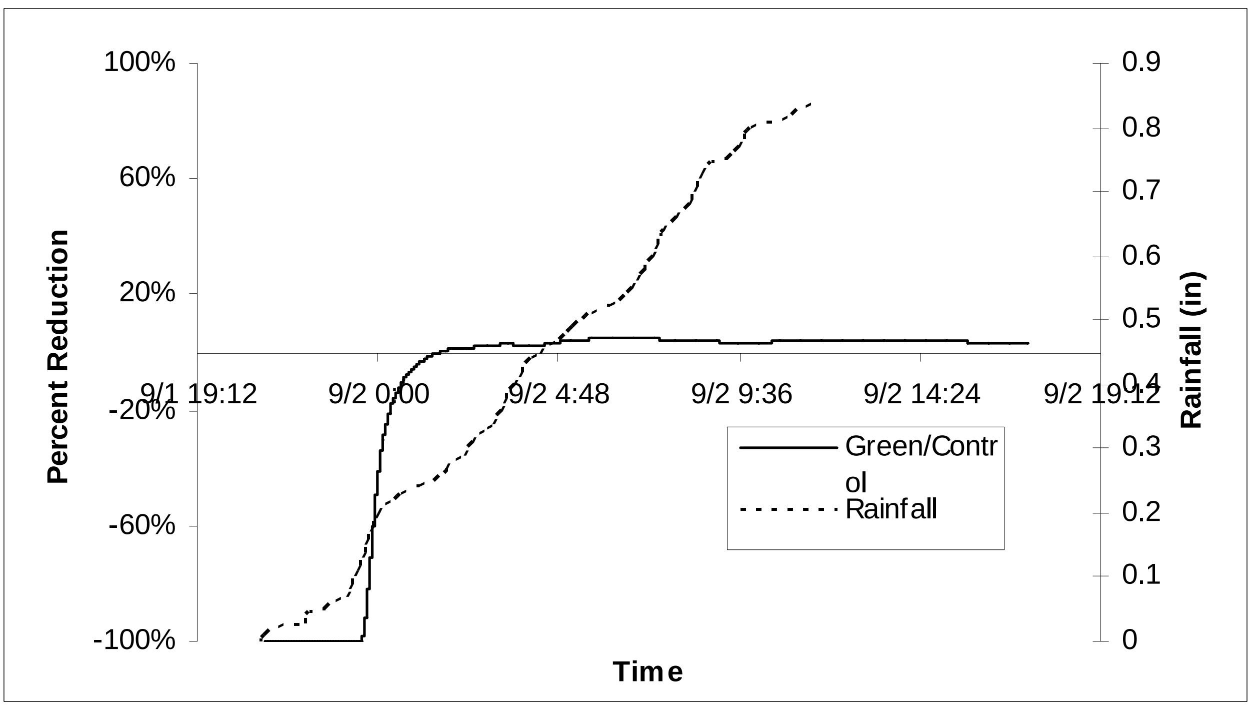

Figure 135 - Adjusted Runoff Reduction - September 2, 2006 Storm

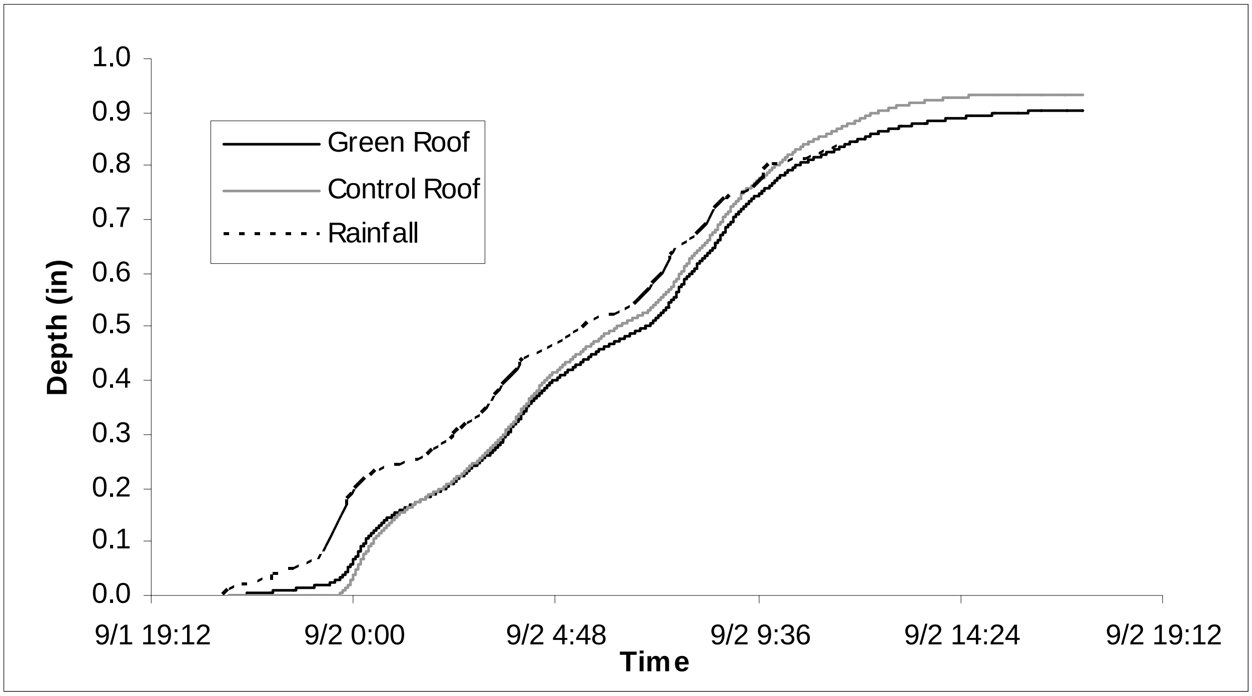

Figure 136 - Adjusted Runoff as Rainfall - September 2, 2006 Storm

Table 16 - September 2, 2006 Storm Summary

September 2, 2006 Storm			
Rainfall	Depth (in)	0.84	**Adjusted Values**
	Length	14:39	
Runoff	Delay	5:08	
	Extension	2:01	
Max Flow Rate (cfs)	Green	0.0164	0.0108
	Control	0.0127	
	Reduction	-23%	15%
Total Volume (cf)	Green	294.68	266.26
	Control	274.27	
	Reduction	-7%	3%
Equiv. in of Rain	Green	1	0.91
	Control	0.93	

A.8 SEPTEMBER 5, 2006 STORM

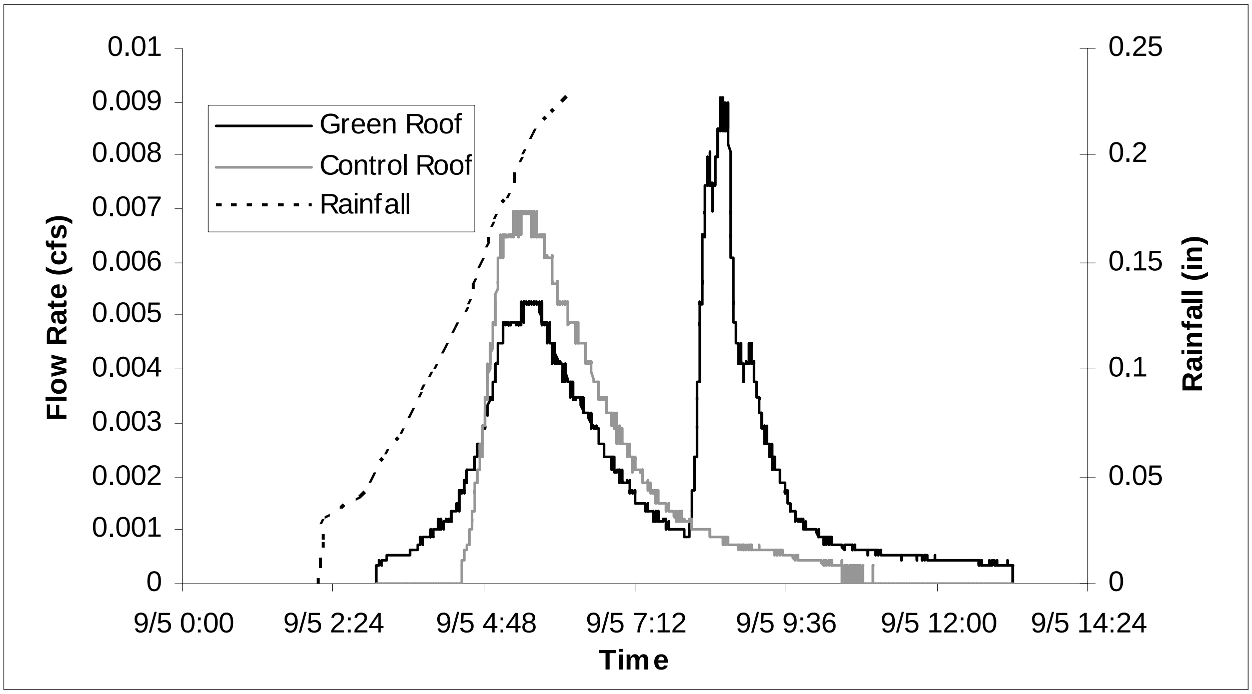

Figure 137 - Runoff Flow Rates - September 5, 2006 Storm

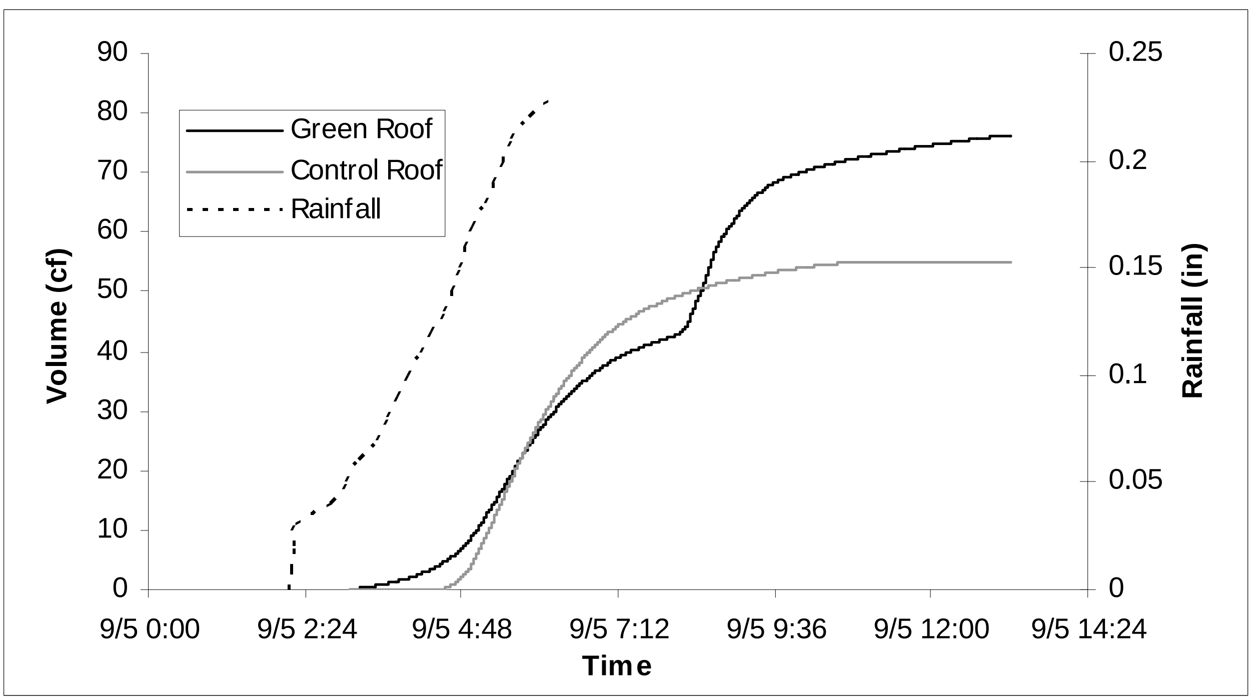

Figure 138 - Runoff Volume - September 5, 2006 Storm

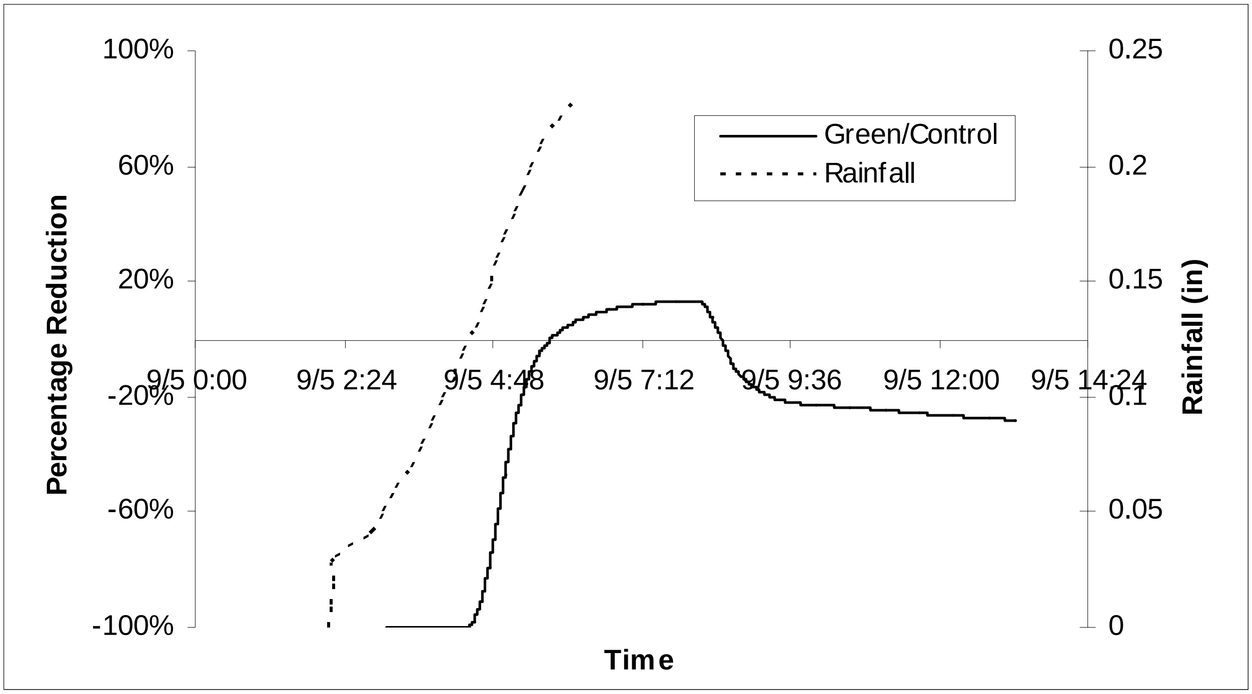

Figure 139 - Runoff Reduction - September 5, 2006 Storm

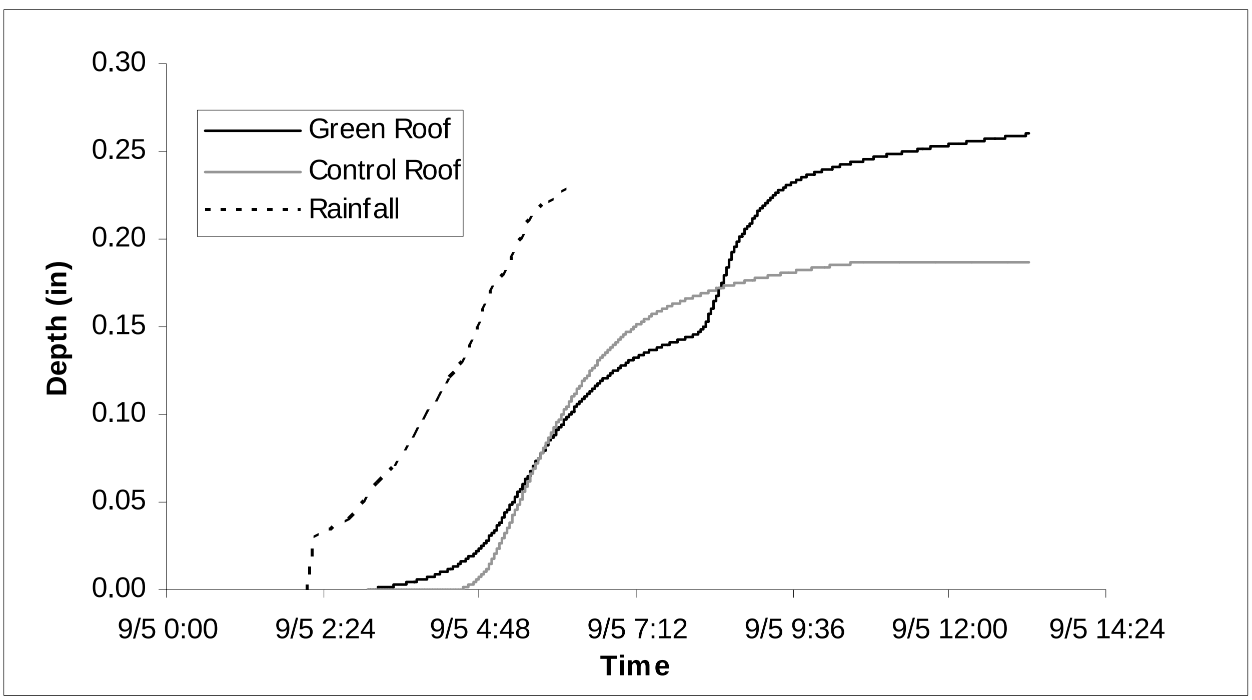

Figure 140 - Runoff as Rainfall - September 5, 2006 Storm

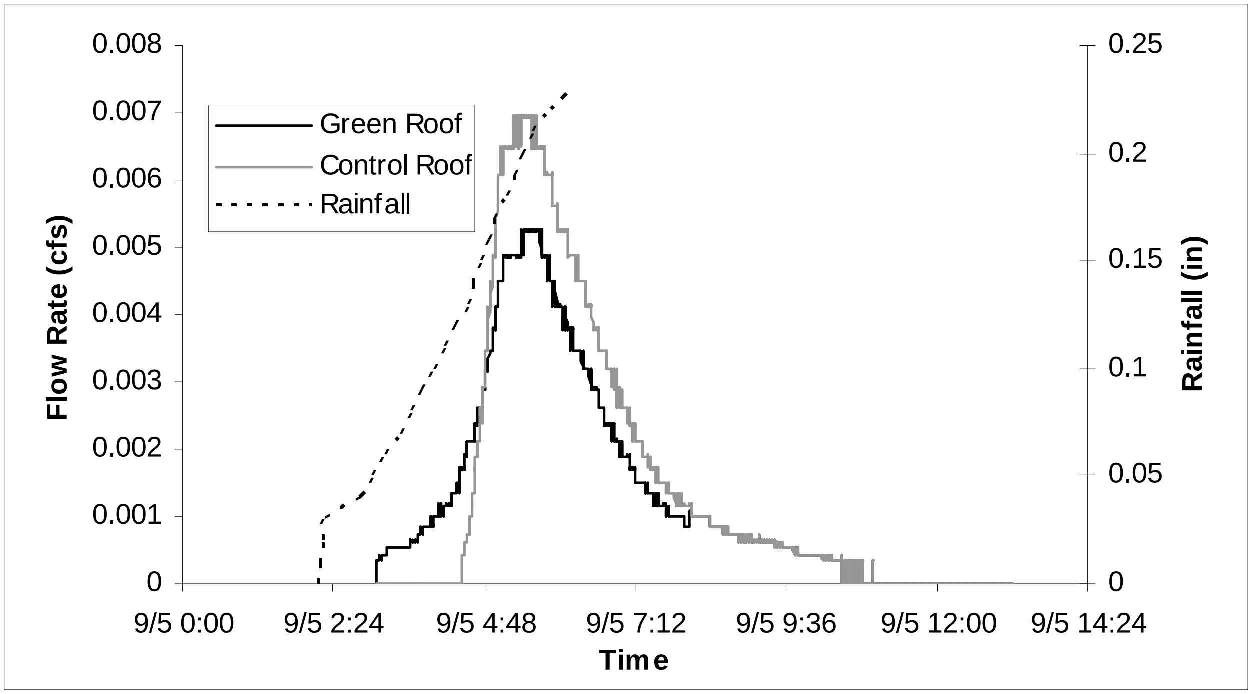

Figure 141 - Adjusted Runoff Flow Rates - September 5, 2006 Storm

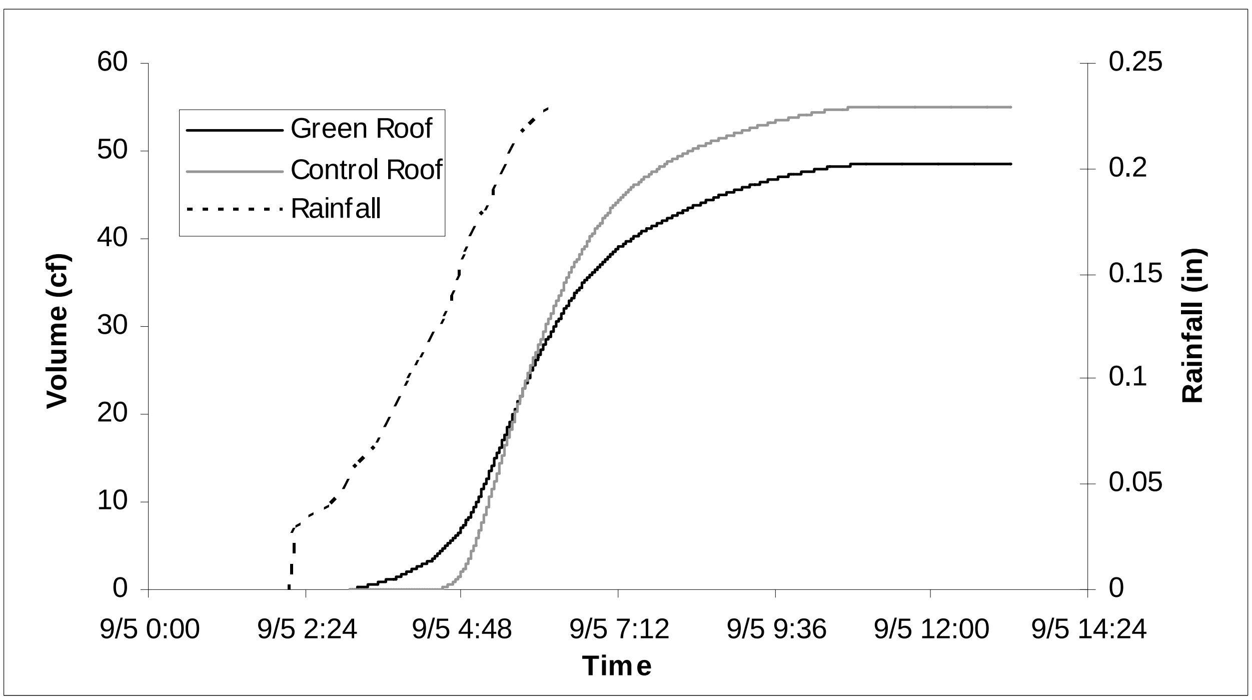

Figure 142 - Adjusted Runoff Volume - September 5, 2006 Storm

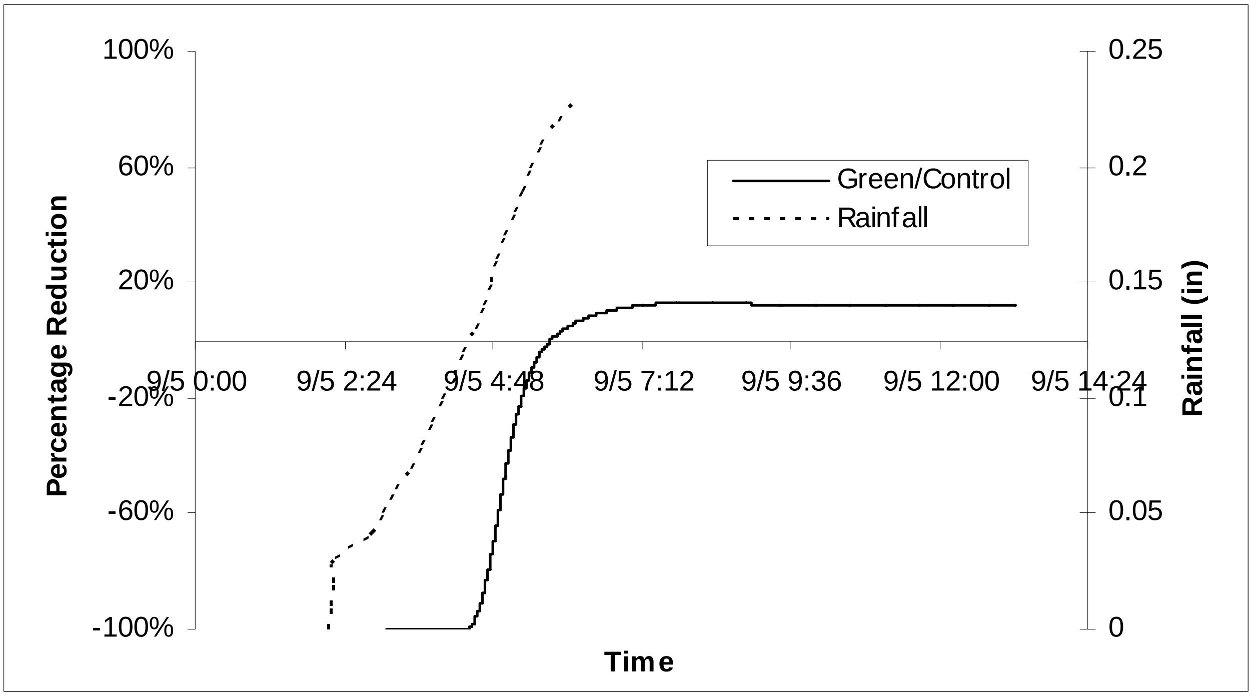

Figure 143 - Adjusted Runoff Reduction - September 5, 2006 Storm

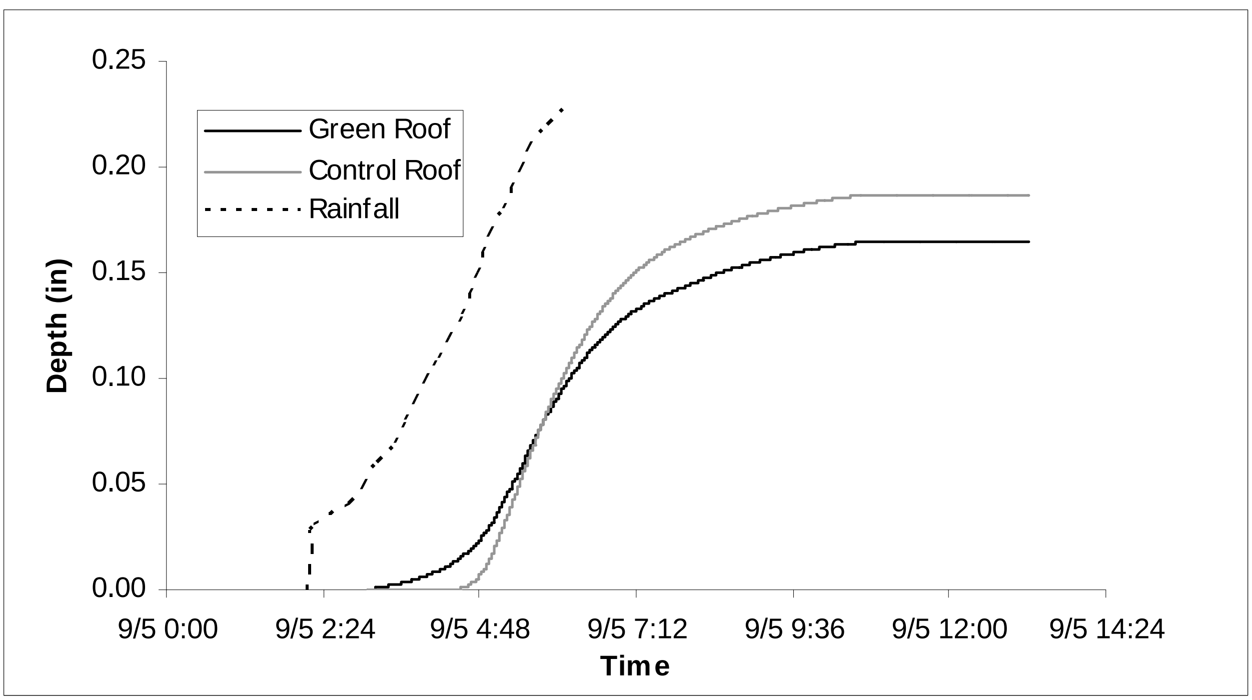

Figure 144 - Adjusted Runoff as Rainfall - September 5, 2006 Storm

Table 17 - September 5, 2006 Storm Summary

September 5, 2006 Storm			
Rainfall	Depth (in)	0.23	**Adjusted Values**
	Length	3:59	
Runoff	Delay	-1:20	
	Extension	2:24	
Max Flow Rate (cfs)	Green	0.0091	0.0053
	Control	0.007	
	Reduction	-23%	25%
Total Volume (cf)	Green	76.36	48.46
	Control	54.98	
	Reduction	-28%	12%
Equiv. in of Rain	Green	0.26	0.16
	Control	0.19	

A.9 SEPTEMBER 19, 2006 STORM

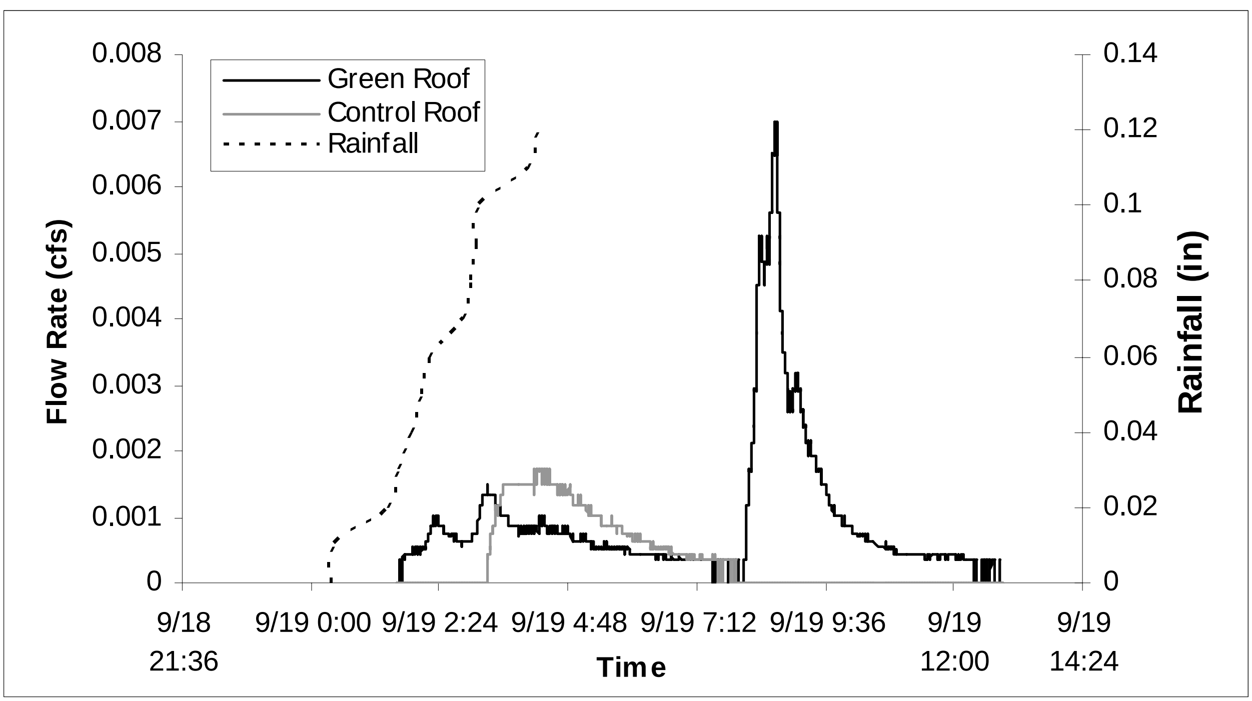

Figure 145 - Runoff Flow Rates - September 19, 2006 Storm

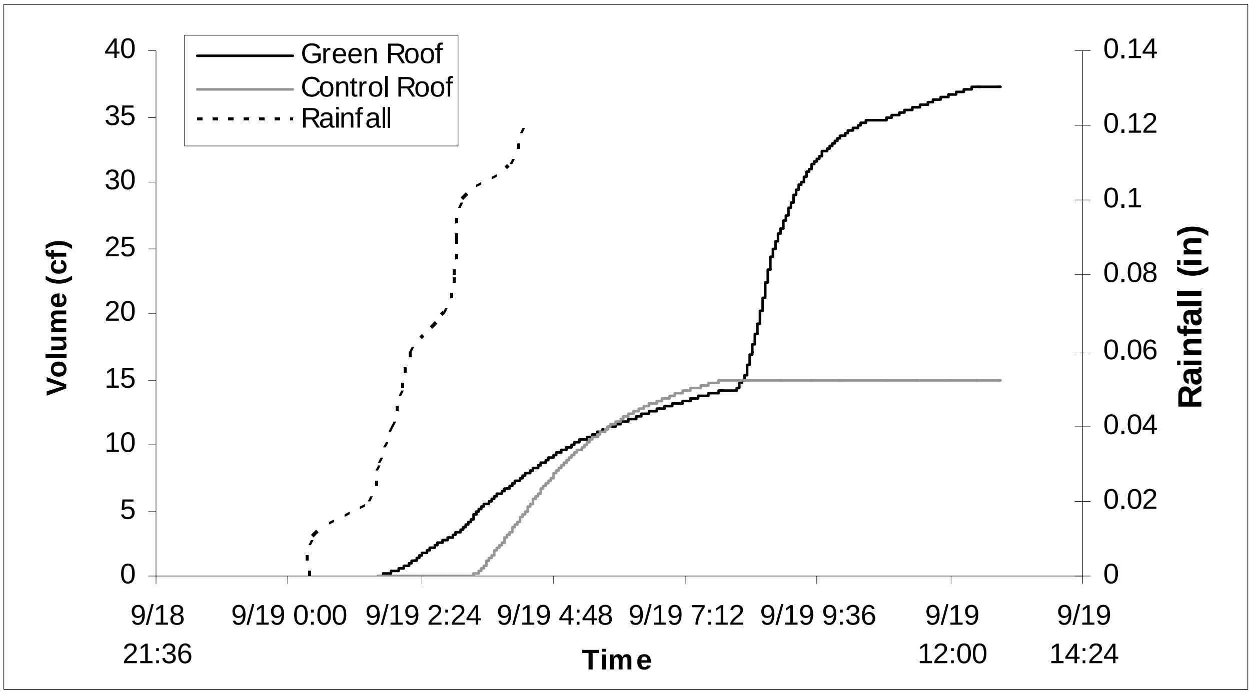

Figure 146 – Runoff Volume - September 19, 2006 Storm

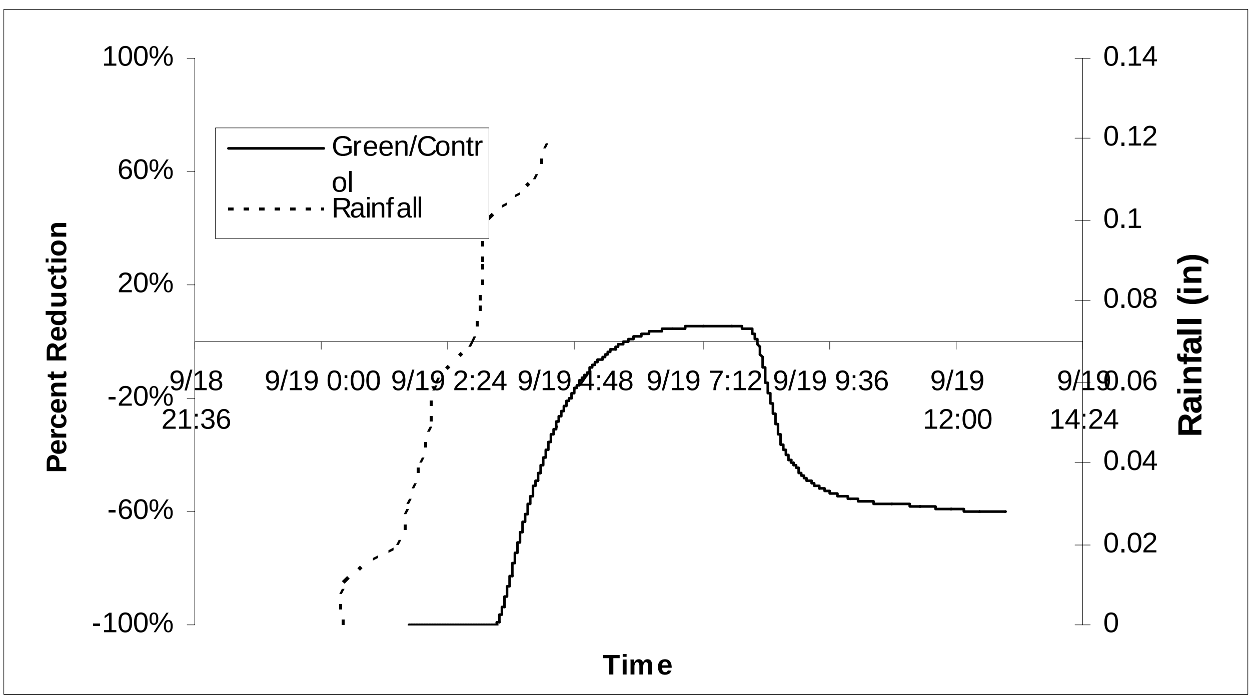

Figure 147 - Runoff Reduction - September 19, 2006 Storm

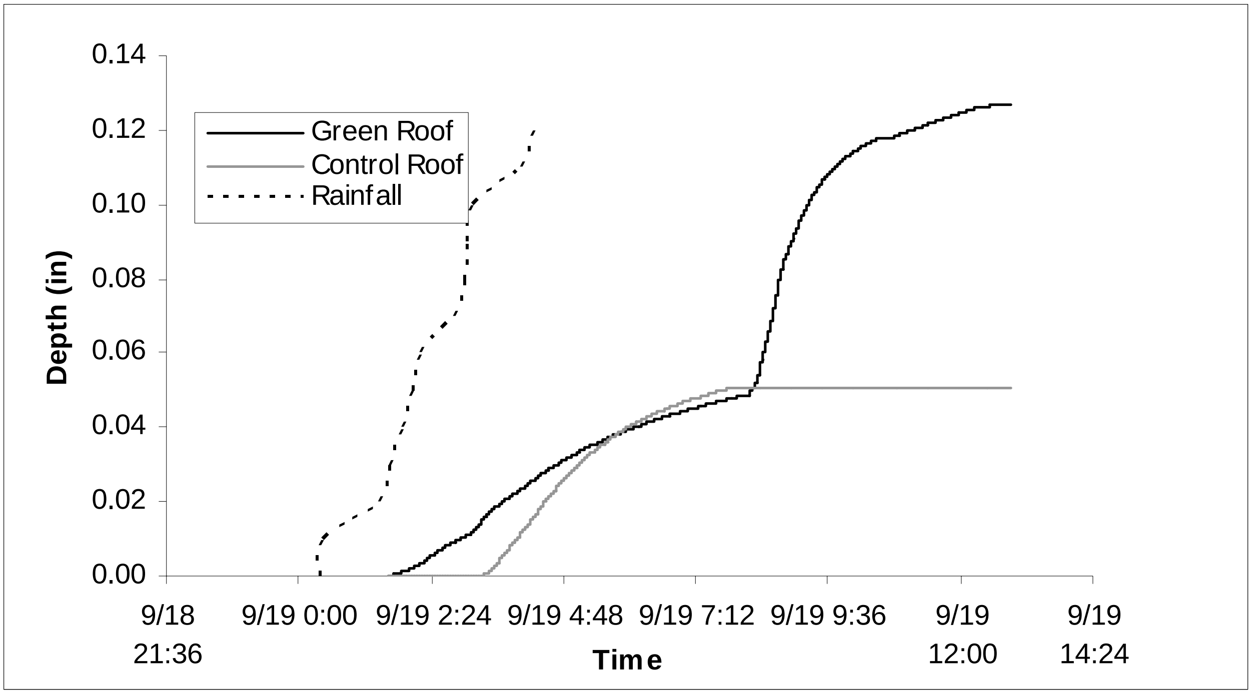

Figure 148 - Runoff as Rainfall - September 19, 2006 Storm

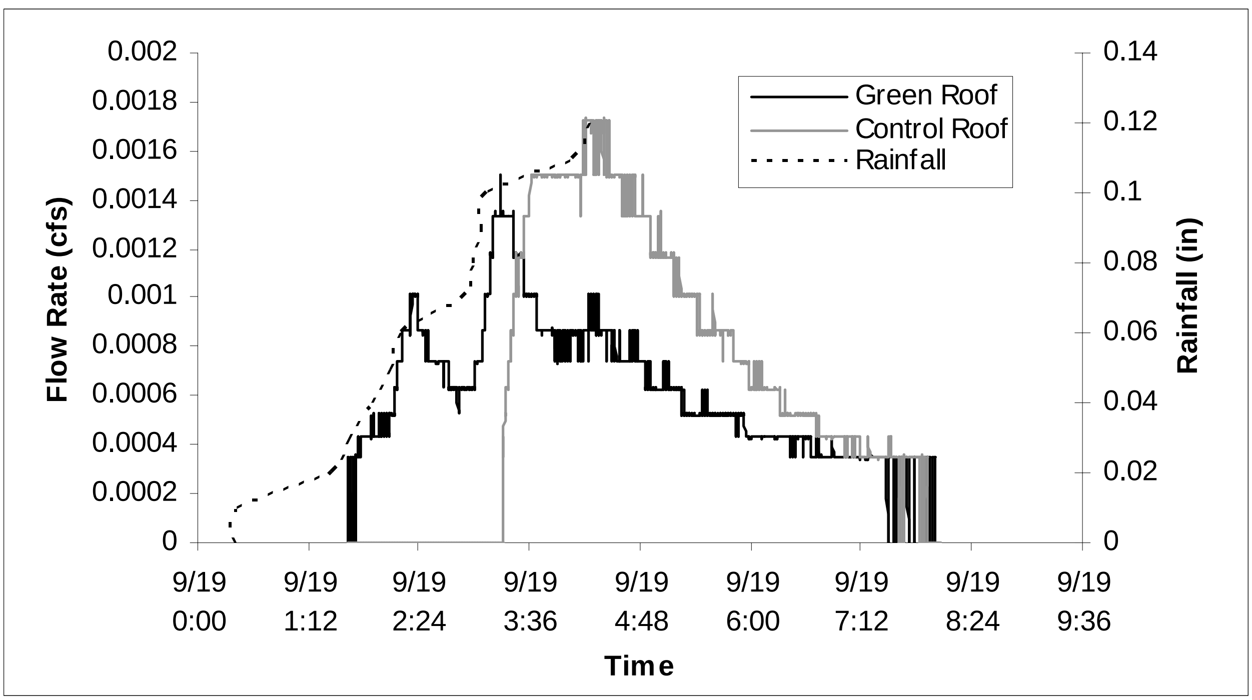

Figure 149 - Adjusted Runoff Flow Rates - September 19, 2006 Storm

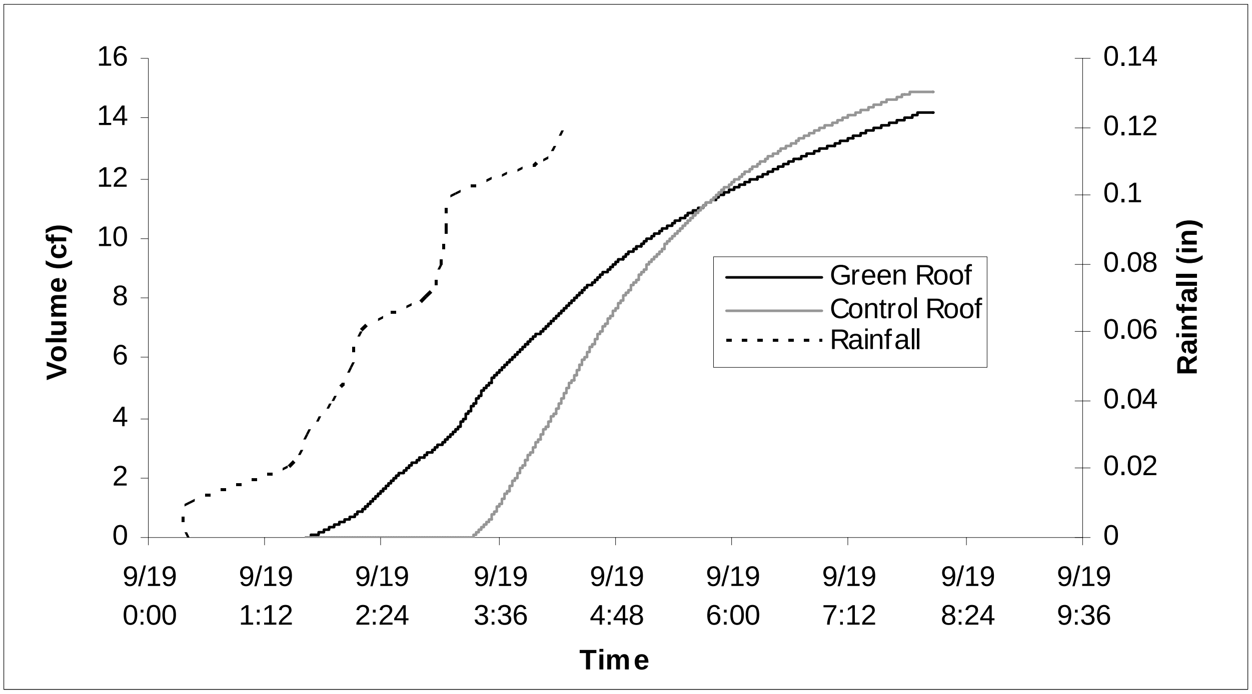

Figure 150 - Adjusted Runoff Volume - September 19, 2006 Storm

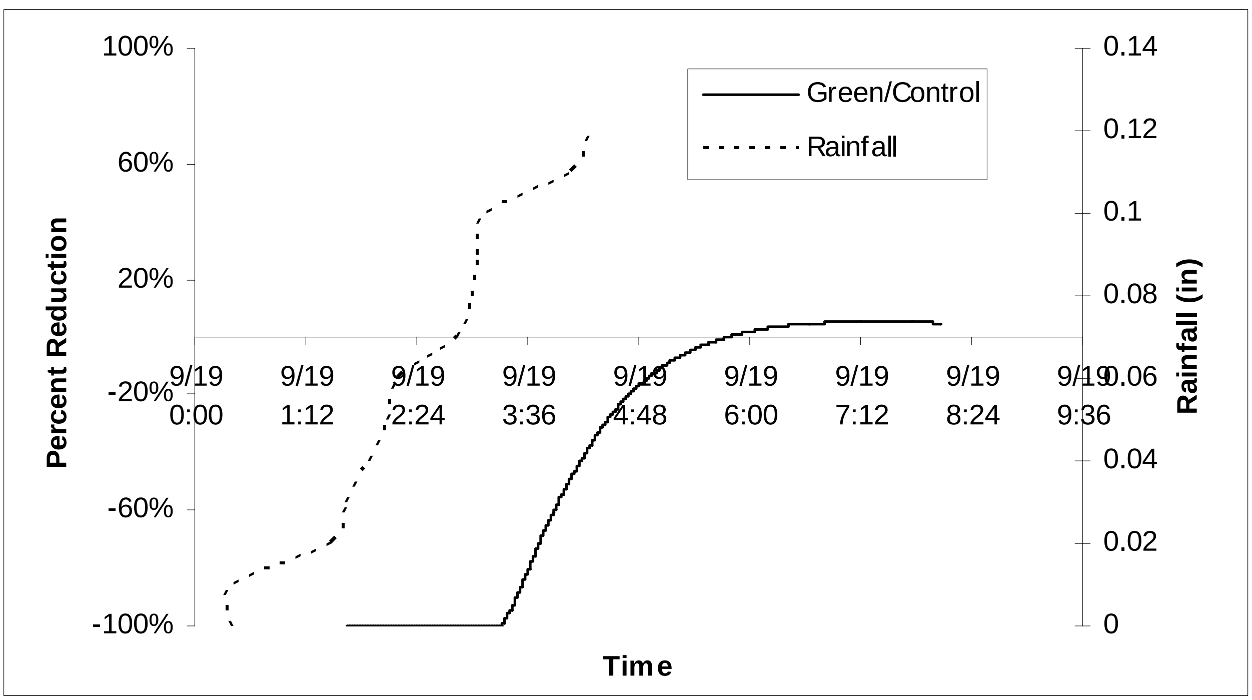

Figure 151 - Adjusted Runoff Reduction - September 19, 2006 Storm

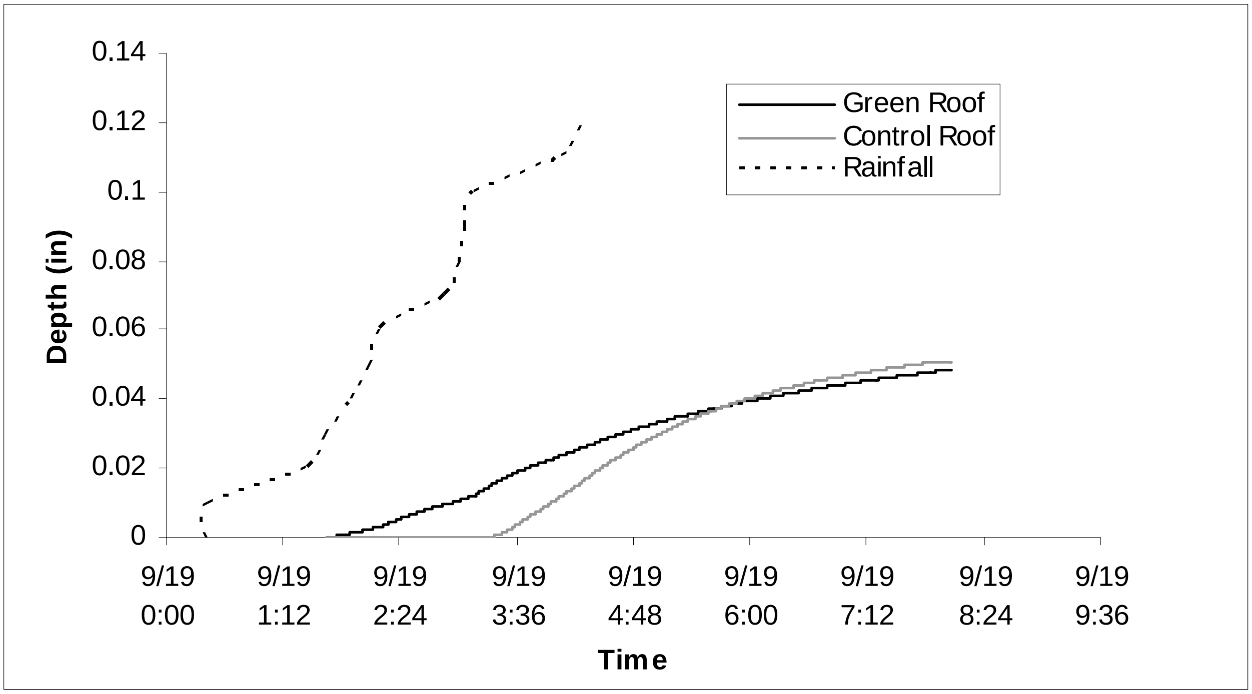

Figure 152 - Adjusted Runoff as Rainfall - September 19, 2006 Storm

Table 18 - September 19, 2006 Storm Summary

September 19, 2006 Storm			
Rainfall	Depth (in)	0.12	**Adjusted Values**
	Length	3:50	
Runoff	Delay	-1:40	
	Extension	4:56	
Max Flow Rate (cfs)	Green	0.007	0.0015
	Control	0.0017	
	Reduction	-75%	12%
Total Volume (cf)	Green	37.35	14.19
	Control	14.91	
	Reduction	-60%	15%
Equiv. in of Rain	Green	0.13	0.05
	Control	0.05	

A.10 SEPTEMBER 28, 2006 STORM

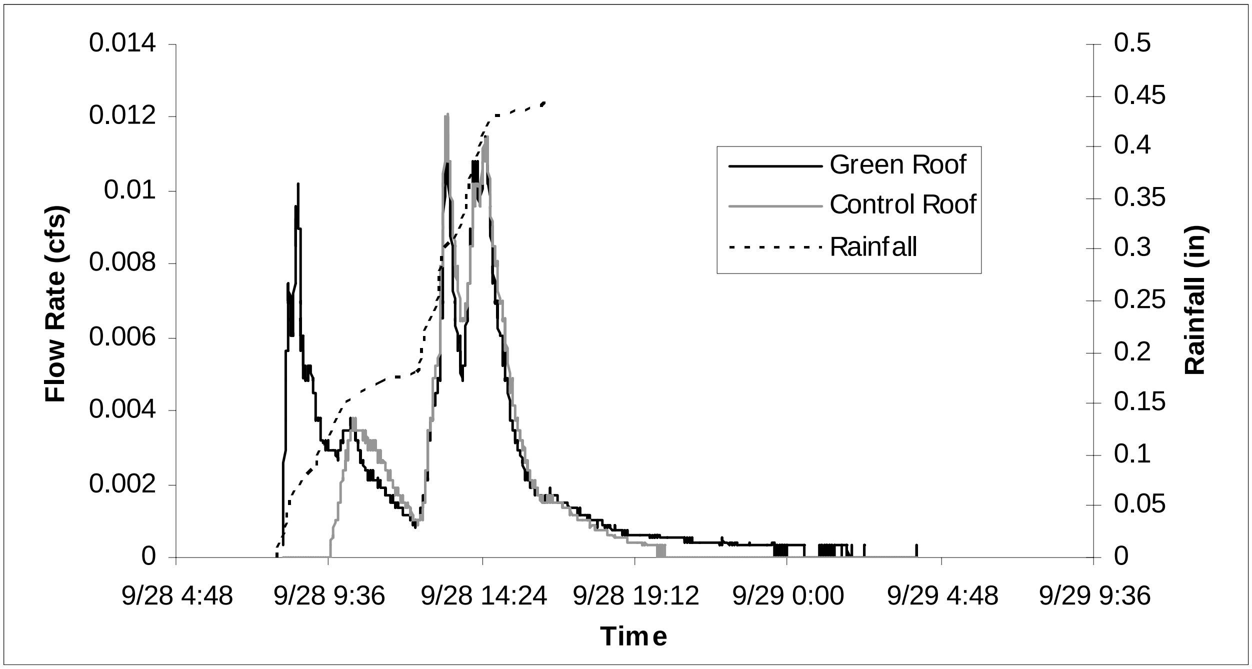

Figure 153 - Runoff Flow Rates - September 28, 2006 Storm

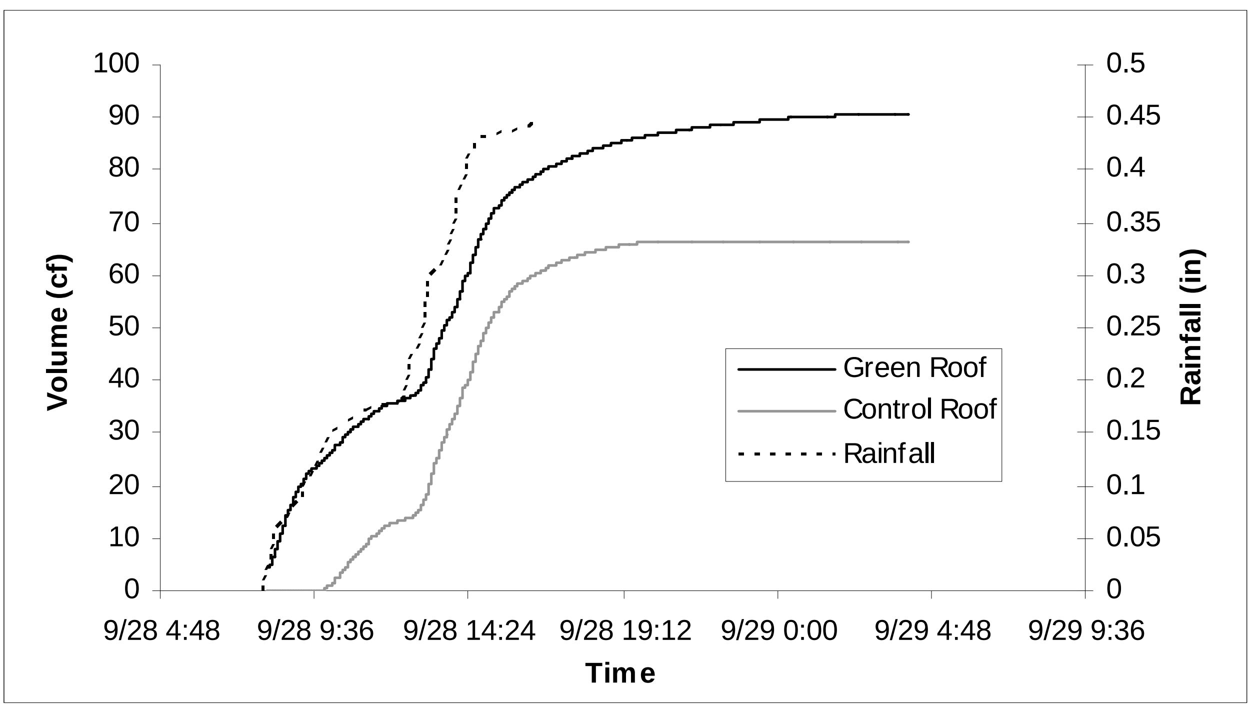

Figure 154 - Runoff Volume - September 28, 2006 Storm

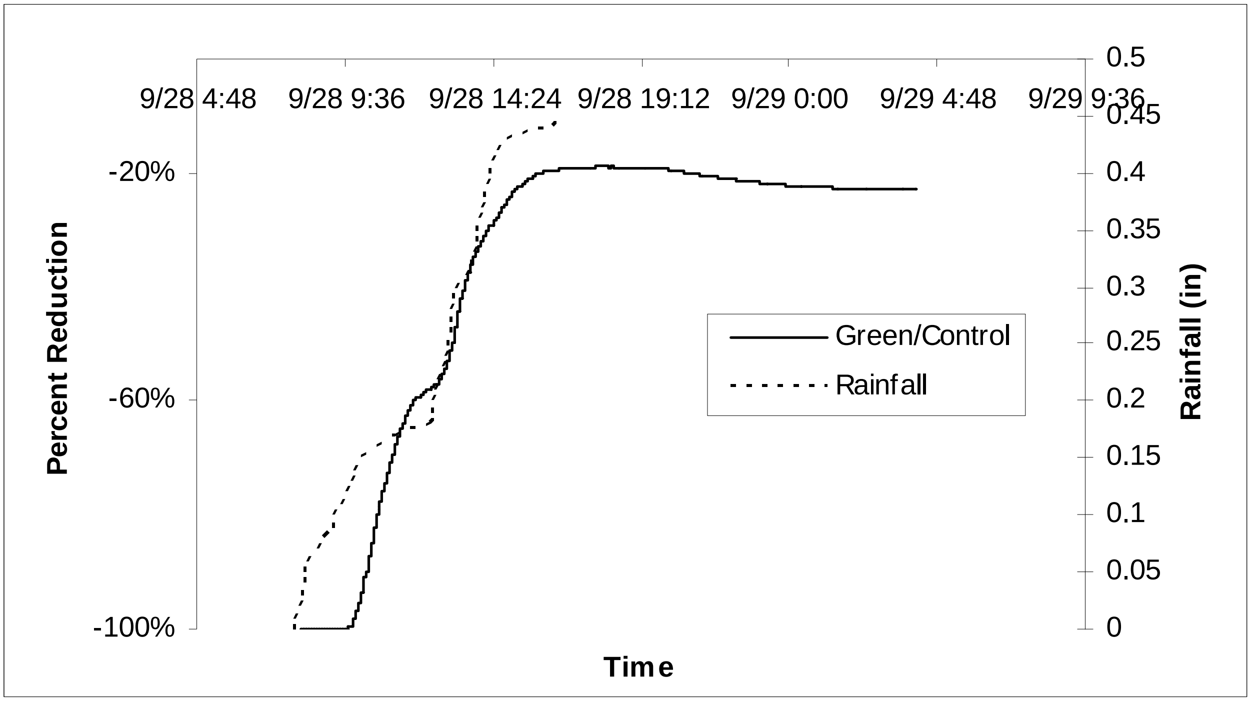

Figure 155 - Runoff Reduction - September 28, 2006 Storm

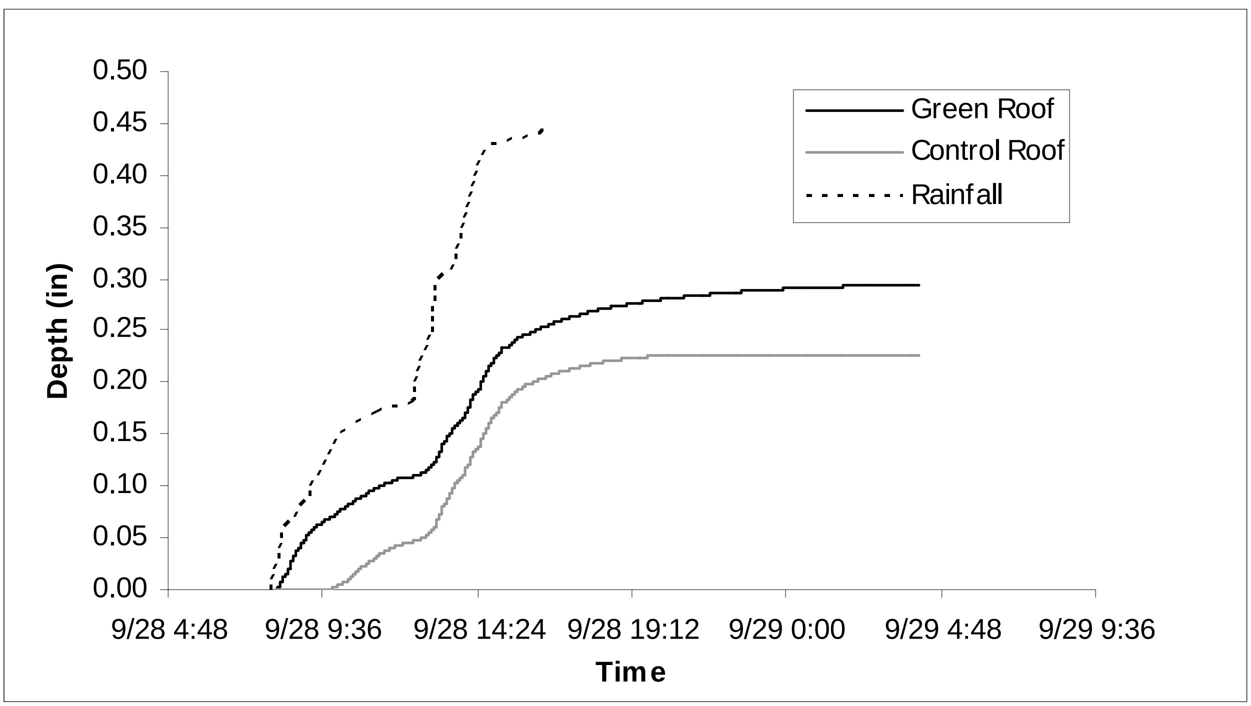

Figure 156 - Runoff as Rainfall - September 28, 2006 Storm

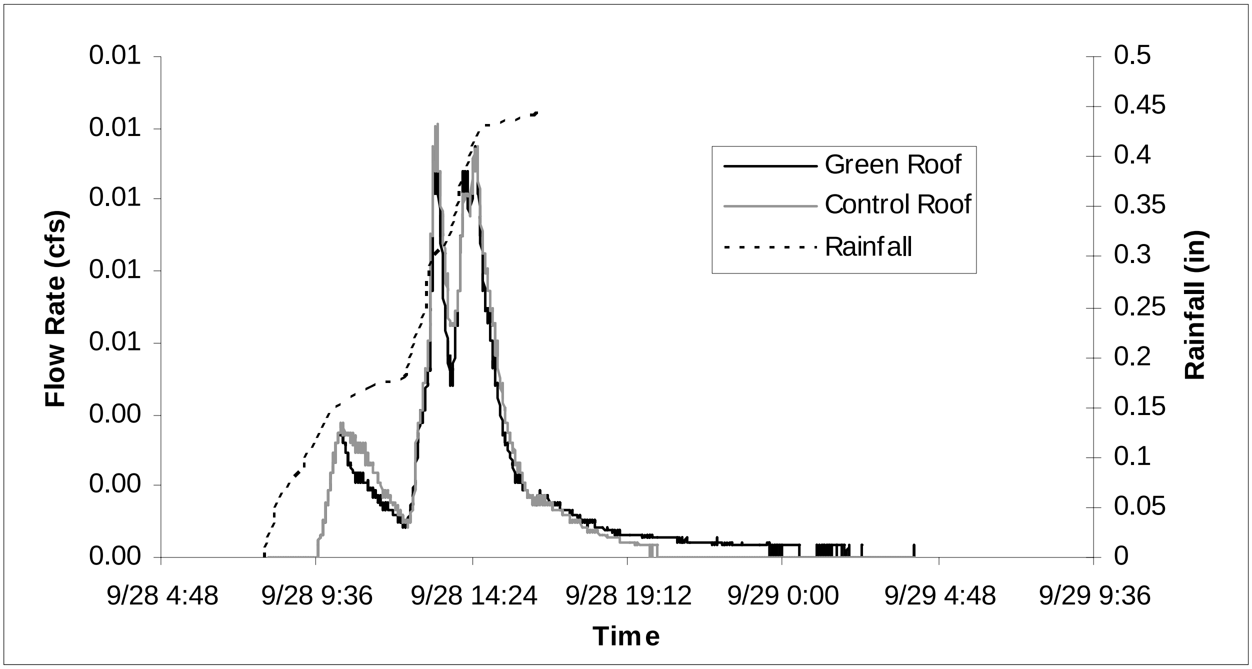

Figure 157 - Adjusted Runoff Flow Rates - September 28, 2006 Storm

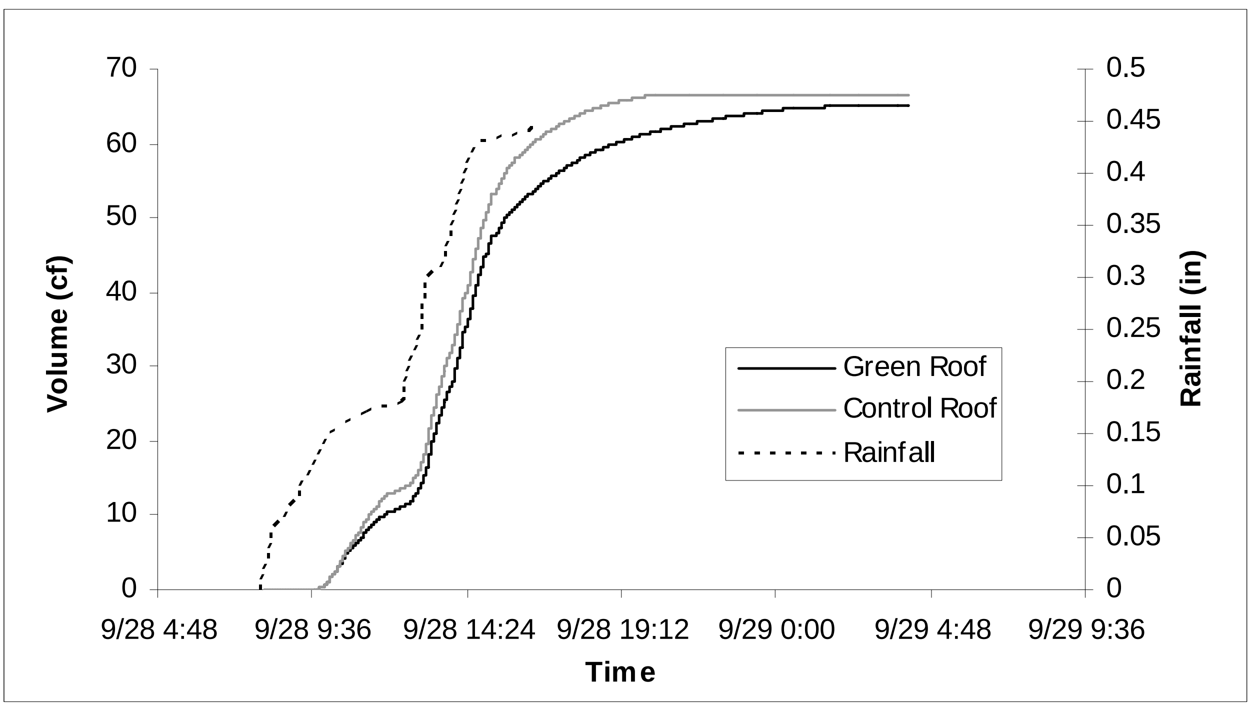

Figure 158 - Adjusted Runoff Volume - September 28, 2006 Storm

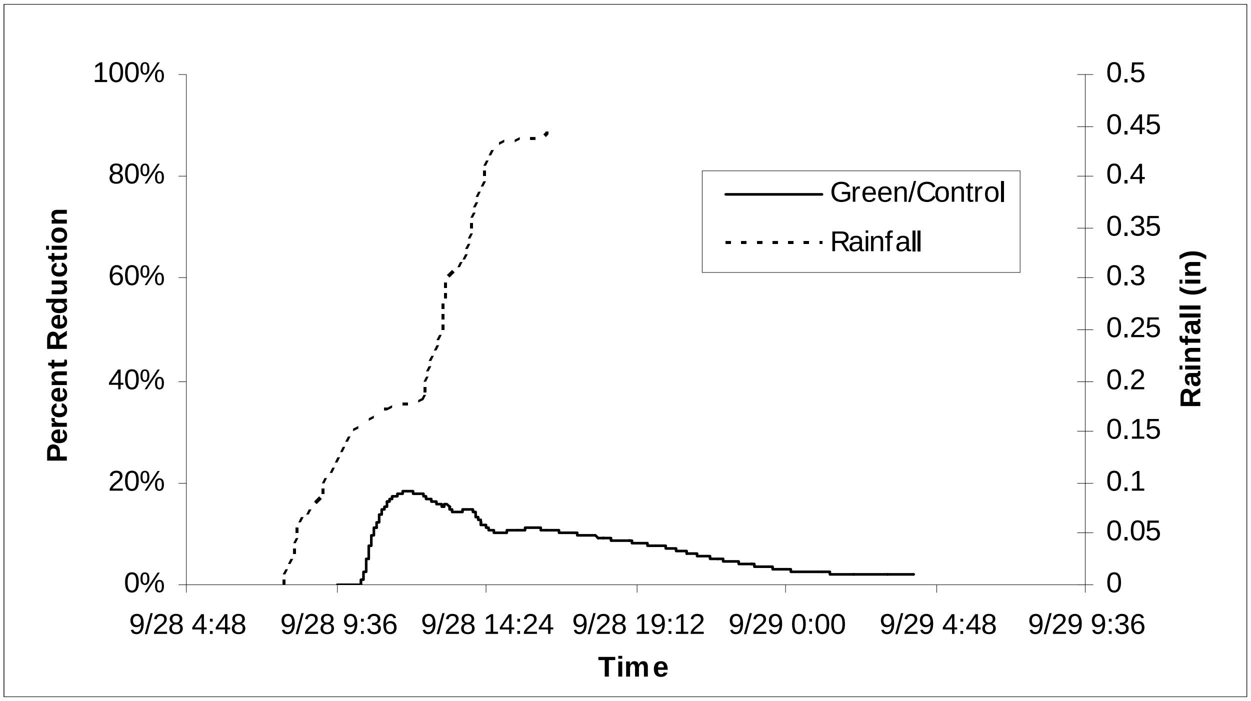

Figure 159 - Adjusted Runoff Reduction - September 28, 2006 Storm

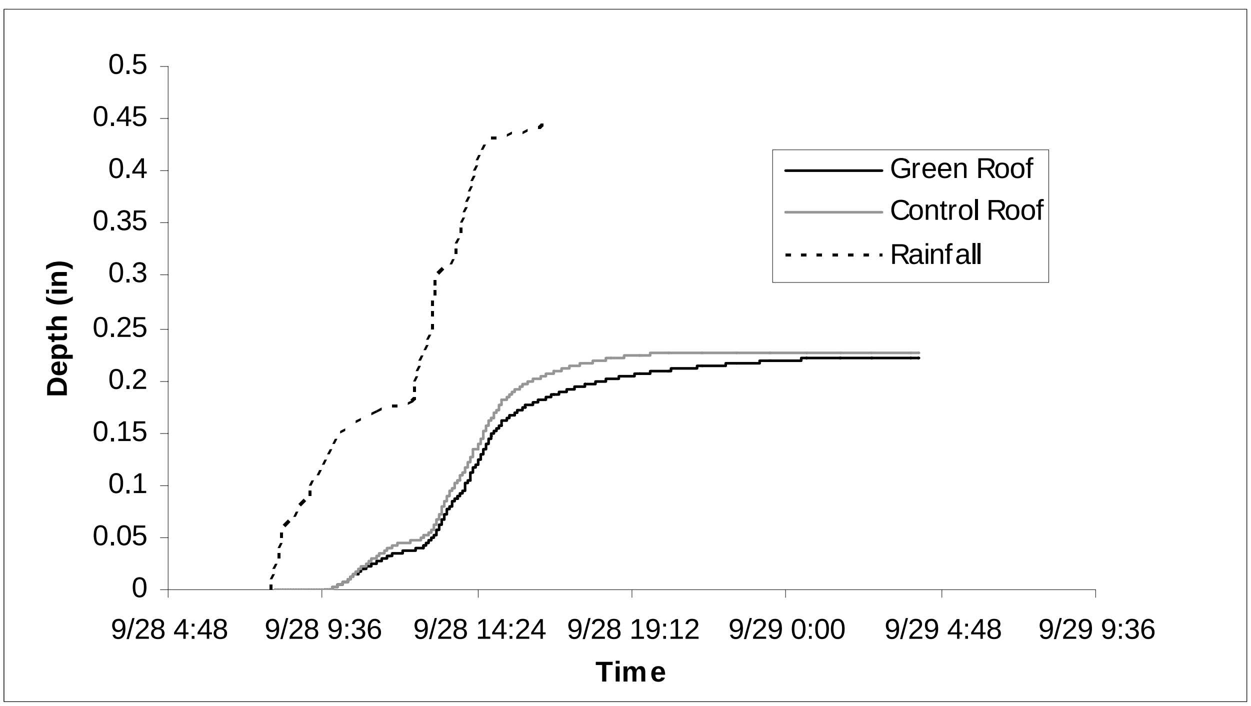

Figure 160 - Adjusted Runoff as Rainfall - September 28, 2006 Storm

Table 19 - September 28, 2006 Storm Summary

September 28, 2006 Storm			
Rainfall	Depth (in)	0.45	**Adjusted Values**
	Length	8:21	
Runoff	Delay	-1:31	
	Extension	12:51	
Max Flow Rate (cfs)	Green	0.0115	
	Control	0.0121	
	Reduction	5%	
Total Volume (cf)	Green	92.12	65.17
	Control	66.44	
	Reduction	-28%	2%
Equiv. in of Rain	Green	0.31	0.22
	Control	0.23	

A.11 OCTOBER 17, 2006 STORM

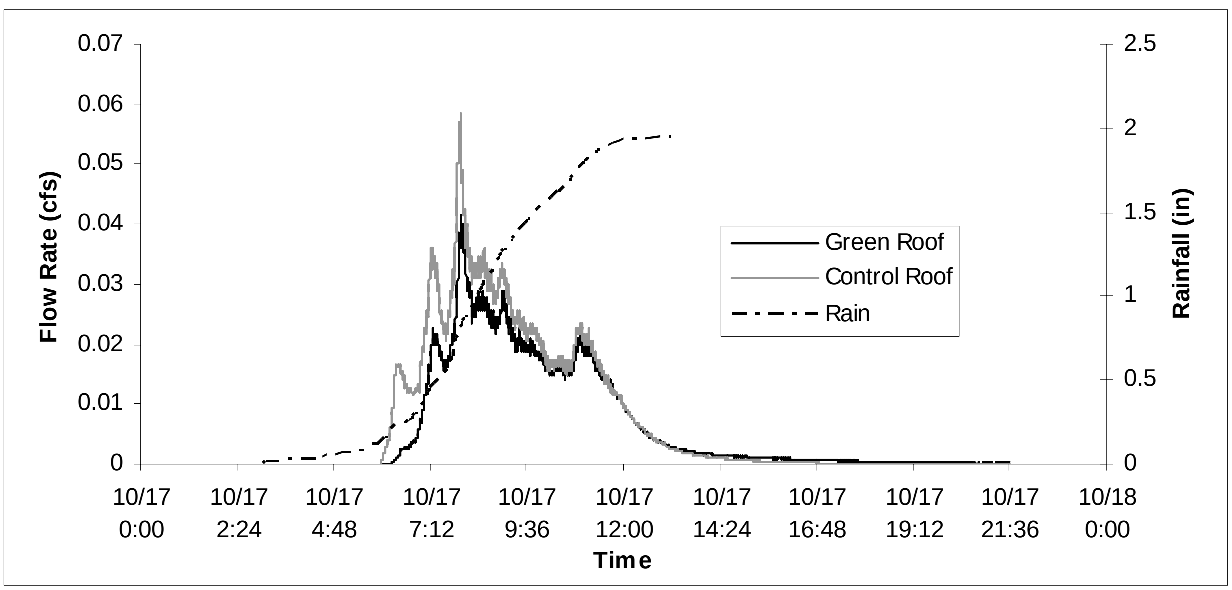

Figure 161 - Runoff Flow Rates - October 17, 2006 Storm

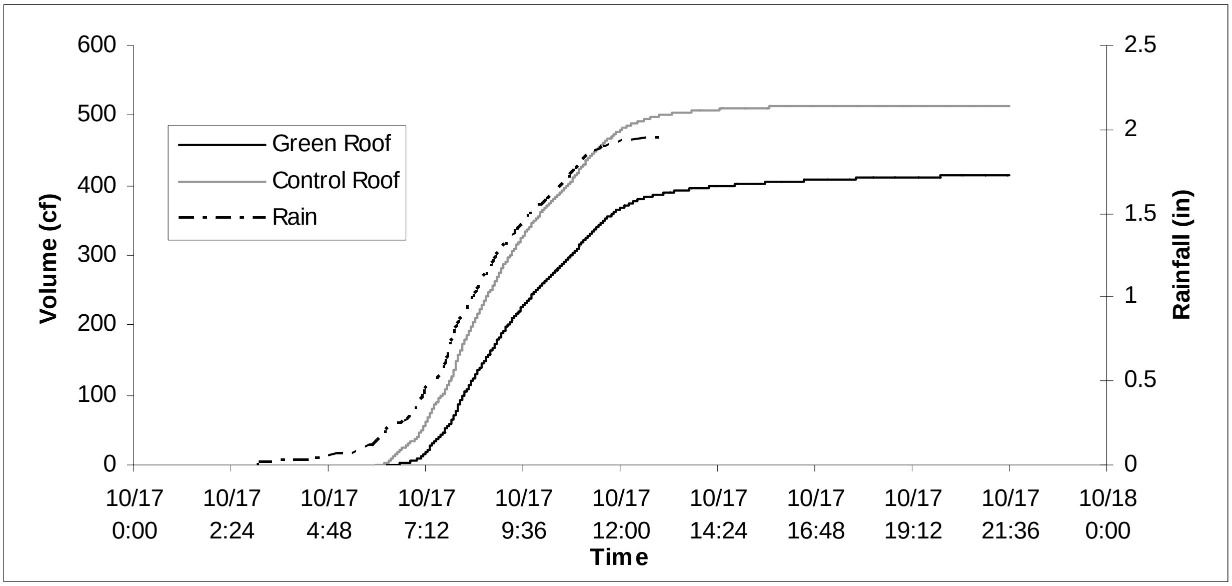

Figure 162 - Runoff Volume - October 17, 2006 Storm

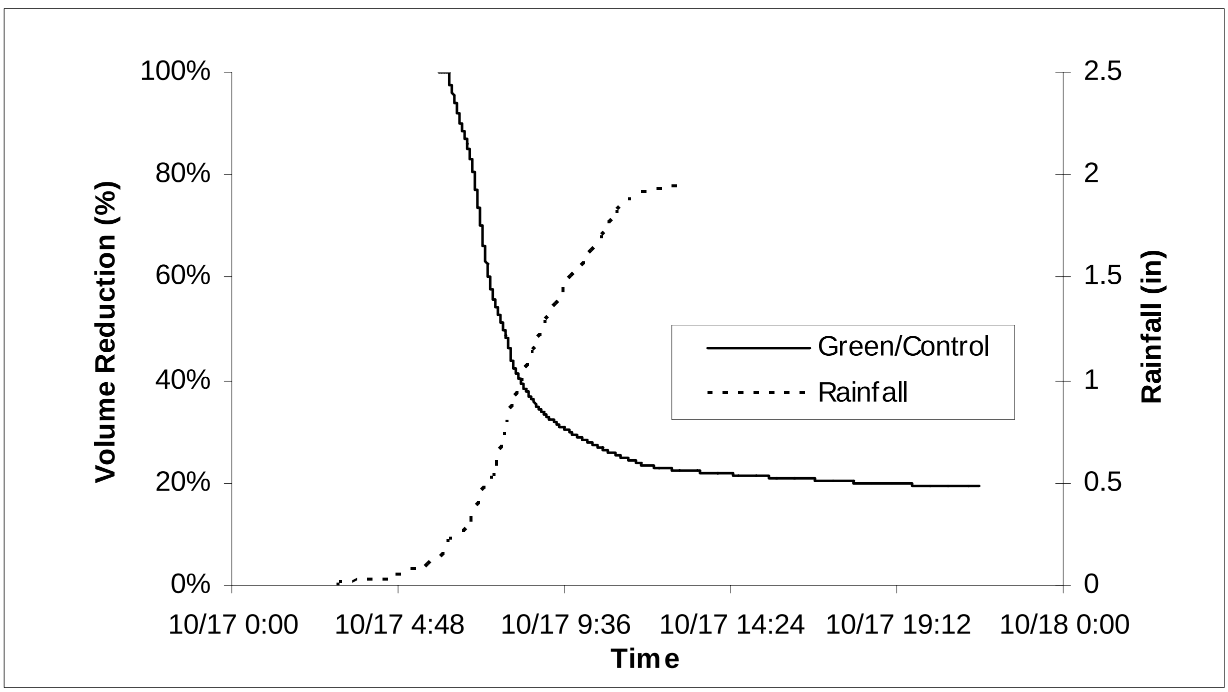

Figure 163 - Runoff Reduction - October 17, 2006 Storm

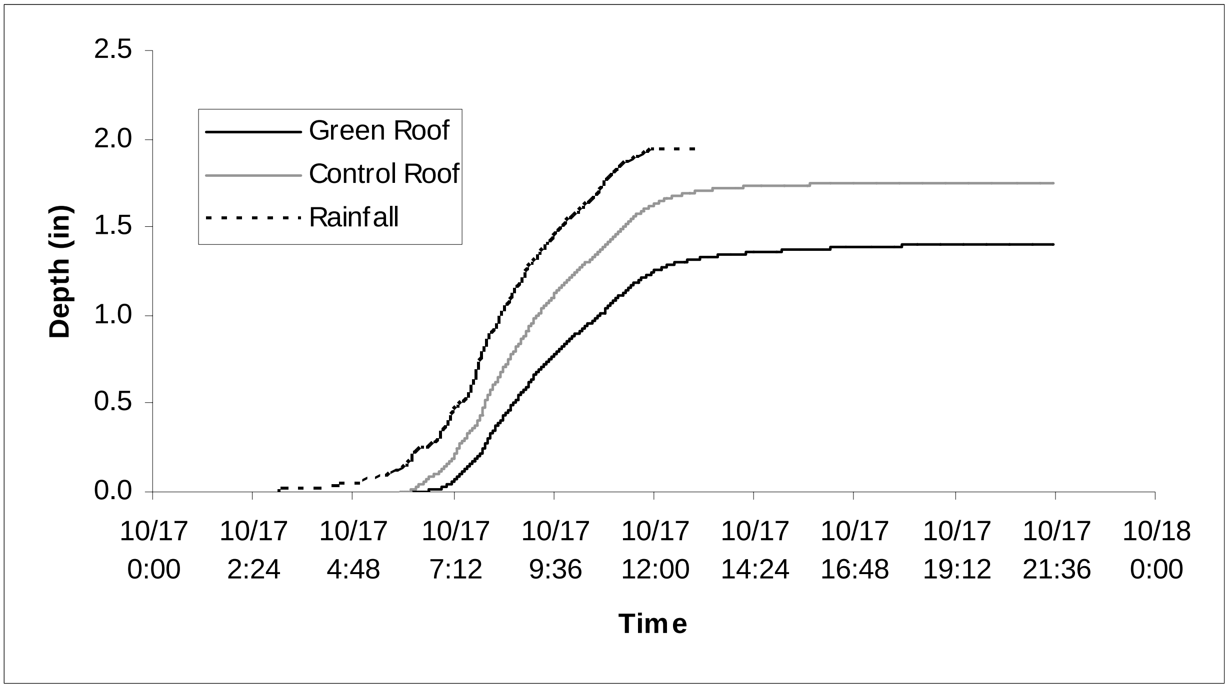

Figure 164 - Runoff as Rainfall - October 17, 2006 Storm

Table 20 - October 17, 2006 Storm Summary

October 17, 2006 Storm		
Rainfall	Depth (in)	1.94
	Length	10:05
Runoff	Delay	0:16
	Extension	4:43
Max Flow Rate (cfs)	Green	0.0415
	Control	0.0586
	Reduction	29%
Total Volume (cf)	Green	413.91
	Control	513.51
	Reduction	19%
Equiv. in of Rain	Green	1.41
	Control	1.75

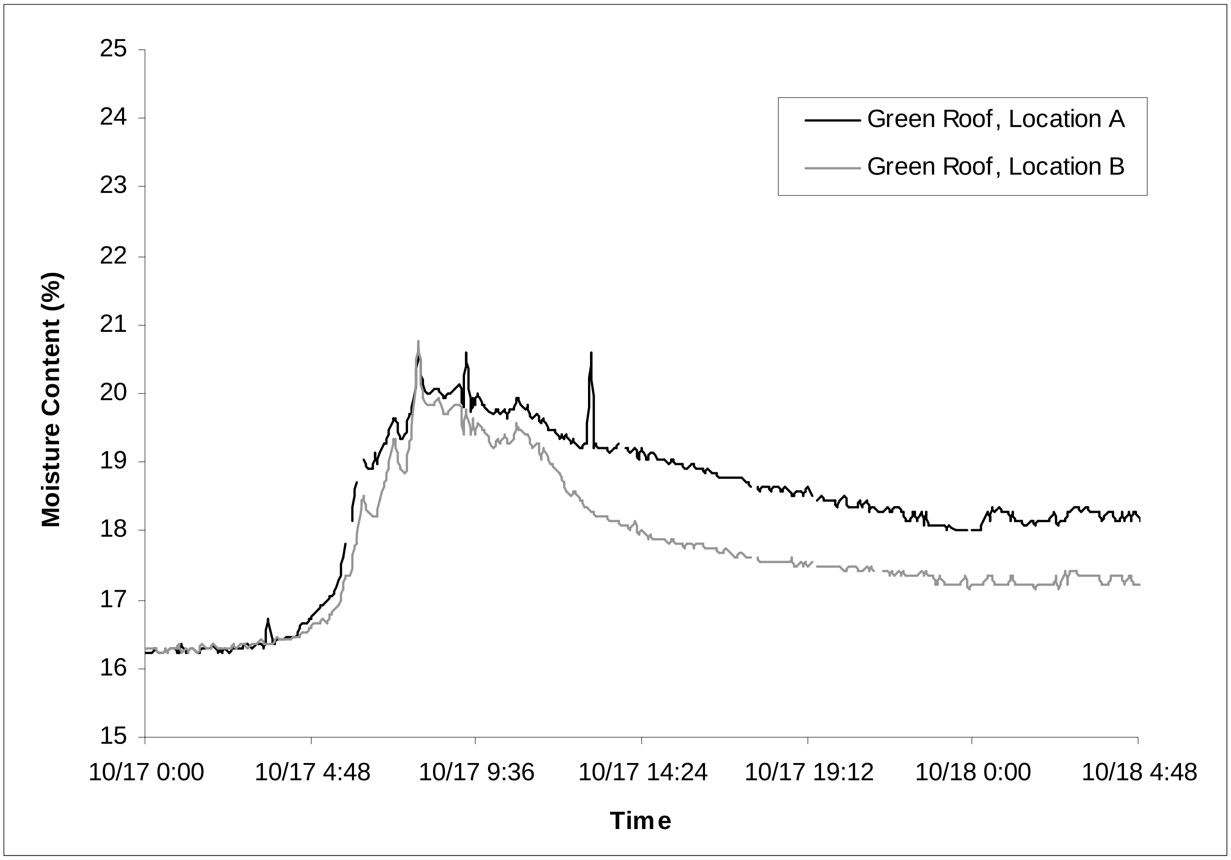

Figure 165 - Green Roof Water Content - October 17, 2006 Storm

Table 21 - Water Content - October 17, 2006 Storm

October 17, 2006 Storm		
	Water Content (%)	
	Location A	Location B
Start	16.16	16.16
Peak	20.6	18.99
End	18.02	17.04

A.12 OCTOBER 19, 2006 STORM

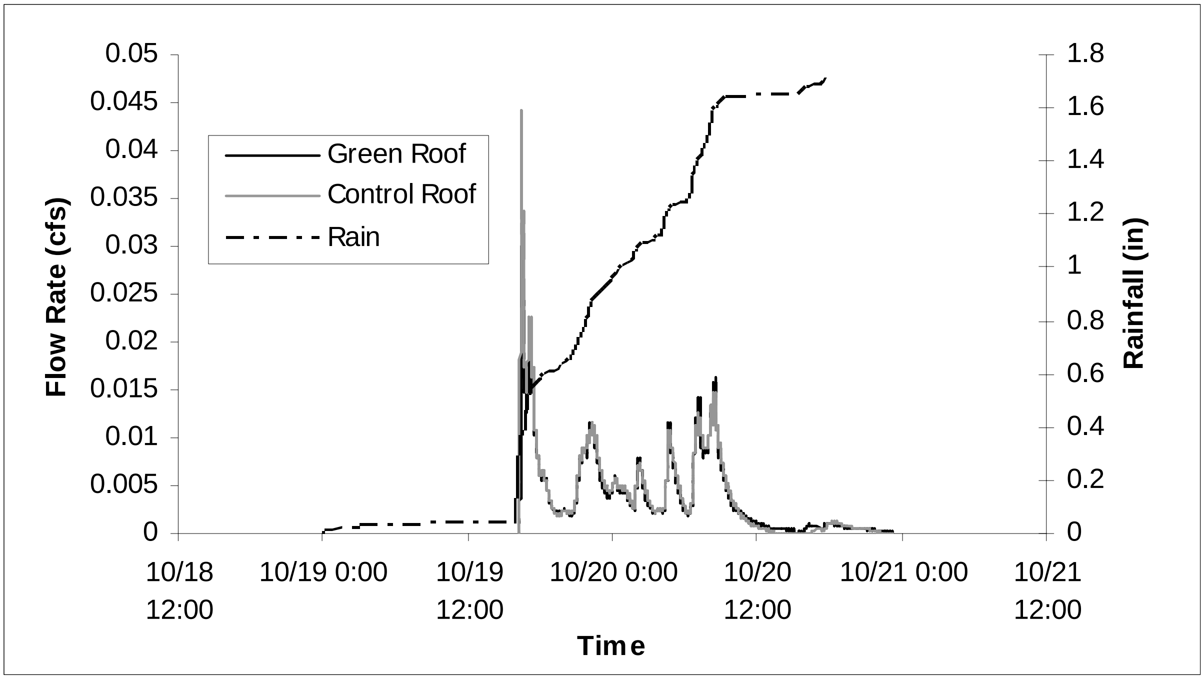

Figure 166 - Runoff Flow Rates - October 19, 2006 Storm

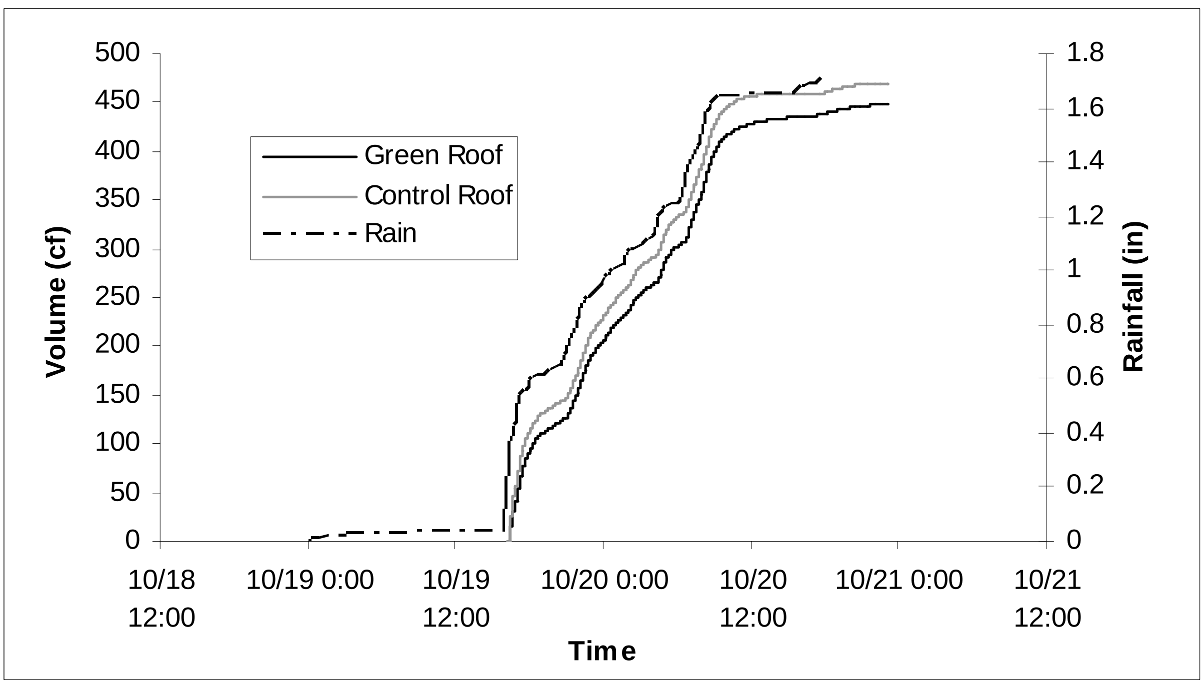

Figure 167 - Runoff Volume - October 19, 2006 Storm

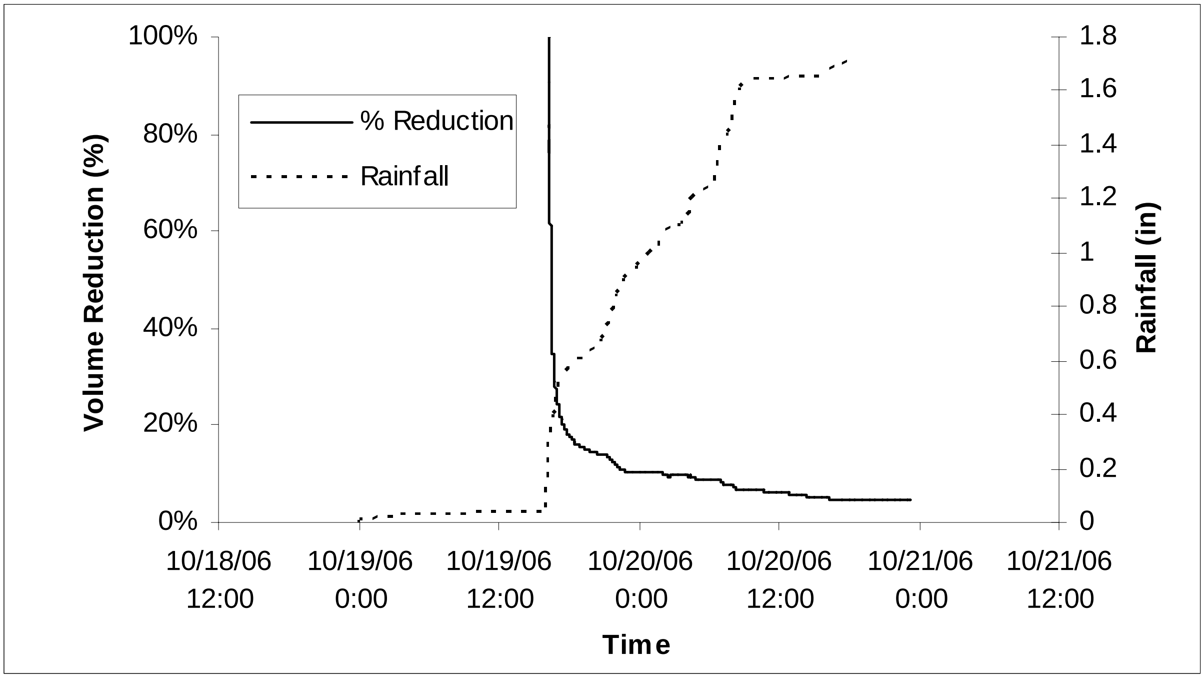

Figure 168 - Runoff Reduction - October 19, 2006 Storm

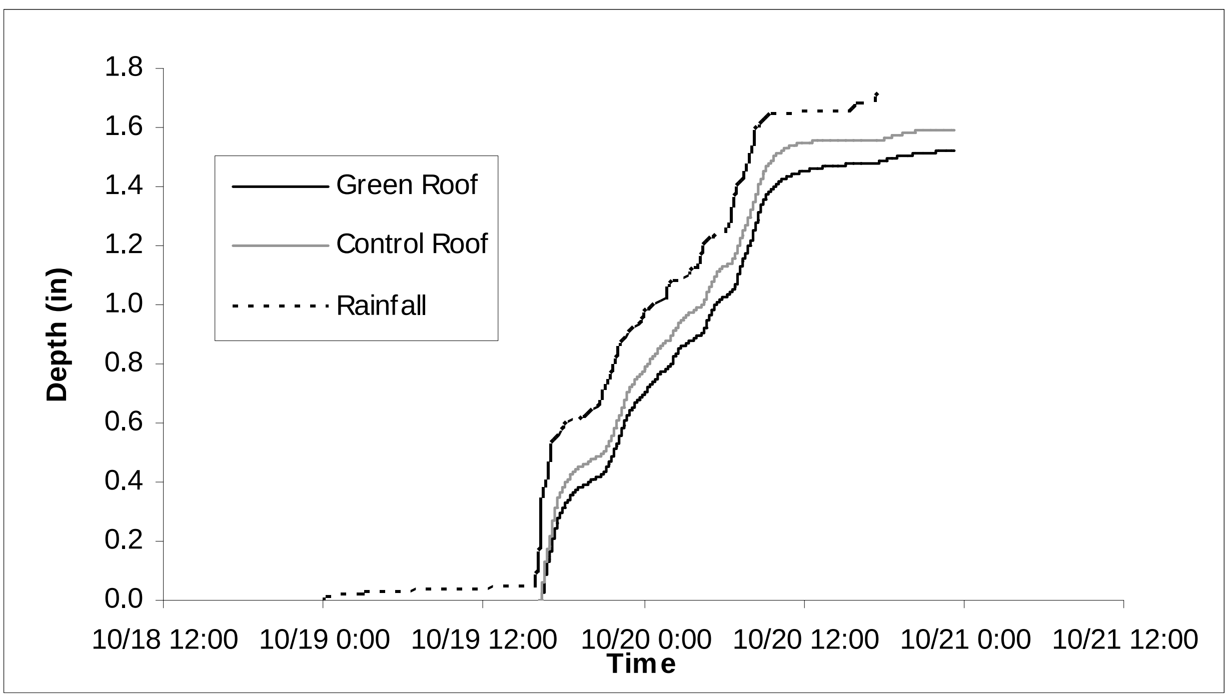

Figure 169 - Runoff as Rainfall - October 19, 2006 Storm

Table 22 - October 19, 2006 Storm Summary

October 19, 2006 Storm		
Rainfall	Depth (in)	1.73
	Length	1 Day, 17:31
Runoff	Delay	0:00
	Extension	1:04
Max Flow Rate (cfs)	Green	0.0301
	Control	0.0443
	Reduction	32%
Total Volume (cf)	Green	448.62
	Control	470.29
	Reduction	5%
Equiv. in of Rain	Green	1.52
	Control	1.6

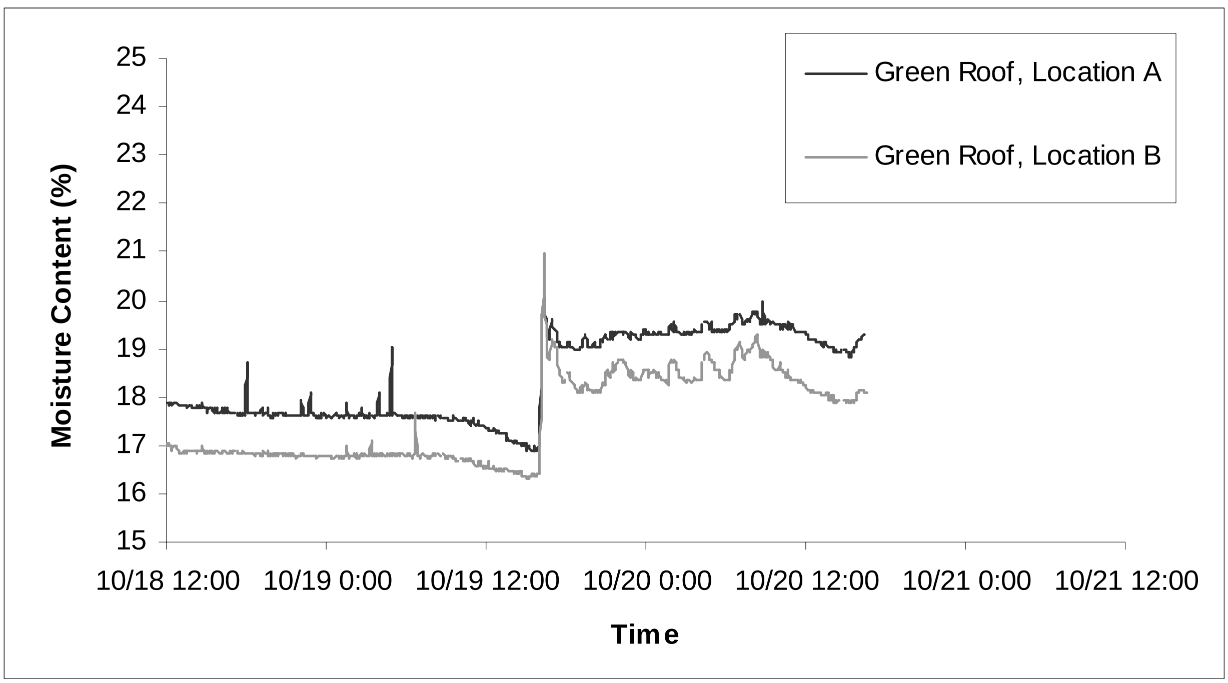

Figure 170 - Green Roof Water Content - October 19, 2006 Storm

Table 23 - Water Content - October 19, 2006 Storm

October 19, 2006 Storm		
	Water Content (%)	
	Location A	Location B
Start	17.95	17.1
Peak	20.29	20.9
End	18.91	17.95

A.13 OCTOBER 27, 2006 STORM

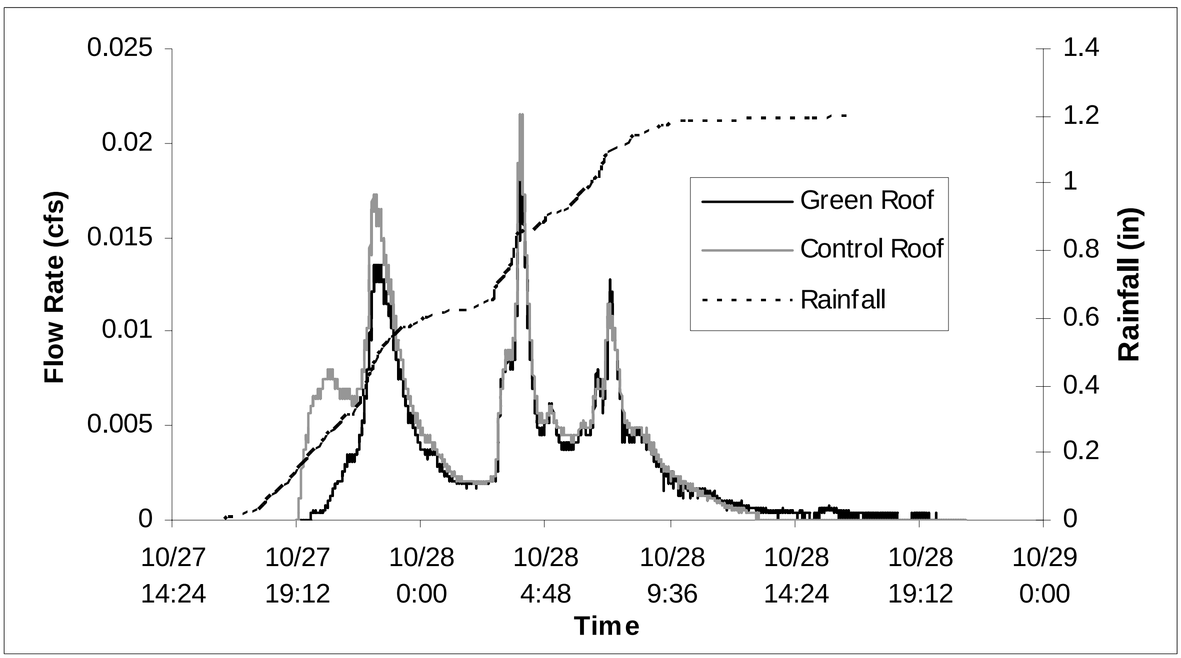

Figure 171 - Runoff Flow Rates - October 27, 2006 Storm

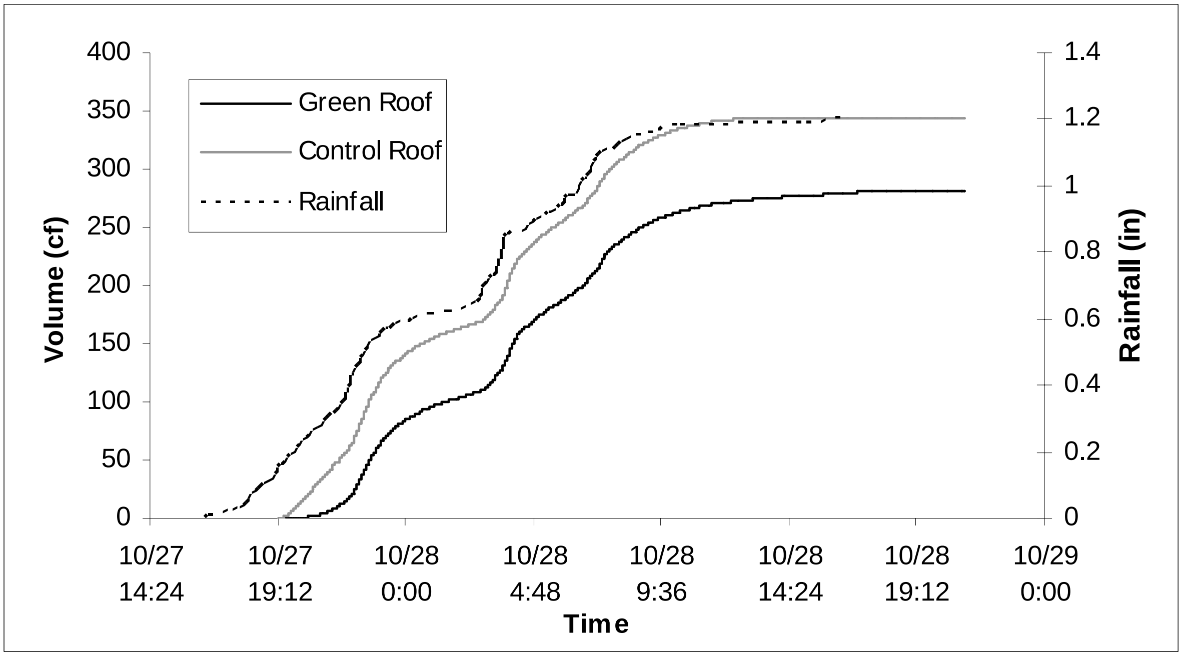

Figure 172 - Runoff Volume - October 27, 2006 Storm

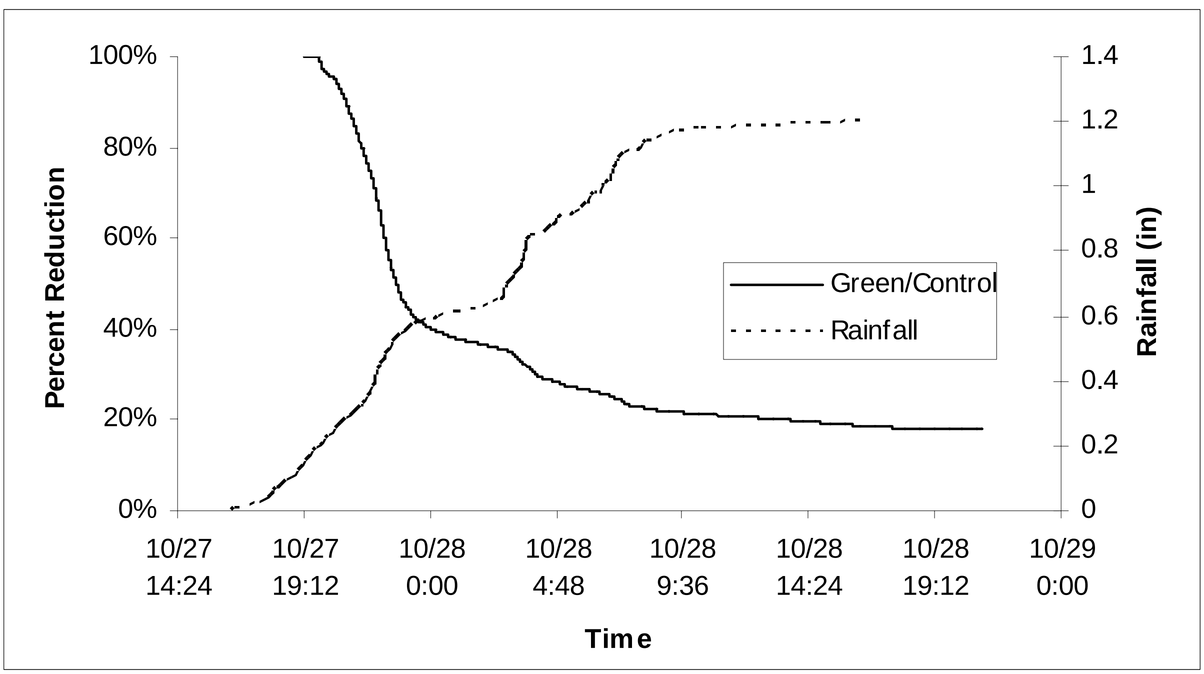

Figure 173 - Runoff Reduction - October 27, 2006 Storm

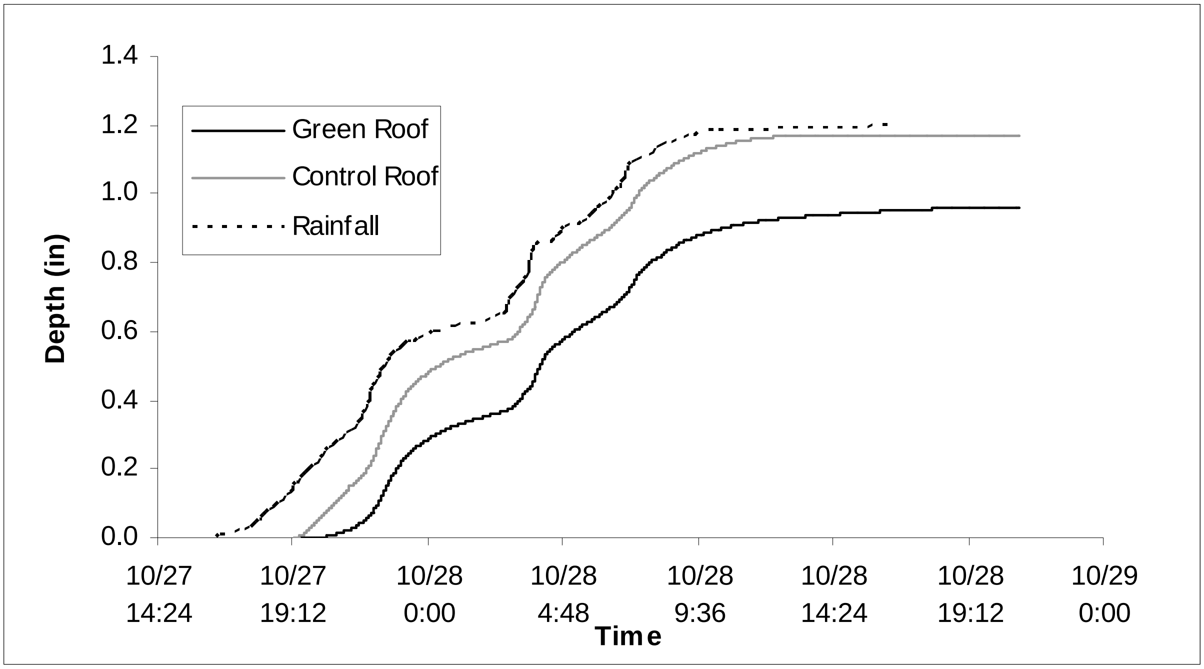

Figure 174 - Runoff as Rainfall - October 27, 2006 Storm

Table 24 - October 27, 2006 Storm Summary

October 27, 2006 Storm		
Rainfall	Depth (in)	1.2
	Length	23:47
Runoff	Delay	0:30
	Extension	6:46
Max Flow Rate (cfs)	Green	0.0181
	Control	0.0216
	Reduction	16%
Total Volume (cf)	Green	281.57
	Control	343.8
	Reduction	18%
Equiv. in of Rain	Green	0.96
	Control	1.17

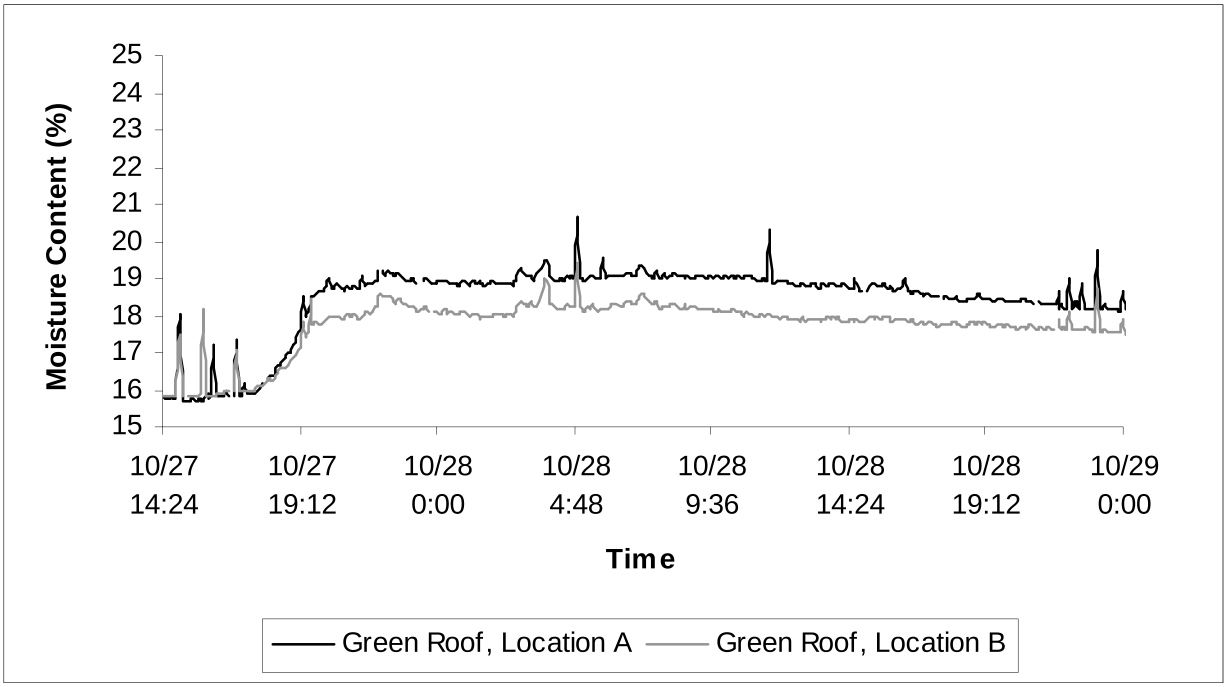

Figure 175 - Green Roof Water Content - October 27, 2006 Storm

Table 25 - Water Content - October 27, 2006 Storm

October 27, 2006 Storm		
	Water Content (%)	
	Location A	Location B
Start	15.8	15.86
Peak	20.29	17.75
End	18.16	17.49

A.14 OCTOBER 31, 2006 STORM

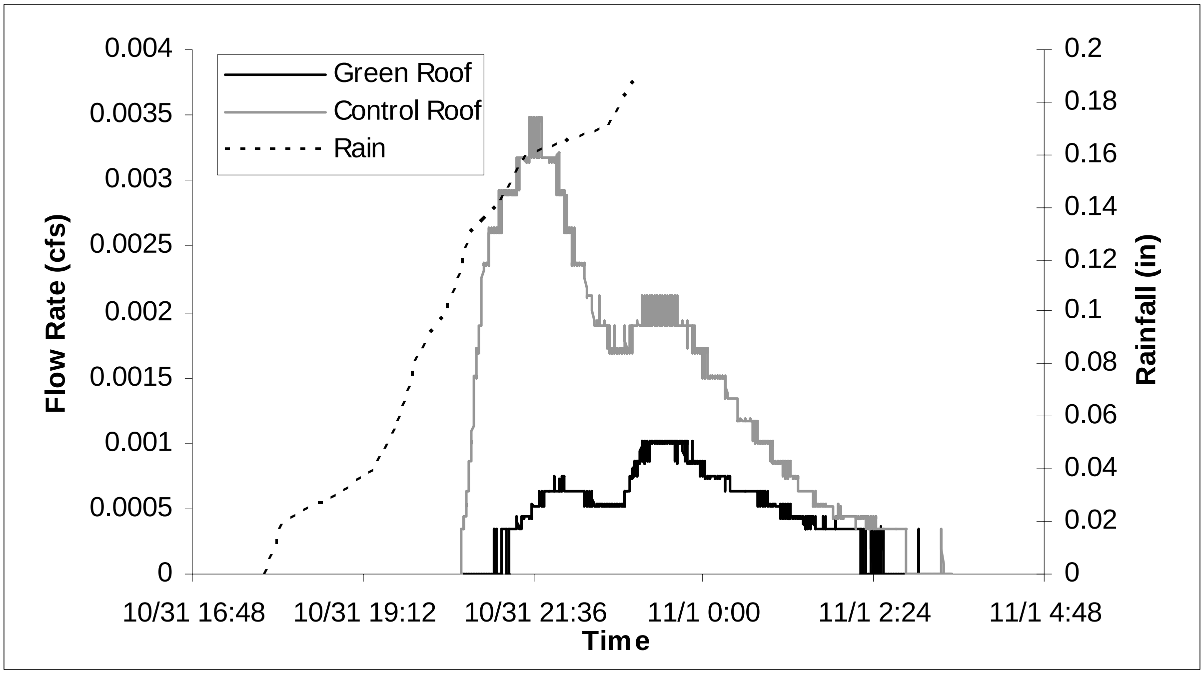

Figure 176 - Runoff Flow Rates - October 31, 2006 Storm

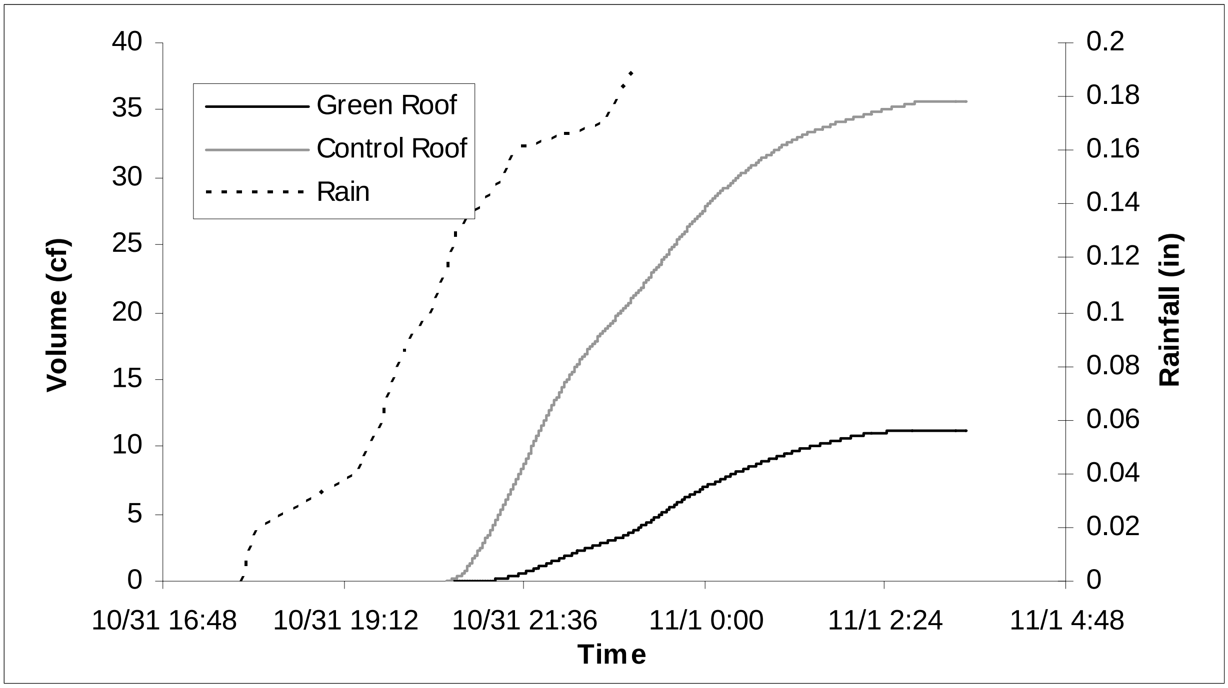

Figure 177 - Runoff Volume - October 31, 2006 Storm

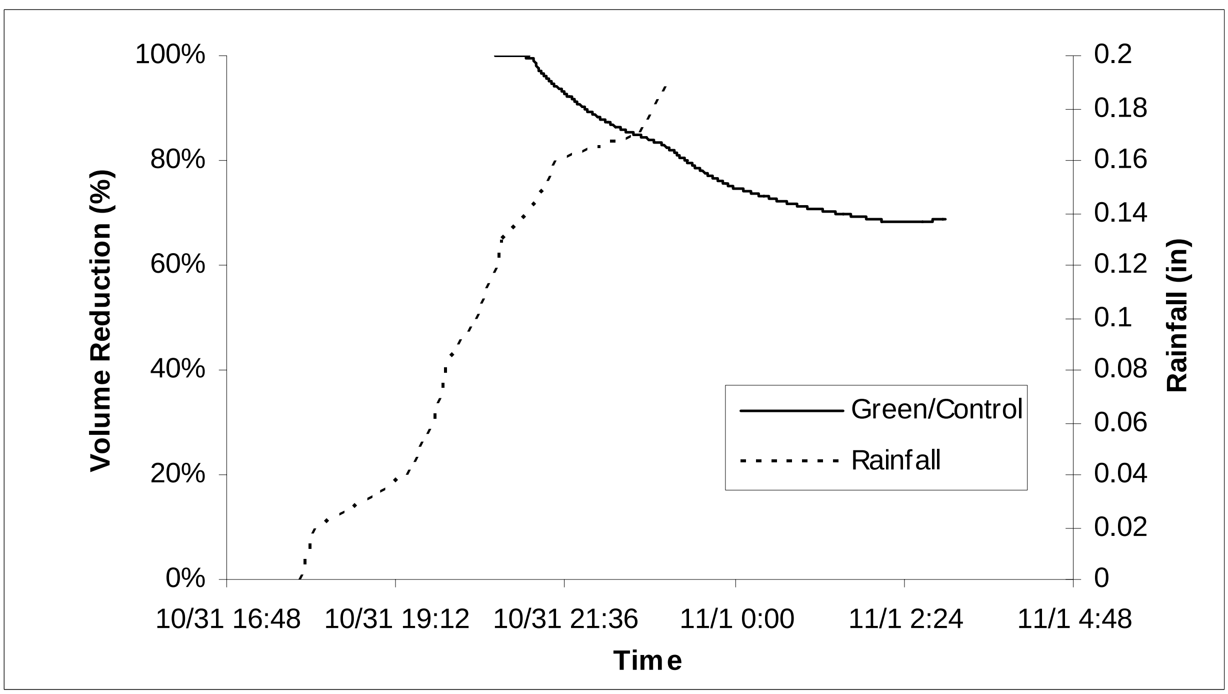

Figure 178 - Runoff Reduction - October 31, 2006 Storm

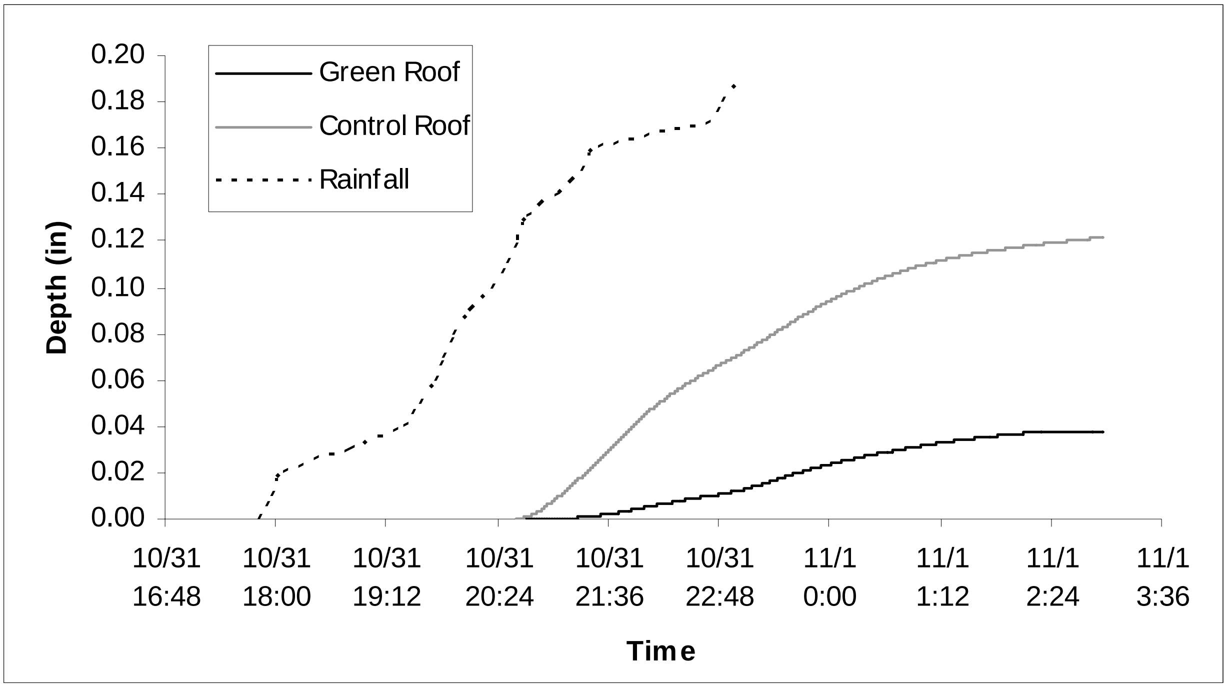

Figure 179 - Runoff as Rainfall - October 31, 2006 Storm

Table 26 - October 31, 2006 Storm Summary

October 31, 2006 Storm		
Rainfall	Depth (in)	0.19
	Length	5:14
Runoff	Delay	0:26
	Extension	0:10
Max Flow Rate (cfs)	Green	0.001
	Control	0.0035
	Reduction	71%
Total Volume (cf)	Green	11.2
	Control	35.62
	Reduction	69%
Equiv. in of Rain	Green	0.04
	Control	0.12

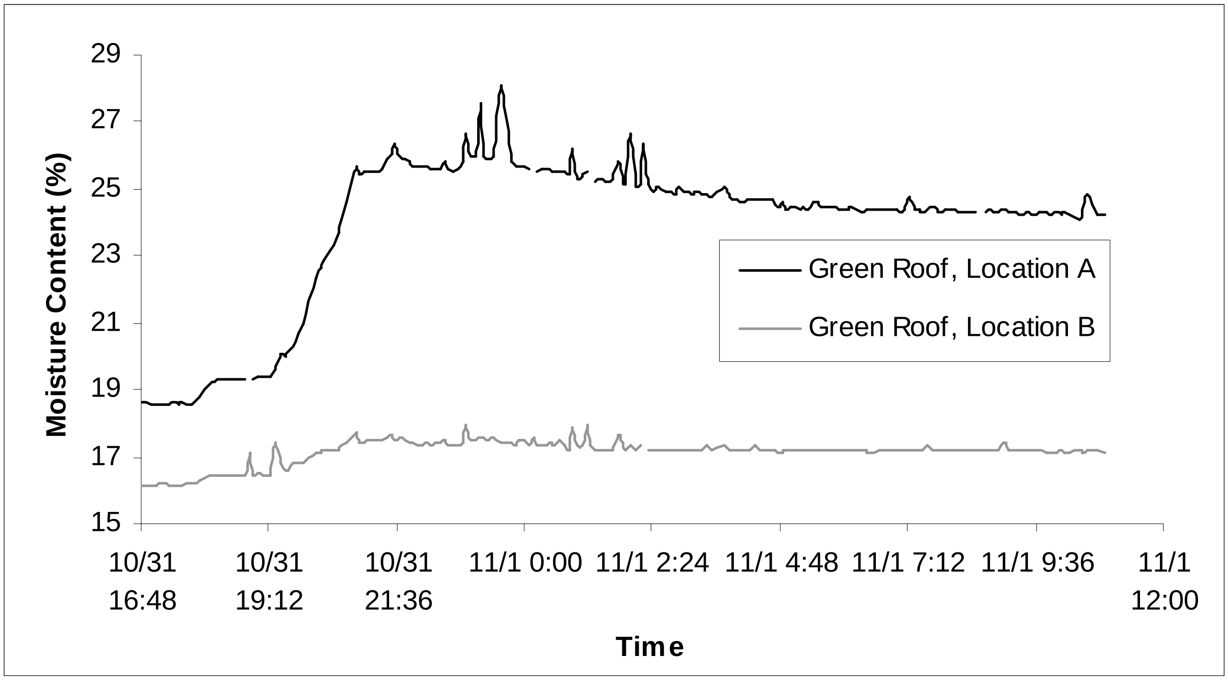

Figure 180 - Green Roof Water Content - October 31, 2006 Storm

Table 27 - Water Content - October 31, 2006 Storm

October 31, 2006 Storm		
	Water Content (%)	
	Location A	Location B
Start	18.64	16.16
Peak	28.06	17.36
End	24.22	17.1

A.15 NOVEMBER 1, 2006 STORM

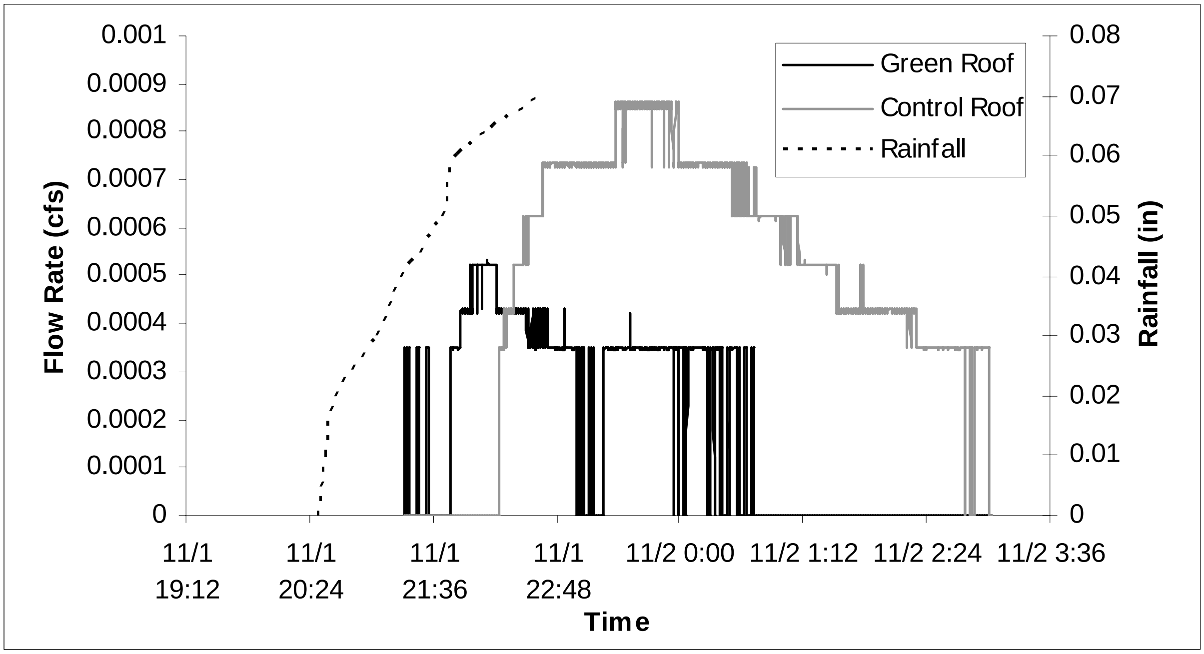

Figure 181 - Runoff Flow Rates - November 1, 2006 Storm

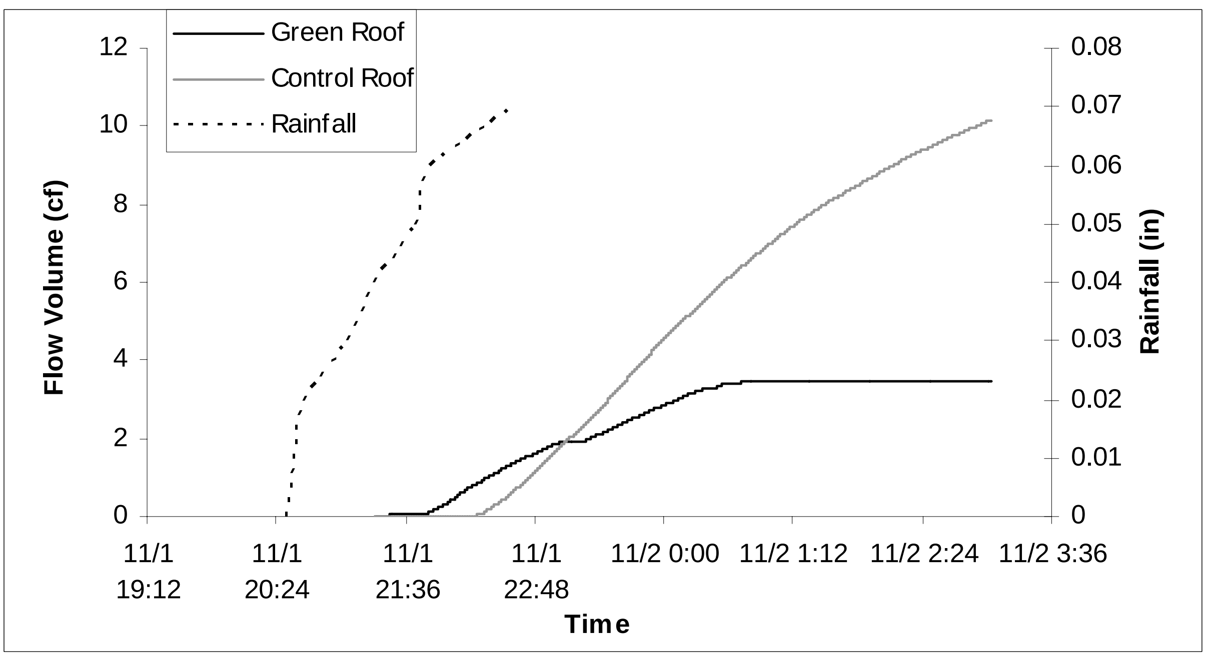

Figure 182 - Runoff Volume - November 1, 2006

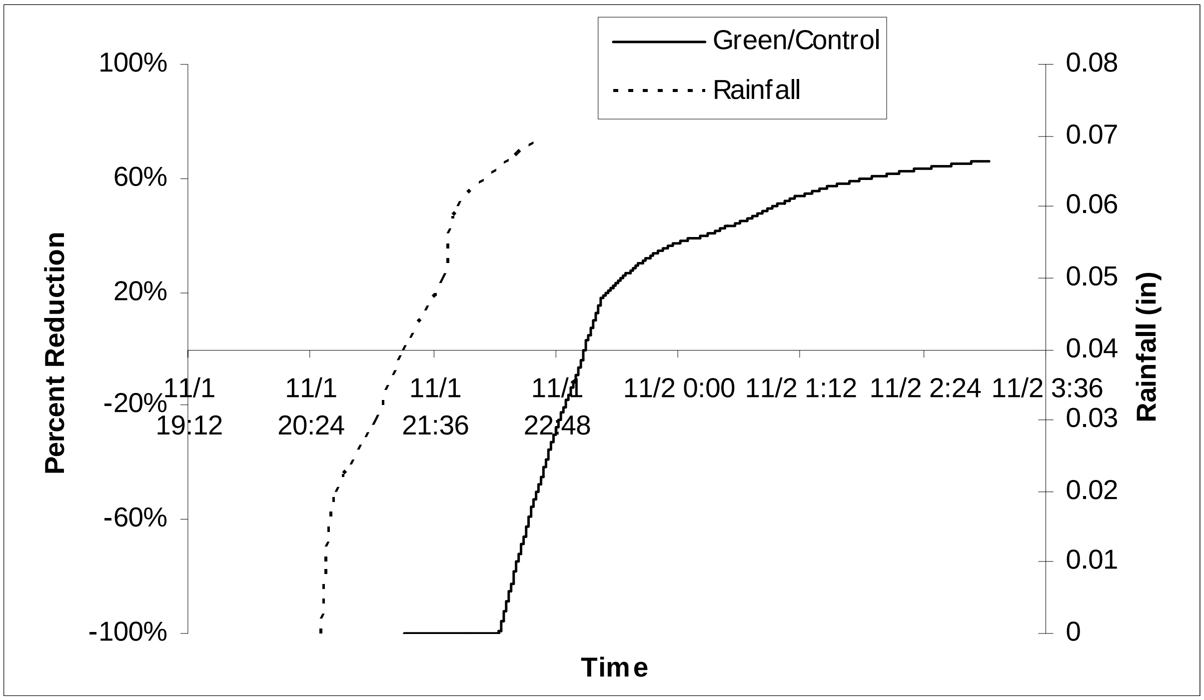

Figure 183 - Runoff Reduction - November 1, 2006 Storm

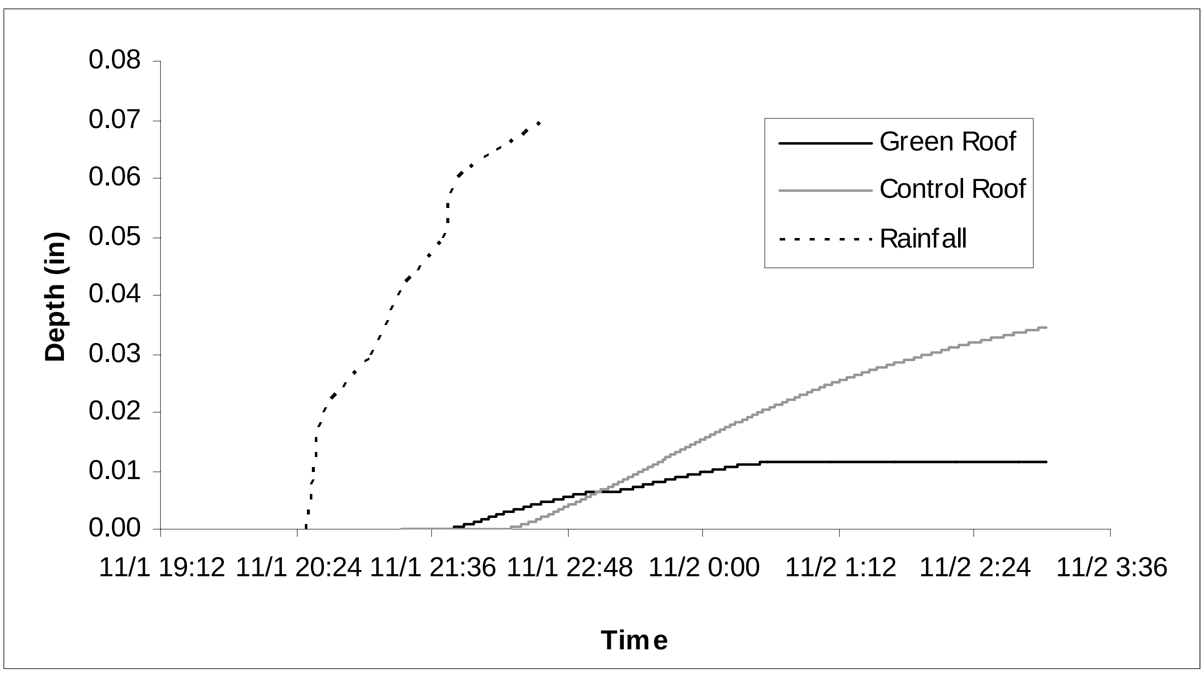

Figure 184 - Runoff as Rainfall - November 1, 2006 Storm

Table 28 - November 1, 2006 Storm Summary

November 1, 2006 Storm		
Rainfall	Depth (in)	0.07
	Length	2:08
Runoff	Delay	0:55
	Extension	3:57
Max Flow Rate (cfs)	Green	0.0005
	Control	0.0009
	Reduction	38%
Total Volume (cf)	Green	3.44
	Control	10.14
	Reduction	66%
Equiv. in of Rain	Green	0.01
	Control	0.03

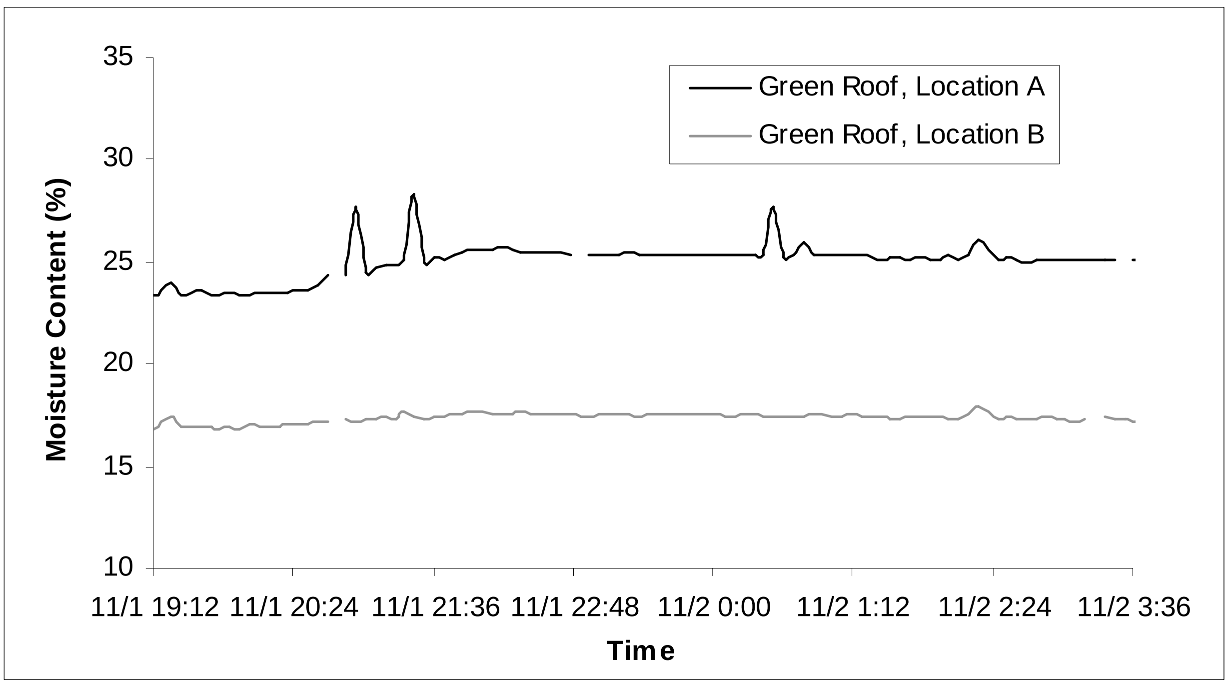

Figure 185 - Green Roof Water Content - November 1, 2006 Storm

Table 29 - Water Content - November 1, 2006 Storm

November 1, 2006 Storm		
	Water Content (%)	
	Location A	Location B
Start	23.43	16.91
Peak	28.38	17.69
End	25.04	17.23

A.16 NOVEMBER 11, 2006 STORM

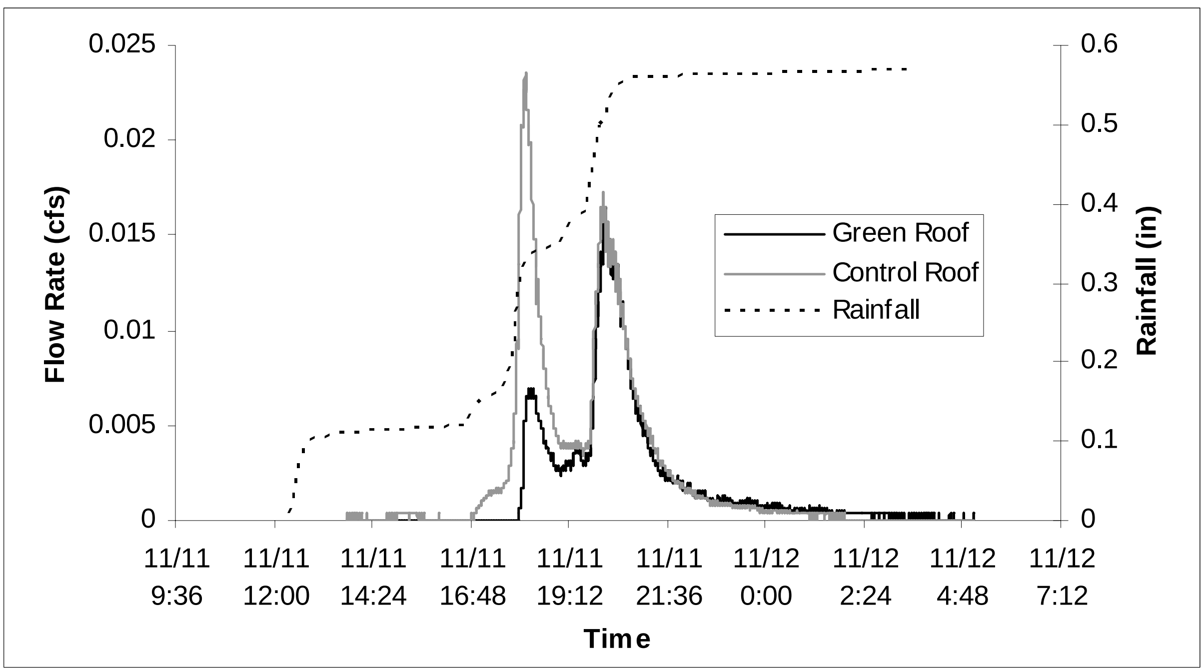

Figure 186 - Runoff Flow Rates - November 11, 2006 Storm

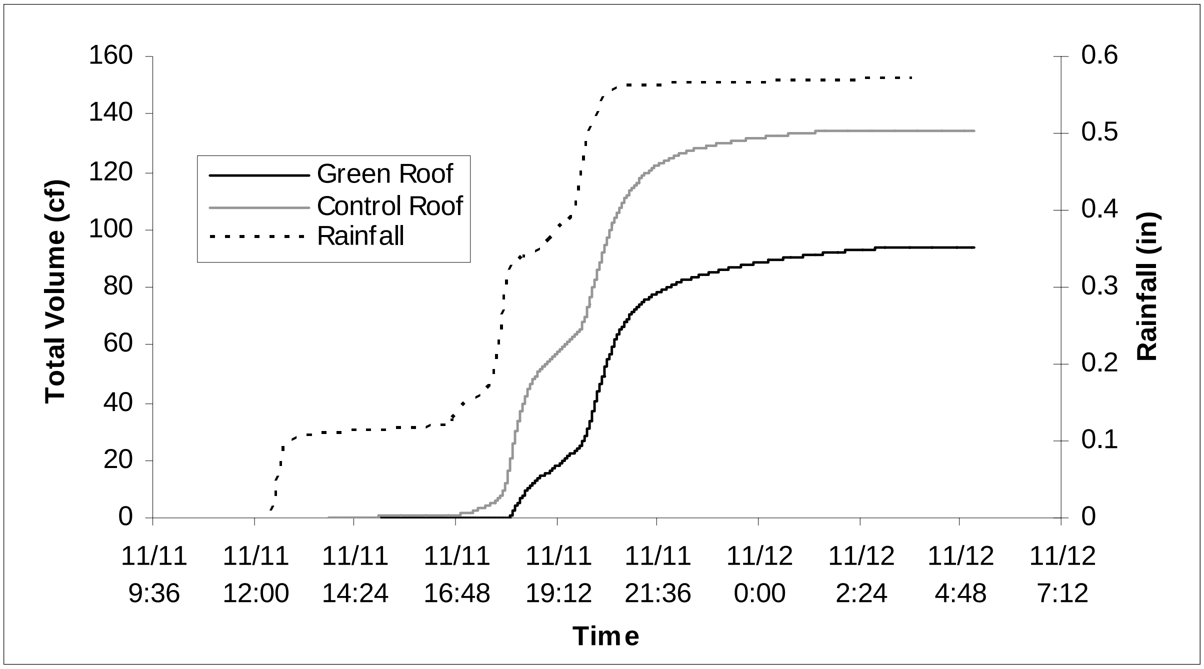

Figure 187 - Runoff Volume - November 11, 2006 Storm

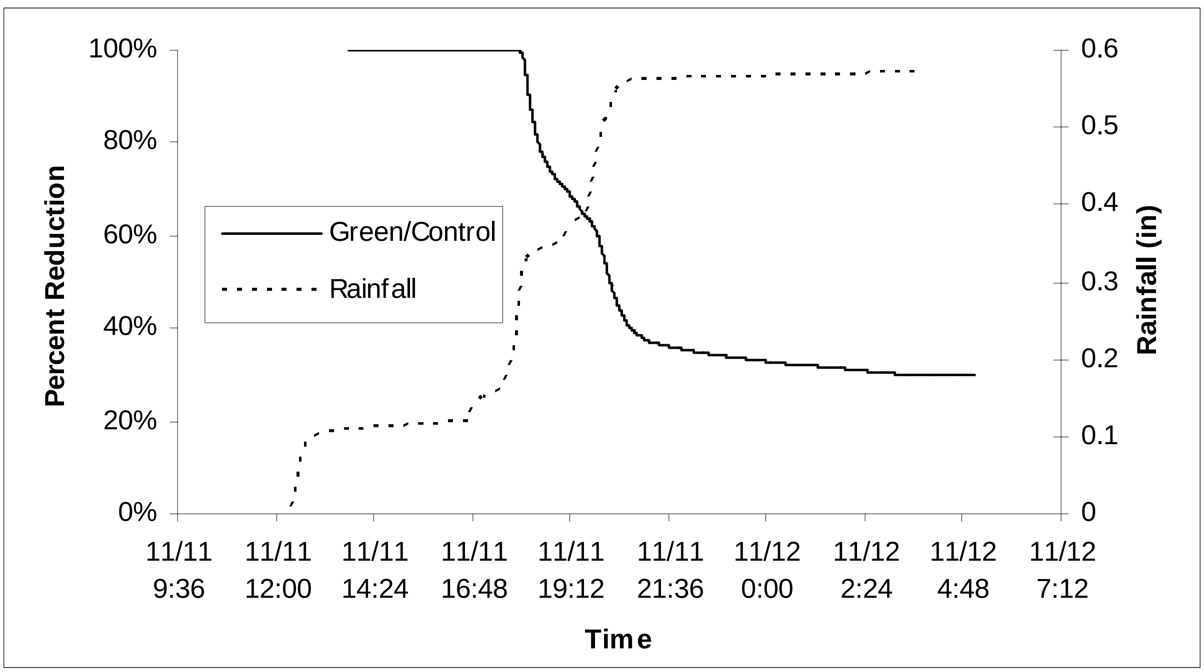

Figure 188 - Runoff Reduction - November 11, 2006 Storm

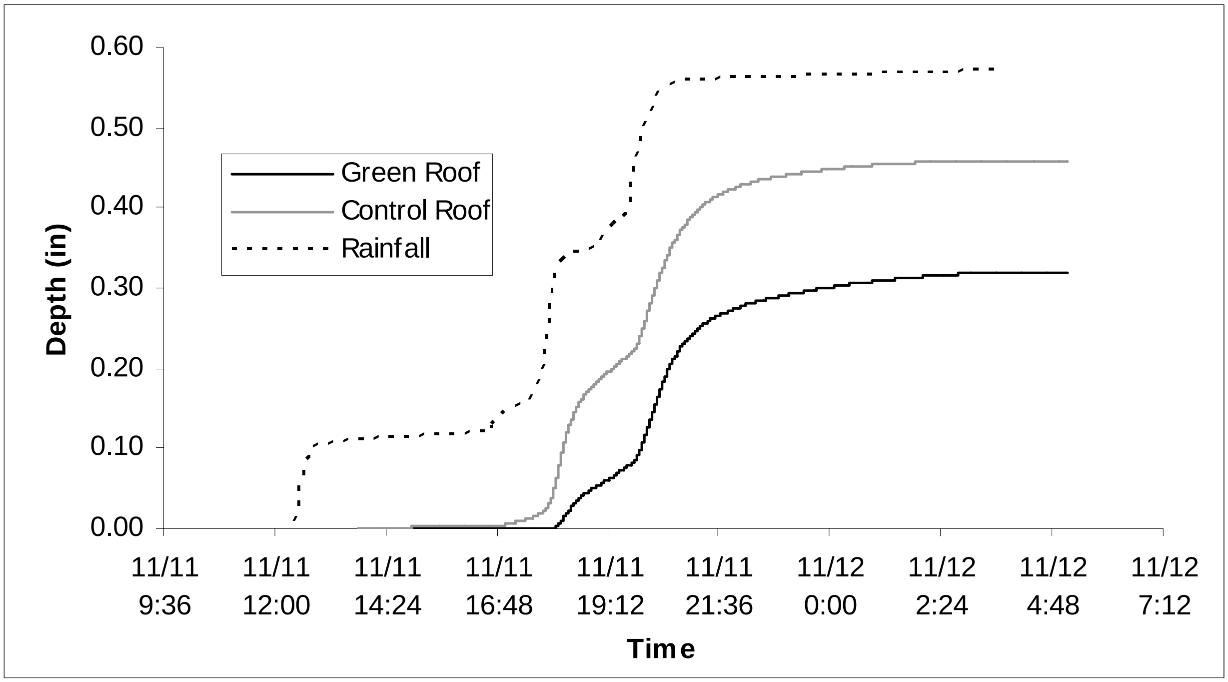

Figure 189 - Runoff as Rainfall - November 11, 2006 Storm

Table 30 - November 11, 2006 Storm Summary

November 11, 2006 Storm		
Rainfall	Depth (in)	0.57
	Length	15:13
Runoff	Delay	4:09
	Extension	3:09
Max Flow Rate (cfs)	Green	0.0164
	Control	0.0236
	Reduction	30%
Total Volume (cf)	Green	94.04
	Control	134.21
	Reduction	30%
Equiv. in of Rain	Green	0.32
	Control	0.46

A.17 NOVEMBER 15, 2006 STORM

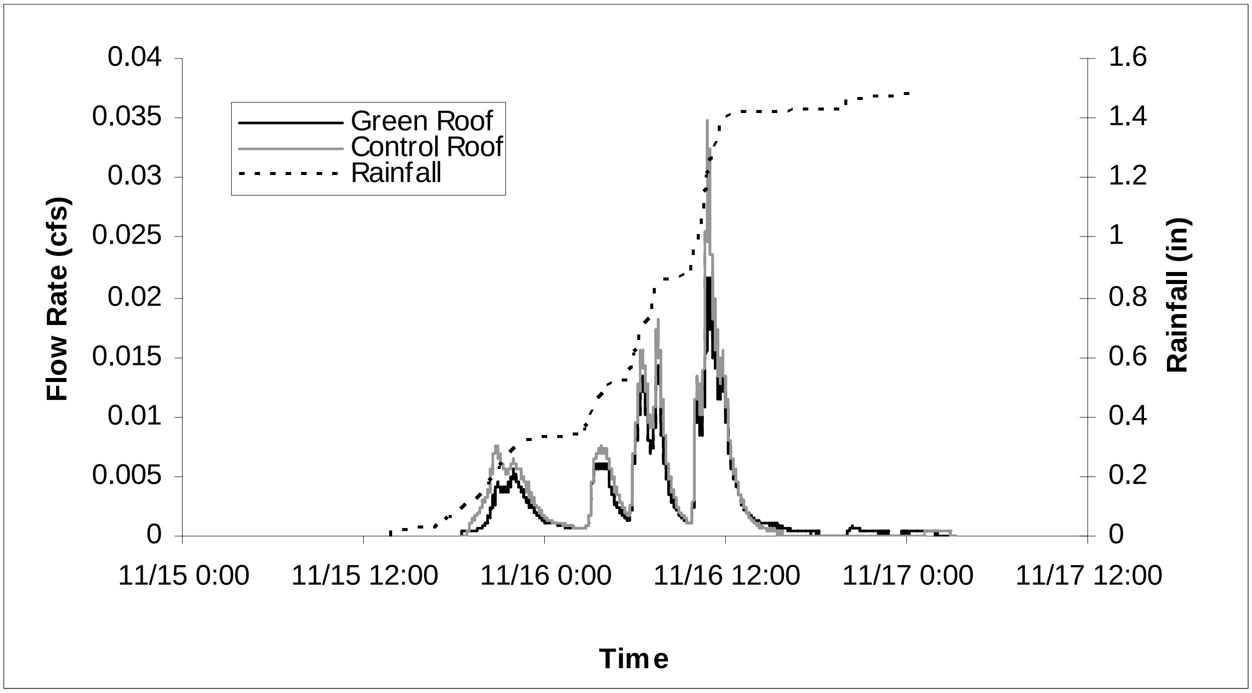

Figure 190 - Runoff Flow Rates - November 15, 2006 Storm

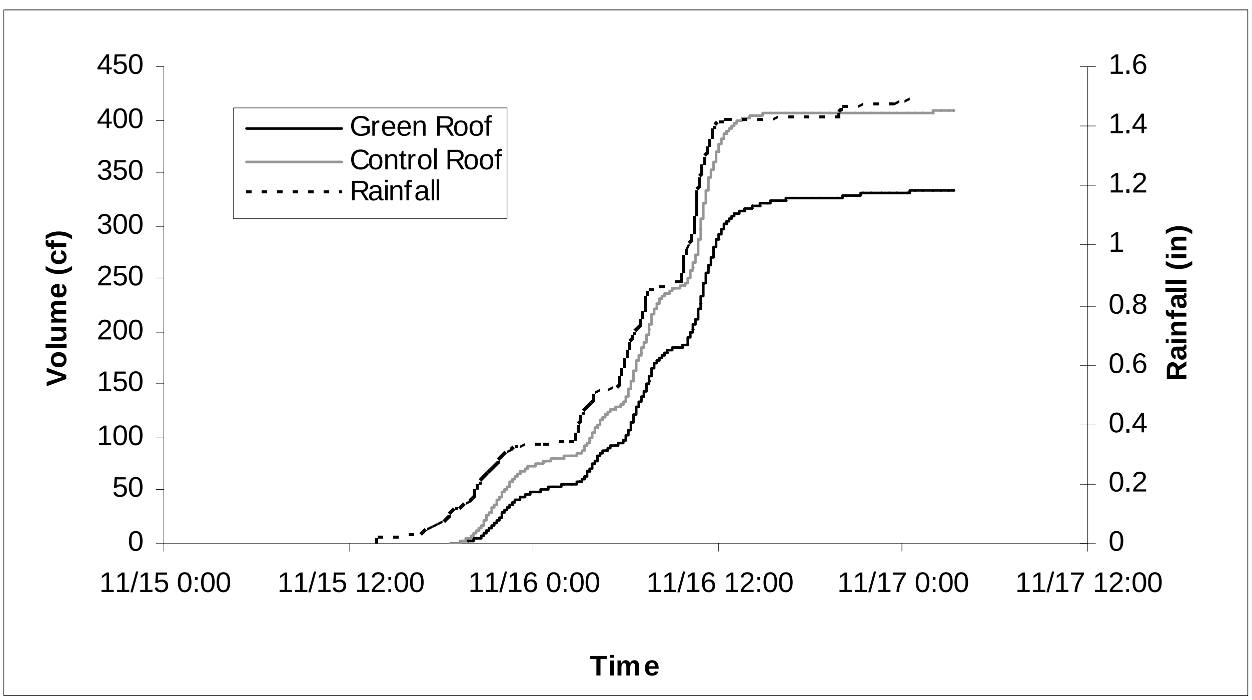

Figure 191 - Runoff Volume - November 15, 2006 Storm

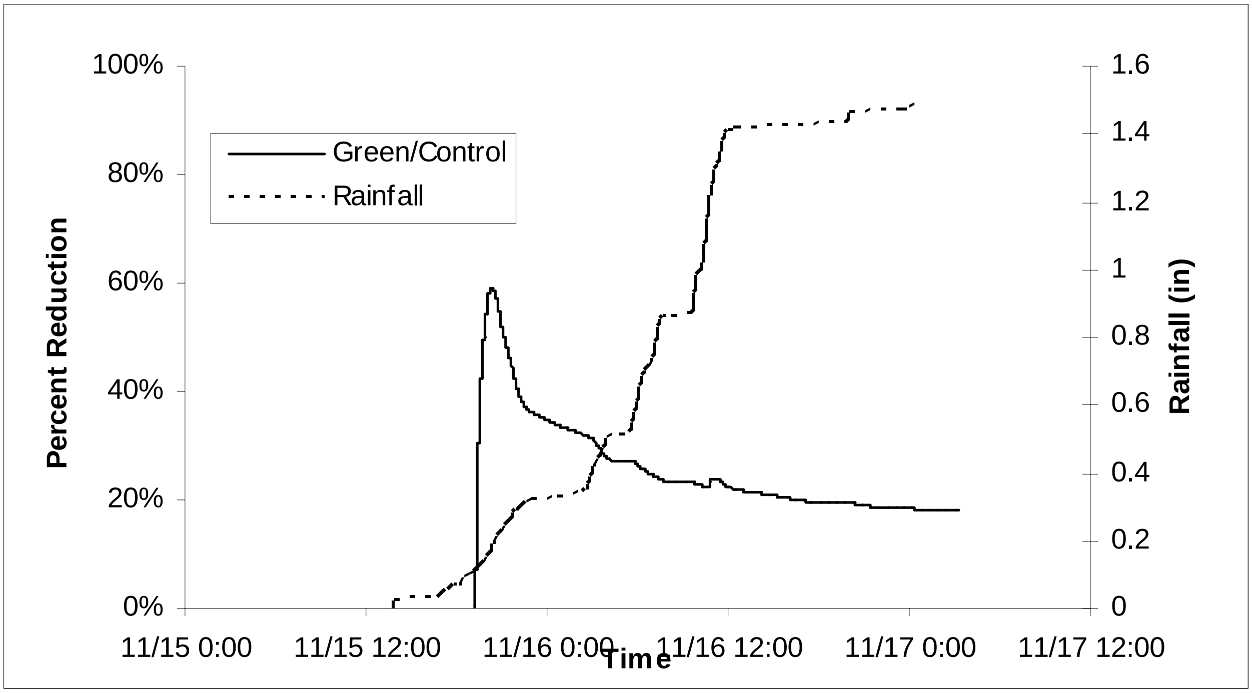

Figure 192 - Runoff Reduction - November 15, 2006 Storm

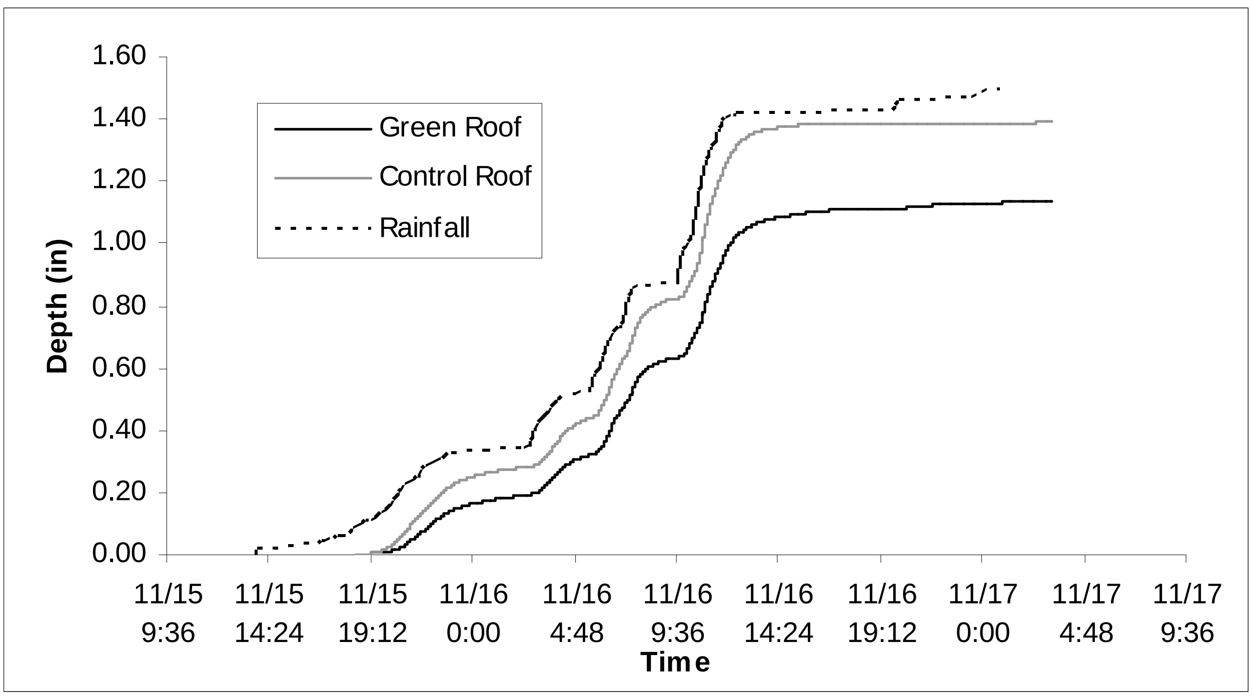

Figure 193 - Runoff as Rainfall - November 15, 2006 Storm

Table 31 - November 15, 2006 Storm Summary

November 15, 2006 Storm		
Rainfall	Depth (in)	1.49
	Length	1 Day, 10:57
Runoff	Delay	0:17
	Extension	0:57
Max Flow Rate (cfs)	Green	0.0217
	Control	0.0348
	Reduction	38%
Total Volume (cf)	Green	333.93
	Control	408.79
	Reduction	18%
Equiv. in of Rain	Green	1.14
	Control	1.39

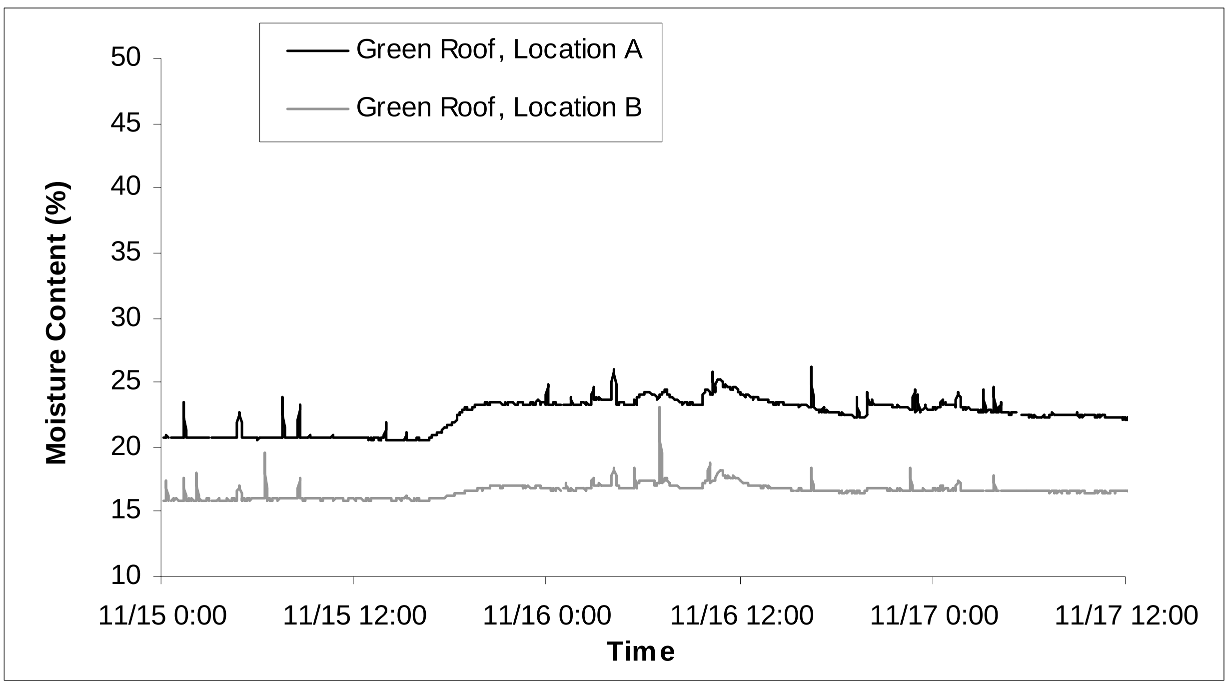

Figure 194 - Green Roof Water Content - November 15, 2006 Storm

Table 32 - Water Content - November 15, 2006 Storm

November 15, 2006 Storm		
	Water Content (%)	
	Location A	Location B
Start	20.75	15.92
Peak	25.22	18.83
End	22.34	16.6

A.18 NOVEMBER 19, 2006 STORM

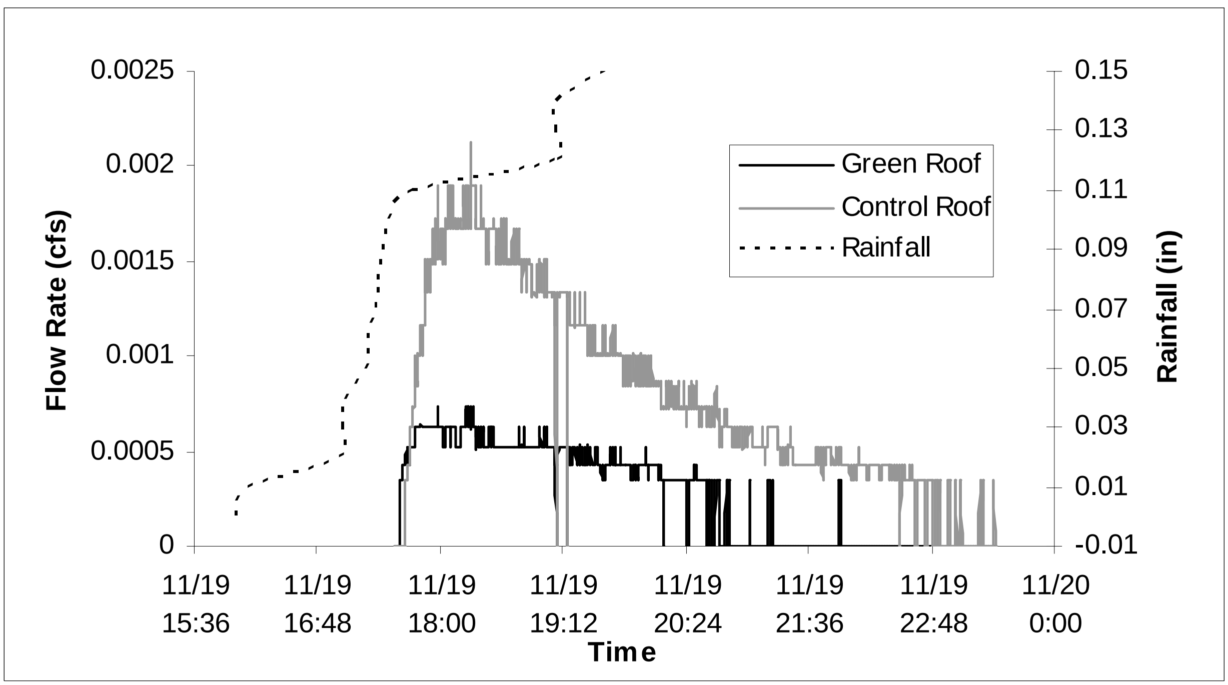

Figure 195 - Runoff Flow Rates - November 19, 2006 Storm

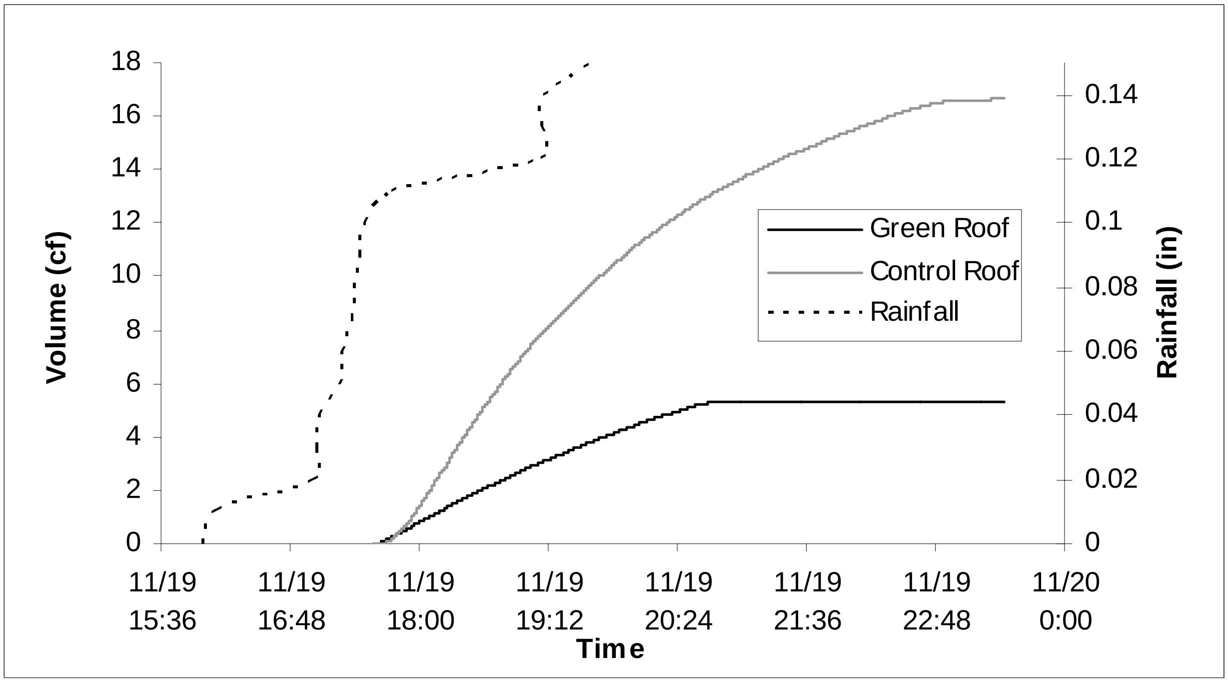

Figure 196- Runoff Volume - November 19, 2006 Storm

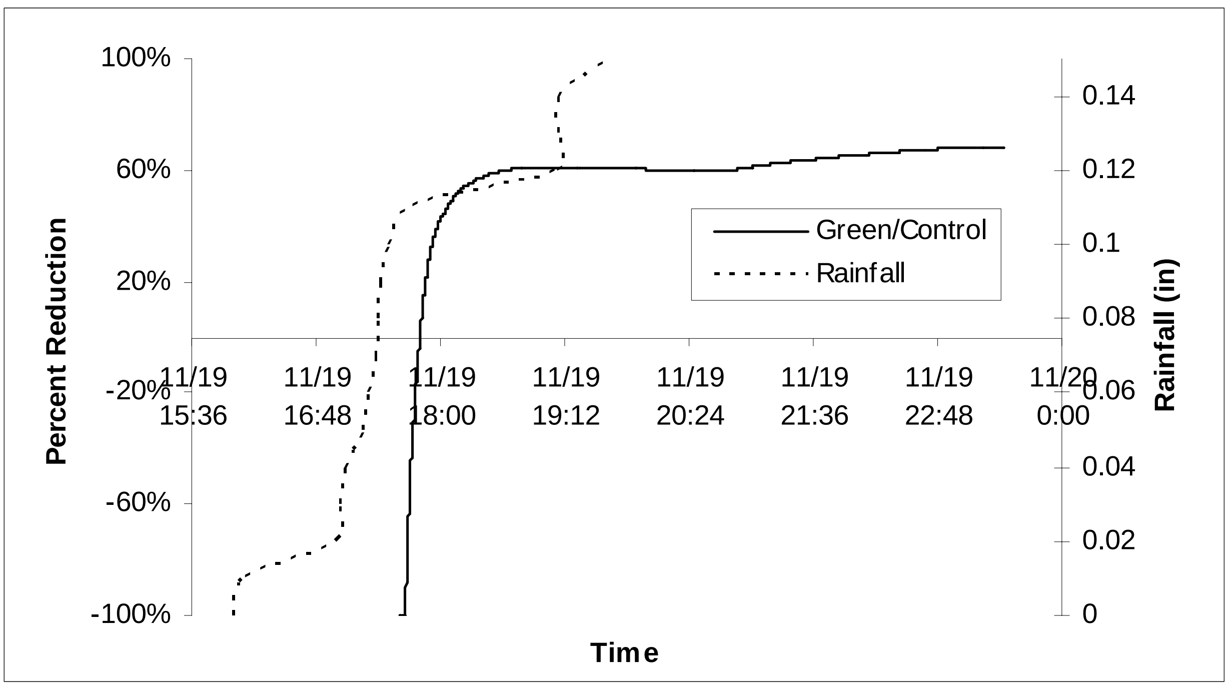

Figure 197 - Runoff Reduction - November 19, 2006 Storm

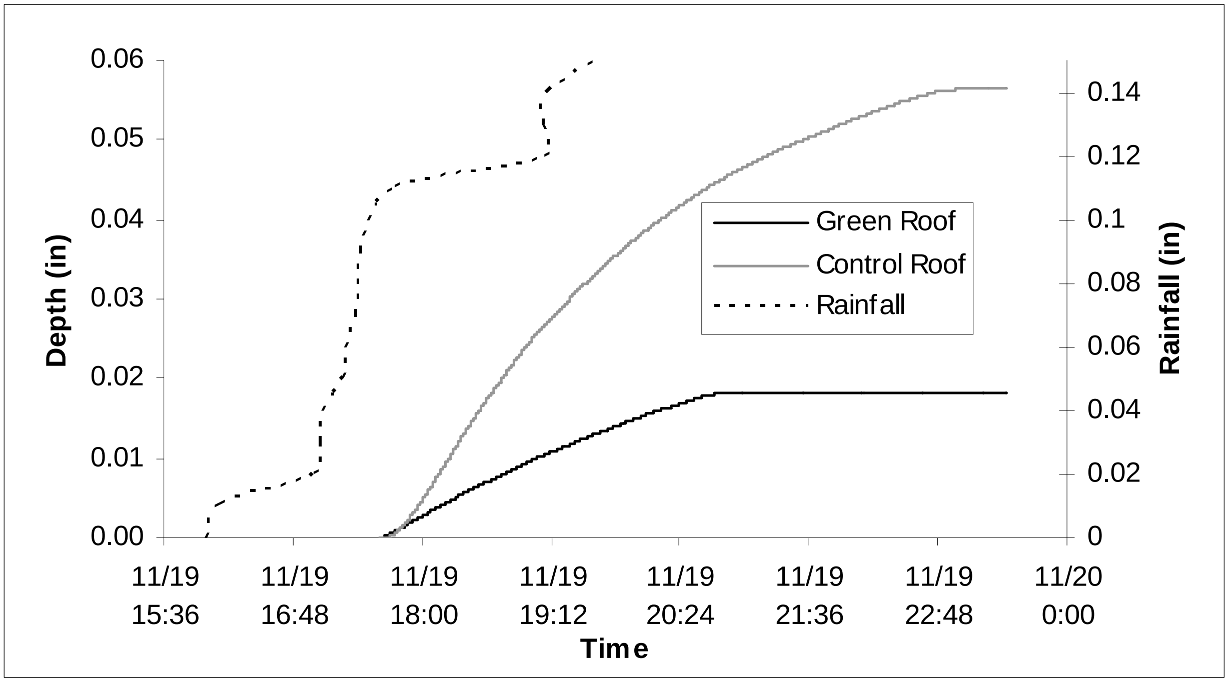

Figure 198 - Runoff as Rainfall - November 19, 2006 Storm

Table 33 - November 19, 2006 Storm Summary

November 19, 2006 Storm		
Rainfall	Depth (in)	0.17
	Length	11:10
Runoff	Delay	0:03
	Extension	1:30
Max Flow Rate (cfs)	Green	0.0007
	Control	0.0021
	Reduction	65%
Total Volume (cf)	Green	5.35
	Control	16.63
	Reduction	68%
Equiv. in of Rain	Green	0.02
	Control	0.06

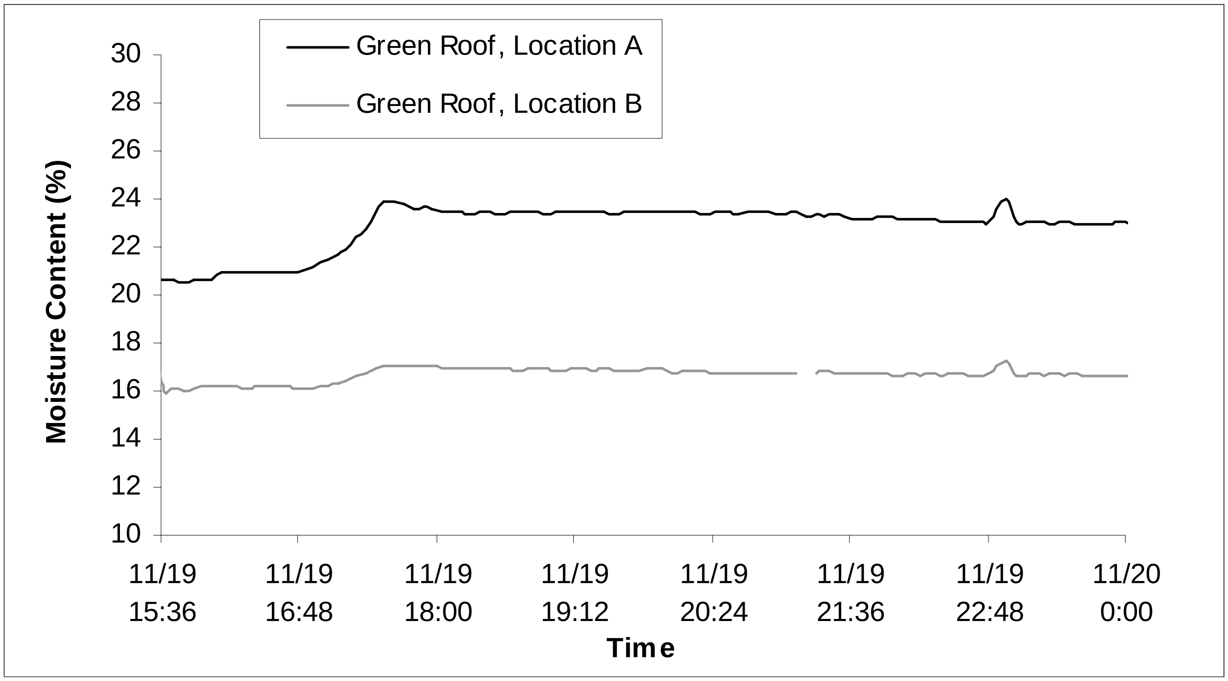

Figure 199 - Green Roof Water Content - November 19, 2006 Storm

Table 34 - Water Content - November 19, 2006 Storm

November 19, 2006 Storm		
	Water Content (%)	
	Location A	Location B
Start	20.6	16.04
Peak	23.52	16.97
End	23.01	16.66

A.19 DECEMBER 1, 2006 STORM

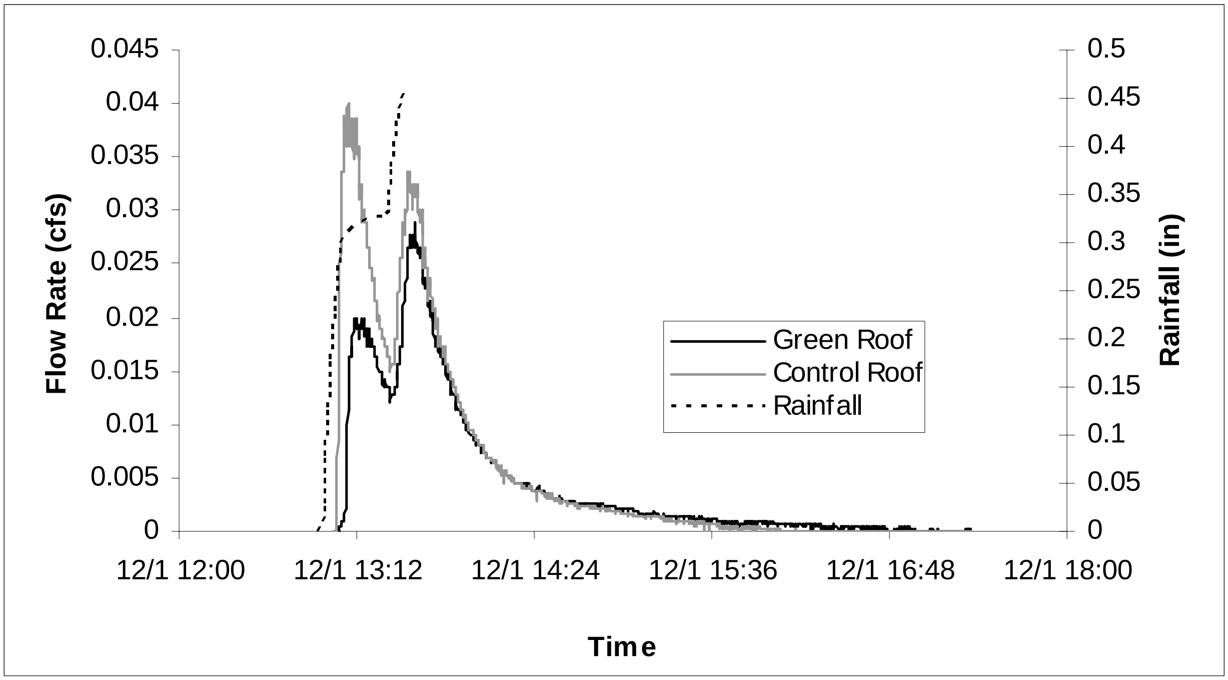

Figure 200 - Runoff Flow Rates - December 1, 2006 Storm

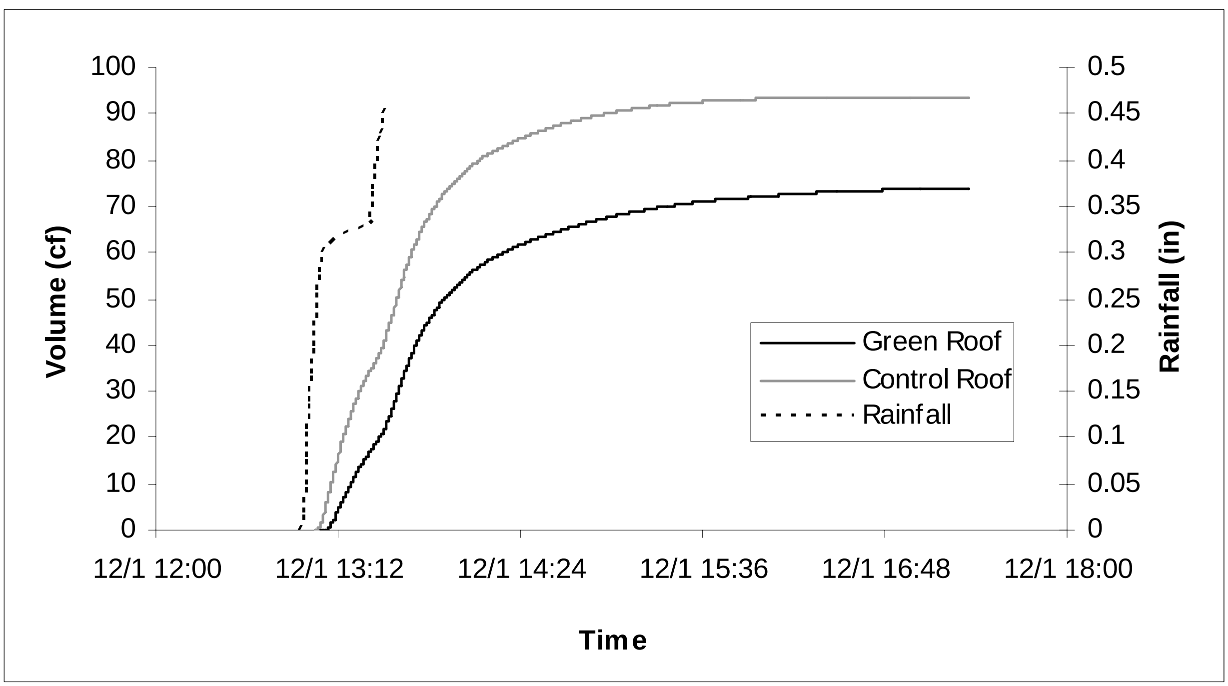

Figure 201 - Runoff Volume - December 1, 2006 Storm

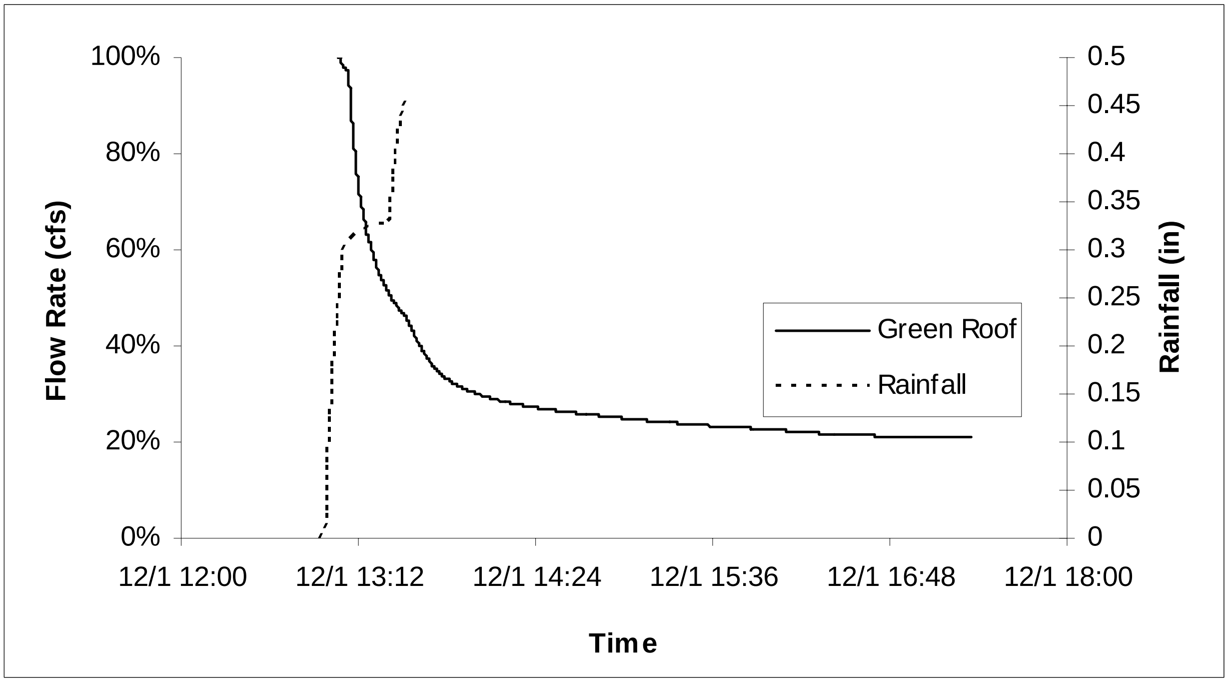

Figure 202 - Runoff Reduction - December 1, 2006

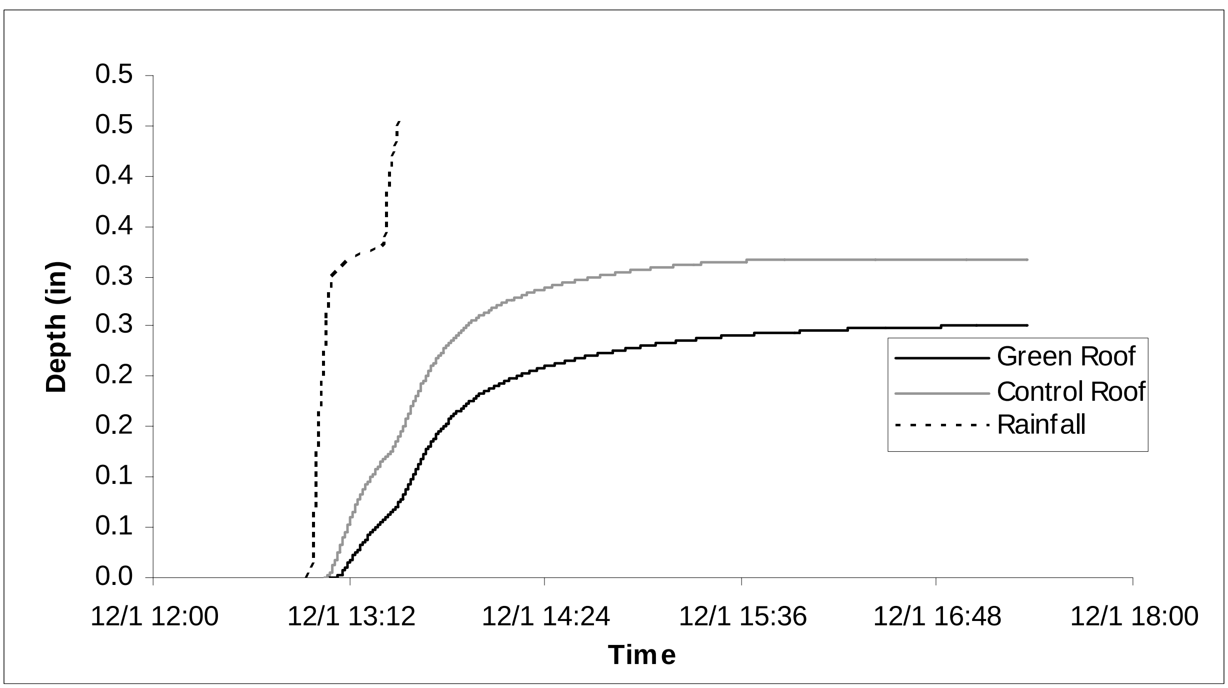

Figure 203 - Runoff as Rainfall - December 1, 2006 Storm

Table 35 - December 1, 2006 Storm Summary

December 1, 2006 Storm		
Rainfall	Depth (in)	0.59
	Length	0:36
Runoff	Delay	0:01
	Extension	1:10
Max Flow Rate (cfs)	Green	0.0288
	Control	0.0401
	Reduction	28%
Total Volume (cf)	Green	73.67
	Control	93.28
	Reduction	21%
Equiv. in of Rain	Green	0.25
	Control	0.32

A.20 JANUARY 5, 2007 STORM

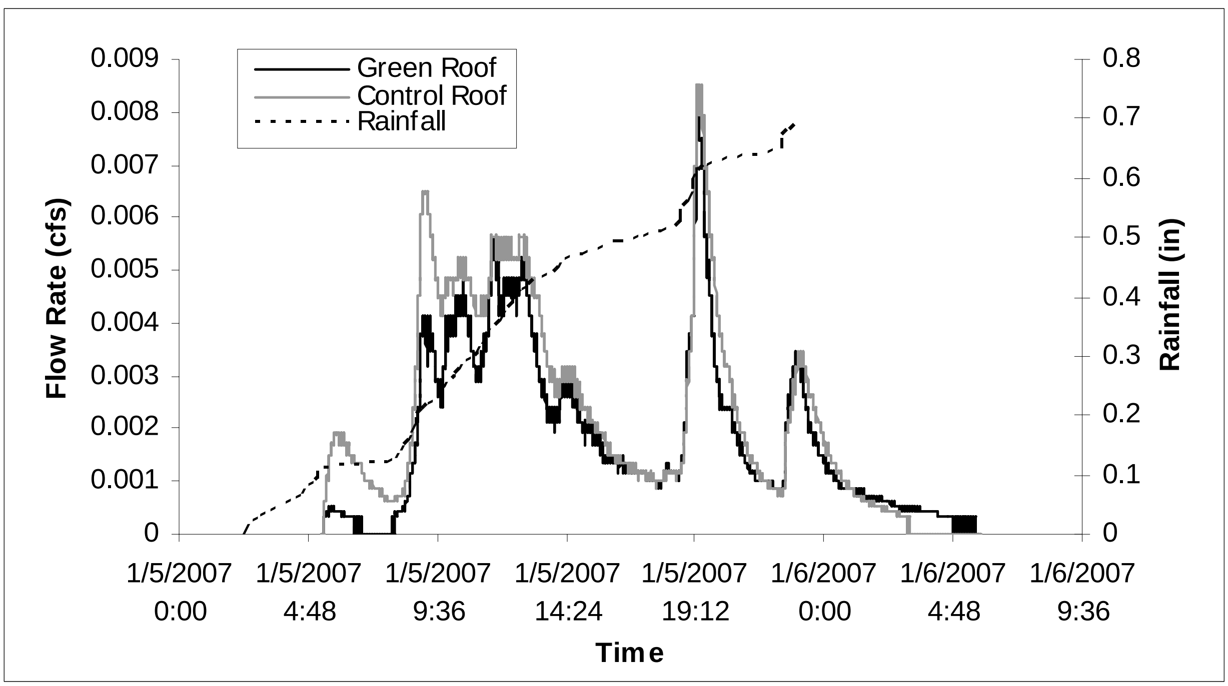

Figure 204 - Runoff Flow Rates - January 5, 2007 Storm

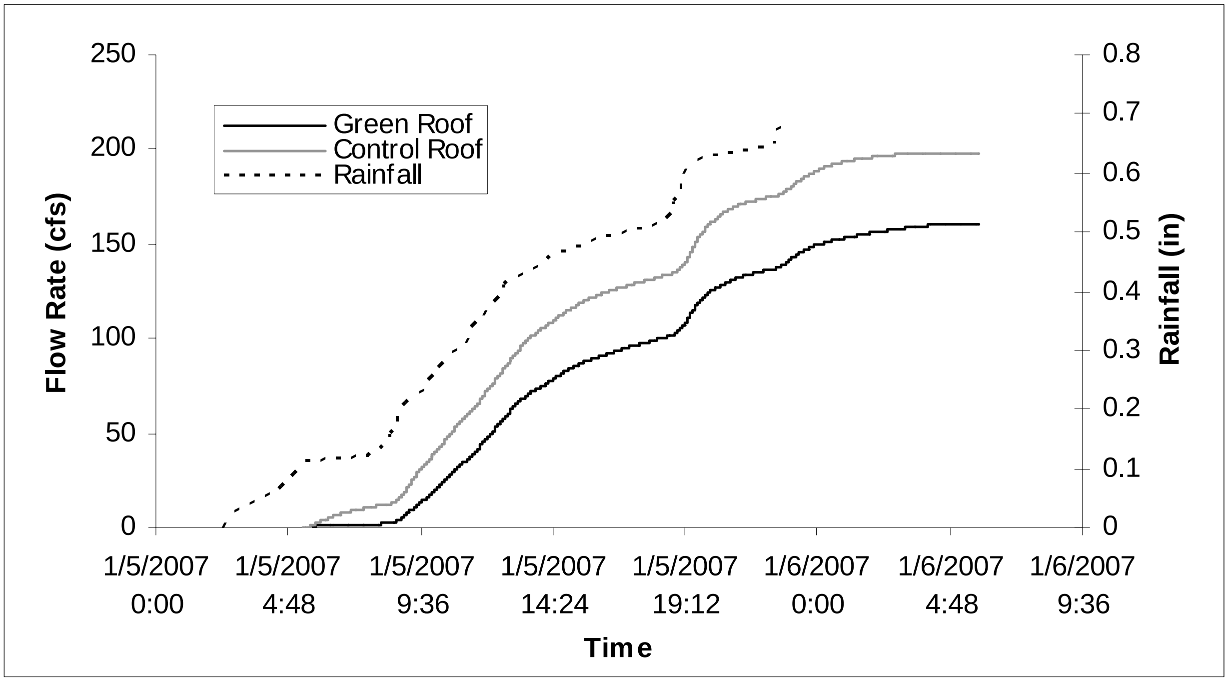

Figure 205 - Runoff Volume - January 5, 2007 Storm

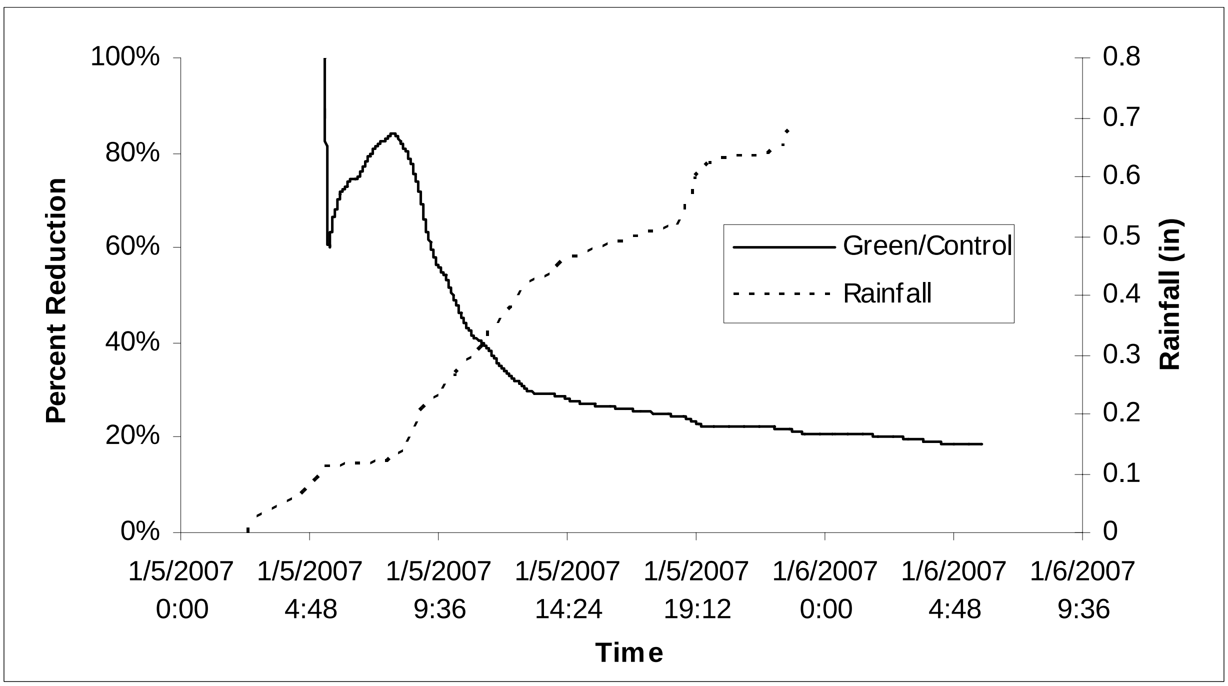

Figure 206 - Runoff Reduction - January 5, 2007 Storm

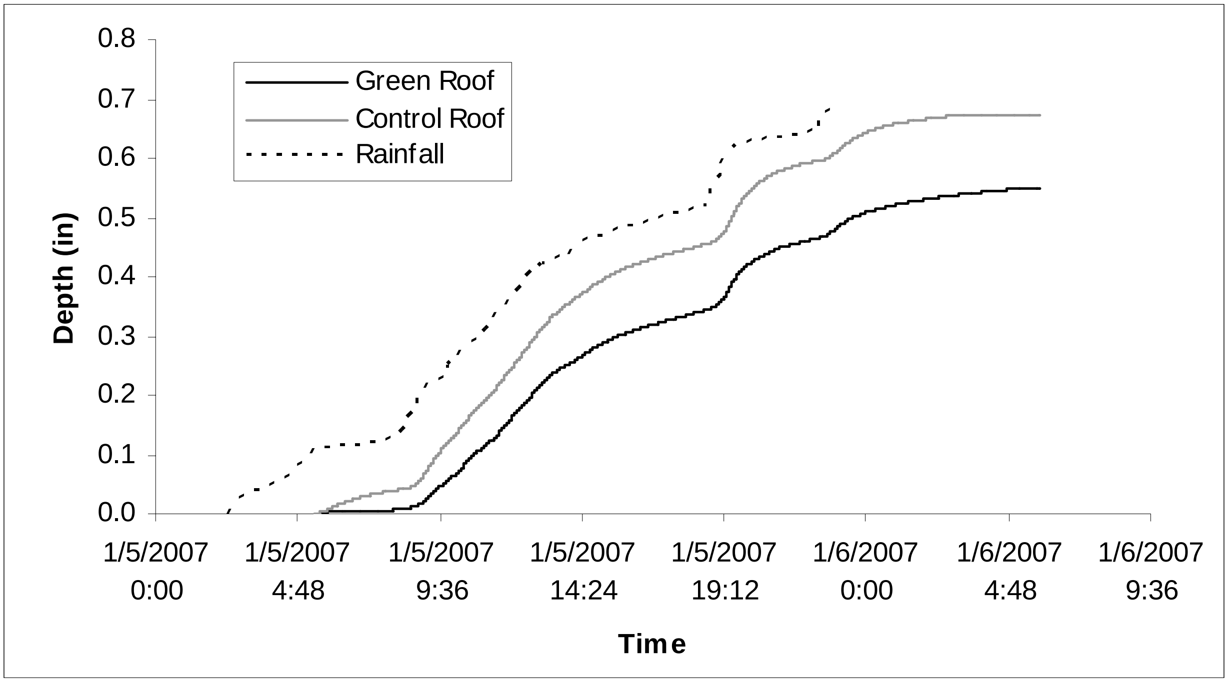

Figure 207 - Runoff as Rainfall - January 5, 2007 Storm

Table 36 - January 5, 2007 Storm Summary

January 5, 2007 Storm		
Rainfall	Depth (in)	0.69
	Length	20:24
Runoff	Delay	0:02
	Extension	2:27
Max Flow Rate (cfs)	Green	0.0081
	Control	0.0085
	Reduction	5%
Total Volume (cf)	Green	161.04
	Control	197.55
	Reduction	19%
Equiv. in of Rain	Green	0.55
	Control	0.67

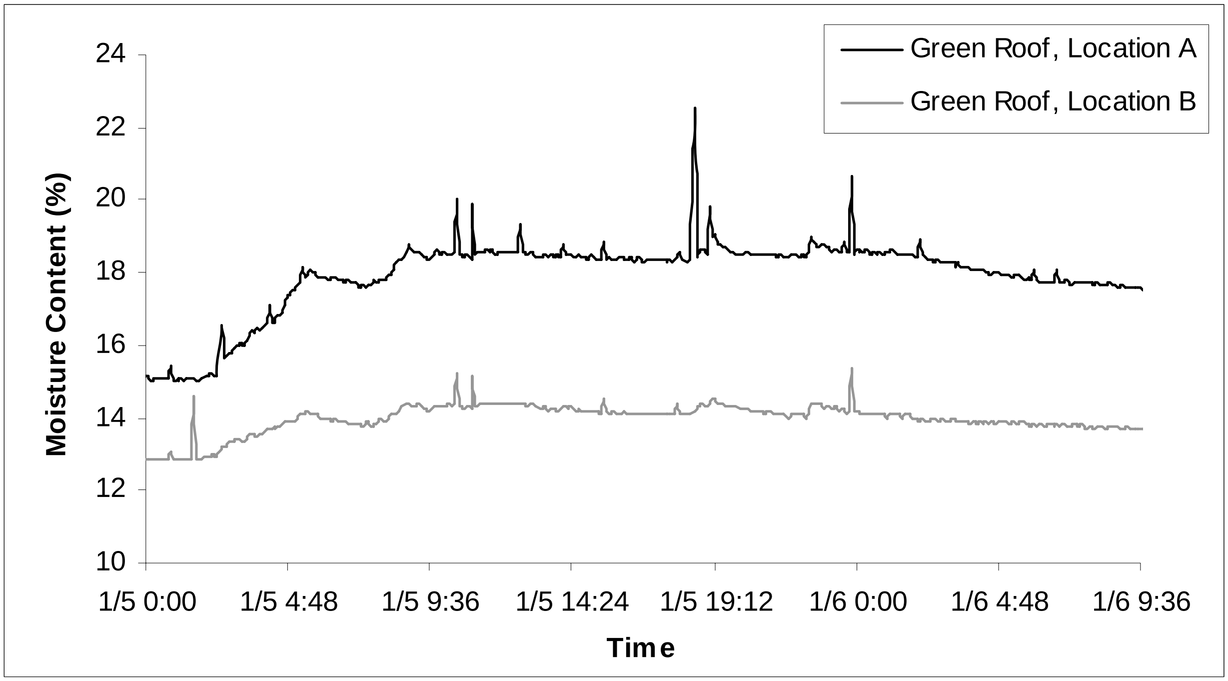

Figure 208 - Green Roof Water Content - January 5, 2007 Storm

Table 37 - Water Content - January 5, 2007 Storm

January 5, 2007 Storm		
	Water Content (%)	
	Location A	Location B
Start	15.1	12.88
Peak	22.5	14.36
End	18.5	13.98

A.21 JANUARY 8, 2007 STORM

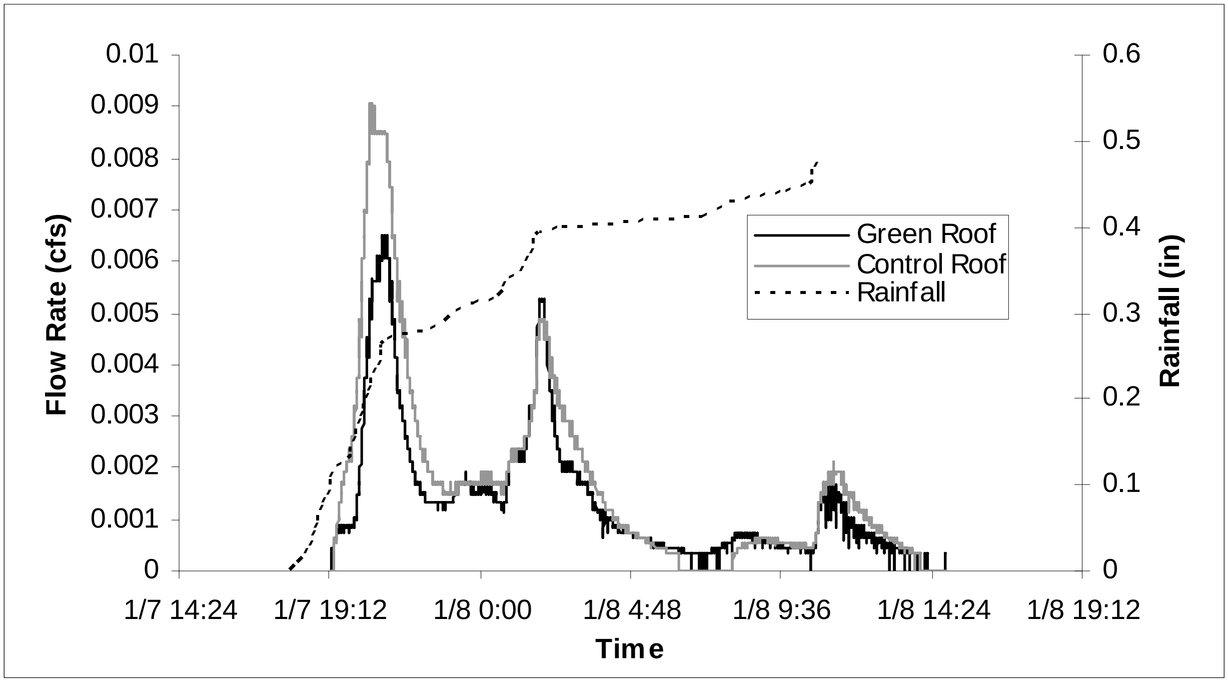

Figure 209 - Runoff Flow Rates - January 8, 2007 Storm

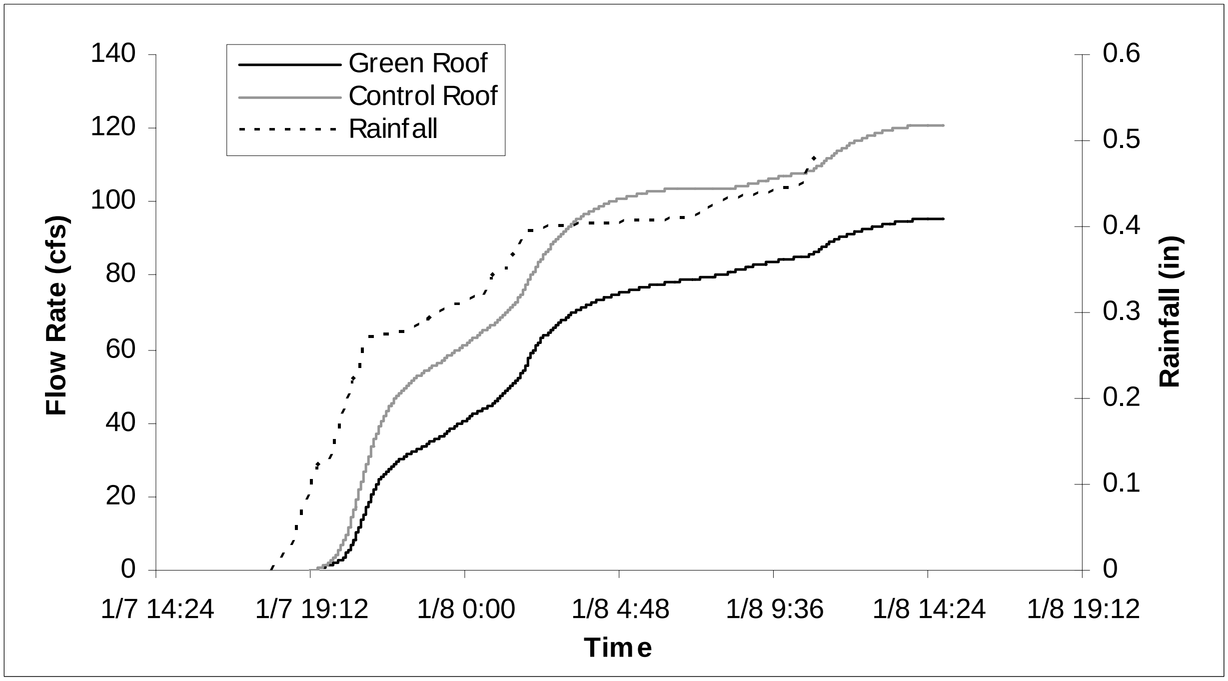

Figure 210 - Runoff Volume - January 8, 2007 Storm

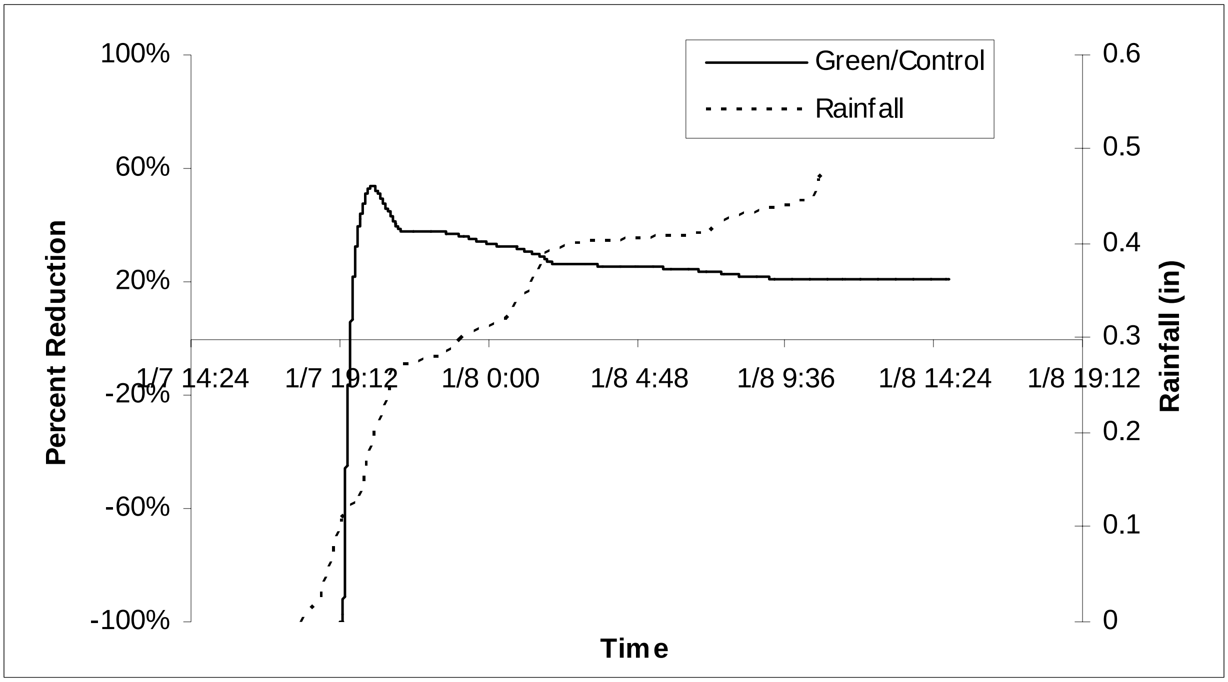

Figure 211 - Runoff Reduction - January 8, 2007 Storm

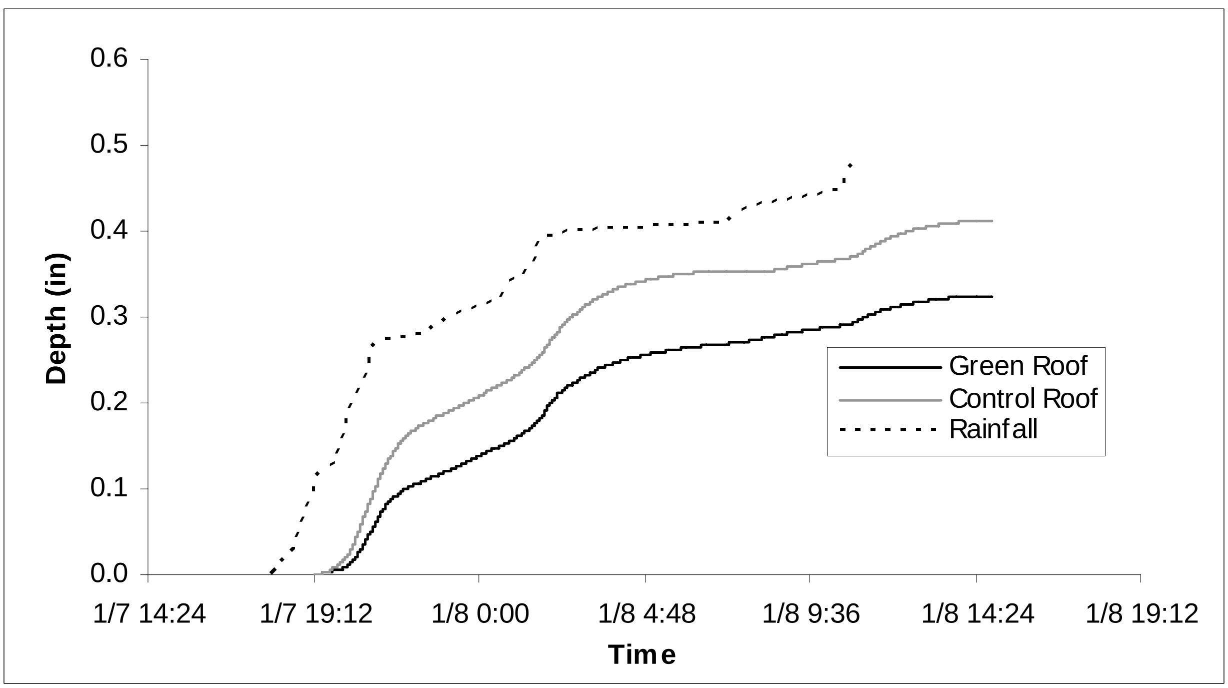

Figure 212 - Runoff as Rainfall - January 8, 2007 Storm

Table 38 - January 8, 2007 Storm Summary

January 8, 2007 Storm		
Rainfall	Depth (in)	0.48
	Length	16:47
Runoff	Delay	0:05
	Extension	0:48
Max Flow Rate (cfs)	Green	0.0065
	Control	0.0091
	Reduction	28%
Total Volume (cf)	Green	95.19
	Control	120.81
	Reduction	21%
Equiv. in of Rain	Green	0.32
	Control	0.41

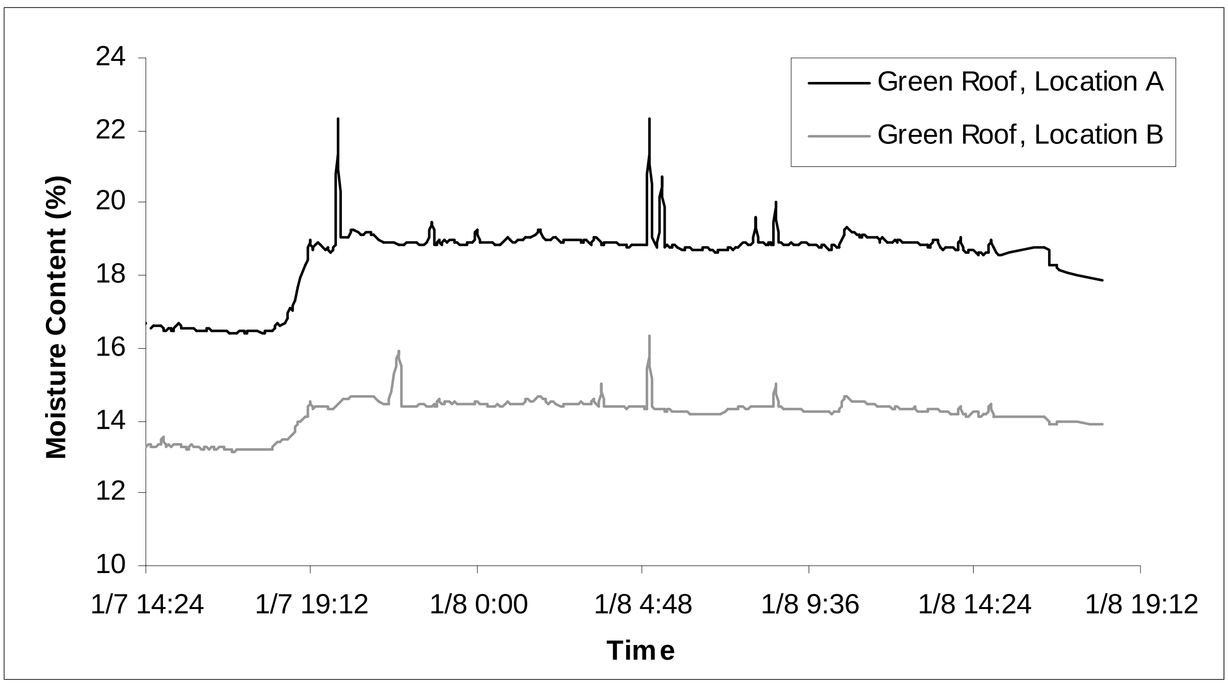

Figure 213 - Green Roof Water Content - January 8, 2007 Storm

Table 39 - Water Content - January 8, 2007 Storm

January 8, 2007 Storm		
	Water Content (%)	
	Location A	Location B
Start	16.66	13.29
Peak	22.34	15.92
End	19.13	14.53

A.22 JANUARY 12 TO JANUARY 16, 2007 STORM

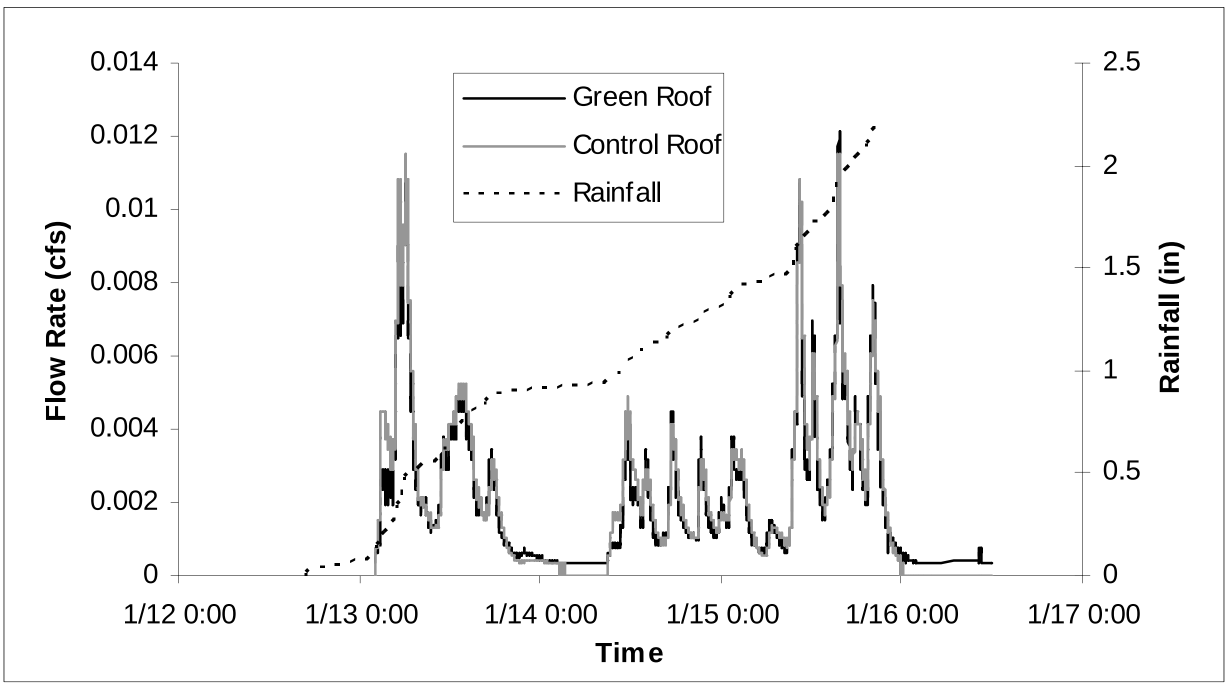

Figure 214 - Runoff Flow Rates - January 12 - 16, 2007 Storm

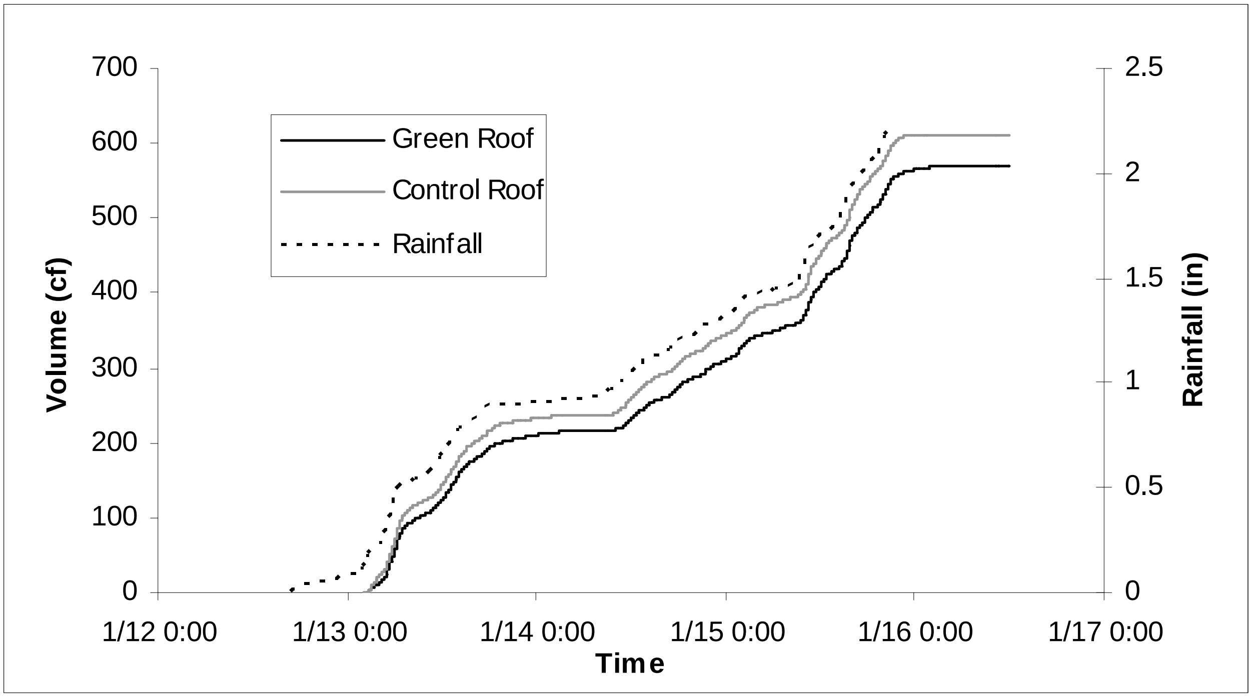

Figure 215 - Runoff Volume - January 12 - 16, 2007 Storm

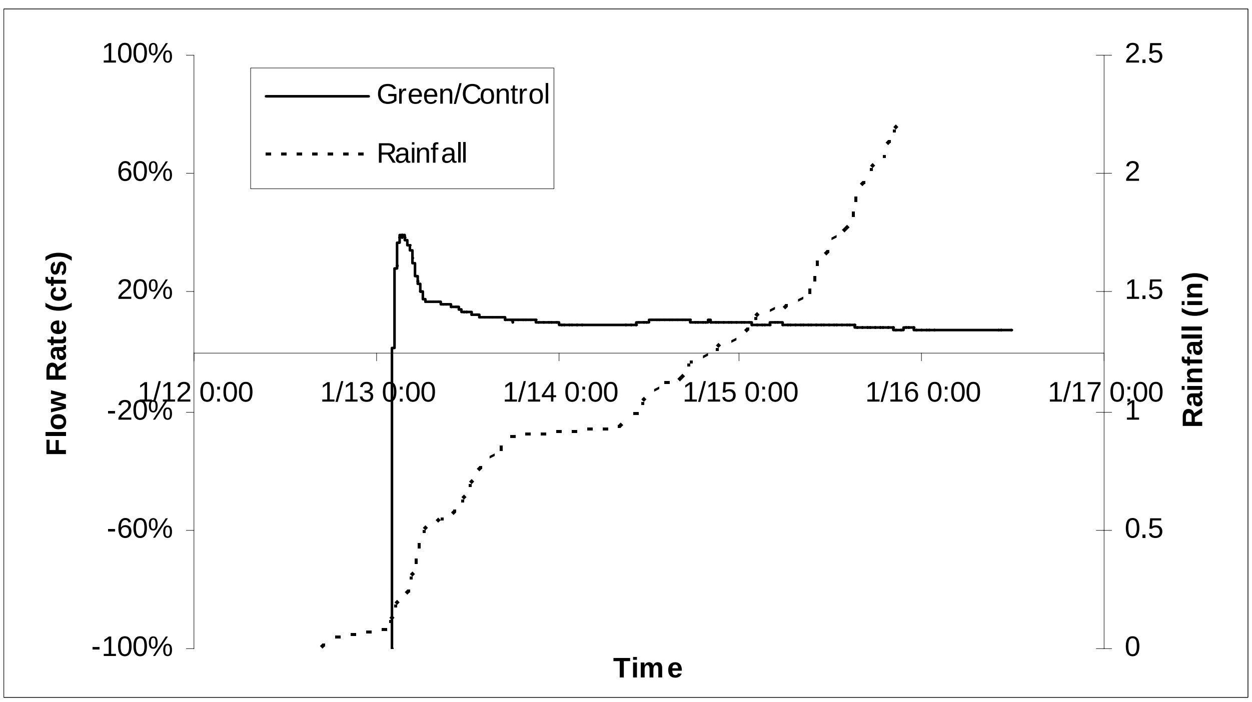

Figure 216 - Runoff Reduction - January 12 - 16, 2007 Storm

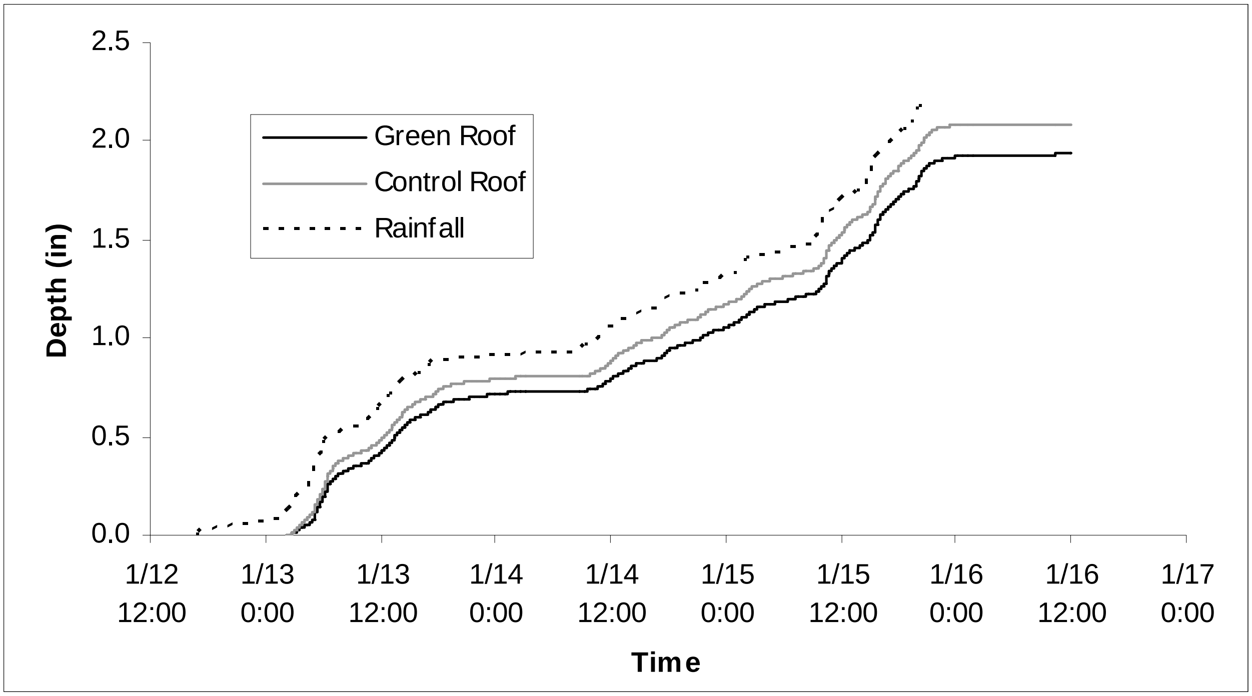

Figure 217 - Runoff as Rainfall - January 12 - 16, 2007 Storm

Table 40 - January 12 - 15, 2007 Storm Summary

January 12, 2007 Storm		
Rainfall	Depth (in)	2.2
	Length	3 days, 3:49
Runoff	Delay	0:01
	Extension	11:44
Max Flow Rate (cfs)	Green	0.0121
	Control	0.0115
	Reduction	-5%
Total Volume (cf)	Green	568.54
	Control	611.91
	Reduction	7%
Equiv. in of Rain	Green	1.93
	Control	2.08

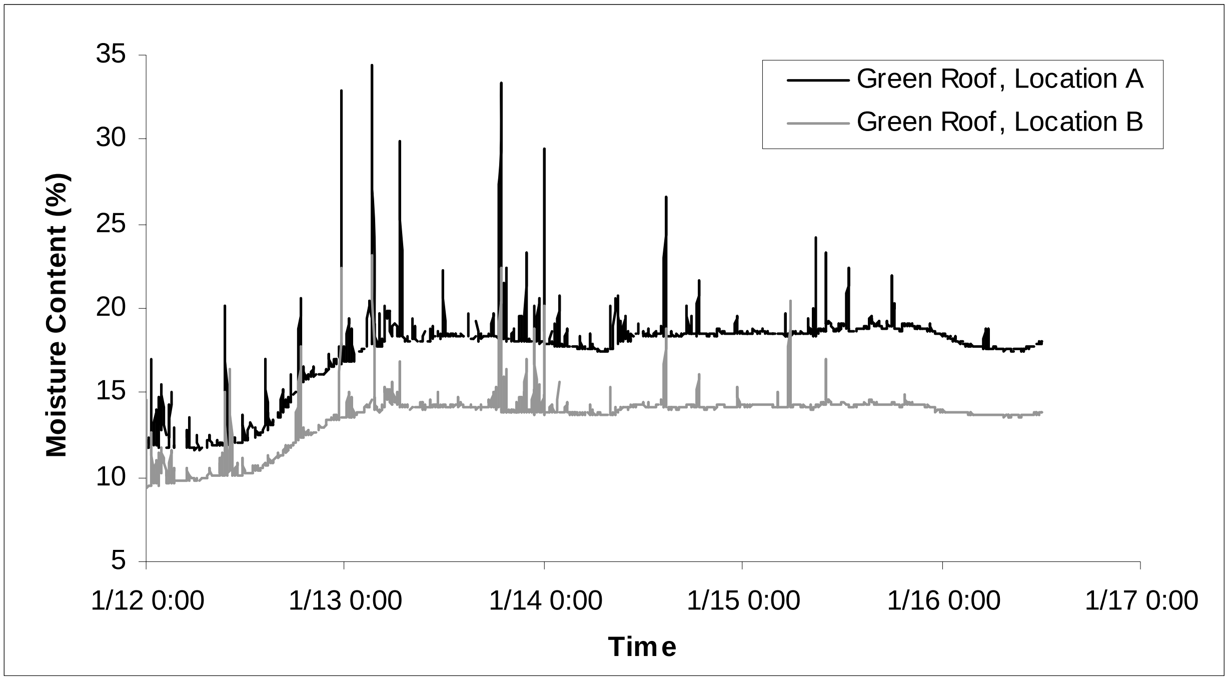

Figure 218 - Green Roof Water Content - January 12 - 16, 2007 Storm

Table 41 - Water Content - January 12 - 16, 2007 Storm

January 12 - 16, 2007 Storm		
	Water Content (%)	
	Location A	Location B
Start	12.38	9.82
Peak	34.41	23.09
End	18.02	13.82

A.23 OVERALL STORM DATA SUMMARY

Table 42 - Overall Storm Summary - Part One

Date	Rainfall		Runoff		Max Flow Rate (cfs)		
	Depth (in)	Length	Delay	Extension	Green	Control	Reduction
7/28/2006 (1)			0:02	4:01	0.0696	0.1542	55%
7/28/2006 (2)			1:57	1:05	0.0032	0.0015	-53%
7/30/2006 (1)			0:01	1:29	0.0081	0.235	66%
7/30/2006 (2)			0:00	- 1:14	0.0903	0.1455	38%
8/27/2006	0.59	15:25	0:02	2:36	0.0375	0.0472	21%
8/28/2006	0.23	8:39	6:03	3:00	0.0142	0.0173	18%
		Adjusted Values					
9/2/2006	0.84	14:39	5:08	2:01	0.0164	0.0127	-23%
		Adjusted Values			0.0108		15%
9/5/2006	0.23	3:59	- 1:20	2:24	0.0091	0.007	-23%
		Adjusted Values			0.0053		25%
9/19/2006	0.12	3:50	- 1:40	4:56	0.007	0.0017	-75%
		Adjusted Values			0.0015		12%
9/28/2006	0.45	8:21	- 1:31	12:51	0.0115	0.0121	5%
		Adjusted Values					
10/17/2006	1.94	10:05	0:16	4:43	0.0415	0.0586	29%
10/19/2006	1.73	1 Day, 16:31	0:00	1:04	0.0301	0.0443	32%
10/27/2006	1.2	23:47	0:30	6:46	0.0181	0.0216	16%
10/31/2006	0.19	5:14	0:26	0:10	0.001	0.0035	71%
11/1/2006	0.07	2:08	0:55	3:57	0.0005	0.0009	38%
11/11/2006	0.57	15:13	4:09	3:09	0.0164	0.0236	30%
11/15/2006	1.49	1 Day, 10:57	0:17	0:57	0.0217	0.0348	38%
11/19/2006	0.17	11:10	0:03	1:30	0.0007	0.0021	65%
12/1/2006	0.59	0:36	0:01	1:10	0.0288	0.0401	28%
1/5/2007	0.69	20:24	0:02	2:27	0.0081	0.0085	5%
1/8/2007	0.48	16:47	0:05	0:48	0.0065	0.0091	28%
1/12 - 1/15/07	2.2	3 days, 3:49	0:01	11:44	0.0121	0.0115	-5%

Table 43 - Overall Storm Summary - Part Two

Date	Total Volume (cf)			Equiv. in. Rain	
	Green	Control	Reduction	Green	Control
7/28/2006 (1)	106.29	147.01	28%	0.36	0.5
7/28/2006 (2)	20.55	6.42	-69%	0.07	0.02
7/30/2006 (1)	36.6	44.4	18%	0.12	0.15
7/30/2006 (2)	112.58	100.76	-11%	0.38	0.34
8/27/2006	116.45	147.08	21%	0.4	0.5
8/28/2006	100.92	66.36	-34%	0.32	0.23
	59.43		10%	0.2	
9/2/2006	294.68	274.27	-7%	1	0.93
	266.26		3%	0.91	
9/5/2006	76.36	54.98	-28%	0.26	0.19
	48.46		12%	0.16	
9/19/2006	37.35	14.91	-60%	0.13	0.05
	14.19		15%	0.05	
9/28/2006	92.12	66.44	-28%	0.31	0.23
	65.17		2%	0.22	
10/17/2006	413.91	513.51	19%	1.41	1.75
10/19/2006	448.62	470.29	5%	1.52	1.6
10/27/2006	281.57	343.8	18%	0.96	1.17
10/31/2006	11.2	35.62	69%	0.04	0.12
11/1/2006	3.44	10.14	66%	0.01	0.03
11/11/2006	94.04	134.21	30%	0.32	0.46
11/15/2006	333.93	408.79	18%	1.14	1.39
11/19/2006	5.35	16.63	68%	0.02	0.06
12/1/2006	73.67	93.28	21%	0.25	0.32
1/5/2007	161.04	197.55	19%	0.55	0.67
1/8/2007	95.19	120.81	21%	0.32	0.41
1/12 - 1/15/07	568.54	611.91	7%	1.93	2.08

Table 44 - Water Content Summary

Data	Water Content (%)					
	Start		Peak		End	
	Location A	Location B	Location A	Location B	Location A	Location B
10/17/2006	16.16	16.16	20.6	18.99	18.02	17.04
10/19/2006	17.95	17.1	20.29	20.9	18.91	17.95
10/27/2006	15.8	15.86	20.29	17.75	18.16	17.49
10/31/2006	18.64	16.16	28.06	19.27	24.22	17.1
11/1/2006	23.43	16.91	28.38	17.69	25.04	17.23
11/16/2006	20.75	15.92	25.22	18.83	22.34	16.6
11/19/2006	20.6	16.04	23.52	16.97	23.01	16.66
1/5/2007	15.1	12.88	22.5	14.36	18.5	13.98
1/8/2007	16.66	13.29	22.34	15.92	19.13	14.53
1/12 - 1/15/2007	12.38	9.82	34.41	23.09	18.02	13.82

APPENDIX B

WATER QUALITY TEST RESULTS

B.1 CALIBRATION STANDARDS

B.1.1 HACH Tests

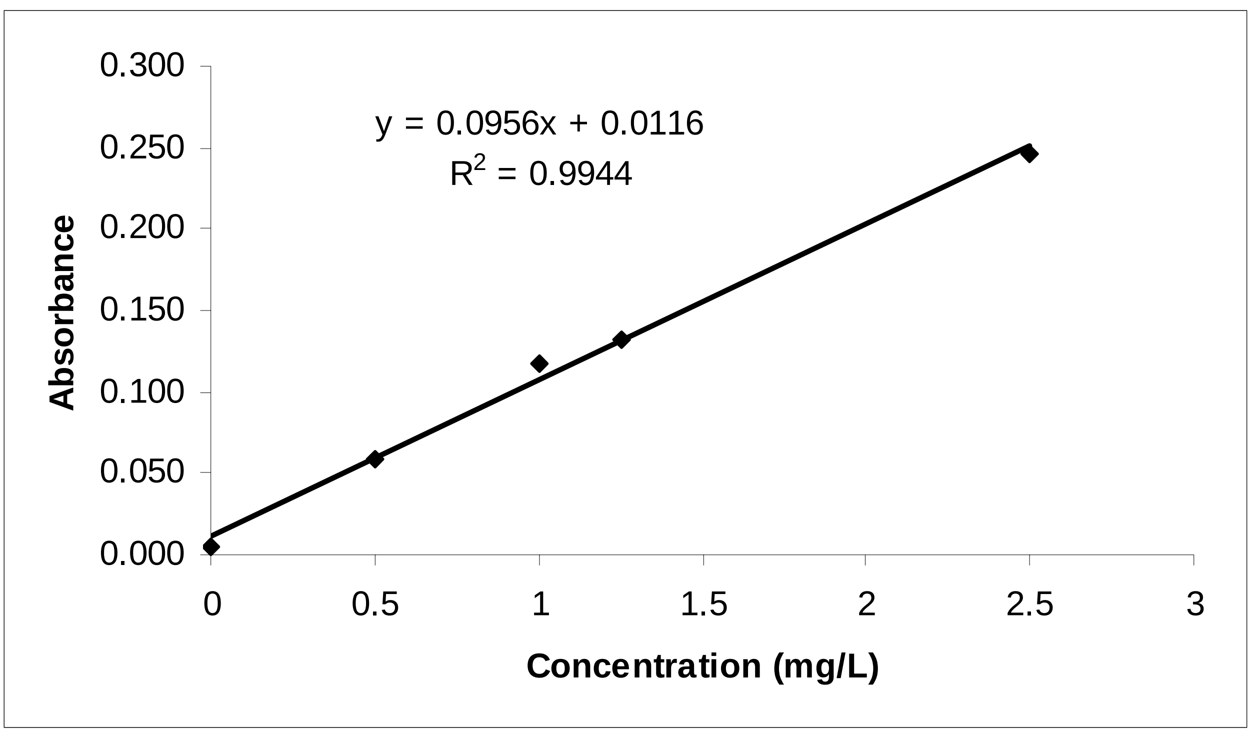

Figure 219 - Phosphorus Standard Curve

The equation listed below was used to calculate the phosphorus concentration.

$$P = 10.398 \cdot A - 0.1146$$

Where, P = Phosphorus Concentration [mg/L]

A = Absorbance

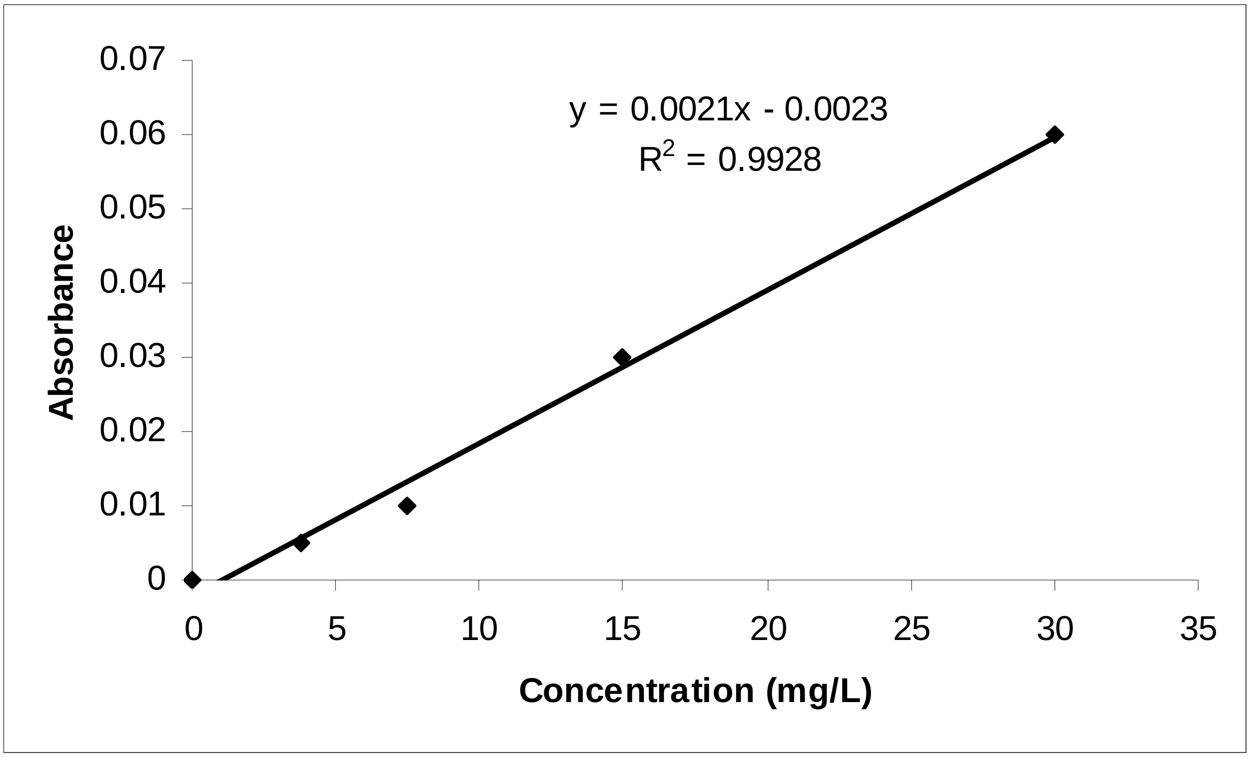

Figure 220 - Sulfate Standard Curve

The equation listed below was used to calculate the sulfate concentration.

$$S = 480.37 \cdot A + 1.1622$$

Where, S = Sulfate Concentration [mg/L]

A = Absorbance

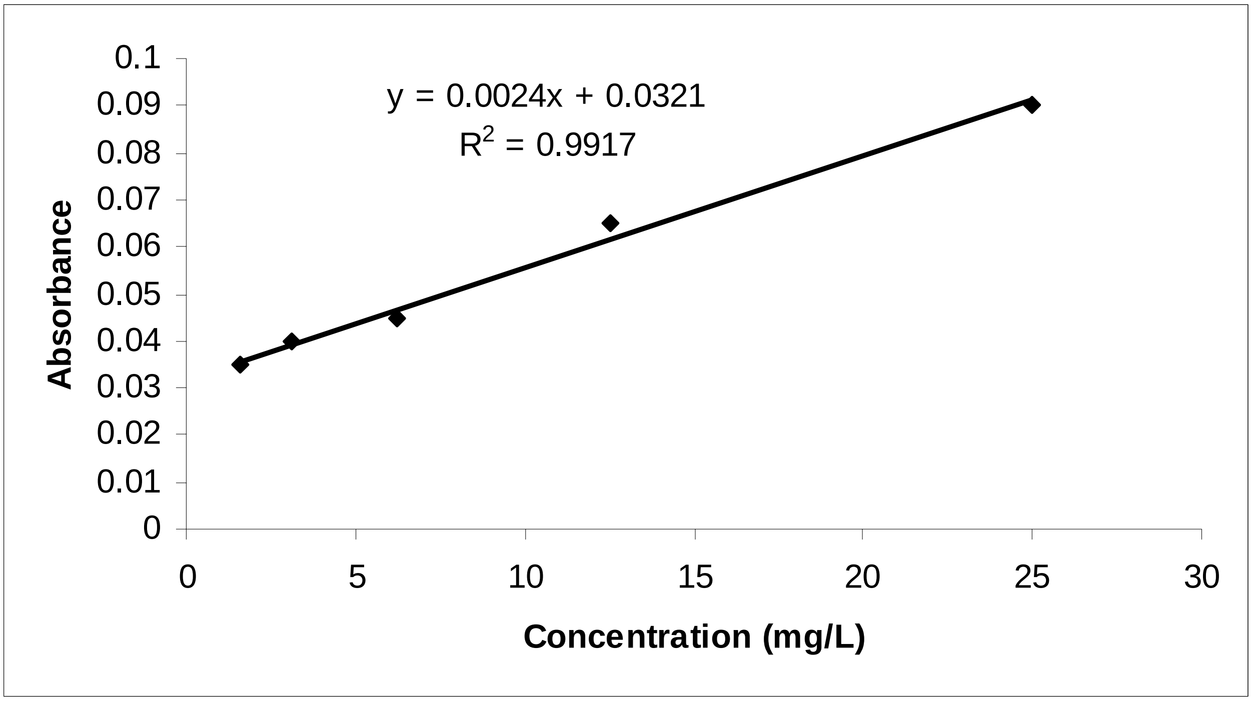

Figure 221 - Nitrogen Standard Curve

The equation listed below was used to calculate the nitrogen concentration.

$$N = 419.2 \cdot A - 13.368$$

Where, N = Nitrogen Concentration [mg/L]

A = Absorbance

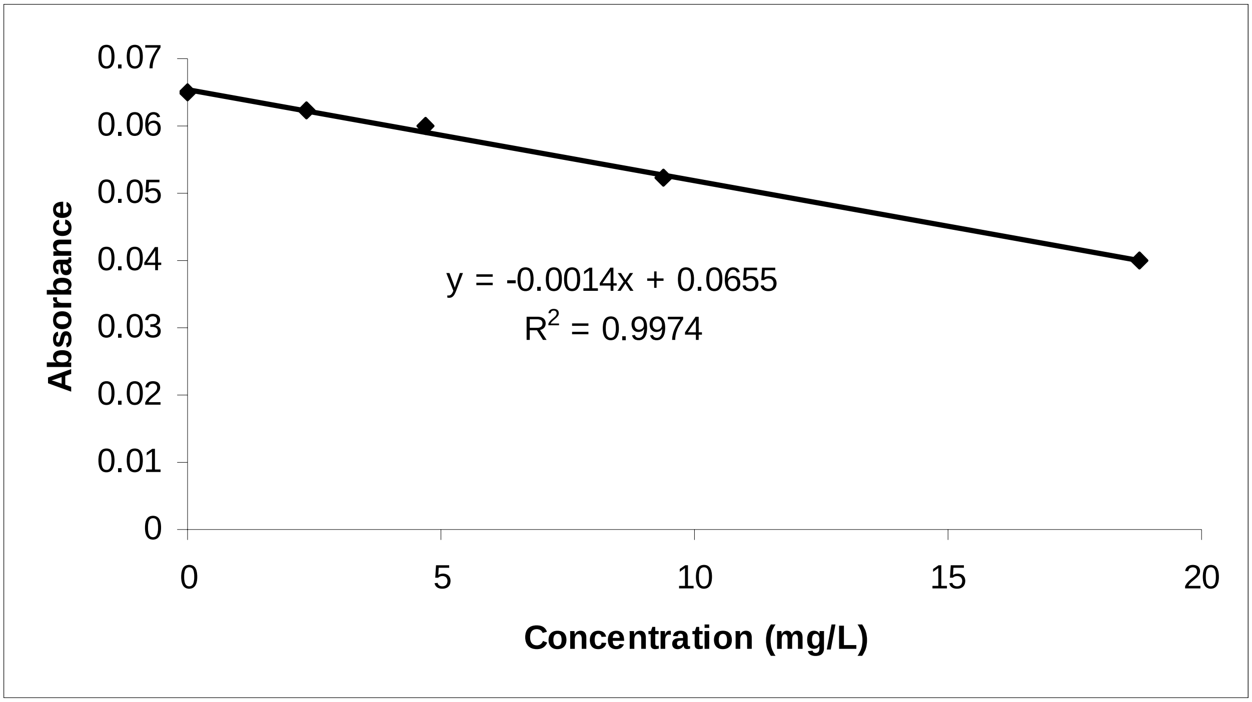

Figure 222 - COD Standard Curve - Ultra Low Range

The equation listed below was used to calculate the COD concentration.

$$COD = -735.46 \cdot A + 48.226$$

Where, COD = COD Concentration [mg/L]

A = Absorbance

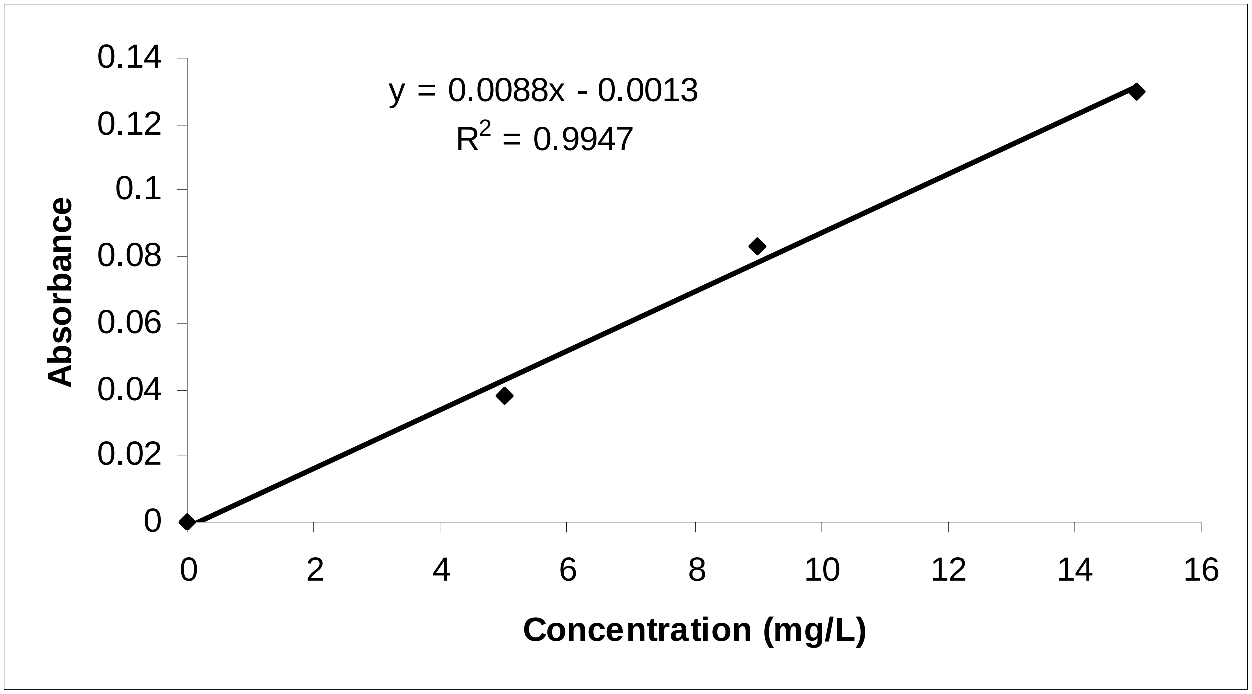

Figure 223 - Lead Standard Curve

The equation listed below was used to calculate the lead concentration.

$$Pb = 112.55 \cdot A + 0.1877$$

Where, Pb = Lead Concentration [mg/L]

A = Absorbance

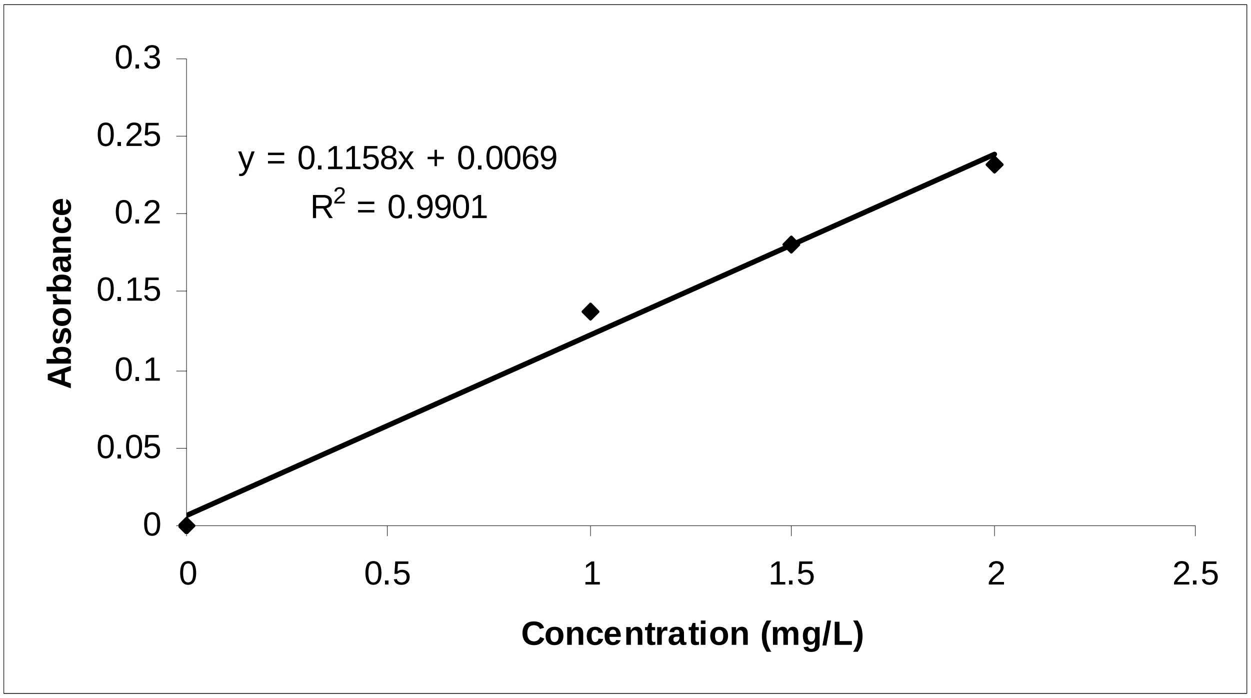

Figure 224 - Cadmium Standard Curve

The equation listed below was used to calculate the cadmium concentration.

$$Cd = 8.5476 \cdot A - 0.0482$$

Where, Cd = Cadmium Concentration [mg/L]

A = Absorbance

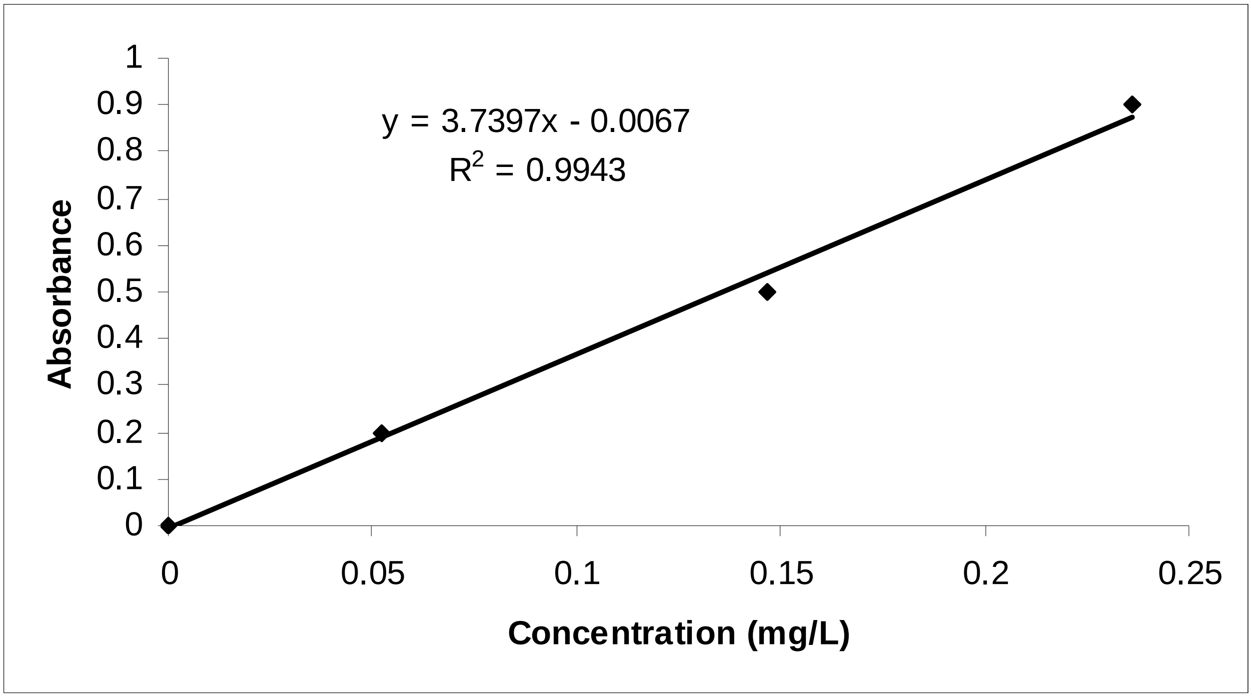

Figure 225 - Zinc Standard Curve

The equation listed below was used to calculate the zinc concentration.

$$Zn = 3.7397 \cdot A - 0.0067$$

Where, Zn = Zinc Concentration [mg/L]

A = Absorbance

B.2 OCTOBER 17, 2006 STORM TEST RESULTS

B.2.1 Phosphorus

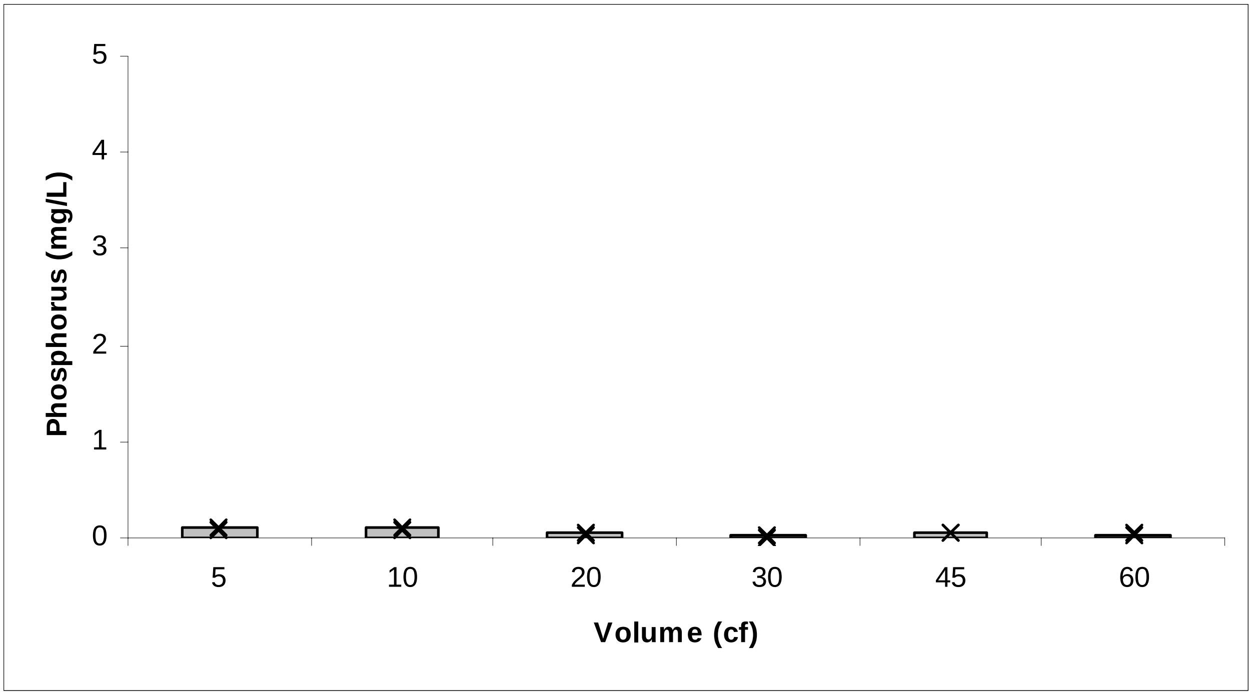

Figure 226 - Phosphorus - Unfiltered Control Roof Samples - October 17, 2006 Storm

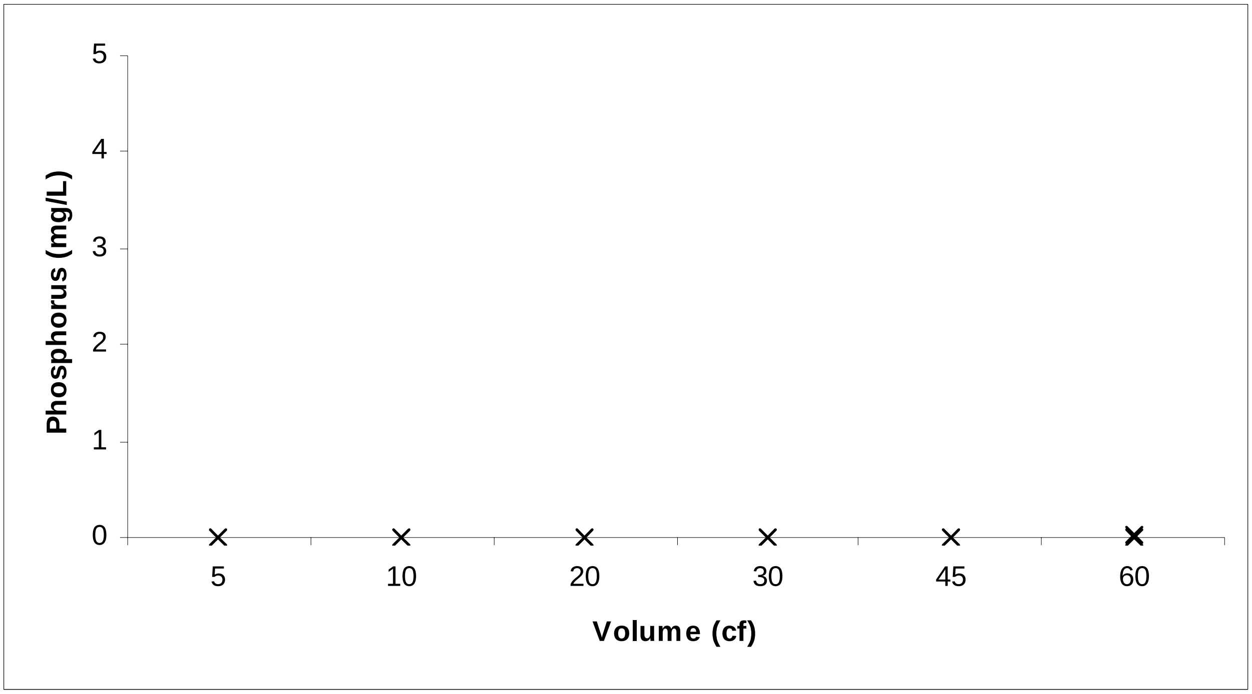

Figure 227 – Phosphorus - Filtered Control Roof Samples - October 17, 2006 Storm

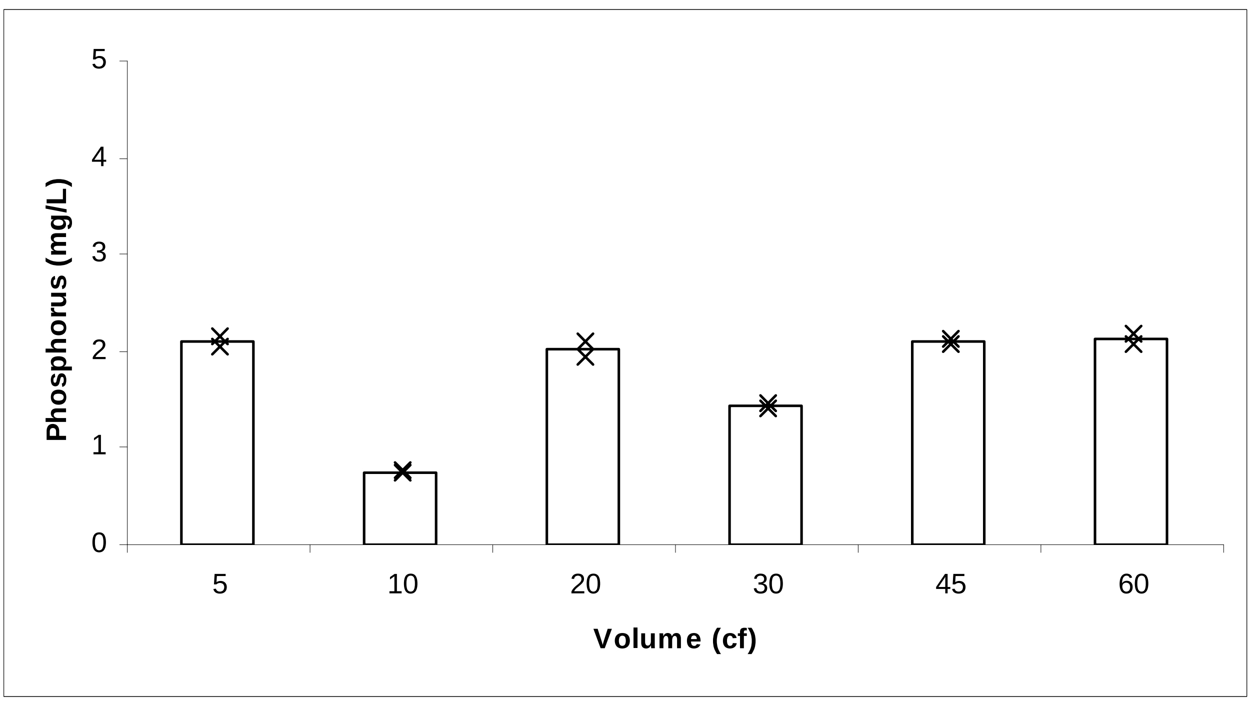

Figure 228 - Phosphorus - Unfiltered Green Roof Samples - October 17, 2006 Storm

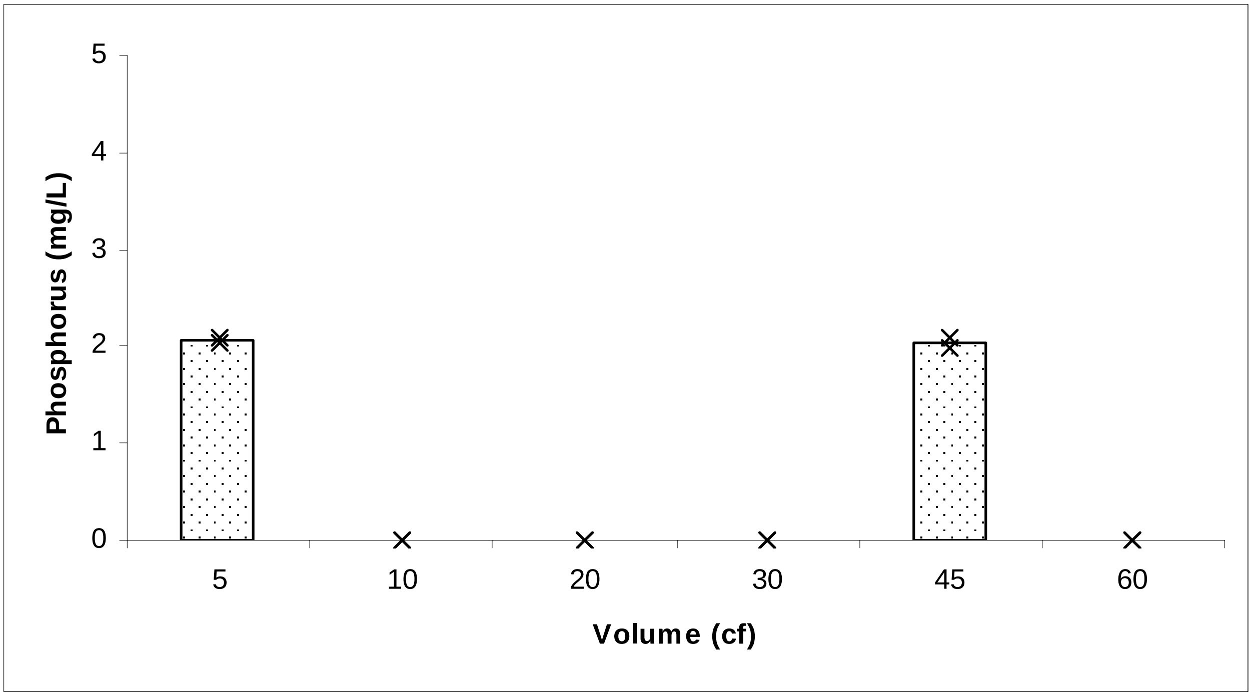

Figure 229 – Phosphorus - Filtered Green Roof Samples - October 17, 2006 Storm

B.2.2 Sulfate

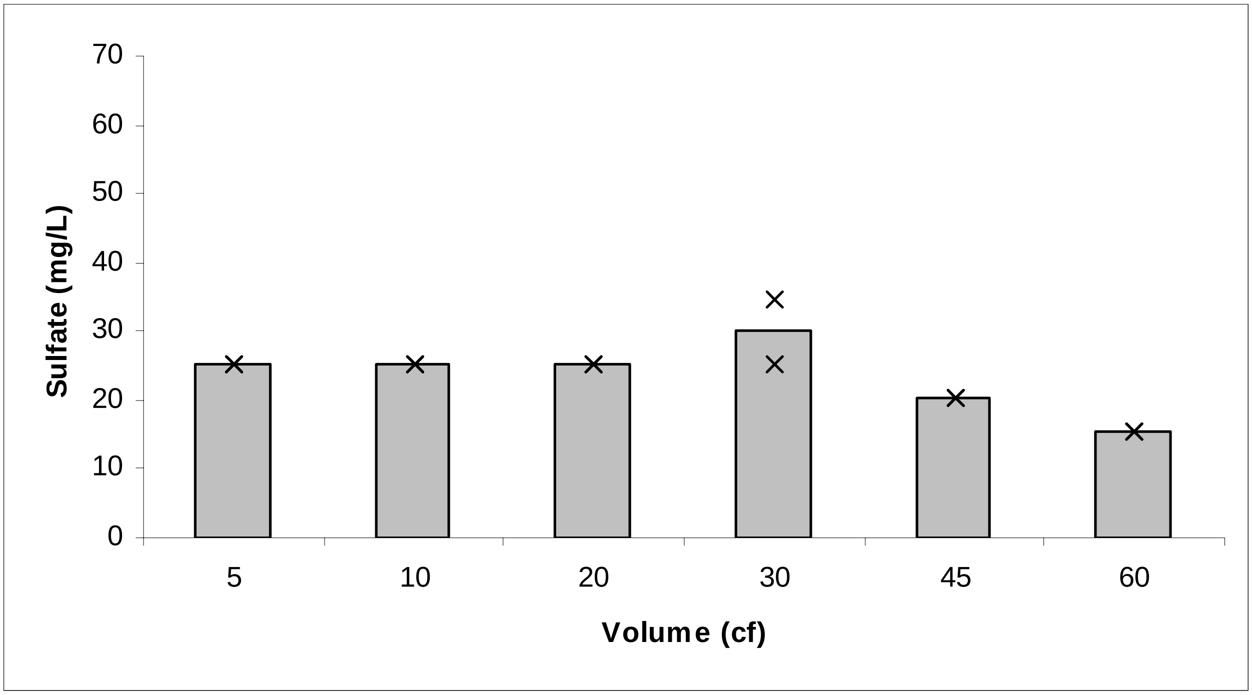

Figure 230 - Sulfate - Unfiltered Control Roof Samples - October 17, 2006 Storm

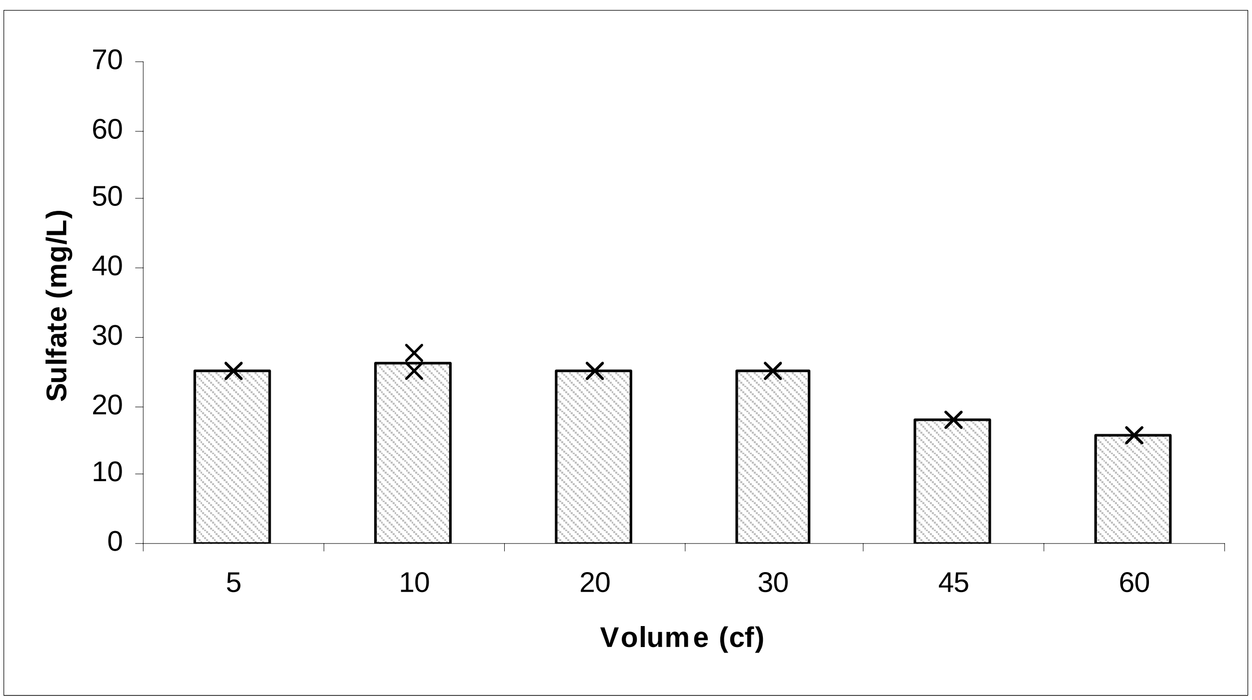

Figure 231 - Sulfate - Filtered Control Roof Samples - October 17, 2006 Storm

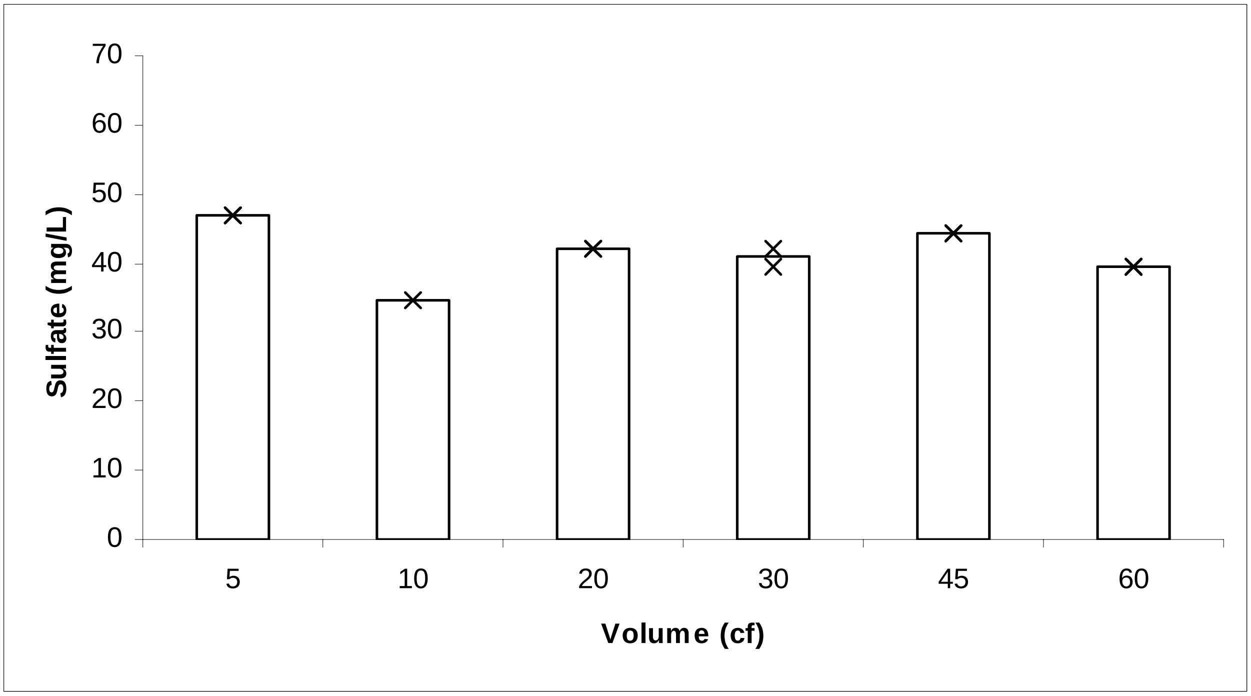

Figure 232 - Sulfate - Unfiltered Green Roof Samples - October 17, 2006 Storm

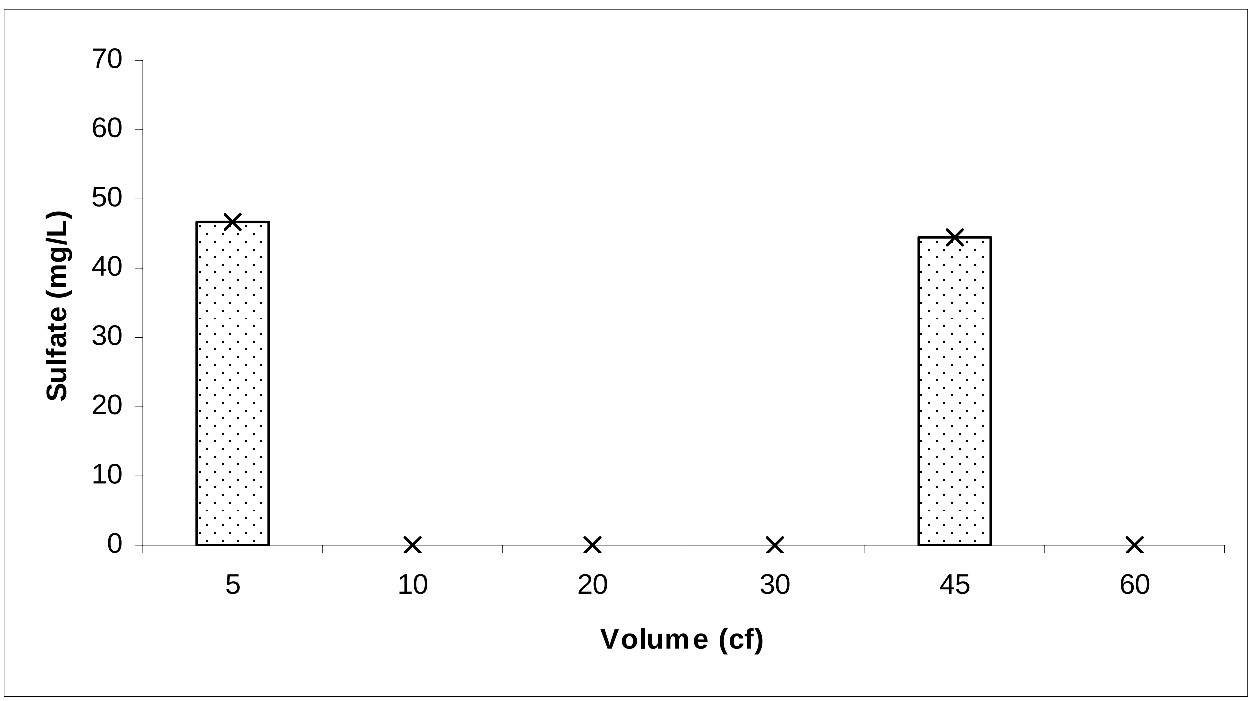

Figure 233 - Sulfate - Filtered Green Roof Samples - October 17, 2006 Storm

B.2.3 Nitrogen

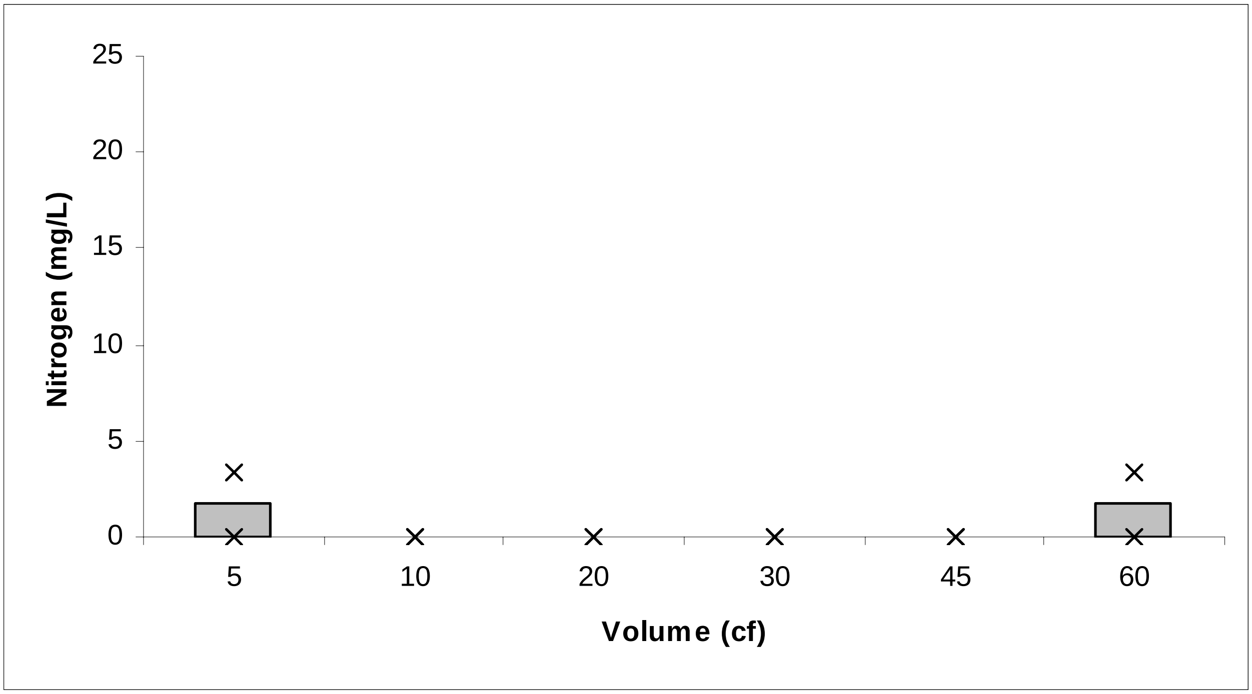

Figure 234 - Nitrogen - Unfiltered Control Roof Samples - October 17, 2006 Storm

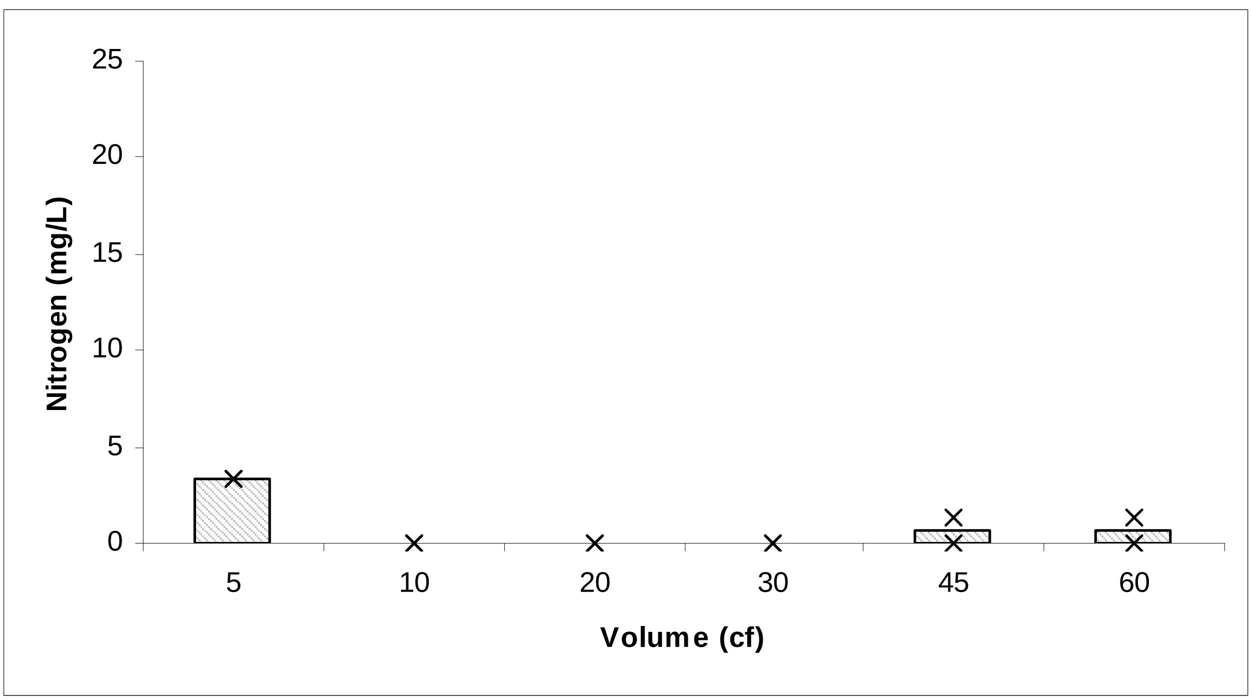

Figure 235 - Nitrogen - Filtered Control Roof Samples - October 17, 2006 Storm

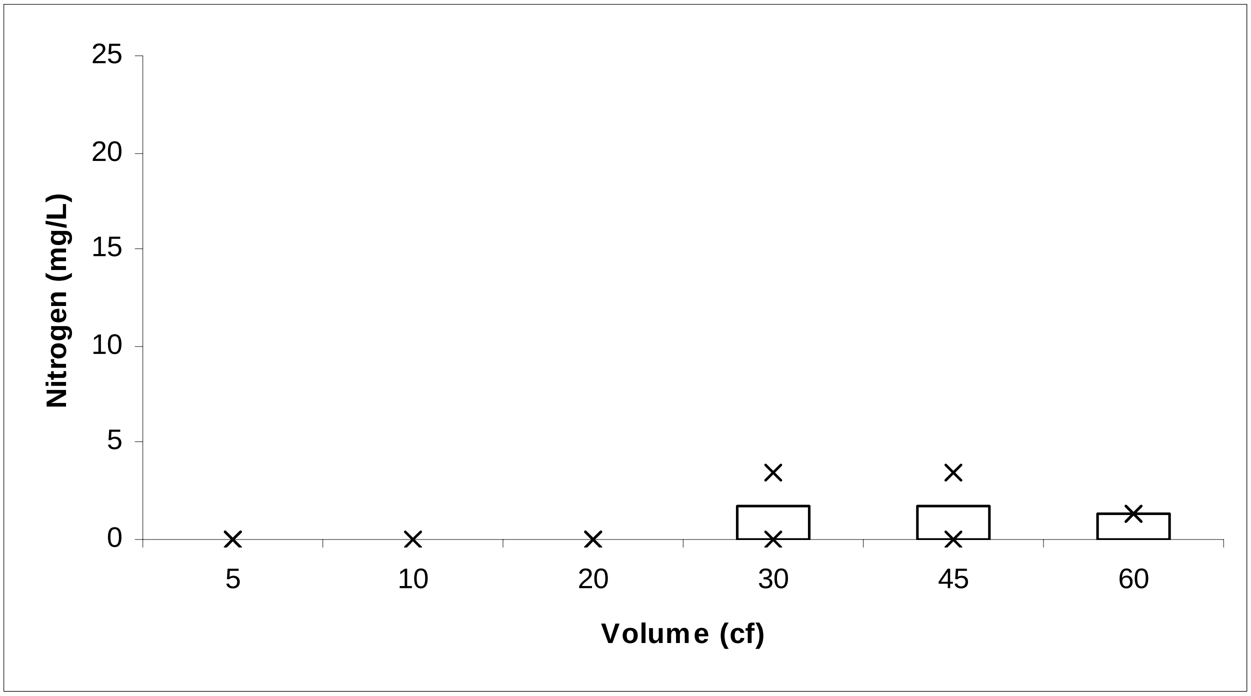

Figure 236 - Nitrogen - Unfiltered Green Roof Samples - October 17, 2006 Storm

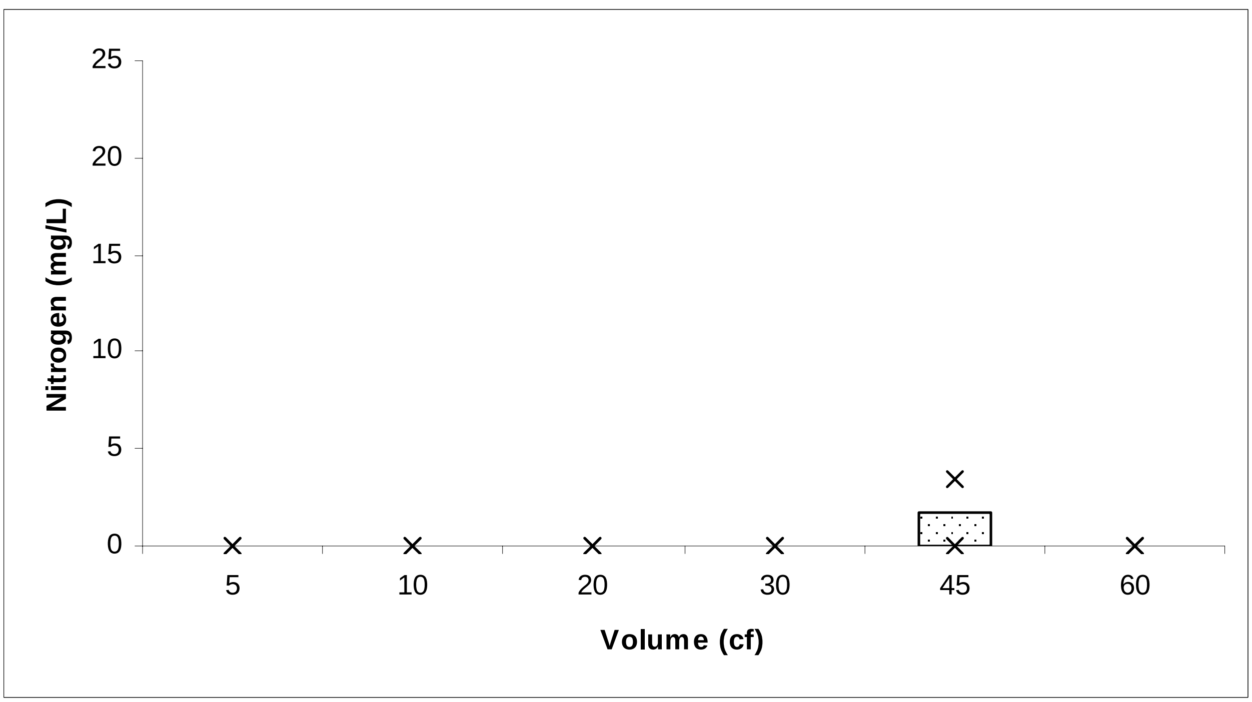

Figure 237 - Nitrogen - Filtered Green Roof Samples - October 17, 2006 Storm

B.2.4 COD

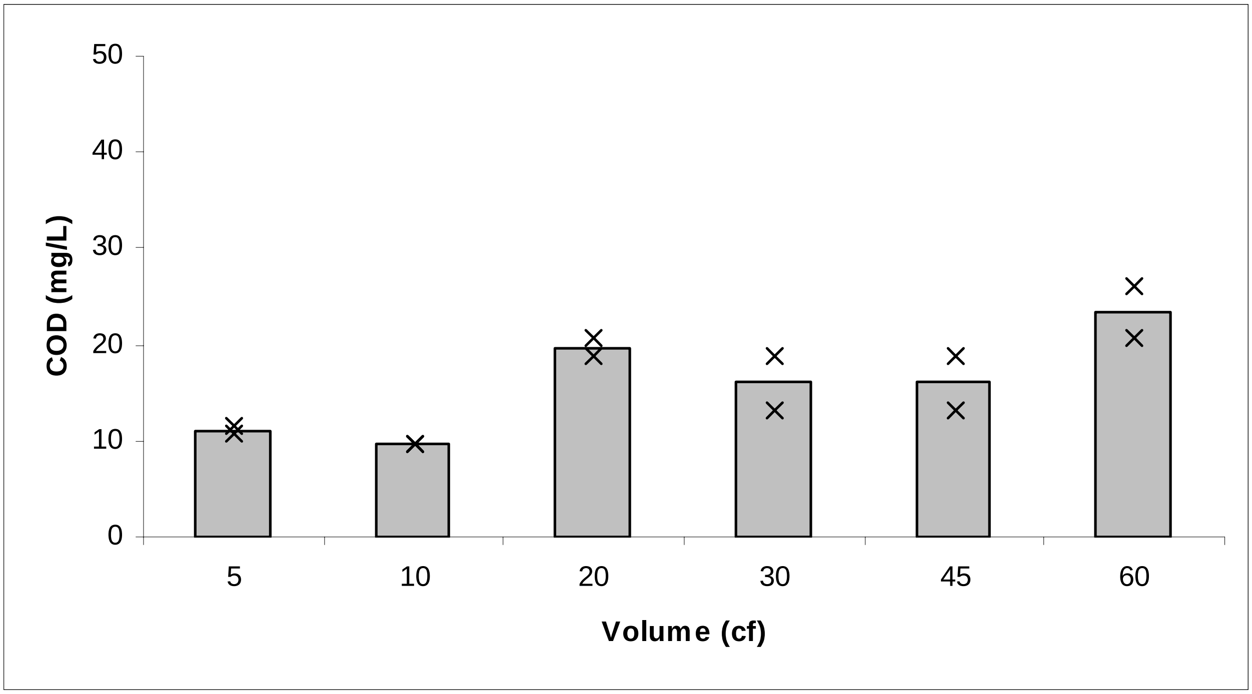

Figure 238 - COD - Unfiltered Control Roof Samples - October 17, 2006 Storm

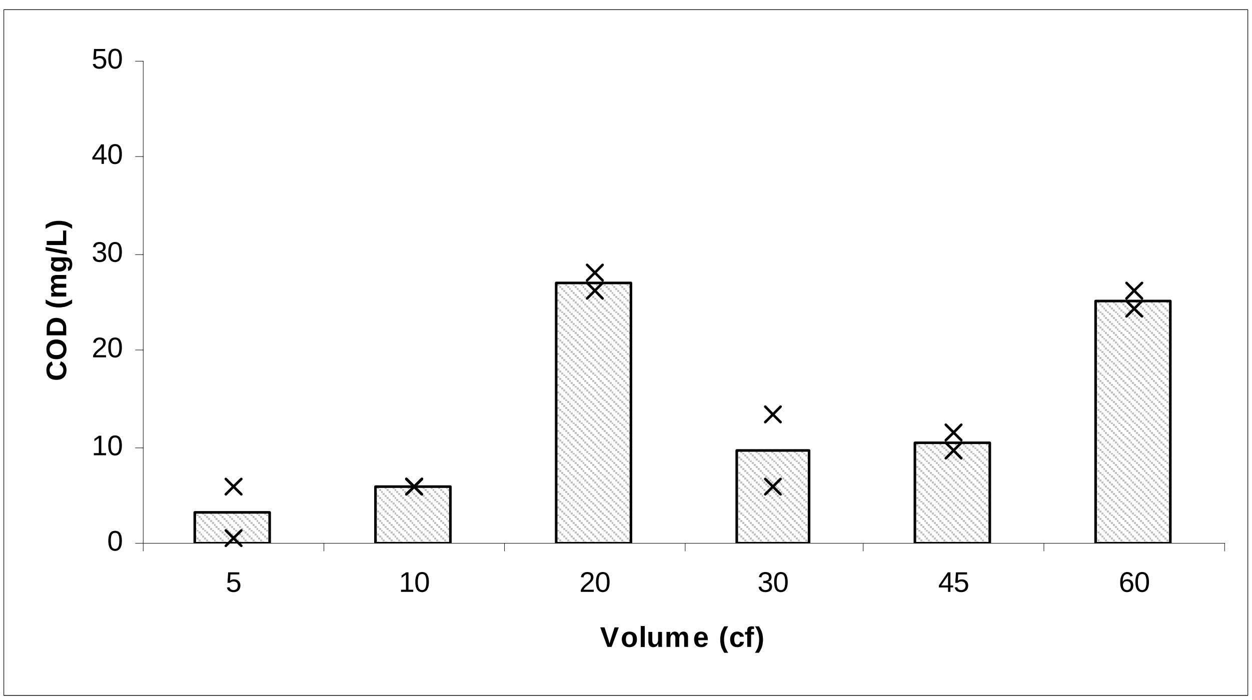

Figure 239 - COD - Filtered Control Roof Samples - October 17, 2006 Storm

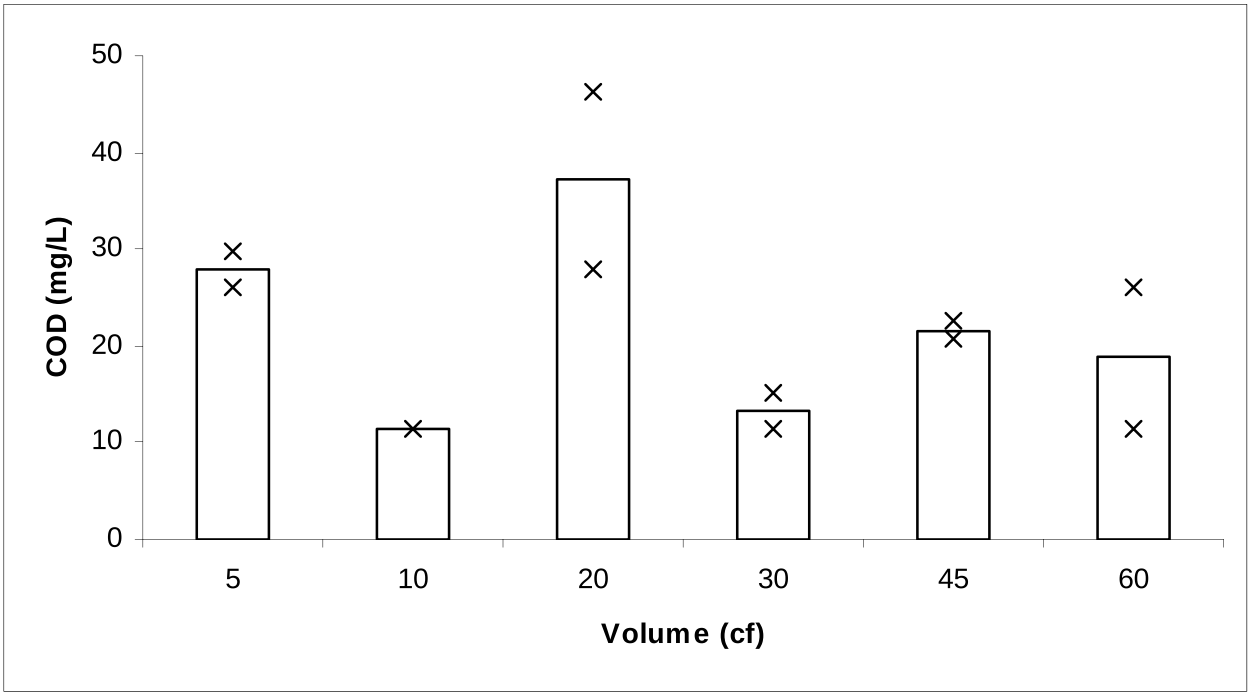

Figure 240 - COD - Unfiltered Green Roof Samples - October 17, 2006 Storm

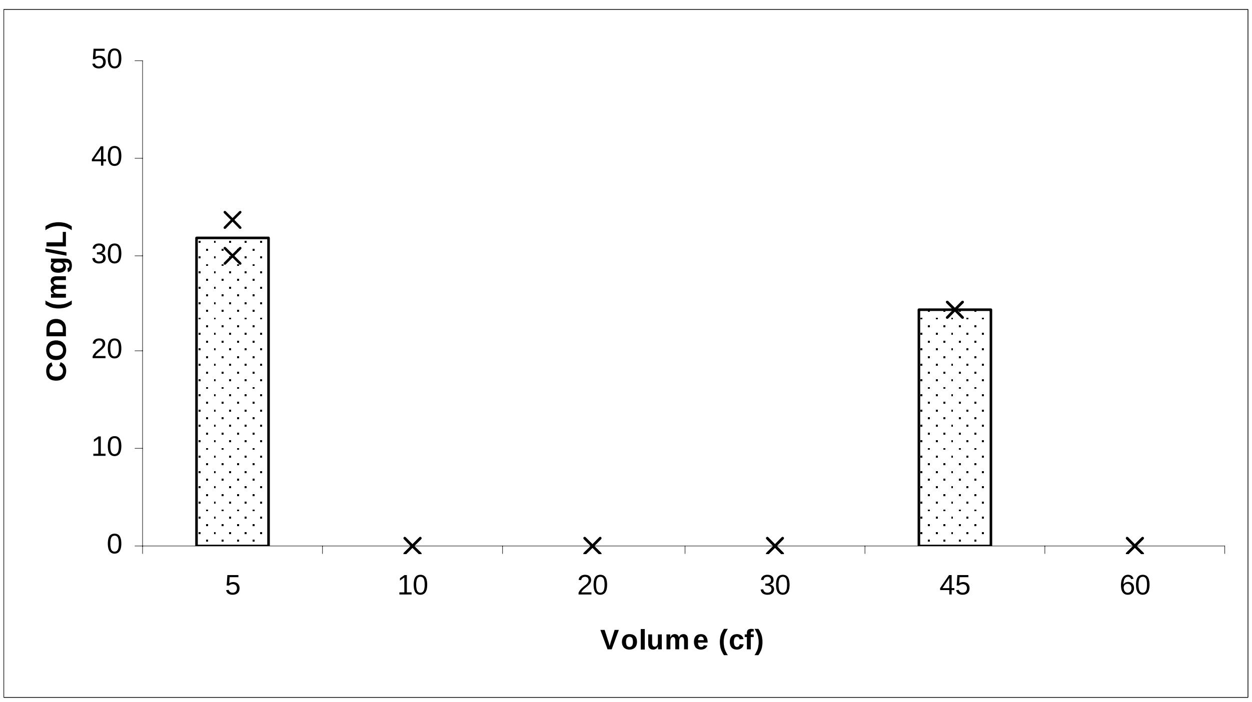

Figure 241 - COD - Filtered Green Roof Samples - October 17, 2006 Storm

B.2.5 pH

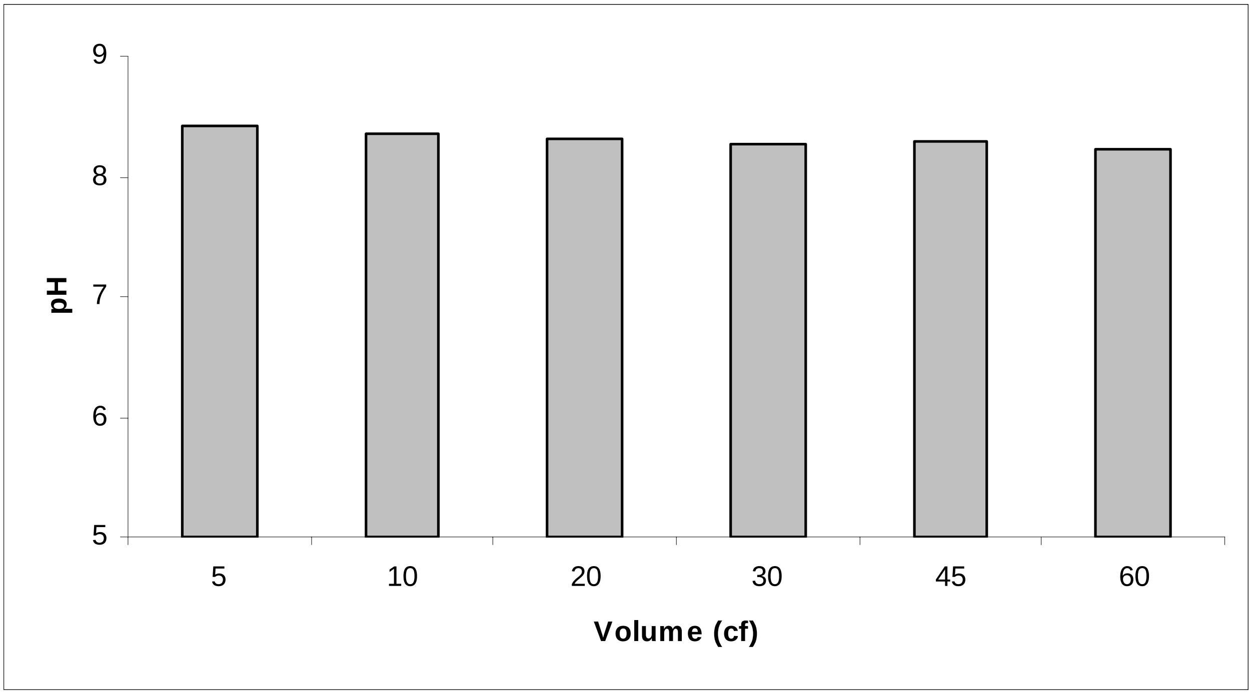

Figure 242 - pH - Control Roof Samples - October 17, 2006

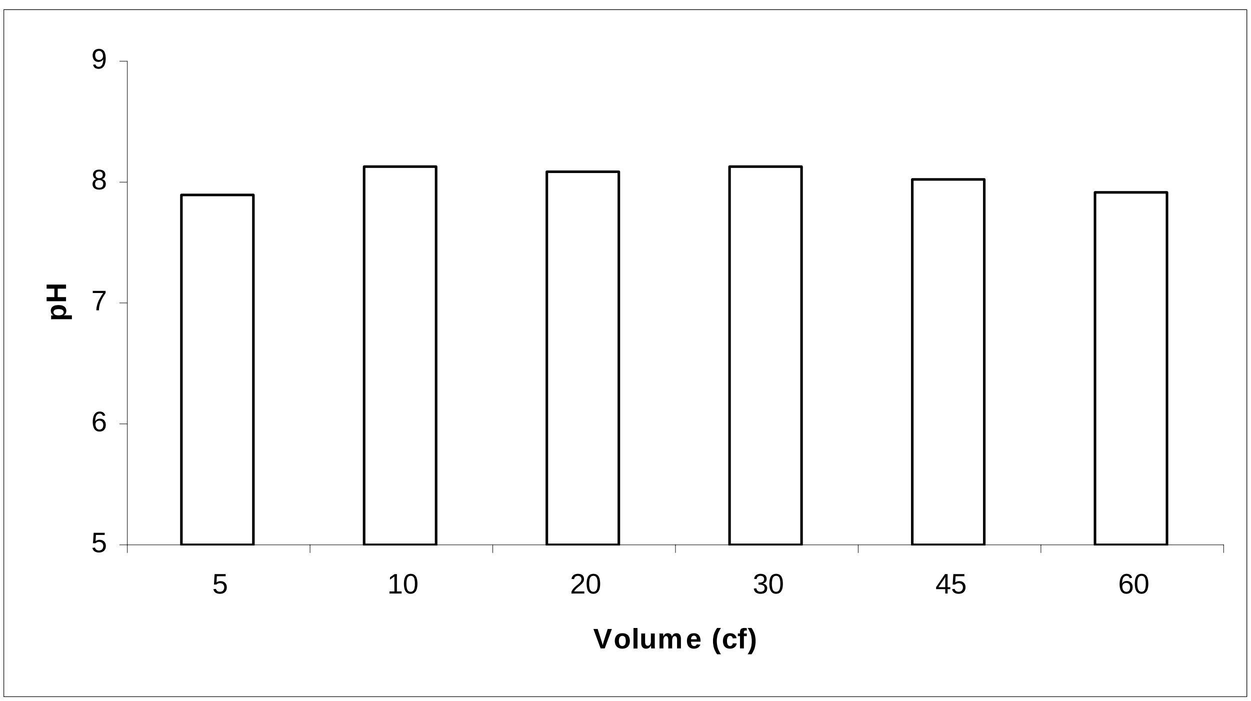

Figure 243 - pH - Green Roof Samples - October 17, 2006

B.2.6 Turbidity

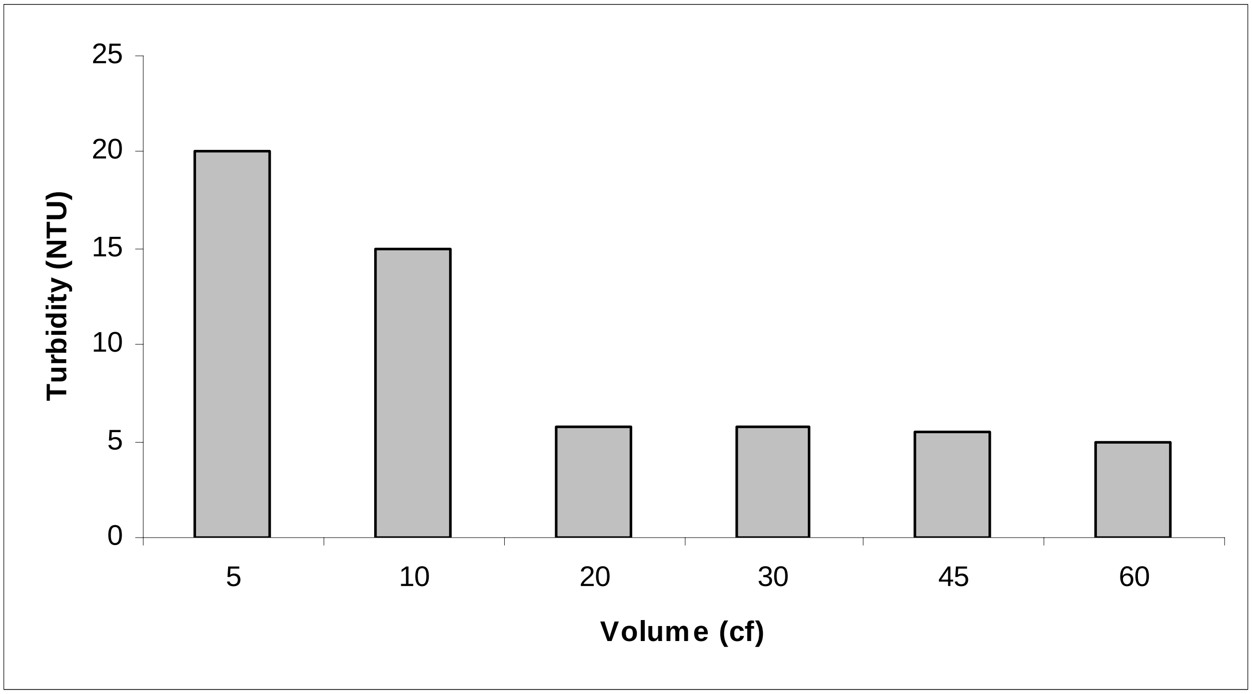

Figure 244 - Turbidity - Control Roof Samples - October 17, 2006

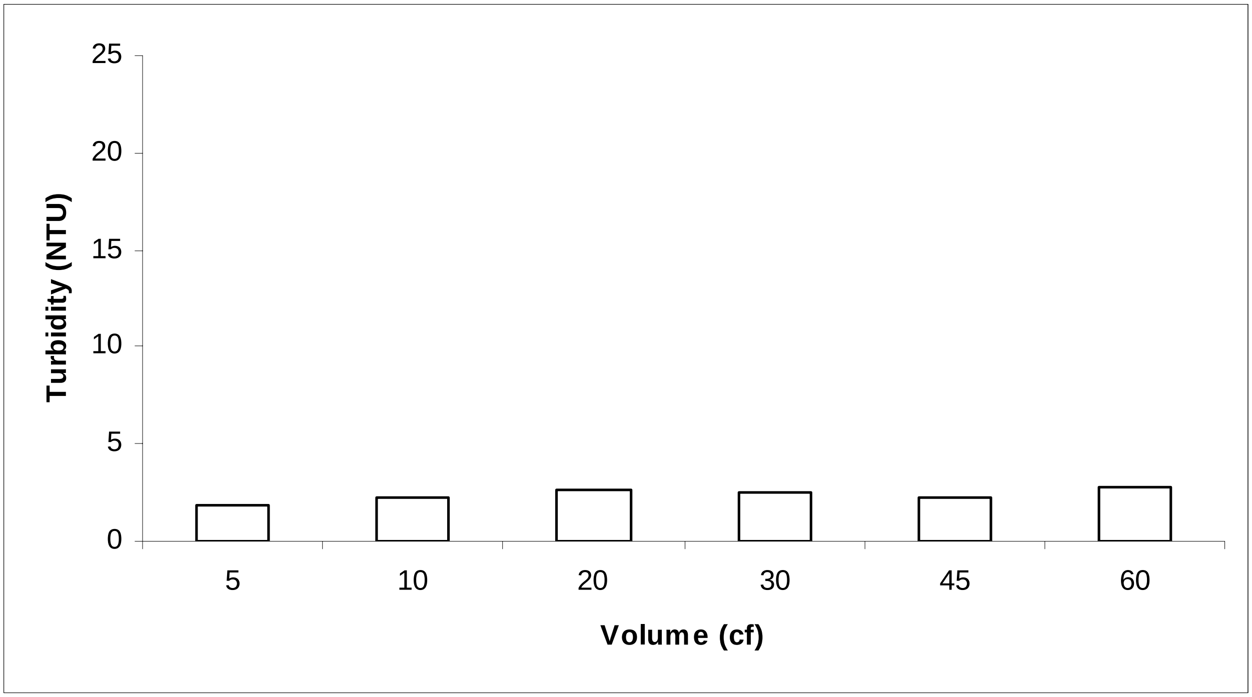

Figure 245 - Turbidity - Green Roof Samples - October 17, 2006 Storm

B.2.7 Lead

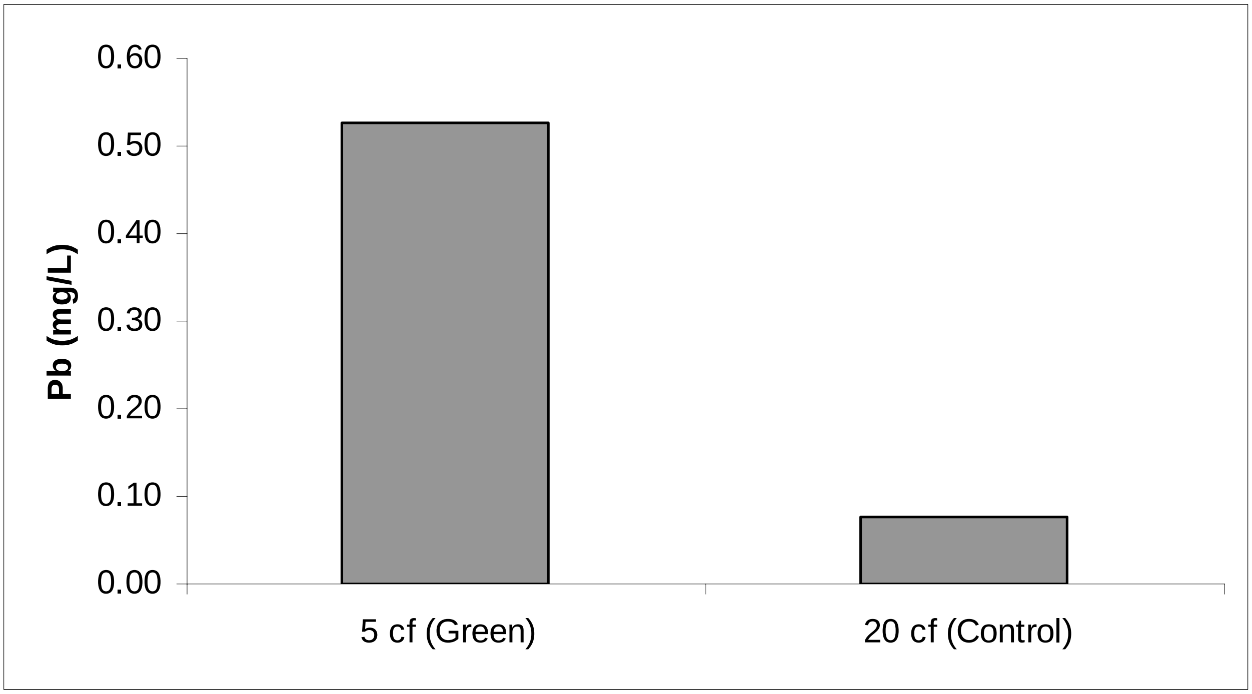

Figure 246 - Lead - October 17, 2006 Storm

B.2.8 Cadmium

The 5 cf sample from the green roof and the 20 cf sample from the control roof were tested for cadmium, but the readings fell below the detectible limits. These samples have a concentration of 0 mg/L Cd.

B.2.9 Zinc

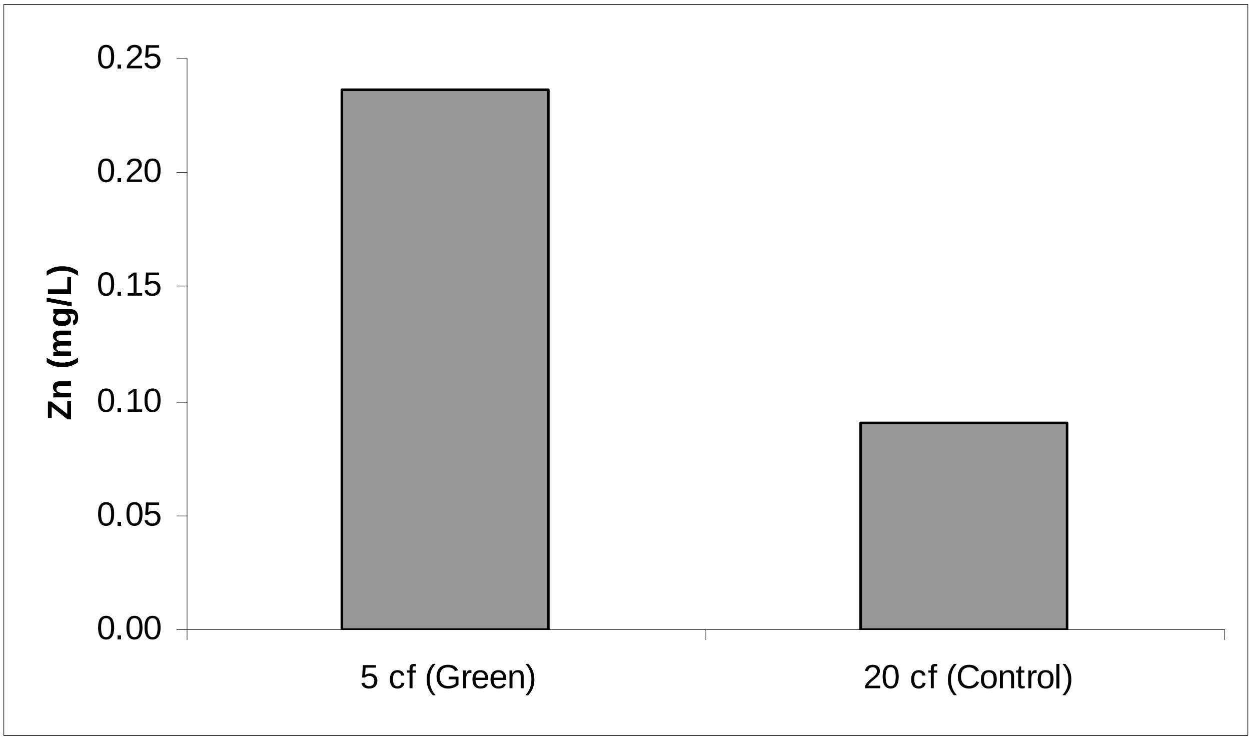

Figure 247 - Zinc - October 17, 2006 Storm

B.3 NOVEMBER 1, 2006 STORM

B.3.1 Phosphorus

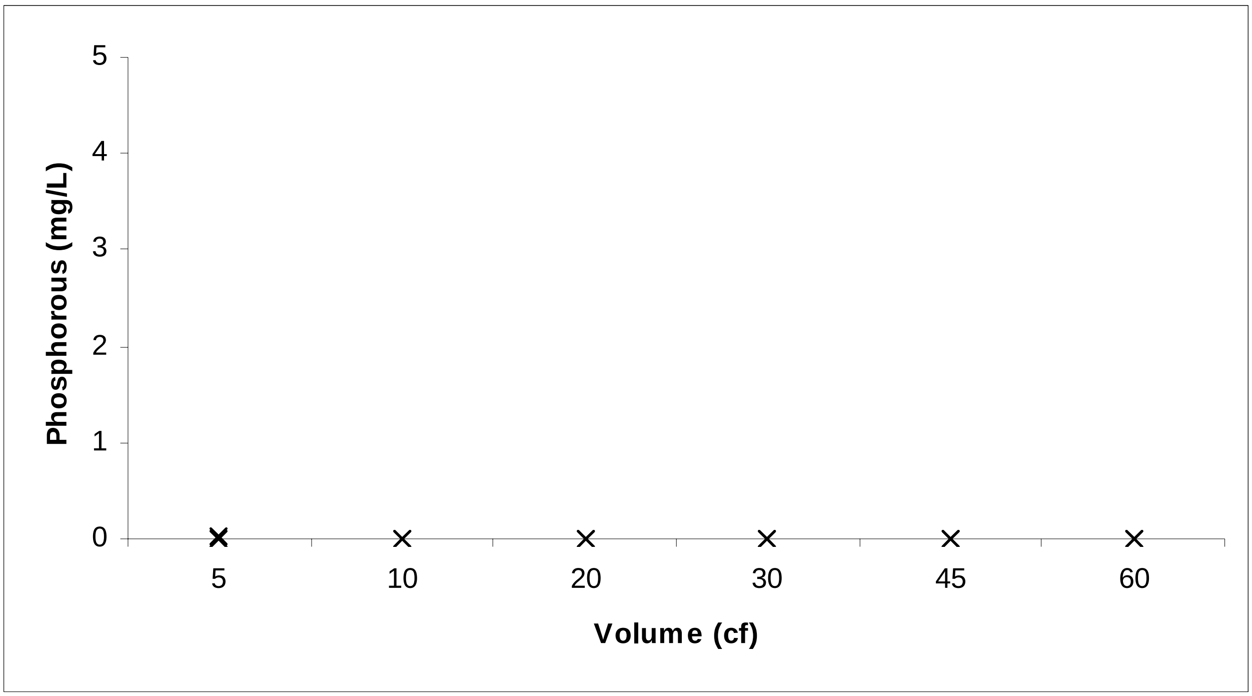

Figure 248 - Phosphorus - Unfiltered Control Roof Samples - November 1, 2006 Storm

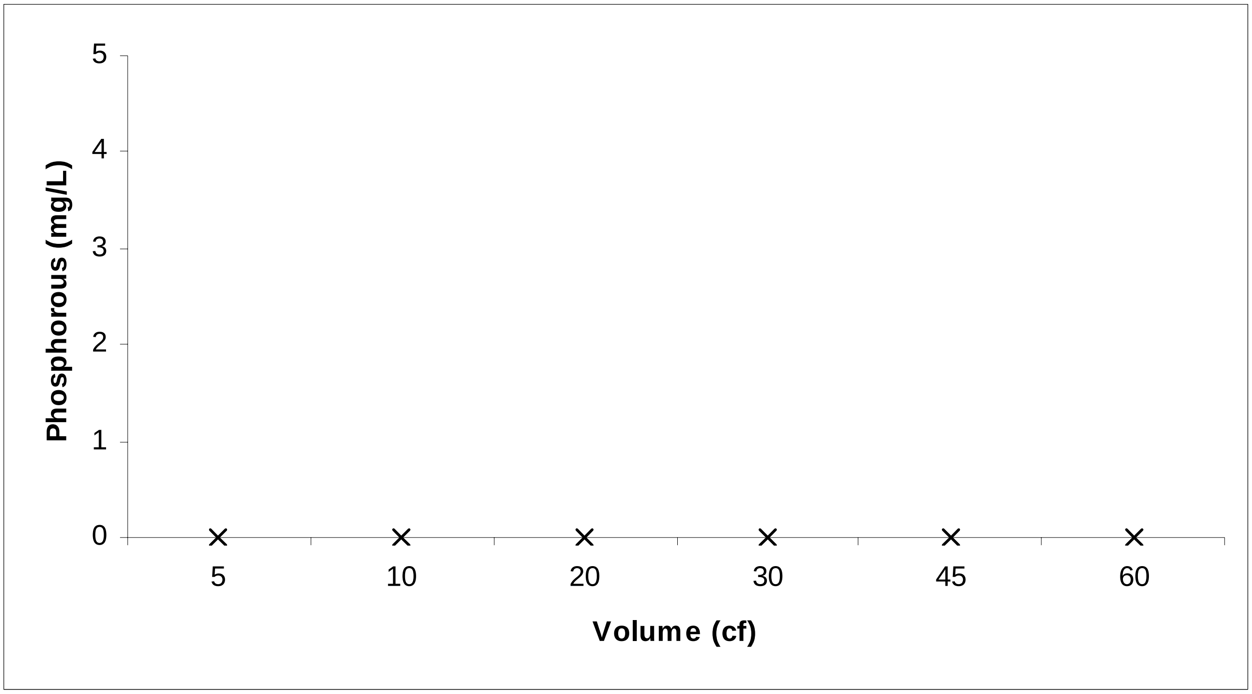

Figure 249 - Phosphorus - Filtered Control Roof Samples - November 1, 2006 Storm

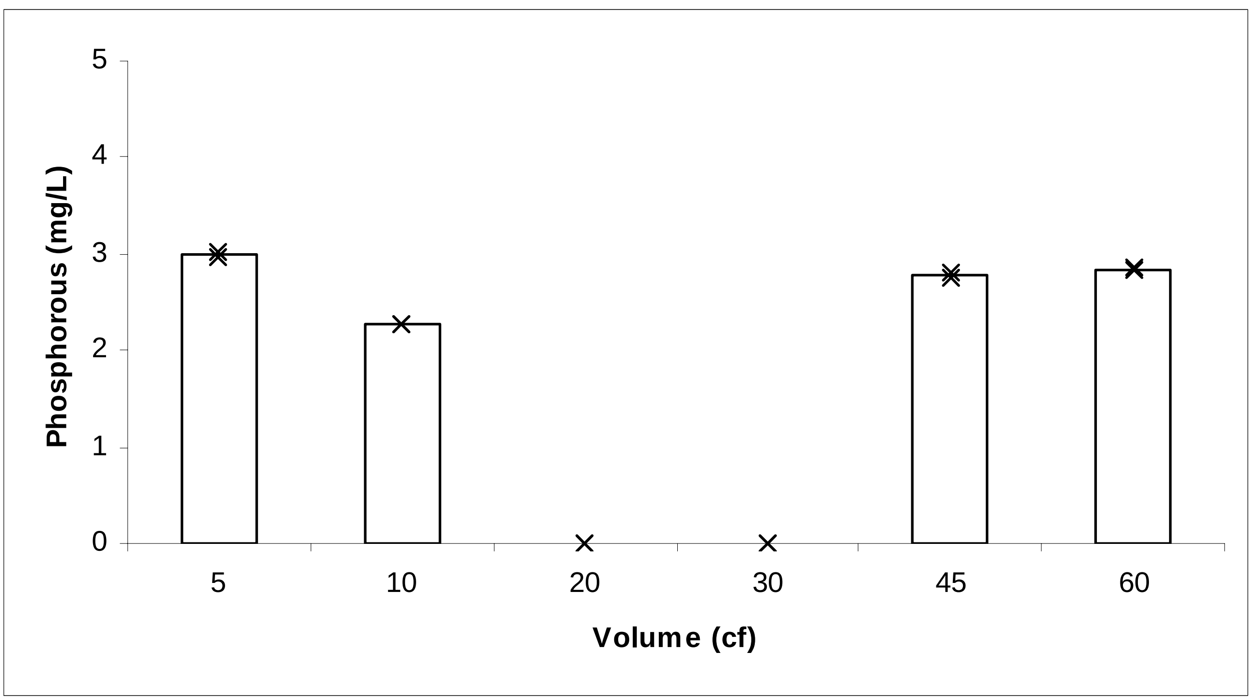

Figure 250 - Phosphorus - Unfiltered Green Roof Samples - November 1, 2006 Storm

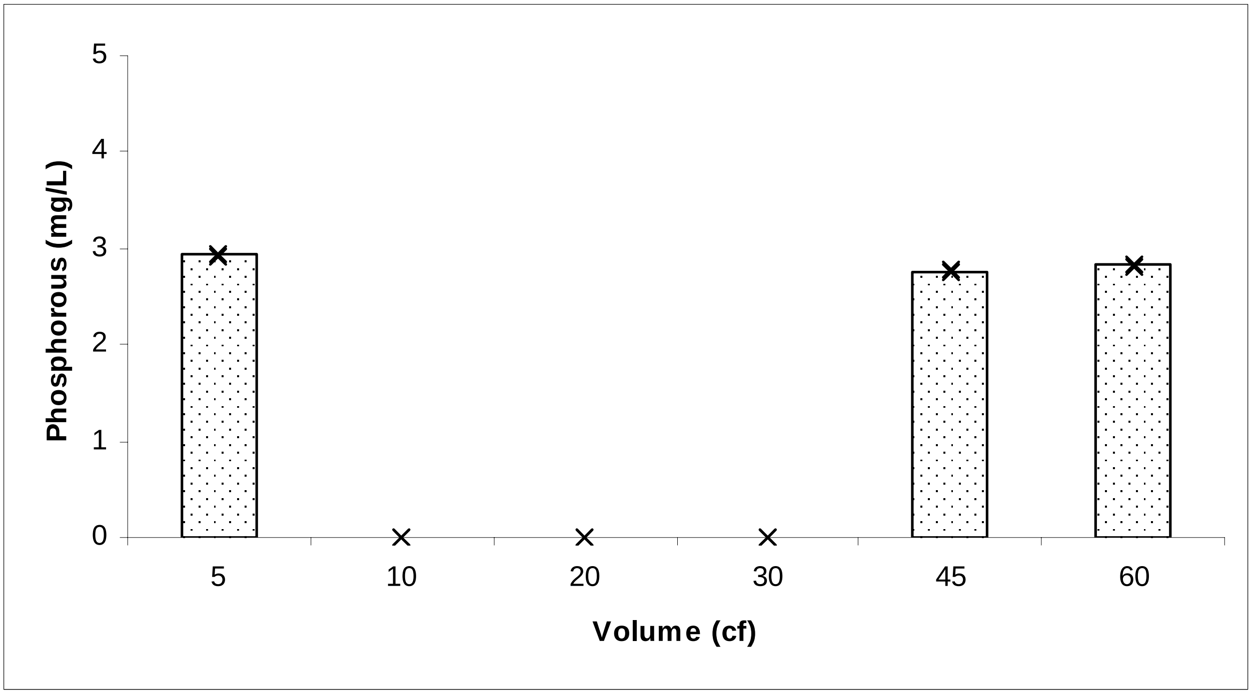

Figure 251 - Phosphorus - Filtered Green Roof Samples - November 1, 2006 Storm

B.3.2 Sulfate

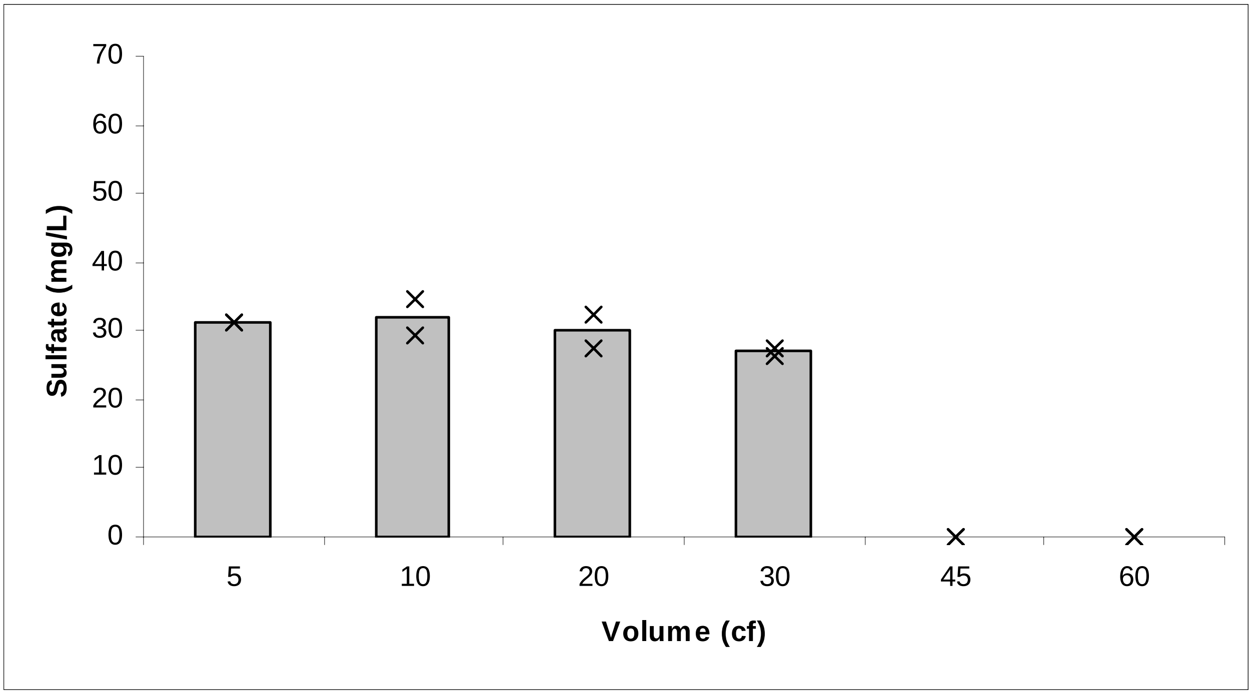

Figure 252 - Sulfate - Unfiltered Control Roof Samples - November 1, 2006 Storm

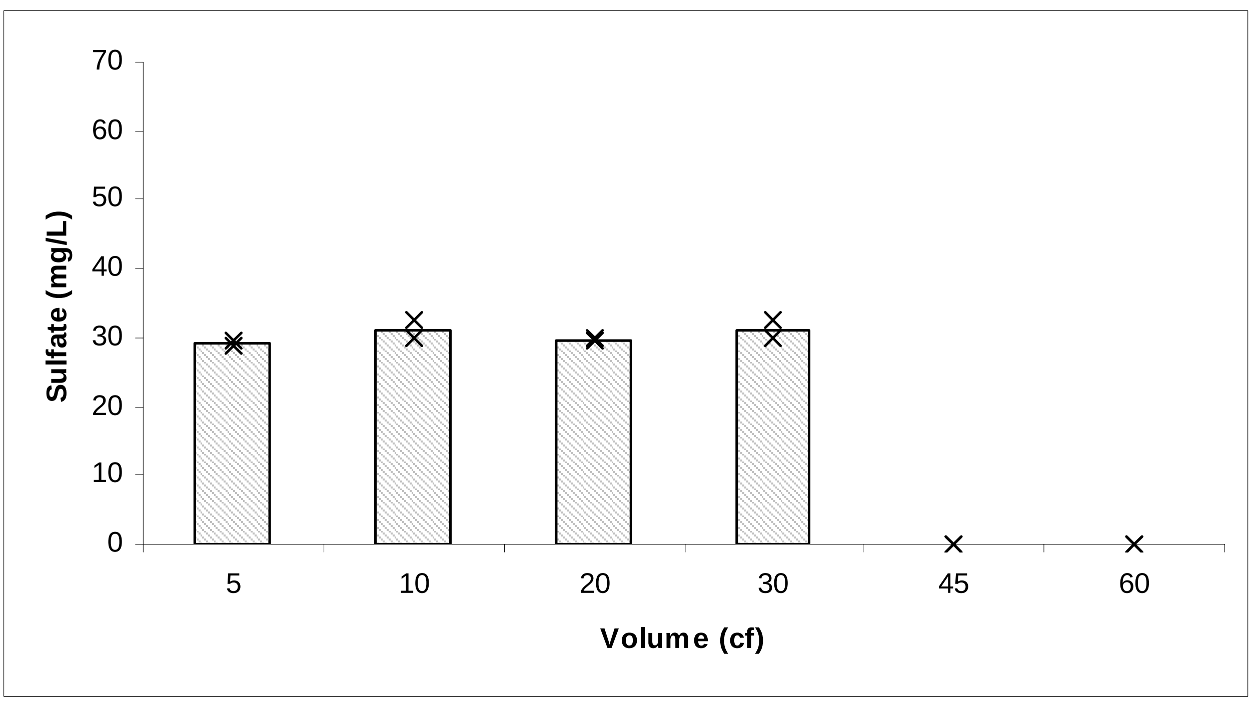

Figure 253 - Sulfate - Filtered Control Roof Samples - November 1, 2006 Storm

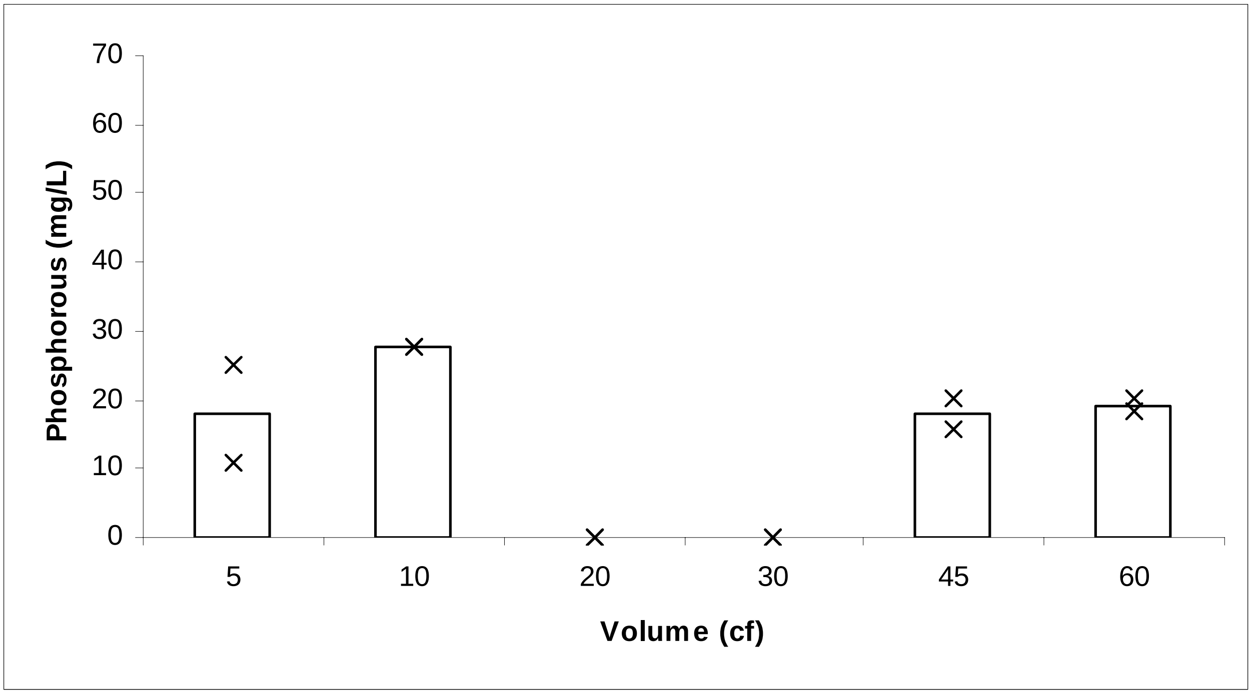

Figure 254 - Sulfate - Unfiltered Green Roof Samples - November 1, 2006 Storm

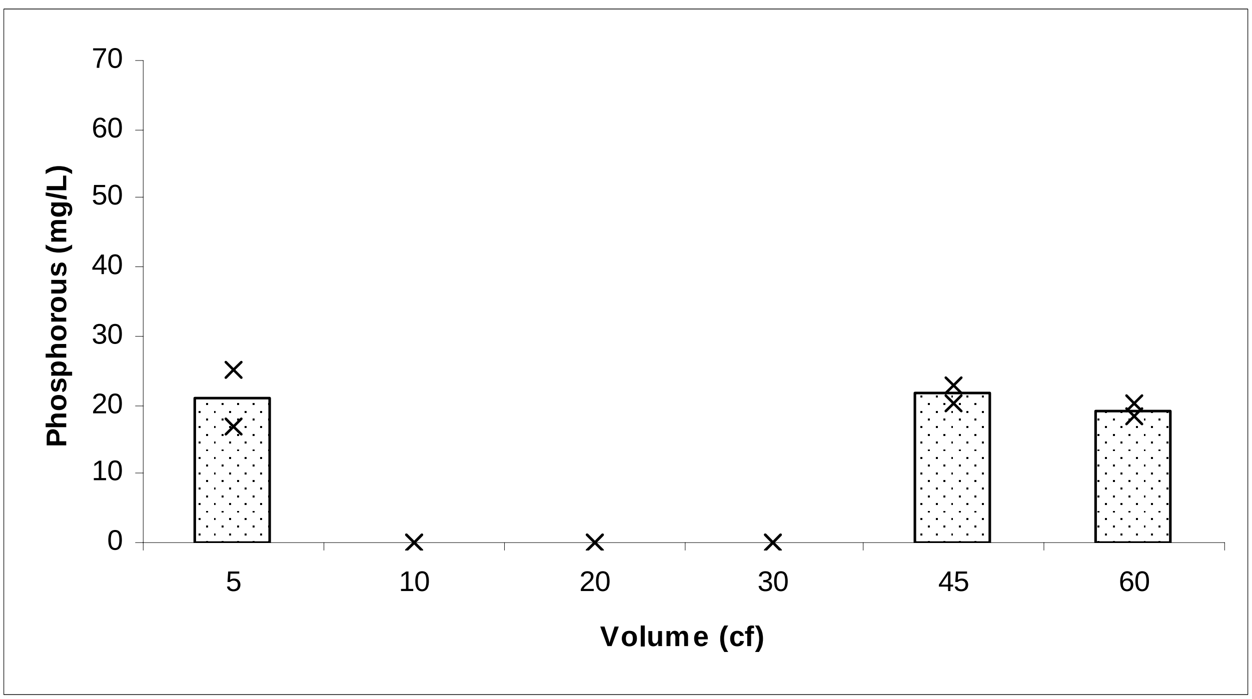

Figure 255 - Sulfate - Filtered Green Roof Samples - November 1, 2006 Storm

B.3.3 Nitrogen

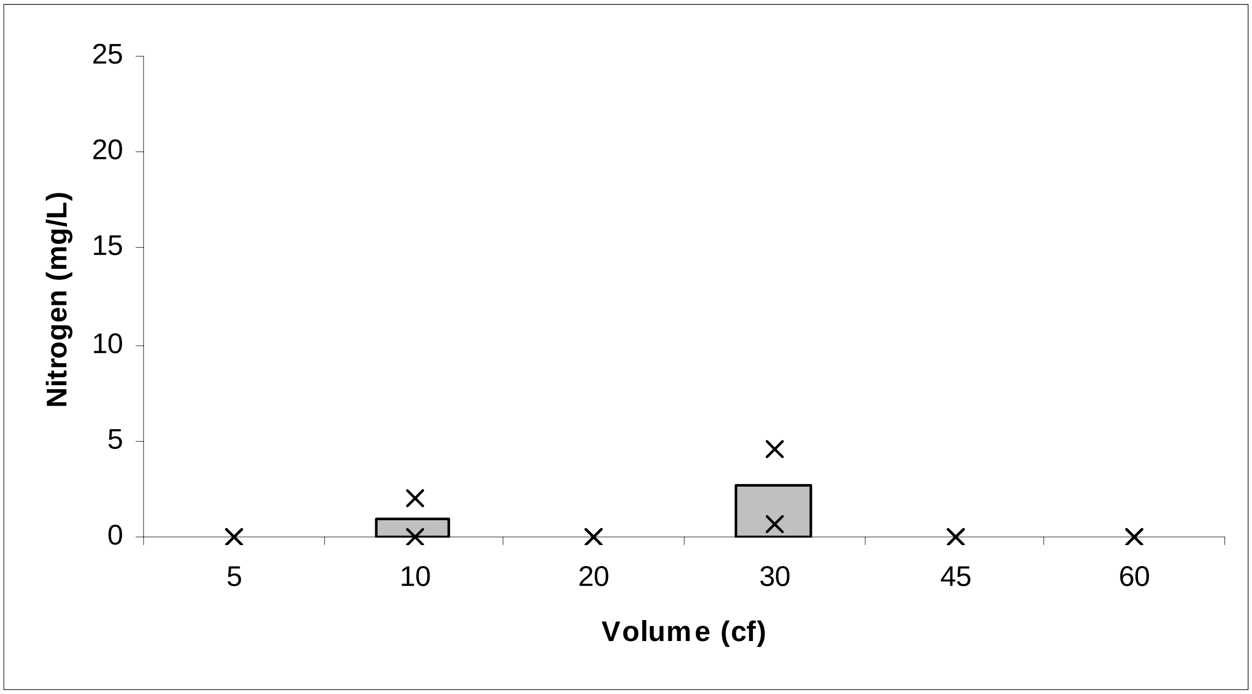

Figure 256 - Nitrogen - Unfiltered Control Roof Samples - November 1, 2006 Storm

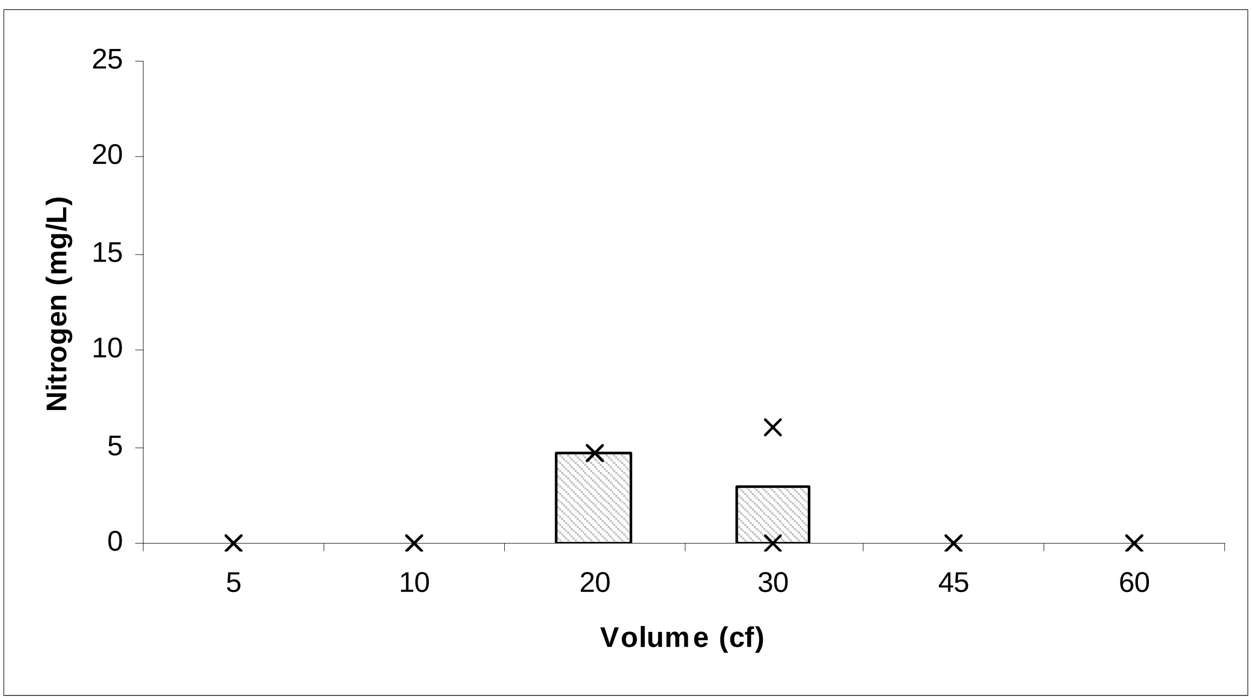

Figure 257 - Nitrogen - Filtered Control Roof Samples - November 1, 2006 Storm

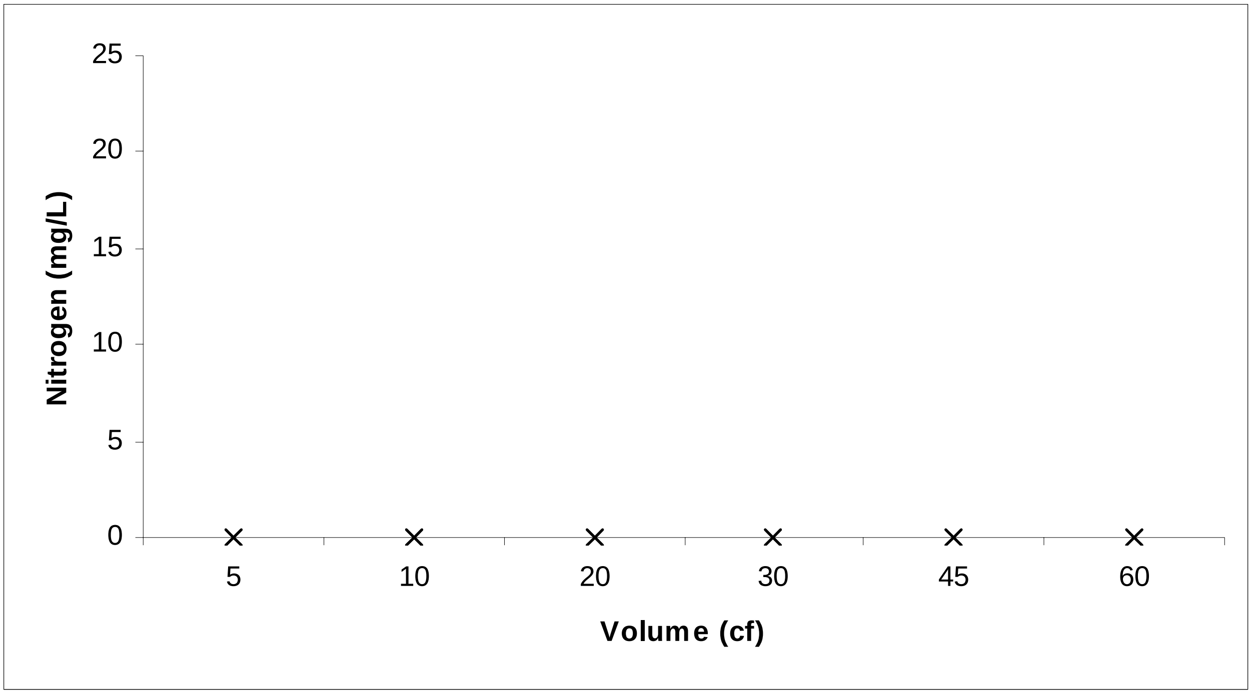

Figure 258 - Nitrogen - Unfiltered Green Roof Samples - November 1, 2006 Storm

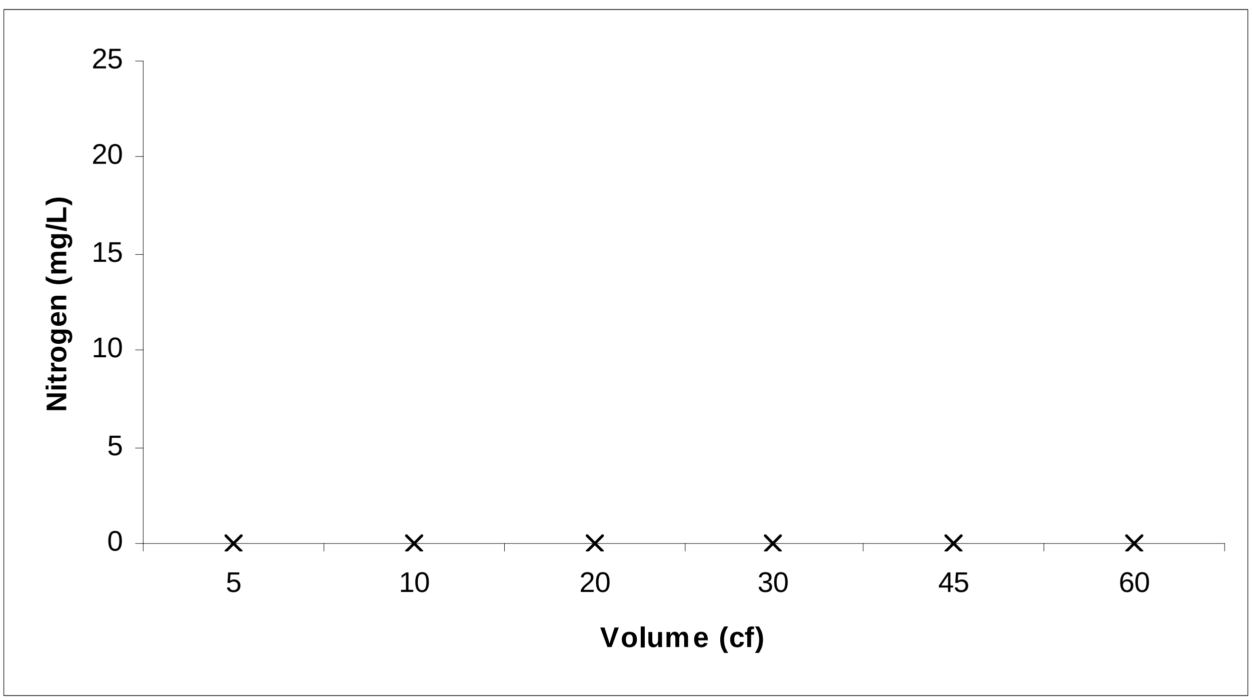

Figure 259 - Nitrogen - Filtered Green Roof Samples - November 1, 2006 Storm

B.3.4 COD

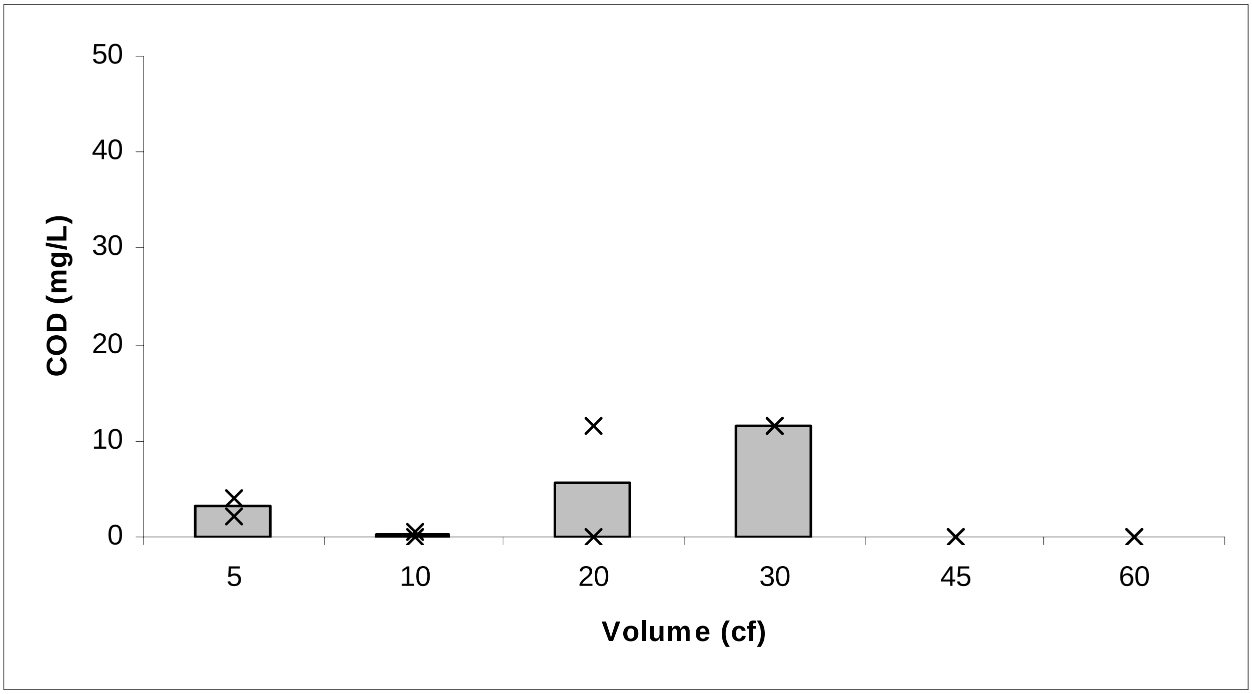

Figure 260 - COD - Unfiltered Control Roof Samples - November 1, 2006 Storm

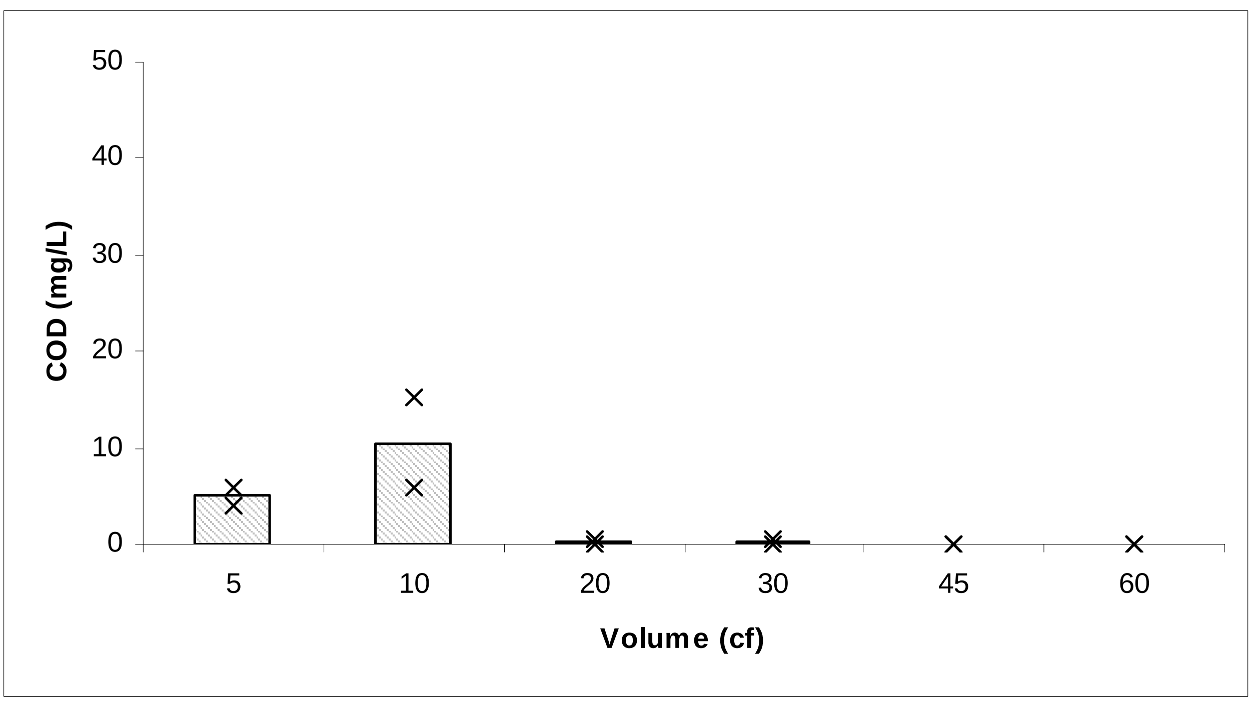

Figure 261 - COD - Filtered Control Roof Samples - November 1, 2006 Storm

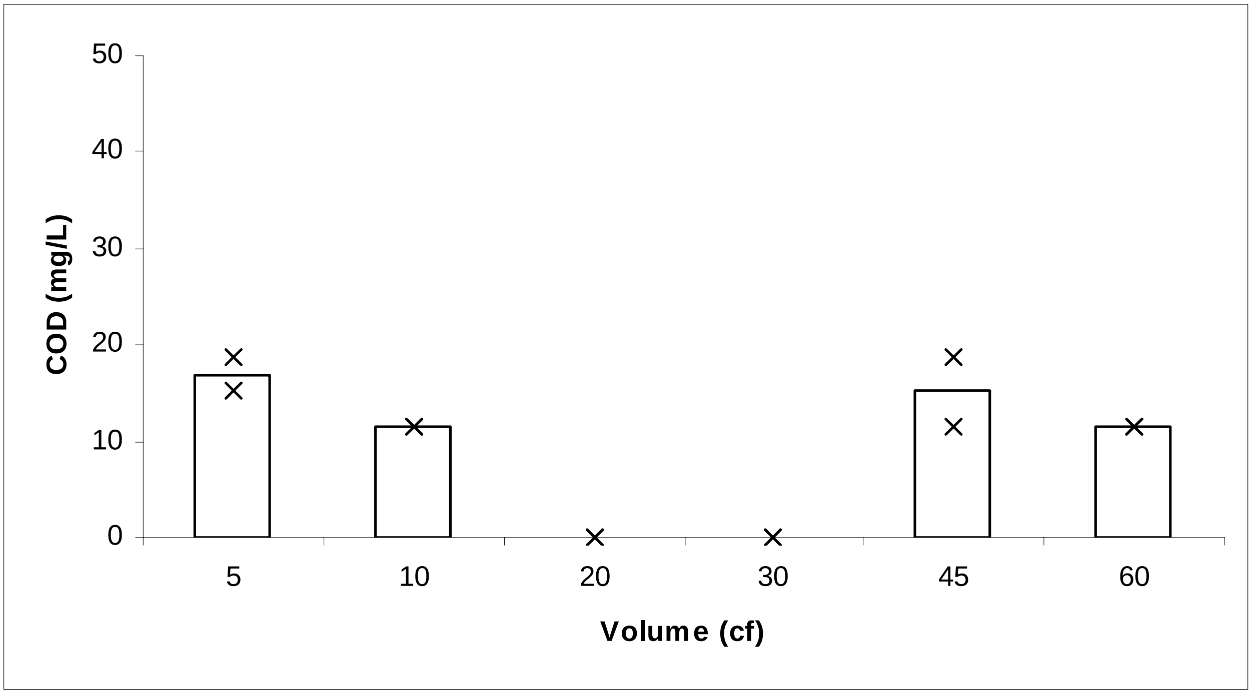

Figure 262 - COD - Unfiltered Green Roof Samples - November 1, 2006 Storm

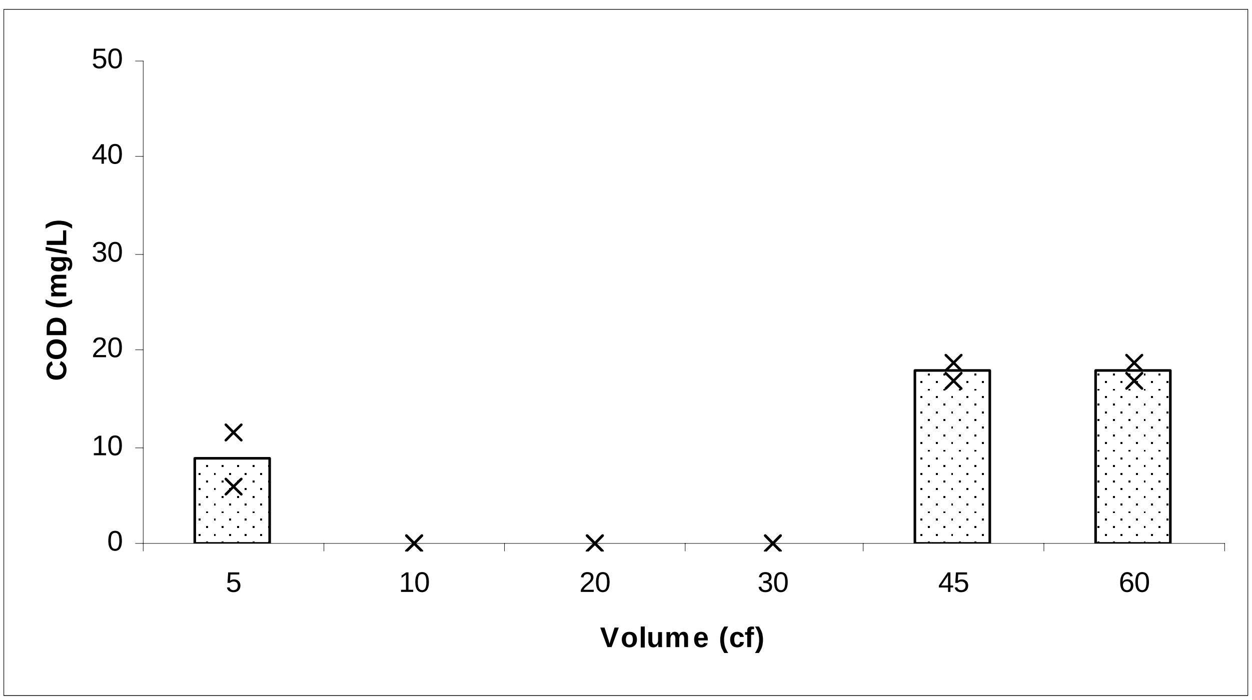

Figure 263 - COD - Filtered Green Roof Samples - November 1, 2006 Storm

B.3.5 pH

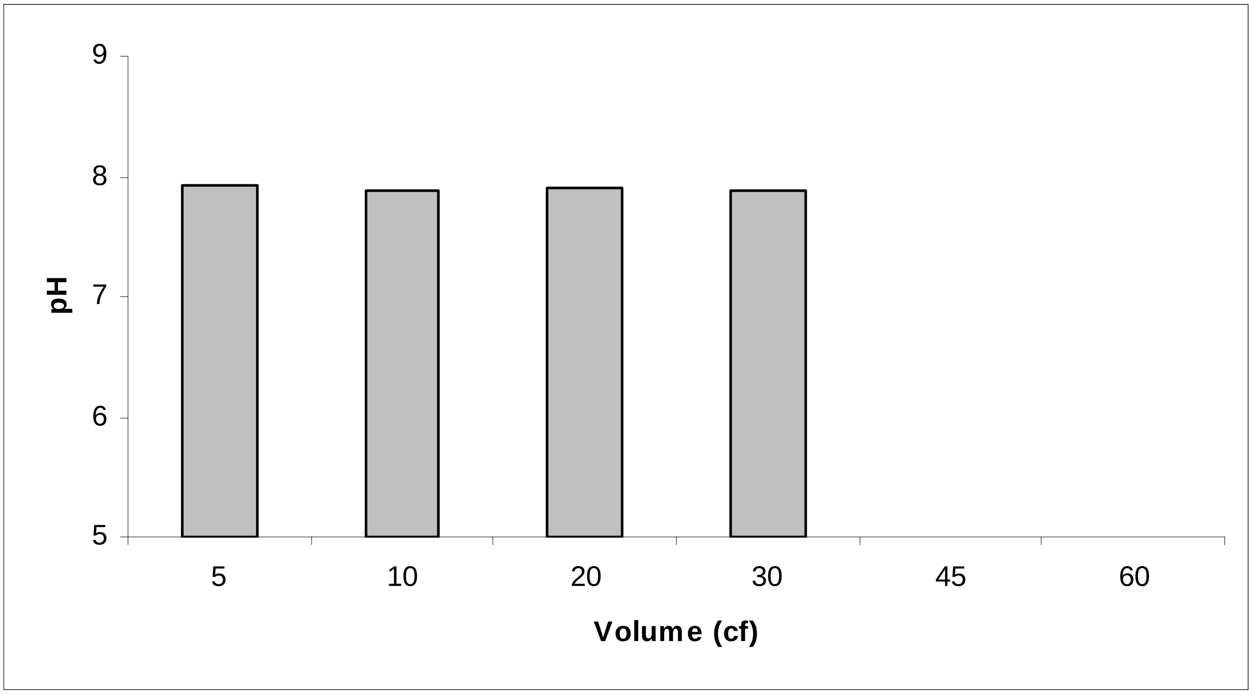

Figure 264 - pH - Control Roof Samples - November 1, 2006 Storm

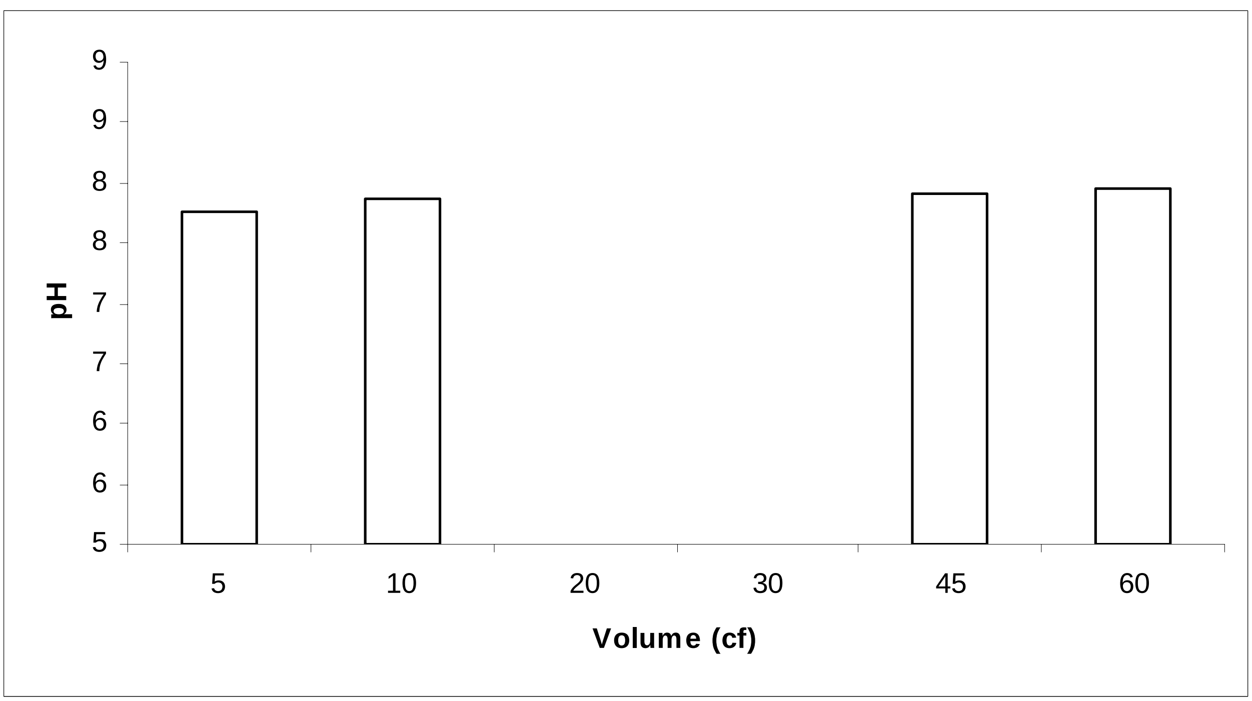

Figure 265 - pH - Green Roof Samples - November 1, 2006 Storm

B.3.6 Turbidity

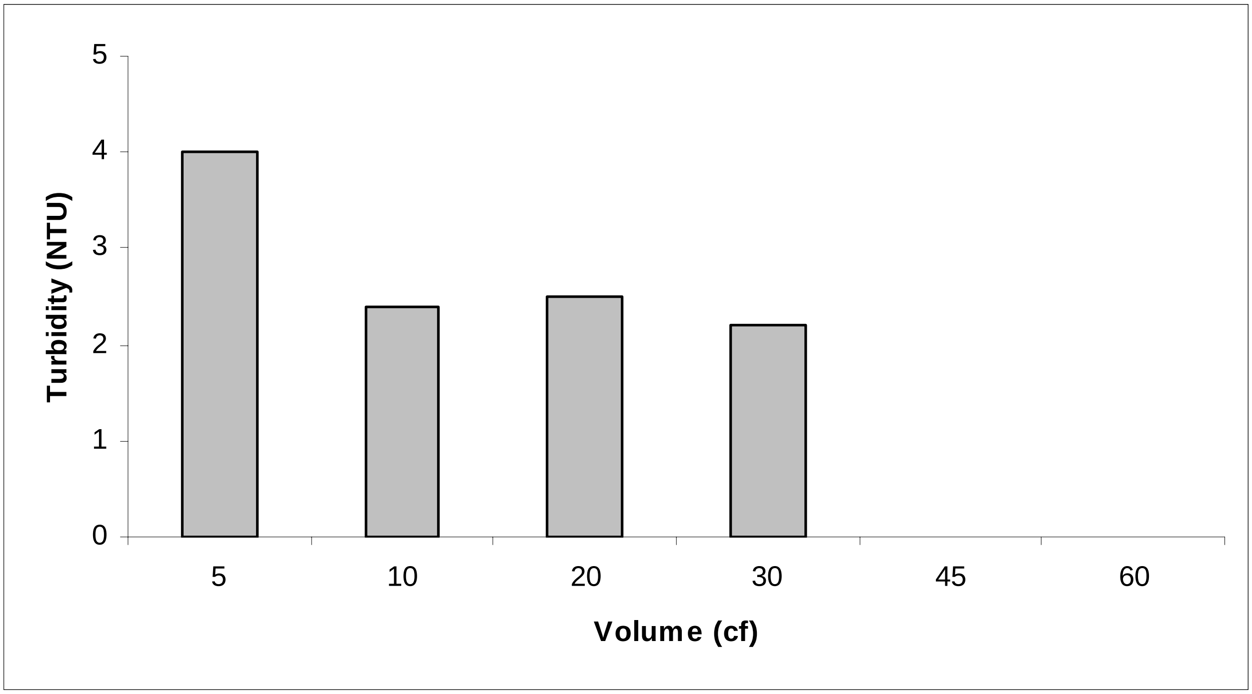

Figure 266 - Turbidity - Control Roof Samples - November 1, 2006 Storm

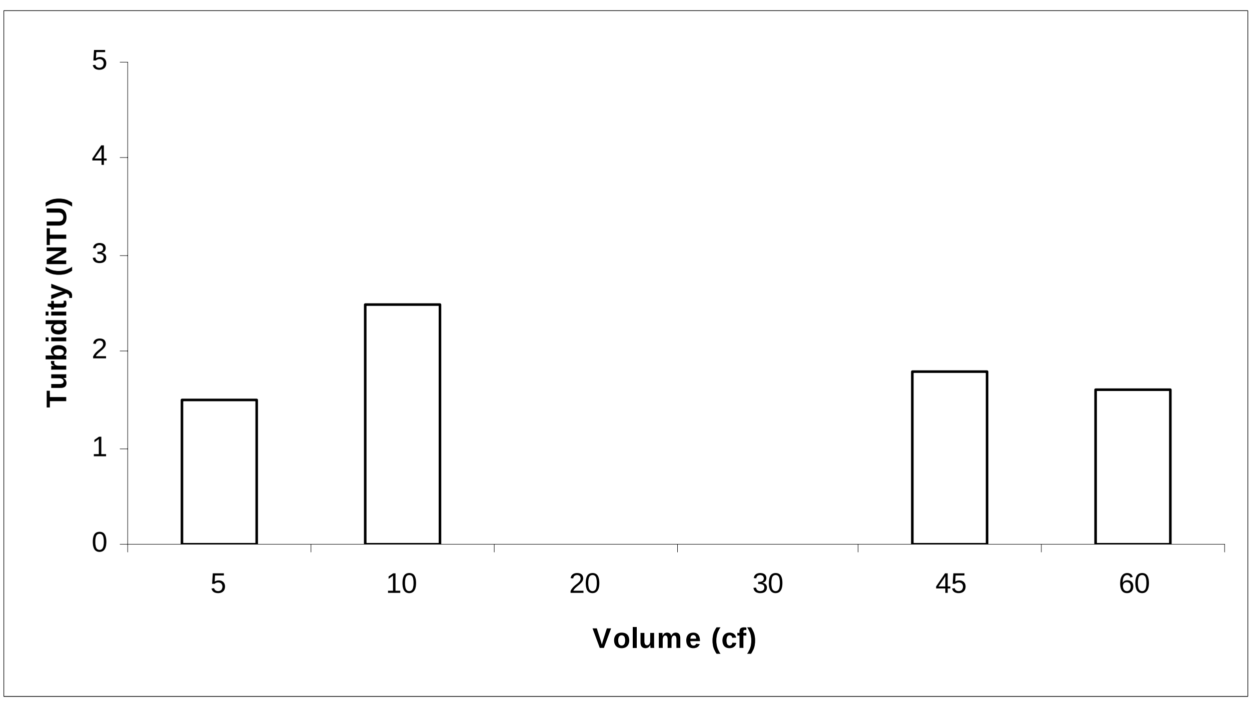

Figure 267 - Turbidity - Green Roof Samples - November 1, 2006

B.3.7 Lead

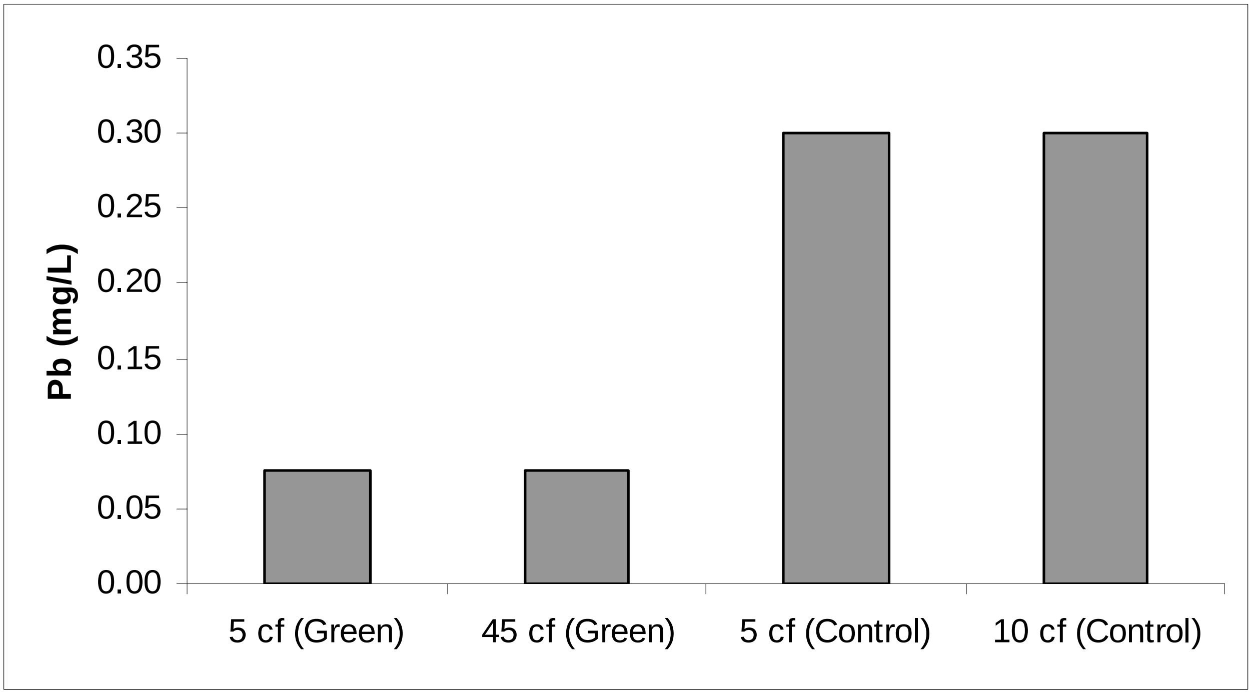

Figure 268 - Lead - November 1, 2006 Storm

B.3.8 Cadmium

The 5 cf and 45 cf samples from the green roof and the 5 cf and 10 cf samples from the control roof were tested for cadmium, but the readings fell below the detectible limits. These samples have a concentration of 0 mg/L Cd.

B.3.9 Zinc

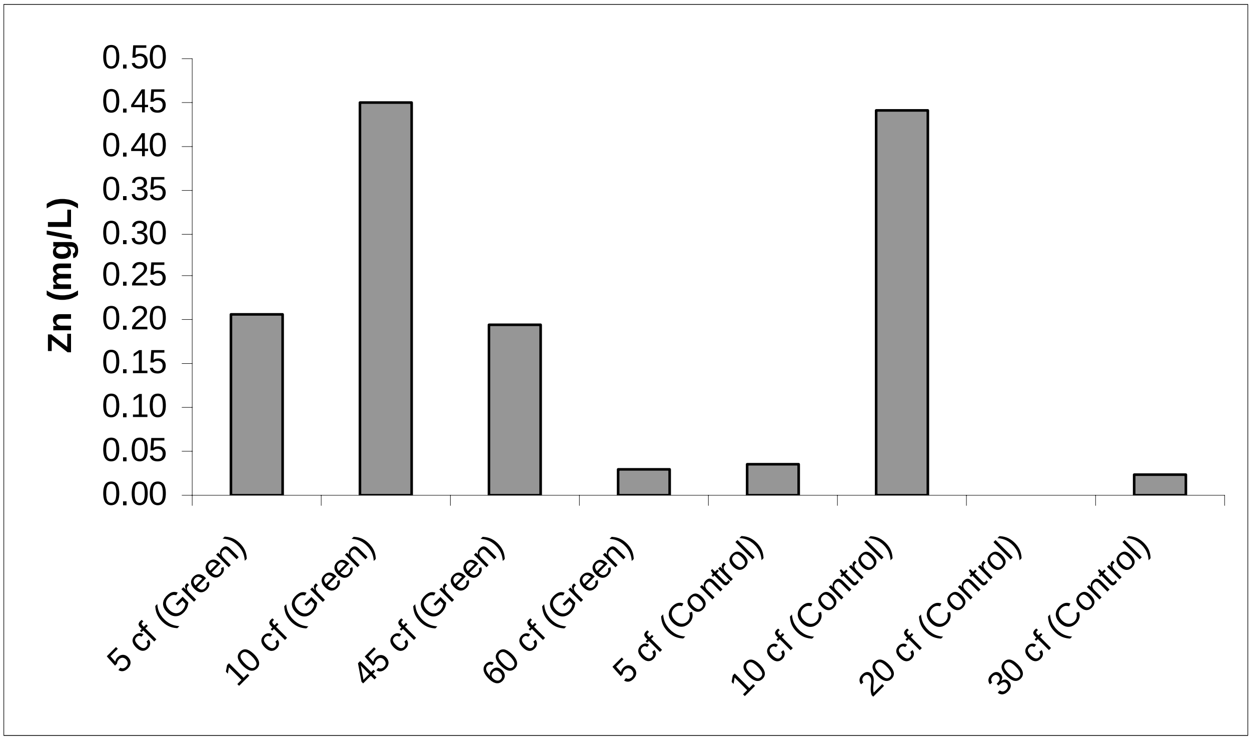

Figure 269 - Zinc - November 1, 2006 Storm

B.4 NOVEMBER 11, 2006 STORM

B.4.1 Phosphorus

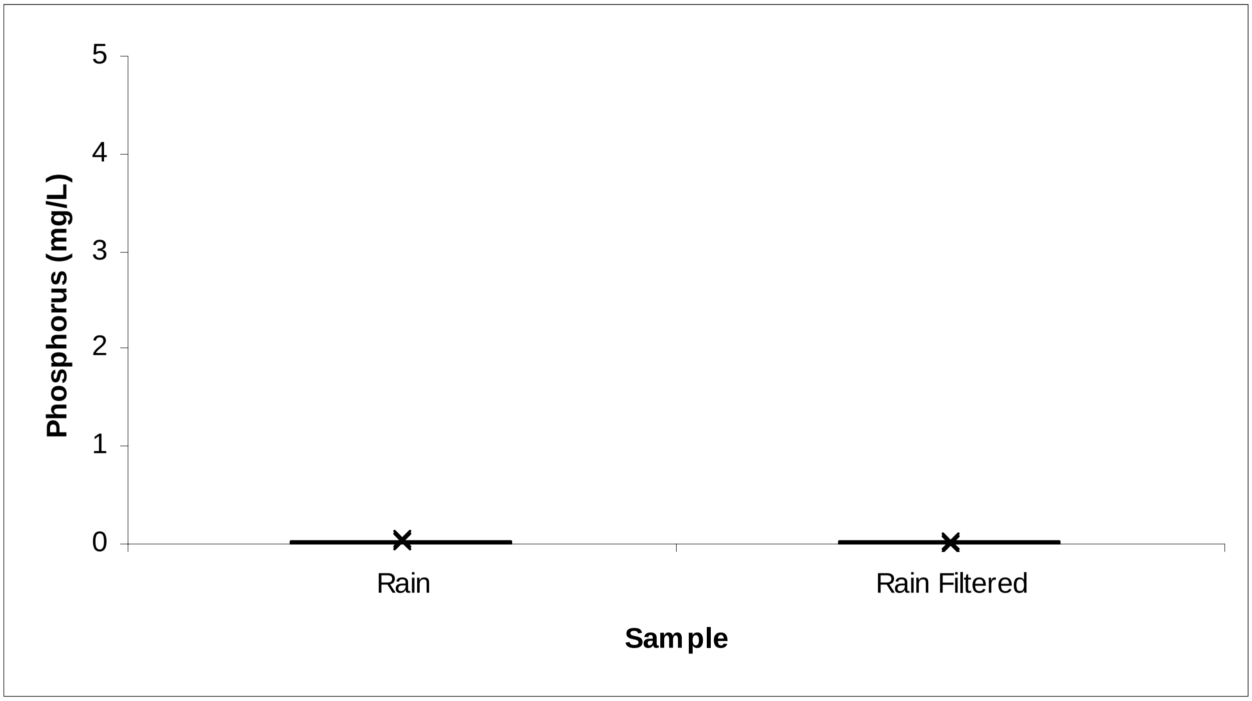

Figure 270 - Phosphorus - November 11, 2006 Storm

B.4.2 Sulfate

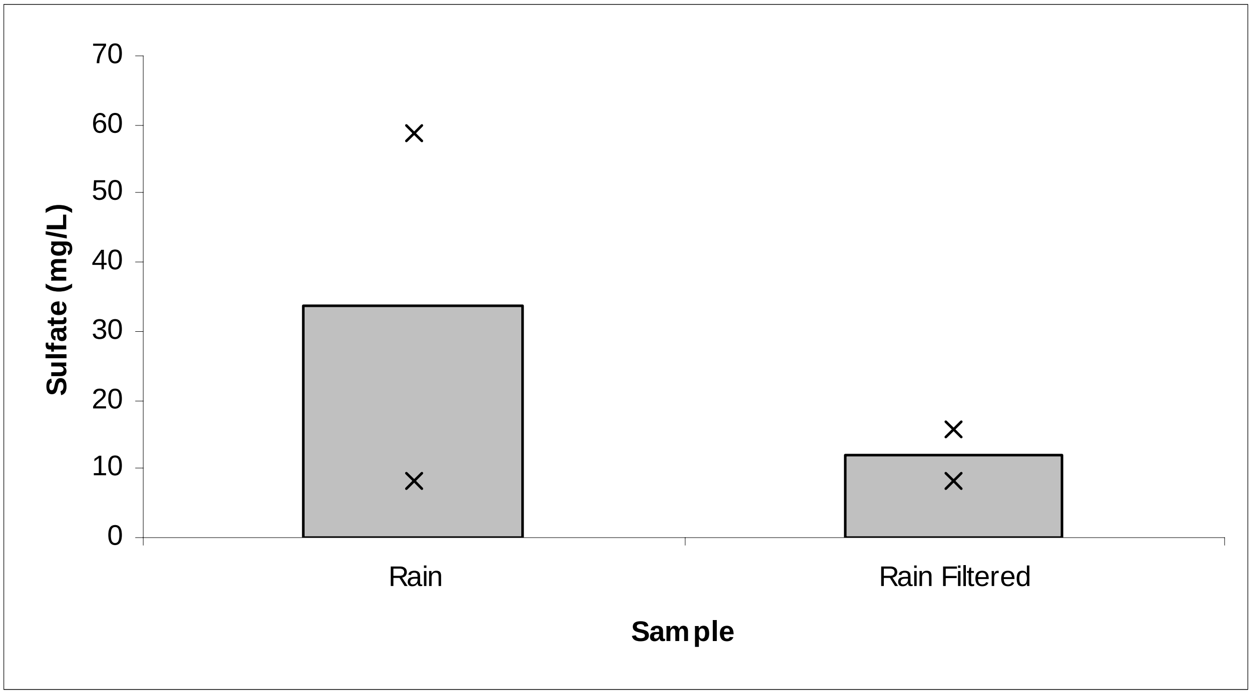

Figure 271 - Sulfate - November 11, 2006 Storm

B.4.3 COD

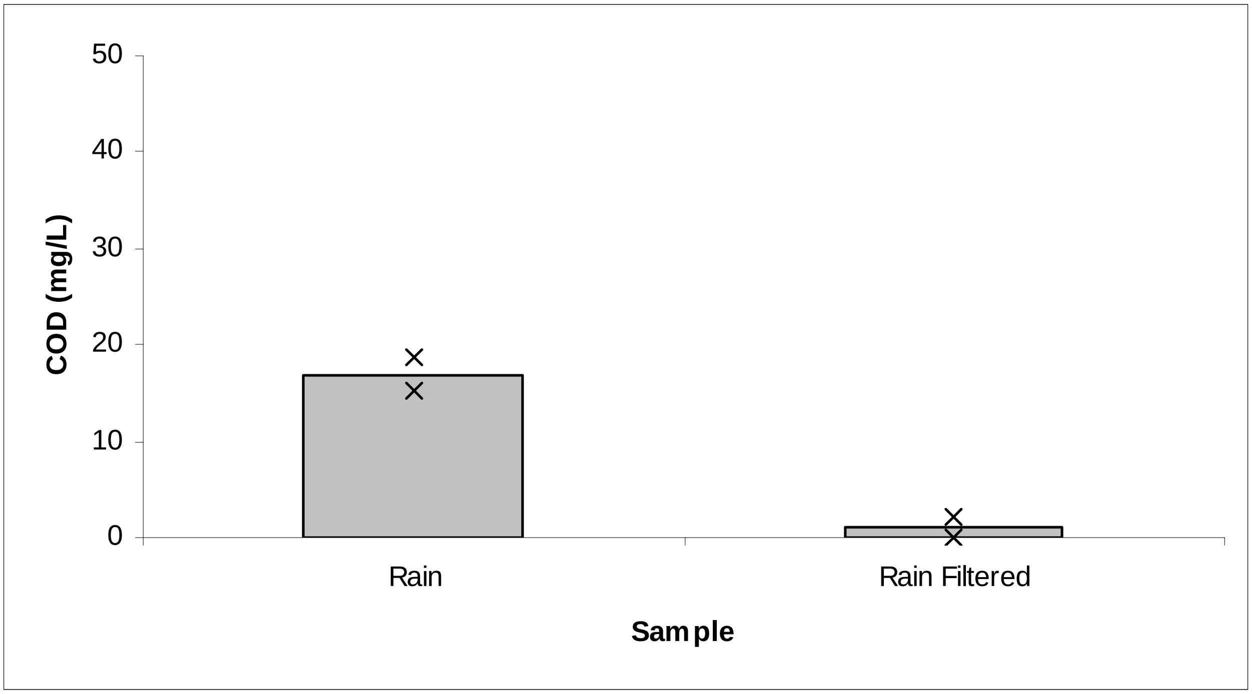

Figure 272 - COD - November 11, 2006 Storm

B.4.4 pH

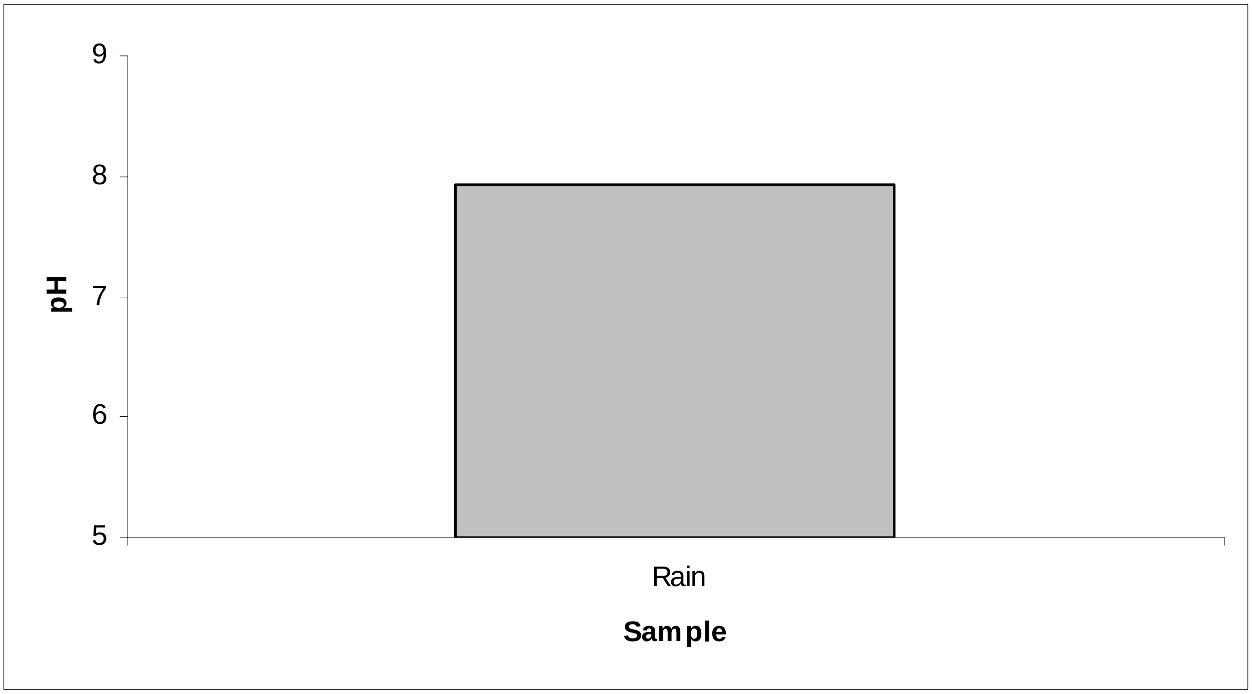

Figure 273 - pH - November 11, 2006 Storm

B.4.5 Turbidity

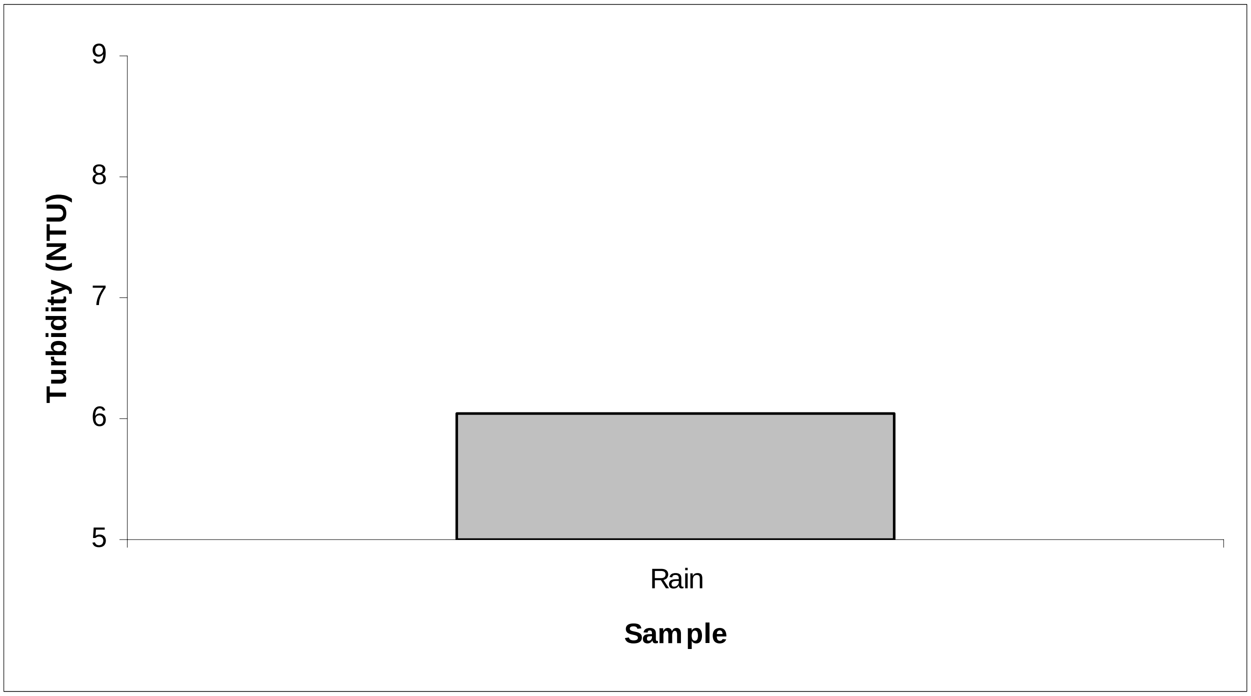

Figure 274 - Turbidity - November 11, 2006 Storm

B.4.6 Lead

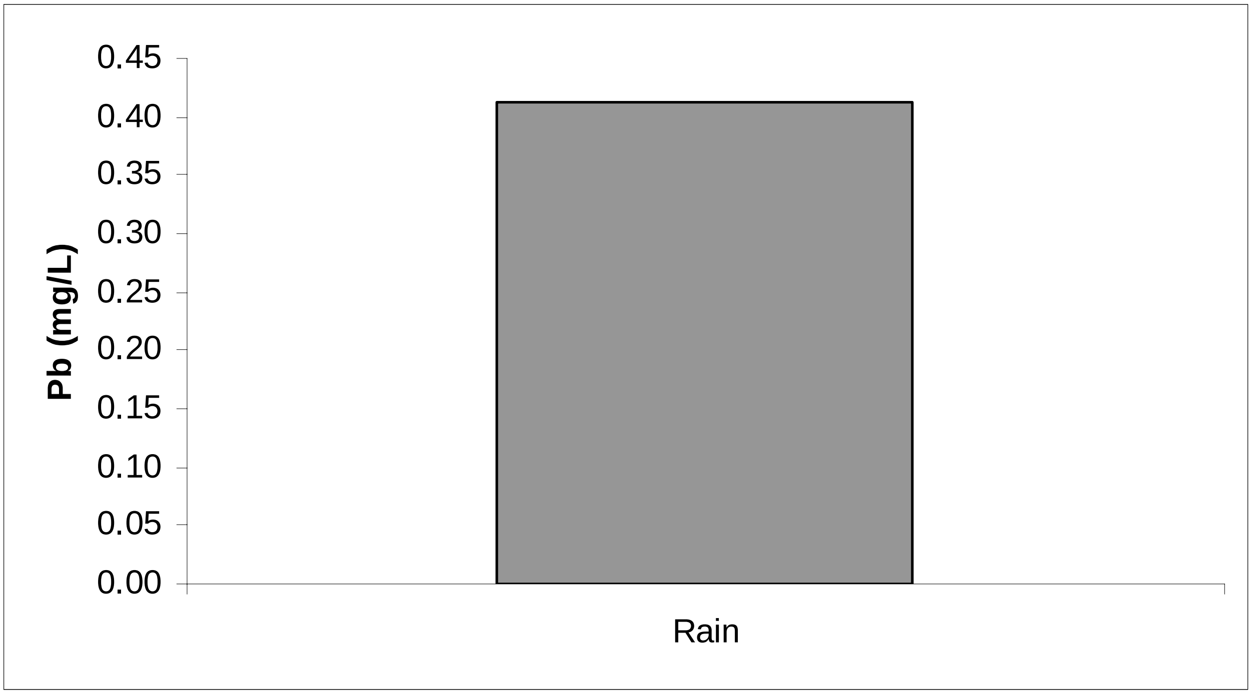

Figure 275 - Lead - November 11, 2006 Storm

B.4.7 Cadmium

The rainwater sample was tested for cadmium, but the readings fell below the detectible limits. The sample has a concentration of 0 mg/L Cd.

B.4.8 Zinc

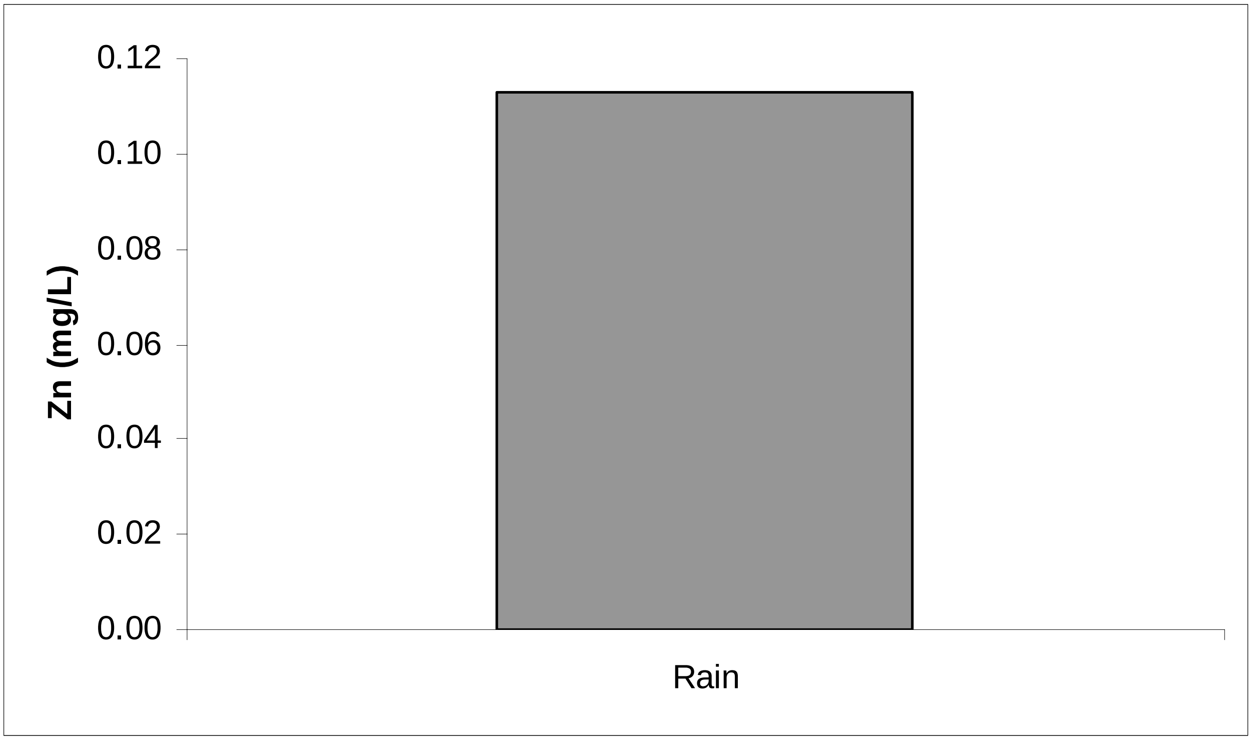

Figure 276 - Zinc - November 11, 2006 Storm

B.5 NOVEMBER 15, 2006 STORM

B.5.1 pH

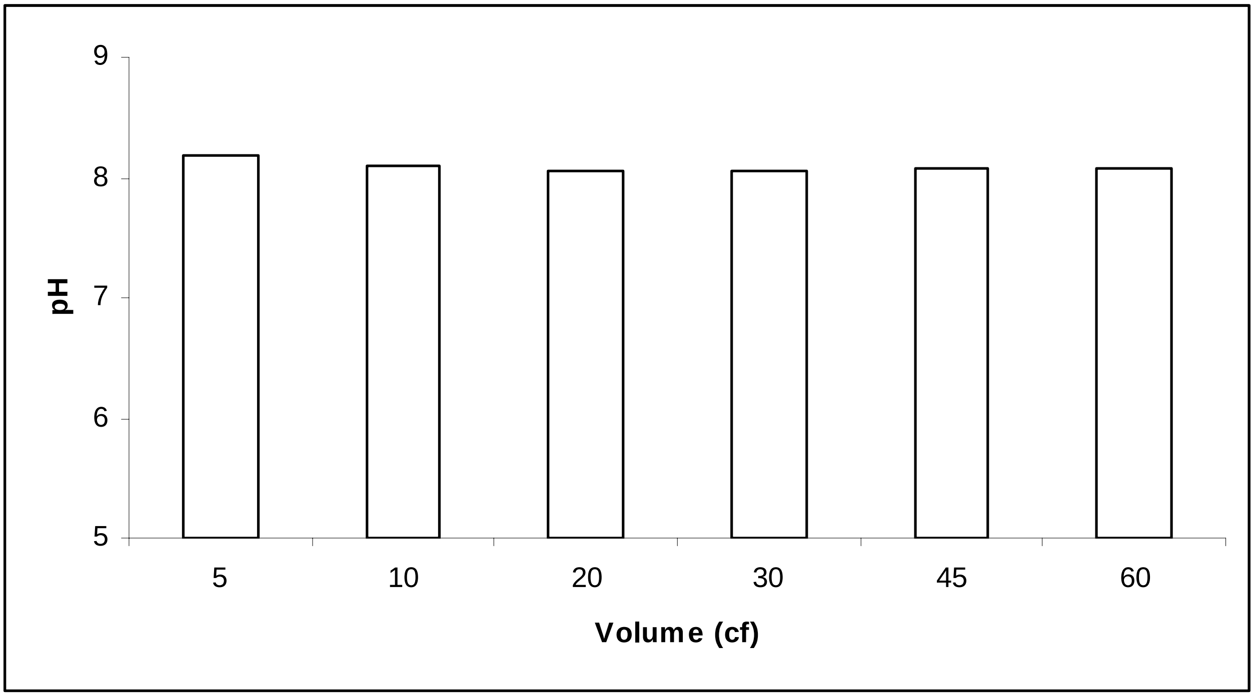

Figure 277 - pH - Control Roof Samples - November 15, 2006 Storm

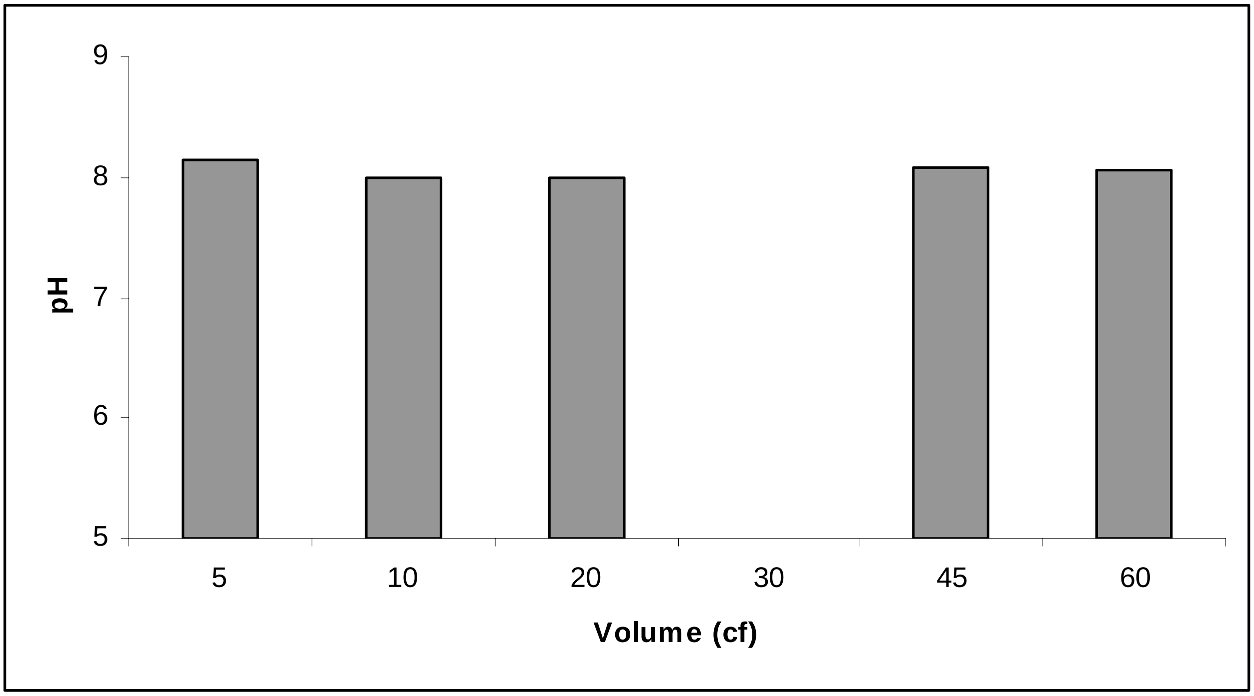

Figure 278 - pH - Green Roof Samples - November 15, 2006 Storm

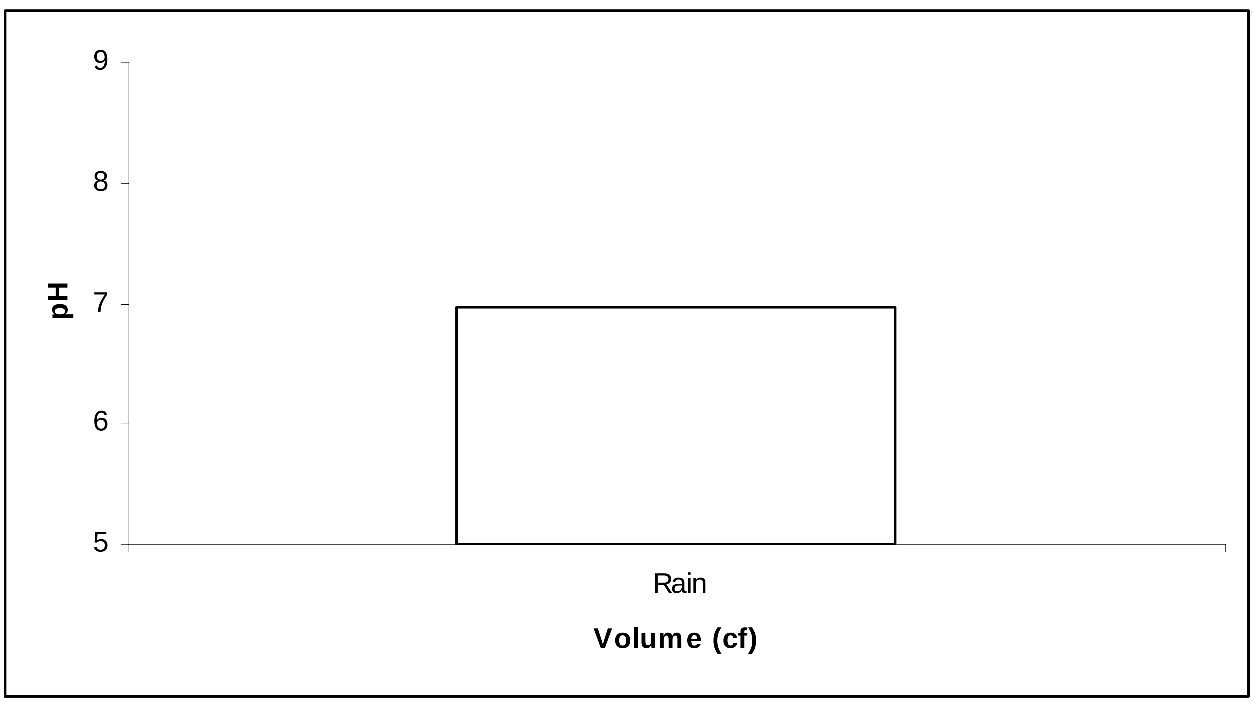

Figure 279 - pH - Rainwater Sample - November 15, 2006 Storm

B.5.2 Turbidity

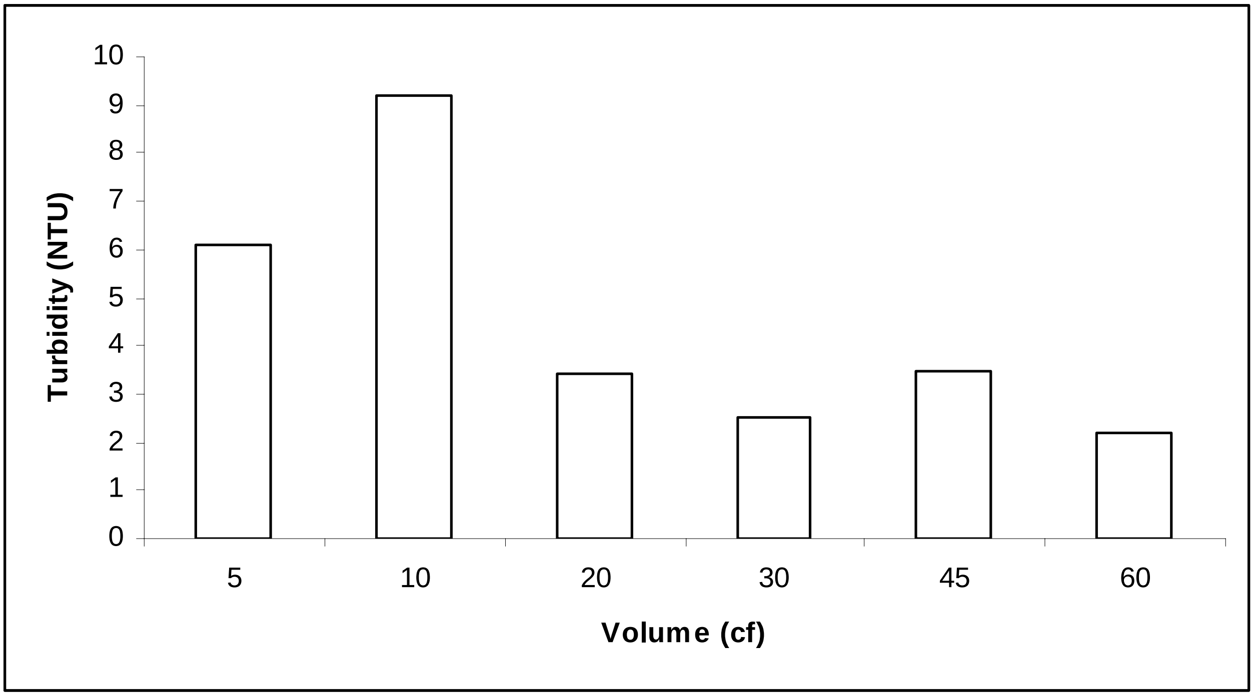

Figure 280 - Turbidity - Control Roof Samples - November 15, 2006 Storm

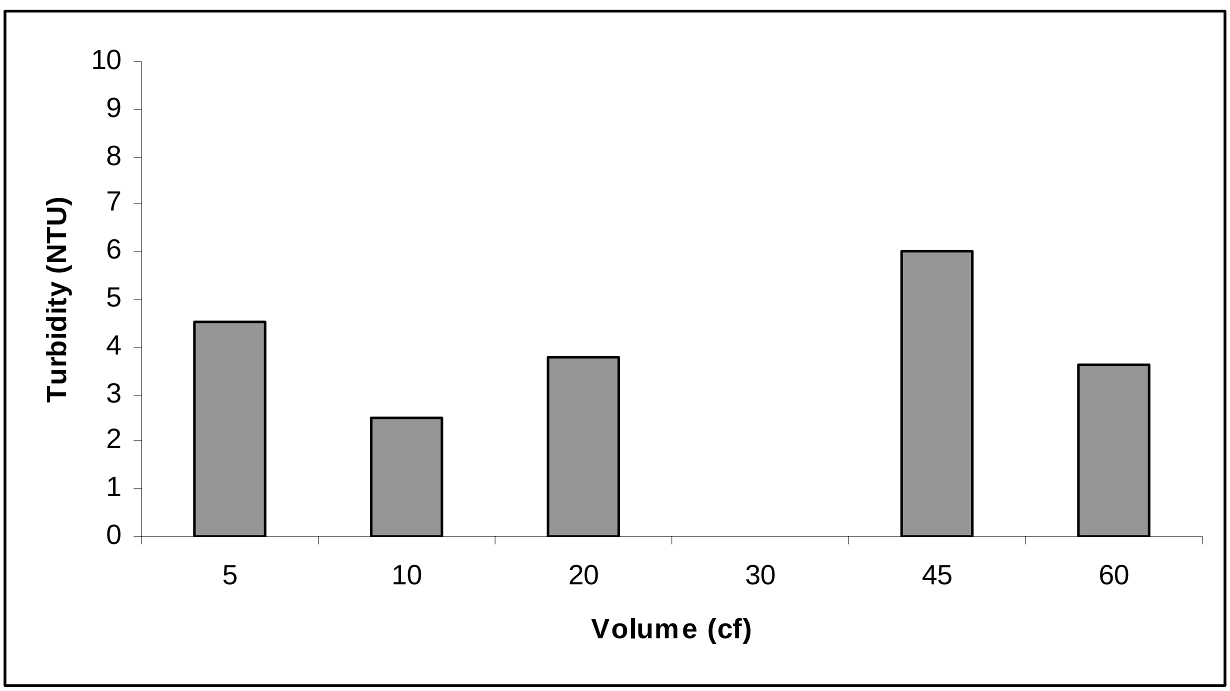

Figure 281 - Turbidity - Green Roof Samples - November 15, 2006 Storm

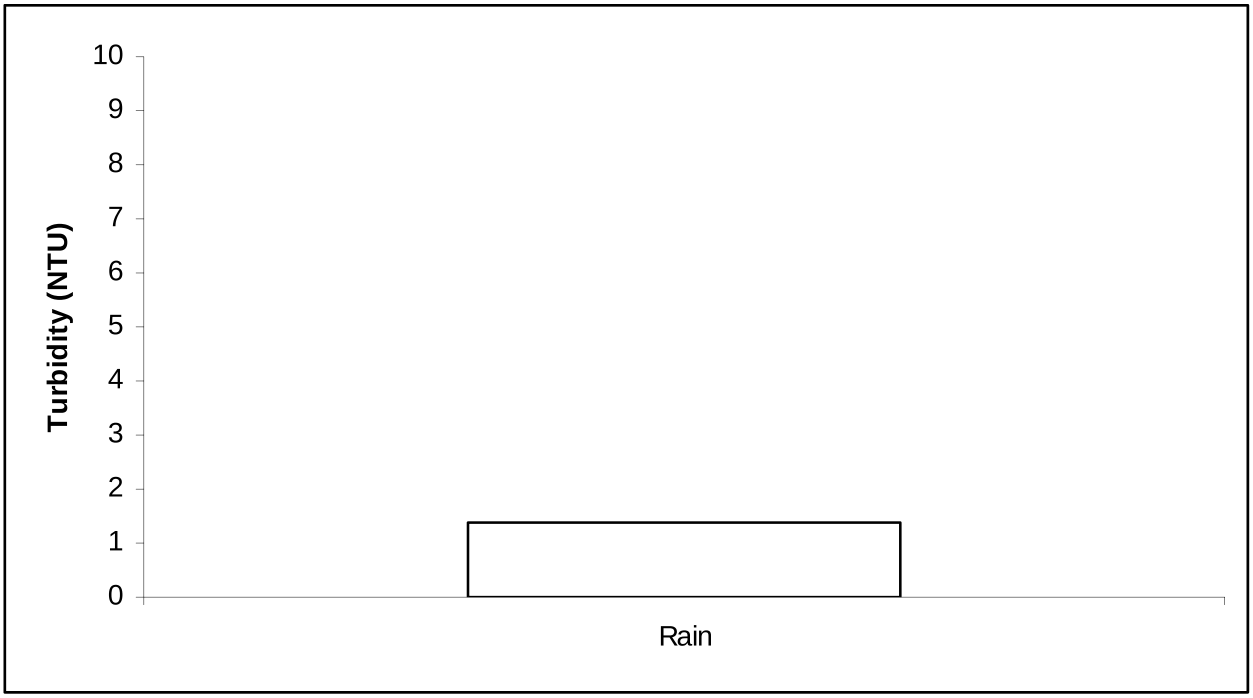

Figure 282 - Turbidity - Rainwater Sample - November 15, 2006 Storm

B.6 DECEMBER 1, 2006 STORM

B.6.1 Sulfate

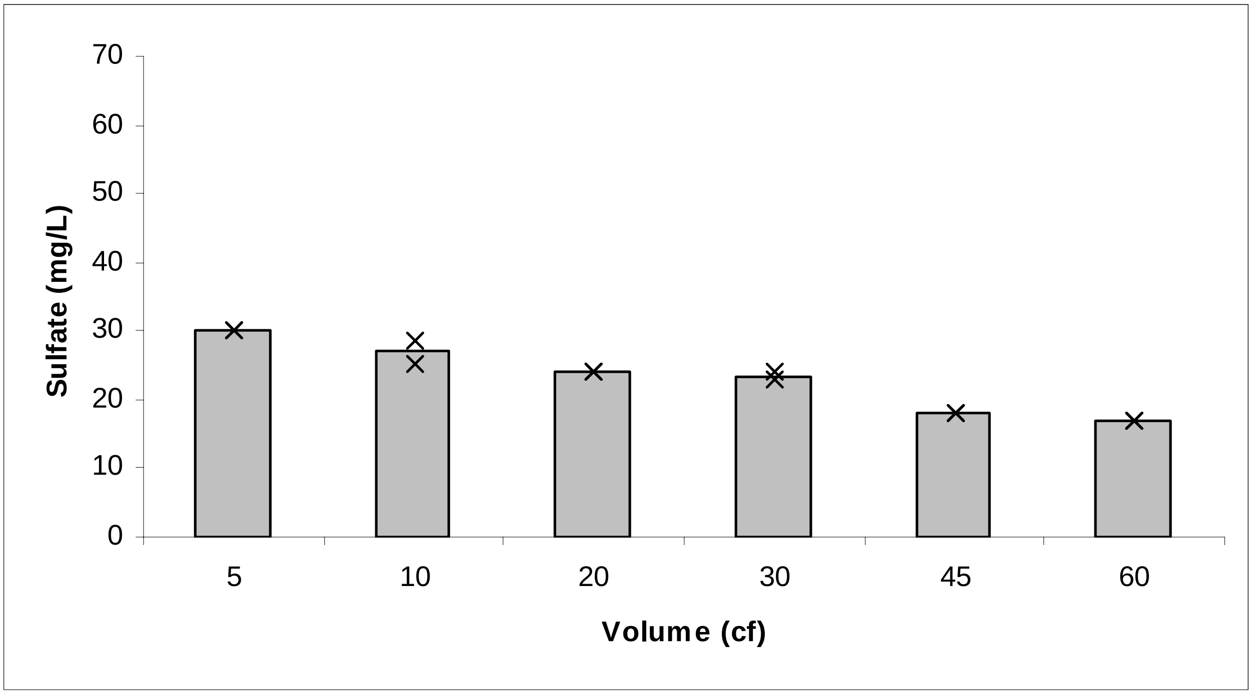

Figure 283 - Sulfate - Unfiltered Control Roof Samples - December 1, 2006 Storm

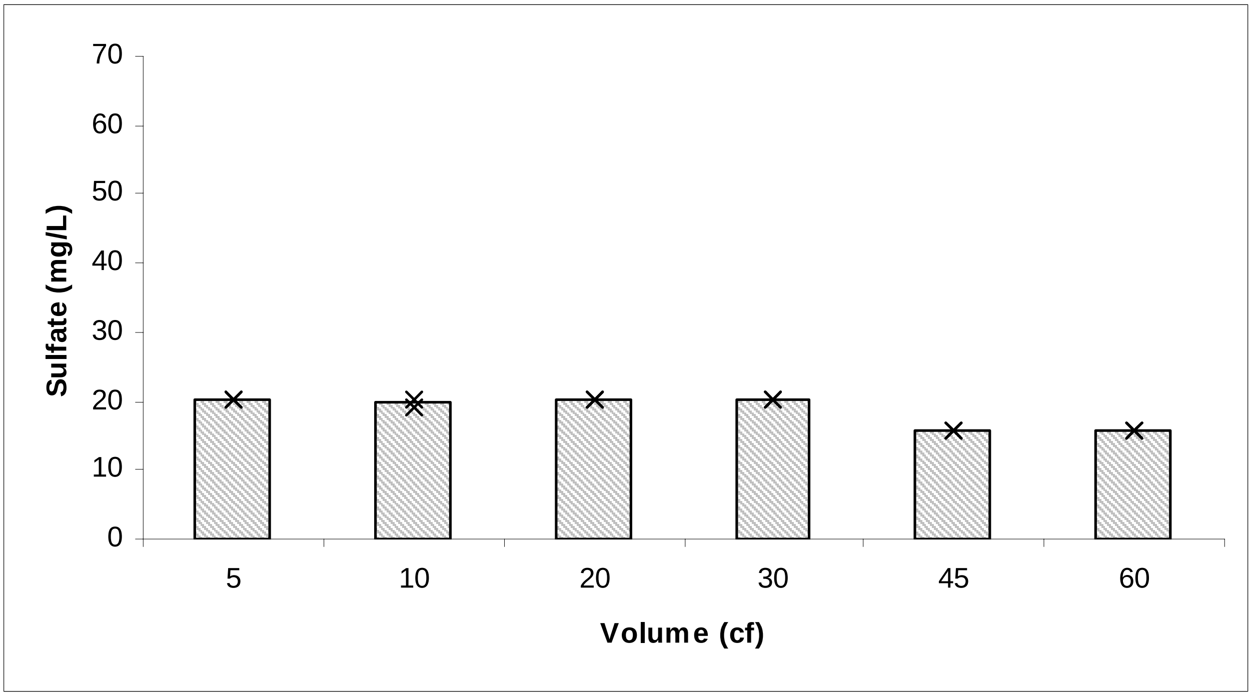

Figure 284 - Sulfate - Filtered Control Roof Samples - December 1, 2006 Storm

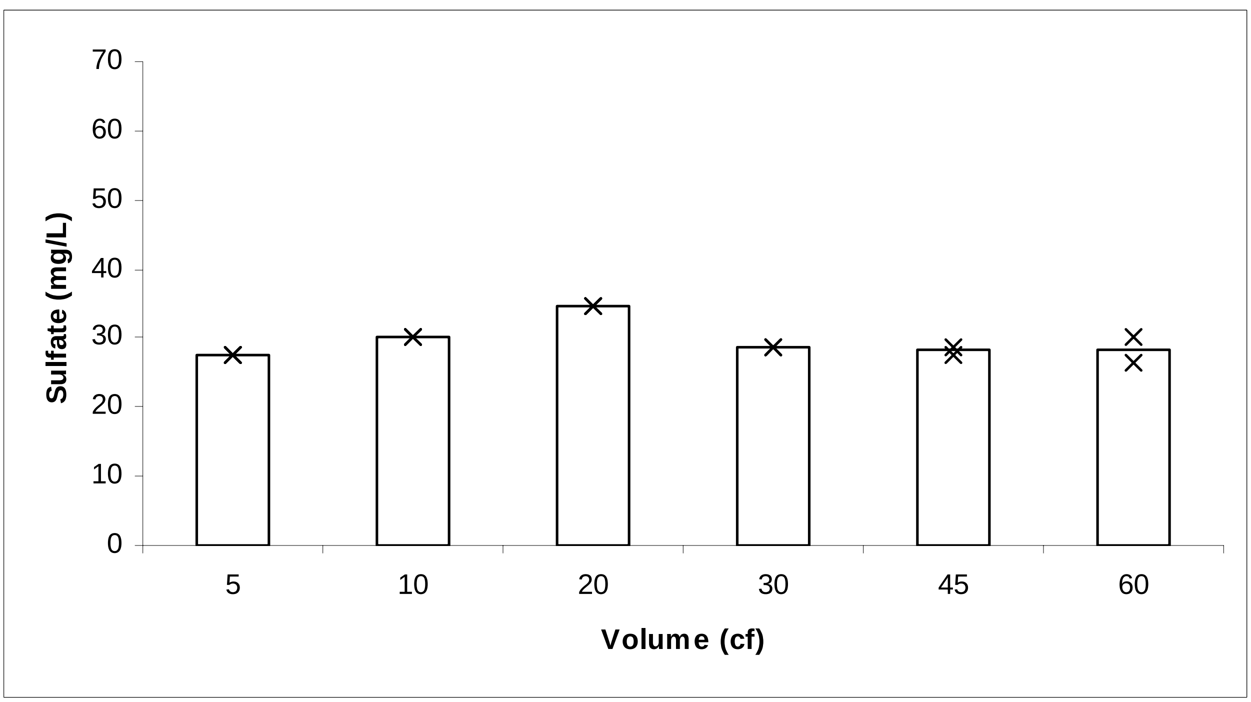

Figure 285 - Sulfate - Unfiltered Green Roof Samples - December 1, 2006 Storm

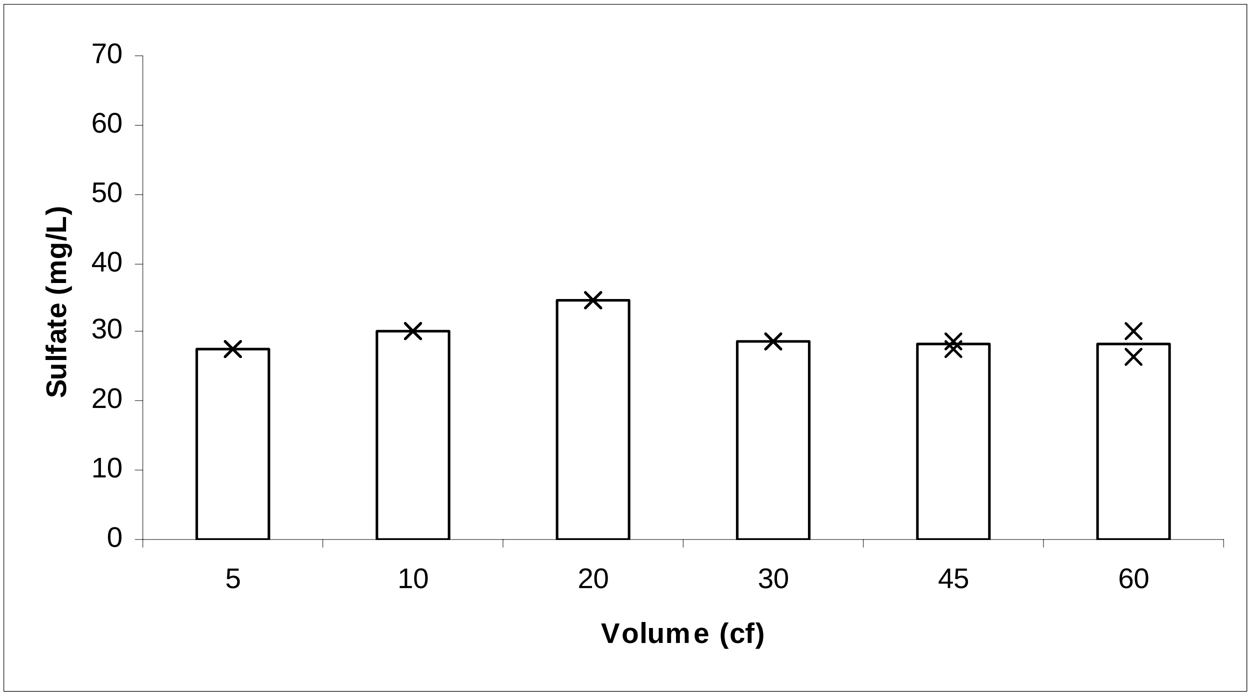

Figure 286 - Sulfate - Filtered Green Roof Samples - December 1, 2006 Storm

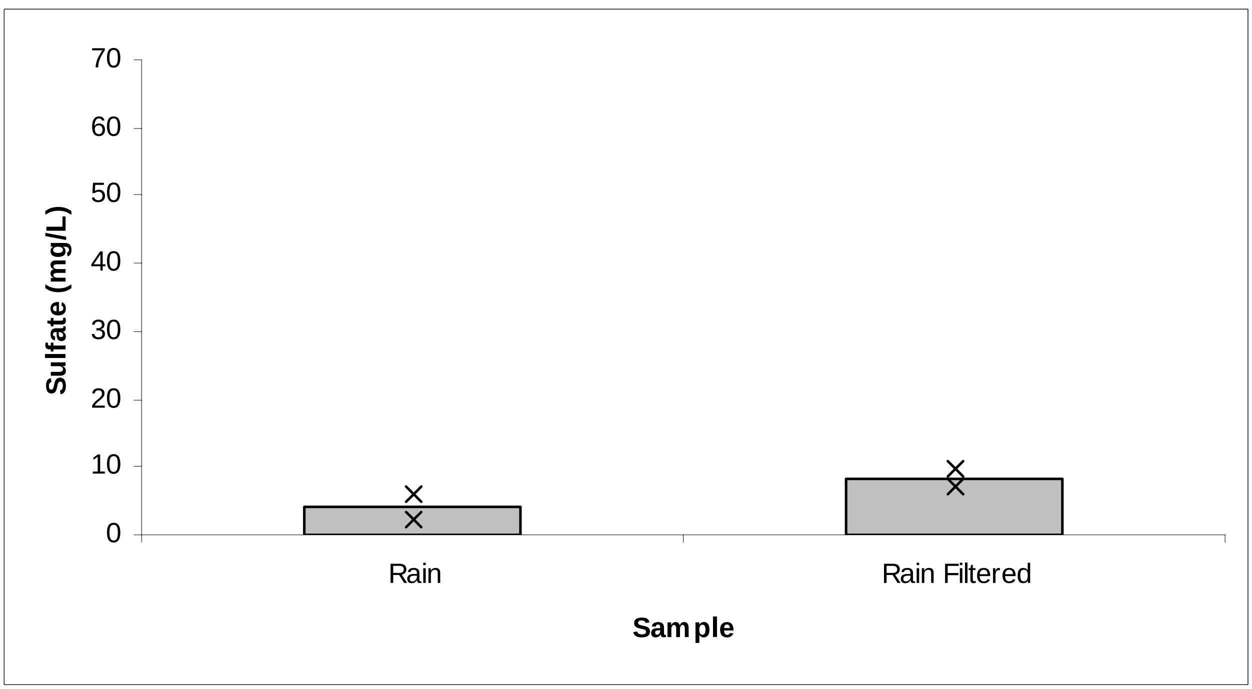

Figure 287 - Sulfate - Rainwater Samples - December 1, 2006 Storm

B.6.2 Nitrogen

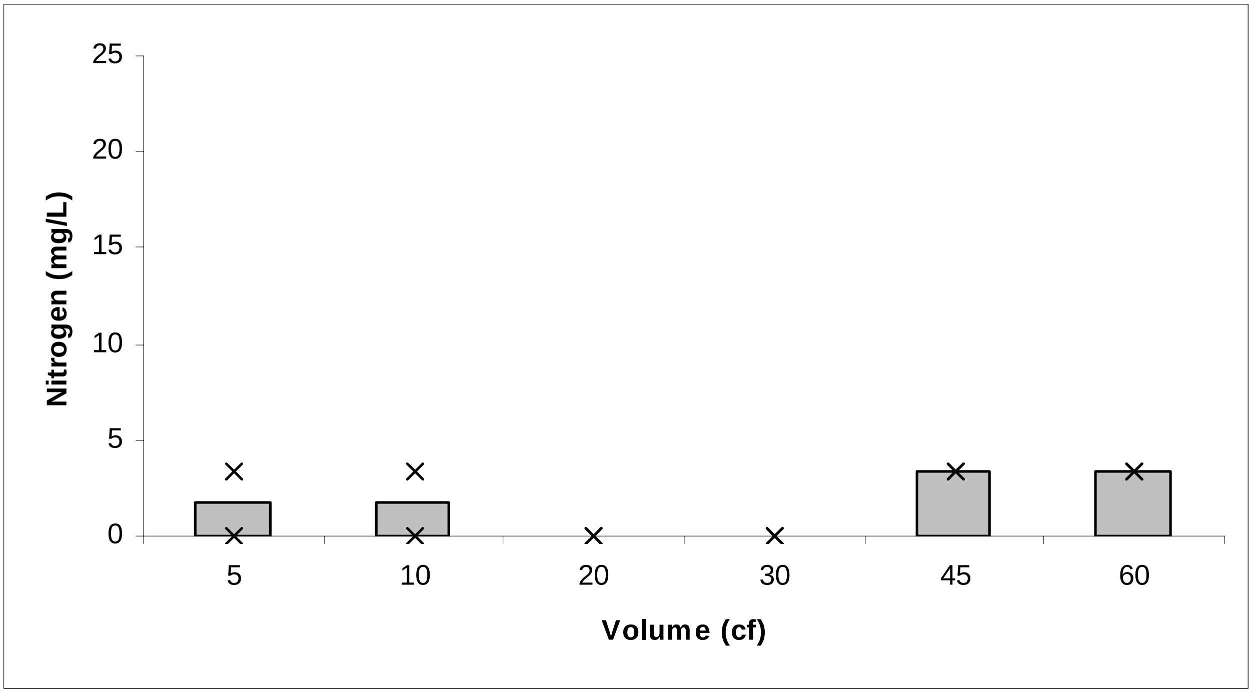

Figure 288 - Nitrogen - Unfiltered Control Roof Samples - December 1, 2006 Storm

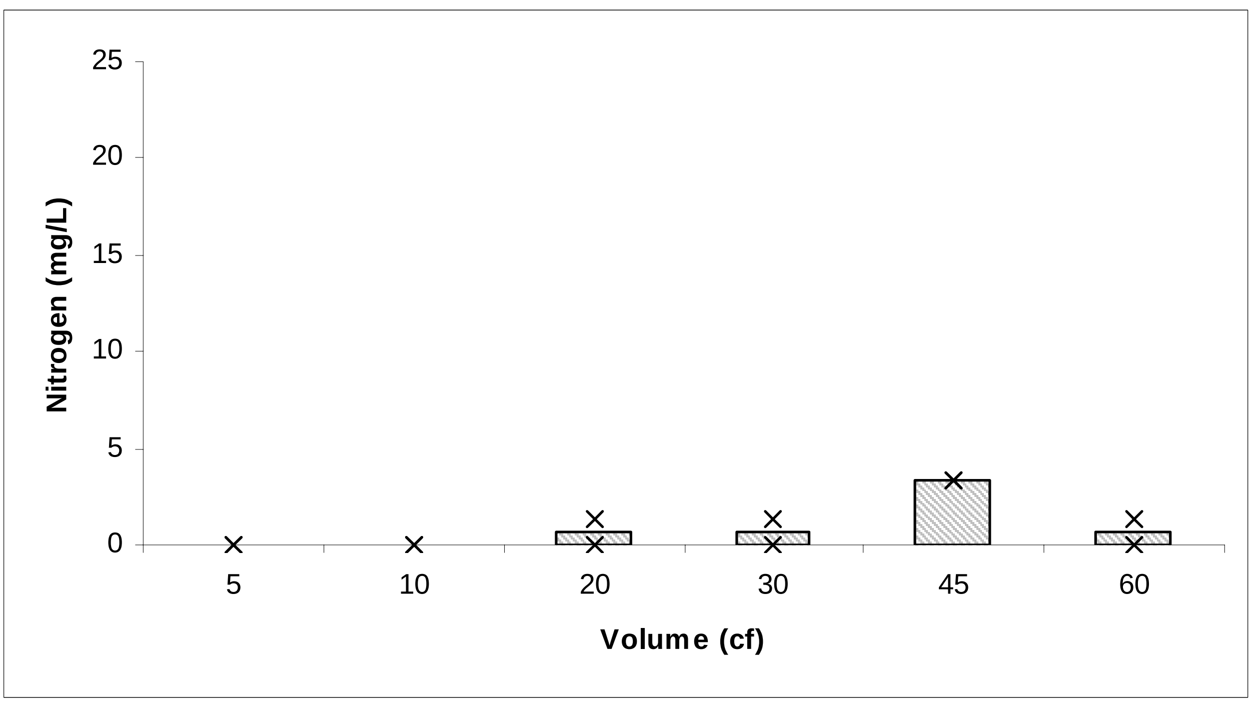

Figure 289 - Nitrogen - Filtered Control Roof Samples - December 1, 2006 Storm

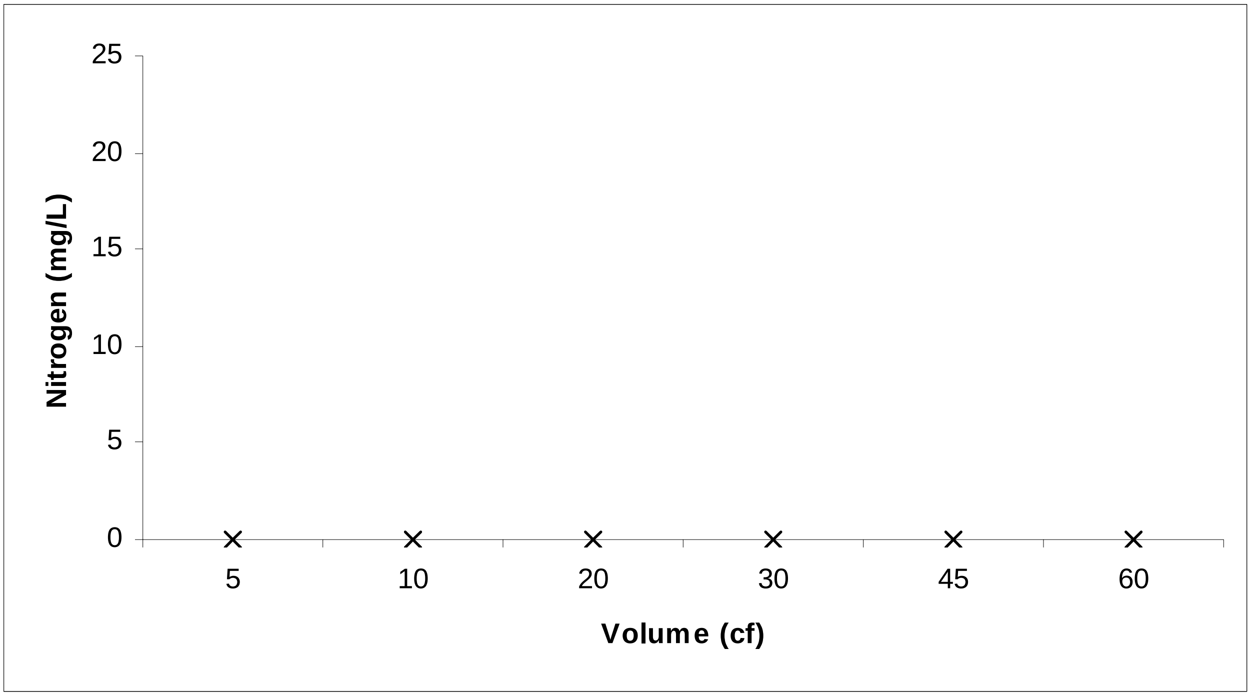

Figure 290 - Nitrogen - Unfiltered Green Roof Samples - December 1, 2006 Storm

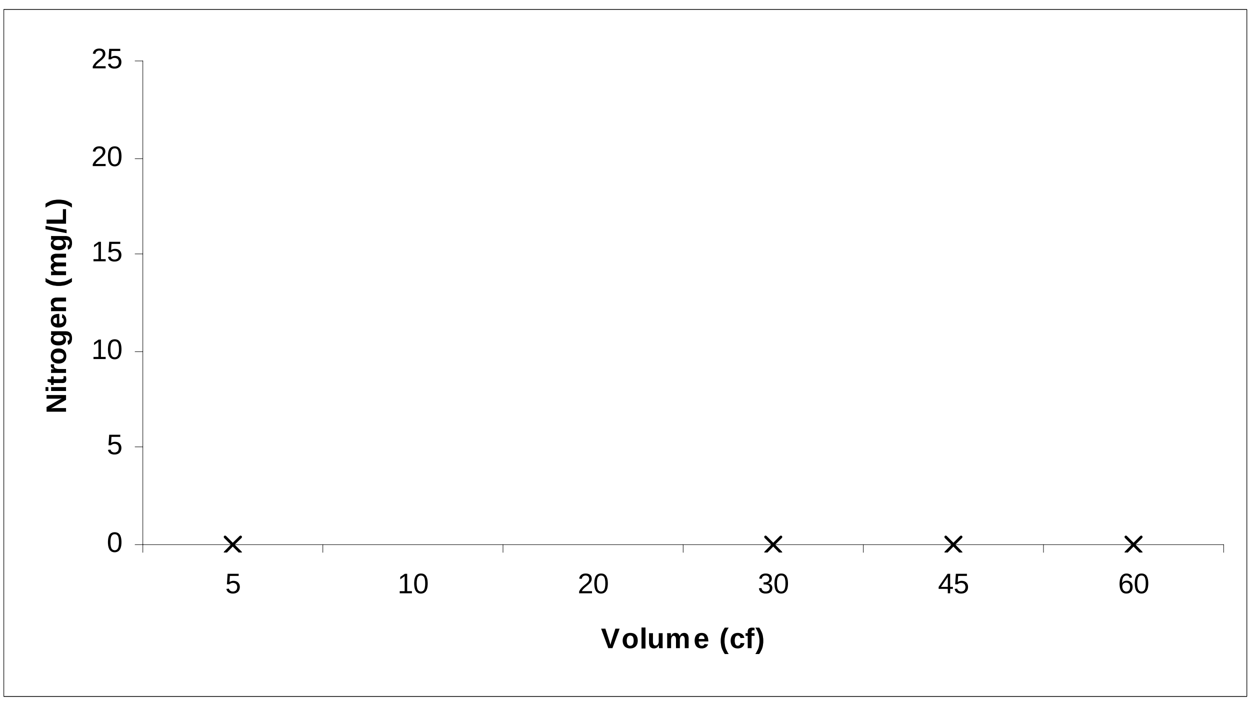

Figure 291 - Nitrogen - Filtered Green Roof Samples - December 1, 2006 Storm

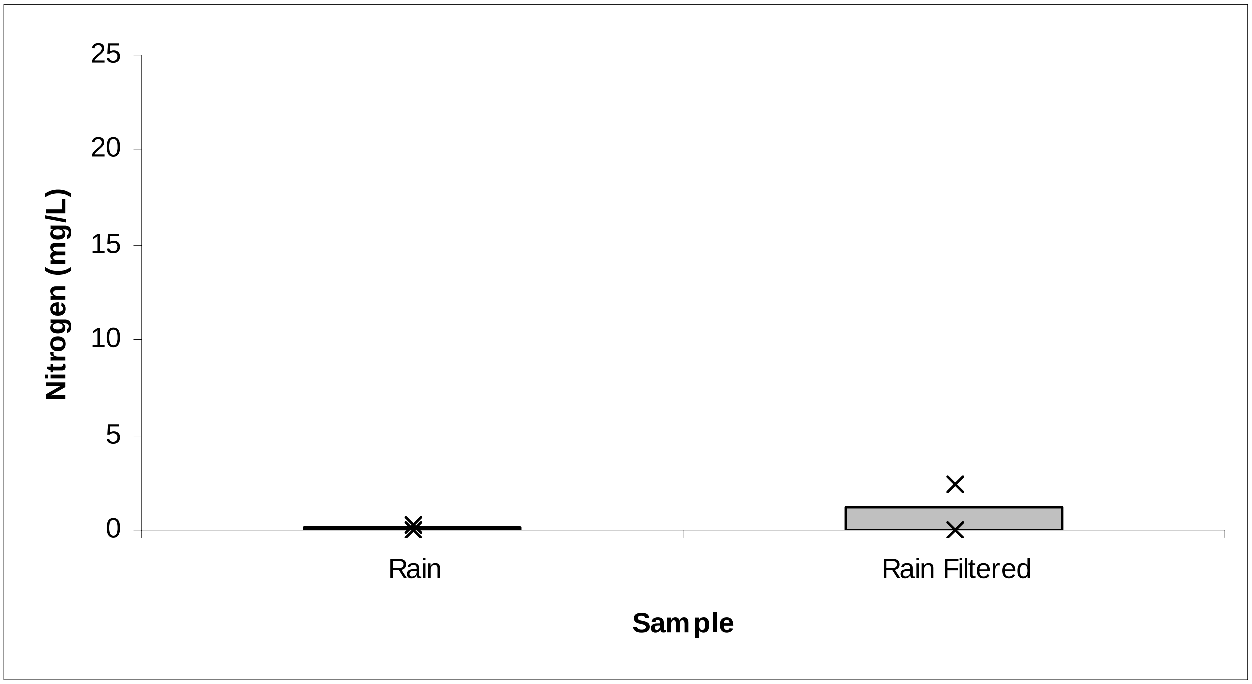

Figure 292 - Nitrogen - Rainwater Samples - December 1, 2006 Storm

B.6.3 COD

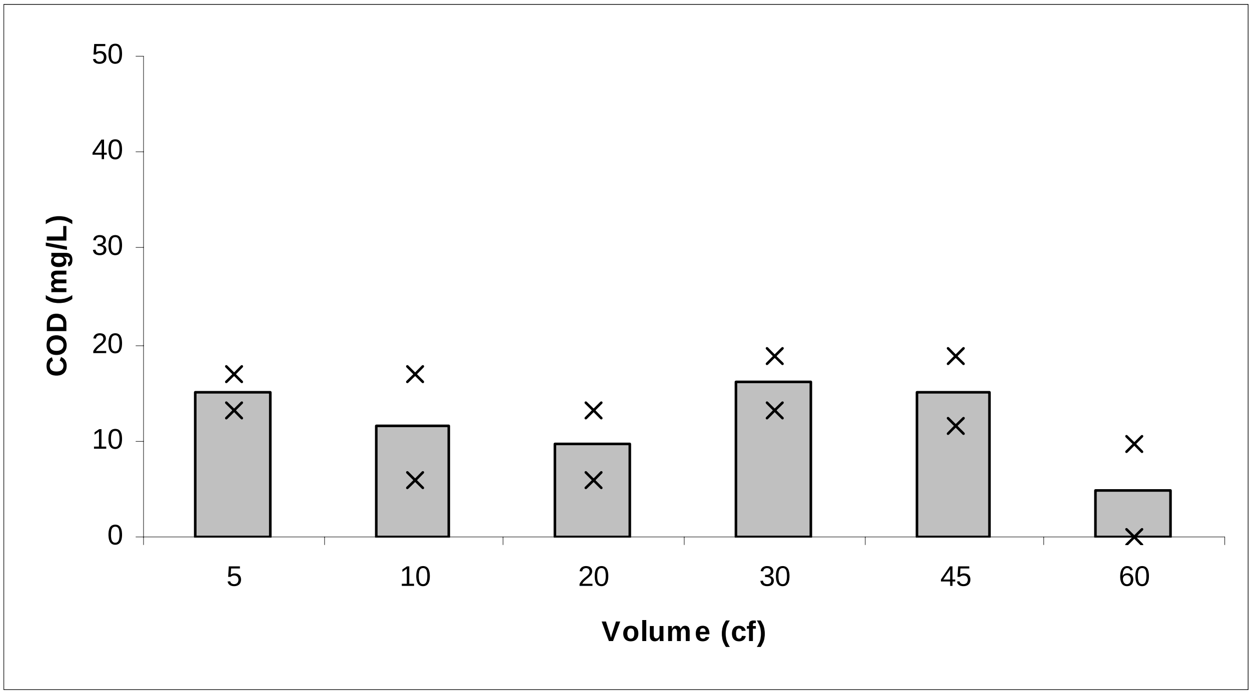

Figure 293 - COD - Unfiltered Control Roof Samples - December 1, 2006 Storm

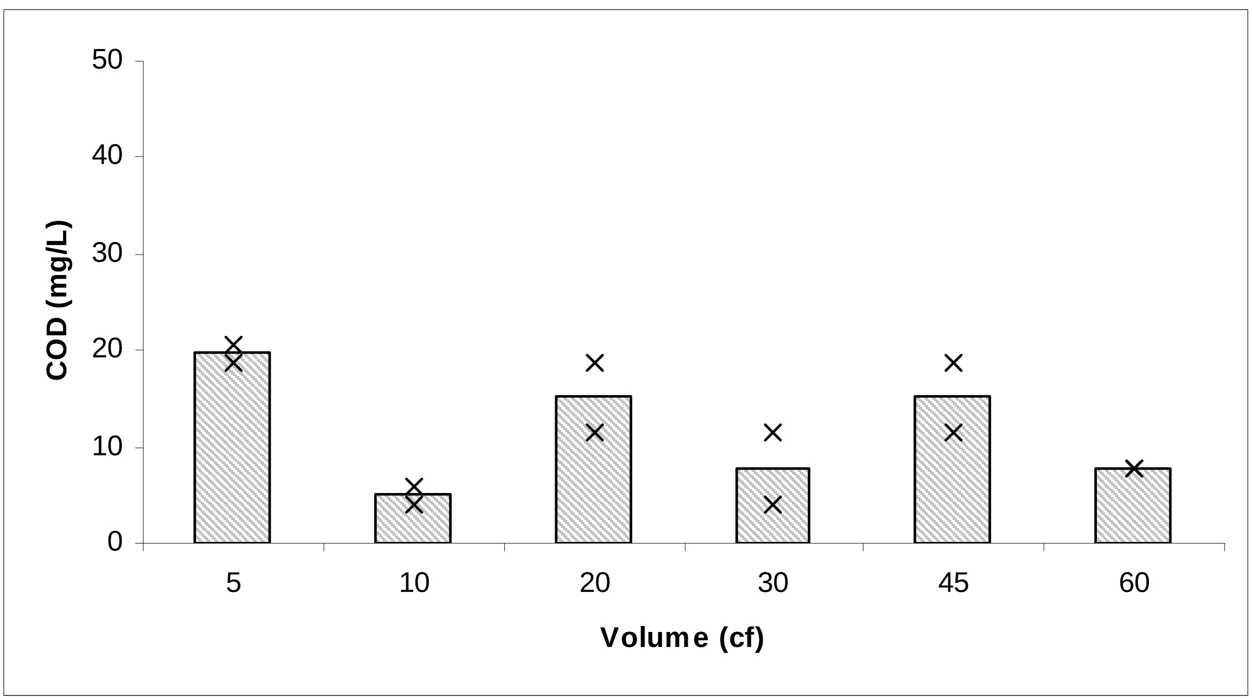

Figure 294 - COD - Filtered Control Roof Samples - December 1, 2006 Storm

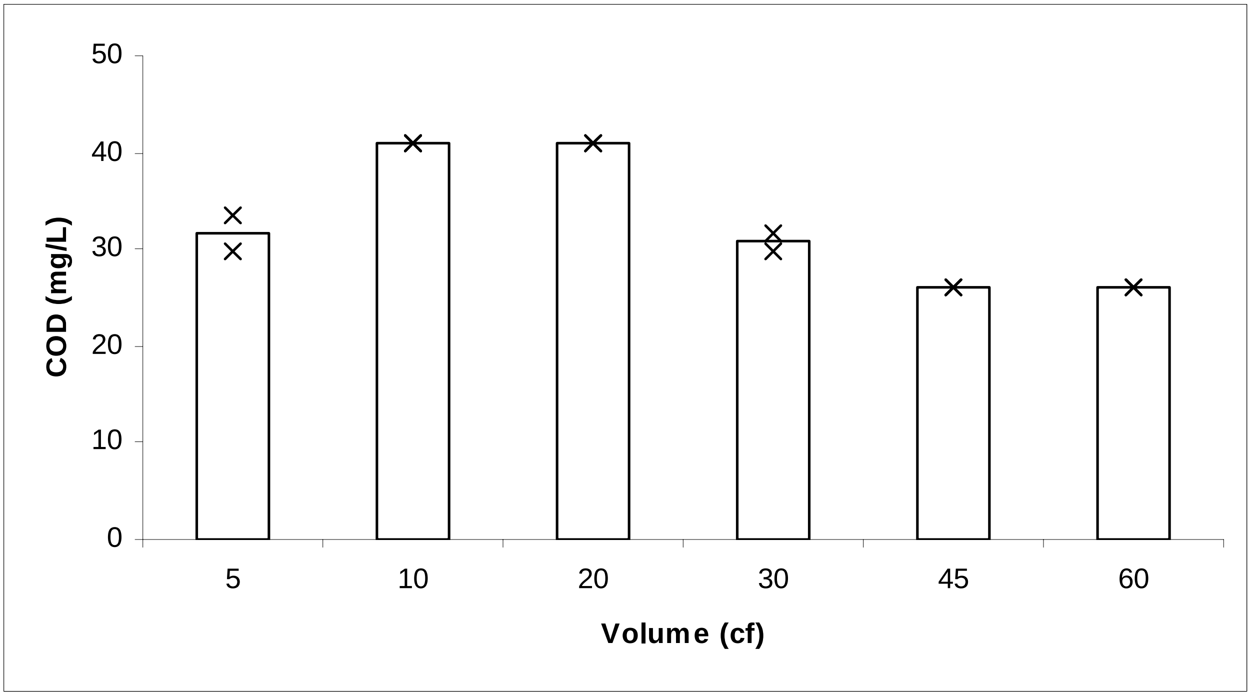

Figure 295 - COD - Unfiltered Green Roof Samples - December 1, 2006 Storm

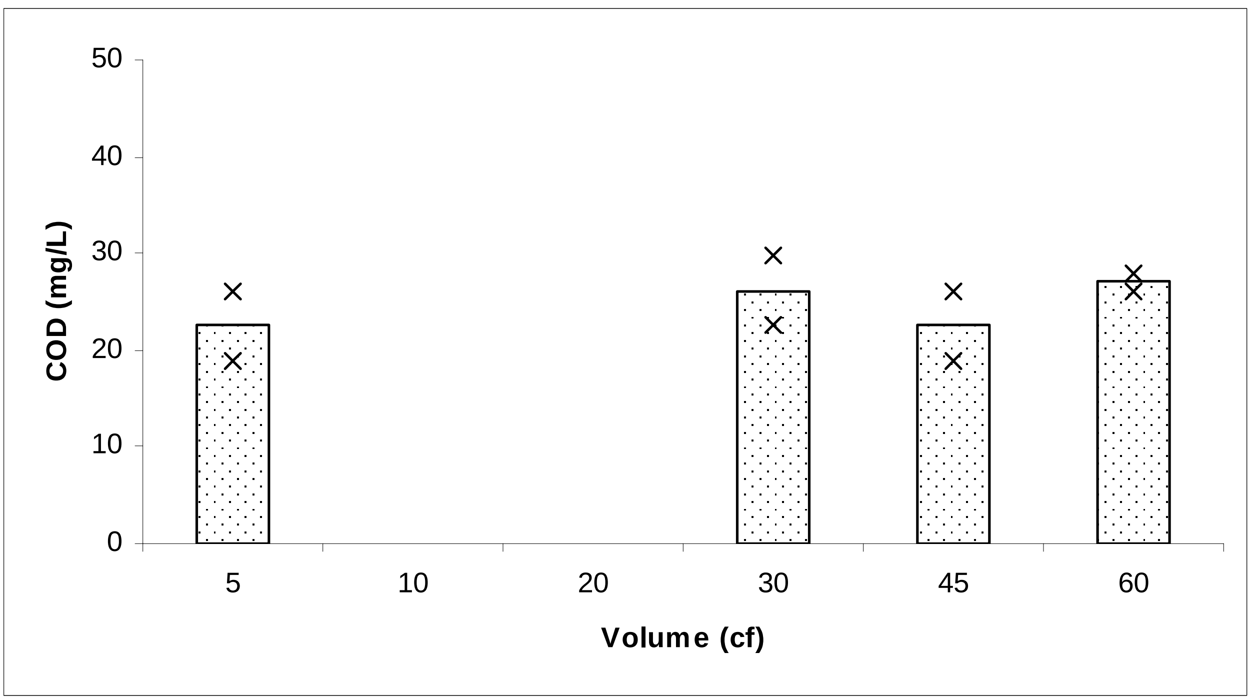

Figure 296 - COD - Filtered Green Roof Samples - December 1, 2006 Storm

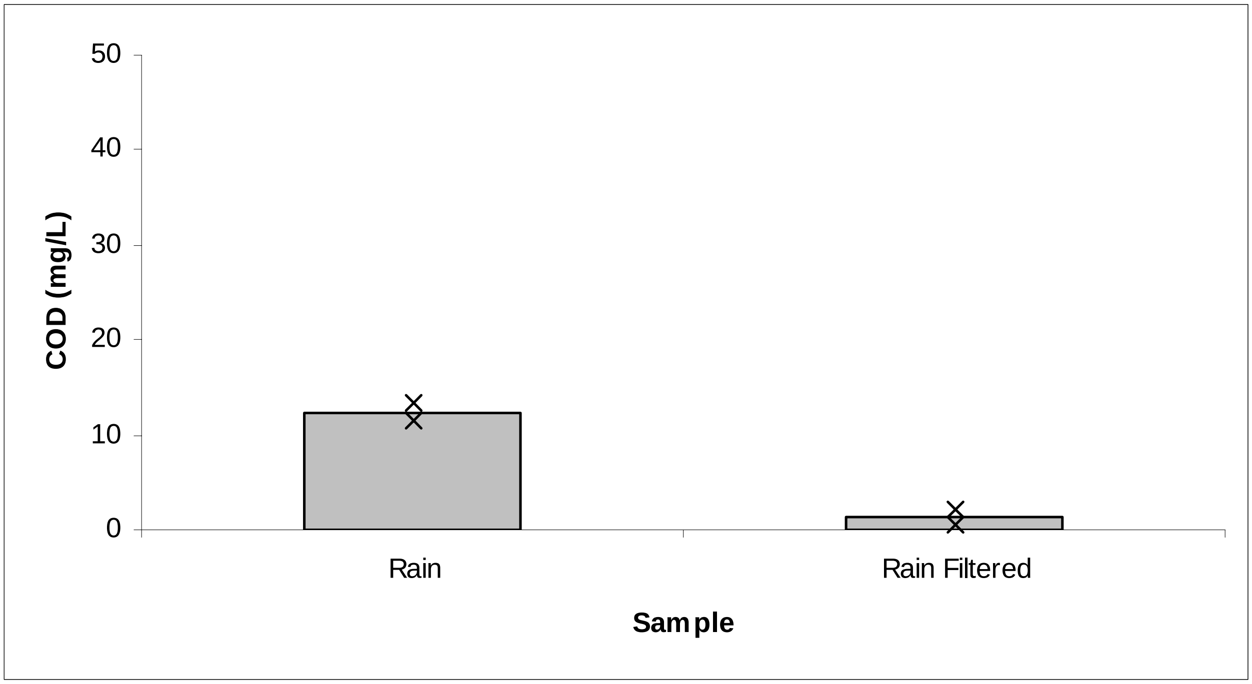

Figure 297 - COD - Rainwater Samples - December 1, 2006 Storm

B.6.4 pH

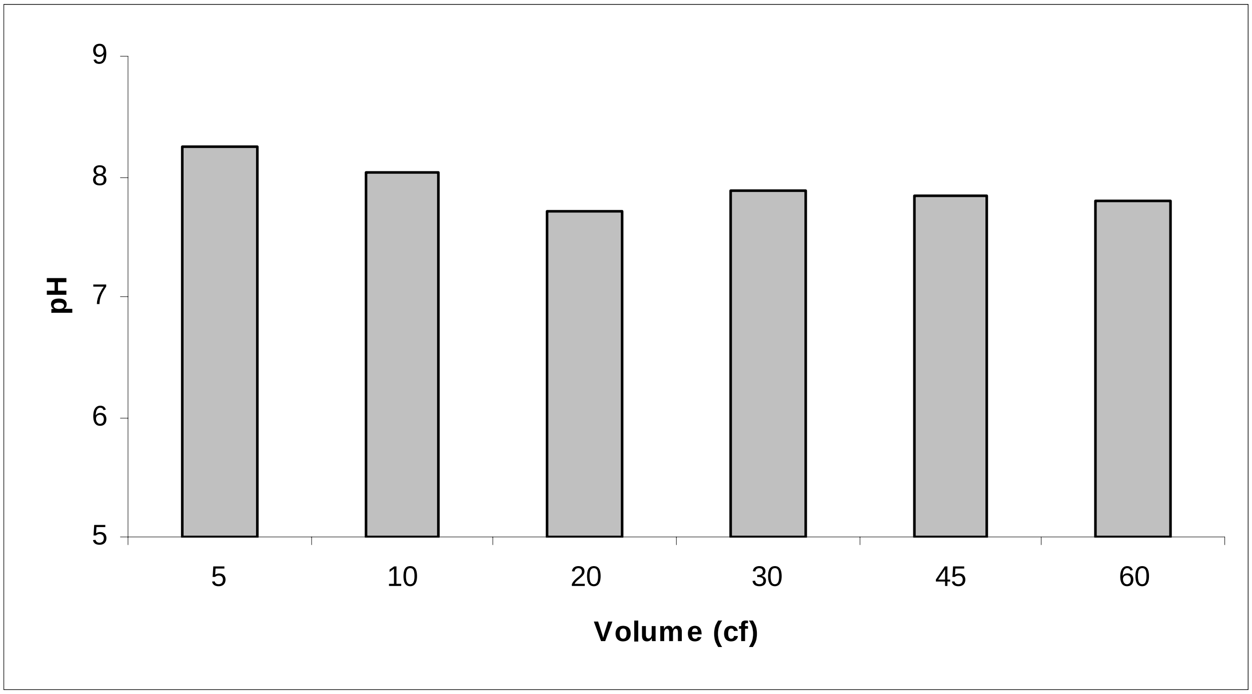

Figure 298 - pH - Control Roof Samples - December 1, 2006 Storm

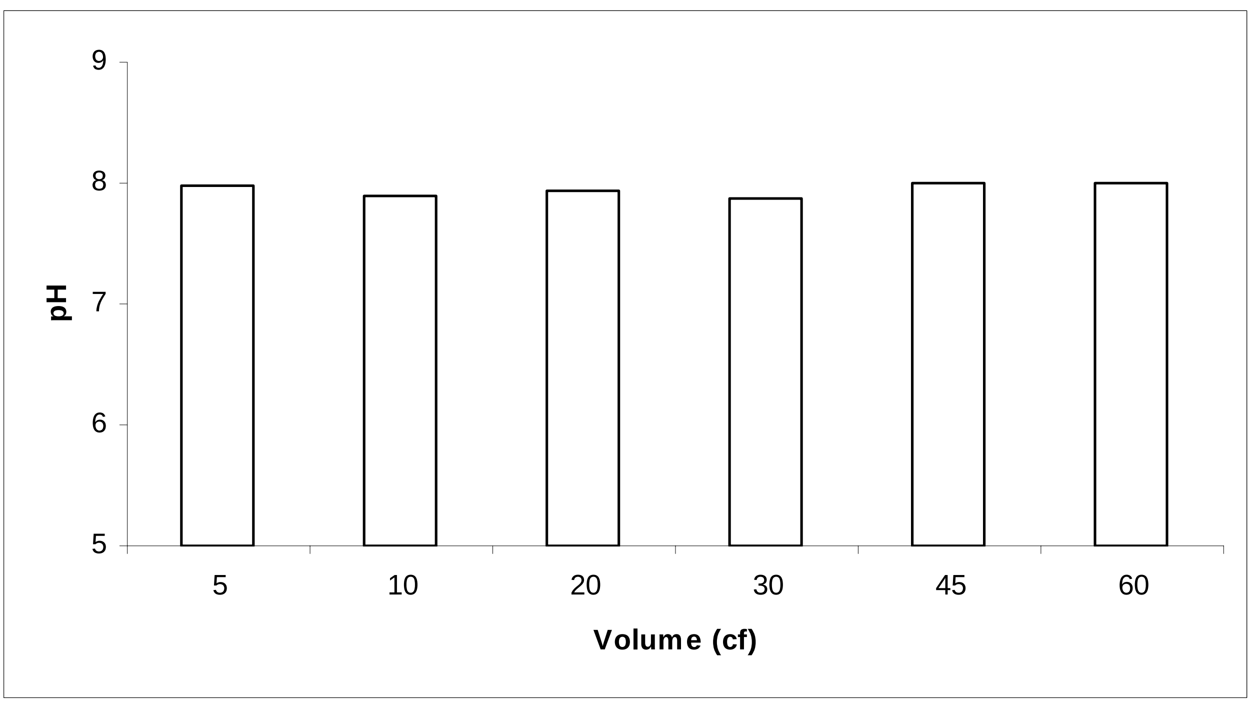

Figure 299 - pH - Green Roof Samples - December 1, 2006 Storm

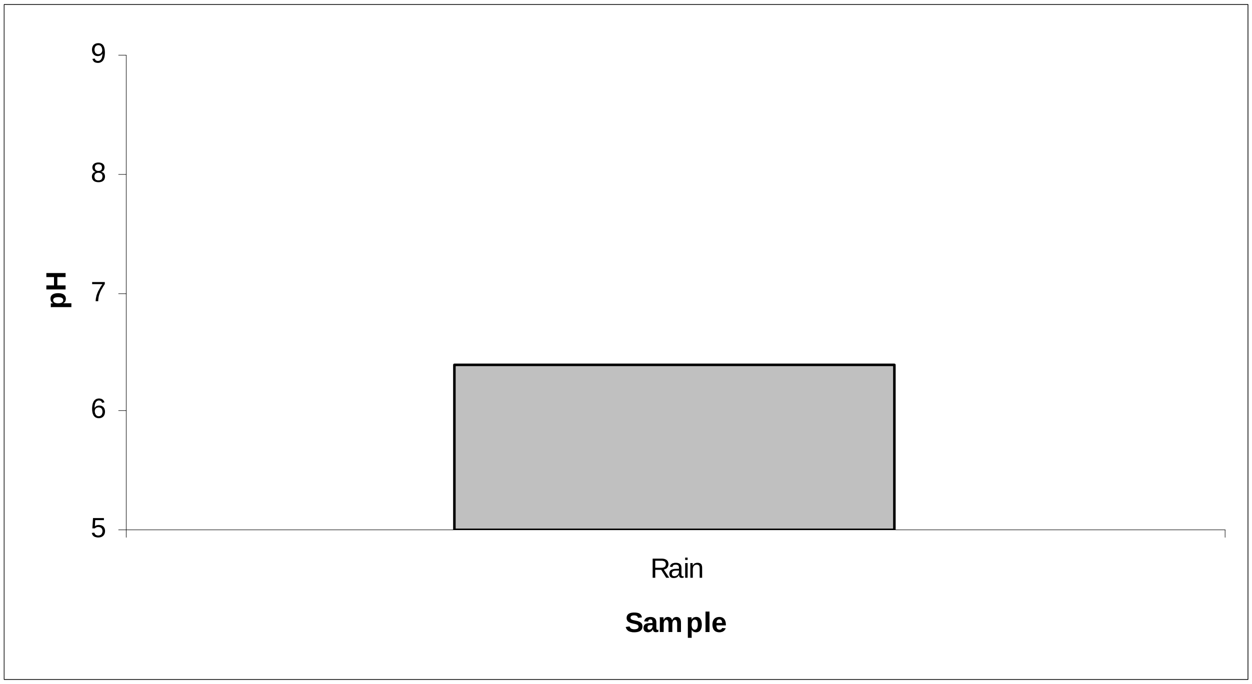

Figure 300 - pH - Rainwater Samples - December 1, 2006 Storm

B.6.5 Turbidity

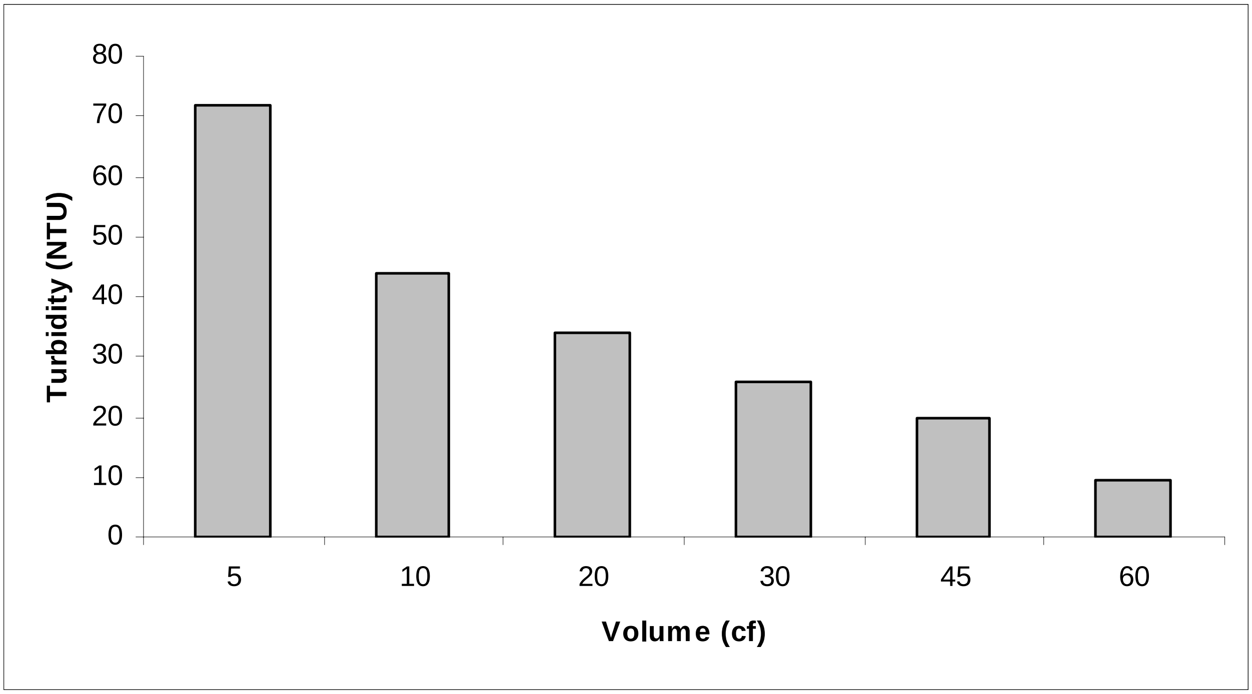

Figure 301 - Turbidity - Control Roof Samples - December 1, 2006 Storm

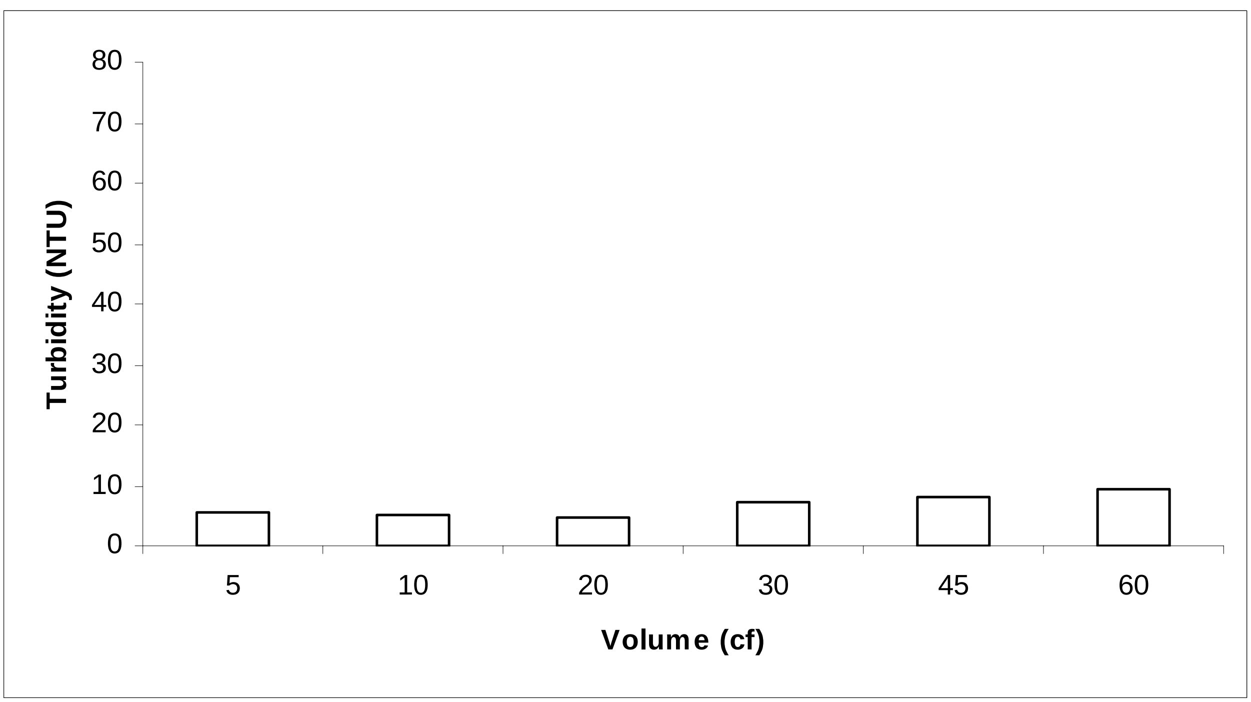

Figure 302 - Turbidity - Green Roof Samples - December 1, 2006 Storm

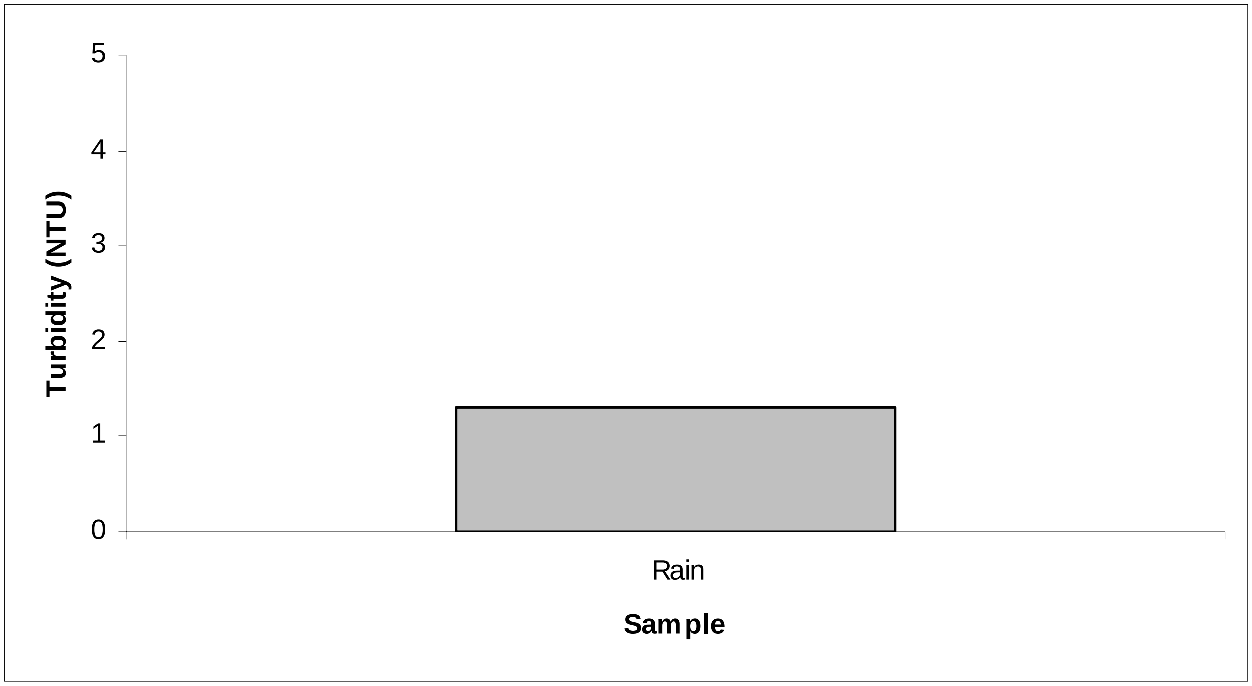

Figure 303 - Turbidity - Rainwater Samples - December 1, 2006 Storm

B.6.6 Lead

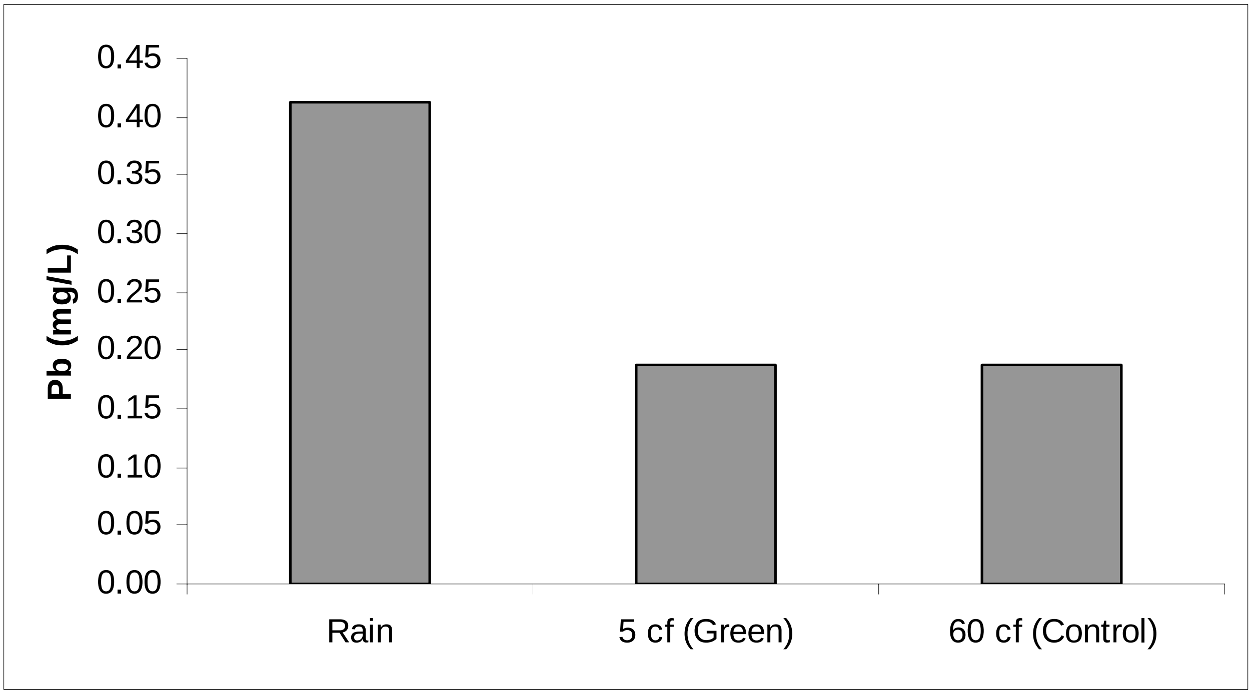

Figure 304 - Lead - December 1, 2006 Storm

B.6.7 Cadmium

The rainwater sample, the 5 cf sample from the green roof and the 60 cf sample from the control roof were tested for cadmium, but the readings fell below the detectible limits. The samples have a concentration of 0 mg/L Cd.

B.6.8 Zinc

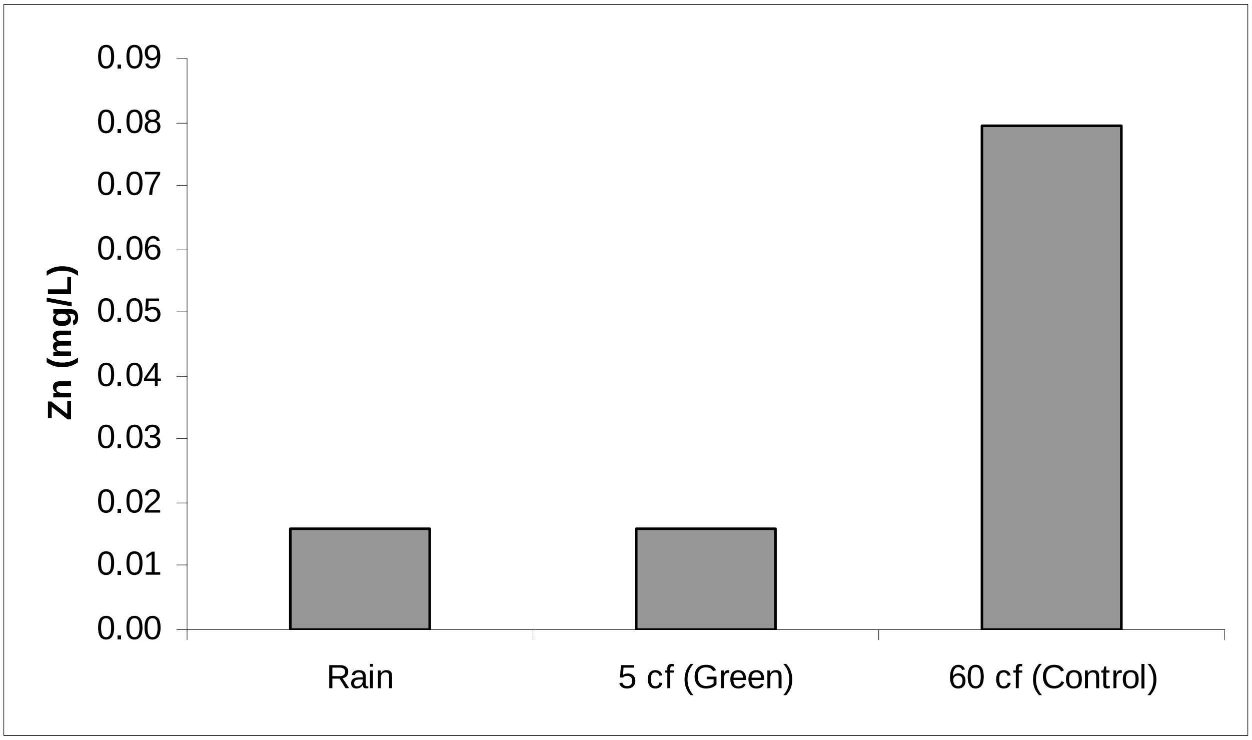

Figure 305 - Zinc - December 1, 2006 Storm

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