Please note: This report contains information on both the Shadyside Giant Eagle and Homestead green roof projects.

Final Report:

Monitoring Protocol and Data Collection:

Comparison of the Runoff Water Quantity, Quality and Thermal Performances of Two Green Roof Technologies; Thin vs. Thick

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EXECUTIVE SUMMARY

This report presents the use of a green roof compared to a conventional (control) roof using modern construction methods. A green roof has many environmental, economic, and aesthetic benefits over a conventional roof. This study examined the environmental benefits of a thick and a thin green roof, with focus on stormwater management and thermal benefits. The results demonstrated that in comparison to the conventional roofs, green roofs retained significantly more water, moderated temperature increases and decreases of the roof, and had marginal effect on the chemistry of the discharged runoff. Two different technologies of green roofs were analyzed and the enhanced performance of two green roofs over their associated conventional roof was found to depend on soil (roof) thickness. Concise descriptions and major distinctions between control and green roof, and comparisons of thick and thin green roof technologies are summarized in Table 0-1 and Table 0-2 of this executive summary.

Monitoring systems were developed to capture the water flows and temperature profiles of both the green roof and control roof. The monitoring systems captured electronic data from sensors and transmitted them to the University of Pittsburgh via modem and electronic network. The portion of the roof at Giant Eagle devoted to this research had conventional and green roof segment of sizes 3,520 square feet each while both the conventional and green roofs at Homestead were approximately 2,000 sq. ft. each. The monitoring systems at two sites included (*for green and control roofs*) separate flumes (at Giant Eagle) or weir boxes (at Homestead) ultrasonic sensors; soil moisture sensors, rain gauge, thermocouples, temperature probes, and net radiometers to measure the runoff and thermal performance of the two roof types over time. Runoff water samples from each roof were collected at both sites and tested in the laboratory for water quality characteristics. The system was implemented and environmental data was collected continuously over a first seven-month period from July 2006 through January 2007 at the Giant Eagle location. This phase encompassed periods of summer, fall, and winter climate conditions. A total of 24 storms, ranging from 0.07 inches to 2.2 inches, occurred during that test period, and the chemical data from most storms was captured during the first phase. A second phase of the study was implemented from April 2008 through April 2009 monitoring both the Homestead and Giant Eagle sites. In sum total, the sensors and data loggers at the two sites recorded 95 storms ranging from 0.02 inches to 2.42 inches of precipitation.

Table 0-1 General Characteristics of the Control and Green roof

	Green roof	Control roof
Runoff quantity performances	1% to 100% of overall flow rate reduction (compared to control roof) observed – high percent under light storm and low percent under heavy storm	Usually has a higher peak flow rate than green roof, but became less different for heavy storm and high soil moisture content
	2% to 100% reduction of total runoff volume (compared to control roof) – green roof retained all the stormwater for 100%	Usually in a higher level runoff than the runoff for green roof – more stormwater discharged from control roof
	Comparing with control roof, initial runoff retardation is ranged from 0 to 16.7 hours. Time delay of maximum peak flow is between 0 to 16 hours. Runoff discharge begins after 0.035-0.6 inches of water released from control roof, depending on soil moisture condition.	Runoff water started to discharge in a short time after occurrence of rainfall.
	The soil moisture content, soil thickness as well as the extent of rainfall influenced runoff quantity performances of green roof.	
Thermal performances	Approximately 90°F (or below) of surface temperature observed on a hot summer day	Approximately 100°F (or above) of surface temperature observed on a hot summer day
	Experience less thermal fluctuation from day to night; protect roof membrane and reduce its thermal stress during days with high ambient temperature	Large thermal fluctuation from day to night, particularly during summer. Exposure of the roof membrane to ambient conditions may reduce its usage life
	Solar energy absorbed by the system and for photosynthesis by the vegetation. Water trapped in soil can be evaporated resulting in cooling.	Reflect more solar energy to the atmosphere and may result in an urban heat island effect.
	During the night in summer, the green roof had a slightly higher roof membrane surface temperature than the control roof, which indicates that a green roof releases heat slowly.	
Runoff quality performances	No first flush detected	
	Neutralize the acidic rainfall (Homestead); act as a filter for pollutant particles from atmosphere	No change in water runoff quality. Direct flow to the roof drain.
	Fertilization during the summer of 2008 by the owner of the Homestead green roof influenced the runoff quality results.	

Table 0-2 Characteristic differences between the thin and thick Green roof technologies

	Thin roof (Homestead)	**Thick roof (Giant Eagle)**
General features	Thickness of soil medium: 1 ½ inches Manufacturer: Green Living Technology Type of plants: a mix of sedum kamtschaticum,worm grass sedum and thymus x citriodorus	Thickness of soil medium: 4 ½ inches. Manufacturer: The Garland Company. Type of plants: a mix of sedum acre,album, sexagular, kamtschaticum, etc.
Runoff quantity performance	For total runoff volume, more stormwater discharged under dry soil condition, due to the limited soil thickness and retention capacity.	For total runoff volume, large capacity of water retention under dry soil condition, due to an additional 4-inches of soil thickness as compared to the thin roof.
	Initial runoff retardation is ranged from 0 to 8.7 hours. Significant retardation of time of maximum peak flow for initially dry soils.	Initial time of retardation of runoff ranged from 0 to 16.7 hours. Significant retardation of time of maximum peak flow for initially dry soils.
	For initially wet soils: small differences in time of runoff or retardation of peak flow were observed between thin and thick roofs.	
Thermal performances	Reflect less heat and lower ambient temperature; less insulation effect between the roof surface and roof deck below	Better insulation due to thicker soil substrate.
	No significant differences in thermal performance between the two green roofs were found during cold weather months.	
Runoff quality performances	The runoff samples from two sites indicated different rainfall pH, however metal constituents were marginally less at Giant Eagle. No statistically significant differences were observed in runoff quality at either green roof except for N & P.	

Part I: Water Quality Results

The results of two green roof studies indicate the potential of green roofs as an effective system in stormwater management. The benefits of a green roof over the conventional membrane "control roof" are as follows:

1. The peak flow rate (normalized as *cubic feet per second of flow per unit roof area*) from the green roof was lower than the control roof in most cases.

In the first study phase, the reduction of the runoff from the thick (Giant Eagle) green roof as compared to the control roof was between 5 to 70%. The peak flow rate reductions during the second study phase were in a ranged from 1% to 100%. The highest comparative reduction in flow rate occurred during light storms while smaller flow rate reductions occurred under heavy storm conditions.

A graphic relationship of the water runoff parameters considered to be of importance for this research is shown on the sketch of Figure 0-1. The dashed line represents a typical runoff flow rate of control roof and the solid line represents the green roof runoff flow rate. The designations "A, B and C" are three significant performance parameters of (A) time of initial runoff retardation, (B) time of peak runoff retardation and (C) magnitude of differences in normalized quantities peak runoff flow rates.

For most rainfall events, both the time of occurrence and magnitude of green roof runoff water flow rates are attenuated as compared to control roof flow rates. This observation however was highly dependent on the soil moisture content (relating to time of occurrence of the previous storm event) and overall magnitude of rainfall precipitation. There was virtually no difference between the green roof water retardation of retention capability once the soil reached water saturation (due to heavy and/or prolonged rain fall events).

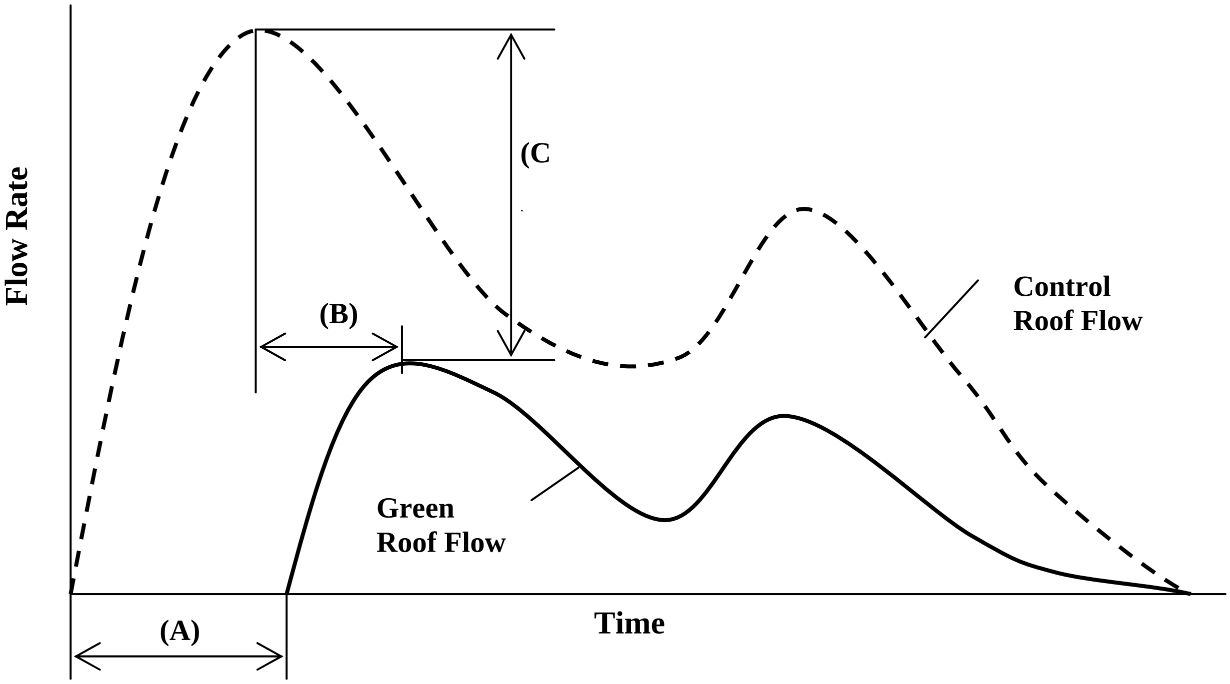

Figure 0-1 Runoff parameters of importance: control and green roof discharges.

(A) Initial runoff retardation: the time difference between which green roof starts discharges stormwater and control roof starts to discharge;

(B) Maximum peak flow retardation: the difference in time between the control roof and the green roof of occurrence of normalized maximum peak flows.

(C) Maximum normalized peak flow rate variation: the difference in maximum peak normalized flow rates between the control roof runoff and green roof runoff.

2. The total quantity of runoff from the green roof was dependent on the soil moisture, the intensity, and duration of the storm. As soil moisture content increased, the capacity of the green roofs to retain water decreased. For heavy storms, the reduction in total flow was less than that under lighter storms, but the reduction was still observable. The reduction observed in both study phases ranged from 100% for the lightest storm to 2% for the heaviest. A reduction of 20% in the total runoff volume was observed in several large storms. For smaller storms (usually less than 0.1 inch of precipitation or slightly higher) where the soil was dry, 100% of reduction of the total runoff volume was often observed. In these cases, the green roof was able to absorb all the stormwater and no runoff was measured.

3. The thickness layer of soil media as well as soil moisture of the green roof impacts the capacity of stormwater retention. Under dry soil conditions, the thick roof (at the Giant Eagle site) retained more water than the thin roof (at the Homestead site). A larger mass of dry soil (from a thicker soil layer) has more available capacity (field capacity) for water retention. However, as the soils became saturated, any additional water that fell on the green roof soil was discharged and little differences in further water retention are observed.

The water cup reservoir specifically incorporated into the thin roof technology is designed to retain part of the stormwater and may yield additional water storage capacity, but this effect was minimally observable. The water cup reservoir, however, can provide moisture during prolonged drought conditions for the plants on the thin roof, and thus has an important benefit.

4. The time of initial discharge from green roof was significantly delayed relative to the initial time of discharge from the control roof. The average retardation time for green roof runoff under dry soil condition was 3 hours behind the control roof runoff and only 1.5 hours under wet soil condition.

It was observed that towards the end of a storm, the runoff from green roof has a prolonged tail consisting of a very low flow rate that did not occur for the control roof. This tailing of flow occurred for a significant amount of time after rain ceased and the runoff from the control roof stopped.

Part II: Temperature Profile Results

There are significant benefits in reduced heat gain and loss that are observed to be a function of roof type and thickness. The most significant results are:

1. The temperature profile shows the stone ballast covering the “rubber” membrane on the control roof at Giant Eagle cannot protect the membrane from the ambient conditions and incoming radiation. Despite the light color of the stone ballast on the roof surface, that membrane surface reached extreme temperatures on a hot summer day. During summer time, the control roof surface reached a temperature above 100°F when the ambient temperature is close to 90°F. The green roof surface temperature remained at or below 90°F during the day, which was about the same as ambient temperature.

   The green roof provided protection to the roof membrane and reduced the thermal stress on the roof membrane during days with ambient temperatures greater than 75°F. During summer nights, the green roof temperature closely followed the ambient temperature. These observations suggest that the green roof has the ability to absorb and release of energy that it was exposed to during the day.

2. Temperature profiles show that the wintertime surface temperature of the green roof and control roof showed little difference during the day when the sun shines. During the night, however, the green roof was able to retain a portion of the heat it absorbed during the day. Although the temperature profiles suggest that the thermal benefits of the green roof in winter is not as significant as it is the summer, the green roof was able to save a small amount of energy by showing reduced heat loss in comparison to the control roof.

3. The net radiation at the site was observed to influence the roof performance. In the summer and fall when the roof is exposed to 400-800 $W*m^{-2}$ net of incoming radiation throughout the day, the control roof easily stores this energy, while the soil and plants on the green roof store and use that energy. The data from the summer and fall indicate that the green roof shows slightly higher positive radiation during the day, meaning the green roof is reflecting less energy during the day, and slightly higher negative radiation at night, meaning the green roof is releasing less energy at night. This suggests there is significant potential for green roofs in mitigating the urban heat island effect. During the winter the two roofs perform nearly the same as the short days, lower sun, and shading by the apartment building greatly limited the energy transfer during the day.

Part III: Water Quality Considerations

Runoff water quality results for the green roof and associated control roof are compared. In addition, T-statistics at the 95% confidence level are utilized to evaluate if the green roof and control roof runoff water quality concentration differences are statistically significant. This is done for both locations. The major conclusions drawn from this information are:

1. No “first flush” effect (*elevation in contaminant level during the initial water runoff)* for the green roof was observed for any test parameter. The “first flush” effect was noticeable for the control roof.

2. There was a significant difference between the green roof and control roof pH at the Homestead site indicating the ability of that green roof to neutralize acidic stormwater (*from acid rain falling at that location*).

3. There is a statistically significant difference in total suspended solids (TSS) between the control and green runoff samples at Homestead, with a relatively lower concentration coming from the green roof. There was not such a difference observed at the Giant Eagle site for TSS.

4. The results of Chemical Oxygen Demand (COD) at Giant Eagle or Homestead sites do not show any significant differences between the control and green roof. Metal ions were not detected at significant levels from runoff samples with the exception of zinc.

5. Chemical fertilization of the Homestead green roof by the building owner during the latter part of the project period was observed to influence green roof runoff water quality. All nutrient contaminants in runoff waters from the Homestead green roof show a significant increase in concentration after fertilization; however, the foliage appeared beautiful.

In summary, green roof technology is an effective and practical way to improve the stormwater management, thermal performance, as well as stormwater quality. The body of the report document provides supporting data and analysis leading to technical insights for the use of this “green” technology for urban stormwater management.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. MOTIVATION AND OBJECTIVES OF THE STUDY

Many older cities throughout North America have antiquated sewer systems that are unable to accommodate the rapidly increasing amounts of runoff from impervious surfaces that has resulted from urban expansion. Excess stormwater runoff often causes systems to become overwhelmed and as a result significant amounts of untreated raw sewage spills into lakes, streams, and rivers. This is a vexing problem since old, undersized sewer systems are difficult to replace and water treatment plants cannot be quickly expanded. Expanding systems to deal with more storm water will be enormously expensive and does not get to the root of the problem: too much stormwater runoff is being produced. From an economic and practical point of view, systems cannot reasonably be expanded to accommodate loading.

A second problem that arises from development is that Urban Heat Islands are form in cities by replacing native land cover with materials like concrete and asphalt, buildings, streets, and parking lots absorb and store solar radiation energy during the day and emit it during the night. This is the exact opposite of what these materials replaced; trees and vegetation cool their surroundings through evapotranspiration. This displacement of vegetation from cities further exacerbates the heat island effect.

Installation of green roofs addresses both of these problems by using plants to cover the roofs of buildings; providing runoff control as well as lowering the amount of radiant heat absorbed by the roof. By putting soil and plants onto roofs, these natural surfaces can absorb rain instead of shedding it. Green layered roofing systems absorb water that otherwise would have become runoff and entered the sewer system, reduce runoff flow rates, delay peak flows and, possibly, improve the water quality of runoff. Further, green roofs typically increase the vegetative land cover in the city and aims in reducing the heat island effect.

This work aimed to quantify the possible environmental benefits of green roofs. To this end, the water qualities, water quantities, thermal envelopes, as well as several other important variables were monitored at two locations in Allegheny County, Pennsylvania. To evaluate the relative performance of green roofs, at each location, a conventional roof and a green roof were installed adjacent to each other and were monitored in parallel.

The objectives of this study were three fold:

1. Develop and install a monitoring system specific to each site capable of qualitative and quantitative sampling of parameters that will be used to assess the long and short term changes in the roof environment as a consequence of the addition of a vegetative area. The instrumentation at each site monitored surface temperature, ambient temperature, precipitation, wind direction and speed, stormwater retention, stormwater runoff, and runoff quality (evaluated via laboratory testing).

2. Quantify the performance of the roofs by type at both sites. This quantitative comparison includes using the control roof as a basis for evaluating the storrmwater retention of the green roof and its potential as an alternative technology to address the issue of combined sewer overflows. It also includes the evaluation of the thermal performance of green roofs, focusing on the benefit green roofs have on the thermal stress of the roof membrane

3. Compare the performance of these two green roof technologies in terms of the runoff water quantity and runoff retention, retardation time of runoff after a storm, retardation of peak runoff flow, thermal effects, and water quality.

2. INTRODUCTION TO GREEN ROOFS

Green roof (vegetated roof) is an ancient technology which has a renewed interest in the past few decades. While the basic principle remains the same, modern green roofs are far more advanced than their ancient counterparts. Engineered to absorb and detain water during rain storms, green roofs reduce the flow of stormwater into sewer systems. With less sewer overflows, the water ways are less polluted. In this way, green roofs can help reverse some of the negative effects of urban sprawl by reintroducing green space into the concrete expanse. Additionally, green roofs can filter various pollutants out of the runoff before it enters the sewer system. Further, the plants on a green roof cool the air above a roof. With a significant increase in green surface area, the overall temperature of a city can be reduced.

Not for profit organizations, including “Green Roofs for Healthy Cities,” have taken the initiative to increase awareness of the economic, environmental, and social benefits green roofs provide throughout North America (Greenroof 2007). In addition to these organizations, professionals in architecture, construction, horticulture, landscaping, urban planners, environmental management, ecology, and conservation are all involved in promoting and studying green roofs and the green roof industry (Dunnett 2004).

2.1 Types of green roofs

The majority of 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 and not considered in the scope of this work. For example, the “eco-roof” is typically an extensive green roof that is only green for a short period of time each year because of the frequently cold weather. While not nearly as common as intensive or extensive green roofs, brown roofs are simply made up of a substrate that is left unplanted and the roofs are left to become spontaneously planted as birds and other small animals track material onto the roof. Often, rubble from brick and concrete is used as a substrate, though soil may also be used. 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, and has slightly larger plants and a slightly thicker substrate (up to about eight inches) than an intensive green roof (Dunnett 2004).

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 deep. Larger depths of soil are required to accommodate the roots of large plants room to grow (Dunnett 2004). Intensive green roofs do not just look like a rooftop park; they often act as one and can be designed to handle the load of groups of people walking around on the roof (Scholz-Barth 2001).

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 was installed on the roof, frequent mowing would be required. Further, 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. In order to keep larger plants healthy, significant amounts of water are required and an extensive irrigation system must be installed. Incorporating an irrigation system into a green roof adds to the cost and complexity of the roof design and installation (Scholz-Barth 2001).

A second issue arises out of the weight of the intensive roof itself. Adding 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). The typical intensive green roof contains at least one foot of soil and the sheer mass of soil puts a significant demand on the roof, even if a lightweight substrate is used. Further the mature mass of trees and shrubs that are intended on being installed need to be considered because they could be a significant contribution to the mass needed to be supported by the roof. Additionally, most intensive green roofs are designed to support use by groups of people further adding another live load to the design constraints. 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). Given all of these considerations and that most structures are designed with some excess dead load capacity, the added load from an intensive green roof would exceed the existing roof support capacities in most instances. Live load requirements vary from building to building, but many roofs are not designed to carry the weight of groups 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 a significant increase of materials to support the weight of the roof. This can again make choosing an intensive green roof an expensive option.

Extensive green roofs provide a much more practical option and are the focus of this study. Extensive green roofs only have a few inches of soil, the depth of which depends on the types of plants used, but 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 since they are placed out of sight or in difficult to access spaces (i.e. home roof tops). For most extensive green roofs, the goal is to reap the environmental benefits of a green roof, not creating a public space (Dunnett 2004). Instead of large trees and shrubs seen on intensive roofs, extensive roofs are planted with low lying, drought resistant ground cover plants chosen to address the site specific needs and constraints. Plants are picked for the climate in the area and should be able to survive solely on the natural rainfall that reaches the roof, reducing and nearly eliminating the need for watering. In many cases, light irrigation systems are installed as safeguards to ensure plant survival. 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. Except for infrequent maintenance, extensive green roofs are not meant to be walked on. Maintenance is typically limited to a few instances a year for weeding and replanting, but varies depending on the types of plants used in the roof. Occasionally, extensive green roofs will have sod that requires more frequent maintenance, but sod is an option that is used less frequently because of this maintenance requirement (Scholz-Barth 2001).

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 with smaller plants, a thinner soil substrate, and significantly reduced live load in comparison to an intensive green roof. A typical extensive green roof with a depth of 2 to 6 inches (5 to 15 cm) will weigh approximately 14 to 35 psf (70 to 170 kg/m^2). The additional weight of thinner extensive green roofs is within acceptable limits for many roofs and 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 can be a practical addition to a building.

2.2 History of green roofs

Documentation of roof top gardens, or green roofs, dates to pre-biblical times to the Tower of Babylon, as depicted in an artist’s rendition in Figure 2-1 (Romer, 1995). More modern examples include early American settlers that utilized sod to roof and insulate their homes in the early 1800’s. The 1868 World Exhibition in Paris, France featured a planted concrete structured “nature roof” that was the first of several similar projects in Western Europe at the time. During the early 1900’s notable architects such as Frank Lloyd Wright and Walter Gropius experimented with green roofs on restaurants (Dunnett 2004).

In the age of modern architecture with engineered materials, roof top gardens have been used to increase the aesthetic value of buildings. Underground parking garages often have a green roof or small urban park on the top-most layer visible to the public. Apartment complexes in dense urban neighborhoods use green roofs to attract renters with additional green space (Dunnett 2004).

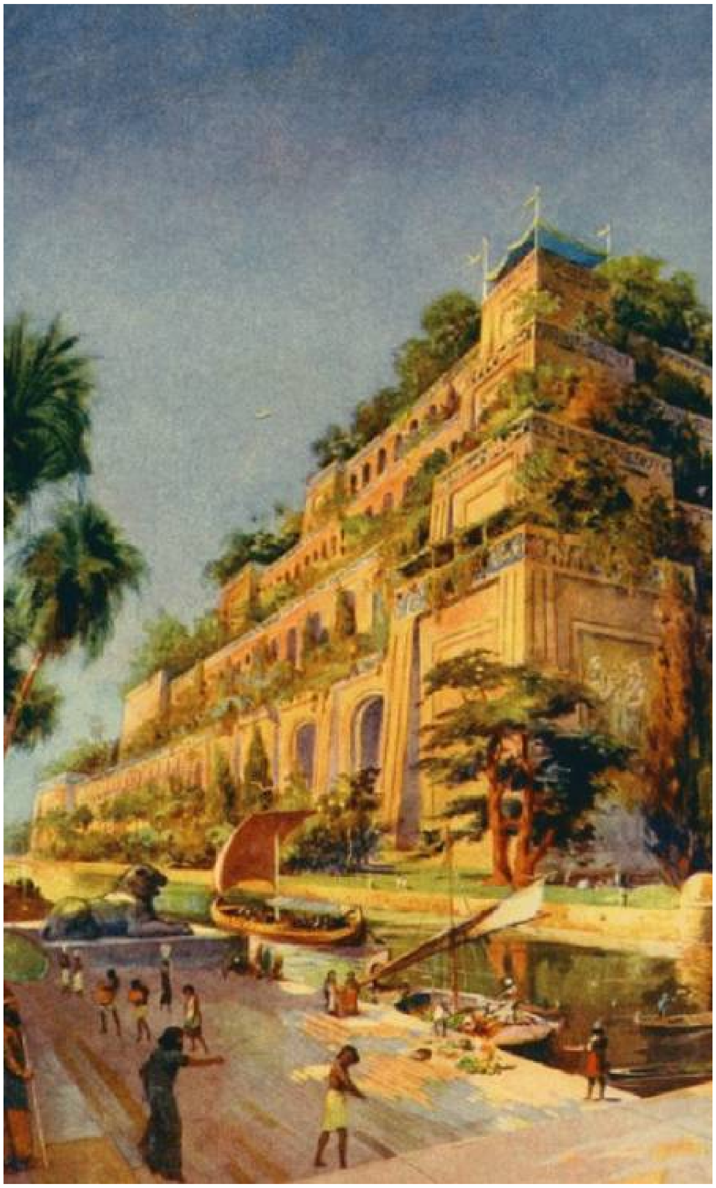


Figure 2-1 Hanging gardens at the Tower of Babylon were an early example of green roofs.

(Romer 1995)

In addition to the aesthetic enhancement, green roofs prolong the life span of roofing materials because the drainage system, growing medium, and vegetation layers protect the waterproofing membrane. Derry and Tom's department store in Great Britain installed an intensive green roof to the top layer of its store in 1938 and as of 1999 has not had to replace the waterproofing membrane (Osmundson 1999). While additional maintenance is required to keep the roof in good condition, the cost of maintenance is significantly less than the cost of replacing the roofing membrane every 10-15 years due to normal degradation.

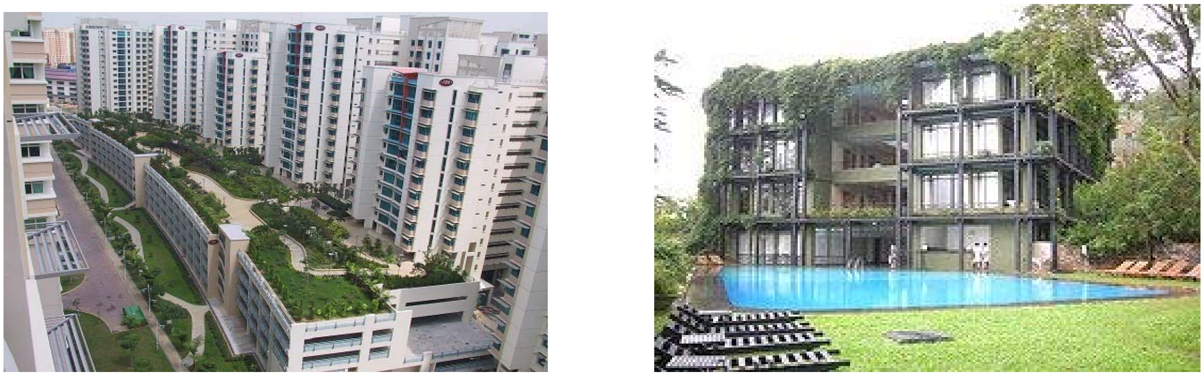
While people have used green roofs for aesthetic and cost-oriented reasons for many years, the environmental benefits of green roofs have only recently been considered. The latter half of the twentieth century brought the technology and materials needed to build large flat roofs that could support the added weight of roof top vegetation. The movement to "green" urban areas by adding vegetation to the large flat rooftop spaces started in Germany in the 1980's (Dunnett 2004) where innovators used green roofs to improve the perception of a city and region. Stuttgart, with its industrial history and location in a valley that led to high levels of air pollution, is an example of one such city. To improve the city's image, green roofs were used to "green" the once industrial town with the hope that the plants would improve the air quality of the city (Toronto 2007). Researchers determined that green roofs provided many environmental benefits beyond aesthetics and air pollution reduction. The increased vegetation in the area reduced the urban heat island. Further, stormwater run-off was reduced and buildings were kept cooler in the summer by virtue of green roofs. Germany quickly became the center of the green roof movement, other European countries started to develop their own green roof research programs, and green roofs installations spread to North America and Asia. This passive mode of environmental improvement quickly spread around globe and is even being adapted to tropical areas, where the warm climate is expected to benefit from additional green space even more that northern countries (Osmundson 1999). Examples of green roofs that have recently been installed in the United States and elsewhere around the world are shown in Figure 2-2.

(a) California Academy of Sciences (USA)

(c) FiftyTwoDegrees Business Innovation Center (Nijmegen, The Netherlands)

(b) Vancouver Olympic Village (Canada)

(d) Financial Dist Banco de Santander (Spain)



(e) Punggol Roof garden (Singapore)

(f) Heritance Kandalama Hotel (Sri Lanka)

Figure 2-2 Examples of green roofs at different locations in around the world.

a) Guevarra, b) Millennium Development Corporation, c) FiftyTwoDegree, d) Vicom S.L., e) Lee f) Aitken Spence Hotel Holdings

2.3 Components of green roofs

A green roof is typically made up of six layers. Moving from the inside of the building to the outside a green roof consists of a structural roofing deck (1), waterproofing membranes (2) that keep moisture out of the structure, root barriers (3) that prevent plants from breaking the waterproof seal, a drainage system (4) carries away excess water, a filter fabric (5) prevents soil particles from washing away in the rain, and the substrate (6) that supports the plant life and aides in water retention. The different layers allow the structural roof and building to remain dry while providing storage for the moisture the plants need to survive. Many green roof systems are now commercially 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 and the green roof can be placed as tiles on the structural roof.

Waterproofing Membrane

The waterproofing membrane provides a durable seal that keeps the structural roof dry and isolated from moisture that may penetrate the upper layers. The most common type of waterproofing membrane used on green roofs is built-up roofs that are composed of layers of asphalt roofing felt placed between asphaltic bitumen. The asphalt and bitumen are the materials that actually waterproof the roof, while the felt adds strength (Osmundson 1999). Since bitumen is an organic material, plant roots may try to feed on it. To avoid this, a root barrier is an essential component of green roof systems.

Another type of waterproofing membrane used with green roofs is inorganic plastic or synthetic rubber single-ply roof membranes that are laid across the roof in sheets or tiles (Dunnett 2004). Seams are overlapped and are joined using heat or an adhesive that bonds the joints (Osmundson 1999). Single-ply membranes have some advantages over built-up roofs. All the materials are inorganic thus there is less chance of root penetration. Further, the material is installed at one time as a single continuous layer, as opposed to in several layers applied over time. Because of these differences, there are far fewer joints where leaks are most likely to occur in single-ply roof membranes (Osmundson 1999). However, if not properly installed, the seams and bonds are susceptible to leaks especially around drainage pipes. For areas that are difficult to install around or are strangely shaped, fluid-applied membranes are used to avoid problems that may be encountered where the other types of membranes would be difficult to install. The hot or cold liquid membrane can be sprayed or painted onto the surface of the roof and creates seals without any seams (Osmundson 1999).

Root Barrier

The root barrier layer is placed directly above the waterproofing membrane and is vitally important in protecting the structural roof, especially where the waterproofing layer contains organic materials, as in a built up roof. 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 chemically welded together. 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).

Drainage Layer

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 ties into the roof drains. While it is important for the plants to be adequately watered, too much can be problematic. Plants will rot if they are in saturated soil for extended periods of time, retarding growth or ultimately result in plant death. Similarly, the roof membrane will deteriorate more quickly if it is in constant contact with water leading to leaks. The roof is far less effective in insulating the building when saturated because it loses some of the insulating qualities that come from the air inside the pores of the soil (Dunnett 2004). Because of these considerations, the drainage layer is designed such that excess water will enter the drainage system and be carried off the roof through drainpipes once the substrate is saturated.

The drainage layer is typically composed of several different types of materials that characteristically have large pore spaces which allows for good drainage (Dunnett 2004). Granular materials including gravel, broken rocks, and clinker are traditional building materials that are commonly incorporated into green roofs. Most pre-World War II green roofs and many built through the 1950s and 1960s used broken rocks. These materials were heavy yet effective (Osmundson 1999) in promoting drainage; whereas lighter materials like pumice and broken clay tiles are now often used. A thin drainage layer usually weighs less than the substrate and protects the plants from standing water in the soil. As a side benefit, the drainage layer offers additional root space for plants (Dunnett 2004).

Man-made and recycled materials are also used for drainage layers. One of the most common types of green roof drainage mediums 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. Another material used is composite porous mats made of recycled materials that absorb water can be incorporated into green roofs. Unfortunately, these mats absorb excessive amounts of water and often deprive water from the plants (Dunnett 2004).

2.4 Environmental Benefits of Green Roofs

Green roofs offer several environmental benefits, with the most being their ability to mitigate the phenomena of: (a) combined sewer overflows, and (b) urban heat island. These benefits have been documented in the North American region since the mid 1990's (Dunnett 2004). In some instances the benefits can be enjoyed by a single building with immediate results and are sometimes scaled with size. Unfortunately, this is not always the case and more commonly, the ability of green roofs to combat environmental issues takes time and large quantities of roof space (Dunnett 2004).

Combined Sewer Overflows (CSO)

Combined sewer systems carry both wastewater and stormwater in one pipe. For clarity, wastewater is defined as any liquid waste that is discharged from domestic, commercial and industrial sources, whereas stormwater is defined as water that ends up in the sewer system that enters through storm grates after running off impervious surfaces in the event of a rain storm. During dry weather, sewers only carry wastewater. When rain begins to fall, stormwater also flows into the system. In wet weather cases, the stormwater usually dominates the flow, even after only a short rainfall (Butler 2004). These heavy flows often overload the wastewater treatment facility and as a result, hundreds of facilities around the world release untreated wastewater into the receiving body of water before the water is treated. This raw sewage release can affect manholes, roadways, and basements of houses (3 Rivers Wet Weather 2006). For example, in the city of Pittsburgh, Pennsylvania, a storm event of as little as 1/10th of an inch of rainfall can result in a raw sewage overflow (3 Rivers Wet Weather, 2006). As a result from raw sewage overflows, river advisories are put into place when bacteria and viruses in the waterway place humans at a health risk, and has been up to 50% (70 days) of the recreational boating season (May through September) in the Pittsburgh area. This phenomenon is often referred to as combined sewer overflow, or CSO.

The change in how water runs off the same area changes dramatically with development. An illustration of the difference in the stream flow before and after urbanization (Figure 2-3) shows there is a marked difference in the time of the peak discharge. The peak flow for an urban area is usually earlier than the peak flow from a pre-urban area. Additionally, the peak flow from the urban catchment is also much higher than the peak flow from a pre-urban catchment. This demonstrates the water retention capacity of soil and vegetation. Temporary storm water retention minimizes the occurrence and magnitude of CSO's, and the subsequent effects on public health.

A system of green roofs can reverse the effect of urbanization on storm water flow and lessen the frequency or magnitude of CSO events by manipulating the water run-off in a number of ways. The soil substrate and vegetation its supports can trap and store precipitation. By trapping the water before it becomes surface run-off, green roofs provide areas where water can evaporate back into the atmosphere, reducing the amount of water that becomes run-off (Dunnett 2004). Green roofs can also increase the time it takes for rainfall to become run-off. During a heavy storm event, rainfall can quickly become run-off as soon as it comes in contact with an impermeable surface and flows into the storm sewer system. Green roofs have been shown to delay the flow of water into the storm water system as well as elongate the time it takes for run-off to reach the storm sewer (Dunnett 2004).

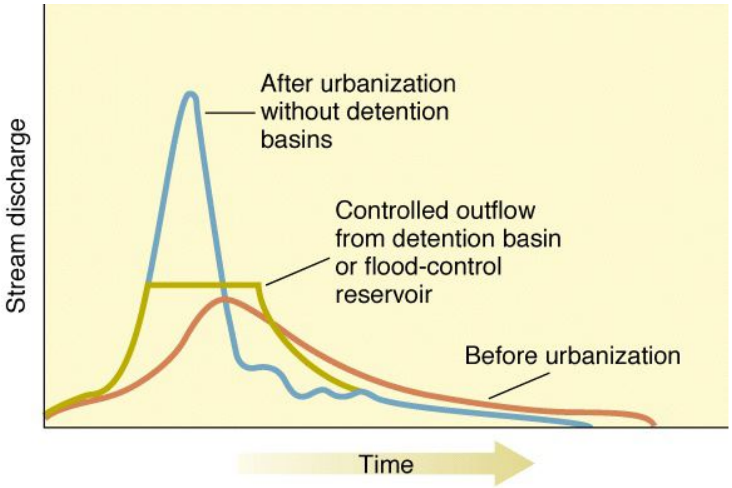


Figure 2-3 Stormwater hydrograph before and after urbanization

[Merritts, D. Undated]

Urban Heat Island

The Urban Heat Island Effect refers to the fact that urban air and surface temperatures can be up to 10° F warmer than the surrounding rural areas as described by the United States Environmental Protection Agency (U.S. EPA) (Dunnett 2004). Heat Islands form as cities replace natural land cover with asphalt and concrete infrastructure. This development displaces trees and vegetation and in effect reduces the natural cooling effects they bring: shading and *evapotranspiration*[2]. During the daylight hours man-made structures of asphalt and concrete absorb and store incoming solar radiation as heat and at night release the stored heat back into the atmosphere. This repetitive cycle leads to an increase in surface and

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[2] Evapotranspiration refers to the combined effect of transpiration, the movement through a plant from its roots to the release of vapor from leaves, and the evaporation of water from soil and plant leaves.

air temperatures. This problem is exacerbated by tall building and narrow streets that constrict the flow of air in urban centers which can help cooling (U.S.EPA 2006). The increased amount of heat absorbing materials such as concrete and asphalt in cities also prevent cities from cooling as much as rural areas at night when radiation from the sun does not contribute to raising temperatures.

Heat islands have numerous negative effects on a city: increased air conditioning demand, increased heat-related public health risks, and reduced thermal comfort. More importantly the need for air conditioning drives energy demands higher that result in higher air pollution and greenhouse gas emissions from the increased output from power plants. These emissions contribute to global warming, thereby magnifying the heat island effect (U.S. EPA 2006). Constricted airflow in the urban environment also leads to increased humidity and air pollution thus increasing risk of asthma and other respiratory problems (Dunnett 2004).

Green roofs can play an important role in reducing the urban heat island effect. Foliage on green roofs absorbs radiant energy and uses it in photosynthesis while providing shade for the area beneath it. The soil medium placed over the roof is a dense thermal mass, which moderates the thermal flux that the roof membrane experiences, absorbing radiant energy during the day and slowly emitting it back to the environment at night. As green roofs moderate extreme temperatures on the roof from peak sunlight to cold nights, the effect is carried inside, reducing the amount of energy needed to control the internal temperature of the building and reducing energy consumption. While providing interior temperature moderation, during warm months green roofs increase evapotranspiration, thus cooling the surrounding air much like undeveloped sites.

2.5 Economic benefits of green roofs

One of the most significant economic benefits of green roofs comes from their thermal protection from outside temperature extremes. Green roofs act as insulators when the growing medium is dry. This can easily translate into cost savings for the building owner from reduced HVAC energy consumption. It has been found that green roofs keep buildings 3-4 °Celsius (5-7° Fahrenheit) cooler when the outdoor ambient temperature is roughly 25-30 °Celsius (77-86° Fahrenheit) (Dunnett 2004). Another important benefit comes from the increase in durability of the waterproofing and other roof layers. Typical roof membranes are constantly exposed to damaging elements like solar radiation and rain. Green roofs actually protect the roof membrane by shielding it from damaging elements and solar radiation (Liu and Baskaran 2003). A conventional exposed roof membrane absorbs solar radiation throughout the day, causing the surface temperature to rise. At night, the roof membrane reradiates the stored energy and drops in temperature. The diurnal temperature fluctuations create thermal stresses, damaging the membrane. A green roof, depending on vegetation selection, can reduce these diurnal temperature fluctuations greatly (Dunnett 2004). Further, green roofs offer other economic benefits like increased property values and marketability.

Green roofs have a higher initial cost than conventional roofs because of the additional materials needed to build up the layers of the green roof. However, while the initial costs are higher, the life cycle costs of a green roof compared to the life cycle cost of a conventional roof are lower. A modeling study by Wong *et al.* (2003b) compared three green roof types to the conventional roof in terms of their economic performance. The extensive green roof showed an increase in life cycle costs of 8.5%, however, the intensive green roof using shrubs showed a decrease in life cycle costs of 22.4% and the intensive green roof with trees showed a decrease in life cycle costs of 42.6%.

2.6 Aesthetic benefits of green roofs

Green roofs can also give a number of amenity and aesthetic benefits to a community. Urban areas can develop additional green space by utilizing the flat areas on rooftops. One of the advantages to having recreation space on a rooftop is security. Since access is limited, green roofs can offer a safe activity space for building tenants or occupants (Dunnett 2004). Roof gardens can be used for socializing, light walks, pet recreation, clothes drying and even barbecuing. With proper planning the possibilities are endless; rooftops can be converted to small golf courses or even playing fields. Green roofs offer building owners and renters a higher quality living or working space.

An additional economic benefit may be the ability to use green roofs for food production. Given that some urban areas have difficulty with transporting fresh local food to supermarkets and shops, green roofs can be used to provide local citizens access to fresher herbs, fruits and vegetables. Most herbs grow well in shallow well-drained soil that is typical of an extensive green roof. With the proper structural support, intensive green roofs could be used to grow and harvest fruit and vegetables (Dunnett 2004). The best example of utilizing roof space in this way is the Fairmount hotel in Vancouver, Canada. The 2098 sq. ft. roof garden has an 18-inch soil depth. The garden provides all the herbs the hotel uses in its restaurant at a great quality and lowered cost (Dunnett 2004).

The hardest to value aspect of green roofs is their aesthetic value. In most urban areas especially buildings surrounding industrial or commercial sites, windows only give views of unattractive asphalt or bituminous rooftops. Even when roof tops are inaccessible but clearly viewed; a green roof garden can still yield therapeutic benefits from the effects of exposure to plants and nature include stress reduction, lowered blood pressure, relief of muscle tension, and increased positive feeling. These therapeutic effects are not restricted to apartment dwellers but for commercial sites include office workers, hospital patients, and school students. In summary, green roofs provide a variety of environmental, economic, and aesthetic advantages over conventional roofs (Dunnett 2004).

2.7 Green roof demonstration projects

Several studies have focused on evaluating and quantifying the benefits of green roofs. The typical procedure is to construct a conventional roof and a green roof adjacent to each other, and simultaneously monitor variables of interest for each of the roofs. The following is an overview of some of the recent studies that evaluated the thermal performance and/or runoff performance of green roofs with respect to conventional roofs.

National Research Council, Canada (Thermal and Runoff performance)

"Energy Efficiency and Environmental Benefits of Rooftop Gardens," by K.K.Y. Liu, describes an experimental study performed by Liu and her associates at a National Research Council site in Ottawa, Canada (Liu 2002, 2003). An 800 square foot low slope roof was divided into two equal areas by a parapet wall. A generic extensive green roof was installed on one side of the wall, while the other half had a conventional roofing assembly known as the control roof. The green roof was planted with a wild flower meadow in the first year and with sod in the second. The substrate had six inches of soil both years. The control was a standard bituminous roof, similar to those commonly found in Canada. Both sides of the roof were equipped to monitor the temperature profile within the roofing system, heat flow across the system, solar reflectance of the roof surface, soil moisture content, and the microclimate created by the roof plants. Local meteorological data was collected with a weather station located on the parapet wall, which measured temperature, relative humidity, rainfall, and solar radiation. Data from an additional weather station was collected at a site 150 feet from the site.

In terms of thermal performance, the research found that the rooftop garden kept the roofing membrane cool in the summer months through shading, insulating, and evaporative cooling. On a sunny summer day with an ambient temperature of 95 degrees Fahrenheit (°F), the reference or conventional roof absorbed solar radiation and its temperature reached 158°F, while the membrane underneath the extensive green roof remained relatively constant at 77°F. The study found that the exposed conventional membrane absorbed heat during the day and re-released it at night. The author expressed that this diurnal temperature fluctuation created thermal stresses on the roof membrane, which may affect its long-term performance. The case study measured roof thermal performance in the fall, winter, and spring seasons.

While the green roof did provide some protection from temperature fluctuations in the winter, the amount was reduced by the accumulation of snow. The rooftop garden significantly moderated the daily temperature fluctuations in the spring and summer months. The median daily membrane temperature *fluctuations* were 83°F for the reference roof and 22°F for the extensive green roof.

In terms of energy efficiency, the green roof reduced the energy demand of the building. The greatest thermal benefit of the green roof came in the spring and summer months, where the shading and evapotranspirative properties of the green roof reduced the energy demand for the corresponding part of the building by 75% compared to the energy needs of the part of the building corresponding to the reference roof. In the winter months the roof garden acted as an insulation layer providing moderate energy demand reduction until the soil layer froze. With snow pack, the two roofs performed similarly. Therefore it was determined that both solar radiation and snow coverage affected the energy demand of the building.

The green roof was found to reduce the runoff volume and peak runoff rate while 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) conducted a study at the same site in Ottawa concentrating on the details about the performance differences during two storms in 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 where 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 the onset of 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 and the nearly identical control roof runoff flow rate over the first four hours of the storm.

Department of Environment, Chicago (Thermal and Runoff performance)

“Green Roof Test Plot; 2003 End of Year Project Summary Report” prepared by MWH Americas Inc. for the City of Chicago Department of Environment, covers an experimental program to compare the temperature and runoff characteristics of green roofs to those of conventional roof systems (Green Roof Test Plot, 2004). Several 6ft by 6ft by 3.5ft structures were built and outfitted with data logging instrumentation. Six unique green roof products were tested along with three conventional roof products, stone, black tar, and white reflective paint. Ambient weather conditions for the test site were monitored for air temperature, rainfall, wind speed and direction, and relative humidity. The data was recorded every 5 minutes with a data logger. For temperature, each structure was monitored at three or four locations. Temperature probes were used to monitor several locations within the horizon of the structure; the surface temperature, the soil temperature (for the green roofs only), the membrane temperature, and the interior temperature of the shed. The probe measuring surface temperature was outfitted with a radiation shield to maintain accurate measurements, and was placed four inches above the roofing surface. The sensor measuring soil temperature was buried in the soil medium. The membrane temperature was taken immediately below the impermeable membrane and sealed with foam insulation. The interior temperature was taken in the shed eight inches from the ceiling. These temperature measurements were acquired every 15 minutes and recorded using a data logger. While undergoing continuous monitoring, data from one week in July 2003 was used in this report.

The data revealed significant differences between the green and differently colored roofs. The black tar roof reached the hottest daytime temperature peaks and the lowest nighttime temperatures. The white roof and stone ballasted roof did not hit the extremes the black tar roof did during the day, and both were cooler in the night. The green roofs had the lowest maximum daytime temperatures the highest daily minimums, and thus the smallest temperature fluctuations. The green roof surfaces were consistently 5-10° C cooler than the conventional roofs in the daytime. The data also showed a time lag between the green roofs and the conventional roof types. The green roofs reached the daily maximum afternoon temperatures 1.5-3.0 hours after the other roofs. At night, the green roofs were also slower to reradiate the heat that was stored during the day. This is likely because the additional layers needed to make the green roofs act as insulators that slow down the absorption ***as well as*** the re-radiation process.

The green roofs were observed to be very effective in reducing stormwater runoff. They typically 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. The runoff rate was also delayed significantly by the green roof and the peak flow was reduced. The conventional roof began to show runoff almost immediately after rain began to fall and declined immediately after it stopped, following 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.

Demonstration project, Singapore (Thermal performance)

Green roofs have also been studies in tropical climates. In “Investigation of Thermal Benefits of Rooftop Garden in the Tropical Environment” a green roof was studied in a tropical and urban area of Singapore (Wong et al., 2003a) to identify the reduction of surface temperatures caused by different plants, the reduction in heat gain caused by the plants, and the variation of ambient variables caused by the plants. Field measurements at the site in Singapore included ambient air, relative humidity, wind velocity, solar radiation and the temperature profiles for the site. Thermocouples were used to capture surface temperature measurements at hard surfaces (pavers), the soil surface, on the surface underneath the vegetation, in the soil layer, and the temperature at the roof membrane. The temperature profile also included 3 points above the hard surface portion of the roof 300, 600 and 1000mm from the surface respectively, and at 3 points above the green roof vegetation 300, 600, and 1000mm above the surface respectively. Interior air temperatures were taken at 2 points in rooms directly below the roof. The air temperature sensors were covered with white wooden shelters that protected the sensors from direct sunshine and rainwater but encouraged natural ventilation. The study found that the green roof plants reduced the roof surface temperature and heat transfer into the rooms below. The hard surfaces reached a maximum temperature of 57 °C in the afternoon when solar radiation was 1400 W/m^2. The temperature taken at the hard surface varied 30 °C throughout the day. The bare soil however, reached a maximum afternoon temperature of 42 °C and only varied 20 °C throughout the day. This is likely because if the affect the evaporation of moisture in the soil had on the soil surface. The temperature of the surface underneath a plant was dependent on the leaf area index (LAI) of the plant. The highest temperature recorded underneath a plant was 36 °C, although temperatures as low as 26.5 °C were found. The variation in surface temperature throughout the day also reduced to 3 °C.

The heat flux throughout several roof types was also calculated. The U-values for different roof surfaces were obtained and total heat gain/m² over a day was calculated. The bare hard surface was found to have the highest heat gain during the day and inverse heat flux at night. While dependent on plant type, surface areas underneath the plants maintain inverse heat flux throughout the day and night. However, the plants did not have a heat saving effect (insulative effect) at night. Areas under the plants performed only slightly better than bare soil at night. The author indicates that this data means that the soil layer provides some added insulation but the real benefits of green roofs come in the shading effect of the plants. The above surface thermocouples also measured a profile of the hard surface and vegetation affects on ambient air temperature and the Urban Heat Island. During the day, temperatures nearer the surface increased about the same amount for both the hard surfaces and vegetated surfaces, while at night the vegetated surfaces had a larger drop in temperature. The greatest difference in temperature between hard and vegetated surfaces was 4.2 °C measured at 300mm height at 1800 hours. No significant difference in relative humidity was found at 1m above the surfaces.

A continuation of this study was documented in “Study of Thermal Performance of Extensive Rooftop Greenery Systems in the Tropical Climate” (Wong et al., 2007). In this case study, temperature measurements taken before and after the building was outfitted with four different extensive green roof systems. The first phase of measurement was carried out for 22 days between May 19th and June 9th 2003. After the extensive green roofs were installed, a second phase of measurement was conducted for 18 days between February 14th and March 3rd 2004. The tropical location of the study site means that weather is relatively constant year-round. The two periods in the paper were selected because the weather was similar in temperature and rainfall for both study periods. The building used in this study is a multi-story parking garage. Thermocouple wire was used to measure the surface temperature at eight points on the top of the parking structure. The monitoring plan was designed to measure two surface points for each section of the future green roof. In addition to the surface temperature, ambient air, relative humidity, and reflected radiation were also recorded at a single site for each future extensive green roof area. Relative humidity and ambient air temperature were measured 30cm and 120cm above the surface. Reflected radiation was measured 80cm above the roof surface. A single weather station on site was used to measure ambient air temperature, relative humidity, solar radiation, wind speed, wind direction, and rainfall. A two day period from both the before and the after sessions were selected for discussion in the paper.

Wong and co-workers determined that the session after installation generally had lower air temperatures, higher relative humidity, and lower wind velocity. The surface temperatures demonstrate the thermal performance of the measured object. The temperature fluctuation of the roof top during the after session was significantly reduced compared to the before session. While the roof membrane had improved thermal performance, the substrate surface of the extensive green roofs did not show any reduction in temperature. The authors found that the color and low thermal capacity of the thin substrate resulted in high surface temperatures. A prolonged drought and limited vegetation may have also affected the results.

Heat flux was also monitored throughout the study period. It was observed that during the before session the roof showed a significant amount of heat gained during the day, and little or no heat lost at night. Therefore, before green roof installation there was minimal heat flux at night and maximum heat flux during the day. The after green roof installation session had the opposite result where the roof showed reduced heat gain during the day and lost heat at night. The author attributed this affect to the wet drainage system installed on the roof that reduced the heat absorbed by the roof system.

The ambient air temperature, or air temperature above the roof actually tended to be warmer over the vegetative surfaces as opposed to the concrete surface in the before session. The high surface temperature of the substrate was the likely cause of this effect. The observed cooling capacity due to the vegetation on the extensive green roofs was minimal. The after installation session did experience lower ambient temperatures at night, with reductions in temperature up to 3.5°C. The two different elevations (30 and 120 cm) above the surface were slightly different. The temperature tended to be warmer at the lower elevation and cooler at the higher elevation. Unfortunately, the low cover in vegetation and dry substrate blurred the effect of the green roof on ambient temperature.

Interestingly, the greatest success in this case study was in monitoring the reflected radiation. The reflected radiation was much lower after the green roof was installed. Unfortunately, a number of factors could contribute to this phenomenon. The extensive green roof reflects radiation less directly and diffuses it, while the smooth concrete surface did not have that effect. Further, the high substrate temperature could increase long wave radiation, a factor the instruments could not measure. Nevertheless, a monitoring point observed a decrease in the peak reflected radiation of more than 50%. The darker color of the substrate absorbed more radiation than the concrete surface. The other monitoring points showed a reduction in reflected radiation by 30%. Overall, the newly installed green roofs had an improved thermal performance than the concrete roof top; however, the effect was skewed by the poor vegetation cover and drought.

Several projects (Mathematical models of thermal performance)

The “Analysis of the Green Roof Thermal Properties and Investigation of its Energy Performance” conducted an investigation in two phases (Niachou et al., 2001). During the first phase, extensive air and surface temperatures were measured inside and outside the building. In the second phase, the thermal properties and energy savings of the green roof were examined using a mathematical approach. Both insulated and non-insulated roof types were included in the study. The case study took place in Athens, Greece. In the instrumentation of the green roof several instruments were used to detect temperature and humidity changes on two roof surfaces, green and flat. An infrared camera measured surface temperatures. An infrared thermometer was used to measure temperature of interior and exterior surfaces. A thermometer-psychrometer measured the indoor and outdoor air temperature and the relative humidity. Temperature sensors were used to record indoor air temperatures for the study of thermal comfort conditions. Measurements were taken at a 30 minute interval for a 1.5 month period from June 30th to August 17th in 2000.

The surface temperatures of insulated buildings with and without vegetated roofs as well as non-insulated building with and without vegetated roofs were measured. The temperatures ranged based on location on the roof for the insulated buildings. Large thick vegetation kept the surface temperature between 25°- 29 °C. Sparse vegetation or bare soil areas had surface temperatures ranging from 36°- 40 °C. However, a similar temperature range was found on the hard roof insulated building were similar. White shaded surfaces had temperatures of 27 °C and white un-shaded areas rose in temperature to 40°C. A significant difference in surface temperature was found on the non-insulated buildings where the green roof held temperatures between 28°- 40 °C, while the conventional roof surface temperature reached 42°- 48 °C. For buildings with no insulation, green roofs greatly improved the thermal performance of the building.

Part of this study focused on the indoor air temperature and comfort levels. Studies were performed throughout periods of air conditioning use and with no air conditioning. The green roof kept the indoor areas cooler (in the summer months) and also decreased the temperature width- or the difference between the maximum and minimum daily temperatures. Throughout the 1.5 month measurement period, 2325 measurements were taken, with 5% of the measurements exceeding 30°C for the green roof and 18% of the measurements exceeding 30 °C for the roof with no vegetation or soil. Of those measurements, 3% of the non-green roof measurements exceeded 32 °C. No measurement under the green roof exceeded 32 °C.

A mathematical model of the thermal performance and energy savings was created by analyzing buildings with various degrees of roof insulation, with and without additional green roof layers. A separate computer model was used to estimate the mass and heat transfer in the interior of the building. Different scenarios were run to include the affects of night ventilation to varying degrees. The results showed that non-insulated roofs with no green roof had the greatest amount of heat transfer. Well insulated roofs performed the same regardless of whether a green roof was present or not. Green roofs provide the biggest benefit to buildings with low or no insulation. However, green roofs provided significant energy saving to all roof insulation types, especially when night ventilation was included in the model. The total energy consumption savings for the building models was 7% for the non-insulated roofs and 2% for the well insulated roofs.

A separate computational model that can predict green roof thermal performance was published in "The Contribution of a Planted Roof to the Thermal Protection of Buildings in Greece" (Eumorfopoulou and Aravantinos, 1998). It determined that while the green roof contributed to the thermal protection of the building, it could not replace the thermal insulation layer. Heat transfer of a green roof differs from that of a bare roof as the external climatic factors; solar radiation, external temperature, relative humidity, and wind, are all slowed down or reduced as they pass through the foliage layer of the roof. A significant part of the solar radiation is absorbed by the foliage and used for their biological functions, photosynthesis, respiration, transpiration, and evaporation. Thermal loads throughout the year also play a role in the thermal performance model. In the summer, the roof takes the greatest thermal load, 2 times greater than the south wall and 1.5 times greater than the east and west walls. However, in the winter, the walls receive the greater thermal load, with the roof only receiving 1/3 or the southern wall's load and 2/3 of the load from the east and west walls. A value of thermal transmittance, U, was calculated for a number of different roof types with varying amounts of thermal insulation, green roof layers, and vegetation densities. The resulting U value helped to model when green roofs are most applicable in the built environment. In fact, a roof with high vegetation but no thermal insulation performed at the same level as a thermally insulated bare roof.

A common conclusion among authors is that green roofs do not act as a cooling device as much as a protective and insulating device, reducing the heat flux through the roof. In "Analysis of the Green Roofs Cooling Potential in Buildings" green roof design parameters, leaf area index, soil density, thickness, and moisture content, are used to evaluate the cooling potential of green roofs (Del Barrio, 1998). The outdoor conditions affecting the mathematical equations are solar radiation flux, air temperature, relative humidity, and wind speed and direction. Heat and mass fluxes are assumed to be vertical to simplify the equations. A significant portion of the mathematical model variables are dependent on the moisture content of the growing medium, and the temperature. Another portion of the model addresses the vegetation canopy. The thermal state of the canopy is dependent on incoming solar radiation, reflective radiation, convective heat transfer, evapotranspiration, evaporation of water in the soil medium, and convective heat transfer. By modeling these factors the author found that LAI (leaf area index) played a significant role in the equations as the role of the canopy as a shadowing device was strong. The soil thickness, density, and moisture content determined its thermal diffusivity. Evapotranspiration also affected the heat flux of the roof due to the hydrothermal state of the canopy. No study was done to compare the thermal performance of the roof during the winter months.

Green roof simulation models should be included building energy simulations because of the effects that green roofs have on the heating and cooling demands. This conclusion is supported by a parametric study entitled "Summer Period Analysis of the Performance of a Planted Roof as a Passive Cooling Technique" that examined an existing construction site in the Mediterranean area and evaluated the main planted roof characteristics which affect the performance of a planted roof as a passive cooling technique (Theodosiou, 2003). Unfortunately, passive cooling techniques tend to be overlooked since they cannot be accurately included in the building simulation model. For this reason, green roofs in Greece are monitored for long-term performance so that model validation can be performed (Del Barrio, 1998). The mathematical part of this model was solved with a Gauss-Seidel method. Temperature measurements were taken at 21 nodes throughout a roof cross-section. Steady U values for the growing medium were not used due to the variation of insulative quality based on time and water content. The author used Suncode P.C. to model the case study building and added an additional module, a thermal zone above the waterproofing membrane, to model the green roof. This method allowed the programmer to model a building with a green roof using a typical building energy modeling program, and created a thermal zone above the conventional roof that affected the building's internal temperature. The study was validated by comparing the measured and calculated temperatures for the 4 node points over a 20 day summer period when the building was not in use. During this period, ventilation, internal temperature, humidity, AC function, and internal gains were controlled and monitored. The climatic file used as input consisted of data measured on the top of the building roof by a weather station. A sensitivity analysis was performed on green roof characteristics including foliage height, foliage density, soil layer thickness, type of soil medium, insulation thickness, relative humidity, and wind speed. The results showed that:

- Foliage Height: Short foliage limited the shading provided, cancelling out the affect of transpiration. A shorter foliage layer also adversely affected the ability of the layer to cool the layers surrounding it. High foliage height was more successful in keeping the building cool even in days of excessive heat.
- Foliage Density: This was dependent on LAI (leaf area index). Hot dry days were optimal for the plants and their biological process (transpiration) were successful in keeping the roof cool. However the plants kept the roof cool based more on their affect on the soil layer, keeping it shaded and cooled via transpiration, with roof cooling having less connection with the ambient air.
- Soil Layer Thickness: Values from 0.05-0.5m were chosen for evaluation. The greatest effect the soil layer thickness had on the model came from thermal inertia, where the lag and reduced variation in thermal flux was apparent. The thicker the soil layer, the longer it was able to maintain a lower temperature.
- Roof Type: When different roof types were utilized, soil thickness, foliage height and drainage layer height changed simultaneously. The combination of these factors drastically changed the thermal flux. The thicker the layers, the better the thermal performance of the roof.
- Insulation Thickness: This controls the thermal connection of the interior of the building to the ambient air temperatures. Higher insulation levels reduce heat flux and neglect the cooling ability of the green roof on the interior.
- Climate Conditions: Relative humidity and to a lesser extent, wind speed, have a significant impact on the cooling ability of the green roof. Dry windy days encourage the evapotranspiration process, while stagnant humid days slow the process.

The notion that green roofs may have a positive impact on the Urban Heat Island is supported by numerous works in addition to Del Barrio’s 1998 paper. A computational fluid dynamic (CFD) model was used to evaluate the real thermal environment of an urban area in “Measurement of Thermal Environment in Kyoto City and its Prediction by CFD Simulation” (Takahashi et al., 2004). This CFD code was then used to investigate the effect of additional green spaces (green roofs and parks) on the urban heat island and the thermal environment at street level. Intensive measurement of urban environment was performed including air temperature, surface temperature of building walls and city streets, solar radiation, long-wave radiation, sensible heat flux, and latent heat flux. The modeling and cooperating measurements show that the urban city center had a distinct air temperature difference when compared to a university campus with ample green space. It was determined that increasing green space should have a significant positive impact on the urban heat island.

Wayne Community College, North Carolina (Runoff performance)

Two green roofs experiment in North Carolina (Moran 2004a, 2004b) examined 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 where a three inch thick substrate was installed to compose a 750 square foot green roof. The other half of the roof remained covered with traditional roofing materials and became the control. The second green roof was put in place over a 290 square foot addition to the Neuseway Nature Center (NNC) in Kinston, NC in April of 2002 where the existing 1820 square foot roof was used as a control. This green roof had four inches of substrate and the same set of sedum plants were used at both WCC and NNC sites.

The WCC site was monitored for nine months from April to December of 2003, while the NNC roof was monitored for four non-consecutive months over that same period. Rainwater retention by the green roofs 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.

Buckman Terrace Apartments, Portland (Runoff performance)

Qualitative water management was performed at the Buckman Terrace Apartments complex which was built in Portland in 1999. This complex houses 150 apartments units, commercial space, and underground parking. The entire building was designed to support an eco-roof, but they were only installed over small portions as a test. The full roof area is 25,000 square feet and is divided into several smaller roofs. For example, 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 and like the entrance; an additional 750 square foot of conventional roofing drains here as well. The green roof sections consisted of American Hydrotech green roofing membranes covered by a four inch deep substrate with plantings consisting mainly of sedums. It should be noted that the only maintenance carried out on the roofs was a singular watering. The plants survived, but it was recommended that at least the grasses should be mowed the following year. Additional stormwater controls that were implemented around the site to control portions of the drainage from the conventional roof downspouts include landscaping swales and stormwater planters.

From the qualitative observations, it was determined that the roofs retained most of the rainfall as well as additional runoff from the adjacent roofs during the summer months, and runoff events from the green roofs were rare occurrences. In the winter, runoff occurred more frequently, but water was detained.

After evaluating the data from the Buckman Terrace apartment that found green roofs to be effective in water management, the same group in Portland moved forward and constructed a full sized two sections eco-roof on the ten-story Hamilton Apartments in late 1999. The east side of the building has a 2520 square foot green roof with three inches of substrate and the western eco-roof 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. However, due to wind erosion, approximately one inch of substrate was lost across both sides of the roof and the group subsequently installed an irrigation system to prevent further substrate loss. The irrigation system was used after the initial plantings and the group has goals to reduce the amount of water applied to the roof through irrigation overtime until the roof is completely self sufficient.

Over the course of the study period, January 2002 to April 2003, the western eco-roof retained 69 percent of the rainfall. The eastern eco-roof data was not reported since additional water flowed onto it from the mechanical penthouse that had conventional roof and separate drainage system during most rainfall events. The water retention rates increased over 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 rainfall pattern likely account for these differences as in 2002, the rainfall was relatively evenly distributed, whereas the 2003 rainfall included several long periods without rain. The researchers hypothesized that these periods allow for more evapotranspiration and drying of the soil structure, allowing more adsorption capacity during rainfall events 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.

Pennsylvania State University (Runoff performance)

The Pennsylvania State University conducted a pilot project by constructing six small buildings with 48 square feet of roof space and installing three green roofs with identical membranes, soil and sedum plants, and three conventional roofs. The thermal and stormwater benefits attributed to green roofs were determined by comparing the three green roofs with three roofs covered with traditional roofing materials.

Data from 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).

Given the wide variety and breadth of experiments conducted to date, the effects of each installation may vary widely by season and rainfall pattern. For these reasons, it is suggested by most authors that more computational and real evaluations of the performances of green roofs in place need to occur in order to accurately and dependably evaluate the contribution to reducing stormwater and contributions to the Urban Heat Island effect made by green roofs.

3. *3* RIVERS WET WEATHER GREEN ROOF DEMONSTRATION PROJECT

The 3 Rivers Wet Weather (3RWW) is a non-profit organization that with a mission of determining sustainable and cost effective ways to improve Pittsburgh's water quality long into the future. Stormwater management and the combined sewer overflow problem are two of the main of concern to solve for 3RWW. The organization provided funding for the Green Roof Demonstration Project that consisted of three green roof projects that were built and studied in Pittsburgh. Each project contains a green roof and some type of conventional roof. Monitoring equipment was installed on each section of roof, with the conventional roof serving as a control for comparison purposes. While the primary concern of 3RWW is stormwater, temperature monitoring was acquired data to determine the temperature benefits of green roofs as well. The results reported herein detail the evaluations of two of the three sites and includes data pertaining to the performance of the green roof when compared to the conventional roof at each site. An additional comparison between extensive and intensive roofs is drawn using the data collected.

Two green roof evaluations were conducted at different locations and were implemented according to construction timeframes of the building owners. Data was collected from the time of installation to April 2009. The larger of the roofs by area is the Shadyside Giant Eagle green roof. It is located in the Shadyside neighborhood of Pittsburgh on a site of a collocated grocery store and condominiums. Construction of the roof was completed in July 2006 and available data described in this report were from July 2006 to December 2007. The second project, which was implemented through April 2008 to April 2009, is located on the roof of a remodeled mixed commercial and residential use building in Homestead, PA. While much smaller than the Giant Eagle project, a similar monitoring plan was carried out for the Homestead roof.

3.1 The Shadyside Giant Eagle Location

The Shadyside Giant Eagle was expanded in 2006 to encompass an area formerly occupied by the original supermarket, several commercial buildings, a parking garage, as well as several houses and an apartment building. The store itself was more than doubled in size, a two-story parking garage was built beneath the structure, and seventy-eight condos occupy five-stories built above the rear of the supermarket. Without the green roof, this development would have dramatically increased the impervious area and contributed to an increase in demand on the sewer system.

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 3-1 summarizes the soil properties. A mix of plants was installed but the majority was 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 and served as the control for all observations. Photographs of the control roof and the green roof just after construction are presented in Figure 3-1.

Table 3-1 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 µmhos/cm (1:20 dilution)

(a) Control Roof

(b) Green Roof

Figure 3-1 Post-installation photographs of the Shadyside Giant Eagle control roof and green roof

Monitoring Site Locations

Four monitoring stations were placed on the Giant Eagle site; two on the green roof and the other two were placed on the conventional roof. The sites over the green roof are referred to in this report as A and B and the sites on the conventional roof are C and D and the general location of these sites are indicated in Figure 3-2. The location of each site was chosen so that the influence of one site on the other attributable to the environment and wind should be minimal. The four sites over the roof area were placed away from the drainage areas of the roof so the measurements remain accurate. A is 40 feet from left edge of the building and 48 feet from the north facing wall of the apartment structure. B is 40 feet from the right edge of the building and 48 feet from the north facing wall of the structure. The conventional roof stations, C and D, are 92 feet directly north from the corresponding green roof measurement sites.

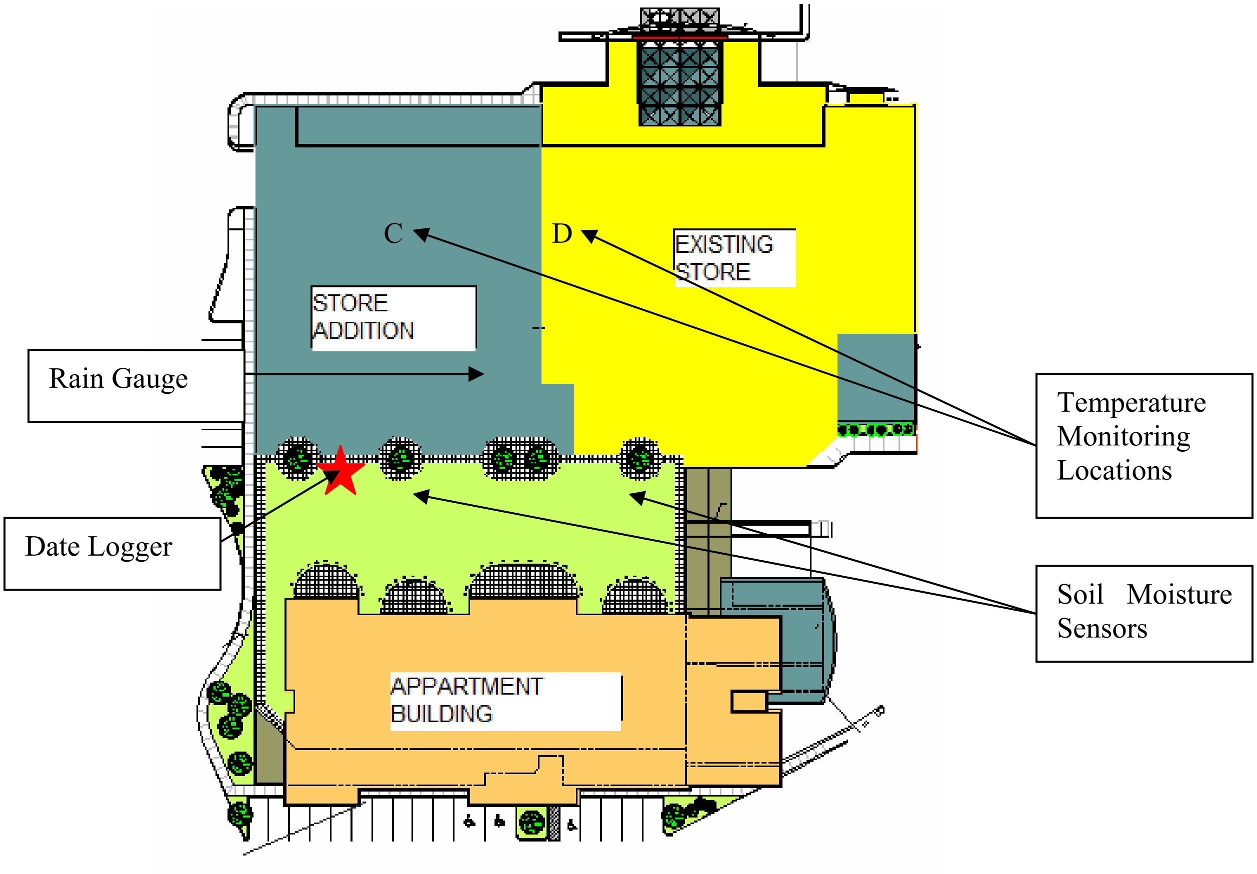

Figure 3-2 Monitoring locations at the Shadyside Giant Eagle roof.

Soil Moisture sensors were positioned at locations A and B. Solar radiation, heat flux, and relative humidity were each measured at two temperature locations, A and C. Wind speed and direction was measured only at location C. Finally, a rain gauge was located on the control roof, between temperature locations C and D.

One roof drain from each of the green and control roofs was separated from the rest of the roof drainage system. These two drains drain similar 3530 square foot areas of the conventional rock-ballasted roof and green roof. The drainage from these two is directed street level to an area next to the parking lot and garage for the supermarket. The flow is directed into 2 flumes, one for each the green roof and control roof drainage, measured with ultrasonic sensors to determine the amount of flow.

Some precautions were taken in the installation of each instrument to minimize adverse influence in the measurements for the green roof portion of the project. Variables such as plant placement were considered when finalizing the location of the monitoring stations. Constant shade may adversely skew the measurements. The layout of the entire supermarket and apartment complex site must also be considered when placing the instruments and measuring stations. The five-story apartment building structure is at the south end of the site. The green roof is situated just north of this structure. This means that the green roof will be shaded from direct sunlight by the apartment building at certain times during the day. Unfortunately the location of the green roof relative to the apartment building was non-negotiable. Thus, the effect of this shade should be considered when analyzing the results from this experiment. Wind current had some effect on all temperature measurements. All four measurement stations were positioned a minimum of 100 feet from all vents and mechanical equipment to keep the wind influences to minimum.

Measured Variables and Instrumentation

This section describes the specific instruments used to monitor the two types of roofs at the Giant Eagle location. Each of the following weather and temperature measurements is necessary to determine how green roofs perform differently from conventional roofs.

Relative Humidity

Two monitoring locations, A and C, have a HMP 45C Temperature and Relative Humidity Probes. This probe monitors the relative humidity near the surface level. It was placed 24”above the roof surface in a radiation shield. For location both locations A and C, the RH probe will simultaneously measure relative humidity and ambient temperature, eliminating the need for multiple pieces of equipment in the same location.

The relative humidity measurement is an important parameter to measure above the green roof because relative humidity affects the rate at which the vegetation transpires. Generally, the less humid it is, the more plants transpire. The more plants transpire, the greater the cooling effect for the green roof. The purpose of monitoring the relative humidity on the roof is to determine if humidity is a significant indicator for green roof performance. The sensor was placed in the vegetation layer to monitor the microclimate at that layer.

As noted, each RH probe was housed in a radiation shield. They require the DC042 12-plate Gill Radiation Shield and Adaptor. For each instrument there was a lead length, or the length of cable between the instrument and the data logger. Ideally, the HMP 45C allows for 6 feet of lead length, but this can be adjusted for longer lengths. The approximate error for lead length is 0.56 °C for temperature and 0.56% for relative humidity per 100 feet of lead length. Maintenance for the RH probe is minimal. The radiation shield and sensor were checked for contaminants and debris monthly. If needed, the sensor was rinsed with distilled water to remove debris. Finally, the RH sensor was recalibrated by Campbell Scientific annually. A picture of the RH sensor in a radiation shield at the site location is shown in Figure 3-3.

Roof, Growing Media, and Plant Level Air Temperatures

All temperature measurements acquired from monitoring stations A, B, C and D. All four stations were designed so the temperature measurements were symmetric at all four locations, with additional measurements taken in the additional layers necessary for the green roof. The temperature measurements were taken with three different probes depending on the specific probe location: a thermocouple wire, HMP 45C Relative Humidity and Temperature Probes, and Model 107AT Temperature Probes. These sensors were set up to measure a temperature profile vertically throughout the green and conventional roof structures. The thermocouples were used to measure temperature throughout the roof structural system; below the corrugated steel deck, above the steel deck, above the insulation, and below the waterproofing membrane; on the surface; and at 7, 15, 30, 60, and 100 cm above the roof surface. The thermocouples exposed to the outside environment needed to be shielded from solar radiation. A simple, aluminum foil-covered, open-air wooden shelter structure was constructed to protect each above surface monitoring point. Additional soil temperature measurements were obtained with the temperature probes. The model 107 temperature probes were buried 3” into the soil substrate on the green roof. The ambient air temperature was monitored by the dual function HMP 45C probes, which are built into radiation shield (Figure 3-3). The temperature profile created is described in
Table 3-2.

Figure 3-3 Relative humidity sensor for recording ambient air temperature and relative humidity in radiation shield (Giant Eagle)

Table 3-2 Temperature Measurement Locations

Horizon ID	Temperature Measurement Location
Overall Ambient	Taken by RH Probe 12" above surface at locations A and C only.
Ambient 1m	Attached to pole 1 meter above roof surface.
Ambient 60cm	Attached to pole 60 cm above roof surface.
Ambient 30cm	Attached to pole 30 cm above roof surface.
Ambient 15 cm	Attached to pole 15 cm above roof surface (above vegetation).
Ambient 7cm	Attached to pole 7 cm above roof surface (just above vegetation)
Surface	Placed on Roof or Soil Surface
Soil	**Buried in planting medium at ½ depth (green roof only).**
Filter Membrane	Just above the filter membrane, sealed in insulation (green roof only).
Drainage Layer	Below Drainage Layer (green roof only).
Waterproofing Membrane	Just below the impermeable membrane, sealed in insulation (both green and conventional roof).
Support Panel	Just below support panel.
Insulation	At the bottom of the insulation layer.
Roof Deck	Just below the roof decking.

Black denotes Thermocouple used.

Bold denotes 107 Temperature Probe used.

Underline denotes RH sensor used.

The temperature profile created by these measurements provided data on the thermal performance of both roofs. The temperatures taken at the different locations within the roof itself provided data used to determine the insulation properties thermal transmittance of each structural layer, as well as the layers of the green roof (Eumorfopoulou, 1998 and Niachou, 2001). These data as well as the temperature readings above the roof surface measure the temperature differential between the roof surface and the air above it (Wong et al, 2003a). They were vital in documenting and modeling the heat flux through the roof structures (Del Barrio, 1998). The actual structure assembly that was built for the temperature measurement locations are based on those depicted in the Ottawa campus experiment (Liu, 2003).

In addition to the temperature monitoring sites below, on, and above the roof surface, two supplementary RH sensors were used to provide additional data. These supplementary measurements from the relative humidity sensors provide the ambient temperature for the site. Since the sensor is protected by a radiation shield, it should provide an accurate ambient temperature, not influenced by radiating or reflected heat from the surrounding building or from the sun.

The 107 Temperature Probes can have lead lengths up to 1000 feet. Precautions must be taken in electronically "noisy" environments. AC power lines can affect the measurements. A 60 MHz rejection filter should be used if the probe is in an electronically noisy environment. The maintenance requirements for the temperature probes are minimal. The radiation shield was checked monthly for debris. Calibration was not needed after the instruments are set up. Thermocouple wire was purchased from Omega and was installed as shown in Figure 3-4.

Figure 3-4 Thermocouple wire for temperature monitoring Attached to Tripod (Giant Eagle)

Incident Solar Radiation and Long-wave Radiation

One site over both the conventional and green roof (at locations A and C) each housed a Net Radiometer, or high-output thermopile sensor, which measured all incoming and outgoing radiation. The sensors were mounted on a tripod roughly 40cm above the roof or vegetation surface (Wong et al, 2003a). The sensor head was aligned so that it pointed south. The sensor had a wind shield pre-installed to minimize the effect convective cooling on the sensor.

Incident and long-wave radiation measurements were very important to this project. The measurement of incident solar radiation was needed to determine the amount of energy received from the sun. This was important to determine the energy balance of the roof (Del Barrio, 1998). The long-wave radiation indicated the amount of energy the roof or vegetation is reflecting. The instrument output was the algebraic sum of short and long wave radiation and was out-putted by the instrument and sent to the data logger. Both incident and long-wave radiation was used in the mathematical model created by Del Barrio in analyzing the cooling potential of green roofed buildings.

The Net Radiometer (Figure 3-5) is a sensitive instrument. It is sensitive to the convective cooling effect wind has on the sensor area. This effect can be compensated for using a correction factor given by the manufacturer. The desiccant needs to be inspected monthly to make sure the gel is blue and white in color. If it turns pink, the gel needs to be replaced which occurs commonly in wet weather. Condensation on the wind shield can block the long-wave radiation reading. An RV2 ventilator was installed per recommendation of the vendor to prevent condensation. The windshields was inspected often and cleaned as needed with distilled water, and replaced on a regular schedule (every 3-6 months). A series of wire ties were used to keep birds from standing on the long arm of the sensor since that part was particularly fragile.

Figure 3-5 Net radiometer for measuring net radiation at the roof surface (Giant Eagle)

Wind Speed and Direction

Wind Speed and direction is another important measurement that was measured using a Young Wind Sentry Anemometer (Figure 3-6). The Sentry Anemometer was placed upwind of eddy causing obstructions as indicated in the map (Figure 3-2). The Sentry anemometer was used to measure the wind speed of the microclimate around the green and control roof. A single instrument was placed in the center of the four monitoring points to generate an overall wind speed for the site. Wind speed is used as another factor in modeling the productivity of the plants of the green roof. Generally, as wind speed increases, so does the ability of the plants to transpire, creating a greater cooling effect.

Figure 3-6 Wind Sentry Set (Giant Eagle)

Rain gauge

A Hydrologic Services RG703 8 inch tipping Bucket Rain Gauge (Figure 3-7) 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 data-logging system. The rain gauge not only acquired measurements 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.

Figure 3-7 Rain Gauge Installed on the Green Roof (Giant Eagle)

Flumes and ultrasonic sensors

To measure the runoff created by each roof, two Tracom 60-degree Extra Large Trapezoidal Flumes (Figure 3-8) were installed and Greyline Instruments LIT25 (Level Indicating Transmitter) Ultrasonic sensors (Figure 3-9) measured the flow through them. The flumes were essentially open pipes, but had a known trapezoid shape, on the upstream side of the flume. By measuring the depth of water at that point, the volume of water in the flume at that instant was calculated using the known dimensions.

Figure 3-8 Two flumes (circled) for discharging stormwater runoff (Giant Eagle)

Figure 3-9 Ultrasonic sensors installed atop the flumes for measuring stormwater runoff (Giant Eagle)

Soil Moisture

Soil moisture is an important parameter that affects the quantity and timing of stormwater runoff. During a rainstorm, the pores in the soil absorb water. As the storm progresses, the soil becomes saturated and reaches its saturated storage point. Past the saturation point, green roofs act similarly to a conventional roofs in regards to runoff quantity, but has delayed the onset of runoff as the water filters through the soil and fills the pores. Because of this process, it is important to monitor the moisture content of the soil both before and during a storm. The drier the soil is when a storm begins, the greater the amount of runoff reduction is possible. In order to monitor this process, two Campbell Scientific SM616 Soil Water Content Sensors (Figure 3-10) 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, whereas soil does not, so any changes in the permittivity are a result of a change in water content. The volume of soil on the roof is known; therefore the amount of water within the soil at each point in time can be calculated. The rate of absorption can be calculated by dividing the volumetric water content by the time in between readings.

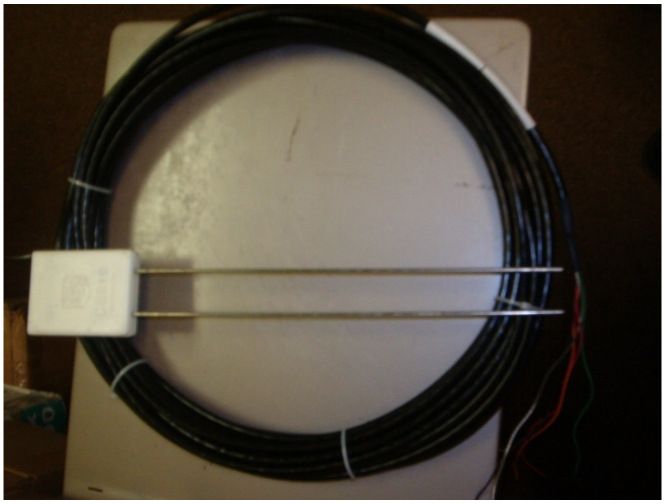

Figure 3-10 Soil Moisture Sensor

Water Collection System

In addition to water quantity monitoring and data collection, a collection system at the site was installed to acquire grab samples to bring to the lab in order to determine qualitative data on the affect of green roofs on water quality:

Runoff samples were collected by a system constructed on site located in the water flow after it passed through the flumes, so as not to affect runoff rate and volume measurements. Samples were collected before the green and control roof drainage pipes were combined and entered 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 was 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 3-11 shows the collection system connected to the green roof flume. These solenoid valves were normally closed and were opened when energized. Each of the valves was connected to a 500 mL low density polyethylene sample bottle (Figure 3-12). The valves were controlled by the datalogger located on the roof. Each of the six valves was programmed to open at a set value of cumulative runoff. Since runoff began at different times and flowed at different rates on the green and control roofs, this system allowed the samples to be time-matched from both roofs. Further, the series of valves allowed for samples to be taken at six different points during a storm. With samples taken in this manner, the first flush effect was studied. Less specifically, it let the changes in water quality throughout the storm be tracked. 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 3-11 Solenoid Valve Sampling Manifold (Giant Eagle)

Figure 3-12 Solenoid Valves and Sample Bottles

Six solenoid valves were attached to each flume with its collection pipe (Giant Eagle)

Water Quality testing

At the site, the samples were collected in 500 mL LDPE (low density polyethylene) plastic bottles. The pH was measured (Oakton pHTestr 30) on-site to minimize error in the measurement that may occur as the sample ages. The unit provides a digital readout of the pH to a hundredth of a unit along with the water temperature. Turbidity tests were performed on the unfiltered samples to assess the amount of suspended particles in the water. The turbidity of the temporally separated samples was measured following the nephelometric method (2130 B) from *Standard Methods* (1992) using a HACH Model 2100A Turbidimeter.

The samples were brought back to the University of Pittsburgh's Environmental Engineering laboratories, and half of each sample was vacuum filtered using 0.45 µm (nominal pore size) cellulose membrane filter (Hunt 1986) and stored in a separate LDPE bottle for later use. In these cases, the filtered samples represent the levels of dissolved contaminant, while the unfiltered samples represent the non-dissolved portion. Analyses for metals used only the filtered samples because fine particulate may interfere with the atomic absorption analysis. For all other experiments, both the filtered and unfiltered samples were tested according to EPA approved methods. In cases where HACH analysis kits were used, the exact procedure for each analysis is outlined in the *HACH Water Analysis Handbook* (2003).

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 reaction set converts all forms of nitrogen to nitrate and detected concentrations in the range of 0.5 to 25.0 mg/L. At the conclusion of testing, absorbance was measured at a wavelength of 410 nm and compared to standards.

Phosphorus: Phosphorus testing followed HACH Method 8048, 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.

Sulfate

Testing for sulfate in water samples followed HACH Water Analysis Handbook (2003) Method 8051 and detected levels from 2 to 70 mg/L. This turbidimetric procedure is equivalent to USEPA Method 375.4 which converts sulfate to a barium sulfate suspension. The turbidity of the suspension was measured. The turbidity is proportional to the sulfate concentration (USEPA 1983) and determined by comparison to known standards.

Chemical Oxygen Demand

COD analysis was performed to test the oxygen demand of the waters exiting the two roofs using HACH Method 8000 following the procedure outlined in the 2003 edition of HACH Water Analysis Handbook. This test analyzes the oxygen equivalent of the amount of organic matter oxidizable by potassium dichromate via two reactions over three hours and was chosen as a more time efficient determination of the oxygen demand than the five of seven day BOD analysis. 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. Two detection ranges were used for the project: the ultra low range (0.7 to 40.0 mg/L) tests for higher resolution and the low range tests (3 to 150 mg/L) were used when the ultra low range results were saturated. The steps to prepare the samples were identical regardless of the range differing only in the analytical wavelength where 365 nm was used for the ultra low range and 420 nm was used for the low range.

Metals Analysis via Atomic Absorption Spectrometry

In order to test for Lead (Pb), zinc (Zn) and Cadmium (Cd), Atomic Absorption Spectrometry (AAS) following the procedures outlined in Section 3111 of *Standard Methods* (1992). The concentration of each substance was determined using its absorption of light at a particular wavelength and comparing it to the absorbencies of known standards using Beer's Law. In all tests for metals, the Giant Eagle samples were undigested, filtered samples. Acid digestion was performed on the pilot project samples prior to the full scale testing to determine if digestion was need for all samples. For each element, a set of standards at various known concentrations was created before analysis began. Along with a blank of de-ionized water, the absorbance of each standard was measured to create a standard curve. Each water sample was then tested. The absorbance was recorded and the concentration was determined after testing using the equation of the standard curve. In between each reading of a standard or water sample, a reading was taken with de-ionized water to ensure that there was no residual sample in the sample uptake tube. At the conclusion of testing, the set of standards was run to check for any drift of the standard curve. The testing procedure was identical for the three metals of interest: lead (Pb), zinc (Zn) and cadmium (Cd).

Solids

Solids testing (TS, TSS, TDS, and VSS) were performed once all the samples were acquired to take advantage of better efficiency with scales of processing. Solids measurements were performed as outlined in EPA method 160.

Datalogging & Programming

A National Instruments Fieldpoint datalogging system was used as the control center for the project; with components that operated all the equipment, recorded all of data, and transmitted it to a server. The Fieldpoint system housed in a six foot long weatherproof metal enclosure and was comprised of two banks of modular units. Both banks contained a power supply (PS-4 module) and a network module (FP-2000), as well as data modules. The network module contained an Ethernet port that allows the bank of Fieldpoint units to communicate with computers, both directly and remotely over the internet. The units also contain a small computer, which allowed simple programs to be run on the unit as well as hosted web pages. Through communication with the network modules, the data that was transmitted from the other units was stored, displayed and studied on campus. The Fieldpoint units were connected inline, with the network module in the first position.

The largest bank of modules received the majority of the data from the thermocouples and controls the solenoid valves. There were five FP-TC-120 units, each accepting eight thermocouples. One FP-CTR-502 counter module recorded the rainfall. The smaller Fieldpoint bank contained a FP-DO-401 and two AI-100 analog input modules that acquired data from all of the equipment on the roof, with the exception of the thermocouples, rain gauge and solenoid valves. The analog input modules were able to accept both voltages and currents that were output by the equipment. The majority of the equipment on this bank was able to draw its power continuously, which was done from the analog input modules. To avoid overheating, the 107-L temperature sensors, wind direction, and soil moisture sensors were only powered when a reading was taken. The digital output module was used to control when these pieces of equipment were energized. At the end of the smaller Fieldpoint bank there was one thermocouple module for the eight additional thermocouples on the roof. Figure 3-13shows the dataloggers prior to installation. For both banks of modules, the first unit on the left was the network module. The others were installed in order as they were described above.

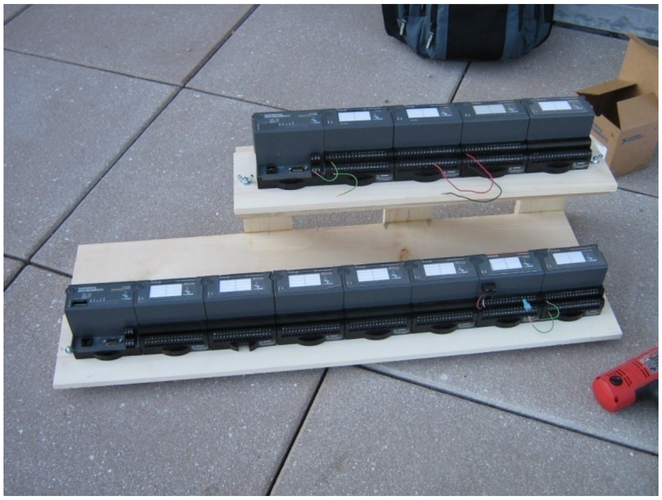

Figure 3-13 National Instrument Fieldpoint Dataloggers.

Thirteen dataloggers were divided into two banks and installed at each location.

To control the equipment, a program was written using National Instrument's LabVIEW 8.0. Briefly, the program acquires data from the Fieldpoint units, and converts the voltage data to a usable form. This data was stored on a server at the University of Pittsburgh and could be displayed in real time on a website hosted by the same server.

3.2 The Homestead Green Roof

The Homestead green roof is located on a 98-year old, four story building in the historic district of Homestead, PA that was structurally stabilized and remodeled after a fire had damaged the upper floors. The green roof was installed in July 2007 and the building remodeling was completed in April 2008.

There are a few key differences between the Shadyside and Homestead green roofs. The most important difference is in the structure of green roofs. The Shadyside green roof is composed of a five and a half inch thick growing ("soil") media placed above the filter fabric and drainage layers. The cross section of the Giant Eagle green roof is similar to a typical green roof as shown in Figure 3-14. The Homestead green roof, on the other hand, has a one and a half inch thick growing media that covers a series of water reservoirs. All water reservoirs are interconnected through holes on its upper portion for drainage purposes. These water reservoirs are able to retain part of stormwater when rainfall comes and the water retained is stored for plant irrigation during dry periods. An illustration of the green roof system manufactured by Green Living Technologies, L.L.C. (GLT) that was installed at the Homestead site is shown in Figure 3-15.

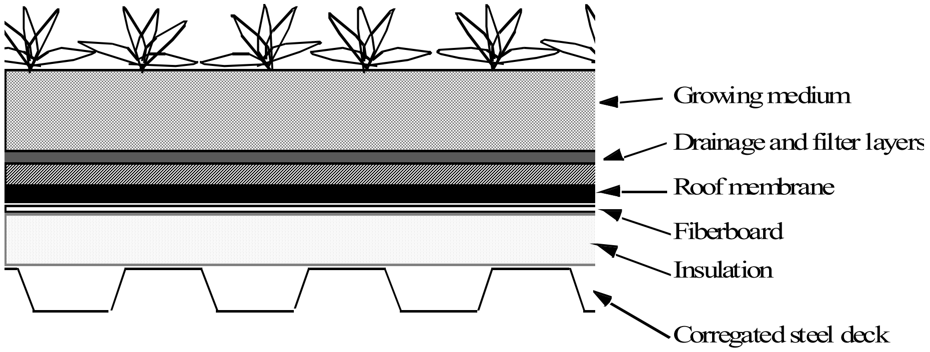

Figure 3-14 Typical Green Roof Cross-Section (similar to Giant Eagle)

Figure 3-15 GLT Green Roof system Cross-Section similar to the one installed at the Homestead site.

(Source: Green Living Technologies, LLC http://www.agreenroof.com/)

Several factors were considered when choosing the green roof technology for the Homestead site. The weight of the roof was a significant consideration factor for the Homestead site, and since the GLT roof is thinner, the roof is also lighter compared to the thick Shadyside Giant Eagle green roof. Thus the lighter GLT roof was more suitable for the Homestead building since it was an existing construction and no structural modifications were needed to accommodate the additional load of the green roof. Another consideration is that the roof at the Homestead site slopes at an angle of ten degrees. The compartmentalized GLT system is more suited for sloping roofs than the conventional layered systems. Also since the GLT system is paneled it is easier to transport and install as it can be cut into irregular shapes to fit around roof top objects.

Photographs of green roof and control roof located at Homestead are shown in Figure 3-16 and Figure 3-17 respectively. Each roof covers approximately 2000 square feet. A small paver-based sidewalk across the green roof gives people access to the roof. The control roof is covered with a waterproofing membrane and separated from the green roof by a parapet wall.

Figure 3-16 GLT Green Roof at Homestead

Figure 3-17 Control Roof at Homestead

Two monitoring locations, one on each roof, were installed at the Homestead site. There are fewer stations at this site than at the Giant Eagle roofs because the two 2000 sq. ft Homestead roofs are considerably smaller. The two monitoring systems were placed on two separate tripods and are shown on the green and control roof in Figure 3-16 and Figure 3-17 respectively. At each monitoring station, thermocouples were placed at the roof surface, and at 7, 15, 30, 60, and 100 cm above the surface. No thermocouples could be placed below the roof surface on the control roof side. In fact, thermocouples internal to the roof could not be placed at Homestead since it was not practical to install them in this older existing structure. On the green roof side, one thermocouple was placed below the green roof panels, and the other was placed below the structural ceiling of the lower floor. The remaining set up of the roof sensors was similar to the Giant Eagle system. During the monitoring phase, the soil moisture sensor and the thermocouple underneath the structural ceiling on the control roof side stopped working and due to a lack of accessibility repair efforts were unsuccessful.

For runoff monitoring, two separate drains conducted all the runoff from the two roofs to the basement (Figure 3-18). In the basement, two weir boxes (V-notch at thirty degrees angle) were installed to receive the runoff. Ultrasonic sensors (Figure 3-19) mounted approximately 1.5 feet above the top of the weirs, measure the change in head before the weir edge. The standard head-discharge relationship was used to calculate the runoff through the weirs. The data collection and recording system (Figure 3-20) was the same as the Giant Eagle system described previously.

Figure 3-18 Drainage system at Homestead Site (located in the basement of the building). The weir next to the wall was used for the control roof and the other for the green roof.

Figure 3-19 Ultrasonic sensors monitored changes in water level over weirs at the Homestead Site.

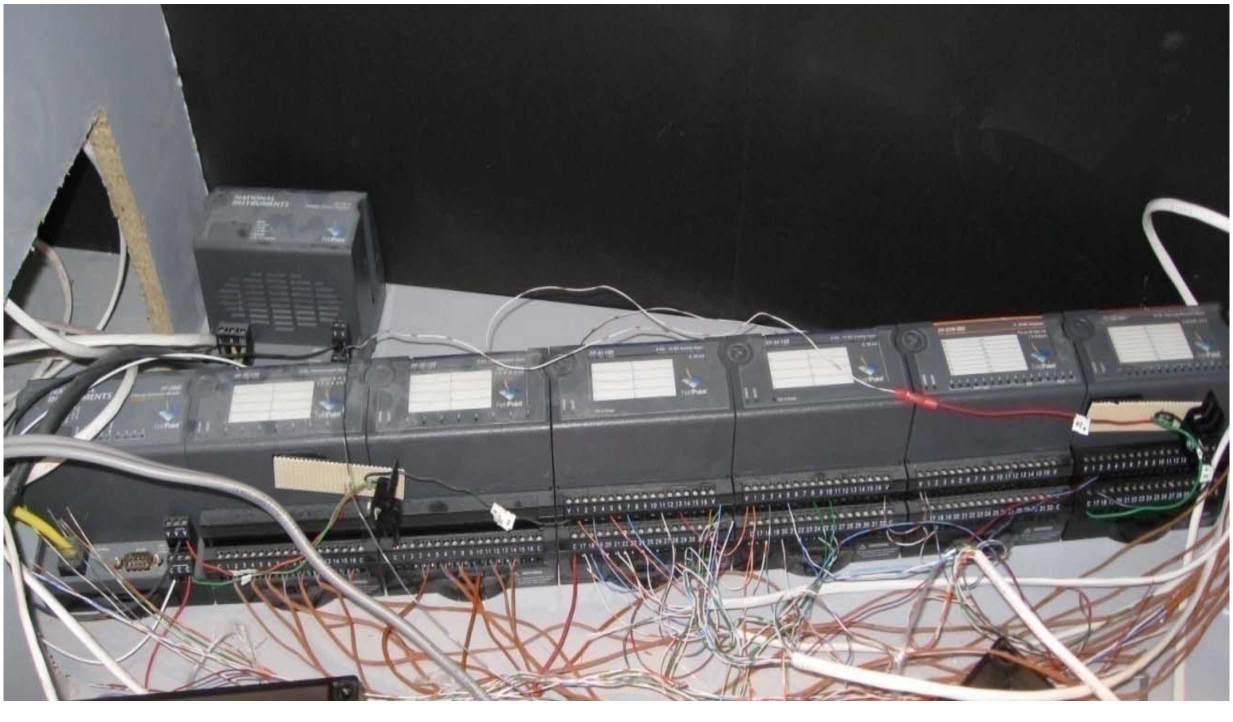

Figure 3-20 National Instruments Fieldpoint Dataloggers at Homestead Site

The runoff sample collection system (Figure 3-21) installed at the Homestead site was slightly different compared to the system that was installed Giant Eagle site. The water sample collection system at Homestead consisted of a set of collection traps that was installed below the major drainage pipe and allowed samples to be collected before draining into the weir boxes. Below each trap, a solenoid valve (circled in Figure 3-21) was connected with a 500mL polyethylene sample bottle via a hose. For each stormwater discharge event, the runoff was collected and stored in a sample bottle. Since only one valve was installed for each trap system, the operation of the valves was much simpler than the one at Giant Eagle site; for the Homestead roofs, each valve is programmed to open and close only once during a storm, whereas for the Giant Eagle site, valves open and close at different time points. After the samples were collected, they were brought to the Environmental Engineering Laboratory at the University of Pittsburgh for analsys. The data obtained from runoff samples collected at Homestead site are presented in herein.

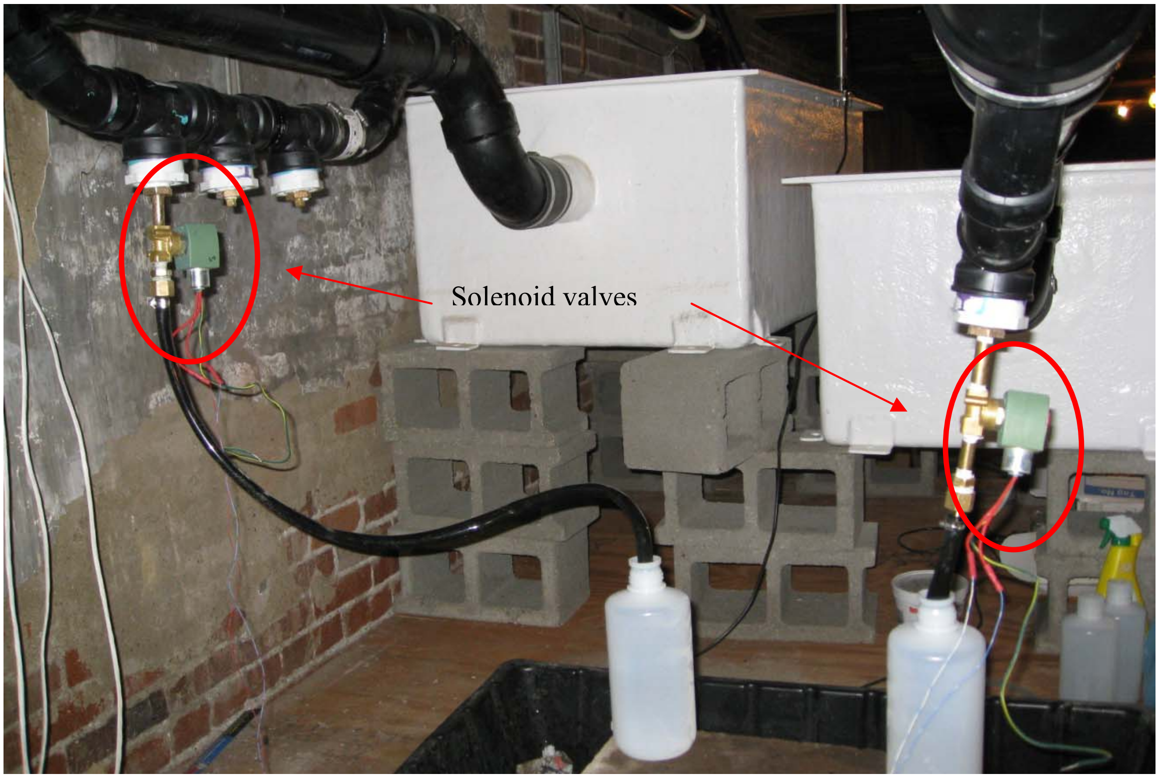

Figure 3-21 Runoff sample collection system at Homestead site.

One solenoid valve (circled) was attached to each weir box which allowed a timed sample to be acquired via tubing into a polyethylene sample bottle.

The green roof technology and data acquisition systems installed at each site differed slightly. A summary of the major parameters and measuring instruments used to the measure performance of the two green roof technologies are listed in Table 3-3.

Table 3-3 Comparative features of Giant Eagle and Homestead site

	Giant Eagle ***(thick green roof)***	**Homestead** ***(thin green roof)***
Size of roofs (drainage area)	Green roof: 3530 sq. ft. Control roof: 3530 sq. ft.	Green roof: 2000 sq. ft. Control roof: 2000 sq. ft.
Water discharging systems	2 flumes	2 weir boxes
Sample collection systems	6 solenoid valves for each roof	1 solenoid valve for each roof
Monitoring techniques	Ultrasonic sensor, thermocouple, rain gauge, soil moisture sensor, temperature and relative humidity probe, solar radiation,	
Recording techniques	13 dataloggers	8 dataloggers
	National Instruments LabVIEW 8.0, National Instrument Measurement and Automation, National Instruments DIAdem 9.1 (for data output)	

4. RESULTS AND DISCUSSION

The data collected at Shadyside Giant Eagle during the first period of the study (from July 2006 to December 2007) are presented in this section. The analysis is divided into two subsections, one each for runoff performance and thermal performance. In this section, the description of runoff performances and thermal performance were referred to as Bliss (2007, 2009) and Kosareo (2007), respectively.

4.1 Giant Eagle Runoff performance

Through the end of January 2007, a total of 24 storm events were recorded. 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. The data acquired during these storms are summarized in Table 4-1. A subset of these storms is discussed in this section to highlight the benefits of green roofs over a range of storms with different properties.

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 measure how the water retention effectiveness of a green roof varies as a storm progresses.

$$\%\ reduction = \frac{V_C - V_G}{V_C} \cdot 100$$

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

Runoff from the control roof or from rainfall sensors (as appropriate) was normalized to the roof area and converted to “inches of rain”. 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] and SA = Surface Area [sf]

Table 4-1 Summary of observed storms during July 2006 to January 2007

Date	Rainfall		Runoff		Max Flow Rate (cfs)			Total Volume (cf)			Equiv. in. Rain	
	Depth (in)	**Length**	**Delay (hr)**	**Exten. (hr)**	**Green**	**Control**	**Reduc.**	**Green**	**Control**	**Reduc.**	**Green**	**Control**
7/28/2006 #1			0:02	4:01	0.0696	0.1542	55%	106.29	147.01	28%	0.36	0.5
7/28/2006 #2			1:57	1:05	0.0032	0.0015	-53%	20.55	6.42	-69%	0.07	0.02
7/30/2006 #1			0:01	1:29	0.0081	0.235	66%	36.6	44.4	18%	0.12	0.15
7/30/2006 #2			0:00	- 1:14	0.0903	0.1455	38%	112.58	100.76	-11%	0.38	0.34
8/27/2006	0.59	15:25	0:02	2:36	0.0375	0.0472	21%	116.45	147.08	21%	0.4	0.5
8/28/2006 *	0.23	8:39	6:03	3:00	0.0142	0.0173	18%	59.43	66.36	10%	0.2	0.23
9/2/2006 *	0.84	14:39	5:08	2:01	0.0108	0.0127	15%	266.26	274.27	3%	0.91	0.93
9/5/2006 *	0.23	3:59	- 1:20	2:24	0.0053	0.007	25%	48.46	54.98	12%	0.16	0.19
9/19/2006 *	0.12	3:50	- 1:40	4:56	0.0015	0.0017	12%	14.19	14.91	15%	0.05	0.05
9/28/2006 *	0.45	8:21	- 1:31	12:51	0.0115	0.0121	5%	65.17	66.44	2%	0.22	0.23
10/17/2006	1.94	10:05	0:16	4:43	0.0415	0.0586	29%	413.91	513.51	19%	1.41	1.75
10/19/2006	1.73	1 Day, 16:31	0:00	1:04	0.0301	0.0443	32%	448.62	470.29	5%	1.52	1.6
10/27/2006	1.2	23:47	0:30	6:46	0.0181	0.0216	16%	281.57	343.8	18%	0.96	1.17
10/31/2006	0.19	5:14	0:26	0:10	0.001	0.0035	71%	11.2	35.62	69%	0.04	0.12
11/1/2006	0.07	2:08	0:55	3:57	0.0005	0.0009	38%	3.44	10.14	66%	0.01	0.03
11/11/2006	0.57	15:13	4:09	3:09	0.0164	0.0236	30%	94.04	134.21	30%	0.32	0.46
11/15/2006	1.49	1 Day, 10:57	0:17	0:57	0.0217	0.0348	38%	333.93	408.79	18%	1.14	1.39
11/19/2006	0.17	11:10	0:03	1:30	0.0007	0.0021	65%	5.35	16.63	68%	0.02	0.06
12/1/2006	0.59	0:36	0:01	1:10	0.0288	0.0401	28%	73.67	93.28	21%	0.25	0.32
1/5/2007	0.69	20:24	0:02	2:27	0.0081	0.0085	5%	161.04	197.55	19%	0.55	0.67
1/8/2007	0.48	16:47	0:05	0:48	0.0065	0.0091	28%	95.19	120.81	21%	0.32	0.41
1/12 - 1/15/07	2.2	3 days, 3:49	0:01	11:44	0.0121	0.0115	-5%	568.54	611.91	7%	1.93	2.08

* The green roof flow characteristics are adjusted for runoff due to irrigation.

Extn: green roof runoff time after the storm. **Delay:** time difference of initial runoff between green and control roof.

November 11, 2006 Storm

The November 11, 2006 storm was made up of three periods of heavier rain interspersed with lighter rainfall and resulted in 0.57 inches of rain being deposited on the Giant Eagle roof over an approximately 15-hour period. Of the 0.57 inches of rainfall, 0.32 inches became runoff on the green roof and 0.46 inches of the 0.57 inches became runoff from the control roof as shown in Figure 4-1.

The runoff flow volumes were observed to be correlated with rainfall. The control roof began to produce runoff during the first period of heavier rain, about one hour and ten minutes after the rainfall begins. The green roof, however, did not begin to produce runoff until four hours and ten minutes later (nearly five and a half hours after the storm began) and there was a two hour delay between the time the control roof and the green roof reached their peak flows. This initial difference for the runoff flow volumes is shown in Figure 4-2, and continues to be present throughout the storm. There was also a very significant difference in flow rate between the two roofs when the control peaked. When the control roof reached its storm maximum of 0.024 cfs, the green roof was only at 0.0065 cfs (a 73% reduction). The maximum flow rate from the green roof over the entire storm was 0.016 cfs; 30 percent less than the control roof maximum. The gap between the flow rates decreased as the storm progresses; this was observed for most of the other storms recorded. By the time the green roof had reached its maximum level of discharge, the flow rates for the two roofs were nearly identical. At the end of the storm, runoff continued to flow from the green roof for three hours whereas flow stopped ten minutes after it has stopped raining on the control roof.

The runoff attenuation changed over the course of a storm. Figure 4-3 shows how the runoff changes during the course of the storm. There was a long period at the start of the storm with a 100 percent reduction in flow volume and by the conclusion of the storm, the control roof had produced 134 cf of runoff while the green roof had produced 94 cf. The attenuation decreased rapidly in two stages, corresponding the later two periods of heavier rain and had an overall 30 percent reduction as shown in Figure 4-4.

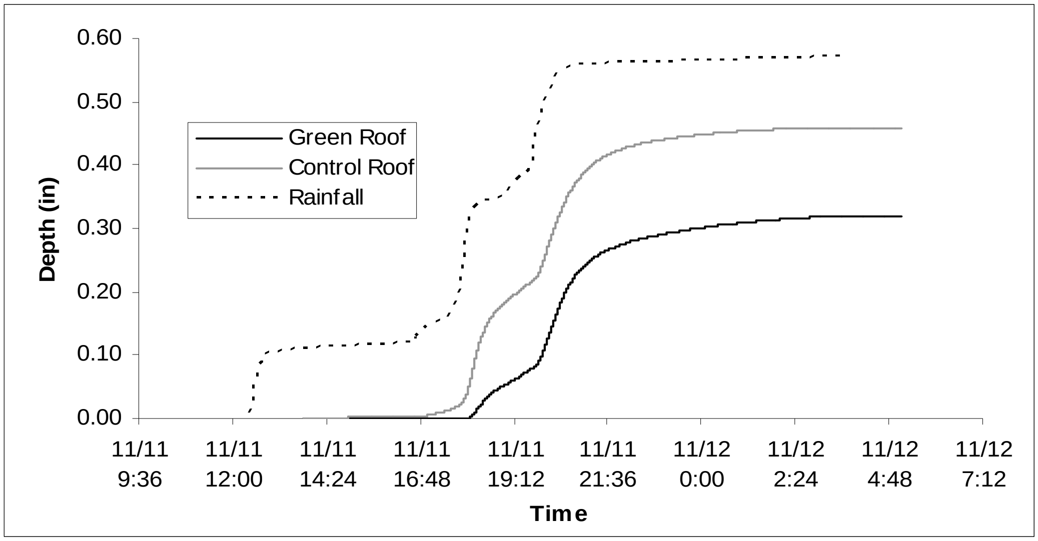

Figure 4-1 Runoff as Rainfall - November 11, 2006 Storm

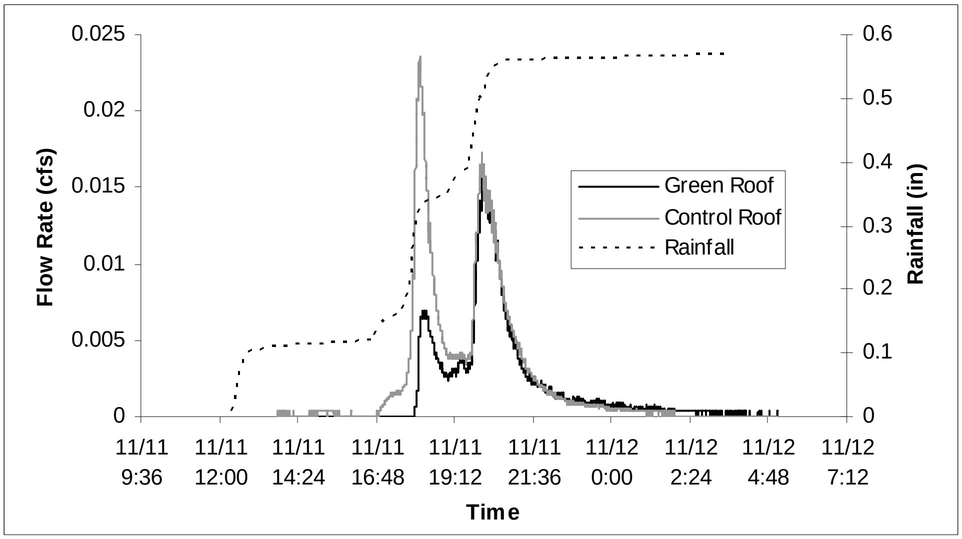

Figure 4-2 Runoff Flow Rates - November 11, 2006 Storm

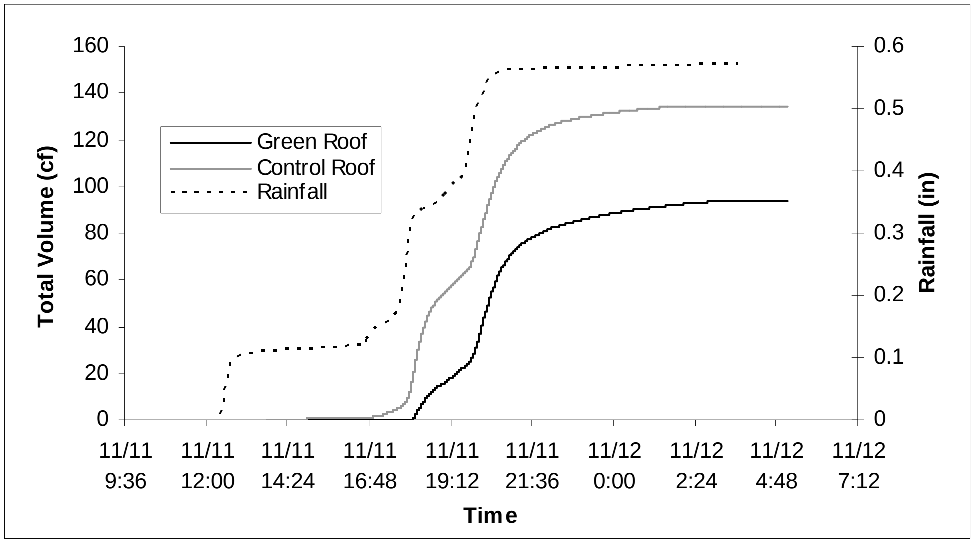

Figure 4-3 Runoff Volumes - November 11, 2006 Storm

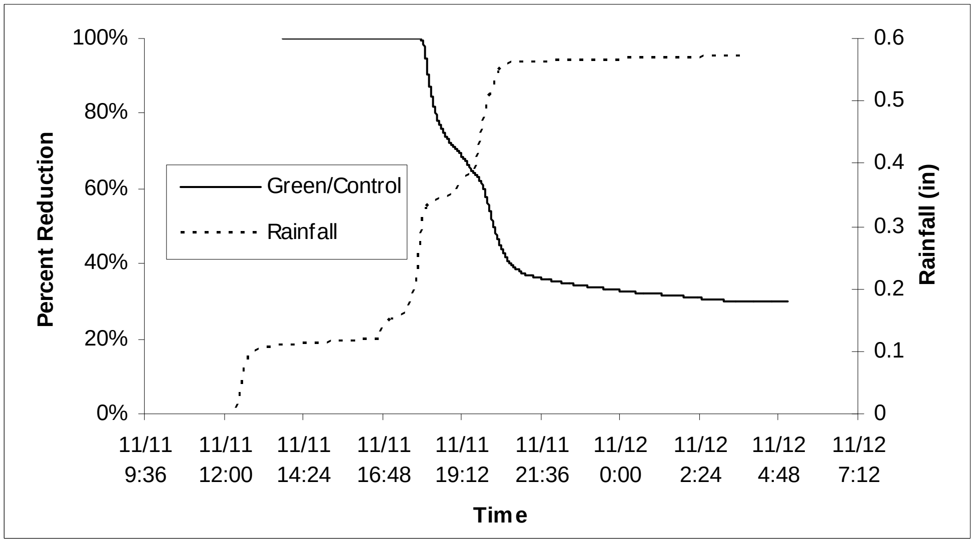

Figure 4-4 Runoff Reduction - November 11, 2006 Storm

October 31, 2006 Storm

The October 31, 2006 storm was an event that most closely resembles the 0.25 inch average rainfall for Pittsburgh (BBC 2007) where a total of 0.19 inches of rain fell in approximately $5^1/_4$ hours. The green roof produced the equivalent of 0.04 inches of runoff and the control produced 0.12 inches (Figure 4-5) which is a much lower percentage of rainfall was converted to runoff for this lower intensity storm compared to the November 11th rainfall event. There was discharge from the control roof beginning three hours after the rainfall started and a twenty five minute additional delay for the green roof. The runoff flow rates throughout the storm are shown in Figure 4-6. For this storm, there was no extension of runoff. The green roof actually stopped first while the flow from the control roof only persisted for an additional 10 minutes. In total, the control roof produced 36 cf of runoff for the entire storm, compared to 11 cf for the green roof. This 69 percent reduction is shown in Figure 4-7 and the reduction of runoff changes gradually during the course of the storm (Figure 4-8).

The green roof reduced the flow rate by 70% with the maximum value of 0.001 cfs for the green roof, compared to 0.0035 cfs for the control roof discharge. There was 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 was sustained for several minutes. The difference in discharge rate was greatest at the start of the storm but the lighter intensity of rainfall did not allow the two values to converge, where such a convergence would indicate that the green roof became saturated.

Measurements of the volumetric soil moisture throughout the storm indicated that the rainfall was absorbed into the soil matrix. These measurements are summarized in Figure 4-9. The values begin at 18.6% and 16.2% at locations A and B. The peak is 28.1% at location A and 19.27% at location B. By the end of the storm, levels had decreased to 24.2 % and 17.1%, respectively.

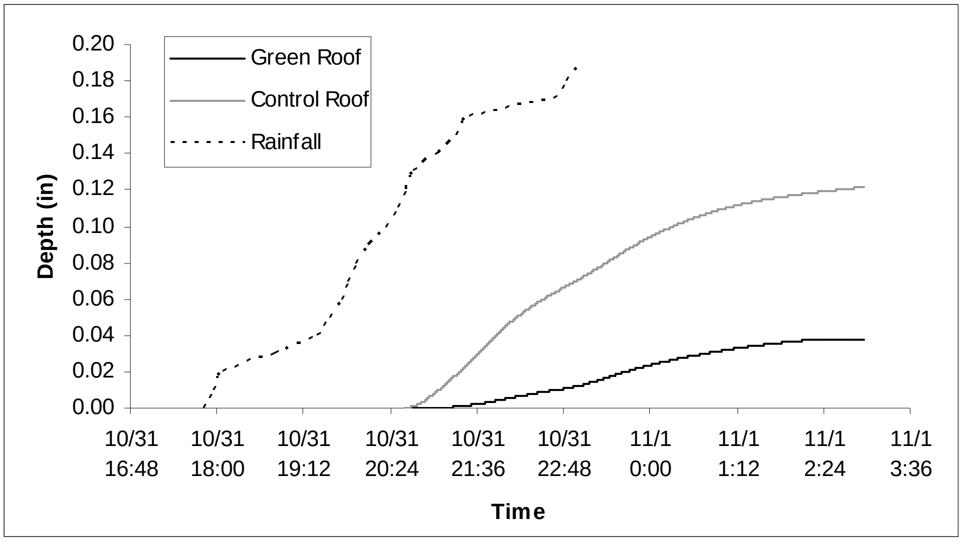

Figure 4-5 Runoff as Rainfall - October 31, 2006 Storm

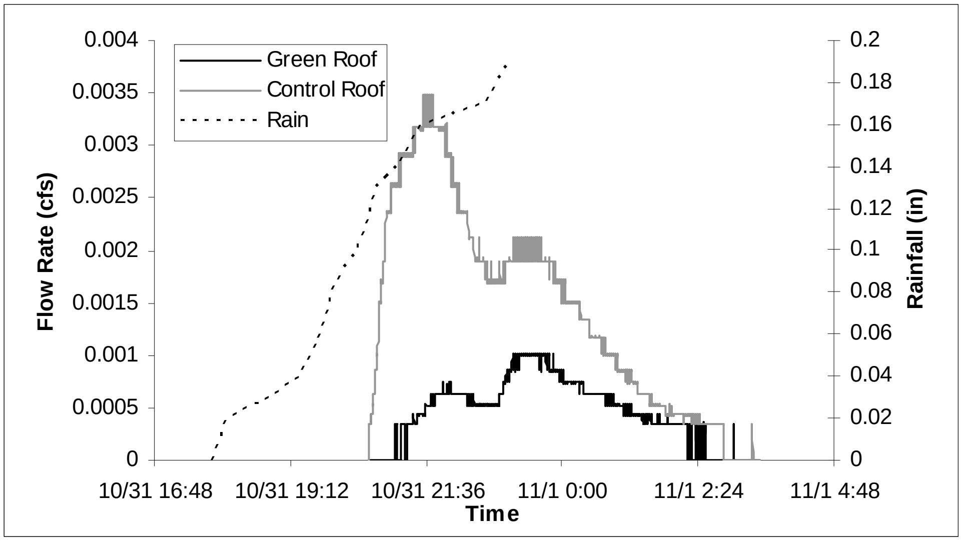

Figure 4-6 Runoff Flow Rates - October 31, 2006 Storm

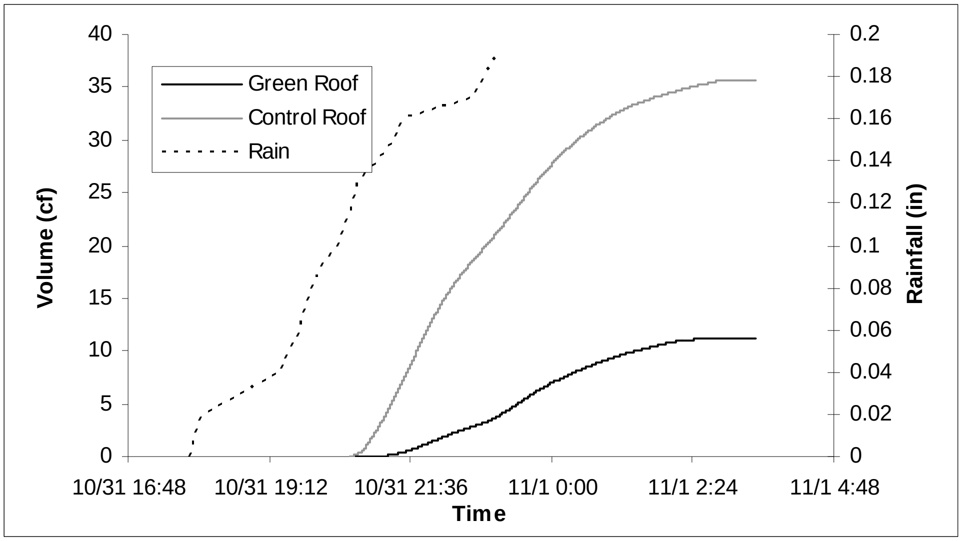

Figure 4-7 Runoff Volumes - October 31, 2006 Storm

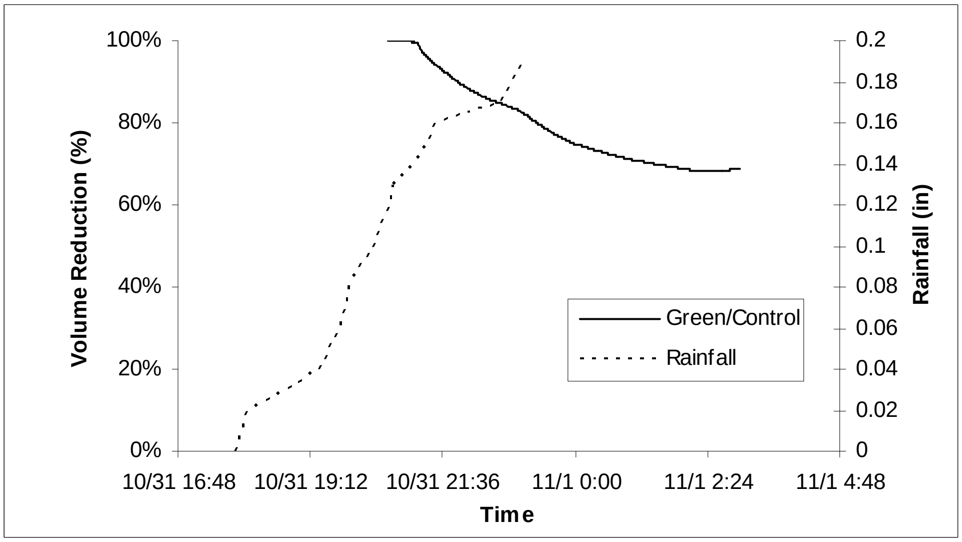

Figure 4-8 Runoff Reduction - October 31, 2006 Storm

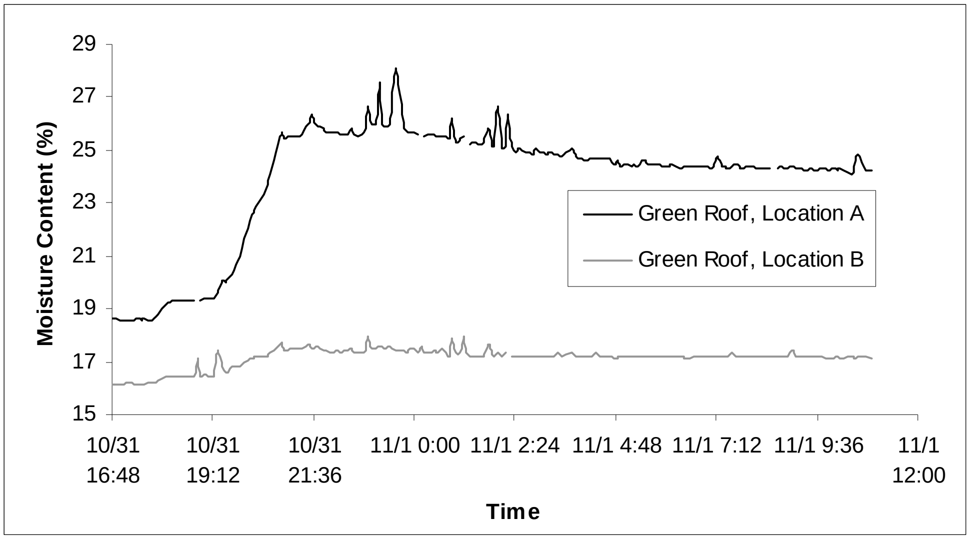

Figure 4-9 Green Roof Water Content - October 31, 2006 Storm. Locations A and B are both on the Giant Eagle green roof

October 17, 2006 Storm

The October 17, 2006 storm was a heavy rain where 1.94 inches of rain fell over about 10 hours. The 0.19 inches per hour intensity during a portion of the storm corresponds to roughly a 5 year storm for the Pittsburgh area. Figure 4-10 shows the equivalent inches of rainfall that became runoff for each roof. For the green roof, 1.41 of the 1.94 inches (73%) of rainfall became runoff. For the control roof, the figure is 1.75 of 1.94 inches (90%).

Runoff began flowing from the control roof after two hours of rain with an additional 21 minute delay from the time the control roof begins to produce runoff to the time it began to flow from the green roof. When runoff did begin to flow from the green roof, it had been raining for over three hours. The runoff flow rates throughout the storm for both roofs are shown in Figure 4-11. There was also an extension of flow at the conclusion of the storm. Runoff continued to flow at a very low rate from the green roof for four hours and forty five minutes longer than the control roof.

The difference in flow rate changed over the course of the storm. Early on, there was a significant difference between the two roofs. When the control roof hit its first peak, its flow rate was 0.016 cfs. At that same time, the green roof was 88% less at 0.0019 cfs. As the soil became more saturated, the flow rates become much closer. By the end of the storm, they were 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 was no significant delay between the peak flows from each roof, as the peaks occurred at virtually the same time.

There was a 20% reduction (100 cf) in runoff in comparing the totals from the two roofs, where the green roof produced 414 cf of runoff compared to 514cf for the control. The total volume of runoff during the storm is shown in Figure 4-12 and the change in runoff reduction over the course of the storm is plotted as Figure 4-13. As in the August 27, 2006 storm, there was drastic decrease in the rate of reduction after the rainfall stops.

This was the first storm that occurred after the irrigation system was turned off for the winter and soil moisture content data was measured. The volumetric water soil moisture content for two locations on the green roof is shown in Figure 4-14. At the start of the storm, both locations had an identical water content of 16 percent by volume. Water content reached a maximum at 20.6% at location A and 19% at location B at approximately the same time the green roof reached its peak runoff flow rate. The water content began to steadily decline at the point most of the rain had stopped falling, eventually reaching values of 18 and 17% water by volume by the time runoff stopped flowing from the green roof.

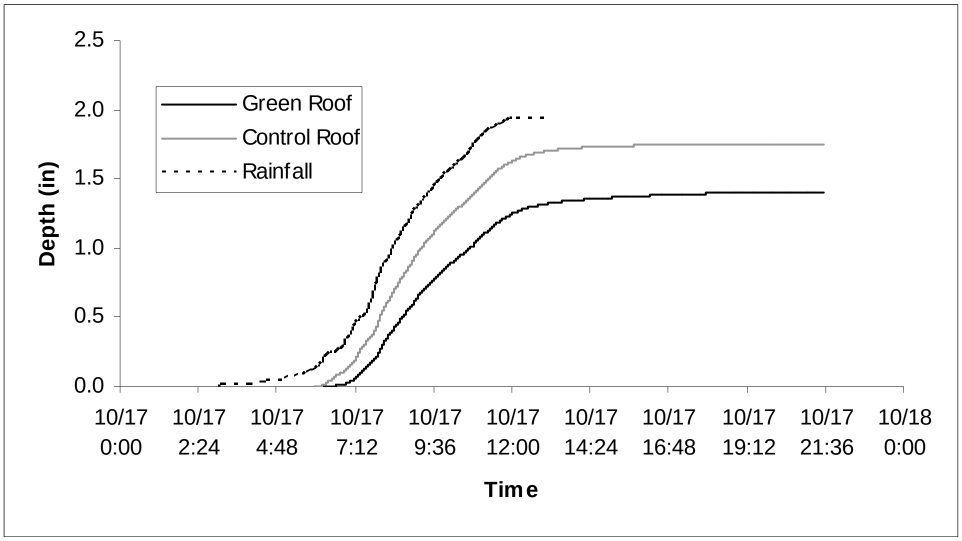

Figure 4-10 Runoff as Rainfall - October 17, 2006 Storm

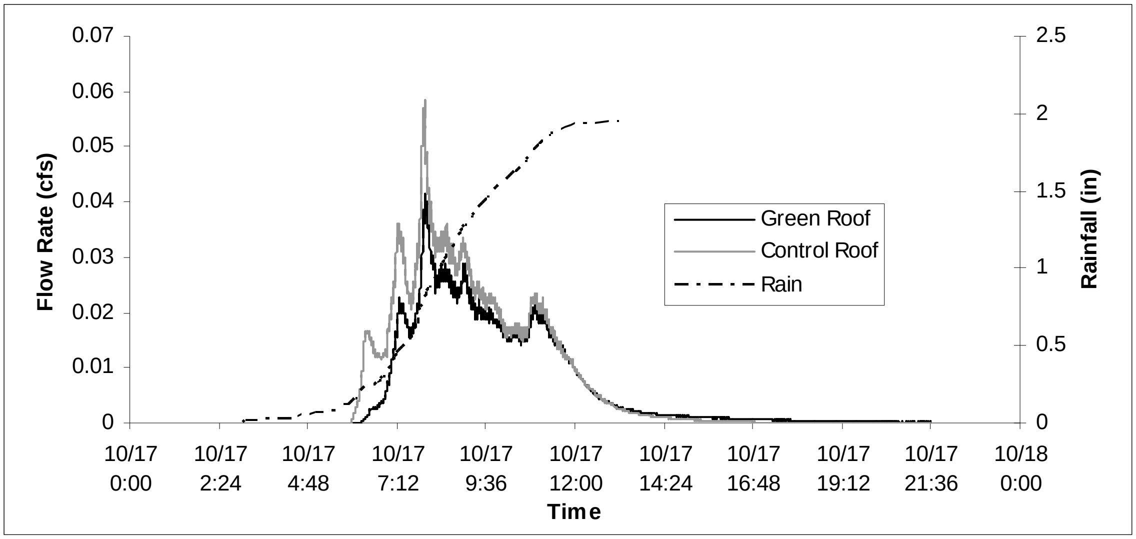

Figure 4-11 Runoff Flow Rates - October 17, 2006 Storm

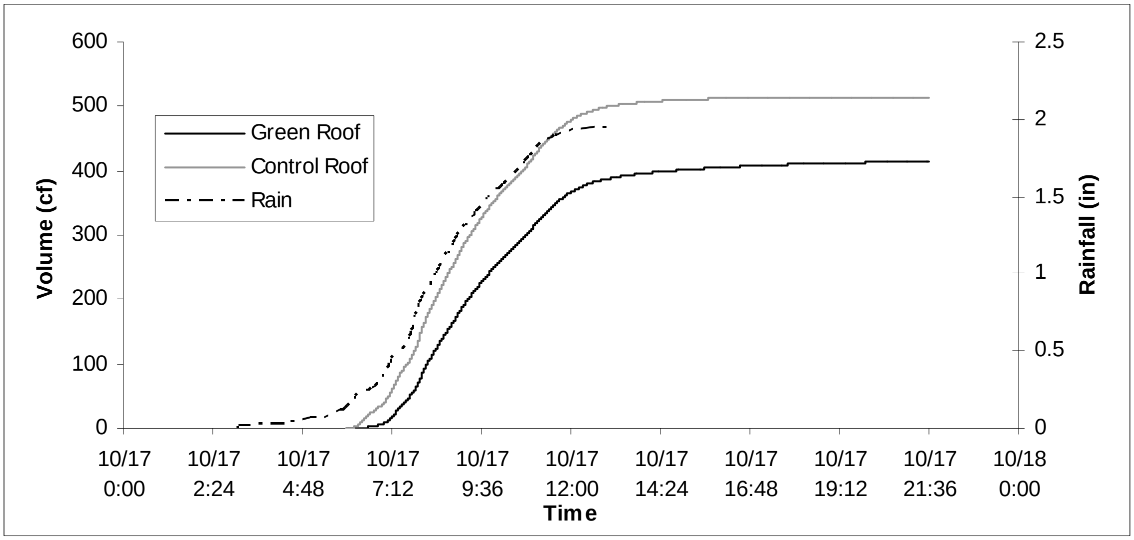

Figure 4-12 Runoff Volumes - October 17, 2006 Storm

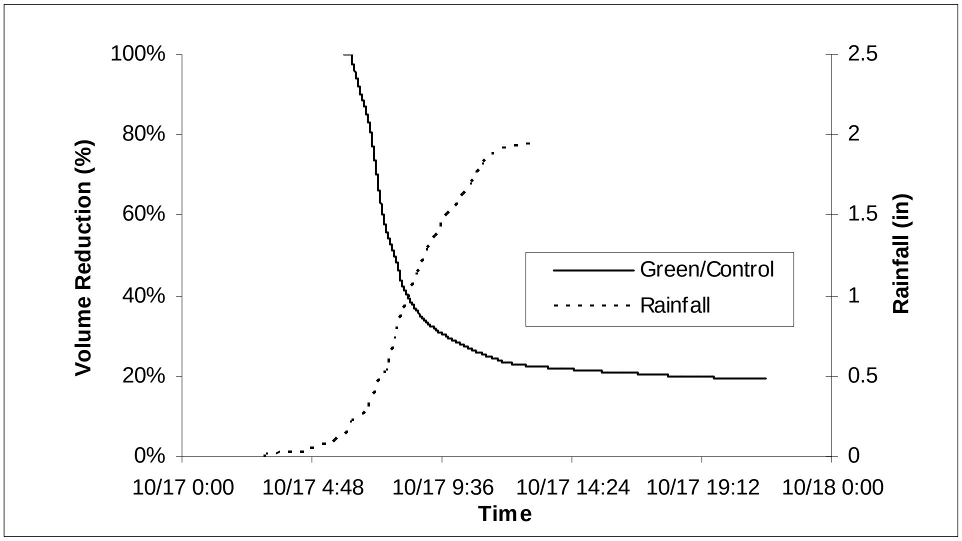

Figure 4-13 Runoff Reduction - October 17, 2006 Storm

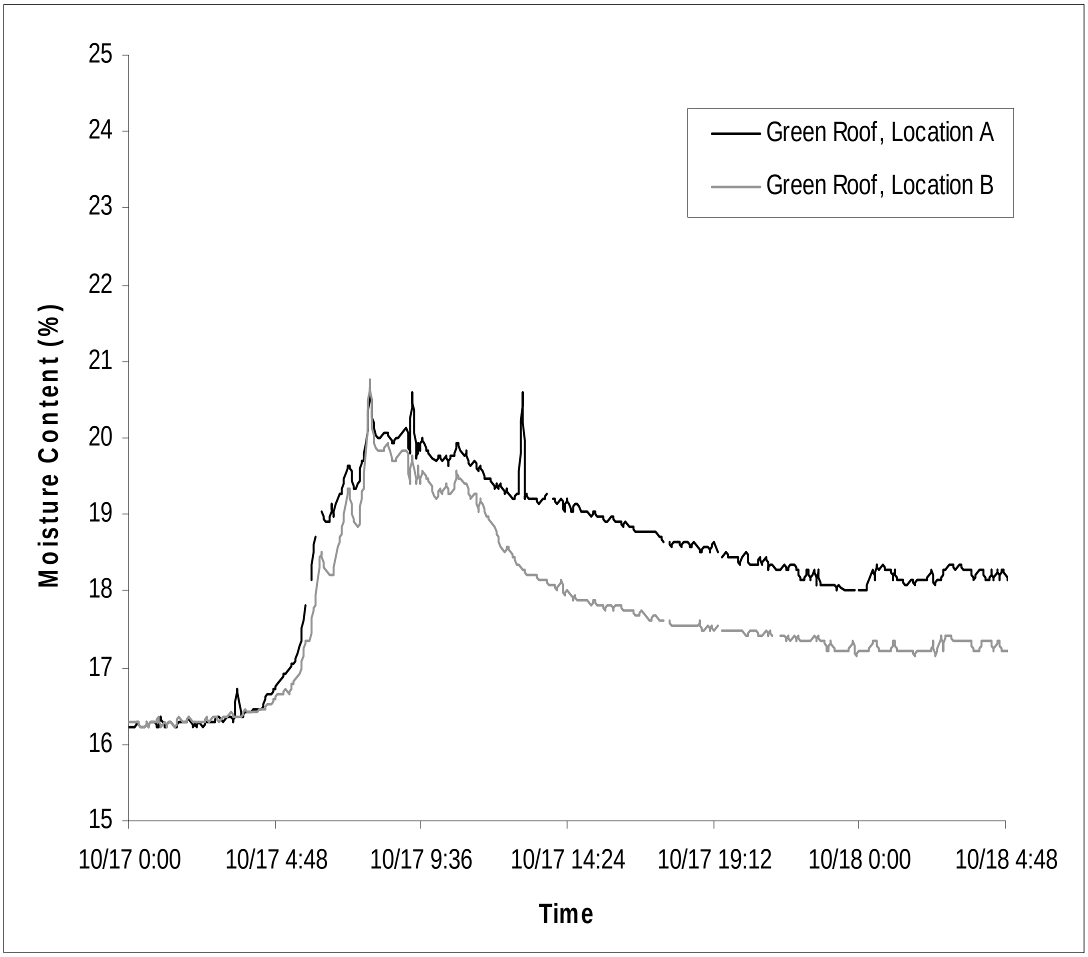

Figure 4-14 Green Roof Moisture Content - October 17, 2006 Storm

4.2 Discussion: Giant Eagle Runoff

There is a large difference in the flow rates from the green and control roofs early in a storm for a typical storm. The maximum flow rate from the green roof was observed to be consistently lower than the flow rate from the control roof. For instance, the green roof runoff flow rate was 73% less than the control roof runoff during the beginning of the November 11, 2006 storm. As the storm progresses and the soil on the green roof become saturated, the flow rates converged.

In a multistage rainfall on August 27, 2007 storm, each progressive peak saw the difference between the flow rates of the two roofs decrease. The peak flow rate for the green roof was consistently lower than the control roof, ranging from 5 to 71%, depending on the storm characteristics and previous soil moisture content. 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 during this study period. Discounting the period of flow extension, the flow rate of the green roof was higher than the control roof for approximately 15% (~11 ½ hours) of the storm. This did not occur until late in the storm after over half an inch of rain fell in 15.25 hours. While the flow rates were higher, it must be noted that the green roof flow rates for this storm were not substantially greater than the control roof. For example, the green roof peak flow rate for the storm was higher than the control, but only by 5%. 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 were atypical.

A delay between peak flow rate off the control roof and the green roof was not consistently observed. During the October 31 and November 11, 2006 storms, the green roof reaches its peak about two hours after the control. However, more often than not this was not the case and during most storms, the peak flows from both roofs were reached at approximately the same time.

The green roof consistently reduced the total volume of runoff. Overall, the reduction ranged from about 70% less than the control roof for the three lightest storms to 5% for one of the heaviest storm. The average reduction in total volume for “heavier storms” was approximately 20%.

Irrigation skewed the results for 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 most likely saturated at the time the storms started. The runoff on July 28th was minimal, with the lowest totals for any storm indicating significantly dry soils. The July 30th storm produced significant runoff compared to storms similar in magnitude. For this storm, it was only at the very end of the storm that the green roof overtook the runoff volume of the control roof due to the extended low rate of flow from the green roof. Throughout the bulk of the storm, the control roof produced more runoff, though it produced 11% less total. Given the temporal coupling of these data, it is believed that the excess water that was observed to runoff the green roof originated from the irrigation system.

The soil moisture at the start of the storm is an important parameter which decides green roof performance. Before the October 27, 2006 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 drier soil before the October 27th storm, there was noticeably better performance by the green roof. The storm had a higher intensity than the storm on the 27th, as the first 0.19 inches of rain fell in several hours less time than the October 31st storm. These two storms were chose for comparison because of their proximity in time so factors such as plant growth and weather were essentially unchanged.

Generalizations in delays for producing runoff were not as clear to delineate. There were many instances (at times significantly delays) where the runoff from the green roof began flowing after it had begun to flow from the control roof. 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 were some cases where the green roof produced runoff first, although these were usually insignificant delays. Each instance of no delay or that the green roof produced runoff first occurred in one of two conditions. Several times, irrigation flow started just before a storm, thereby negating any potential delay. The other condition was that another storm 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% 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 the soil is not saturated with water. For example in the case that there is a dry period prior to the storm, the soil is somewhat dry and has room to absorb moisture. However, 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 commonly a delay from the time rainfall begins and when runoff is produced from the green roof. With one exception, this delay was at least 45 minutes after rainfall began. In many instances the delay 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.

The green roof was often observed to extend runoff flow by a significant amount of time past the conclusion of a storm, whereas runoff from the control roof was not extended. 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 some of the smallest storms, the green roof stopped producing runoff first.

The volumetric water content of the green roof substrate affects the overall performance of the green roof, although 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 reaching a low in January of 2007 where the temperature was below freezing and the soil moisture content dropped to as low as 10 to 12 percent. The water content always were at a local maximum during a rainfall, reaching a 34 percent water content by volume during the longest and heaviest rainfall (January 12 to 15, 2007 storm) and with peak values typically between 20 to 28%. These values are much lower than the Garland specifications for the soilless mix with maximum water content of 45% by volume. It is believed that compaction of the soil during plant and instrument installation is likely the cause for the reduction in maximum capacity for water content. 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 4-15 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 in Figure 4-15, but location A is the most important because measurement point is situated a few feet from the green roof drain where runoff measurements are recorded. Figure 4-15 indicates that the green roof retained more rainwater when the substrate is drier. Dry soil has more void spaces available to absorb water. Results presented in the graph show all storms with available data from October 17, 2006 through the end of 2006 These storms all produced runoff after approximately 0.1 inches of rain fell, at starting volumetric water contents of 14 to 19 percent. As mentioned earlier, during this time period temperatures were often below freezing, including periods of snow accumulation, which likely affected the results that contrast the earlier data.

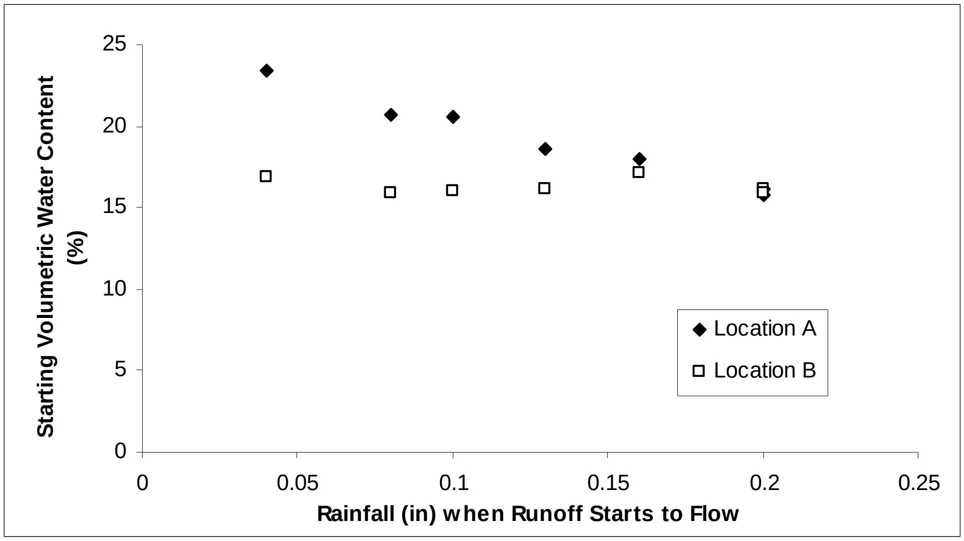

Figure 4-15 Soil Water Content versus Rainfall Depth at the Start of Runoff Flow

To further illustrate the effect of the starting volumetric soil water content on runoff flow, three consecutive storms from October 27 through November 1, 2006 are examined. The volumetric water content is 15.8 percent at both green roof locations on October 27th, before there was 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 was less of a delay during the second storm. Furthermore, the November 1st delay was significantly shorter than both. Despite being the lightest storm recorded (0.07 inches), it was the second shortest delay during the monitoring period. The elevated water content levels at the start of this storm were the highest of any storm.

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 were similar, at 30 and 26 minutes, despite the significant difference in storm intensities.

The starting volumetric water content does not statistically affect the overall runoff volume or runoff flow rate characteristics. The October 27th storm was heavier than most measured storms at 1.2 inches, while the October 31st (0.19 inches) and November 1st (0.07 inches) were among the lightest. Conversely, the overall runoff volume reduction was on the low end (20 percent) for the October 27th storm, while the other storms were two of the three best in terms of performance (about 70 percent reduction). The flow rate reduction was 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. Another important conclusion is that the starting volumetric water content affects the delay in runoff when comparing the green roof to both rainfall and the control roof.

The overall trends of the overall depth, duration and intensity of storm that were observed from the data are summarized in Figure 4-16 through Figure 4-19. The Intensity-Duration-Frequency graph is shown as Figure 4-16 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 which represents the average intensity that should be expected with a 99 and 20 percent probability, respectively, for a given duration and frequency. The green roof data plotted alongside 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 that occurred on October 17, 2006 with 1.94 inches of rain that fell in 10 hours which corresponds to 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.

A general trend observed was that as the amount of rain (inches) or duration of the storm (hours) increases, the fraction of runoff reduced decreases. The relationship between runoff reduction and rainfall depth is shown in Figure 4-17 and runoff reduction versus rainfall duration is plotted in Figure 4-18. The three storms with the best green roof “performance” have the lowest total rainfall and durations. Likewise, the two worst cases are two of the largest storms with the longest durations. The remaining storms have a reduction of about 20 percent. Figure 4-19 combines these two graphs into intensity versus runoff reduction plot where we see that green roofs are most effective for low to moderate rainfall events.

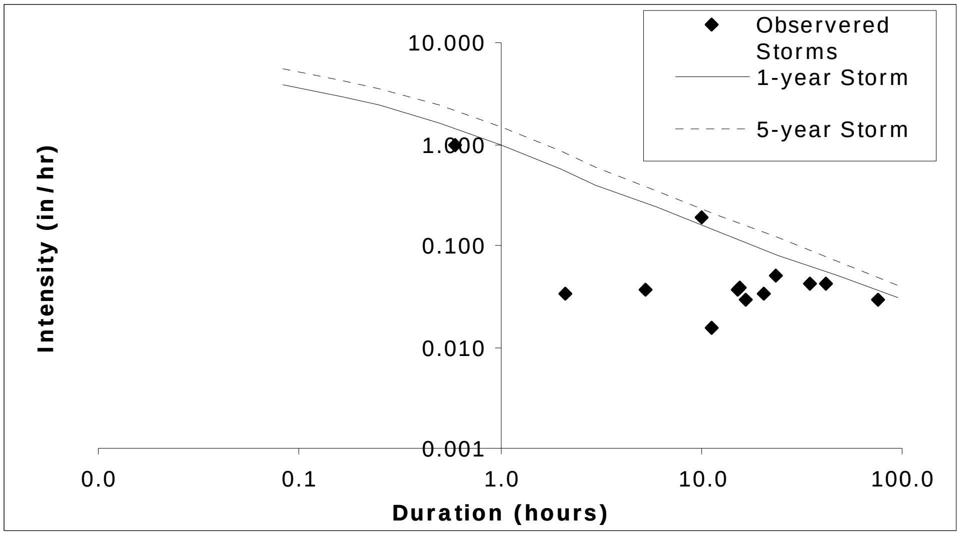

Figure 4-16 Intensity-Duration-Frequency Curve - Shadyside Green Roof and NOAA Data

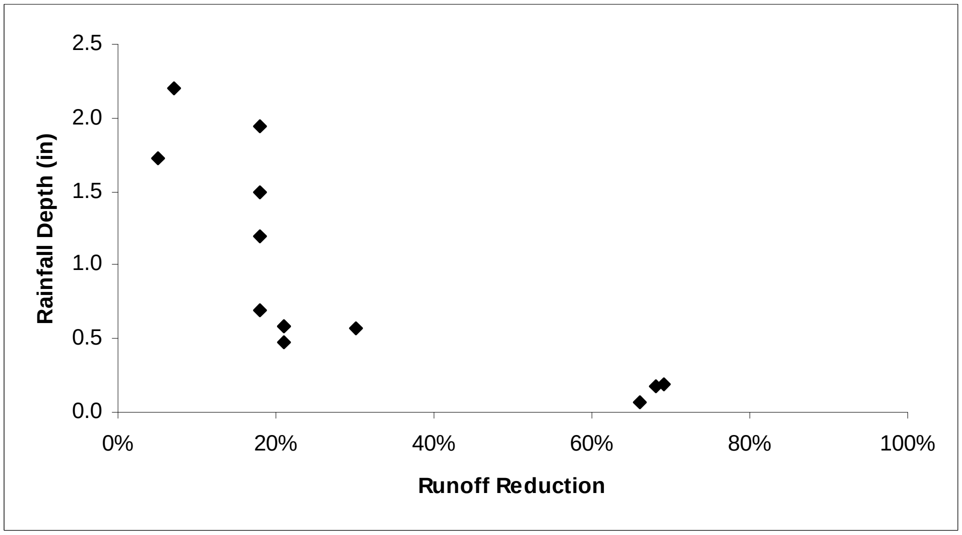

Figure 4-17 Fraction Runoff reductions versus Rainfall Depth (inches)

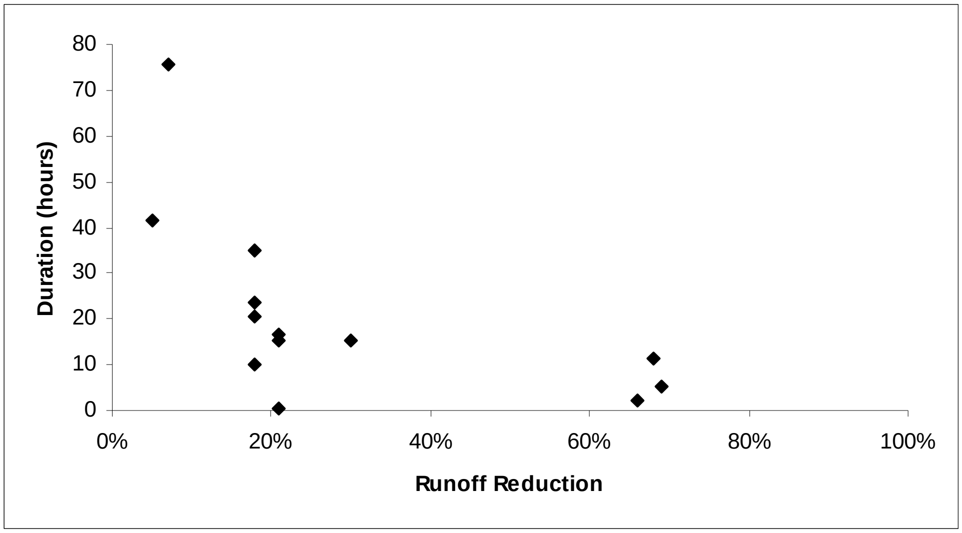

Figure 4-18 Fraction Runoff reductions versus Storm Duration

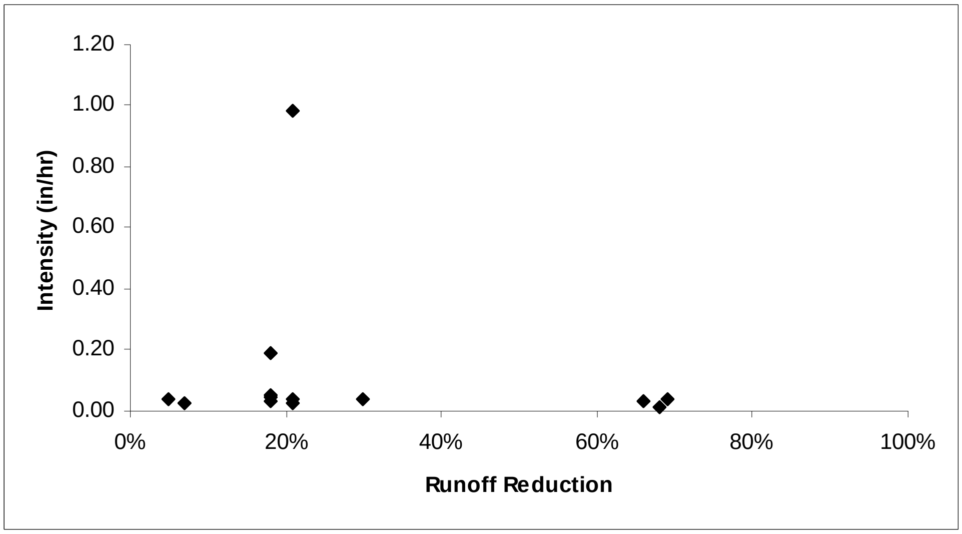

Figure 4-19 Fraction Runoff reductions versus Storm Intensity

4.3 Runoff Quality

Laboratory tests were conducted in order to determine any runoff water quality benefits that may originate from the Giant Eagle green roof. Samples from both the green and control roofs and rainwater were tested for three storms: October 17, November 1, and December 1.

Turbidity

Turbidity testing revealed a first flush effect for the control roof at the onset of several storms, whereas there was no first flush detectable from any of the corresponding green roof samples. Turbidity was determined for each sample from all storms selected for complete sampling as well as for several other storms where only turbidity was tested.

The turbidity data of the composite rainwater samples tested serves as a base line (Figure 4-20) that all the results are compared to. The November 11, 2006 storm has a turbidity of 6 NTU whereas the November 16, 2006 and December 1, 2006 storms have turbidities of approximately 1.5 NTU and were free from excess debris. The higher data for the 1st storm is likely due to a large amount of debris that was atmospherically deposited during dry weather in the rainwater sampling container at the site.

The December 1, 2006 storm exhibited the most dramatic first flush effect from the control roof. The sample collected after 5 cf of runoff had a turbidity of about 70 NTU, which was the highest of any sample tested during the observation period and 30 NTU higher than the sample collected after 10cf of runoff. The turbidities of runoff from the control roof and green roof are shown as Figure 4-21 and Figure 4-22, respectively. After the first flush, there was a steady decline in turbidity in each successive control roof sample. By the final sample (after 60 cf), the turbidity had dropped to about 9.5 NTU (rain water for this event was ~1 NTU). There was no consistent trend observed for the runoff turbidity from the green roof with values that ranged from 4.5 to 9.2 NTU without a first flush effect.

Two other storms showed similar although less pronounced first flush results. For 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 with turbidity that ranged from about 2 to 3 NTU. For both the control roof and green roof, the turbidity measurements were considerably lower than the December 1, 2006 storm. The November 1, 2006 storm showed a very slight first flush effect for the control roof with the first sample having a turbidity of 4 NTU and the remaining samples were approximately 2.5 NTU. The green roof turbidities were lower than the control roof, ranging from 1.5 NTU to 2.5 NTU and showed no first flush effect.

Not all storms showed this first flush effect. The November 15, 2006 rainfall event had no first flush effects on turbidity from either roof as shown in Figure 4-23 and Figure 4-24. The turbidity of samples from the control roof ranged from approximately 2 to 9.5 NTU and sample turbidity from the green roof values ranged from 4.5 to 9.5 NTU. While this storm was a heavy rainfall (over 1 inch), the runoff was significantly less turbid; this lower turbidity may be attributed to the roof being 'washed' by the storm immediately preceding it on November 11th (over ½ inch).

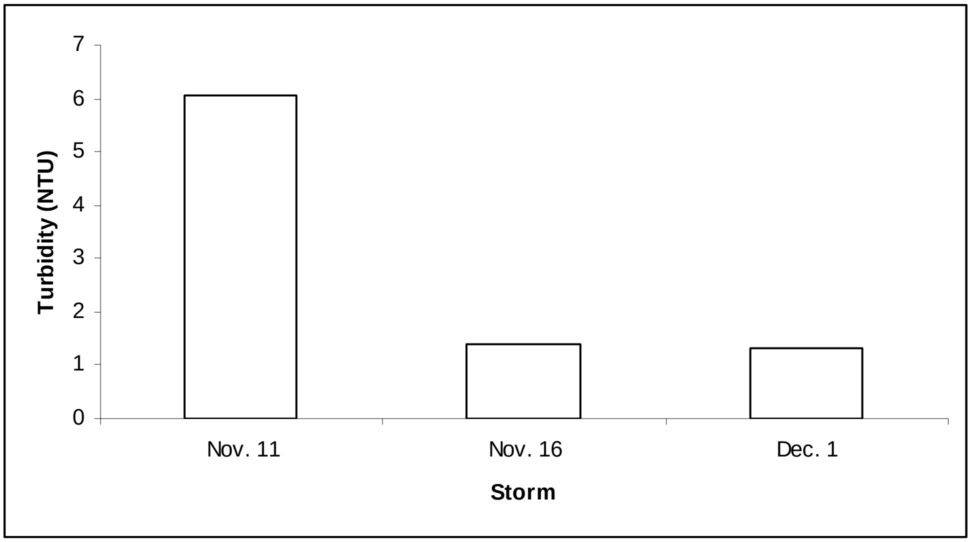

Figure 4-20 Turbidity - Rainwater Samples

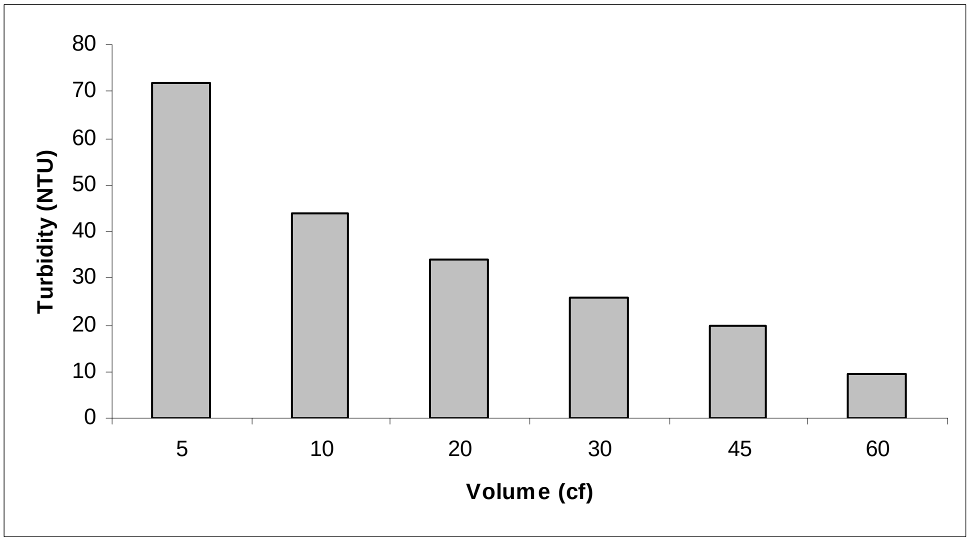

Figure 4-21 Turbidity in runoff during the 12/1/2006 storm - Control Roof Samples

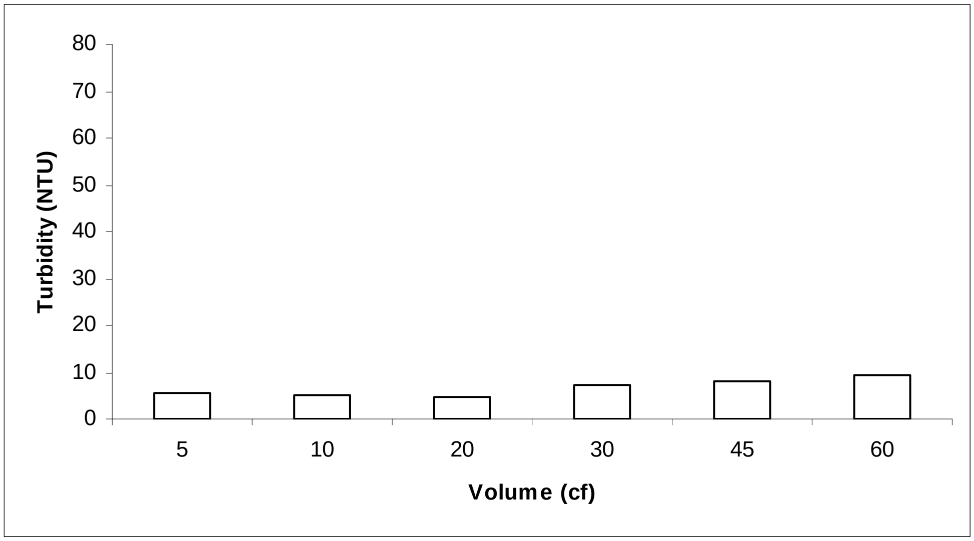

Figure 4-22 Turbidity - Green Roof Samples - December 1, 2006 Storm

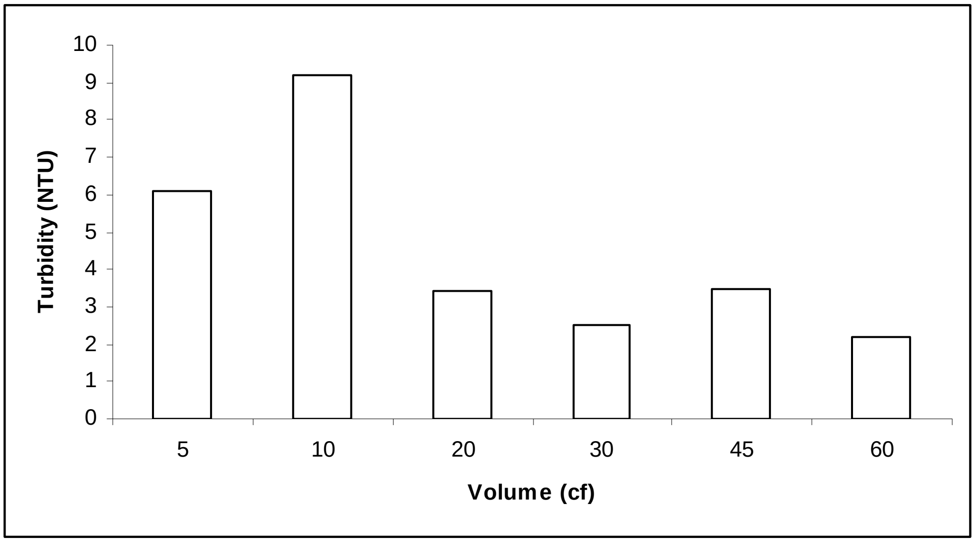

Figure 4-23 Turbidity of samples collected during the 11/15/2006 storm: Control Roof

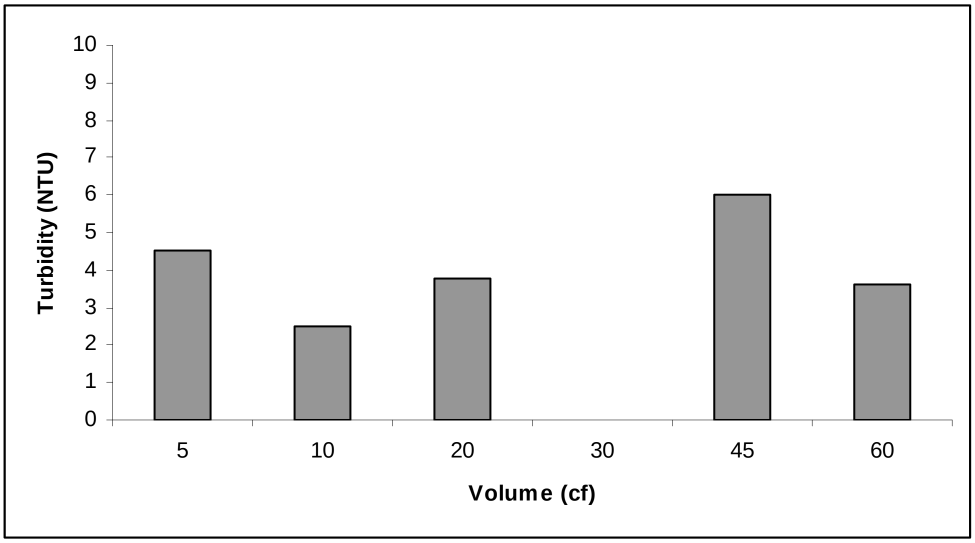

Figure 4-24 Turbidity of samples collected during the 11/15/2006 storm: Green Roof

pH

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 for all storms that received the full battery of tests as well as several additional storms. No first flush effects were detected and neither of the roof's runoff samples was consistently higher or lower than the others. Measurements of the pH of the rainfall and runoff sampled on November 16, 2006 and December 1, 2006 revealed that rain samples were slightly more acidic (pH of 7.0 and 6.4, respectively) than the runoff.

Phosphorus

Phosphorus testing for the October 17, 2006, November 1, 2006 and November 11, 2006 storms revealed consistent levels of phosphorous in the rainwater and runoff.

The phosphorus levels in the rainwater samples are very low. For example, results from the November 11, 2006 storm are shown in Figure 4-25. The unfiltered rainwater sample had a concentration of 0.04 mg/L and the filtered sample contained 0.02 mg/L, thus, approximately half of the phosphorus was dissolved and half was particulate-bound.

The green roof runoff samples showed significant levels of phosphorus. Results from a representative storm (November 1, 2006) for unfiltered samples and filtered samples are shown in Figure 4-26 and Figure 4-27. The phosphorus levels for the unfiltered samples were 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 for an average value of 2.7 mg/L. The filtered phosphorus levels were nearly identical, with only the 5 cf sample dropping to 2.9 mg/L. The results were similar to those acquired for the October 17, 2006 storm where the average value was 2 mg/L for most samples. There was no significant difference between the filtered and unfiltered samples indicating that all the phosphate in the green roof runoff was dissolved.

For the same storm, Phosphorus was not detected in any control roof samples and there was no difference between the filtered and unfiltered samples (Figure 4-28 and Figure 4-29). In the October 17, 2006 storm, levels were also extremely low with three of the unfiltered samples yielding 0.1 mg/L of phosphorus and all other samples had no detectable phosphorus.

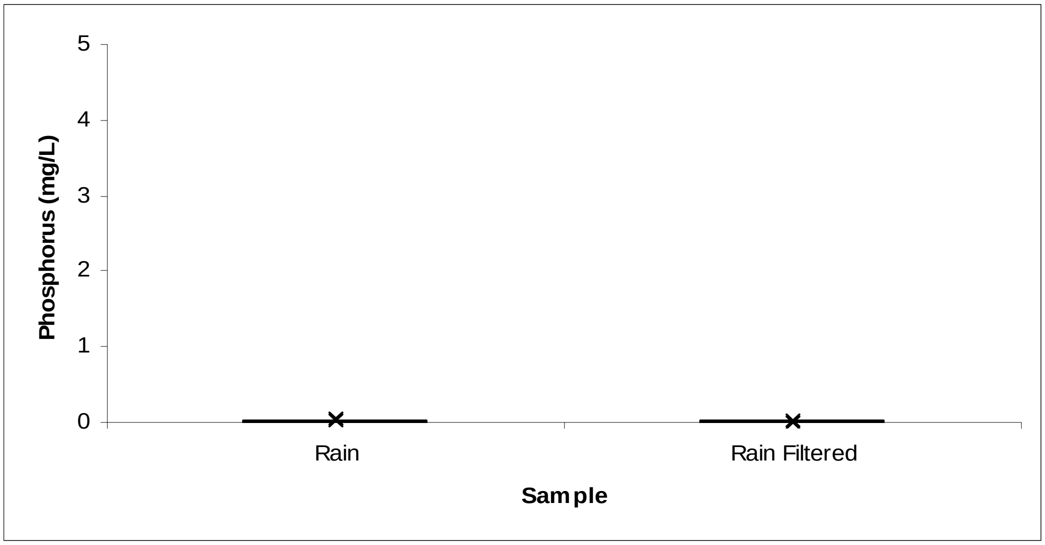

Figure 4-25 Phosphorus - Rainwater Samples - November 11, 2006 Storm

The bars in this graph (and all subsequent water quality graphs) represent the mean value and the ‘x’s’ show the minimum and maximum values for the respective samples.

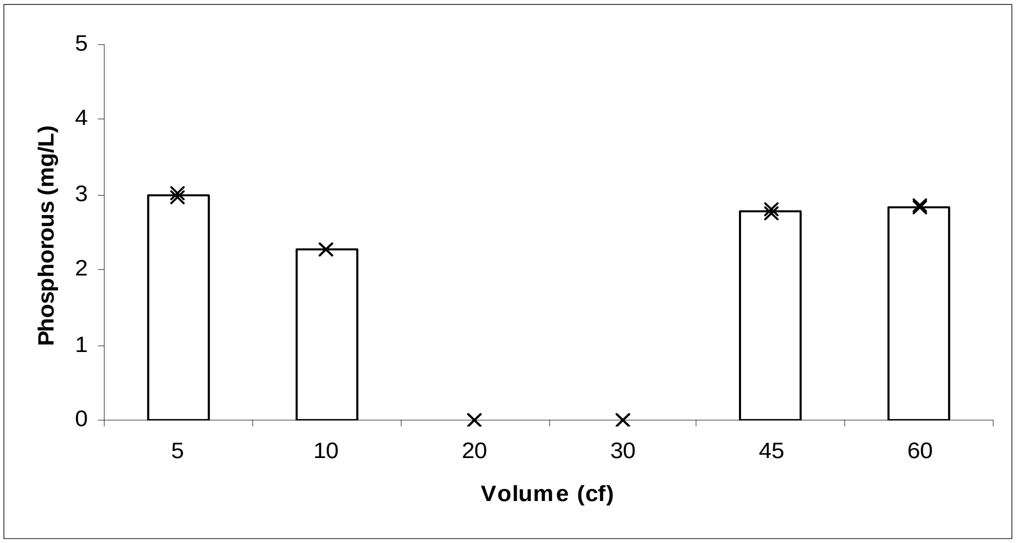

Figure 4-26 Phosphorus - Unfiltered Green Roof Samples collected during the 11/1/2006 storm

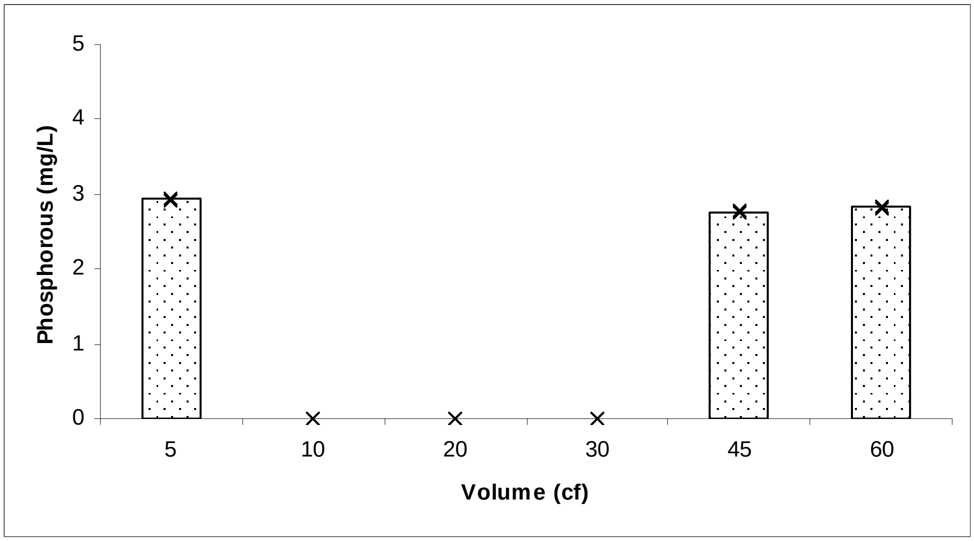

Figure 4-27 Phosphorus - Filtered Green Roof Samples - November 1, 2006 Storm

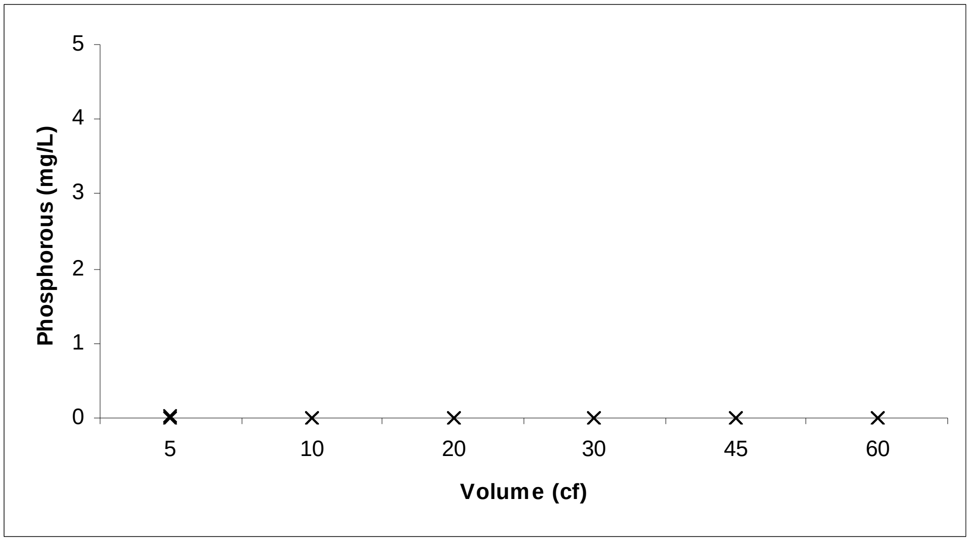

Figure 4-28 Phosphorus - Unfiltered Control Roof Samples - November 1, 2006 Storm

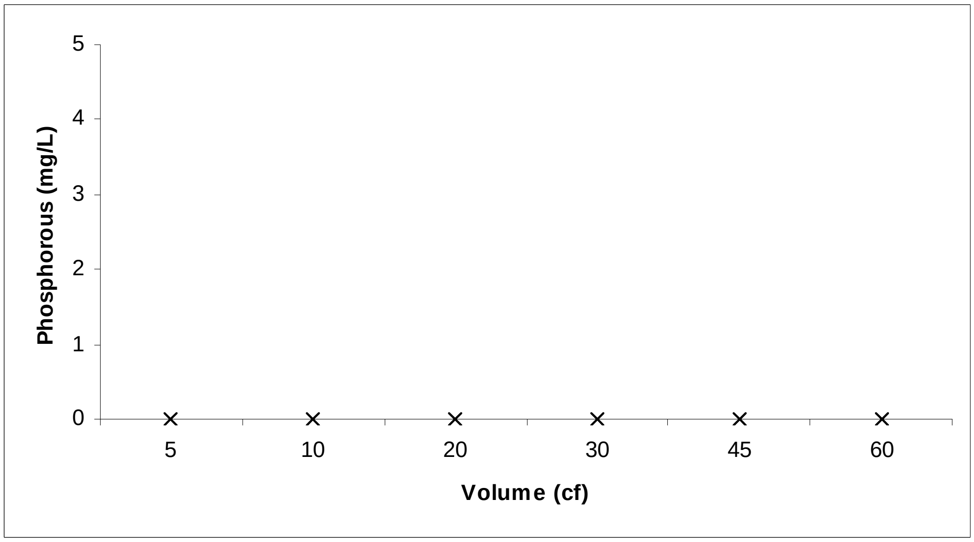

Figure 4-29 Soluble Phosphorus – Collected during the 11/1/2006 storm, Control Roof

Sulfate

The sulfate content of the runoff from three storms (October 17, 2006, November 1, 2006 and December 1, 2006) was tested and revealed that sulfate content in the rainwater and runoff samples were somewhat inconsistent. For rain that fell on The November 13, 2006 the filtered sample had 8.4 mg/L sulfate and 12 mg/L for the unfiltered sample, while the values for the December 1, 2006 storm were 4.2 and 8.4 mg/L, respectively. However, the sulfate content of rainwater samples that did not come in contact with the roof was consistently lower than the runoff samples from both roofs.

Samples acquired during rainfall on October 17th revealed that the sulfate from the Green roof had sulfate concentrations that range from 35 to 47 mg/L and were higher than the control roof concentrations that ranged from 16 to 25 mg/L. There was no first flush effect, even though the final control roof sample (60 cf) was the lowest. The only significant difference between the filtered and unfiltered samples from both roofs was the 30 cf sample from the control roof, where the sulfate concentration in the unfiltered sample was 30 mg/L and the filtered sample was 25 mg/L.

Data collected from the November 1 samples revealed no first flush effect evident and no significant different between the filtered and unfiltered samples on either roof. Opposite to the October 17 rainfall, the control roof had higher sulfate (27 to 31 mg/L) than the green roof (18 to 21 mg/L).

A first flush effect was observed for sulfate and turbidity from the unfiltered control roof samples on December 1, 2006 where sulfate levels drop consistently from 30 mg/L to approximately 17 mg/L (Figure 4-30). As revealed in Figure 4-31, filtered control roof samples decreased from 20 to 16 mg/L. This indicates that the first flush was the result of increased non-soluble sulfate-bearing particles. On the whole, green roof sulfate levels were less than the control roof values and there was little difference between the filtered and unfiltered samples and shown in Figure 4-32 and Figure 4-33.

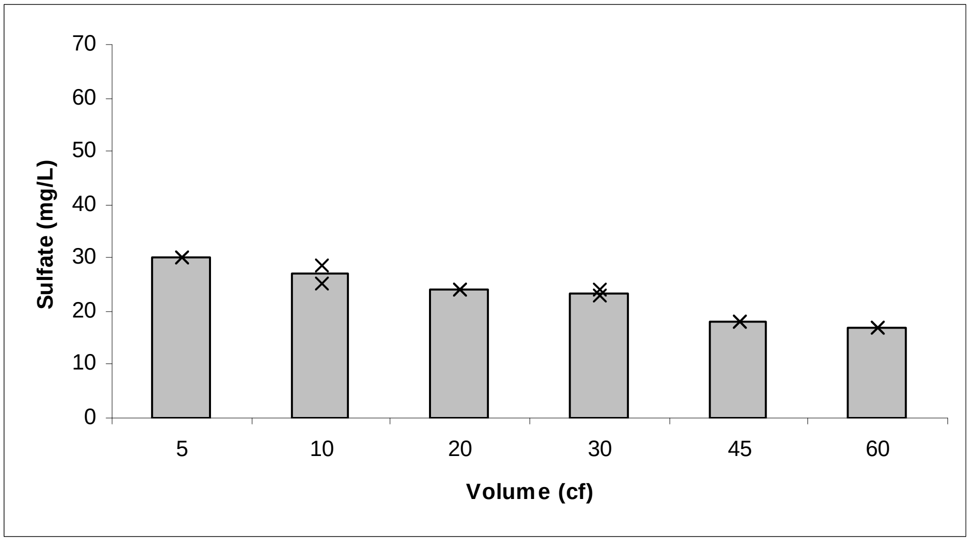

Figure 4-30 Sulfate - Unfiltered Control Roof Samples - December 1, 2006 Storm

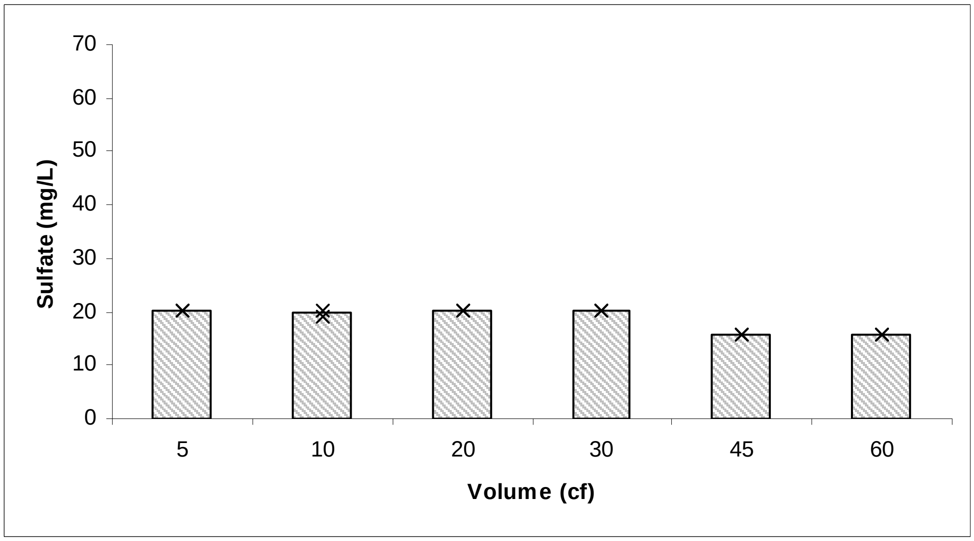

Figure 4-31 Sulfate - Filtered Control Roof Samples - December 1, 2006 Storm

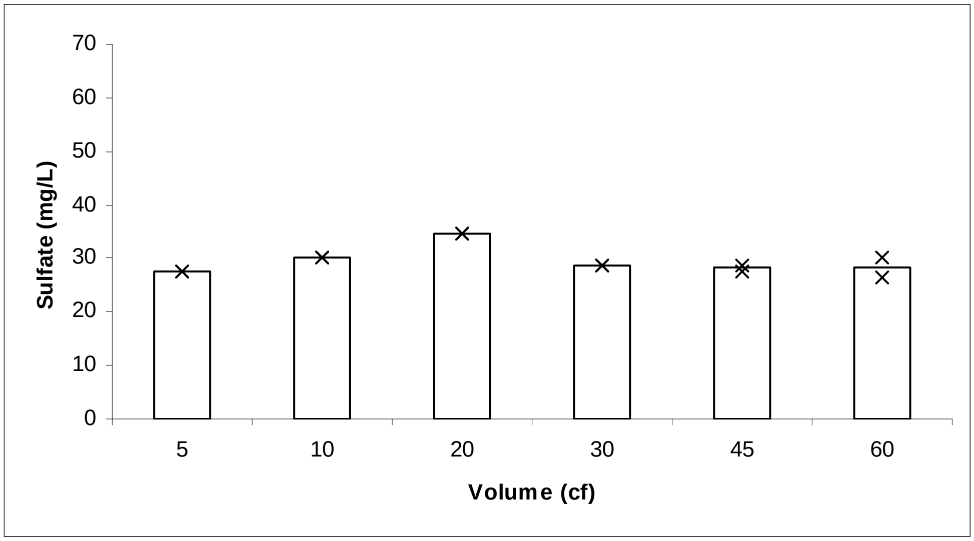

Figure 4-32 Sulfate - Unfiltered Green Roof Samples - December 1, 2006 Storm

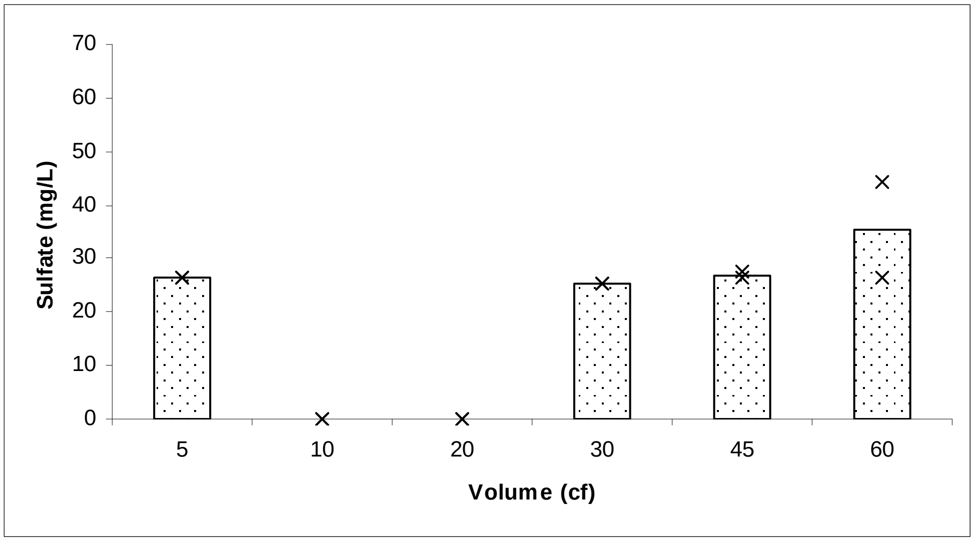

Figure 4-33 Sulfate - Filtered Green Roof Samples - December 1, 2006 Storm

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

The vast majority of samples, regardless of their source, registered a nitrogen concentration of approximately zero. Many of the samples that did show traces of nitrogen had very low concentrations (below 1 mg/L). The highest concentration was about 4.5 mg/L for a filtered control roof sample.

COD

COD testing was performed for the green and control roof runoff samples resultant from rainfall on October 17, 2006, November 1, 2006 and December 1, 2006 and rainwater was tested after the November 13, 2006 and December 1, 2006 storms.

Unfiltered samples from the green roof were observed to consistently have the highest COD of all samples. In comparing unfiltered data from the green roof (Figure 4-37), control roof (Figure 4-35) and rainfall (Figure 4-34), COD decreases from 26-41mg/L to 5-15 mg/L to 12.4 mg/L. COD levels dramatically decreased upon filtering for rainfall (12.4 to 1.3 mg/L) but not for the two roof, indicating that COD is largely due to materials that pass through 0.45μm filters. For the other two storms tested, the green roof also had consistently higher values than the control roof and rainfall, although the overall values were lower for both roofs during both storms. The results of COD testing from the December 1, 2006 rainfall are representative of data from the other rainfall events.

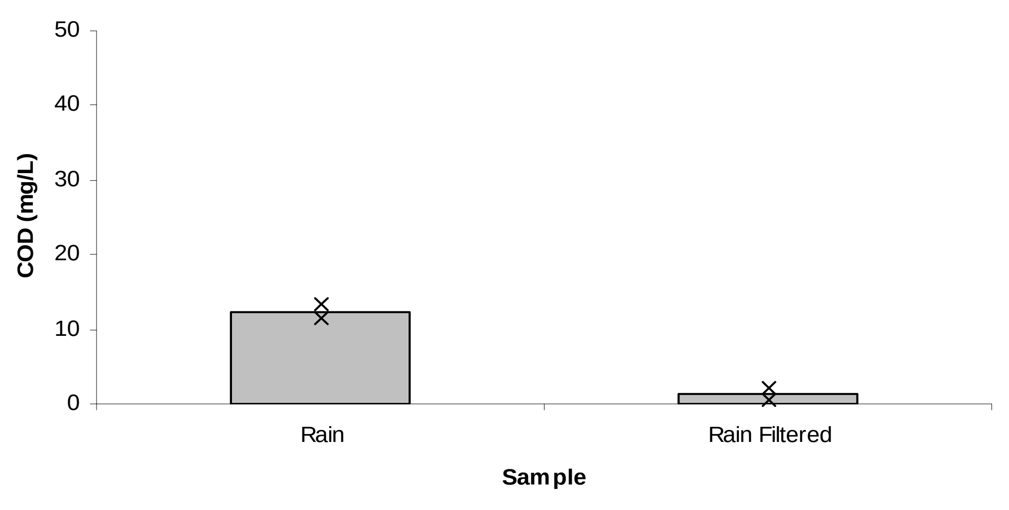

Figure 4-34 COD - Rainwater Samples - December 1, 2006 Storm

X = max and min data values

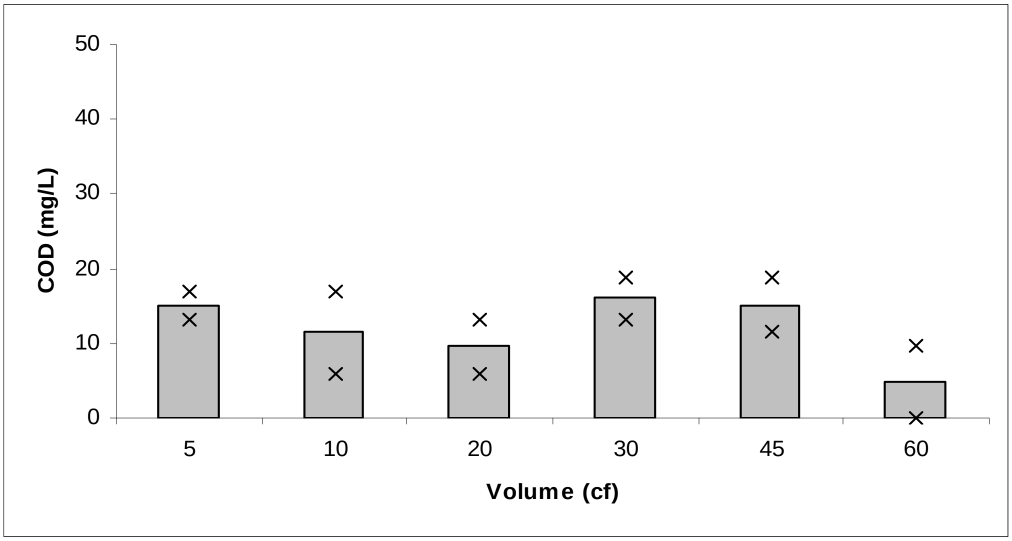

Figure 4-35 COD – Unfiltered Control Roof Samples - December 1, 2006 Storm

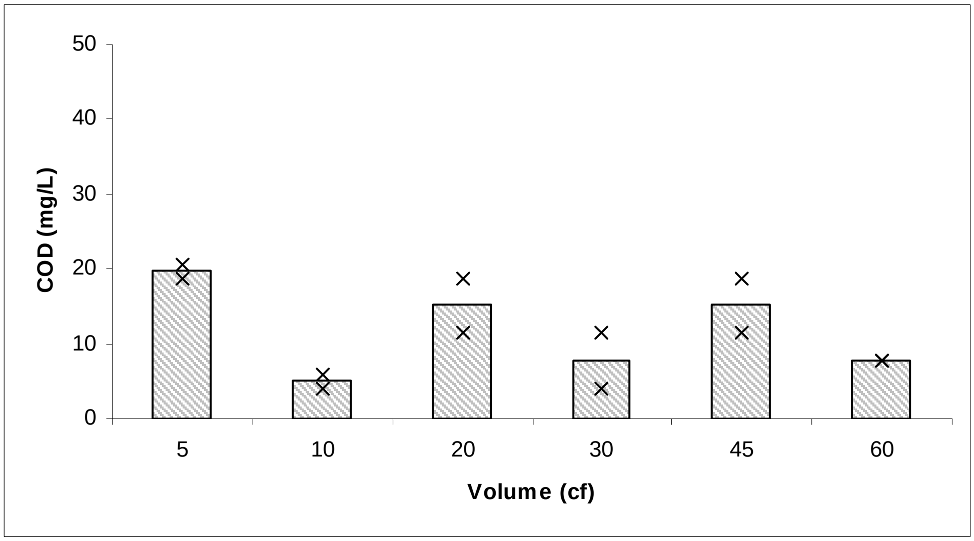

Figure 4-36 COD - Filtered Control Roof Samples - December 1, 2006 Storm

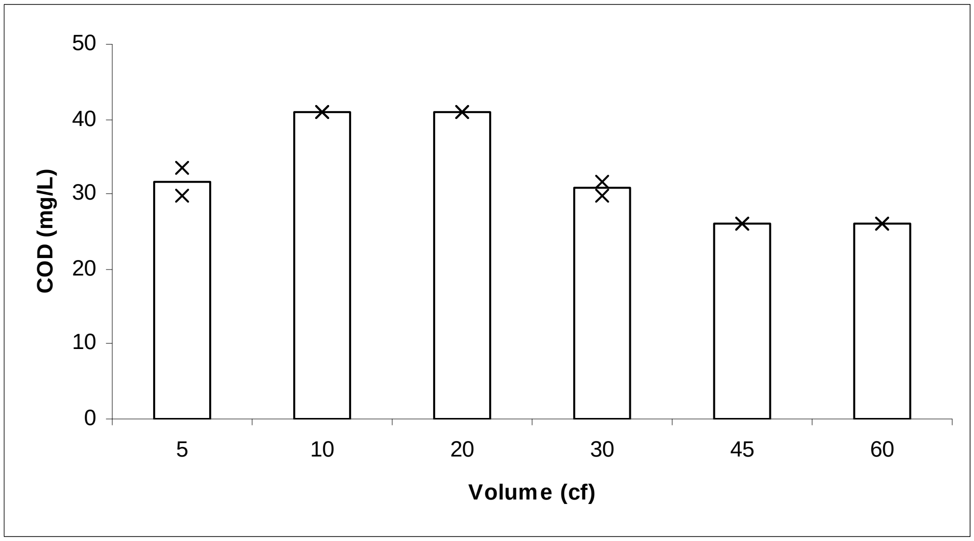

Figure 4-37 COD - Unfiltered Green Roof Samples - December 1, 2006 Storm

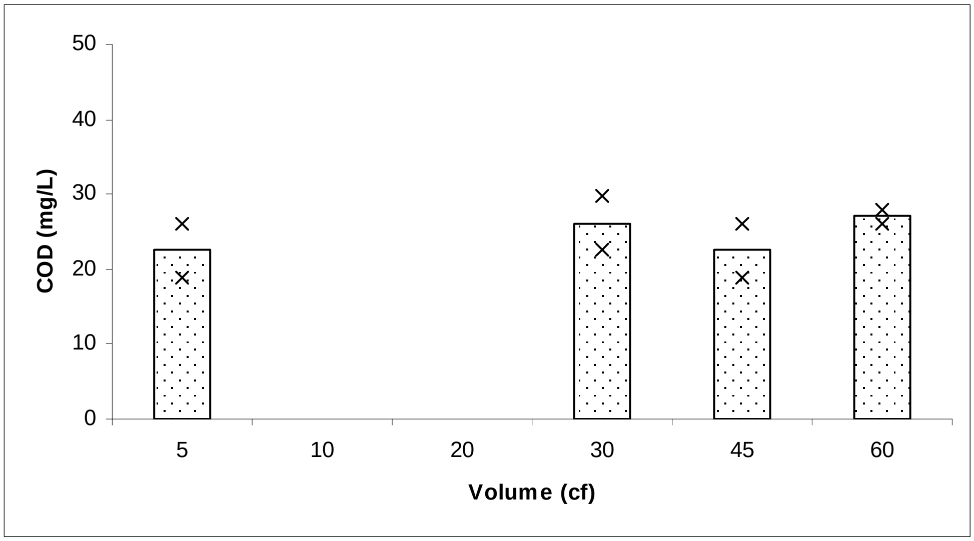

Figure 4-38 COD - Filtered Runoff Samples - December 1, 2006 Storm

Zinc

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

The detected levels were very low, with the highest at 0.44 mg/L of zinc. There was no consistent difference between the green and control roof samples or evident of a first flush effect. The rainwater samples were also not consistently higher or lower than the runoff samples. All samples with detectable results are shown in Figure 4-39.

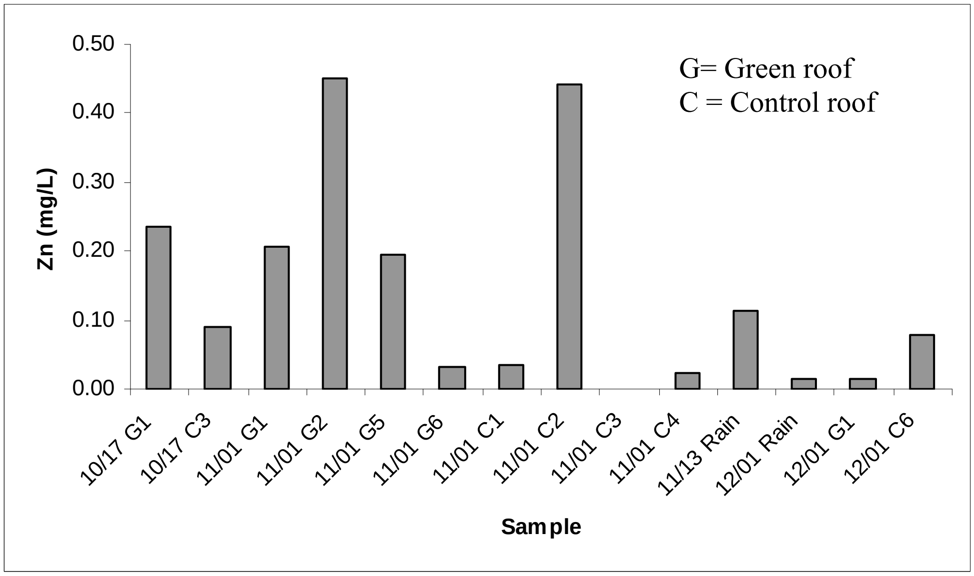

Figure 4-39 Zinc - All Storms

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.

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.

Only low levels of lead were detected (similar to zinc) as shown in Figure 4-40. The maximum concentration was 0.53 mg/L. The concentration in the runoff from either roof was not consistently greater than the other. Both rainwater samples had higher levels of lead than all but the green roof sample from the October 17, 2006 storm. There was no first flush effect evident from this data.

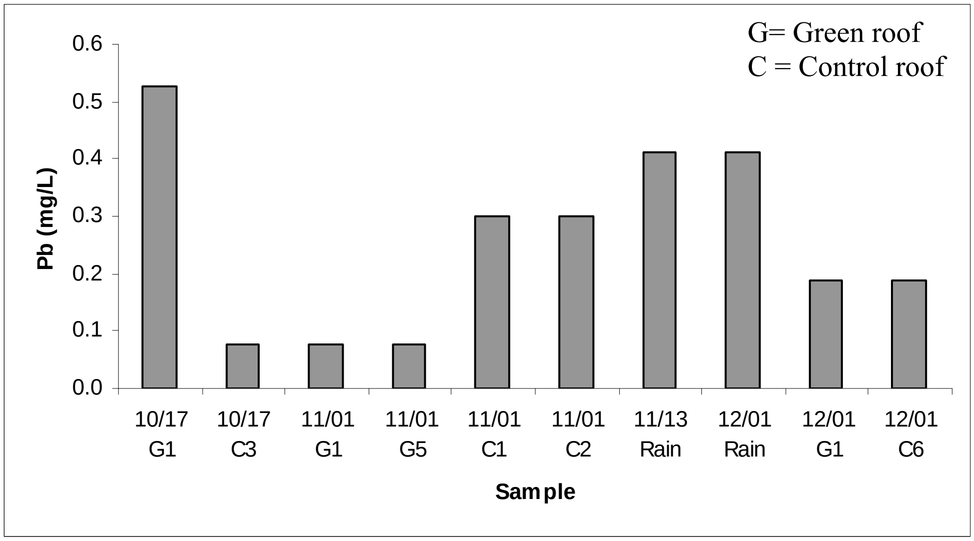

Figure 4-40 Lead - All Samples

4.4 Discussion: Giant Eagle Runoff Quality Results

There was no significant first flush effect observed as manifested in the composite of the water quality results. The green roof runoff samples did not exhibit any first flush characteristics for any parameter. However, the control roof runoff samples showed some first flush effects, but on a limited basis where some rainfall events showed a steady decrease in turbidity as well as sulfate. Based on the data, the first flush on the control roof may be correlated to an increased amount of non-dissolved sulfate-bearing particulates. These particles build up on the roof during dry periods prior to storms, thus it is likely that the duration and particulate deposition during dry periods prior to a rainfall and first flush effects are correlated.

The control roof consistently had more turbid samples. In the cases where there was an observed first flush effect, there was a significant difference between the first control roof sample and any sample from the green roof. However, for most rainfall events there was not a significant difference between the two roofs. While the green roof runoff may intuitively be expected to be more turbid than the results show, there are some considerations for why turbidities may be lower. In the green roof drainage system, there was often a soil build up just before the flumes that may have acted like a retention filter. Had soil particles remained in the runoff water all the way to the sampling point, a higher turbidity may have been observed. Additionally, some green roof sampling valves became clogged. This was presumably the result of larger soil particles becoming jammed in the valve mechanics and not making it into the sampling bottles. Frequent irrigation during the initial installation at Giant Eagle likely decreased the period where high turbidity would be expected. Samples were not collected for several months after the roof was completed, so the effect of the initial wash may have been missed.

Phosphorus leaches from the green roof especially during the period after the initial planting. The green roof runoff samples consistently had phosphorus concentrations of 2 to 3 mg/L while both the control roof runoff and rainwater contained very little, if any, phosphorus. It is believed that the significant phosphorus concentration observed is likely due to the natural flushing from the initial installation. The Giant Eagle samples were collected between three and four and a half months after the installation. Phosphorous leaching from green roof decreased over time.

COD levels followed a similar pattern to the phosphate results and were consistently higher for the green roof runoff than the control or the rainwater. In fact, green roof samples had roughly twice the COD of the control roof.

Both green and control roof runoff samples contained at least two to three times more sulfate than the rainwater. There was not a clear difference between sulfate levels on the two roofs and there was little pattern in the leeching as each roof produced higher concentrations than the other during at least one storm. Based on these observations, it is likely that sulfate atmospherically deposited on the roof is a significant source for the runoff.

Testing revealed that nitrogen was not significantly released. The majority of samples tested had a non-detectable concentration of total nitrogen and for samples that did have detectable nitrogen it was at very low levels. Metal analysis revealed that there were very little metals released by either roof. No detectible concentrations of cadmium were found in the samples tested. For zinc, the observed levels had a maximum of 0.44 mg/L for a green roof samples with the majority of the samples having concentrations of ~0.1 mg/L.

The measured pH levels in runoff from both roofs were consistently slightly basic, with pH readings in the range of 7.5 to 8.25, whereas the rainfall was slightly acidic (especially as compared to the Homestead site.) The Giant Eagle green roof did not have the opportunity to demonstrate a capability for neutralizing acid rain since rain at that location was not significantly acidic.

4.5 Thermal Performance of the Giant Eagle Roof

In this section, thermal data was examined from a representative warm weather week, a moderate temperature week, and a cold weather week to evaluate season dependent roof performances. The thermocouple data will be examined by monitoring station and by height profile. Single station temperature profiles indicate how the roof behaves throughout the cross section, most notably the roof membrane, roof surface, and ambient temperature. Comparing temperature measurements at the same profile height (i.e. roof membrane, roof surface) at all four monitoring location will show if roof type has an effect on the thermal stress endured by the material compared to material at other points on the roof. This data is also useful in determining if roof type influences the urban heat island effect. Thermocouple data will be then compared to the other weather monitoring instrument results to show how other factors in the climate have an effect on roof thermal performance.

Temperature Profiles

Thermocouples and temperature probes were used to observe the temperature profile at the four monitoring locations A, B, C, and D. Locations A and B are placed over the green roof, Locations C and D the control roof. The individual monitoring points used to create the temperature profiles are: below the decking, above the roof decking, below the waterproofing (roof) membrane, soil midpoint temperature (green roof only), soil or roof surface, 7cm above surface, 15cm above surface, 30cm above surface, 60cm above surface, and 1m above surface. The temperature profiles are as complete as possible with omissions occurring because several times thermocouples, temperature probes, and or data logger malfunctioned. All temperature profiles show a single color coded line for the temperature of the monitoring point over time. Most temperatures points were taken using thermocouple wire. The soil temperature data points on the green roof were acquired using a temperature probe such that standing water in the soil would not damage the instrument. The ambient temperature is also shown on each temperature profile. The ambient temperature was recorded by the relative humidity and temperature probe protected in a radiation shield. In addition, some temperature data from June 2007 to December 2007 are included in APPENDIX II. (see Figure II-13 to Figure II-32).

Summer Profiles:

The summer data group selected for the results section spans July 27, 2006 to August 1, 2006. The temperature profile for each monitoring location A, B, C, and D are shown in Figure 4-41, Figure 4-42, Figure 4-43, and Figure 4-44 respectively. In each profile, the temperature locations “Roof Membrane,” “Roof or Soil Surface,” and “Ambient” are highlighted. The thermocouple points are color coded such that the blue and purple colors represent points located at the waterproofing membrane or below. The green colors are used for the roof surface and soil temperature when applicable. The red, pink, and orange colors are used for temperature points above the surface, including the ambient temperature. The axis scales on all the temperature profiles remain constant for ease of comparing temperature from one monitoring location to another.

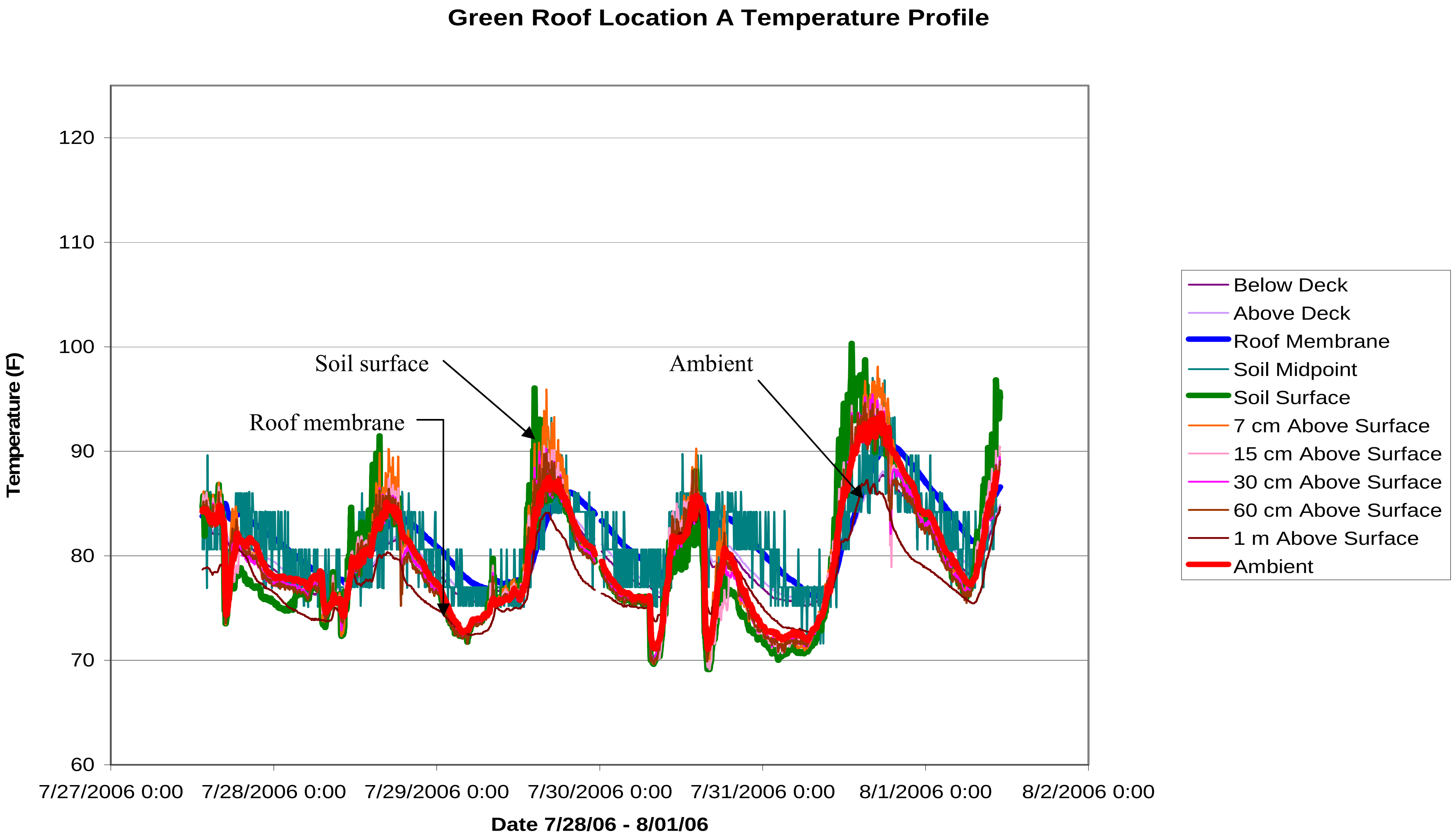

Figure 4-41 Green Roof Location A Temperature Profile for 7/28/06 through 8/1/06

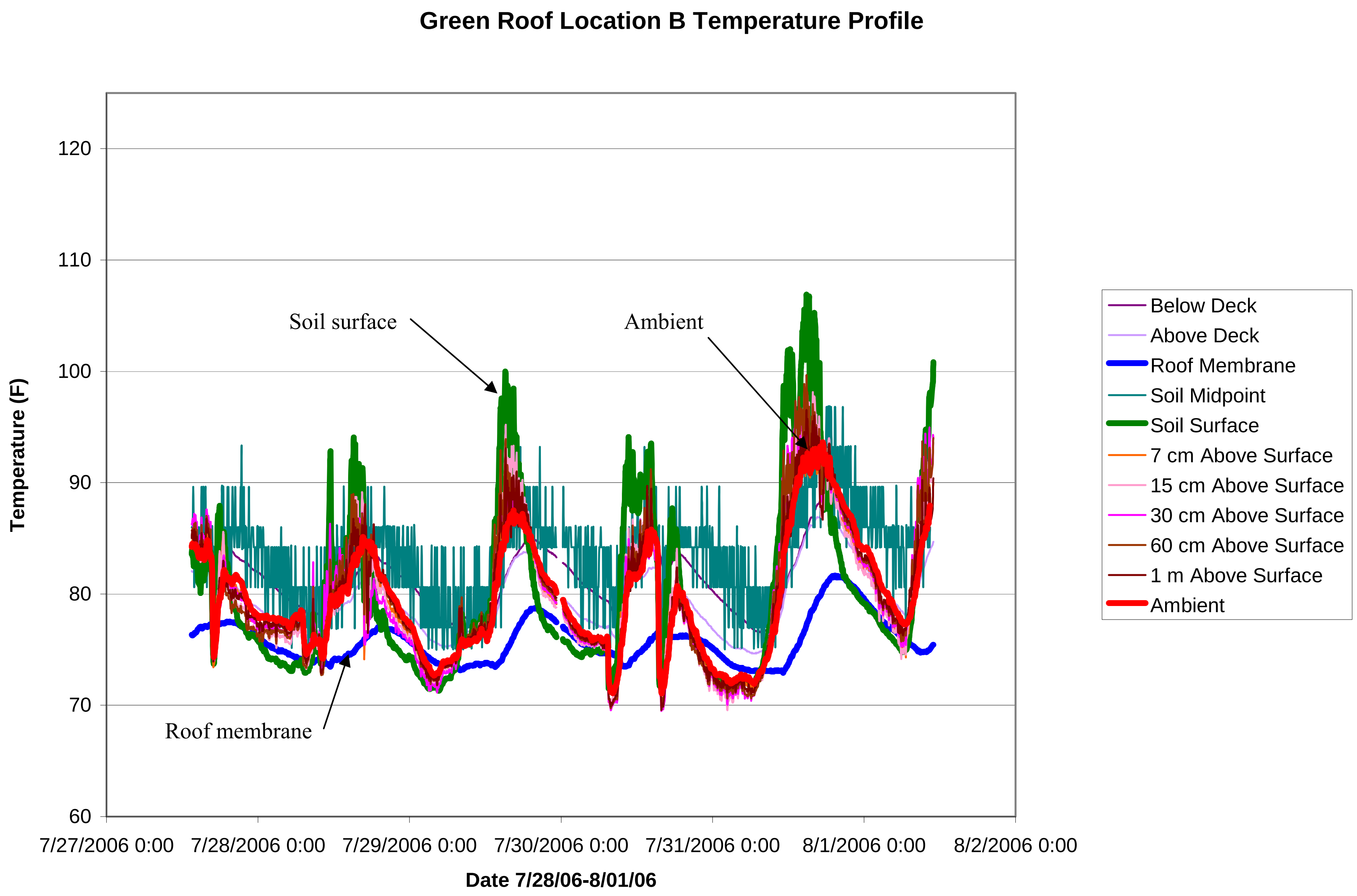

Figure 4-42 Green Roof Location B Temperature Profile for 7/28/06 through 8/1/06

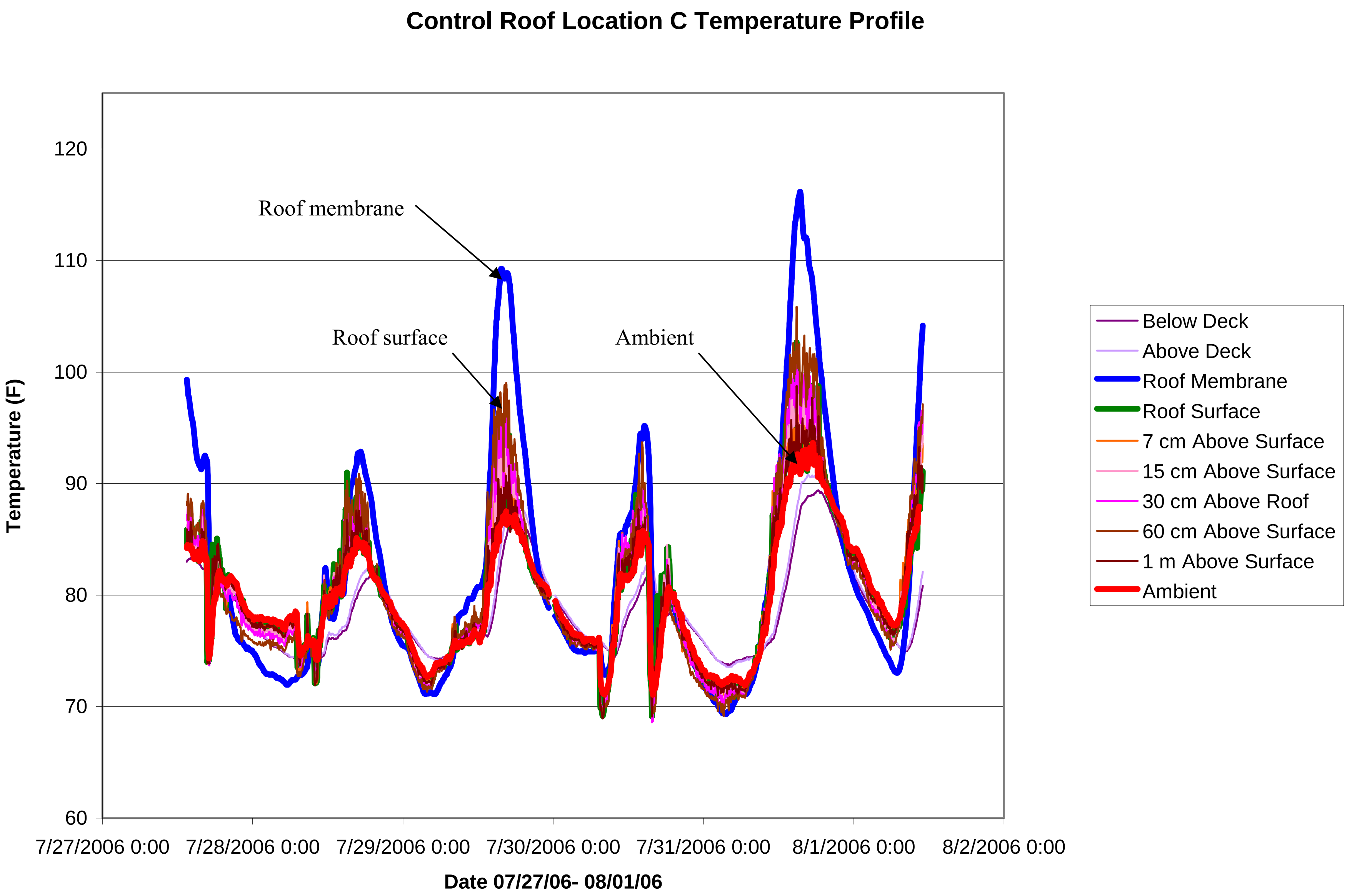

Figure 4-43 Control Roof Location C Temperature Profile for 7/28/06 through 8/1/06

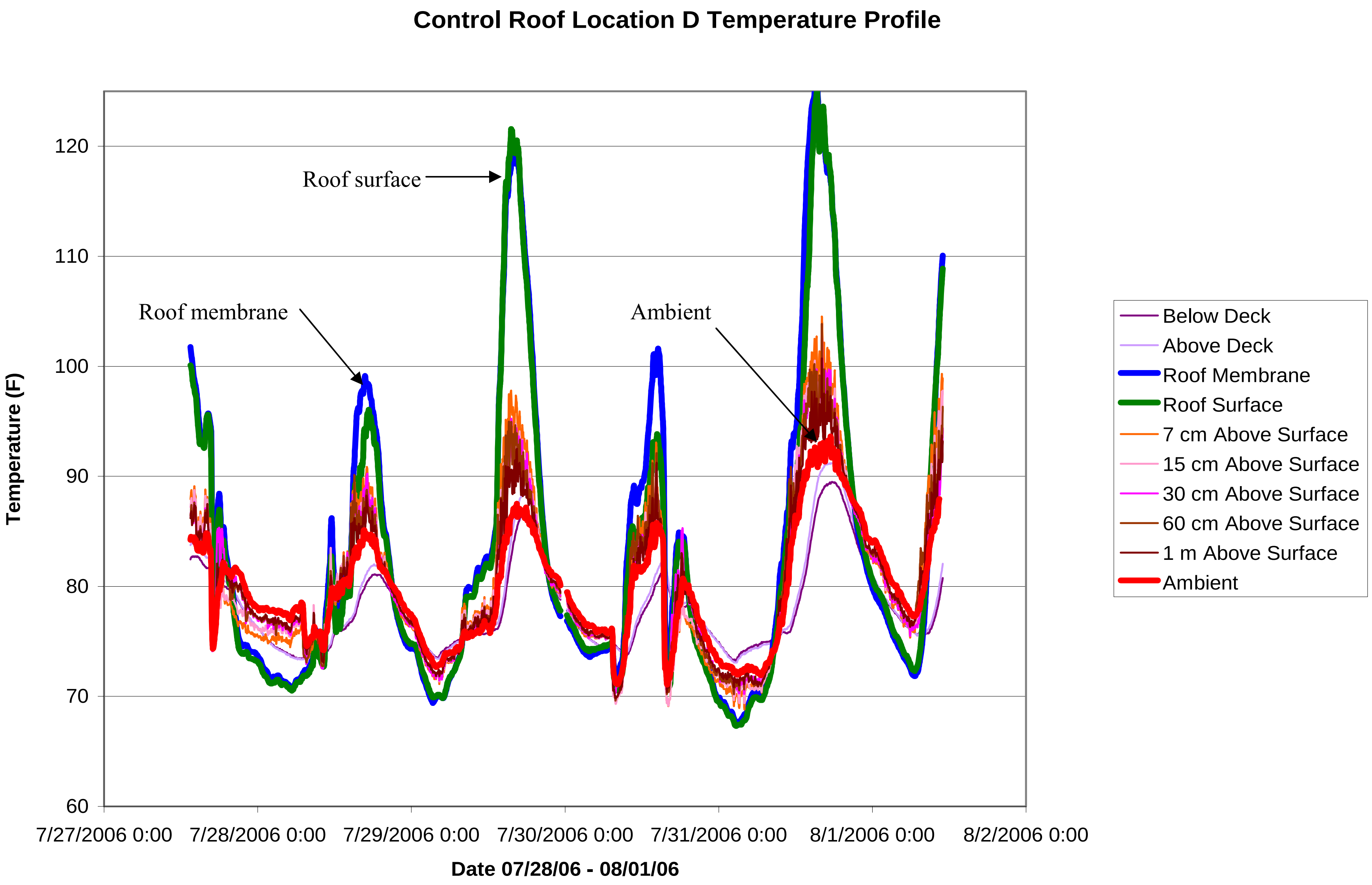

Figure 4-44 Control Roof Location D Temperature Profile for 7/28/06 through 8/1/06

The temperature profiles provide significant data about the performance of a roof type in warm summer weather. The ambient air temperature remained relatively constant for the time period that the data was collected where the nightly lows were around 70-75° F and the daily highs were around 85-90° F. Storms early in the week tapered off into sun and warmer temperatures. (Wunderground.com, 2007) The ambient air temperature was warmer than the air on the interior of the building. The interior of the building was kept around 65-70° F at store level.

The maximum temperature variation for the roofing membrane (14.7°F at Location A and 15.8°F at Location B) was roughly ½ that of temperature variations on the soil surfaces of the green roof (31.2°F and 35.6°F, at the same locations respectively). These significant variations are shown in the temperature profiles for the green roof locations A and B (Figure 4-41 and Figure 4-42). This is true even though all temperatures, above and below the roof surface remained similar to one another. The high and low temperatures experienced at each thermocouple point as well as the average temperature and greatest temperature fluctuation for monitoring Locations A and B are shown in Table 4-2 and Table 4-3. This data illustrates the shading benefit the green roof has on the roofing membrane, by reducing the thermal variation the membrane undergoes.

Table 4-2 Temperature Statistics for Monitoring Location A (7/28/06-8/01/06)

Temperature Statistics for Green Roof Monitoring Location A

	High	Low	Average	Fluctuation
Below Deck	87.8	75.2	81.5	12.6
Above Deck	88.1	75.5	81.8	12.6
Roofing Membrane	90.8	76.1	83.45	14.7
Soil Surface	100.3	69.1	84.7	31.2
7cm Above	98	69.5	83.75	28.5
15 cm Above	95.1	69.1	82.1	26
30 cm Above	95.4	69.7	82.55	25.7
60 cm Above	94.4	69.6	82	24.8
1 m Above	94.6	72.4	83.5	22.2

Table 4-3 Temperature Statistics for Monitoring Location B (7/28/06-8/01/06)

Temperature Statistics for Green Roof Monitoring Location B

	High	Low	Average	Fluctuation
Below Deck	88.5	76.6	82.55	11.9
Above Deck	87.5	74.6	81.05	12.9
Roofing Membrane	88.7	72.9	80.8	15.8
Soil Surface	106.8	71.2	89	35.6
7cm Above	94.7	69.9	82.3	24.8
15 cm Above	98.6	69.5	84.05	29.1
30 cm Above	97.4	69.4	83.4	28
60 cm Above	99.5	69.7	84.6	29.8
1 m Above	96.5	69.6	83.05	26.9

The temperature data for average lows were similar to those found on the green roof, ranging from 67° to 73° F. However, the high temperatures recorded on the control roof were warmer than those on the green roof and ranged from 89° to 125° F. The data collected for the control roof are summarized in Table 4-4 and Table 4-5. In terms of evaluating green roof performance, key metrics to consider are the variations in the roofing membrane and roof surface temperatures. At Location C the change in temperature over the week for the roof surface was 33.5° F, at Location D it was 57.7° F. The roofing membrane varied in temperature by 46.9° F at Location C and 58.1° F at Location D. While the maximum change in temperature occurred on the soil surface at the green roof locations, for the control roof locations the maximum variation occurred at the roofing membrane.

Table 4-4 Temperature Statistics for Monitoring Location C (7/28/06-8/01/06)

Temperature Statistics for Control Roof Monitoring Location C

	High	**Low**	**Average**	**Fluctuation**
Below Deck	89.4	73.8	81.6	15.6
Above Deck	90.9	73.5	82.2	17.4
Roofing Membrane	116.2	69.3	92.75	46.9
Roof Surface	102.6	69.1	85.85	33.5
7cm Above	100.3	69.2	84.75	31.1
15 cm Above	102.5	69.3	85.9	33.2
30 cm Above	104.6	68.6	86.6	36
60 cm Above	105.8	69.2	87.5	36.6
1 m Above	98.7	68.9	83.8	29.8

Table 4-5 Temperature Statistics for Monitoring Location D (7/28/06-8/01/06)

Temperature Statistics for Control Roof Monitoring Location D

	High	**Low**	**Average**	**Fluctuation**
Below Deck	89.5	73.3	81.4	16.2
Above Deck	91.2	73.1	82.15	18.1
Roofing Membrane	125.6	67.5	96.55	58.1
Roof Surface	125	67.3	96.15	57.7
7cm Above	104.4	68.8	86.6	35.6
15 cm Above	101.9	69.2	85.55	32.7
30 cm Above	102.8	70.2	86.5	32.6
60 cm Above	103.8	69.6	86.7	34.2
1 m Above	100.7	69.8	85.25	30.9

Autumn Profiles:

The ambient temperature, roof membrane, and roof surface data are highlighted for the period between October 20, 2006 and October 25, 2006. The temperature profile for each monitoring Location A, B, C, and D are shown in Figure 4-45, Figure 4-46, Figure 4-47, and Figure 4-48, respectively. The figures are organized in similar fashion to those presented for the summer data.

The temperature profiles recorded in this time period provide data about the performance by roof type in mild autumn weather. The ambient air temperature remained relatively constant in this time period where the nightly lows were between 35-45° F and the daily highs range from 40-60° F. Much of the week was rainy, and on the 23rd and 24th the rain changed into snow. (Wunderground, 2007) With the much colder temperatures and winter approaching, the interior of the building was heated.

The data recorded on the green roof at locations A and B indicate that while the exterior of the building was exposed to cold temperatures, the interior measurements (acquired above and below the steel deck) remained warm between 65-70°F. Despite being exposed to the grocery store climate and protected from the outdoor climate by the insulation, the temperature at these locations varied only by 5F° between day and night as shown in Figure 4-46 and Figure 4-47 (locations A and B). The majority of the other measurement locations closely followed the ambient air temperature. Table 4-6 and Table 4-7 show the high and low temperatures experienced at each thermocouple point, as well as the average temperature and largest change in temperature for monitoring Locations A and B. Both profiles for the green roof locations show lows ranging from 35° for thermocouples exposed outdoors to 65° F for those protected indoors, and highs ranging from 56-70° outdoors and near 71° F indoors. The maximum temperature variation for the roofing membrane was 11.0° F at Location A, again half of the temperature variations on the soil surfaces of the green roof are 23.6° and 20.7° F. This data illustrates the reduced range of temperature the membrane experiences and the diurnal temperature stabilizing effect the green roof has on the roofing membrane.

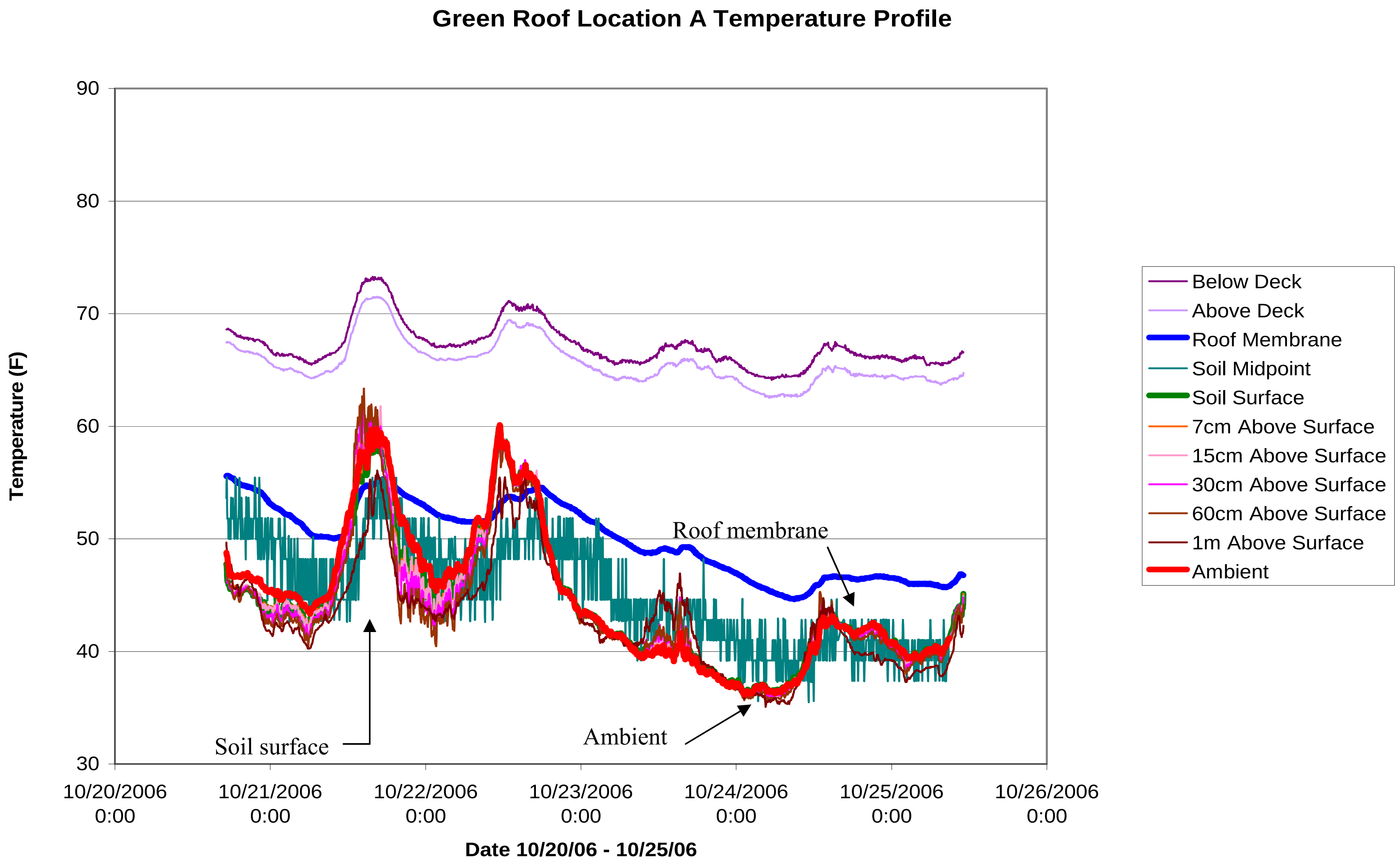

Figure 4-45 Green Roof Location A Temperature Profile for 10/20/06 – 10/25/06

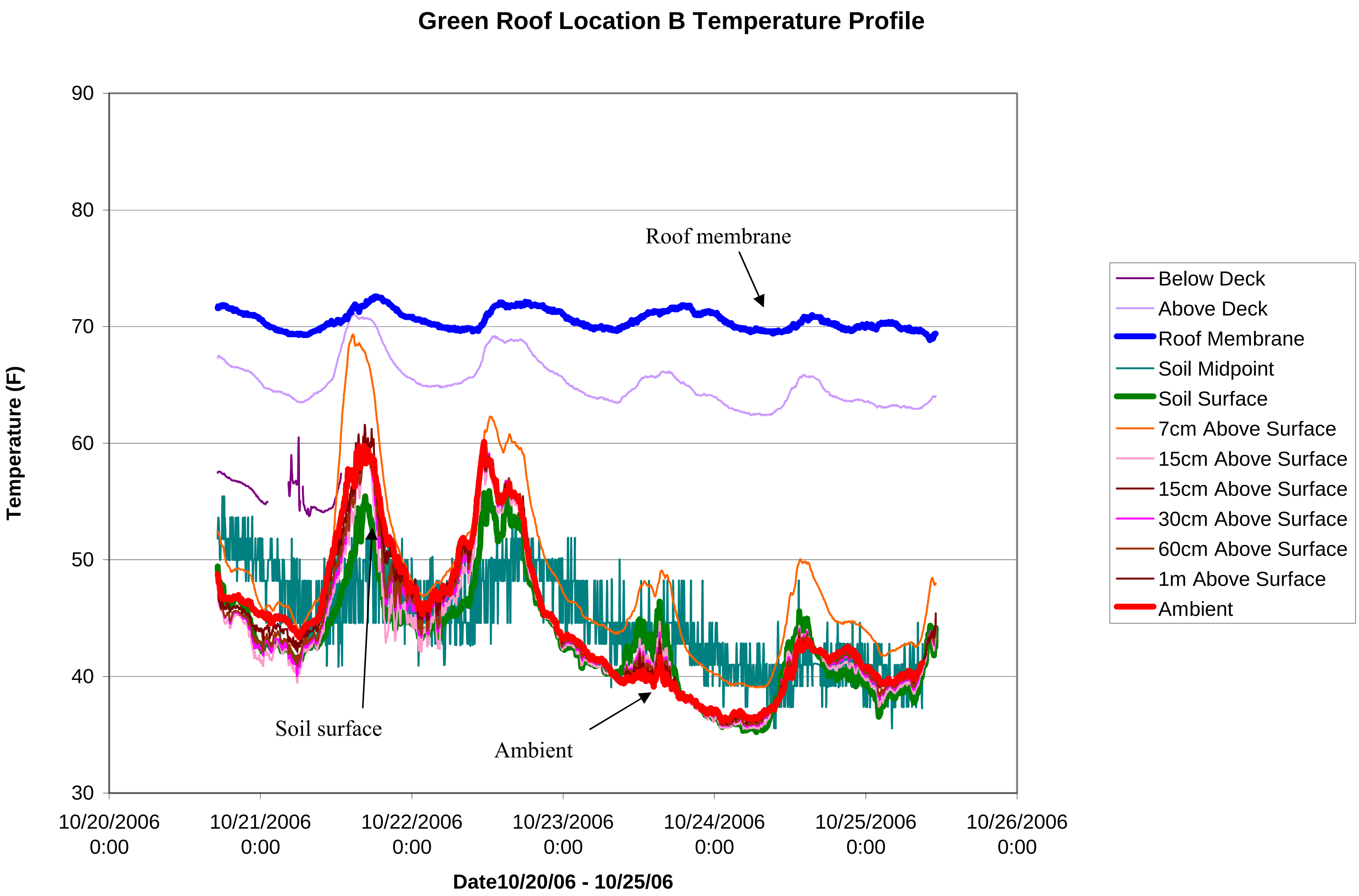

Figure 4-46 Green Roof Location B Temperature Profile for 10/20/06 – 10/25/06

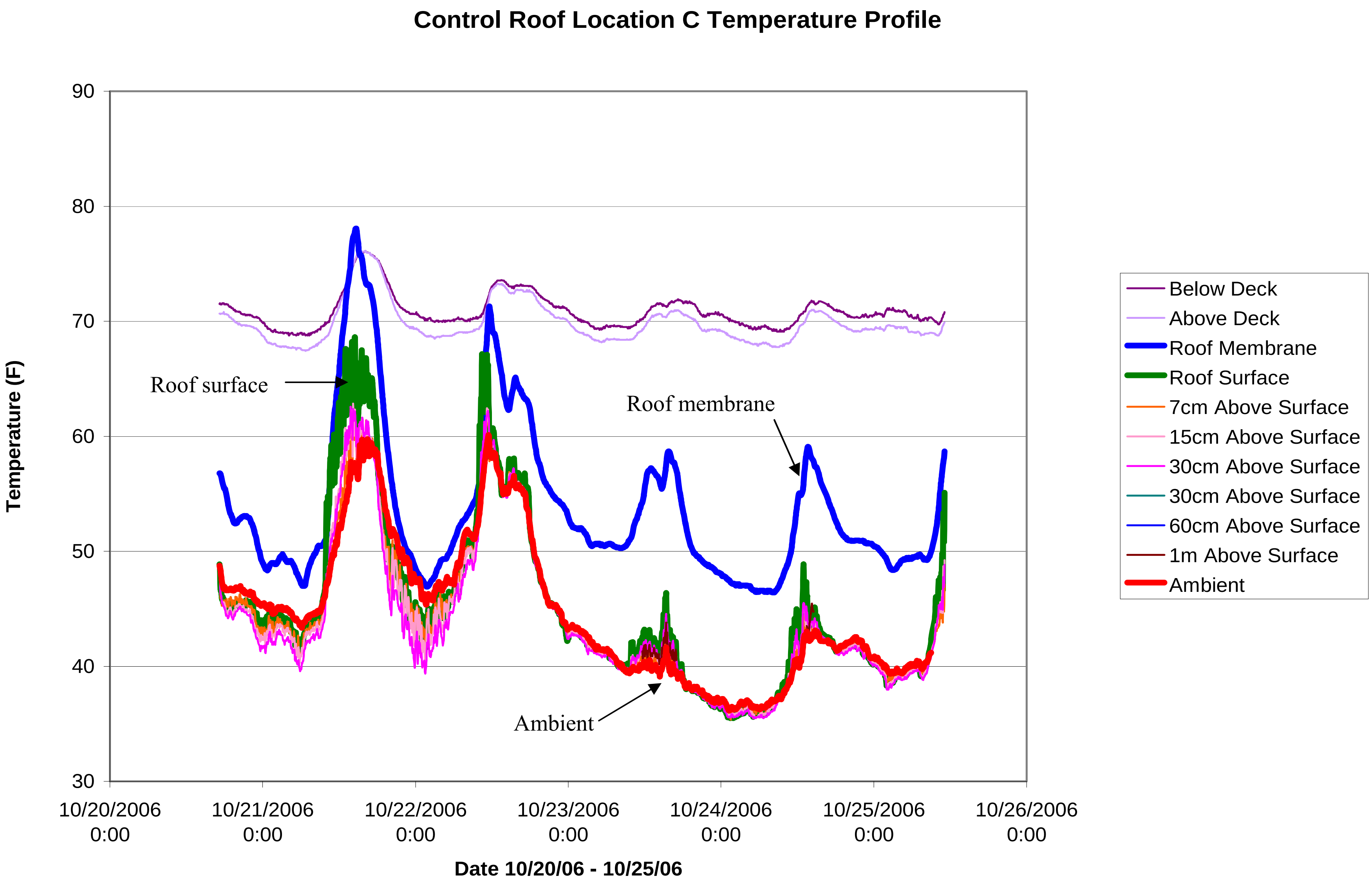

Figure 4-47 Control Roof Location C Temperature Profile for 10/20/06 – 10/25/06

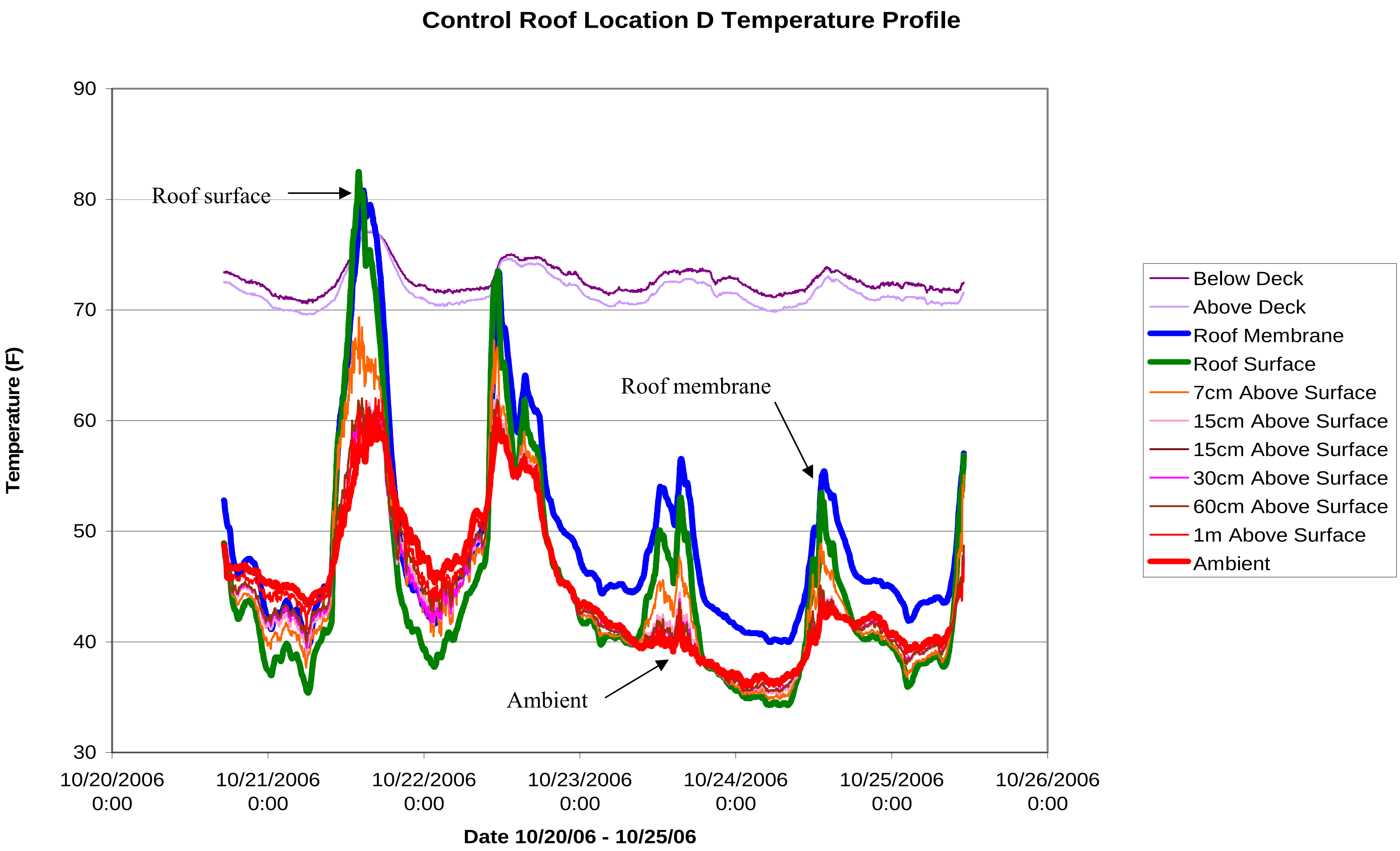

Figure 4-48 Control Roof Location D Temperature Profile for 10/20/06 – 10/25/06

Table 4-6 Temperature Statistics for Monitoring Location A (10/20/06-10/26/06)

Temperature Statistics for Green Roof Monitoring Location A

	High	Low	Average	Fluctuation
Below Deck	73.3	64.1	67.2	9.2
Above Deck	71.5	62.5	65.6	9.0
Roofing Membrane	55.6	44.6	50.0	11.0
Soil Surface	59.9	36.3	44.2	23.6
7cm Above	60.8	36.0	44.2	24.8
15 cm Above	61.8	35.9	44.3	25.9
30 cm Above	61.8	35.8	44.0	26.0
60 cm Above	63.3	35.7	43.7	27.6
1 m Above	56.1	35.1	43.0	21.0

Table 4-7 Temperature Statistics for Monitoring Location B (10/20/06-10/26/06)

Temperature Statistics for Green Roof Monitoring Location B

	High	Low	Average	Fluctuation
Below Deck	60.5	52.0	55.7	8.5
Above Deck	71.1	62.4	65.2	8.7
Roofing Membrane	72.6	68.8	70.5	3.8
Soil Surface	55.9	35.2	43.1	20.7
7cm Above	69.3	39.1	48.2	30.2
15 cm Above	61.4	35.5	43.4	25.9
30 cm Above	60.7	35.7	43.9	25.0
60 cm Above	61.0	35.8	44.0	25.2
1 m Above	61.5	35.9	44.4	25.6

Temperature differences between the green and control roofs were not as pronounced in the autumn as they were in the summer months. The average lows were similar to those observed for the green roof, ranging from 35° outdoors to 70° F in the interior of the building. The difference in high temperatures between the control roof and green roof were not as obvious as before, but still relevant. On the control roof, the high temperatures in the temperature profile range from 62-80° F outdoors and reach 76° F indoors. The data for the control roof are summarized in Table 4-8 and Table 4-9. Overall, the change in temperature over the week for the roof surface At Location C was 33.1° F, at Location D it was 48.2°F. The roofing membrane varied in temperature by 31.7° F at Location C and 41.8° F at Location D. The temperature variation in the roof membrane is two times the variation experienced by the roof membrane below the green roof. Therefore it was determined that even in milder weather, the green roof provided thermal protection to the roof membrane.

Table 4-8 Temperature Statistics for Monitoring Location C (10/20/06-10/26/06)

Temperature Statistics for Control Roof Monitoring Location C

	High	Low	Average	Fluctuation
Below Deck	76.1	68.8	70.9	7.3
Above Deck	76.1	67.4	69.9	8.7
Roofing Membrane	78.1	46.4	53.7	31.7
Roof Surface	68.6	35.5	45.1	33.1
7cm Above	62.3	35.4	44.2	26.9
15 cm Above	62.8	35.5	44.2	27.3
30 cm Above	62.6	35.5	43.8	27.1
60 cm Above	-	-		
1 m Above	45.5	40.2	41.8	5.3

Table 4-9 Temperature Statistics for Monitoring Location D (10/20/06-10/26/06)

Temperature Statistics for Control Roof Monitoring Location D

	High	Low	Average	Fluctuation
Below Deck	77.1	70.6	72.7	6.5
Above Deck	77.1	69.6	71.7	7.5
Roofing Membrane	80.8	39.0	49.0	41.8
Roof Surface	82.5	34.3	44.9	48.2
7cm Above	69.3	34.8	44.5	34.5
15 cm Above	62.3	35.3	44.0	27.0
30 cm Above	61.7	35.5	43.9	26.2
60 cm Above	62.0	35.5	44.2	26.5
1 m Above	61.9	35.8	44.4	26.1

Winter Profiles:

The temperature data from each monitoring station allowed us to evaluate the thermal performance of the roofs during a period of typical winter weather. The period between January 23, 2007 and January 29, 2007 was chosen as representative of typical Pittsburgh winter weather where the ambient air temperature remained constant. During this period, the ambient temperature was consistently cold throughout the day and night. The coldest night dropped to 9° F and the warmest day reached 41° F. There was light snow every day of the week (Wunderground, 2007).

Temperature profile data for Locations A and B shows that while the exterior of the building was exposed to cold temperatures, the interior measurements (taken above and below the steel deck) remained warm. For the green roof locations these measurements varied between 55-70° F as shown in Figure 4-49 and Figure 4-50 (Locations A and B, respectively). Despite being exposed to the grocery store climate and protected from the outdoor climate by the insulation, the temperature at these locations varied 10° F day to day. Most of the above surface temperatures followed the ambient air temperature closely. Table 4-10 and Table 4-11 show the high and low temperatures experienced at each thermocouple point, as well as the average temperature and largest change in temperature for monitoring Locations A and B. The outdoor measuring points average below freezing. The two indoor points were influenced by the grocery store heating system. Under the green roof, the roof membrane reached a minimum temperature of 35° F, 25° F warmer then the lowest evening temperature during the week.

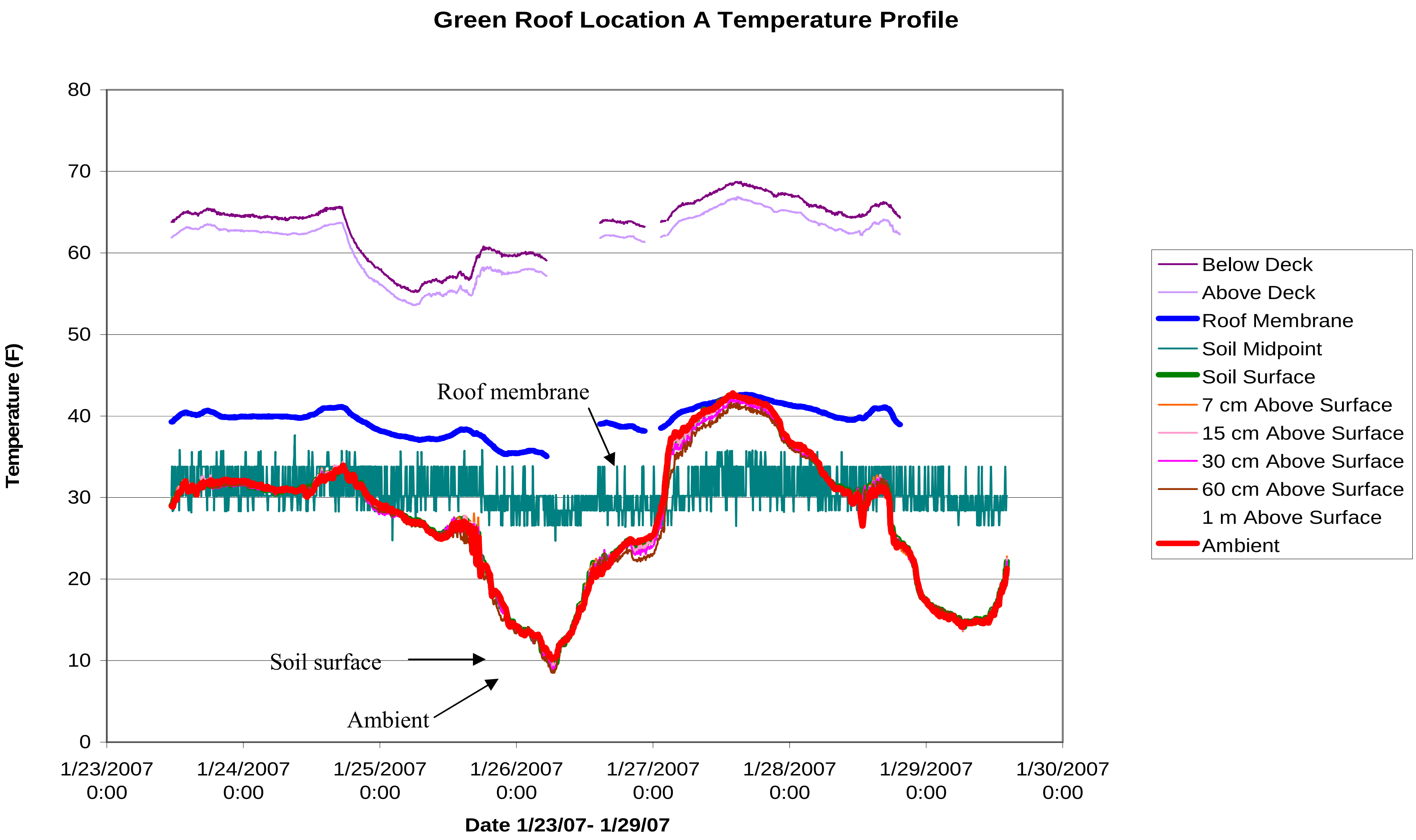

Figure 4-49 Green Roof Location A Temperature Profile for 01/23/07 – 01/29/07

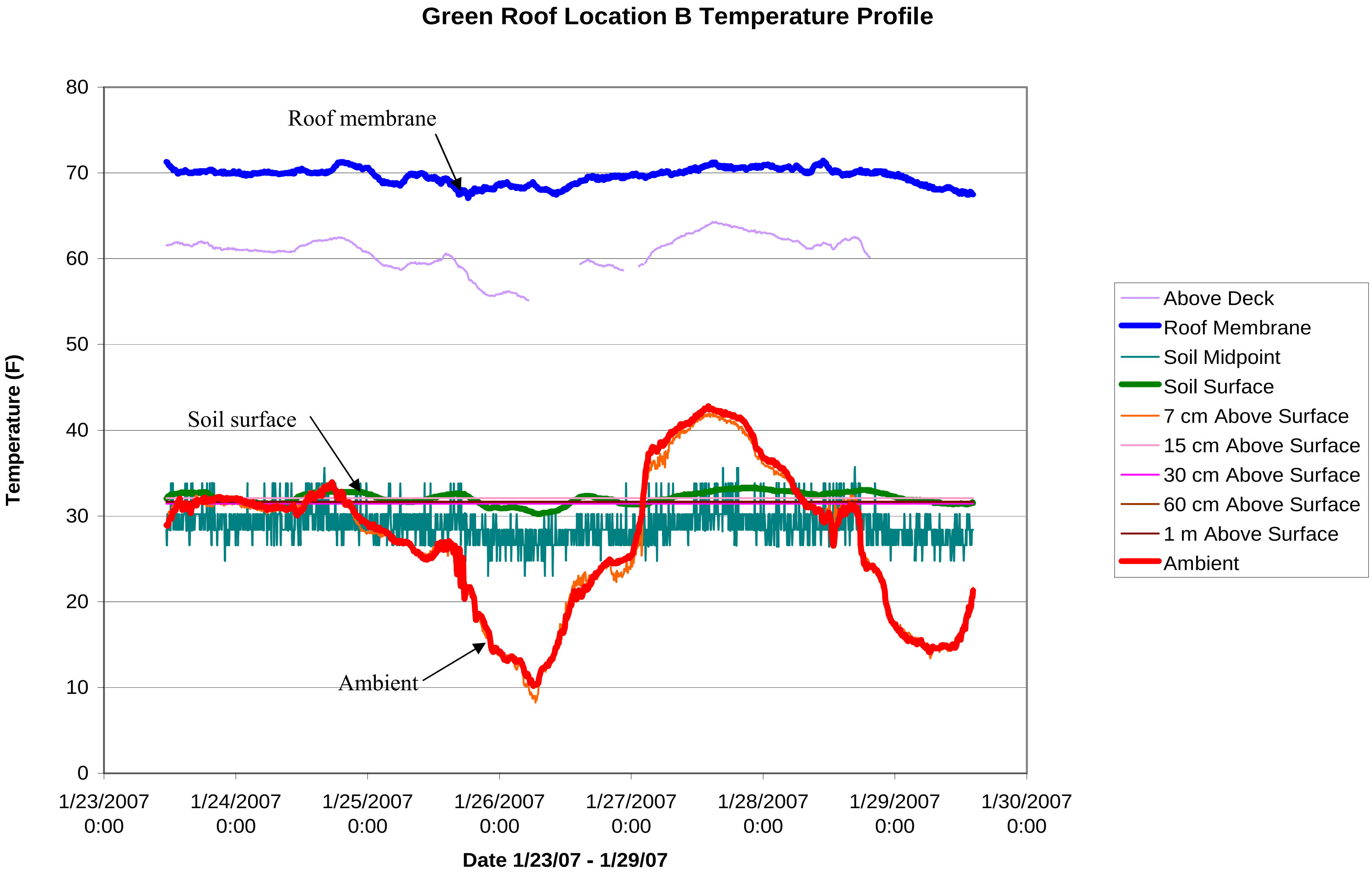

Figure 4-50 Green Roof Location B Temperature Profile for 01/23/07 – 01/29/07

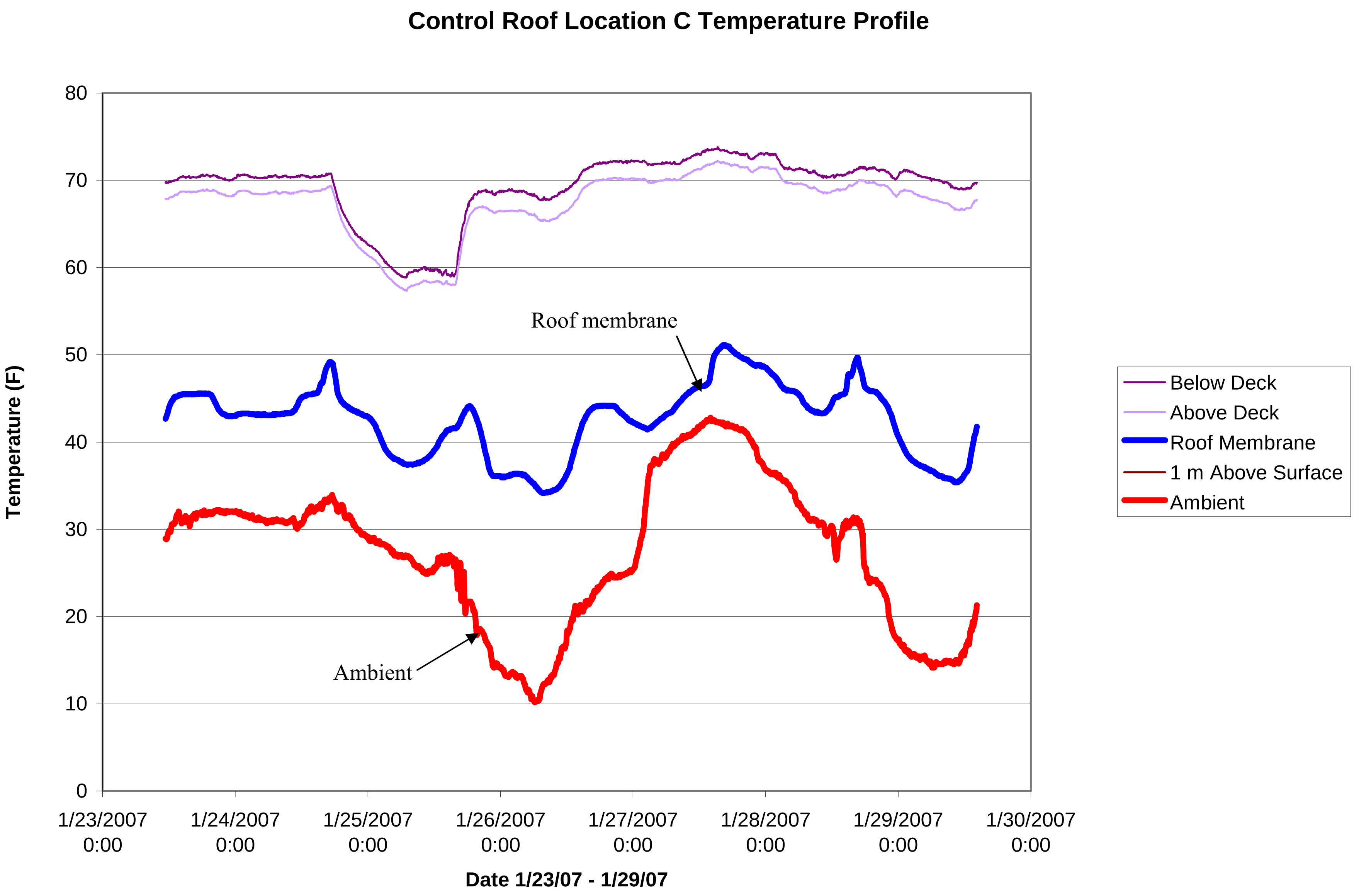

Figure 4-51 Control Roof Location C Temperature Profile for 01/23/07 – 01/29/07

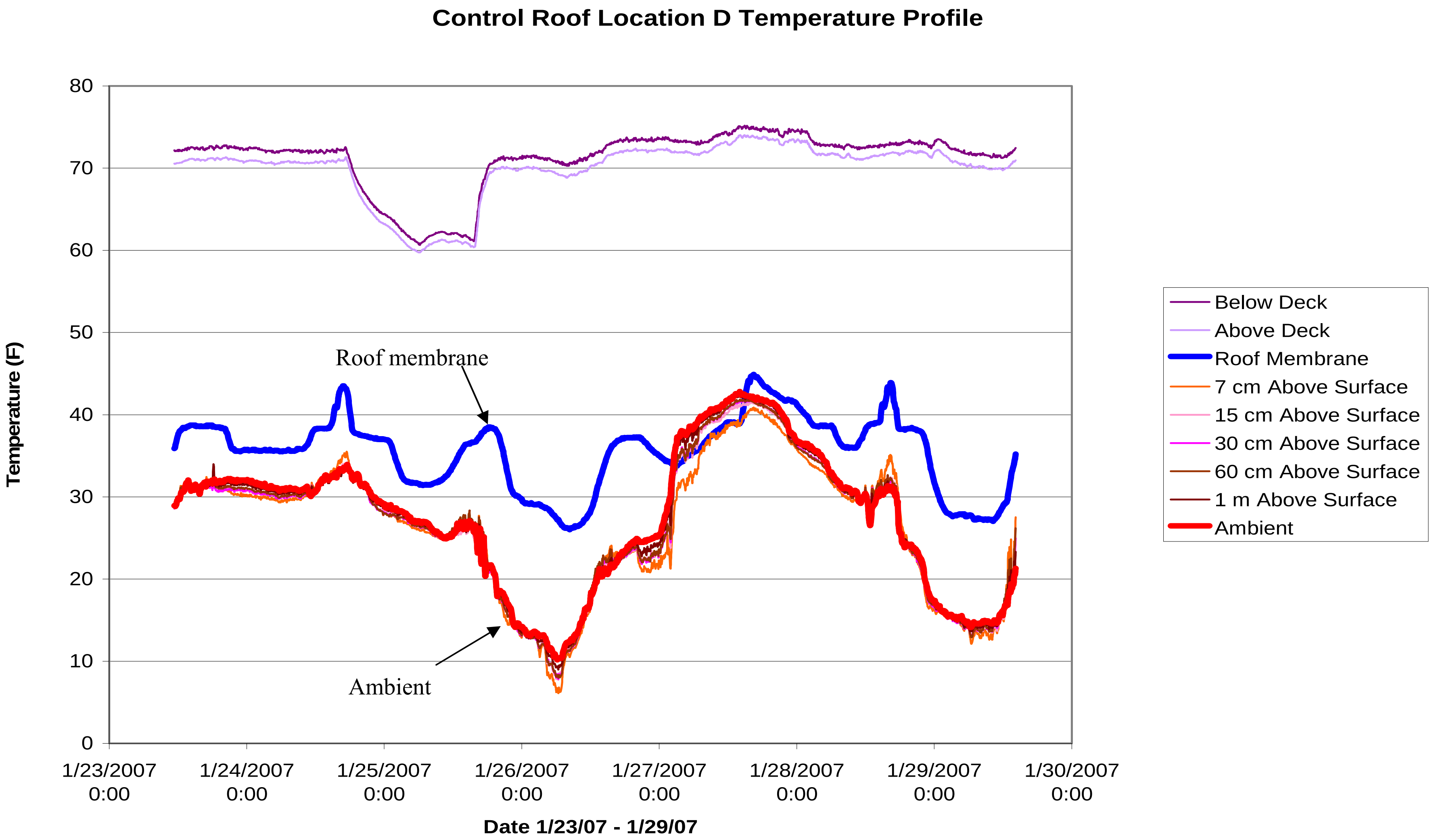

Figure 4-52 Control Roof Location D Temperature Profile for 01/23/07 – 01/29/07

Table 4-10 Temperature Statistics for Monitoring Location A (01/23/07-01/29/07)

Temperature Statistics for Green Roof Monitoring Location A

	High	Low	Average	Fluctuation
Below Deck	68.7	55.2	63.3	13.5
Above Deck	66.9	53.6	61.4	13.3
Roofing Membrane	42.7	35.0	39.5	7.7
Soil Surface	42.5	9.4	27.5	33.1
7cm Above	42.5	8.8	27.4	33.7
15 cm Above	42.4	9.0	27.5	33.4
30 cm Above	42.2	8.8	27.2	33.4
60 cm Above	41.7	8.5	27.0	33.2
1 m Above	33.9	29.2	31.8	4.7

Table 4-11 Temperature Statistics for Monitoring Location B (01/23/07-01/29/07)

Temperature Statistics for Green Roof Monitoring Location B

	High	Low	Average	Fluctuation
Below Deck	-	-	-	
Above Deck	64.3	55.2	60.8	9.1
Roofing Membrane	71.5	67.0	69.6	4.5
Soil Surface	33.3	30.2	32.1	3.1
7cm Above	41.9	8.3	27.2	33.6
15 cm Above	32.1	32.1	32.1	0.0
30 cm Above	32.5	31.5	31.5	1.0
60 cm Above	31.6	31.6	31.6	0.0
1 m Above	31.7	31.7	31.7	0.0

There was no significant change in temperature from the green roof membrane to the control roof membrane in winter, unlike the observations for summer and fall. The average temperature of the control roof membrane was comparable to the green roof (Location A) at 42.6° F and 35.5°F (Locations C +D). The ambient high and low temperatures were also similar to those observed on the green roof as indicated in Table 4-12 and Table 4-13. The low temperature of the control roof membrane was 34.1° F and 26° F at Locations C and D respectively (as shown in Figure 4-51 and Figure 4-52) while the low on the green roof (Location A) was 35° F. These numerical data coupled with the facts that Locations A and C had very similar temperature profiles, were exposed to the same amount of daylight and shadowing, and that the above surface temperatures at Location D are similar those above the green roof (location A and B), provide evidence that in cold weather, green and conventional roofs have similar thermal performances.

Table 4-12 Temperature Statistics for Monitoring Location C (01/23/07-01/29/07)

Temperature Statistics for Control Roof Monitoring Location C

	High	Low	Average	Fluctuation
Below Deck	73.8	58.9	69.2	14.9
Above Deck	72.2	57.3	67.5	14.9
Roofing Membrane	51.1	34.1	42.6	17.0
Roof Surface	-	-	-	
7cm Above	-	-	-	
15 cm Above	-	-	-	
30 cm Above	-	-	-	
60 cm Above	-	-	-	
1 m Above	-	-	-	

Table 4-13 Temperature Statistics for Monitoring Location D (01/23/07-01/29/07)

Temperature Statistics for Control Roof Monitoring Location D

	High	Low	Average	Fluctuation
Below Deck	75.2	60.6	71.2	14.6
Above Deck	74.0	59.7	69.9	14.3
Roofing Membrane	44.9	26.0	35.5	18.9
Roof Surface	-	-	-	
7cm Above	40.9	6.1	26.4	34.8
15 cm Above	41.5	7.8	26.8	33.7
30 cm Above	41.8	7.8	26.8	34.0
60 cm Above	41.8	8.0	27.0	33.8
1 m Above	42.2	9.0	27.2	33.2

4.6 Net Radiation

Net radiometers were placed at Giant Eagle monitoring locations A and C to measure the amount of solar energy the roof material is exposed to day and night thereby capturing the amount of energy that passes in and out of the roof microclimate. This data was used to determine the efficiency of the green roof vegetation to use this energy, versus the control roof's ability to store and release the energy. To allow easy comparisons of the net radiation gained in each season, the net radiation from a summer, fall, and winter data set was plotted such that the y-axis remains constant, from -200 $W*m^{-2}$ to 1000 $W*m^{-2}$ and are presented as Figure 4-53 (summer), Figure 4-54 (fall), and Figure 4-55 (winter).

For the summer dataset, the net radiation curves for the green and control roofs closely followed each other and both had peak net radiation above 600 $W*m^{-2}$ each day.[3] The green roof radiometer peaked above the control roof radiometer indicating that the green roof surface absorbed more and reflected less energy than the control roof. In the evening, the net radiation at both locations dropped below zero thus the reflected radiation exceeded the incoming radiation. Note that in the evening, the control roof radiation dropped slightly below the green roof radiation thereby indicating that the control roof released more radiation into the atmosphere than the green roof. The green roof benefited from three factors that affect its ability to absorb and use energy; its higher thermal mass, the use of solar energy for photosynthesis by the vegetation, and the use of solar energy to evaporate water trapped in the substrate. These factors allow the green roof to absorb more energy, reflect less energy, and release less energy at night in comparison to the control roof that had a significantly lower mass and darker color. During the day the control roof surface absorbed incoming radiation that heated the membrane material twice as much as the green roof. Then at night, additional energy that the control roof had collected during the day was re-emitted thereby cooling the roof membrane by releasing (heat) into the microclimate around the building. The net difference between the two roofs was observed to be between 1-5 $W*m^{-2}$ suggesting that the control roof contributes more to the Urban Heat Island Effect by reflecting more energy during the day and releasing more energy in the evening.

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[3] Positive Net radiation indicates that the incoming radiation exceeded the reflected radiation by that amount.

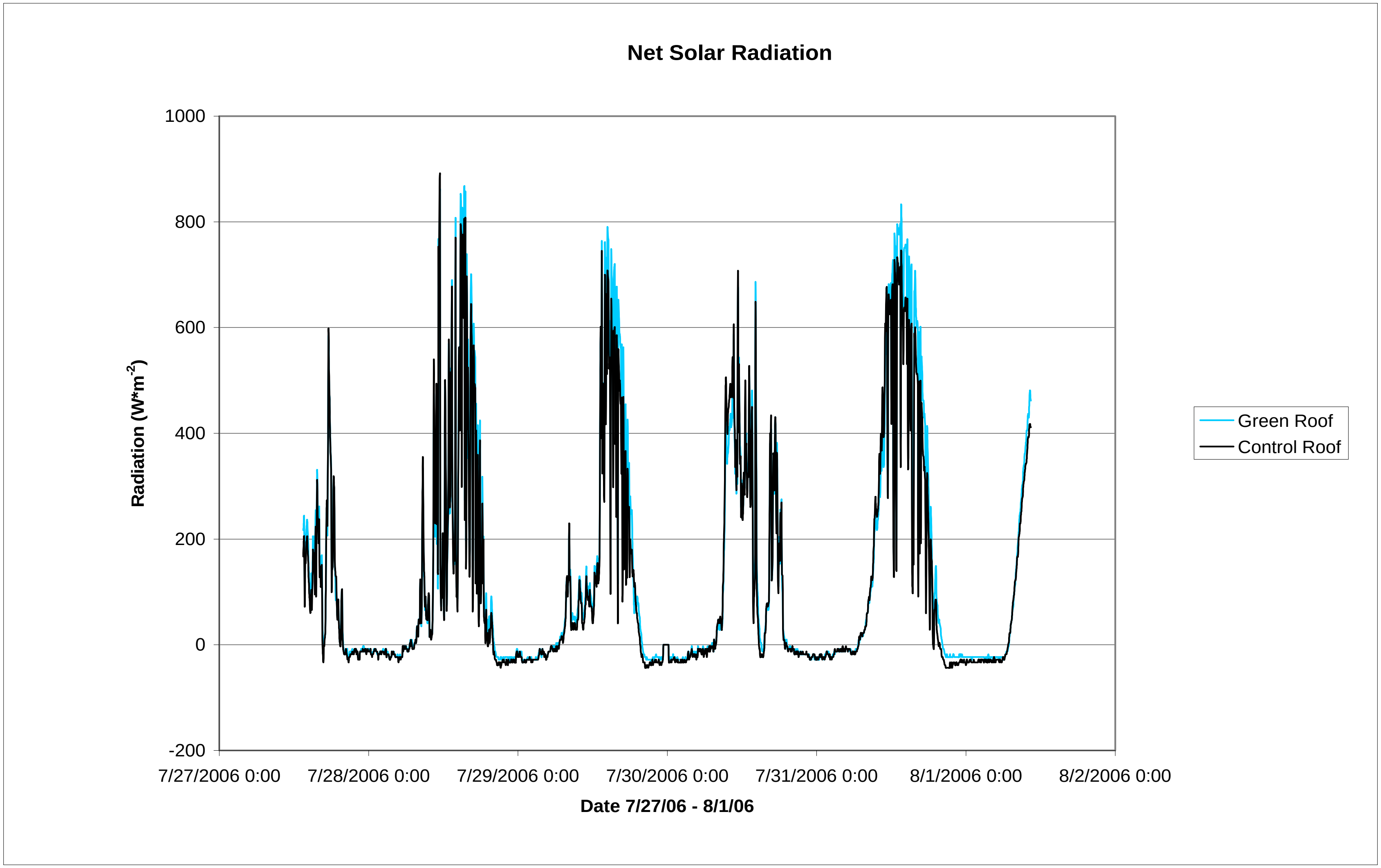

Figure 4-53 Summer Net Radiometer at Giant Eagle Data for 7/27/06 – 8/1/06

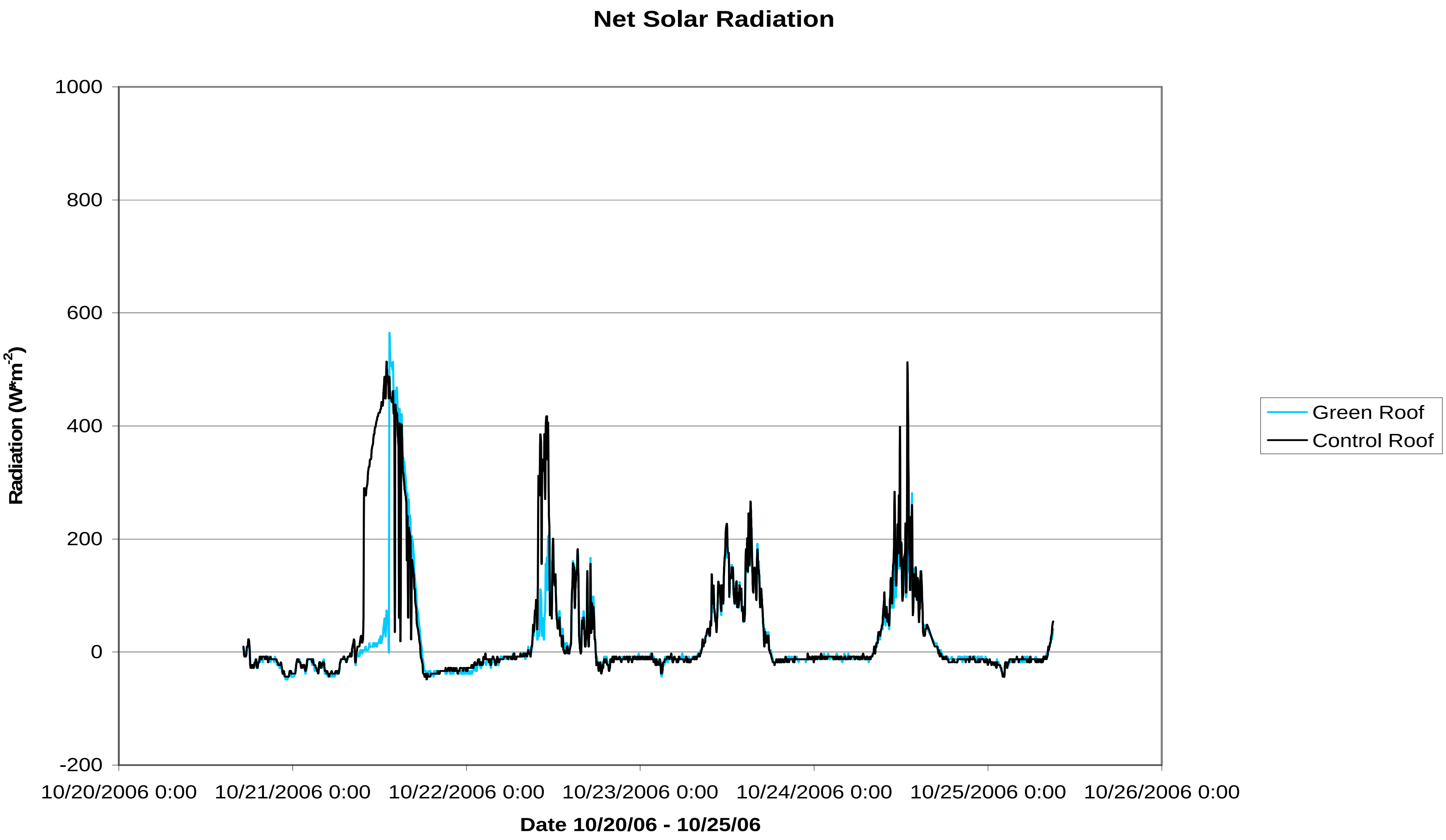

Figure 4-54 Fall Net Radiometer at Giant Eagle Data for 10/20/06 – 10/25/06

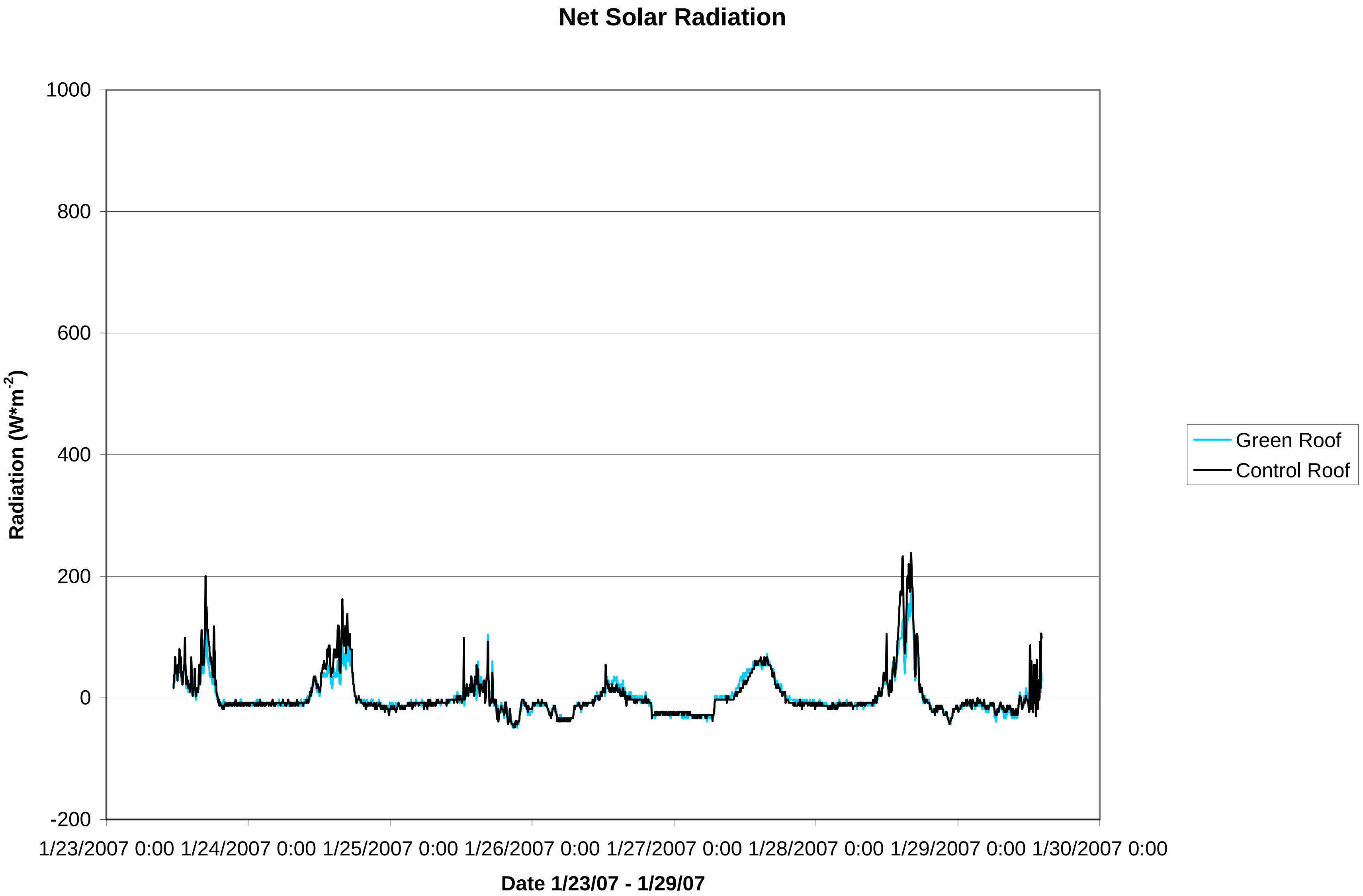

Figure 4-55 Winter Net Radiometer at Giant Eagle Data for 1/23/07 – 1/29/07

Differences in net radiation for the ‘typical autumn period’ between the green and control roof were measured to be 1-2 Wm^{-2} as indicated in Figure 4-54. Net radiation from both roofs peaked above 200-400 $W*m^{-2}$ each day and the measurements closely followed each other. The first day had the largest integrated radiation where the control roof received more total radiation whereas the green roof had the highest peak radiation. This trait was not consistent, and most other days, the control roof equaled or exceeded the green roof net radiation. As with the summer data, the net radiation at both locations dropped below zero in the evening and the evening control roof radiation was roughly equal to the evening green roof radiation. This indicates that both roof surfaces released equivalent amounts of energy. The fall data suggests that any reduction in the UHI effect green roofs have during the summer is lost when the incoming solar radiation is reduced and both roofs perform equally in autumn.

The short daylight hours and the angle of the northern hemisphere from the sun greatly reduced the incoming solar radiation and the net radiation rarely reached 200 $W*m^{-2}$ each day in the winter study period. Unlike the summer and fall periods, the apartment building casted a shadow over the roof though most of the day thereby reducing the net radiation. Like the fall data set, the winter data shows that the net radiation over both roof surfaces was roughly equal as indicated in Figure 4-55. The day and evening radiation totals were equivalent for both roof types. The winter data suggests that any benefit green roofs pose towards the Urban Heat Island during the summer is lost when the incoming solar radiation is reduced. As with the fall data, the winter net radiation data shows that both the control roof and the green roof perform similarly in cold weather.

4.7 Discussion: Thermal Data

The thermal data collected for the green and control roofs showed that the conventional roof membrane, when exposed to direct solar radiation and warm ambient temperatures, absorbed energy and increased in temperature much more than the membrane on the green roof. The data also shows that the conventional roof released that stored energy at night. Under summer conditions, the roof membrane underneath the extensive green roof was shielded from the extensive thermal flux and stayed at a relatively moderate temperature. For example, variations in temperature of the roof membrane on July 31, 2006 was 15° F and 16°F on the green roof, and 47°F and 58°F on the control roof. These four composite single layer measurements temperature data show that the roof membrane for the control roof was influenced by the air temperature and incident solar radiation significantly more than the green roof. The control roof membrane experienced extremes in temperatures in response to the high ambient temperatures and high incident solar radiation during the day, and release of the stored energy as heat at night. While the above surface measurement points were easily influenced by other factors, the points closest to the roof membrane did warm with the roof membrane. Measurements at the 7 cm and 15 cm above surface locations showed increases in temperature of 1-10° for the ambient temperature on the control roof and increases of 0-2° F over the green roof. Therefore, the conventional roof has a more adverse effect on the urban heat island effect than the green roof. Further, it is largely believed that large thermal stresses the control roof membrane undergoes may reduce the expected life of the membrane, giving another advantage to green roofs relative to the overall membrane performance and lifetime.

The membrane underneath the green roof had a much different experience as it was largely protected from the temperature extremes seen on the control roof during the summer. The green roof assembly was observed to effectively absorb the incoming solar radiation and used that energy for plant growth and water evaporation, as opposed to transferring it to lower layers of the roof. It should be noted that during the July to October monitoring period the green roof was regularly irrigated and that the additional water increased the evaporative capabilities of the green roof, and contributed to the reduction of the roof membrane temperature. The combination of shading and evaporative cooling protected the waterproofing membrane beneath the green roof from extreme thermal stress. This protection may increase the membrane life cycle. However, during the winter months, the conventional and green roofs performed similarly. The green roof’s thermal benefit was greatest during periods of warm temperatures and extended exposure to solar radiation but continued somewhat into the warmer fall months.

5. COMPARISON OF GIANT EAGLE AND HOMESTEAD GREEN ROOF TECHNOLOGIES

This section contains a comparison of the data collected at Homestead and Giant Eagle during the second phase of the project (April 2008 to April 2009) when both sites were being monitored. The comparison is divided into three subsections: comparisons of the runoff quantity, runoff quality data and comparative temperature. Comparisons are made between green and control roofs, as well as between performance differences of the two green roofs, which differ by technology and thickness of soil medium.

5.1 Runoff quantity performances

Flow rate and runoff performance data were gathered from both Homestead and Giant Eagle sites. The data are available from April 20, 2008 to April 30, 2009, with the exceptions of when instruments malfunctioned in field or there were data transmission problems. Additionally, the data stopped transferring from Homestead site at the middle of March due to internet connection problem.

The flow rate and runoff volume were recorded by dataloggers in the field, transmitted to the remote server, and analyzed via LabVIEW as described in section 3.0. The method utilized in plotting the runoff graphs in this section was slightly different compared to the methods which were used in the section 4.1. The time scale was adjusted to an hourly basis for each rainfall events. The hourly flow rate was calculated based on average flow rate for every hour when there was available flow rate data detected. The cumulative runoff volumes were directly determined from the original rainfall intensity and cumulative rainfall data recorded. The unit for the cumulative runoff volumes and amount of rainfall used in this section is cf/1000sf: the equivalent cubic feet of the runoff that occurred per 1000 square feet of roof area.

The quantity of runoff measured for flow from the green and control roofs at both sites during rainfall events is compared. A summary table of the runoff quantity data is presented in Table I-1 in APPENDIX I. APPENDIX I. includes data of peak flow rates; retardation times; cumulative runoff; precipitation; and computed ratios of green roof to control roof cumulative runoffs. Additionally, summary graphs are presented that illustrate the relationship between the runoff performance and rainfall as well as illustrate the differences in performance between the roof types under multiple conditions.

5.1.1 *Runoff quantity data for the Homestead Site*

The runoff performances for both control and green roof for individual rainfall events are evaluated by comparing rainfall, runoff flow rate and volume.

April 20, 2008 Storm (Moderate rainfall)

Over eight hours, 0.57 inches of rainfall were recorded at the Homestead rain gauge with three periods of peak intensity. Runoff started nearly immediately for the conventional roof and was delayed for the green roof as indicated in Figure 5-1**.** The cumulative volumes of water received (rainfall) and discharged (runoff) are presented in Figure 5-2. The total runoff from the control roof was very close to the total rainfall volume and the green roof retained approximately 45% of the rainfall from this event.

The green roof retarded the time of appearance of runoff and showed significant water retention capacity in comparison to the conventional roof. The runoff from the green roof started approximately two hours after the time that the control roof began discharging as illustrated in Figure 5-1**.** One plausible explanation for the 2-hour retardation time may be that the soil was dry conditions prior to the storm, since there was little rainfall preceding this event (0.09 in. of rainfall on April 19) (*data from Weather Underground Inc*). The dry soil would be able to absorb water and maintain the runoff until the soil became saturated. In contrast to runoff from the green roof, the control roof runoff rate follows the rainfall intensity very closely where the three peaks in the control roof runoff coincide with the corresponding peaks in rainfall intensity. However, the green roof runoff rate was constant during the first peak in rainfall intensity. Subsequent peaks of in the green roof runoff rate coincide with the peaks in rainfall intensity. It was observed that the peaks in the runoff rate from the green roof are consistently lower than the control roof peaks. For the first peak in the rainfall intensity, the runoff rate from the green roof was less than 8% of the rate of runoff from the control roof. Overall, peak runoff rate of the green roof was less than 80% of the control roof. While there was an onset of runoff delay, there was also a delay when runoff ceased to flow as the flow from the control roof stopped nearly an hour before the green roof indicating tailing and longer term soil-moisture drainage.

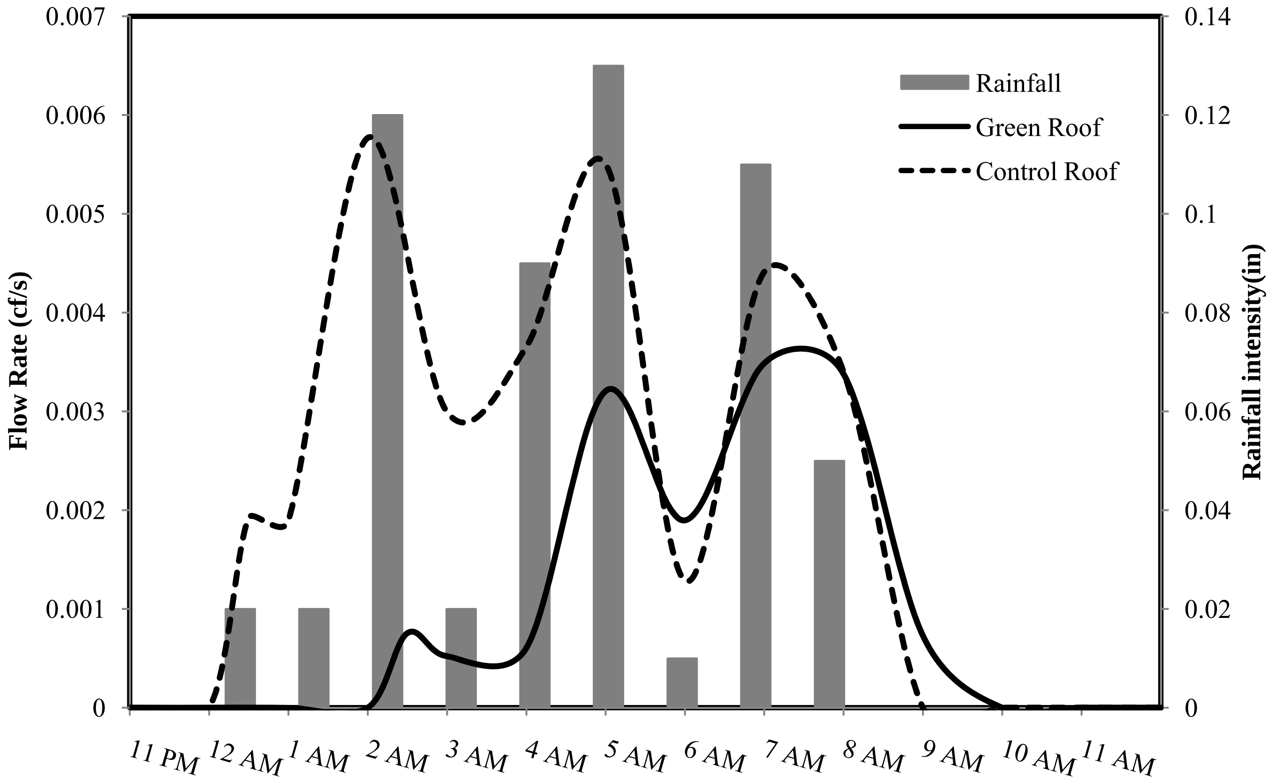

Figure 5-1 Runoff Flow Rates and Rainfall Intensity – April 20, 2008 Storm (Homestead)

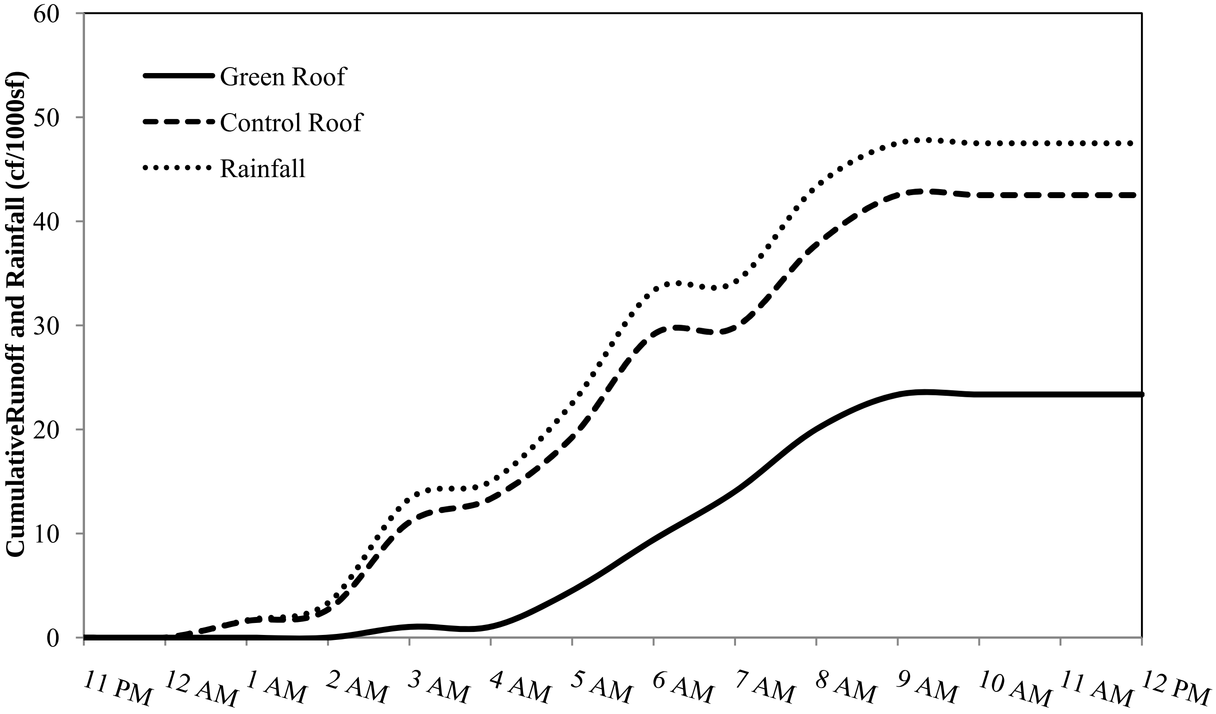

Figure 5-2 Runoff and Rainfall Volumes – April 20, 2008 Storm (Homestead)

June 13-14, 2008 storm (Heavy storm)

In a period of two days three discrete events dropped approximately 2.25 in. of rain onto the Homestead site. The runoff rate and rainfall intensity data recorded are shown in Figure 5-3, and Figure 5-4 shows the cumulative runoff volume and rainfall. Since the previous precipitation was on June 5 (8 days prior to this storm), it is assumed that the soil condition was dry before this storm.

Unlike the April 20 storm, there was no runoff retardation (Figure 5-3). The most probably reason for zero runoff retardation may be that the extremely high rainfall intensity at the beginning of the storm (1.11 inches of rain fall during the first hour) immediately saturated the thin roof soil. Since rainfall was nearly equivalent to the thickness of the soil at Homestead green roof (1.1 in. rain to 1.5 in. soil), the enormous rainfall most likely caused the thin soil layer to become rapidly water-saturated, resulting no runoff retardation, and no lag time for the green roof. For this heavy storm event, from a water runoff point of view, the system behaved as if there was no green roof.

The measurements of control roof runoff were adversely affected by this heavy storm (Figure 5-4). In large measure, this was due to an under-design of the Homestead weir box for large and intensive storms. For this storm, the high velocity of runoff water rushing into the weir box (and hitting the baffle in the "stilling area" that was supposed to reduce water velocities) resulted in an overflow of runoff onto the basement floor before the ultrasonic sensor could measure it. Even with the water loss onto the basement floor, there was less green roof runoff than from the control roof. As shown in Figure 5-3, the maximum peak flow rate of green roof runoff was 52% of the maximum peak flow rate from the control roof. The cumulative runoff volume (Figure 5-4) from the green roof was 30% of the total equivalent rainfall volume, leaving 70% of stormwater retained by the green roof.

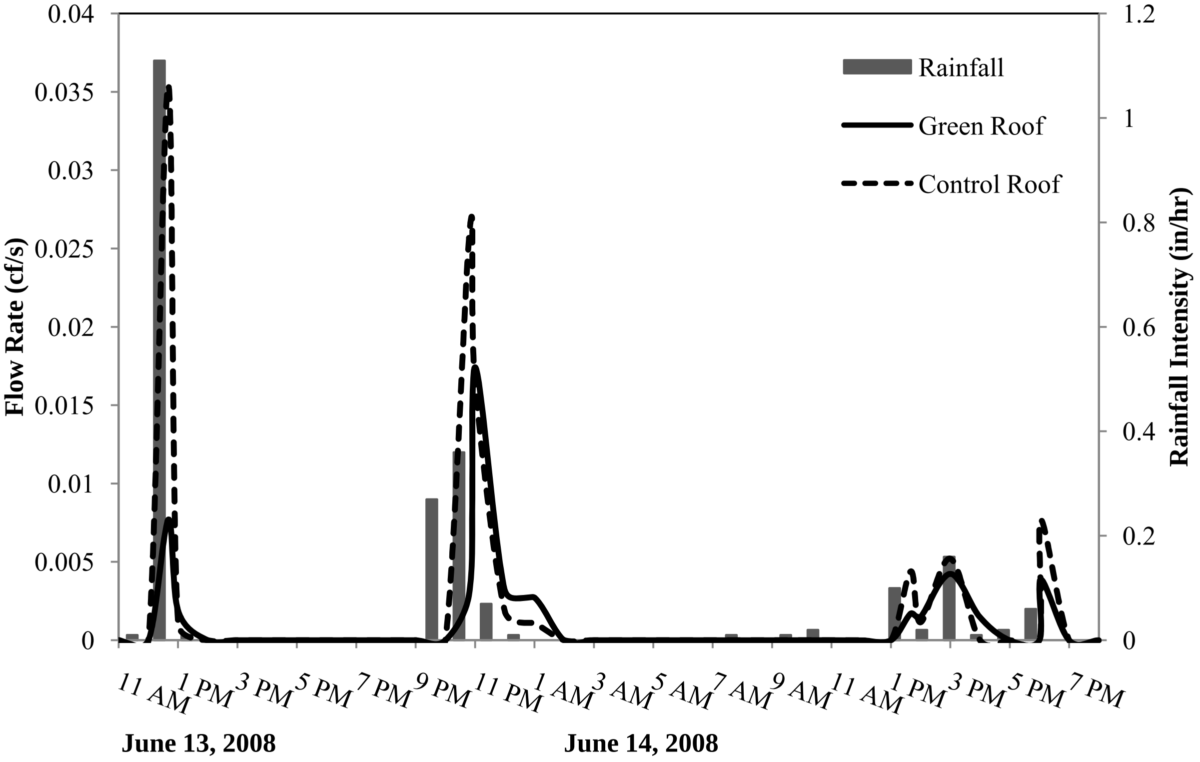

Figure 5-3 Runoff Flow Rates and Rainfall Intensity – June 13-14, 2008 Heavy Storm (Homestead)

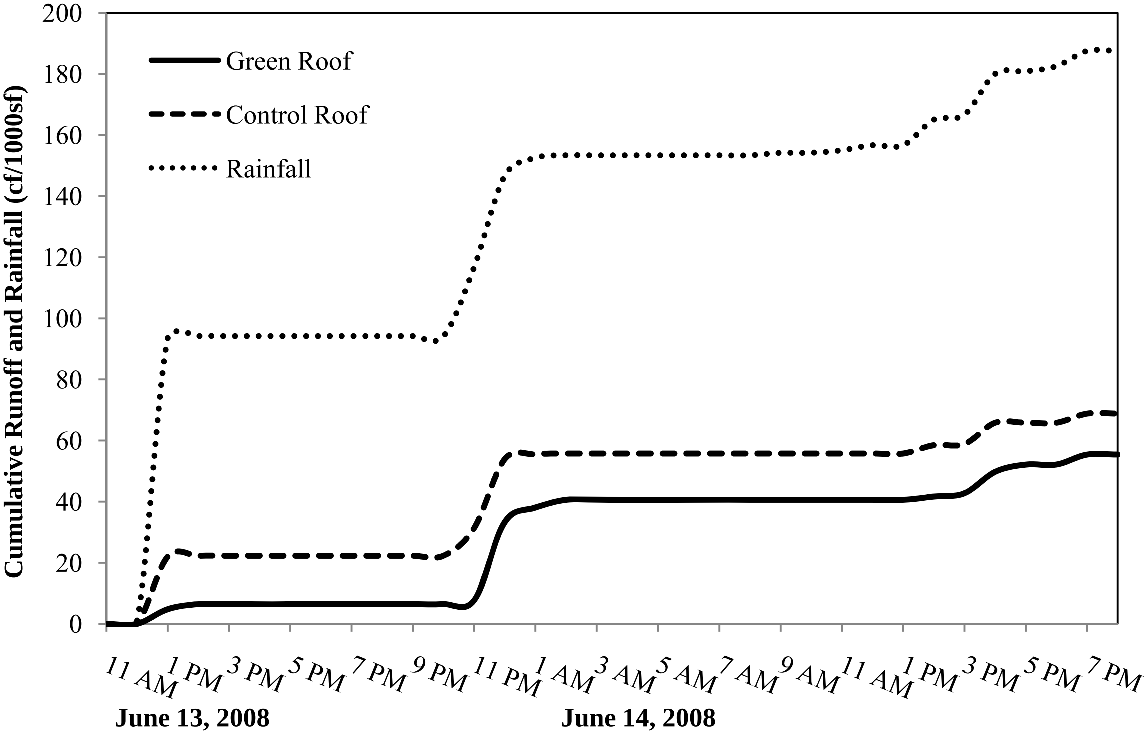

Figure 5-4 Runoff and Rainfall Volumes – June 13-14, 2008 Heavy Storm (Homestead)

September 9, 2008 storm (light storm)

A low volume rain event of 0.17 inches occurred on September 9, 2008. This followed a thirteen day dry period (the previous rainfall was observed on August 27, 2008) that left the soil in a dry condition. As shown in Figure 5-5, there was no runoff from the green roof and all of the rain that fell on the green roof was absorbed by the soil medium. The total runoff from the control roof was 3.15 cf/1000sf which was 22% of the total equivalent rainfall, as shown in Figure 5-6.

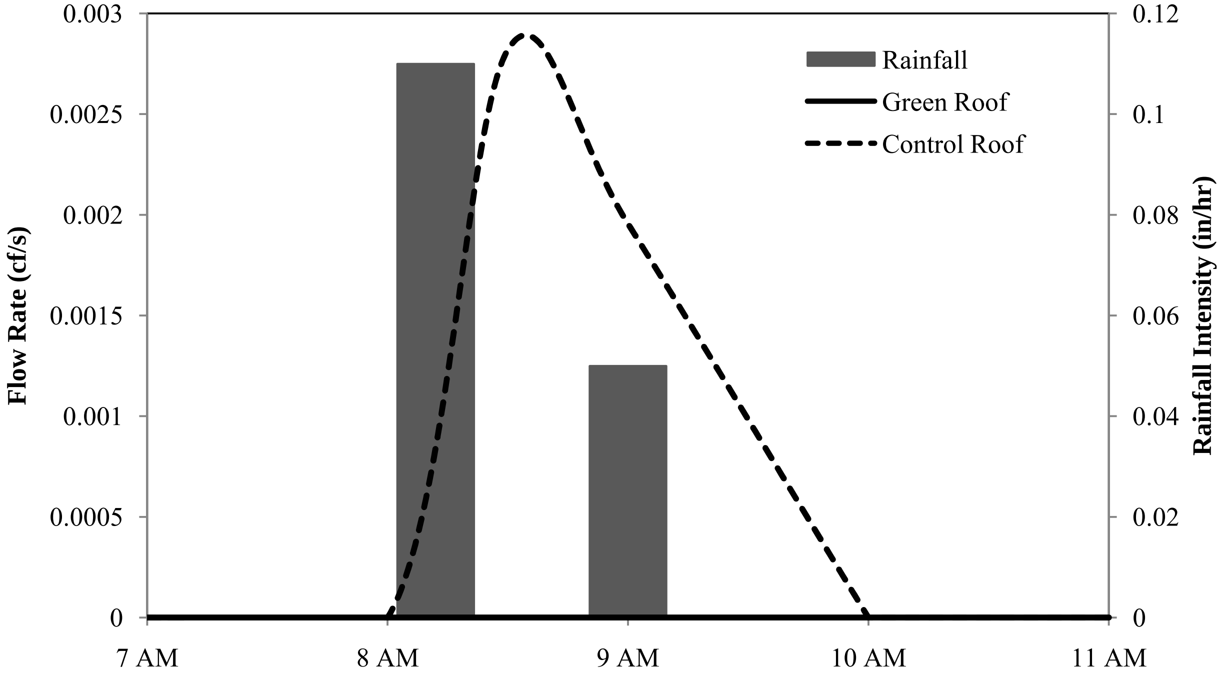

Figure 5-5 Runoff Flow Rates and Rainfall Intensity – September 9, 2008 Storm (Homestead)

The green roof absorbed all rainfall during this "light storm".

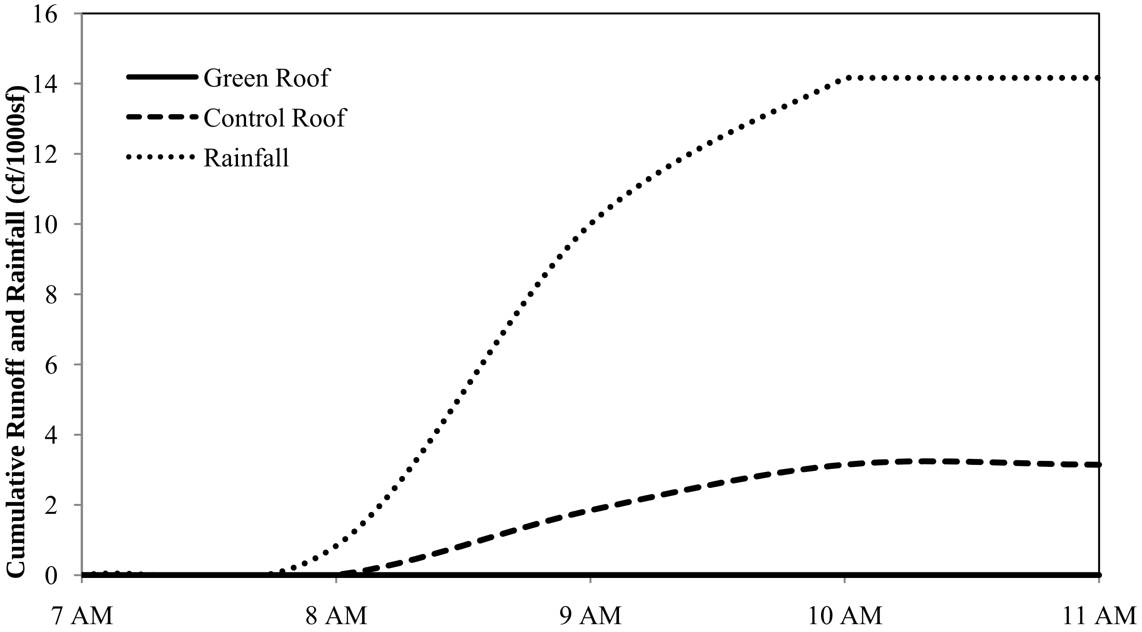

Figure 5-6 Runoff and Rainfall Volumes – September 9, 2008 Storm (Homestead)

The green roof absorbed all rainfall during this "light storm".

February 18, 2009 storm (winter storm)

During winter months, snow is more frequent than rain in Pittsburgh. Periodic snowfall followed by snow melting and refreezing typically causes high soil moisture content. With this in consideration, the soil prior to 0.34 inches of rainfall (as measured by the rain gauge) on February 18, 2009 was considered to have wet soil conditions.

Even though the soil was considered to be moist, the beginning of residual snowmelt + rainfall runoff flow from the green roof lagged behind the initial control roof runoff by 6 hours (as seen in Figure 5-7). The two peaks of green roof runoff for Homestead are in a much lower level than control roof runoff. The maximum peak flow rate of green roof runoff was only 13% of the control roof runoff. The total runoff from the green roof (as shown in Figure 5-8) was 3% and 18% of the total equivalent rainfall and control roof, respectively.

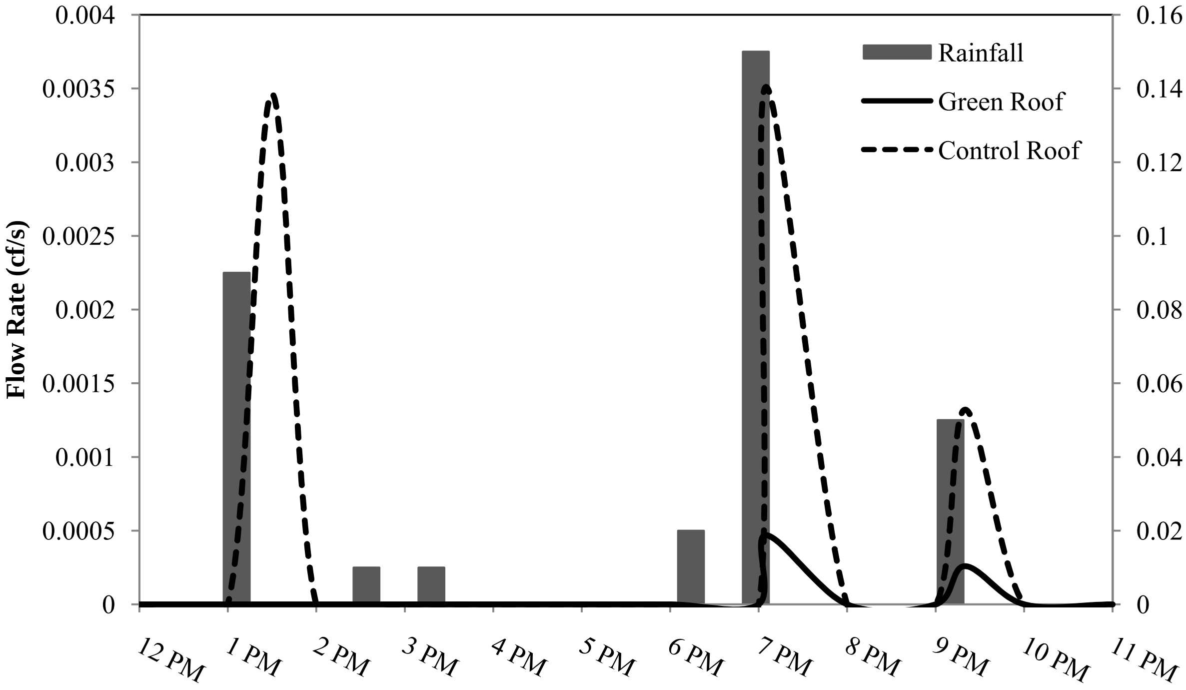

Figure 5-7 Runoff Flow Rates and Rainfall Intensity – February 18, 2009 Storm (Homestead)

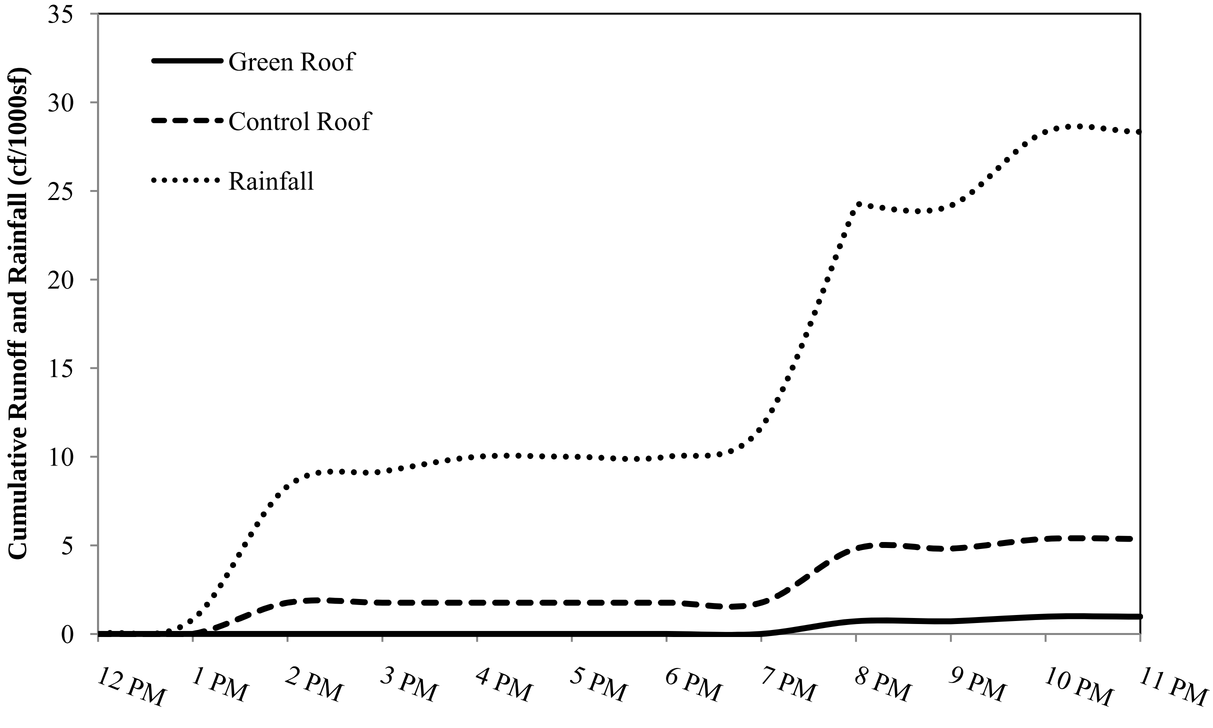

Figure 5-8 Runoff and Rainfall Volumes – February 18, 2009 Storm (Homestead)

5.1.2 *Runoff quantity data for Giant Eagle*

April 20, 2008 storm (Moderate storm)

Rainfall intensity and cumulative rainfall volume data were not measured because the rain gauge malfunctioned during this storm and as a result, only runoff data was collected from both the control and green roofs. For comparison purposes only, 0.57 inches of rainfall were recorded at the Homestead rain gauge with three periods of peak intensity. Even though the rainfall data at Giant Eagle was not available, the runoff performance of control and green roof can be compared.

Runoff characteristics similar to those observed at Homestead were observed for both Giant Eagle roofs. The runoff rate from the green roof was zero when the first peak in the control roof runoff rate was observed, and the first peak flow in the green roof runoff occurred much later in the storm at the same time of the third peak flow from the control roof (Figure 5-9, 5-10).

The delay for runoff onset from the green roof at the Giant Eagle site was 4 hours which was approximately 2-hour longer retardation period that the Homestead green roof for the same rainfall event. The extended runoff retardation that occurred at Giant Eagle was likely caused by the much larger water absorbance capacity due to the 5.5 inches of soil on the Giant Eagle site in comparison to the Homestead site that has 1.5 inches of soil. Also similar to the Homestead green roof, there was an hour extension of flow from the Giant Eagle green roof, which ultimately yielded a total runoff volume from the green roof of 43% of the runoff volume from the control roof.

With its longer initial runoff retardation, the Giant Eagle roof had a higher initial resistance to discharge. The total runoff volume reduction for the Giant Eagle green roof was 57%, compared to the control roof runoff. Peak runoff rate of the green roof at Giant Eagle was between 0 and 92% of the control roof.

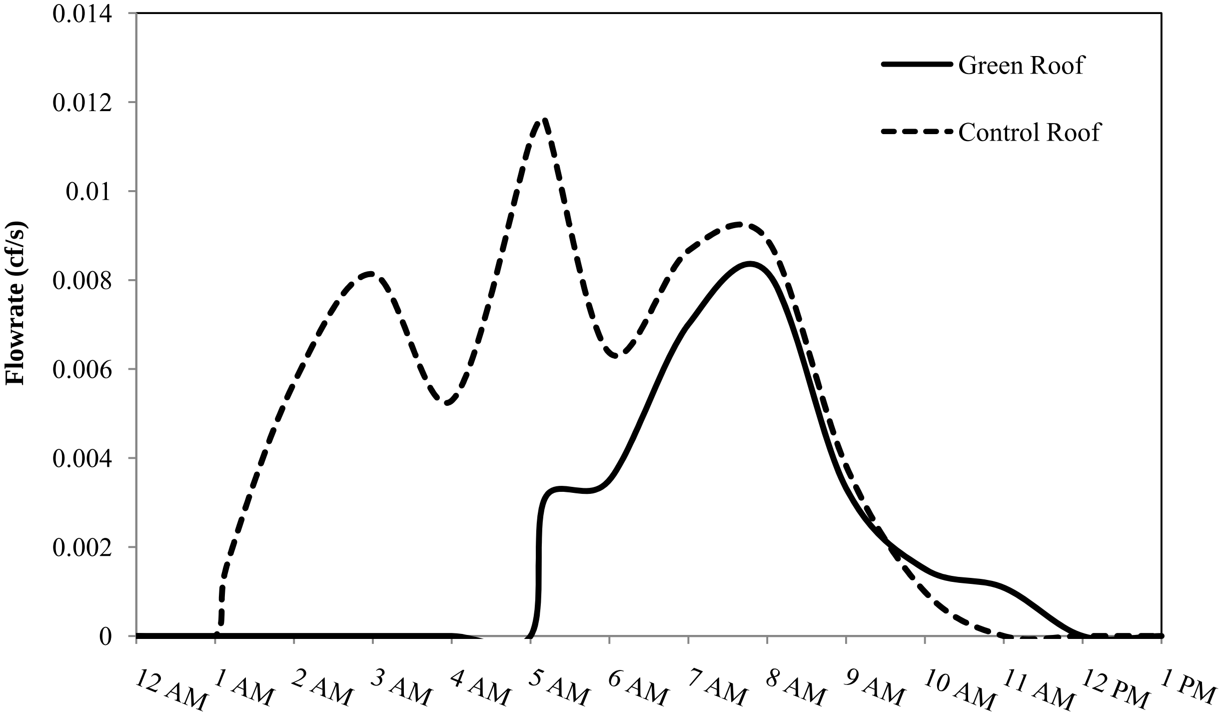

Figure 5-9 Runoff Flow Rates – April 20, 2008 Storm (Giant Eagle)

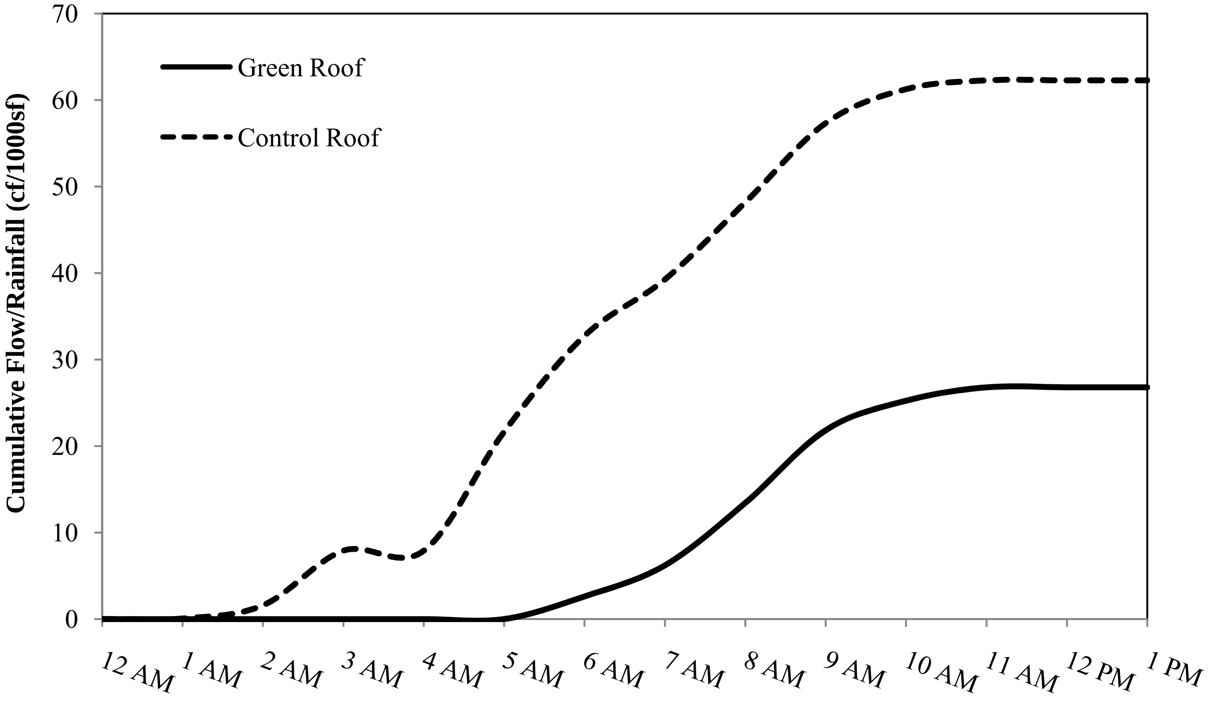

Figure 5-10 Cumulative Runoff Volumes – April 20, 2008 Storm (Giant Eagle)

June 13-14, 2008 storm (Heavy storm)

Three periods of precipitation occurred over two days, dropping approximately 1.65 inches of rain at the Giant Eagle site (2.25 in. of rain fell at the Homestead site). The precipitation and runoff from the Giant Eagle control and green roofs are shown in Figure 5-11. The initial rain lasted two hours and there was no discharge from the green roof for the first 12 hours. The initial rain was followed by two additional discrete events where the green roof became saturated during the second event and began to discharge after providing significant rainfall absorption. Runoff closely followed rainfall during the third event. Unlike the green roof, the control roof runoff followed the rainfall (Figure 5-12) at a much higher level of discharge than the green roof runoff for all periods of rain.[4]

The maximum peak flow rate of the green roof was 46% of the maximum peak flow rate from the control roof at Giant Eagle site (hourly data is presented as Figure 5-11). The total runoff volume was lower for the green roof, with 74% of total rainfall being withheld. As shown in Figure 5-12, runoff from the green roof equals 39% of the runoff from the control roof and 26% of the total rainfall.

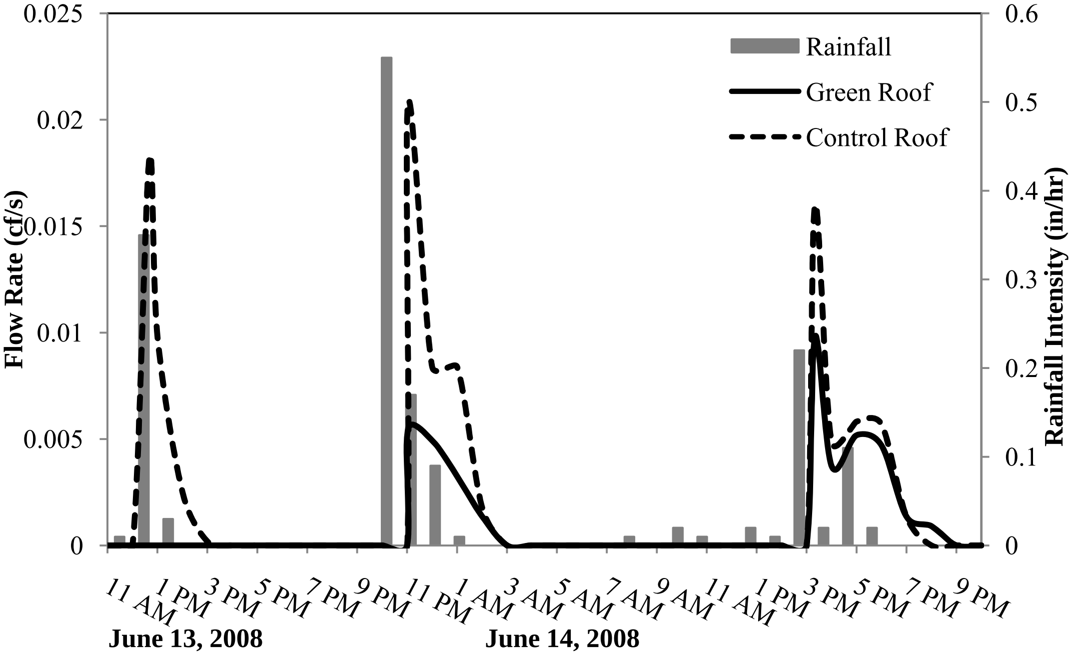

Figure 5-11 Runoff Flow Rates and Rainfall Intensity – June 13-14, 2008 Storm (Giant Eagle)

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[4] Weir boxes were used at Homestead, and flumes were used at Giant Eagle for flow measuring systems.

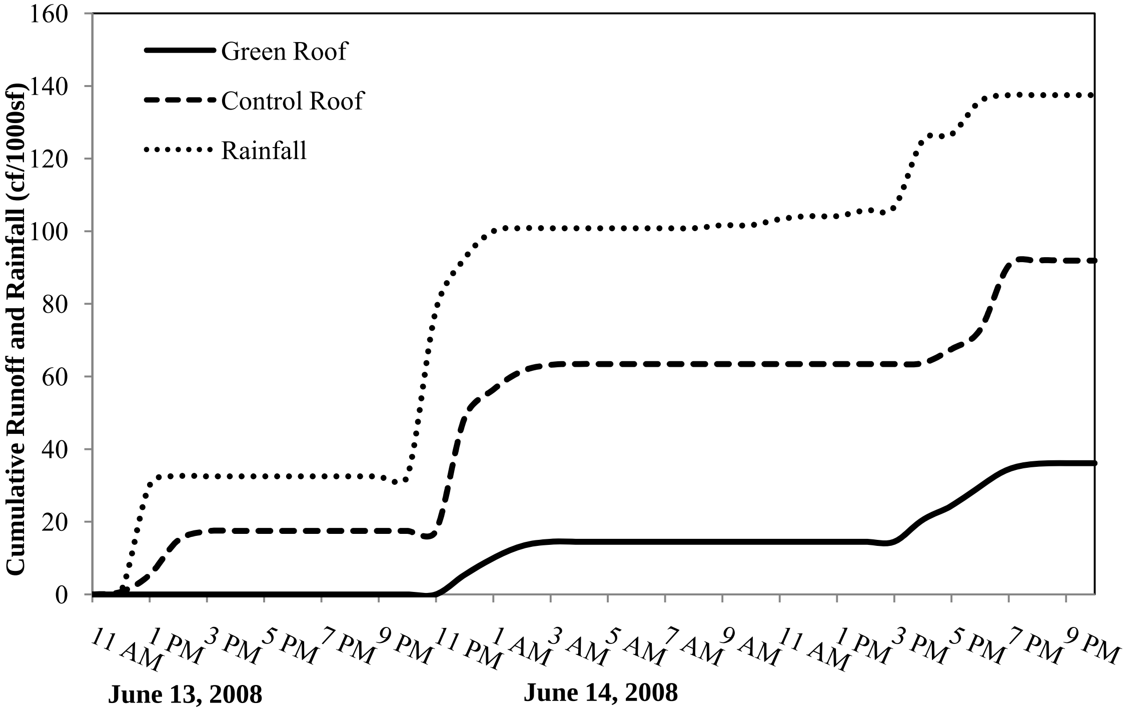


Figure 5-12 Runoff and Rainfall Volumes – June 13-14, 2008 Storm (Giant Eagle). A total of 1.65 inches of rain fell during this period.

September 9, 2008 storm (light storm)

On September 9, 2008 a light rain dropped 0.12 inches of rain on Giant Eagle and 0.17 inches on the Homestead site. There was a 13 day period of dryness between the previous storm and this event; therefore, the soil prior to this rainfall was considered "dry".

There was no runoff detected by the ultrasonic sensor from the green roof. The data suggests that the green roof retained 100% of the rain water at lower rainfall and dry soil condition (as shown in Figure 5-13). The normalized total runoff volume from the control roof (Figure 5-14) was 1.83 cf/1000sf; 18% of the total equivalent rainfall, thereby indicating that the water flow was measurable by ultrasonic sensors and that indeed the green roof did not allow any runoff.

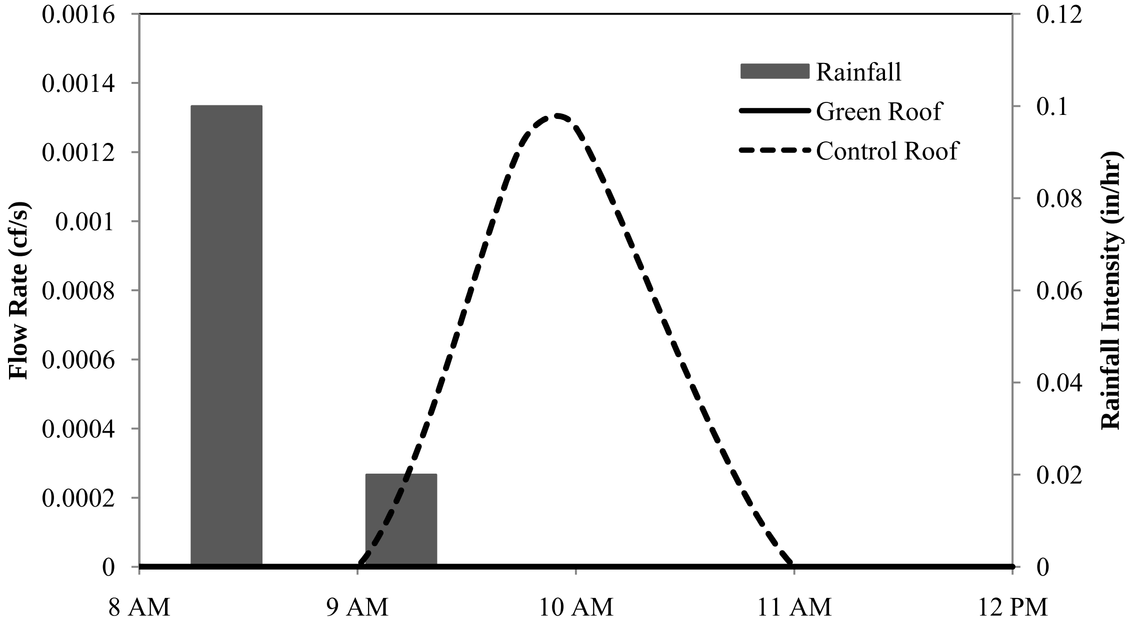
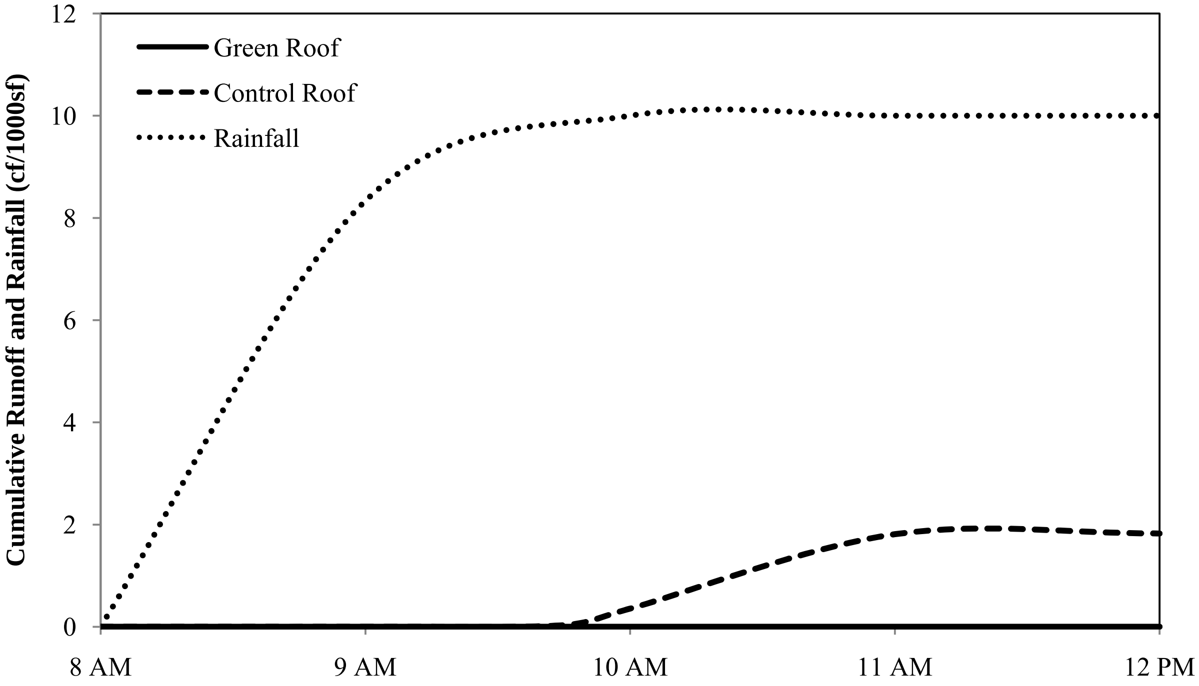


Figure 5-13 Runoff Flow Rates and Rainfall Intensity



September 9, 2008 Moderate Storm (Giant Eagle)

Figure 5-14 Normalized Runoff and Rainfall Volumes – September 9, 2008 Moderate Storm (Giant Eagle)

February 18-19, 2009 storm (winter storm)

Periodic snowfall followed by snow melting and refreezing caused high soil moisture content on the Giant Eagle roof during the winter. With this in consideration, the soil prior to 0.32 inches of rainfall (as measured by the rain gauge) between February 18 and 19, 2009 was considered to be “wet”.

Even though the soil was wet before the storm, the initial runoff from the green roof occurred six hours later than the control roof (Figure 5-15). This was coincidentally the same retardation as measured at the Homestead site for a similar amount of rainfall (0.34 in.). Additionally, the green roof runoff from Giant Eagle exhibited a three hour long tail of extended flow compared to the control roof. The green roof runoff at Homestead did not show a similar extension or tailing over time after the storm. The maximum peak flow rate from the green roof at Giant Eagle was 55% of the control roof and 58% of the total runoff volume from the control roof. Compared to the total rainfall, the runoff was 42% as indicated in Figure 5-16.

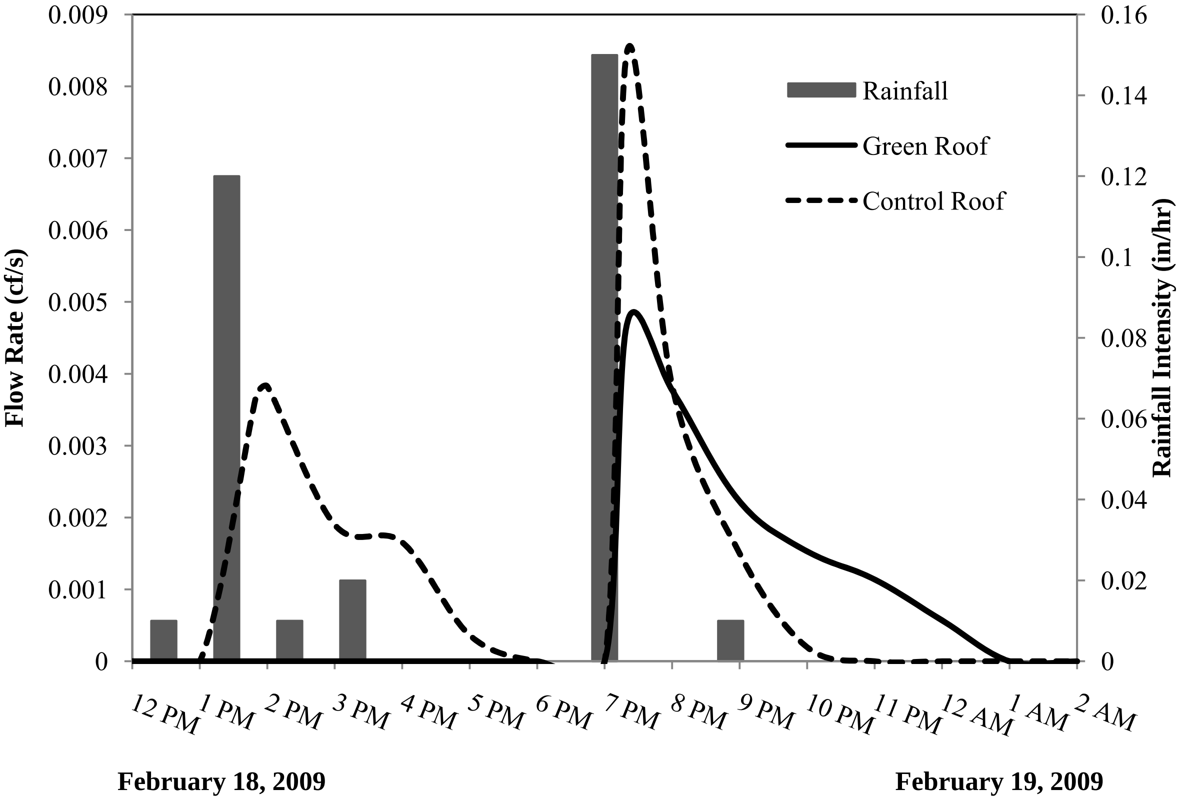


Figure 5-15 Runoff Flow Rates and Rainfall Intensity – February 18-19, 2009 Storm (Giant Eagle)

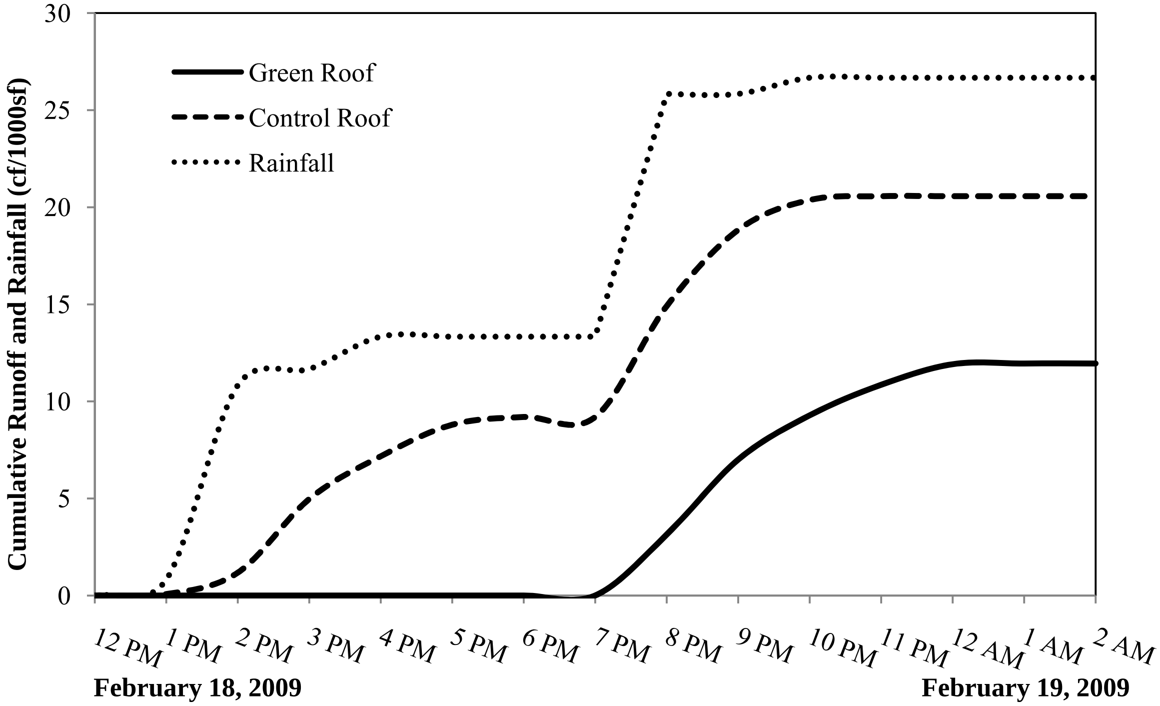


Figure 5-16 Normalized Runoff and Rainfall Volumes – February 18-19, 2009 Storm (Giant Eagle)

6. DISCUSSION AND ANALYSIS: COMPARATIVE RUNOFF QUALITY, AND HEAT ABSORPTION

The green roofs were divided into two groups based on the roof thickness. Since the soil layer for the green roof at Homestead site was one and half inches and thinner than the Giant Eagle roof, it was defined as the “thin roof”. With the five and half inches of soil layer for the green roof at Giant Eagle site, it was defined as the “thick roof”. The soil conditions prior to each rainfall event were classified as “dry” or “wet” based on the amount of rainfall and weather conditions preceding the rain event. This classification scheme was used because soil moisture data was largely unavailable as the soil moisture content was not reliably measured and recorded by the instrumentation. The classification assumes that the soil condition was directly related to rainfall events, and was defined as dry when there was at least two day without raining prior to storm being evaluated, or if the previous rain event dropped less than 0.1 inches of water. In all other cases, the soil condition was categorized as wet soil and contained more than ½ the capacity for water moisture.

Retardation and retention of runoff waters during similar rain events are compared. The classification for each rainfall event was done by depth of rainfall, where the amount of rainfall measured by the rain gauge is classified as light (≤ .1inch), and heavy (>1.0inches) with the term “moderate” covering the range between light and heavy.

All data regarding precipitation, soil condition, flow rate of control and green roofs, retardation time of green roof runoff, cumulative runoff volume and its relative ratio of runoff from the green roof to the control roof, as well as percent of water retained in the green roof that was recorded during the observation periods are reported in tabular format in APPENDIX I. Table I-1. For clarity, the maximum peak flow rate is defined as the highest flow rate of either green or control roof observed during each rainfall event. The percent of reduction for the maximum peak flow rate for the green roof was calculated as follows:

$$\%\ \text{Reduction} = 1 - \frac{\text{Maximum peak flow rate of green roof}}{\text{Maximum peak flow rate of control roof}} * 100$$

The two individual columns in APPENDIX I. Table I-1 titled “cumulative runoff ratio” are the proportional relationships of the cumulative runoff from the control and green roofs, to the amount of rainfall. The quantity “water retained” is defined as the difference between the cumulative green roof runoff and the total rainfall.

This data revealed that green roofs provide three important contributions to water quantity control: runoff retardation (when the green roof begins to discharge runoff water and retardation of the magnitude of peak flow rate and when it occurs), and runoff water quantity retention (relative area under the two hydrographs). These temporal relationships are graphically illustrated on Figure 6-1.

6.1 Runoff Retardation (Delay from rain onset to time when flow begins)

The parameters of time after the onset of rain and runoff flow rate were compared relating to the green and control roof, as well as thin and thick green roof. The runoff retardation was classified into two groups, dry and wet soil conditions since the water moisture content in the soil medium was observed to significantly impact the retardation time. Figure 6-1 is a graphical representation of the multiple parameters considered important when defining the runoff flow (hydrograph) differences between green and control roof. These parameters include: initial runoff retardation (A), maximum peak flow rate (B) and maximum peak flow variation (C), as shown on Figure 6-1. Furthermore, the relative total area under the two curves represents the mass of water released from the control and green roof respectively. The dashed-line curve in the graph represents the control roof flow rate, while the solid line curve represents the green roof flow rate. All of these parameters (A, B, and C) were measured to be dependent on the thickness of the roof as well as the soil moisture content of the roof before the onset of rain.

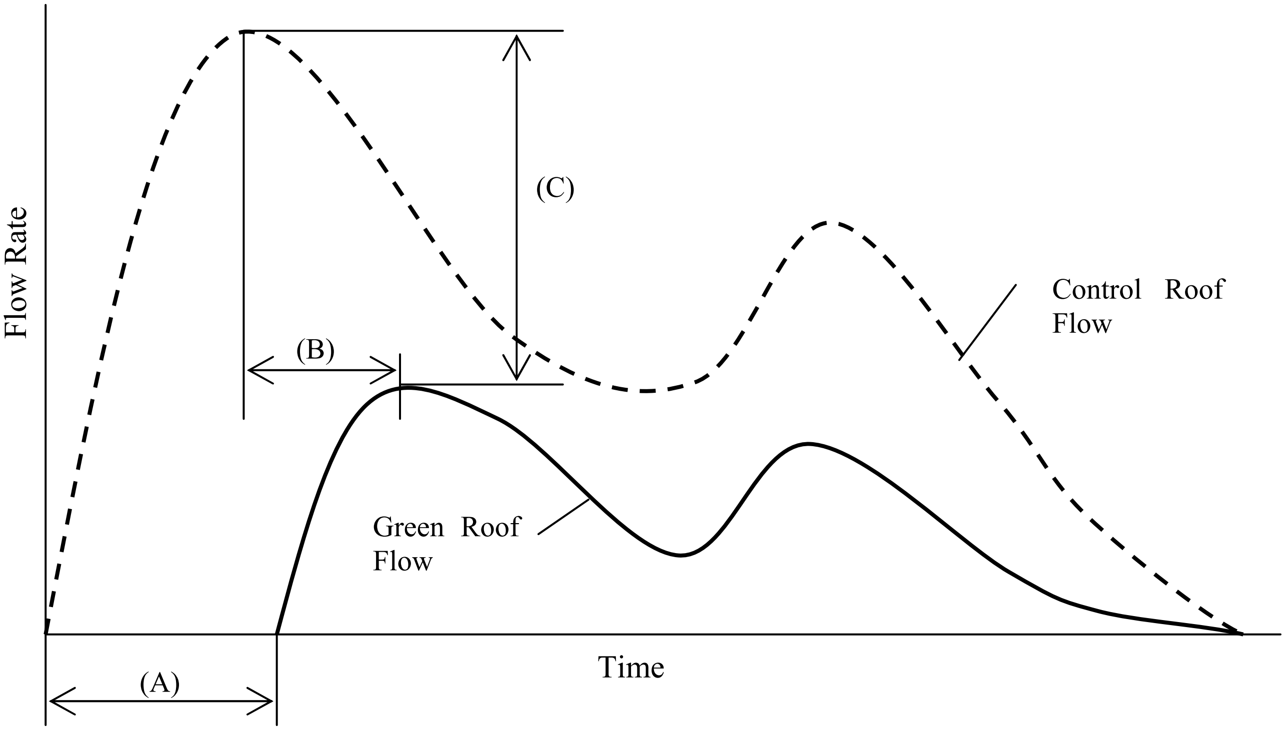


Figure 6-1 Different measuring parameters related to green and control roof runoff flow rate

(A) Time for initial runoff retardation: the time difference between which green roof starts discharging stormwater and control roof starts discharging.
(B) Time of maximum peak flow retardation: the time when maximum peak flow rate occurred at green roof subtracts the time when maximum peak flow rate occurred at control roof.
(C) Maximum peak flow rate variation: the difference of the maximum peak flow rate between control roof runoff and green roof runoff.

The green roofs at both locations exhibited time delays between the onset of precipitation and onset of runoff. This parameter is shown as (A) in Figure 6-1. The time of runoff retardation ranged from 0 to 16 hours at the two locations. At times the green roof had zero discharge and these events were not plotted.

The initial runoff retardation was compared as a function of green roof type and soil condition (wet or dry). As seen in Figure 6-2, when the soil is initially dry, the thick green roof takes a longer time for initial runoff to appear (*initial runoff retardation*) with a maximum time of 16.7 hours and an average time of 3.9 hours.

For the wet soil-thick roof, however, a maximum time of runoff retardation of 8.7 hours and an average of 2.9 hours had been observed. With about 4 inches more of soil the thick green roof is able to retain more water and better delay the onset of stormwater discharge. Wet soils exhibit less of a capability to retain runoff water. For the both the thin or thick wet soil green roof, there is a similarity average time delay of runoff of about 1.2 hours.

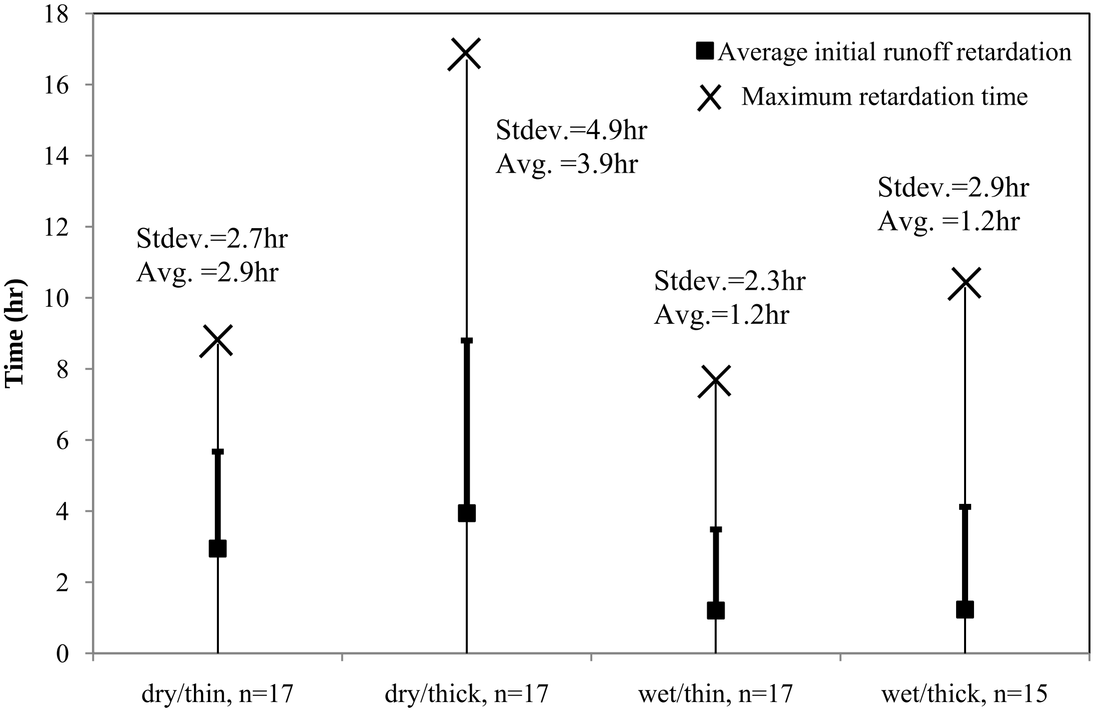


Figure 6-2 Time of initial runoff retardation under different soil condition and thickness

The maximum peak flow retardation is the relative delay in time of occurrence of the maximum peak flow between the control and green roof. This is parameter (B) shown in Figure 6-1. The green roof in most cases showed a longer delay for the maximum peak flow than the control roof. This was determined to depend on whether the thick or thin soil was wet or dry prior to the storm event. Figure 6-3 compares the time of maximum peak flow retardation for thick and thin and wet and dry soils.

For the dry soils, the <u>maximum</u> time retardation of peak flow for both green roofs is about 16 hours. The average time retardation for the thin and thick green roof are 2.1 and 2.5 hours respectively.

For wet soils, the retardation of maximum peak flow is approximately 0 hour suggesting saturated soils. The <u>maximum</u> time retardation of thick roof however was 1 hour.

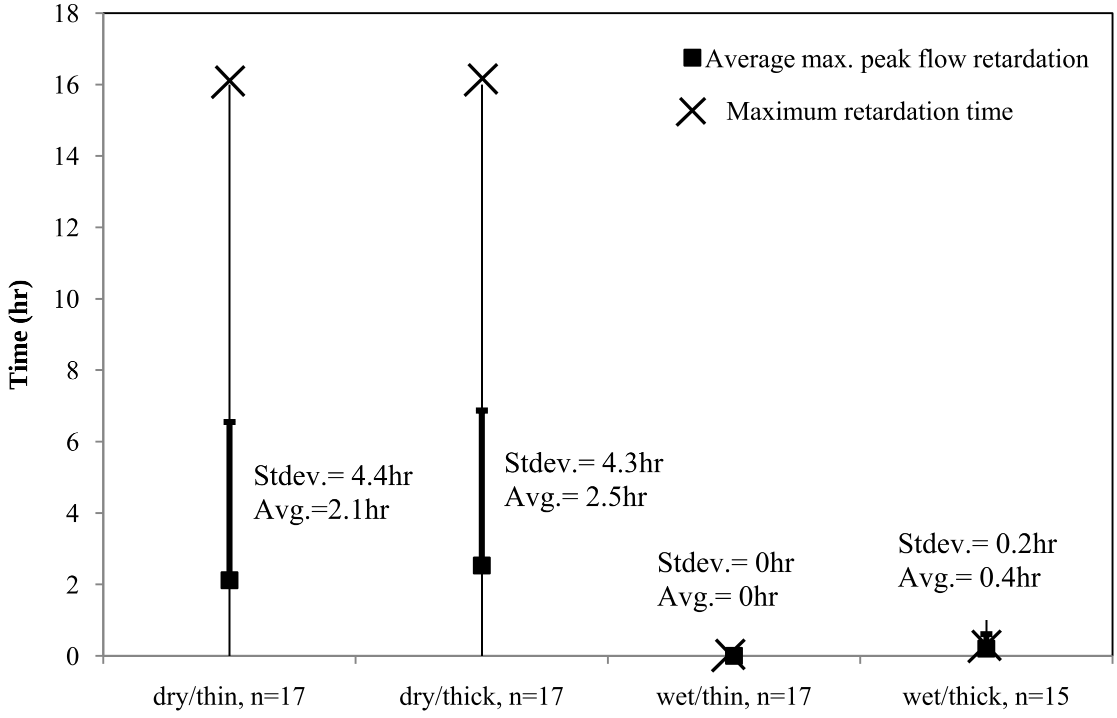


Figure 6-3 Retardation of occurrence (hr) of maximum peak flow with wet/dry & thick/thin soils

Figure 6-4 and Figure 6-5 show the cumulative probability of occurrence of maximum peak flow rate under dry and wet soil condition (parameter C from Figure 6-1). Each data point presents the maximum peak flow rate for a storm event, either for green or control roof runoff.

Data points of the maximum peak flow rate from all experiments are arranged from the lowest to the highest. The X-axis is in the form of a probability scale, and Y-axis is normalized peak flow (cfs/thousand sq ft roof area). Flow rate data is plotted against the fraction-of-time of occurrence. As seen in Figure 6-4, the flow rate data of green roof runoff are always lower than that of the control roof either in Homestead or in Giant Eagle, which is one of the essential characteristics of green roof runoff performance. It is also indicative that the green roof has its benefit in retaining peak runoff in the time that peak storm occurs thus alleviating the hydraulic stress on receiving sewers.

When it comes to the wet soil condition, the peak flows of green roof runoff at both locations are always lower than that of the control roof runoff. Figure 6-5, shows the thin roof peak flow is slightly higher rate than that of the thick roof. Rainfall intensity is a key variable for runoff flow rates.

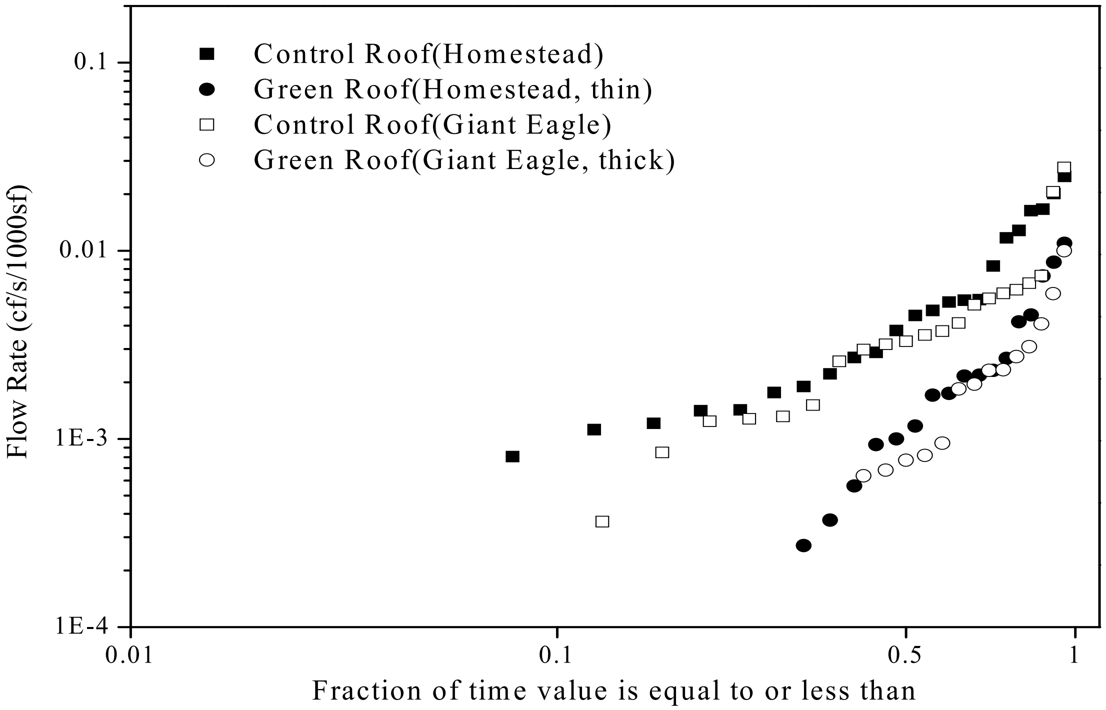


Figure 6-4 Probability of occurrence of maximum peak flow rate under dry soil condition

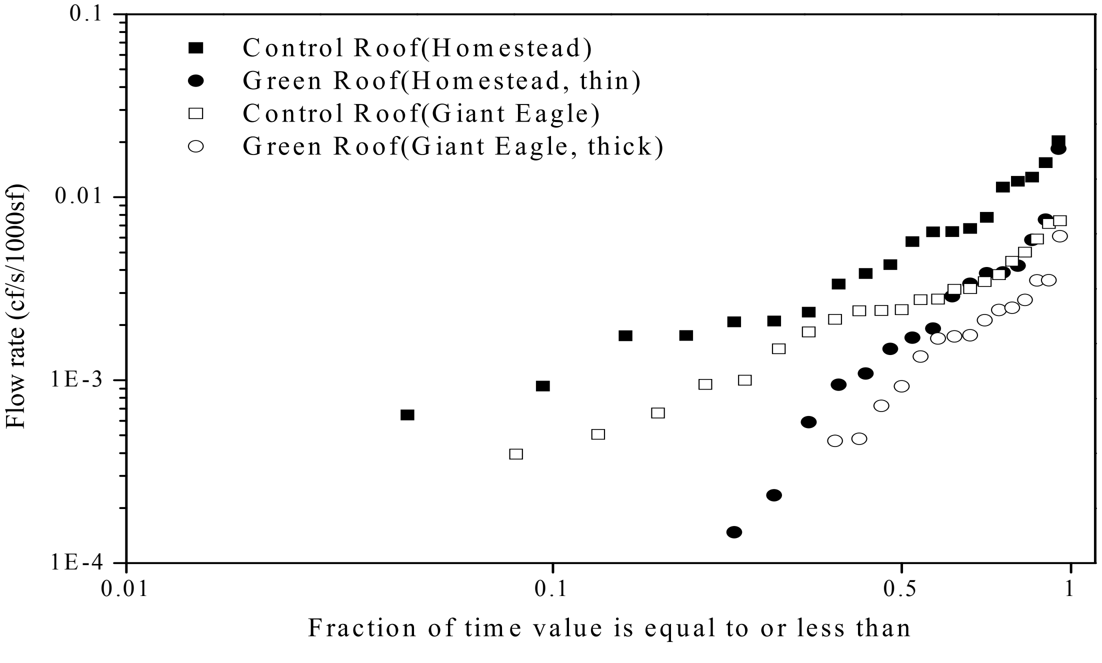


Figure 6-5 Probability of occurrence of maximum peak flow rate under wet soil condition

The figures Figure 6-6 and Figure 6-7 present runoff of control roof versus ratio of water released from green roof to control roof. As above, this data is classified by green roof types (thin and thick) and soil condition (dry and wet). In each graph, X-axis is the runoff from control roof (plotted on a log scale) with the unit of inches of water which best approximates received rainfall[5] . The Y-axis is the ratio of the water released from the green roof vs. the control roof ("*green roof/control roof*" *runoff water*). The runoff ratio calculations are based upon cumulative runoff from respective roofs over the duration of the same storm event.

Figure 6-6 and 6-7, show available data of dry soil and wet soil at the Homestead thin roof showing the ratio of water released vs. inches of water discharged from the control roof. It should be noted that at very low intensities of rainfall, there was virtually no runoff from the dry green roof (ratio = zero) but small amounts of water were released from the control roof. For wet soil conditions, runoff started sooner. As a good approximation, the green roof was able to usually retain water at about 0.25 inches of rain or less (measured as control roof runoff, inches of water.)

For the thick roof at Giant Eagle, available dry-soil data were used for Figure 6-8. As a good approximation, the thick green roof with initially dry soil conditions (Figure 6-8), was able to usually retain water at about 0.6 inch of rain or less (rain is measured as control roof runoff, inches of water). Similarly, the thick green roof, with initially wet soil conditions (Figure 6-9) was usually able to retain water at about 0.2 inches of rain water or less (rain is measured as control roof runoff, inches of water).

Thicker green roofs with more soil have a greater water retention capability. However, the thin roof technology as employed in Homestead was accommodated with small "cups" under each small set of plants that acted as multiple small water reservoirs across the green roof. This technology feature possibly added to runoff retardation times and overall water retention, and thus may be a good application for use on older structures that cannot support the weight of a thick roof technology.

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[5] Control roof runoff is used as a surrogate measure of rainfall when the field rain gauges were not functioning properly.

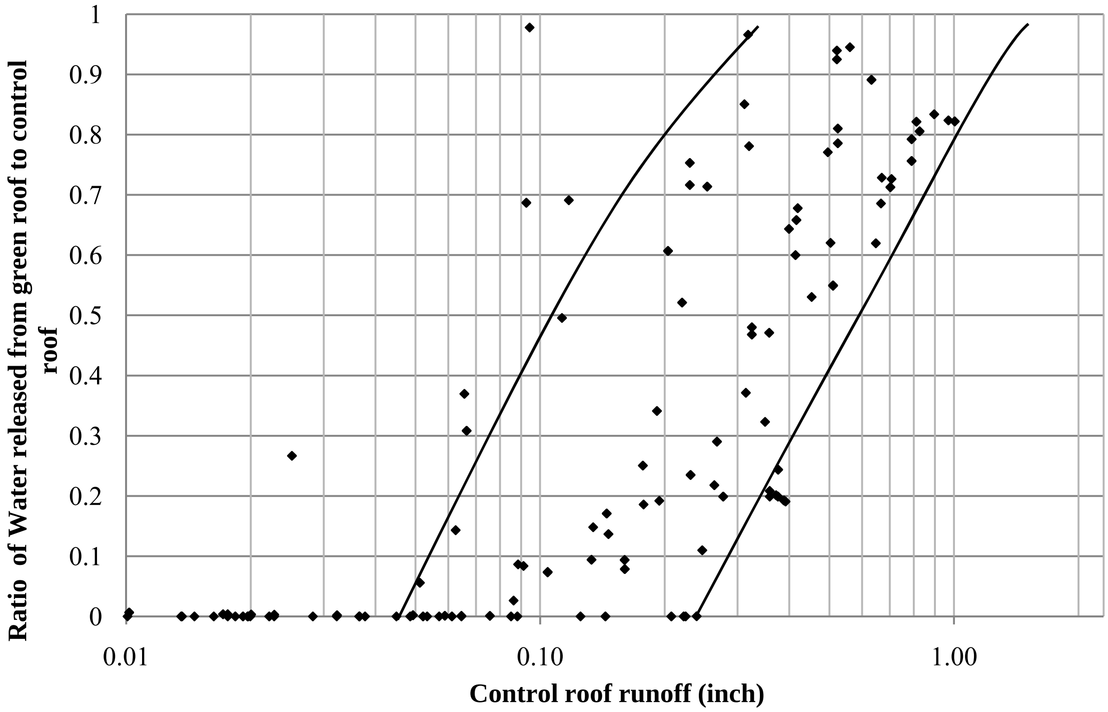

Figure 6-6 Ratio of water released from green roof to control roof vs. control roof runoff: thin roof at Homestead with dry soils (140 data points in total)

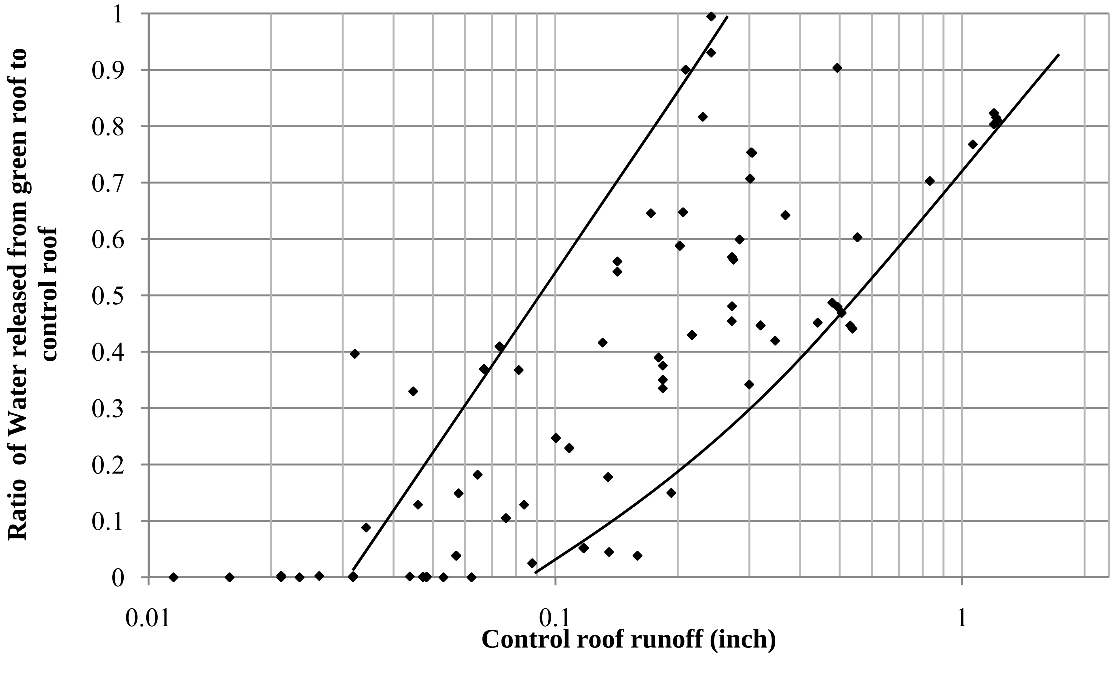

Figure 6-7 Ratio of water released from green roof to control roof vs. control roof runoff: thin roof at Homestead with wet soils (104 data points in total)

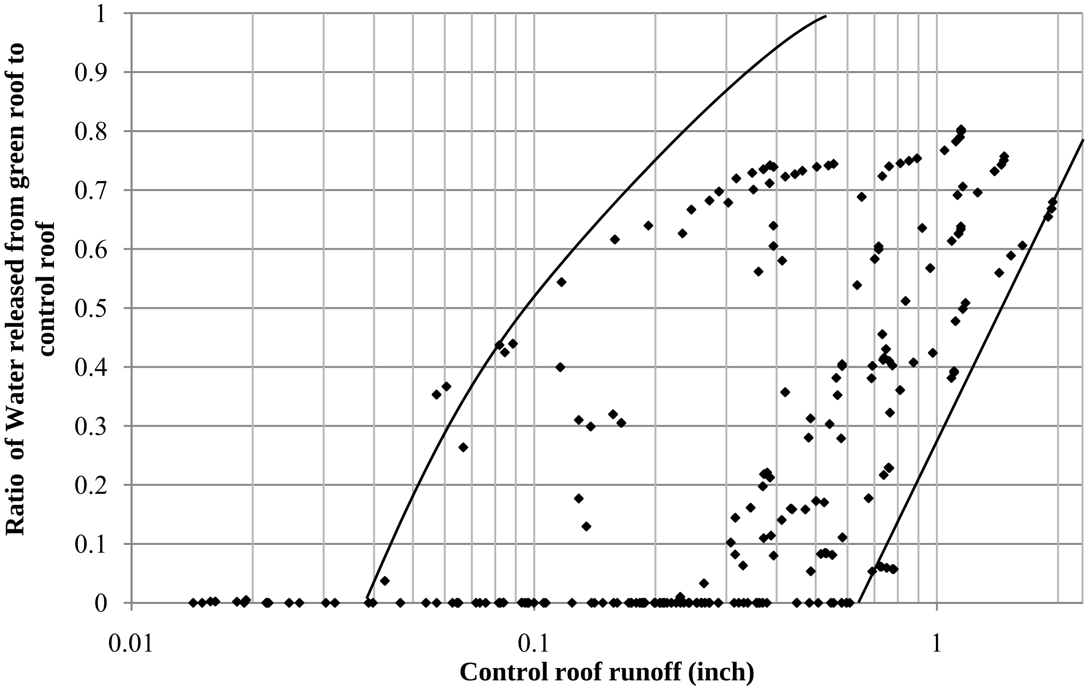

Figure 6-8 Ratio of water released from green roof to control roof vs. control roof runoff: thick roof at Giant Eagle with dry soils (258 data points in total)

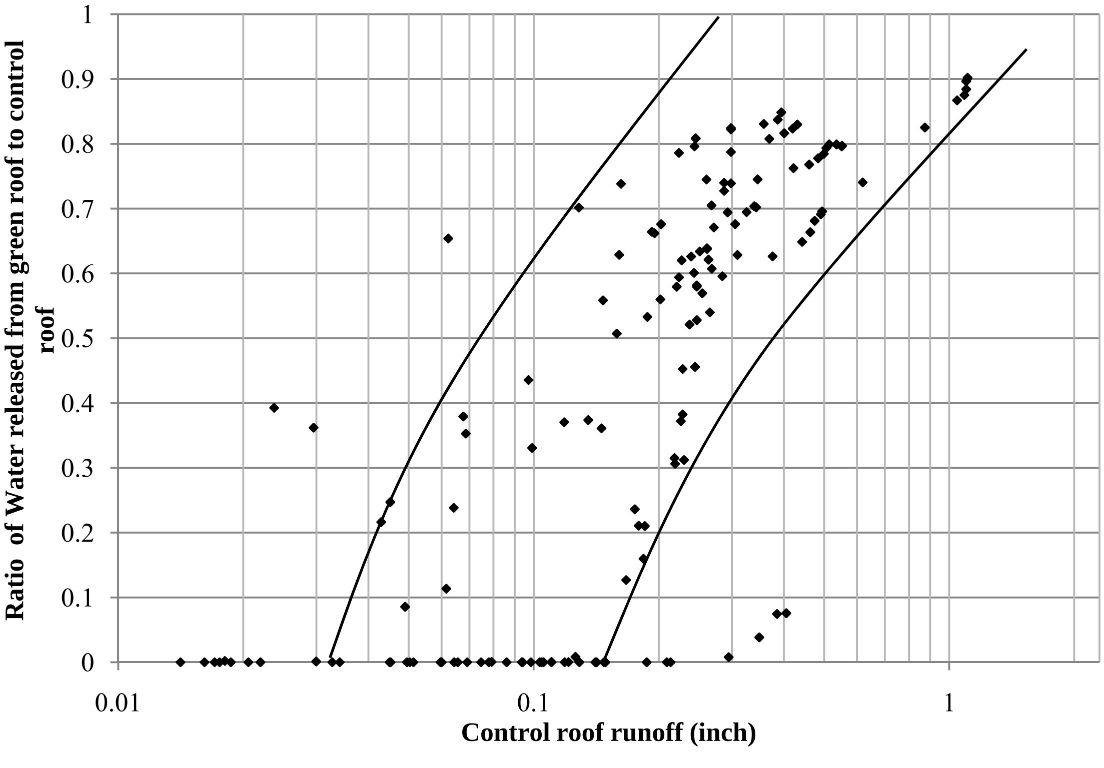

Figure 6-9 Ratio of water released from green roof to control roof vs. control roof runoff: thick roof at Giant Eagle with wet soils (179 data points in total)

In summary, dry soil conditions led to a longer retardation time of rainfall runoff than wet soil, presumably due to the higher capacity of water retention of dry soil compared to wet soil. Likewise, wet soil that was partially or totally saturated with water moisture was able to absorb less water than the dry soil and began to discharge runoff shortly after rainfall started. *The runoff delay and attenuation of magnitude of peak flow attributed to green roofs strongly depends on the green roof technology employed as well as the soil moisture content at the time of the rain event.*

6.2 Runoff Quantity Reduction

The ratio of green roof runoff to control roof runoff was determined to largely depend on the soil moisture content and ranged from 0% to 90% (this data is summarized in Table I-1 in APPENDIX I.). Zero runoff ratio means that there was no stormwater runoff discharged from green roof. As the runoff ratio grows larger, pre-existing soil moisture caused the quantity of runoff from the green roof to be closer to that of the control roof. A negative ratio denotes that water loss or a measurement error occurred and caused more runoff to be recorded from the green roof side.

The ratio of green roof runoff and amount of rainfall shows a lowest percent of 0% and highest of 91%. One hundred percent retention occurred during lower rainfall events with dry soil conditions indicating that there was no runoff from the green roof. In these cases, the dry-soil green roof acted as a storage reservoir for stormwater.

The thick roof was able to retain more stormwater than the thin roof under dry soil conditions. The amount of water retained by the thin and thick green roof was plotted against the runoff volume from the respective control roof, as shown in Figure 6-10a. While the data is scattered from the trend line, it was observed that the ratio of green roof discharge to control roof discharge for the same storm events was much smaller for the thick roof.[6] This shows that for most rain events when the soil is ‘dry’, the thick roof was able to retain much more water than the thin roof, primarily because of the thicker soil layer with greater “field capacity” for water.

Under wet soil conditions, the difference in water retention between the two roofs is negligible and the thin roof was observed to retain just as much rainfall as the thick roof. As more of the stormwater was absorbed by the soil, excess was discharge after the soil was saturated. As a result, the amount of stormwater discharged from the both green roofs will be similar to each other, depending on the similar amount of rainfall occurred at both sites.

In summary, the capability of water retention of green roof soil for a given storm is largely dependent on the soil moisture. Less runoff was discharged from green roofs under dry soil conditions than under wet conditions. At dry conditions, there was more runoff from the thin roof (Homestead) than

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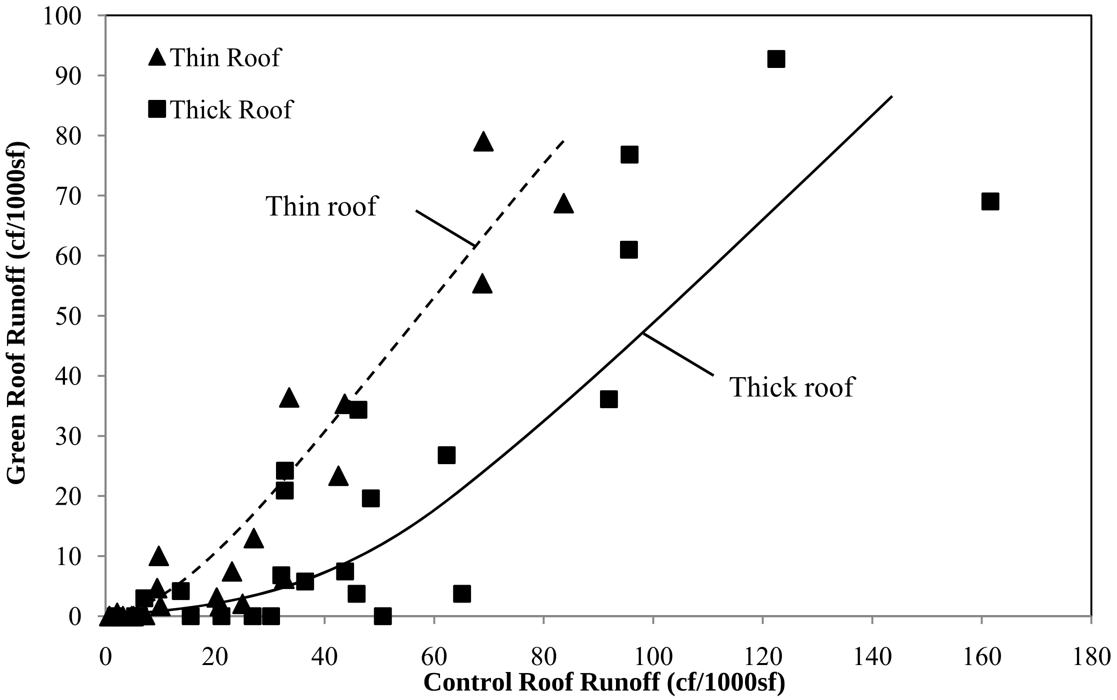
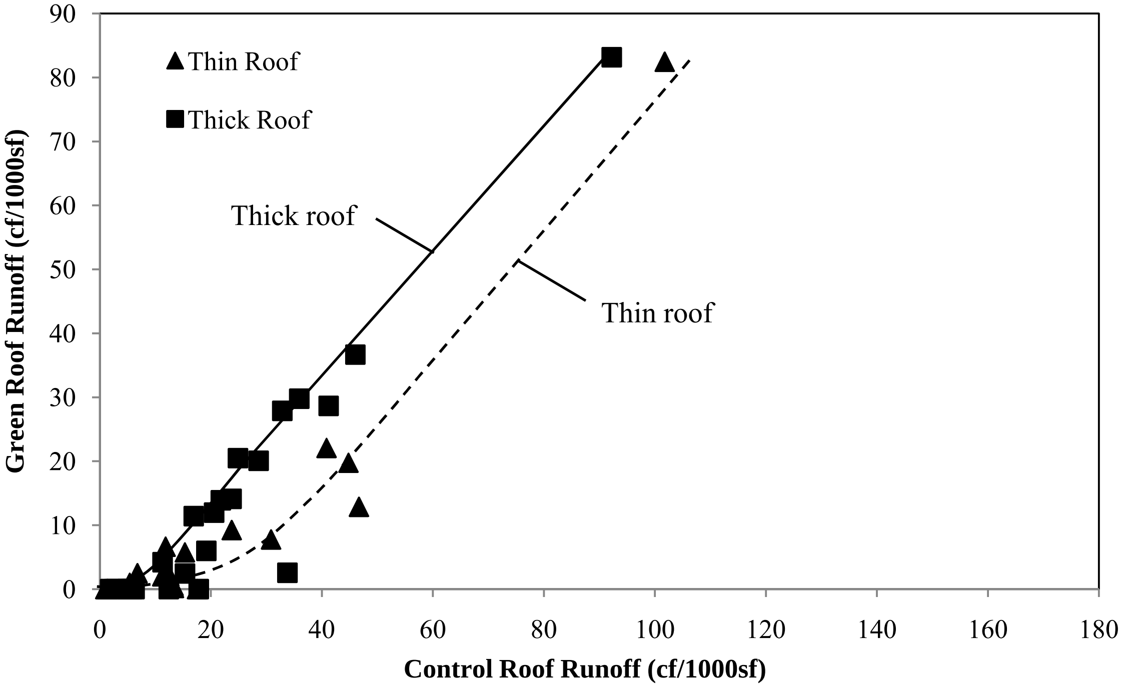
[6] data was plotted only when data from both sites was available

the thick roof (Giant Eagle), and at wet conditions there were little differences in runoff between the two types of green roofs. Furthermore, it is evident that thick roof, with four inches more of soil layer than the thin roof, had a greater capacity to retain water simply due the greater quantity of soil.



(a) Dry soil condition



(b) Wet soil condition

Figure 6-10 Comparative runoff performance of thin and thick green roofs for wet and dry soils

6.3 Thermal performance

The thermal performances of the green roofs were compared as a function of seasonal weather exposure measured over the 16-month period of January, 2008 to April 2009. The temperature profiles in this section are monthly-based, and they are divided into three groups: cold weather (recorded average daytime temperature < 50°F), medium weather (50~80°F) and warm weather (>80°F). Cold weather includes the thermal performance on January, February, March, November and December. Spring and autumn (medium) weather includes April, May, September and October. Warm weather was found in June, July and August.

The installation of thermocouples was site dependent and slightly different due to the physical differences between the two sites, as described in previous sections. There were two monitoring locations on each roof at Giant Eagle site and one monitoring location on each roof at the Homestead site. The interior spaces under the roof deck at the Homestead site were not environmentally controlled since the interior of the building had been gutted and was being rehabilitated. As a result, the heat flux through the roof was not measurable. At the Homestead site, fewer temperature monitoring points were installed between the roof surface and the bottom of the structural deck. A summary of thermocouple locations used for monitoring points at Giant Eagle and Homestead site is given in Table 6-1 and locations graphically shown on Figure 6-11.

Table 6-1 Initial Installation of Thermocouples at Giant Eagle and Homestead site

Data Point		**Giant Eagle**	**Homestead**
A	Overall Ambient	One RH probe for each roof	One RH probe for each roof
B	Ambient 1m	1m above roof/soil surface (2 thermocouples for each roof)	1m above roof/soil surface (1 thermocouple for each roof)
C	Ambient 60cm	60cm above roof/soil surface (2 thermocouples for each roof)	60cm above roof/soil surface (1 thermocouple for each roof)
D	Ambient 30cm	30cm above roof/soil surface (2 thermocouples for each roof)	30cm above roof/soil surface (1 thermocouple for each roof)
E	Ambient 15cm	15cm above roof/soil surface (2 thermocouples for each roof)	15cm above roof/soil surface (1 thermocouple for each roof)
F	Ambient 7cm	7cm above roof/soil surface (2 thermocouples for each roof)	7cm above roof/soil surface (1 thermocouple for each roof)
G	Surface	Placed on roof or soil surface (2 thermocouples for each roof)	Placed on roof or soil surface (1 thermocouple for each roof)
H[7]	Soil	½ depth of the soil medium (green roof only)	½ depth of the soil medium (green roof only)
	Filter Membrane	above the filter membrane, sealed in insulation (green roof only)	
	Drainage Layer	Below Drainage Layer (green roof only)	
	Waterproofing Membrane	Below the impermeable membrane, sealed in insulation	
	Support Panel	Below support panel	
	Insulation	At the bottom of the insulation layer	
I	Roof Deck	Below the roof decking	Below the roof decking

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[7] At Giant Eagle, it is the average temperature recorded at soil, filter membrane, drainage layer, waterproofing membrane, support panel and insulation for green roof, while the data for the control roof is average temperature at waterproofing membrane, support panel and insulation for control roof. At Homestead, it is the temperature of the interior soil for green roof and there is only one monitoring point installed for this level. However, no temperature profiles were recorded at this point for the control roof.

Temperature profiles were plotted as the average value of the temperature data recorded on a daily basis. At the Giant Eagle site, the average temperature data of the two monitoring locations was plotted, while the temperature data of Homestead were the temperature data from each monitoring location at each roof. Temperature monitoring positions for green and control roof are shown graphically in Figure 6-11.

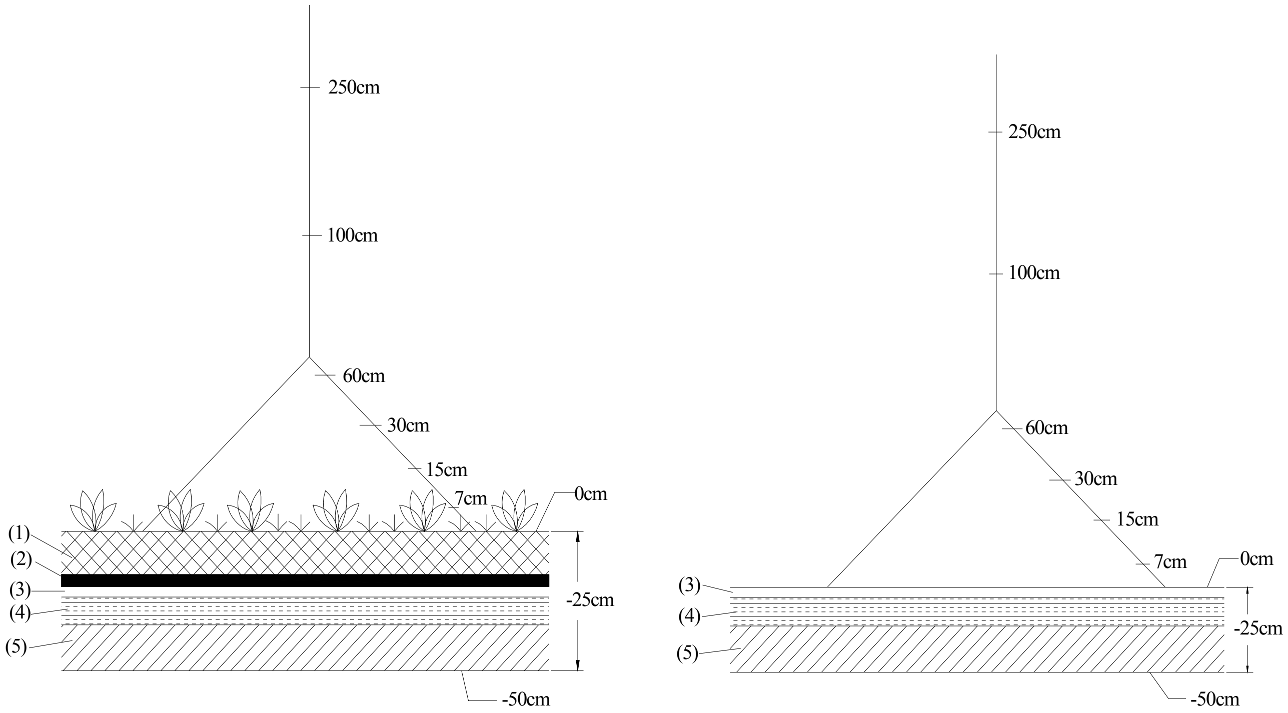


Figure 6-11 Vertical Layout of temperature monitoring positions of green (left) and control (right) roof

1- Growing medium (soil)
2- Drainage and filter layer
3- Roofing membrane
4- Insulation
5- Structural deck

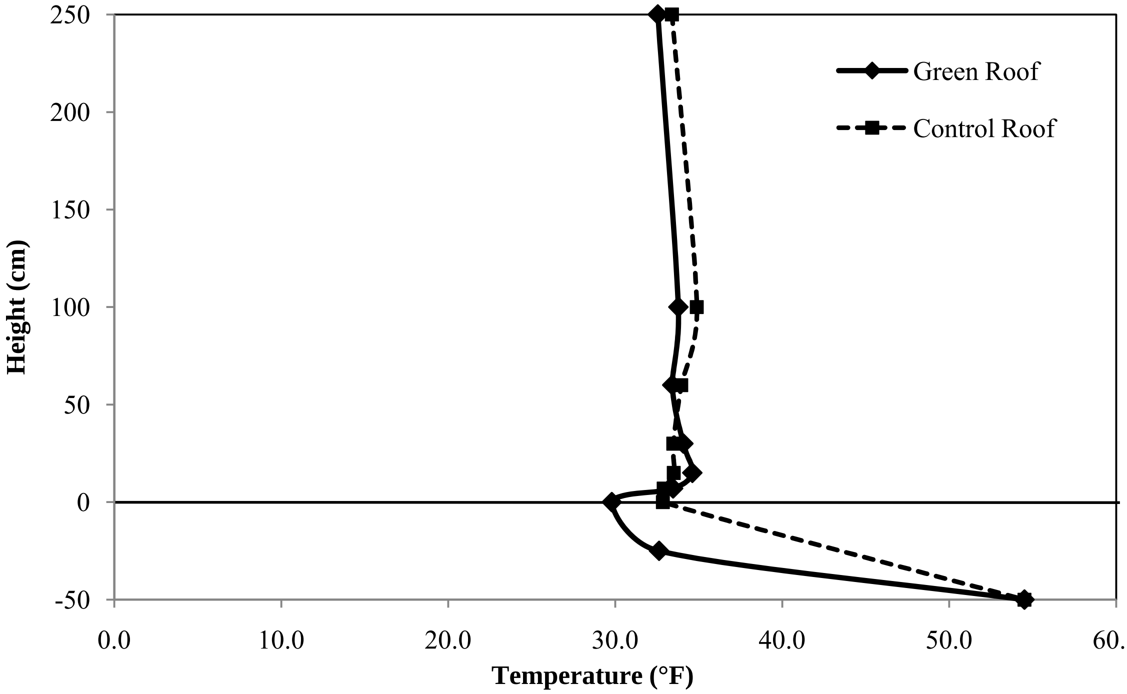
Temperature sensors tended to fail over time after being installed and operated in the field. For example because its location, the thermocouple below the control roof deck (referred to as "-50") at Homestead was irreparable and irreplaceable. However, there was a working sensor at the same point on green roof side, and since this data sensor belonged to the same building and was regularly at building inside temperature, we believe there was no significant sensible temperature difference existed for this point. From January to May in 2008 at Giant Eagle, the thermocouples at the control roof surface malfunctioned and the temperature data were not available during those five months.

6.3.1 *Seasonal thermal performances for Homestead*

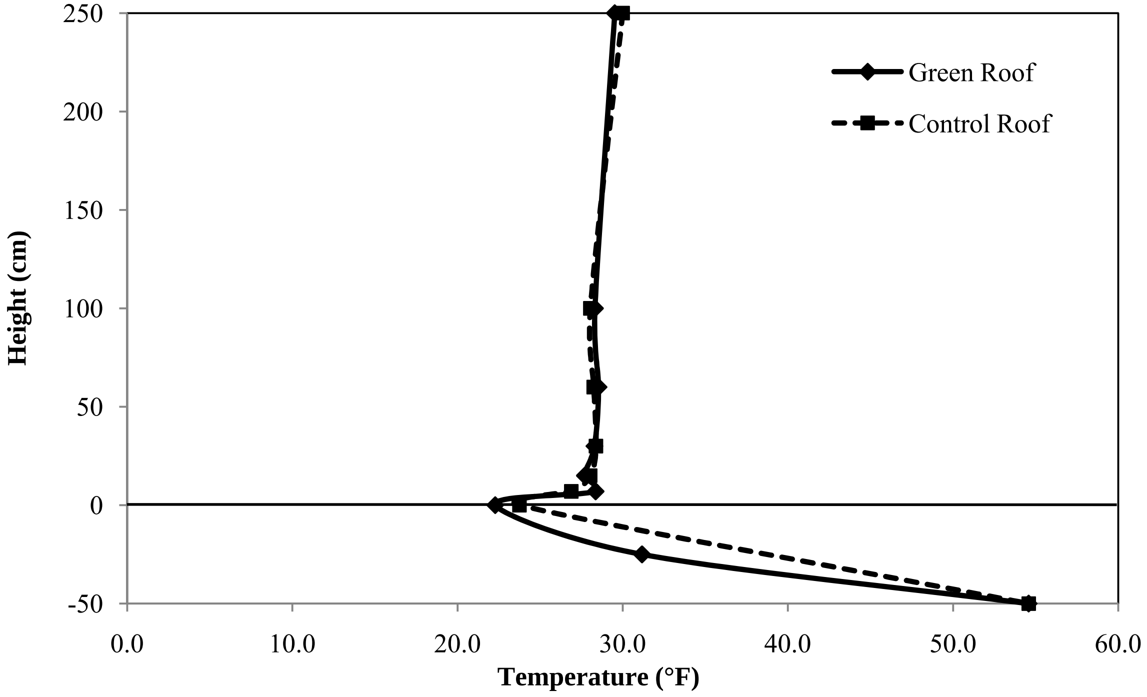
Winter Thermal performance (cold weather condition)

The temperature profile recorded during January 2008 at the Homestead site was chosen as representative of the thermal performances for green and control roofs during cold weather conditions. The graphs of thermal performances for other winter months are in APPENDIX II. During the daytime, temperatures above the conventional roof were measured to be just slightly warmer (3.1°F) than above the green roof. The surface temperature of the green roof also remained lower than the conventional roof as shown on Figure 6-12a. This lower temperature is likely due to the fact that the more massive green roof required more heat (via solar radiation) to equivalently warm up than the control roof. The temperature differences between the roof surface and roof deck for the green and control roof were 24.7°F and 32.3°F, respectively and may add to the heating requirements of the building.

The advantage of solar heating for the conventional roof disappeared during the night-time, as there was no temperature differences at all control and green roofs monitoring points, as indicated on Figure 6-12(b). Thus, the temperature profiles indicate that the wintertime thermal performances of green roof and control roofs are generally similar and no thermal advantage is gained when during severe cold weather.



(a) Day-time temperature profile



(b) Night-time temperature profile

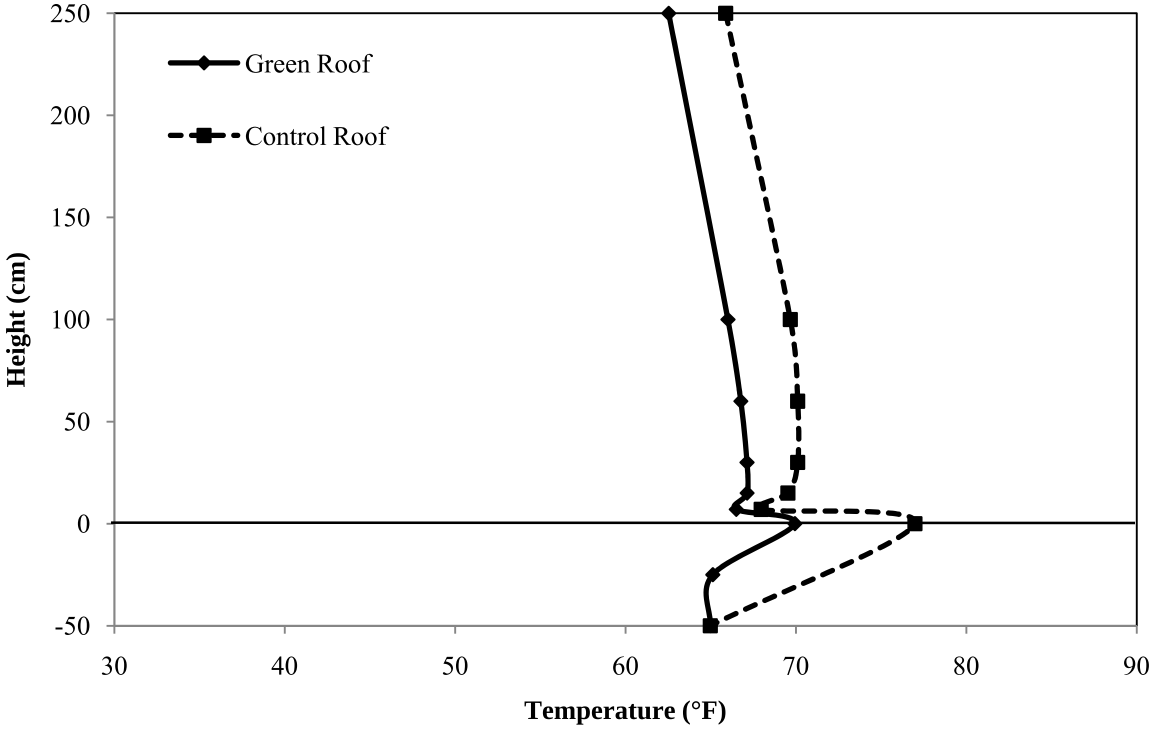
Figure 6-12 January, 2008 temperature profile at Homestead. There is no temperature differences measured between the green and control roofs in cold weather conditions.

Spring and Autumn Thermal performance (moderate weather conditions) -- Homestead

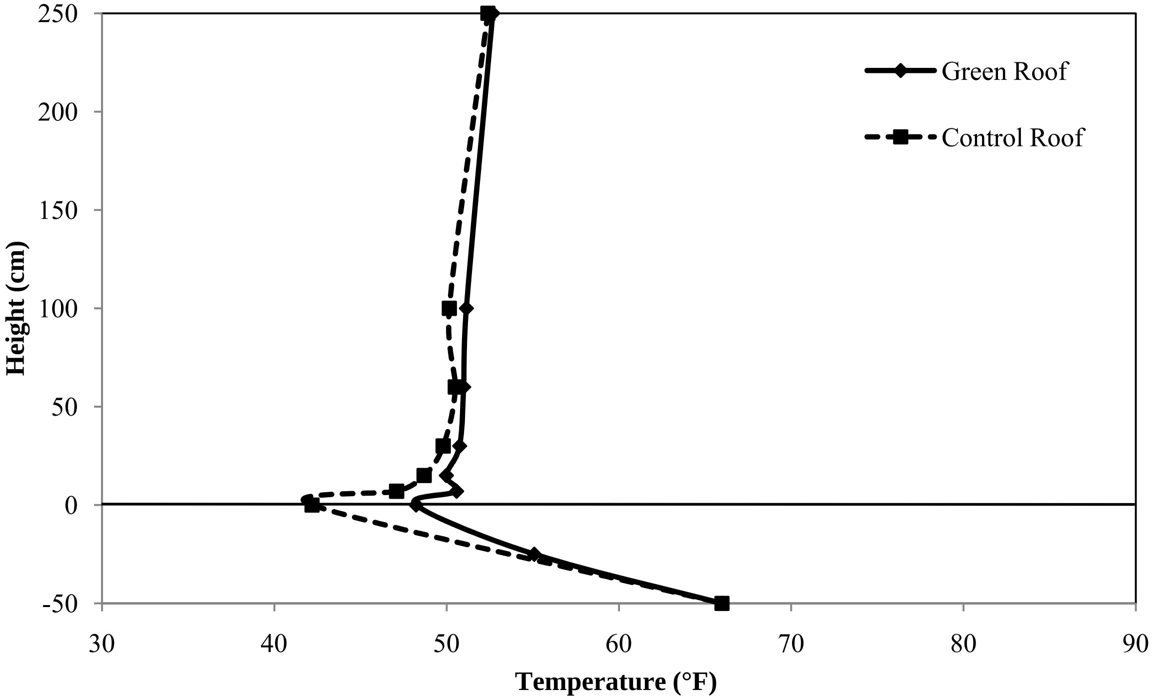
The temperature profile for April 2008 was chosen to be representative for moderate weather conditions. Temperature profiles for addition time periods with moderate weather conditions are in the in APPENDIX II. The temperature data was divided into day as shown on Figure 6-13(a) and night time as shown on Figure 6-13(b). As an overall observation, the control roof membrane experienced a much larger temperature swing, being warmer during the day and cooler during the night.

The ambient day time temperatures above the two roofs was warmer during April than in January, raising the average temperature above the green roof to 66°F and 69°F above the control roof (Figure 6-13a). The green roof surface temperature was lower (70°F compared to 77°F), with the soil media and plants on the green roof acting as effective insulation as outside air temperature increased. The temperature difference of 7°F indicates the green roof was able to dissipate more solar radiation than the control roof.

During night-time (Figure 6-13b), the temperature at roof surface for control and green roof both dropped significantly in response to the cooler outside temperatures, but the control roof had 6°F degree lower temperature than the green roof. The green roofs larger thermal mass likely retained more heat and allowed it to stay warmer than the control roof.



(a) Day-time temperature profile



(b) Night-time temperature profile

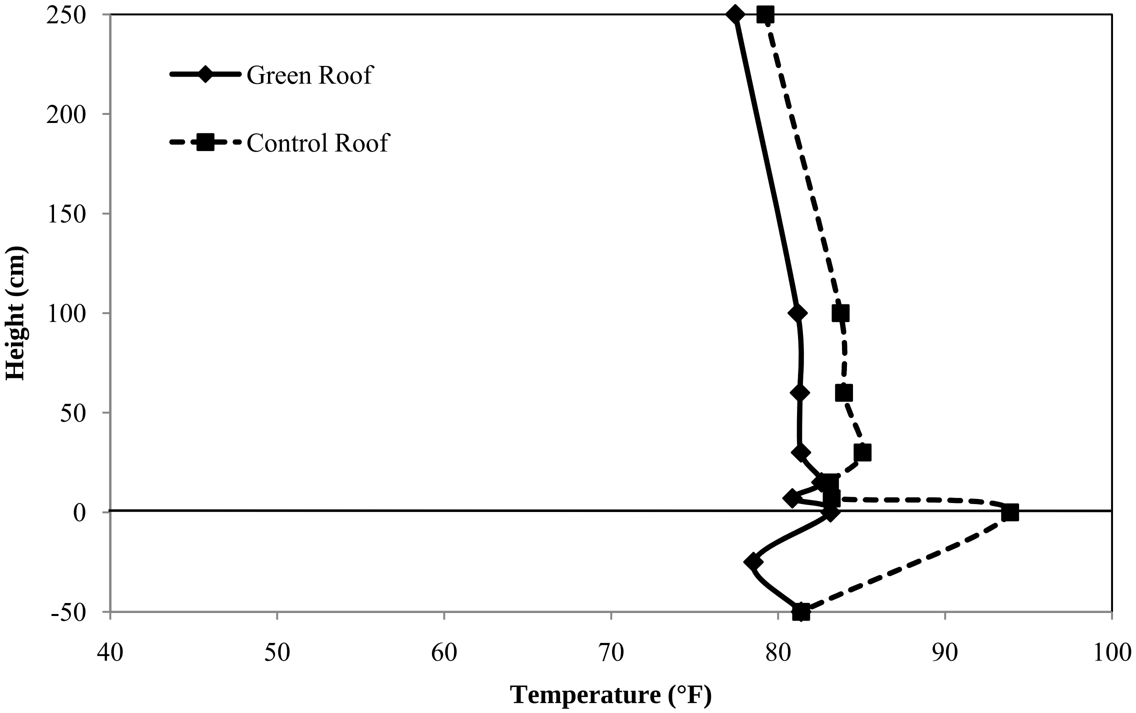
Figure 6-13 April, 2008 temperature profile at Homestead. Moderate weather conditions

Summer Thermal performance (hot weather condition) -- Homestead

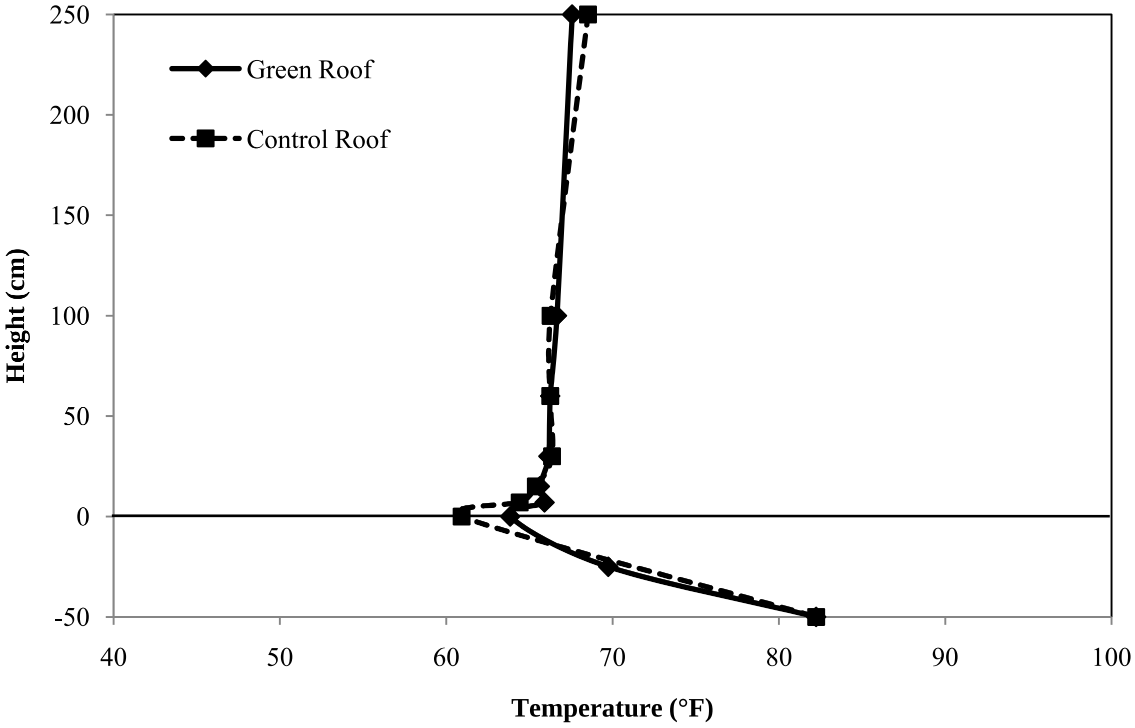
The temperature profile for June 2008 was chosen to be representative for hot weather conditions. Temperature profiles for other time periods during hot weather conditions are in APPENDIX II The temperature data was divided into day (Figure 6-14a) and nighttime (Figure 6-14b) segments. As an overall observation, the control roof experienced a much larger temperature swing, being much warmer during the day and the same temperature as the green roof during the night.

The thermal performance during daytime hot weather condition was similar to that during moderate weather conditions. As seen in Figure 6-14a, the temperature immediately above the control roof was 2.2°F warmer than the air just above the green roof. Of more importance when considering the roof membrane exposure, the control roof surface temperature was 100.3°F compared 87.6°F for the green roof surface temperature. The temperature difference between the control and green roof during the summer was 12.4°F, higher than the 7 °F difference during moderate weather condition. The elevated temperature of the roofing membrane may eventually lead to its premature degradation.

During the night, the green roof maintained a slightly higher surface temperature than the control roof surface and experienced only ½ the 40 °F temperature swing (peak day time to trough night time) that the control roof did.



(a) Day-time temperature profile



(b) Night-time temperature profile

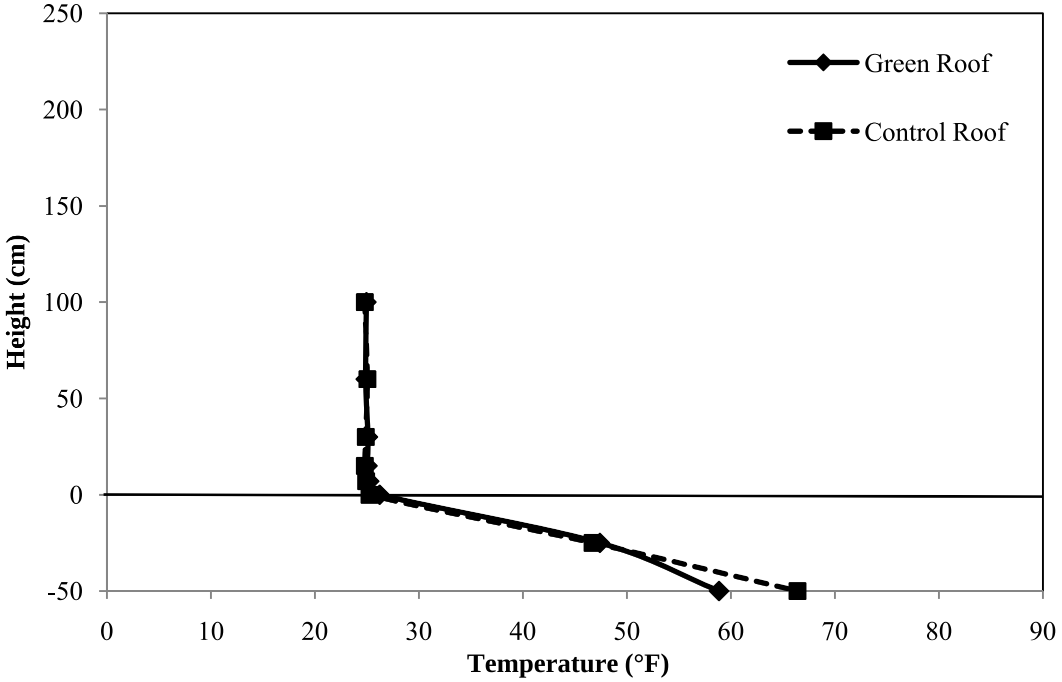
Figure 6-14 June, 2008 temperature profile at Homestead Summer (hot) weather conditions

6.3.2 *Seasonal thermal performances for Giant Eagle*

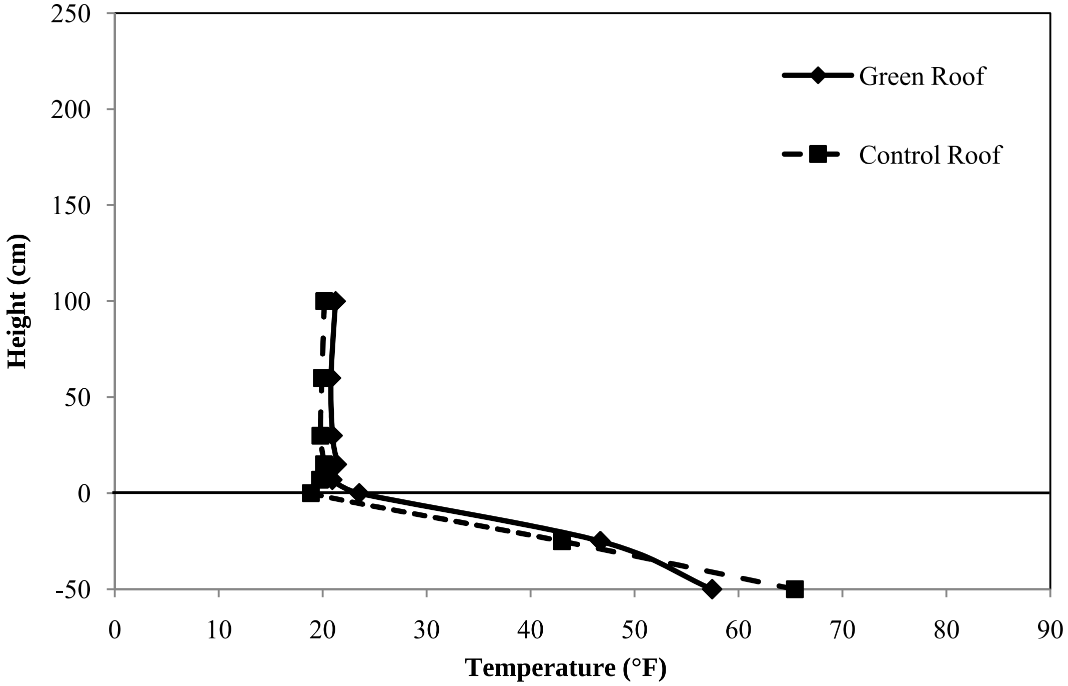
Winter Thermal performance (cold weather conditions)

The temperature profile for the Giant Eagle roofs during January 2009 (shown in Figure 6-15a and b), was chosen to be representative of the thermal performance during cold weather. Temperature profiles for other time periods during cold weather conditions for the Giant Eagle site are in APPENDIX II . The ambient temperature profile monitored along the tripod for control and green roof nearly equaled each other during day time with an average difference of 0.1°F and is shown in Figure 6-15a. Consistent with the tripod temperature profile, there was only a difference of 1°F between surface temperatures upon two roofs, indicating that *there was little difference in the cold weather thermal performances between the two roofs.*

The nighttime thermal performances revealed that temperatures above and at the green roof surface were higher than that of the conventional roof. As shown in Figure 6-15b, the ambient temperature above the green and control roof exhibit more differences than in the day time, being 1.1°F warmer (on average) over the green roof. The same situation occurred at the green and control roof surfaces. The surface temperature upon the green and control roof was 23.5°F and 18.9°F respectively, with a difference of 4.6°F. The higher thermal mass of the green roof did not undergo the large temperature swing that the control roof experienced.



(a) Day-time temperature profile



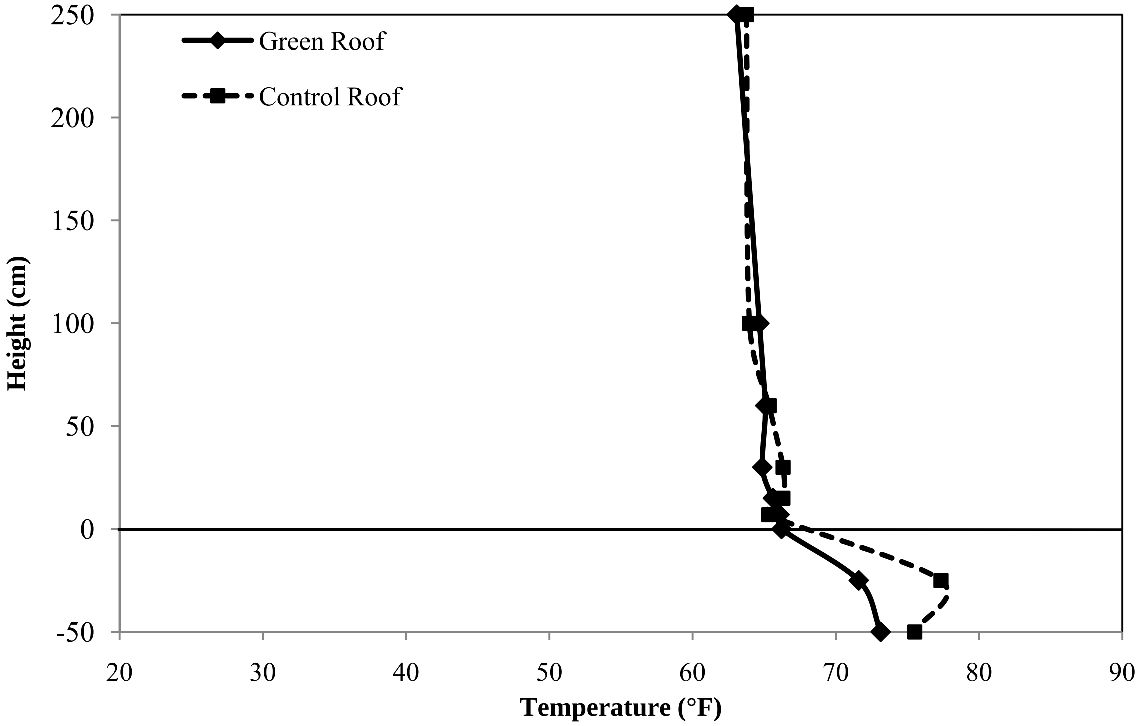
(b) Night-time temperature profile

Figure 6-15 January, 2009 temperature profile at Giant Eagle. Winter (cold) weather conditions

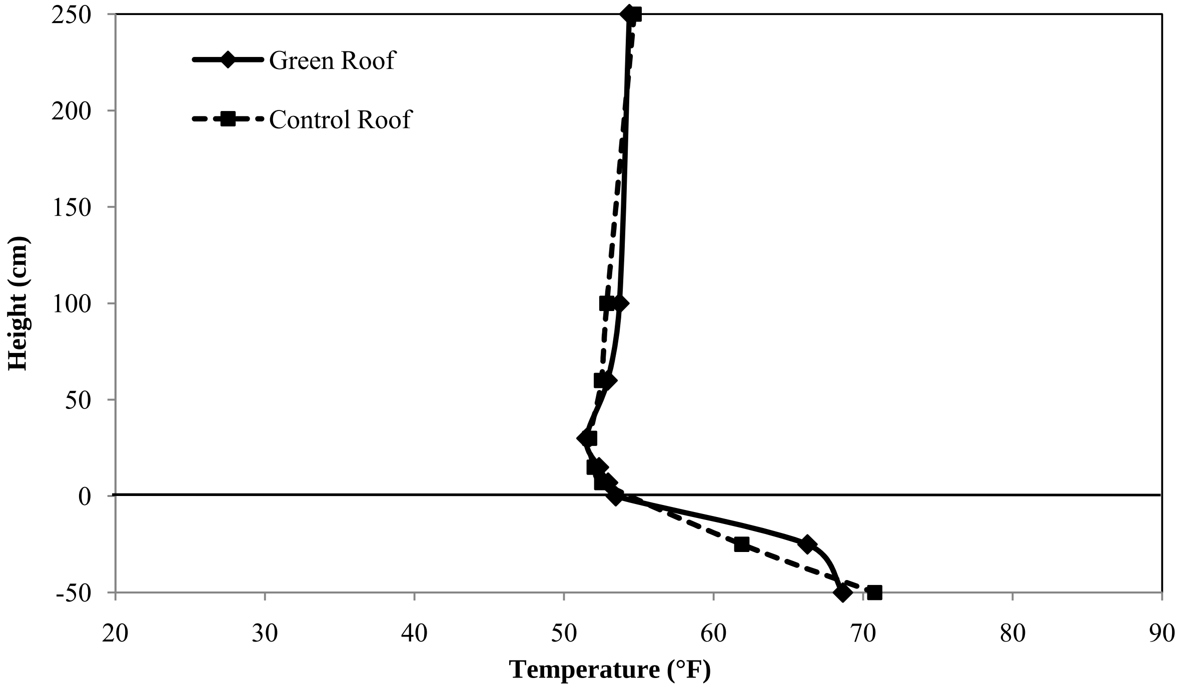
Spring and Autumn Thermal performance (moderate weather conditions) – Giant Eagle

The temperature profile for Giant Eagle during April 2008 was chosen to be representative of the roofs thermal insulation properties during moderate weather. Temperature profiles for other time periods during moderate weather conditions for the Giant Eagle site are in APPENDIX II The daytime and nighttime temperature profiles are presented in Figure 6-16(a) and Figure 6-16(b), respectively. As seen in Figure 6-16(a), there was no significant difference in the actual roof surface temperature or the average ambient temperature above the green roof compared to the control roof during the day or night. For comparative purposes, there was 7°F temperature difference between green and control roof during daytime at the Homestead during the same time period.

As the weather became warmer, the green roof became a better insulator against temperature swings. As shown in Figure 6-16a, the temperature of the green roof at the "-25 cm" (location below the roof deck) during the daytime was 5.7°F cooler than the control roof and was 4.4°F warmer during the nighttime. This data suggests that since the green roof does not experience large temperature swings, the green roof can moderate the roof temperature and protect the waterproofing membrane better than the control roof.



(a) Day-time temperature profile



(b) Night-time temperature profile

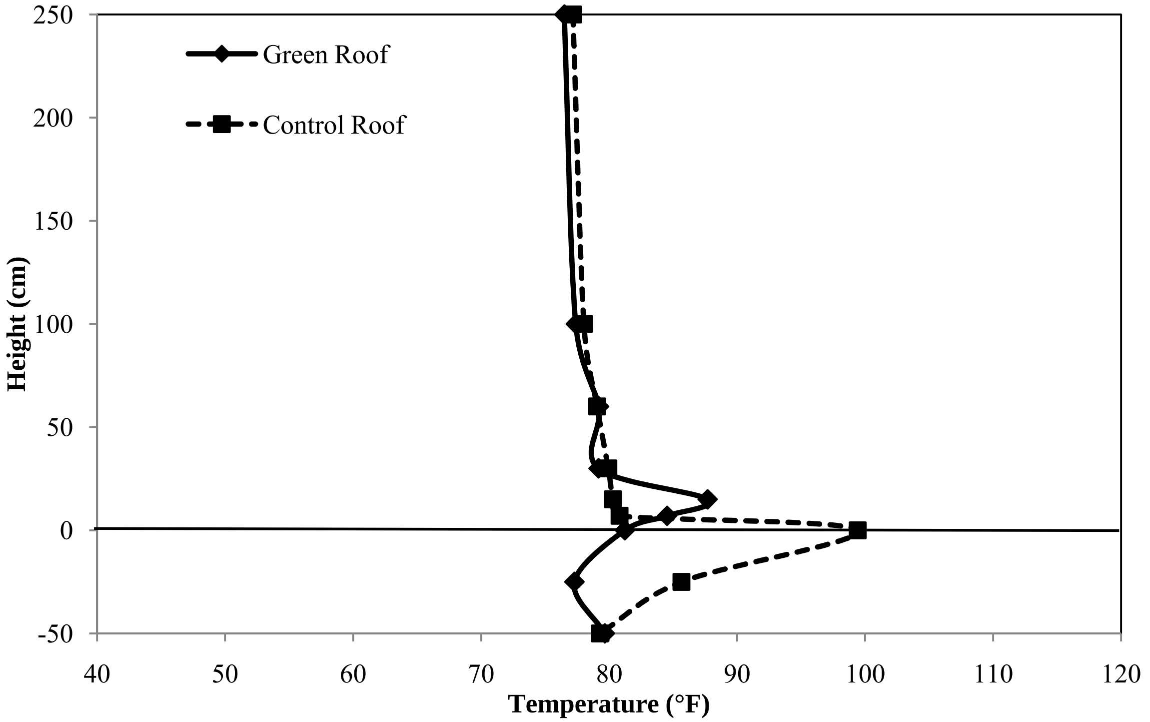
Figure 6-16 April 2008 temperature profile at Giant Eagle. Moderate weather conditions

Summer Thermal performance (hot weather conditions) – Giant Eagle

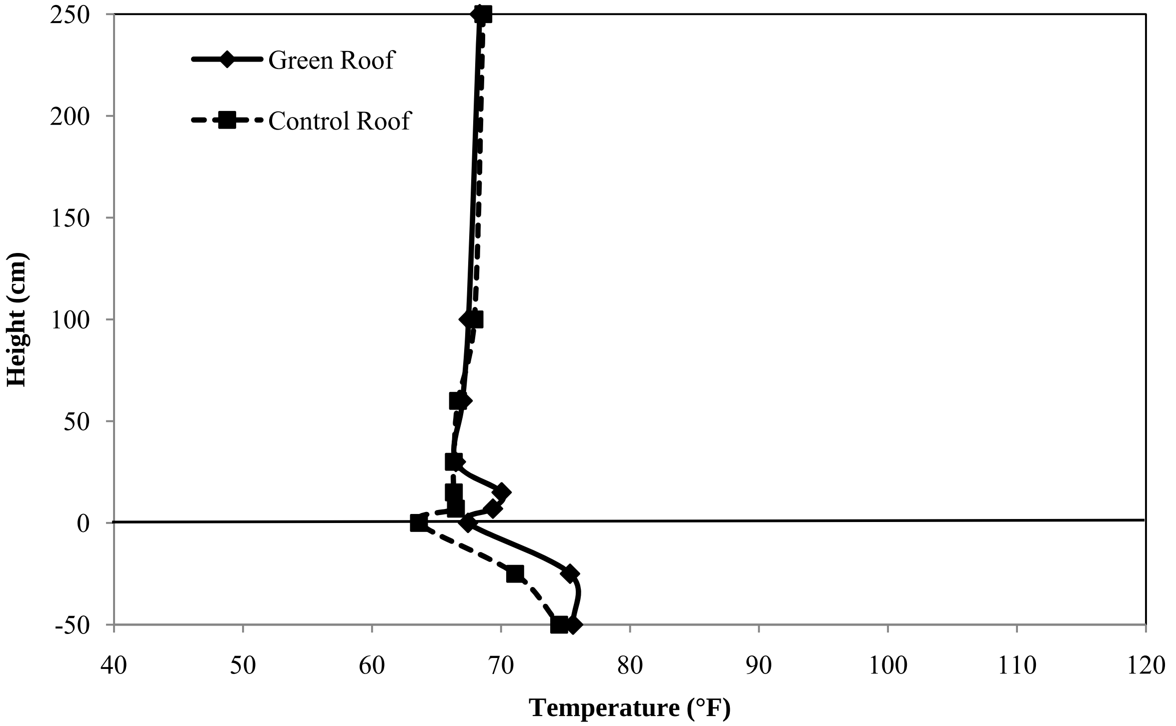
The temperature profile for Giant Eagle during June 2008 was chosen to be representative of the roofs thermal insulation properties during hot weather. Temperature profiles for other time periods during hot weather conditions for the Giant Eagle site are in APPENDIX II. The thermal profiles for daytime and nighttime are presented in Figure 6-17a and Figure 6-17b, respectively.

The ambient temperature above two roofs showed little differences. As seen in Figure 6-17(a), the average ambient temperature was 80.7°F above the green roof and 79.2°F above the control roof, with only 0.5°F temperature difference observed. As for the nighttime temperature profile (Figure 6-17b), there was an average ambient temperature difference of 1°F for green and control roof.

Although there was no significant distinction for temperatures above the two roofs, the green roof temperature profiles suggested provision of better insulation against daytime heating and significant temperature swings. As seen in Figure 6-17a, the green roof surface during the daytime had an average temperature of 81.2°F, while the surface temperature upon the control roof was 99.4°F. The temperature difference between the green and control roofs was 18.2°F, suggesting that the green roof kept heat out of the building. The green roof also provided a moderating effect at night, dropping in temperature only 10 °F whereas the conventional control roof dropped 35°F (Figure 6-17b). Overall, the green roof experienced much less extremes in heating and cooling and provided more thermal stability and protection to the roofing membranes during hot weather. The thermal performance of the two roofs followed the same general trend as during hot weather as it did during moderate weather conditions, but with a higher level of insulation by the green roof during the hot weather months.



(a) Day-time temperature profile



(b) Night-time temperature profile

Figure 6-17 June, 2008 temperature profile at Giant Eagle

6.3.3 **Comparisons of Green Roof Thermal Performances**

In this section, the thermal performance and insulation potential of the two different green roof technologies was compared to their control roofs over the course of about 15 months encompassing two winter seasons.

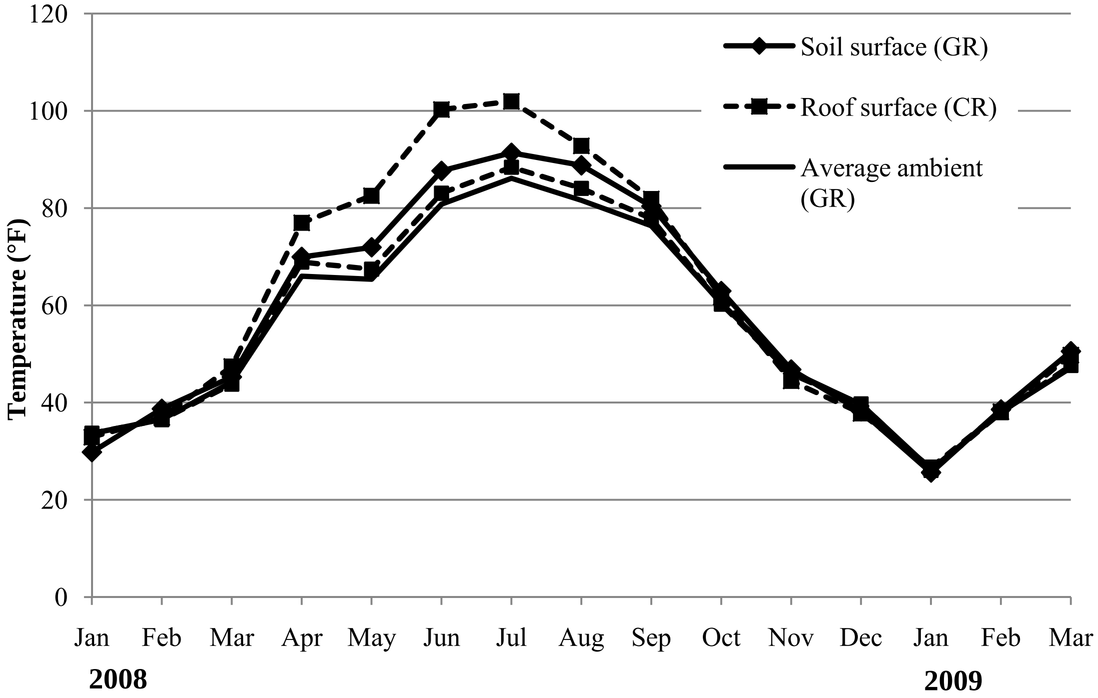
When looking at the entire 16-month time frame when comparative temperature profiles were collected, the average day time temperatures for the soil and roof surfaces were observed to be warmer than ambient for both the green and control roofs at both locations. Data for this section is listed on Table II-2 and Table II-3 of APPENDIX II.

During the warmer months, the thicker roof (Giant Eagle) was observed to maintain its temperature close or equal to ambient temperature (Figure 6-18b), whereas the thinner roof was observed to be generally warmer than the ambient temperature (Figure 6-18a). While the ambient temperatures over both the control and green roof do not show a large variation at Giant Eagle, it is noteworthy that the air temperature immediately above the Homestead green roof was cooler than the control roof. This observation illustrates the local cooling effect that may be occur over green roofs and can serve as an important benefit over the conventional roof.

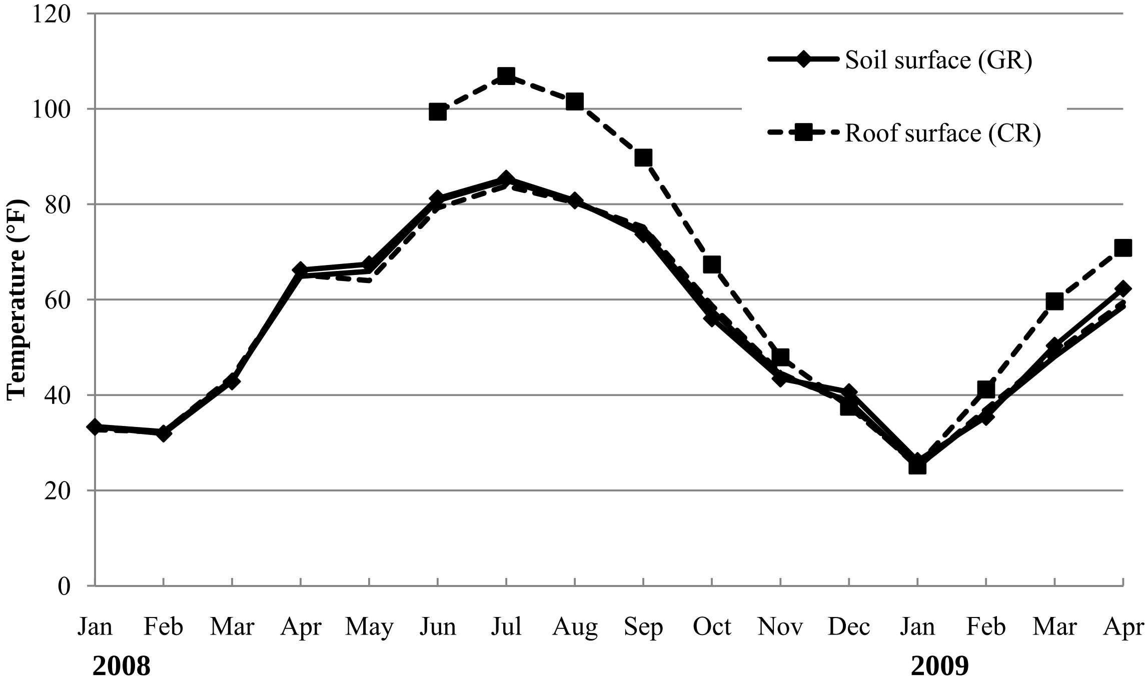
There was virtually no difference between the control roof and green roof surface at either location when the average temperature was below 45°F. As seen in day-time temperature profile at Homestead and Giant Eagle (Figure 6-18a & 6-18b), the four temperature lines of ambient, soil surface and roof surface on January, February, March, November, December, overlapped and no significant temperature differences between control and green roof was observed. This presumably is because that the temperature in wintertime in Pittsburgh is quite cold and the soil media on both of the green roofs was frozen. Thus, the surface temperatures upon two types of roofs were not significantly different.

The temperatures (both ambient and green roof) were *always* higher than control roof surface during nighttime, and this is especially true during hot weather (as seen in Figure 6-19a+b). Thus, both green roofs were able to maintain a portion of heat that was absorbed during daytime, whereas the membrane control roof released more heat than green roof did.

In summary, the green roofs at both sites exhibited a measure of “thermal moderation”, which was significant during hot weather months. This may be explained by observations (at Giant Eagle) that the thick green roof absorbed less solar radiation than the control roof, which kept the daytime surface temperature lower. Temperature profile data show that the control roof surfaces temperature reached highs of 102°F and 107°F at Homestead and Giant Eagle respectively, whereas the related soil surface temperature at the same time were 91°F and 85°F, respectively. However, as the ambient outdoor temperature decreased with colder weather, the surface temperature difference between control and green roofs became less significant and the insulation advantage of the green roofs disappeared.

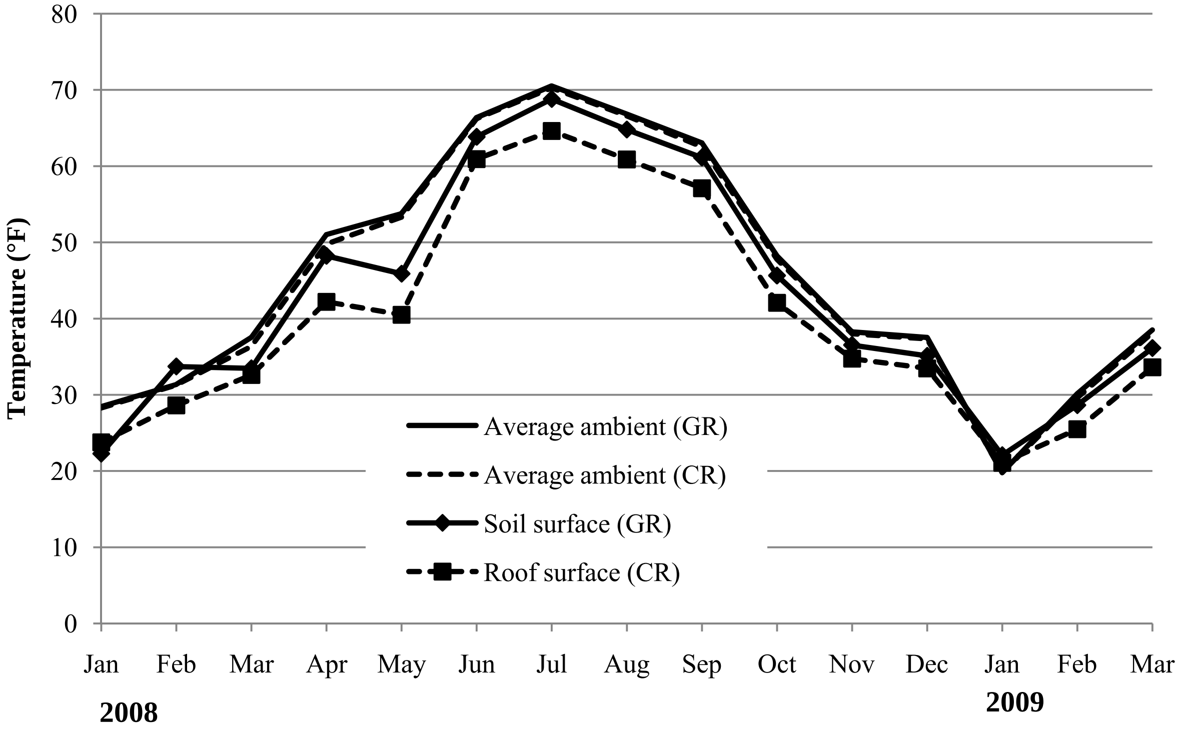


(a) Homestead

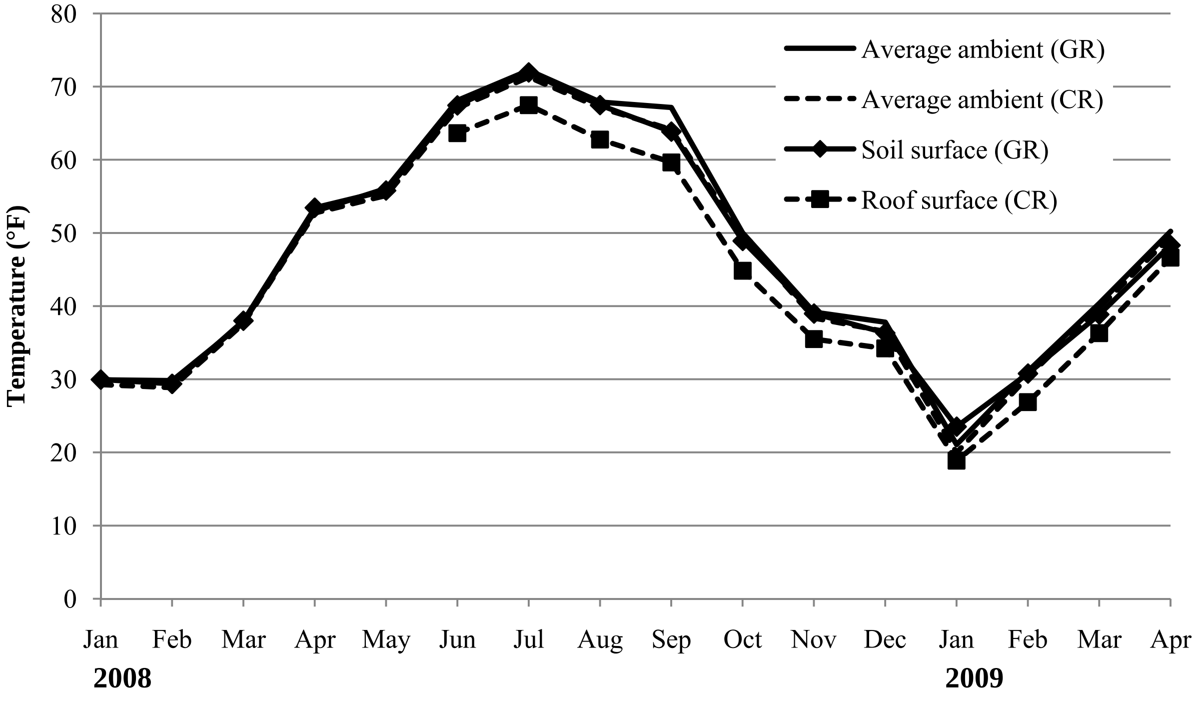


(b) Giant Eagle

Figure 6-18 Day-time monthly average temperature of ambient and soil/roof surface



(a) Homestead



(b) Giant Eagle

Figure 6-19 Night-time monthly average temperature of ambient and soil/roof surface.

6.3.4 **Below Roof Deck Temperature Differences**

The temperature differences just below the roof deck for the green and control roofs suggest further evidence of the insulation potentials of the green roofs. Evaluation of the overall month-to-month thermal profile data indicate that the largest seasonal (Figure 6-20 and Figure 6-21) and day to nighttime temperature (Figure 6-21) differences occur through the thin roof transect (from the soil to the inner roofing deck) compared to the thick roof. The related temperature data are list in Table II-3 and Table II-4 of APPENDIX II.

As shown on Figure 6-20, there was a small difference between the temperature profiles for the two green roofs, especially during hot weather. During summer months, the temperature profiles suggested that more heat was transferred to the inner deck through the thin roof. During cooler weather, the ambient heating effect was less, and temperature differences between the thin and thick roof were largely insignificant.

The insulation effect on the trans-roof temperature profiles is not as significant at night as during the day. As seen in Figure 6-21, the temperature curves of soil surface and roof deck below for the same green roof are nearly identical. Small surface temperature differences exist between the thin and thick roof, where the thick roof was slightly warmer.

In comparison to conventional roofs, both thick and thin green roofs were observed to reduce heat absorption. During the day, the soil surface temperatures on green roofs were significant lower than the surface temperature of the control roofs. Green roofs retained heat absorbed during the day leading to higher but more constant soil surface temperatures than control roof surfaces during the night.

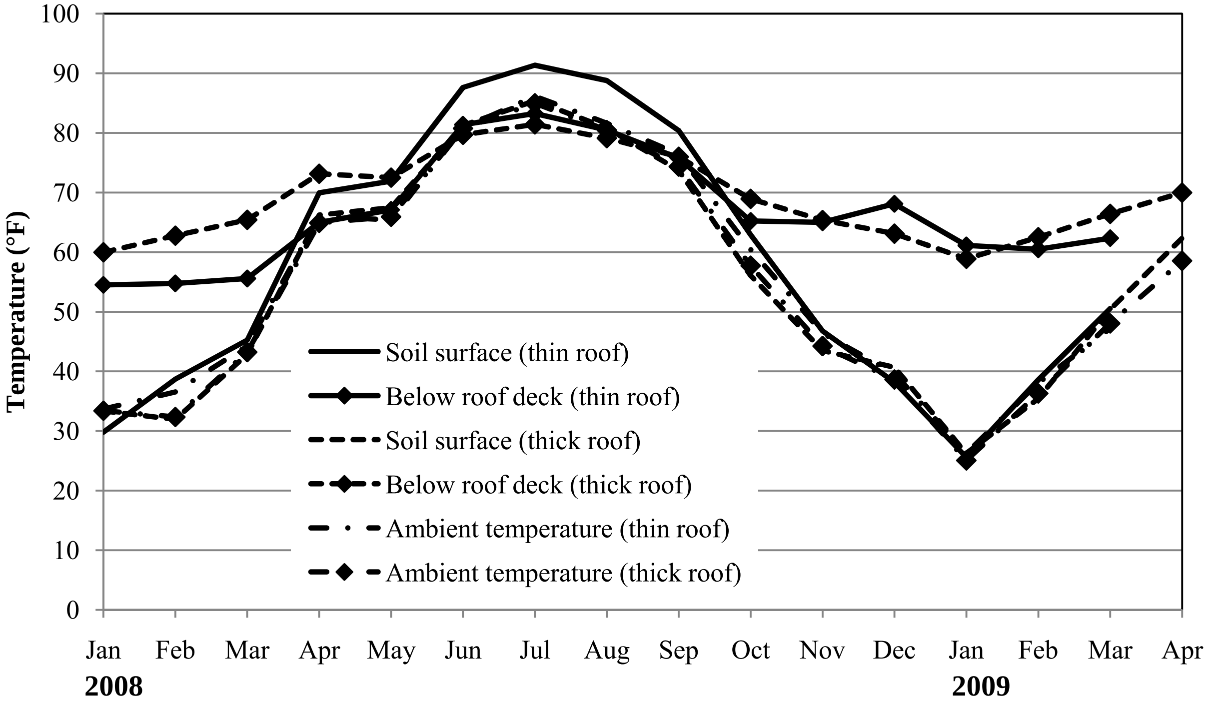


Figure 6-20 Day-time monthly average temperature of green roof soil surface and below roof deck

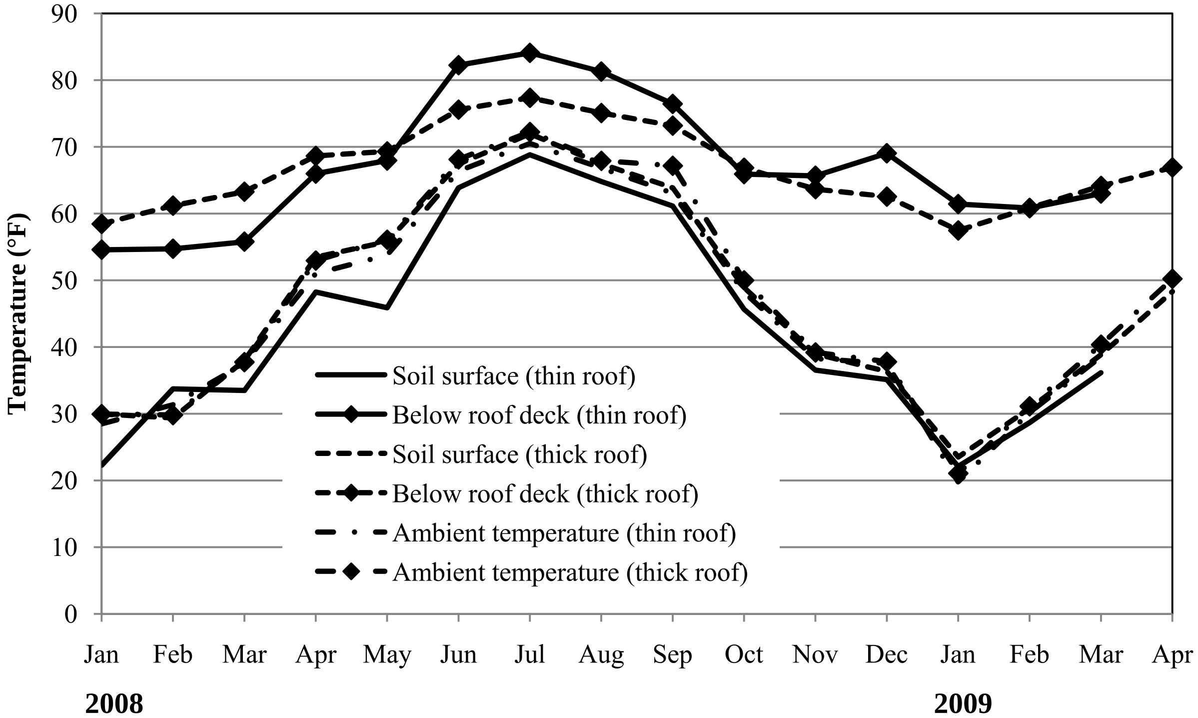


Figure 6-21 Night-time monthly average temperature of green roof soil surface and below roof deck

6.4 Physical and Chemical Environmental Analysis of Runoff Waters

Runoff samples from both Homestead and Giant Eagle site were collected on site during rainfall events. Samples were automatically collected using computer controlled solenoid valves. Once the samples were collected, they were analyzed at the University of Pittsburgh Environmental Engineering Laboratories. Each water sample was analyzed using EPA approved methods via HACH analysis kits; the exact procedures followed for each analysis are outlined in the *HACH Water Analysis Handbook* (2003). Section 4.4 summarized runoff water quality from the Giant Eagle site.

6.4.1 Homestead Runoff – Physical Parameters

Eight sets of runoff samples were collected at Homestead from both control and green roof runoffs. Runoff water flowed into separate weir boxes for the control (Figure 6-22) and green roof (Figure 6-23). Significant quantities of black solids (Figure 6-22) accumulated in the bottom of the control roof weir box resulting from dirt and other particles that were washed off of the control roof. In contrast, few particles were noted in the runoff discharge from green roof, but the overall runoff water color had a reddish-brown hue. This color indicated that iron may have leached from the soil medium, or atmospheric iron deposition passed through the green roof. However, given the lack of settled particles in the weir box receiving green roof runoff, the green roof likely acted as a filter and retained metal-containing particles that may have been atmospherically deposited or solvated within the green roof[8].

6.4.2 Homestead Runoff – Chemical Analyses

The eight sets of runoff samples were tested for a battery of common environmental parameters, including pH, total suspended solids, sulfate, total nitrogen, total phosphates, chemical oxygen demand (COD) and several heavy metals. A summary of the results of the eight sets of runoff samples from Homestead testing is presented in Table 6-2.

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[8] The Homestead site is near a steel mill, and is often down wind of that mill.

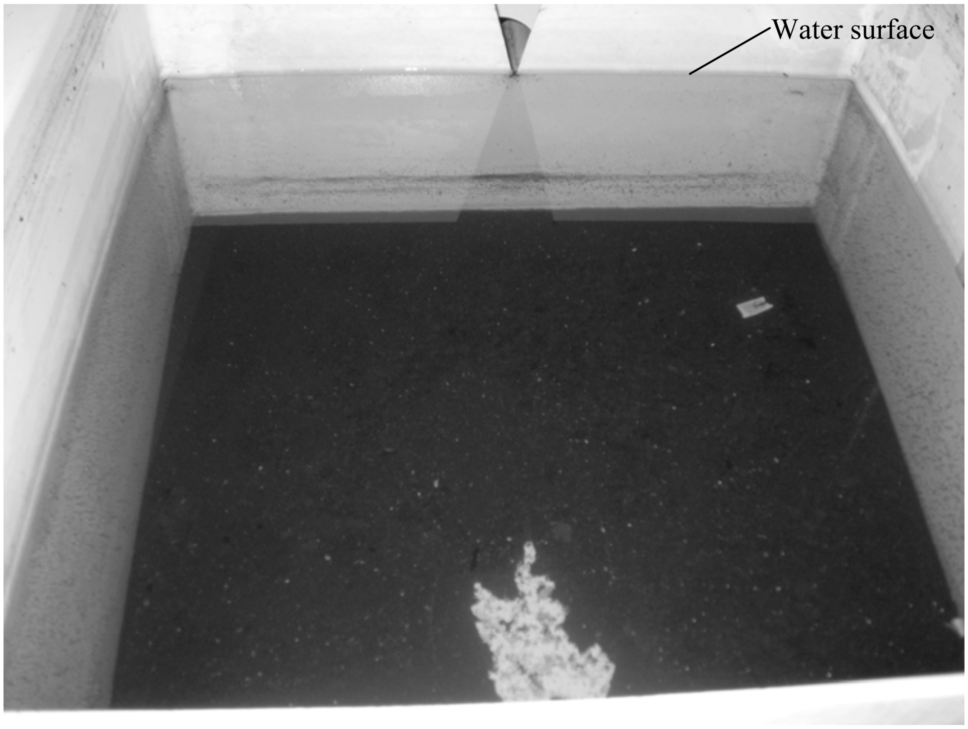

Figure 6-22 Runoff water from control roof stored in the weir box (Homestead)

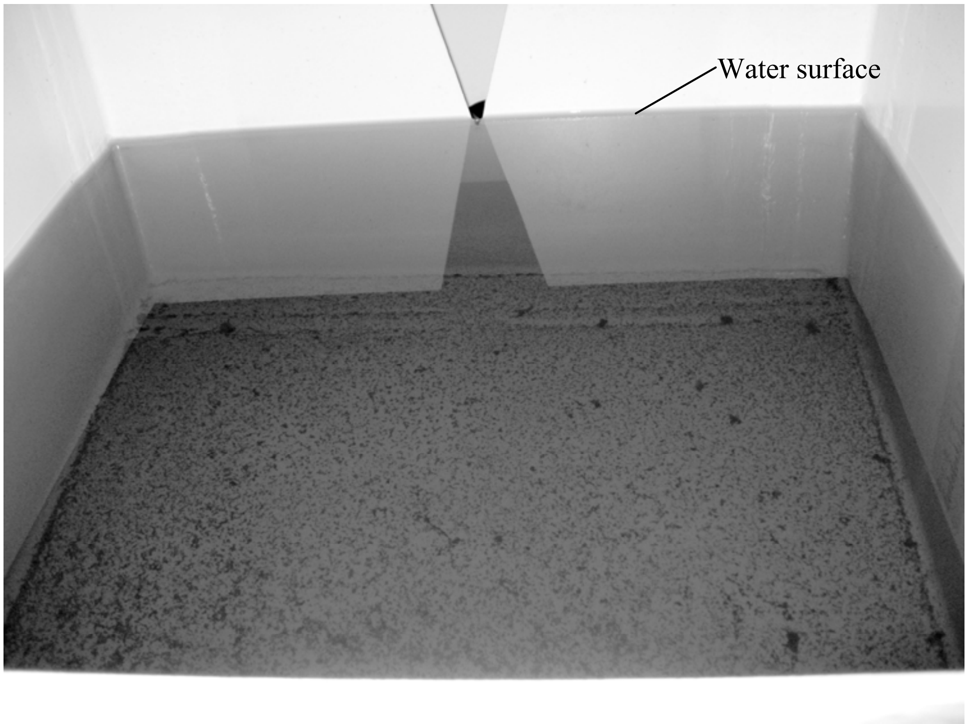

Figure 6-23 Runoff water from the green roof stored in the weir box (Homestead)

pH

The acid content in the runoff from the control roof at Homestead is higher than that from green roof. As seen in Figure 6-24, the pH values from the control roof runoff are between 5 and 5.6, values typical of "acid rain deposition". pH values did not statistically vary with season indicating fairly consistent acid deposition. In contrast, the pH of runoff from the green roof that was about 6.5. These results reveal the green roof's ability to neutralize acid rain deposition.

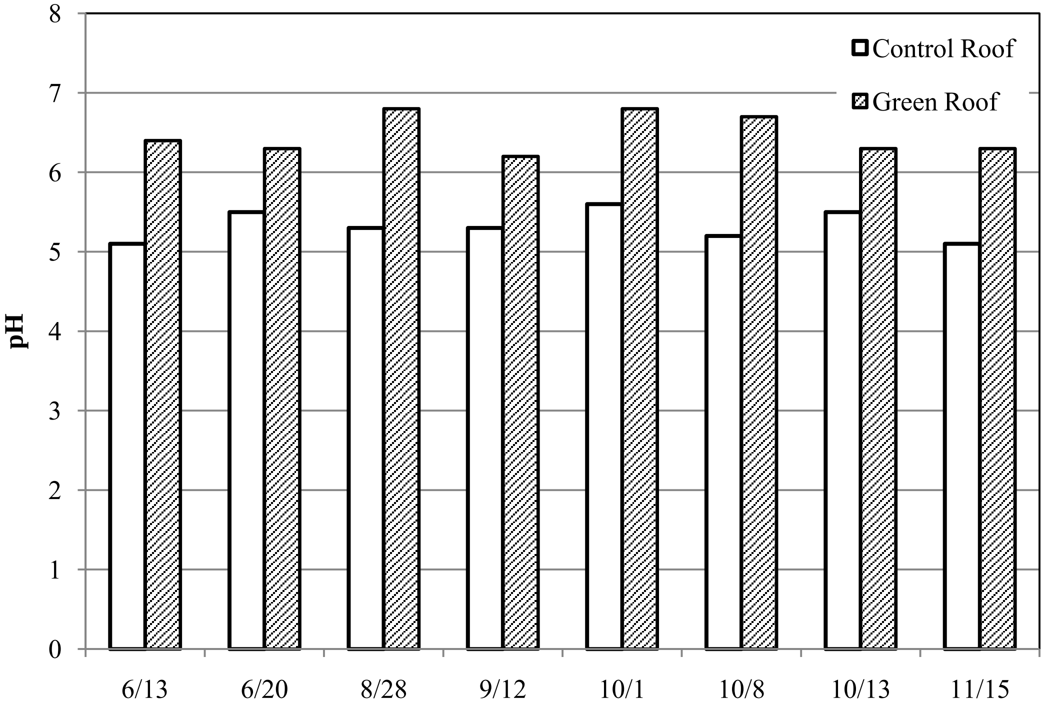

Figure 6-24 pH results (Homestead, 2008)

Total suspended solids (TSS)

The measured TSS from the green roof was lower than that measured from the control roof. The results of TSS are shown in Figure 6-25. There were often large differences of TSS between the control and green roofs. The most dramatic difference was after a significant dry period during the rainfall on June 13, 2008 where 134 mg/L was recovered from the control roof and 6 mg/L was recovered from the green roof. As shown by the TSS data for the control roof, the stormwater flushed the particles that had been atmospherically deposited, which leads to high TSS in the control roof runoff. However, the TSS results for the green roof were consistently at low levels (in most samples), thereby indicating that the green roof soil was able to hold these atmospherically deposited solids and prevent them from entering into the sewage system. This suggests that a green roof can act as a filter for atmospheric deposition.

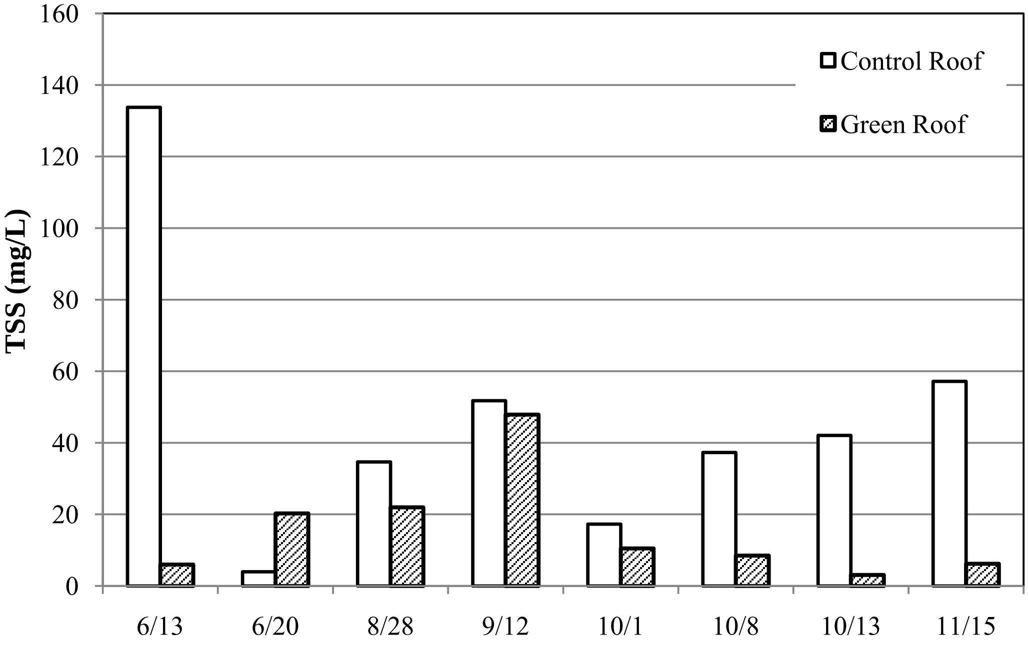

Figure 6-25 TSS results (Homestead, 2008)

Samples were acquired on dates shown.

Sulfate

The overall concentration of sulfate in green roof runoff was higher than that from control roof runoff. Unfortunately, these results may not be indicative of green roof performance in general because the building owner in the middle of July 2008 fertilized the Homestead green roof. The sulfate content of the thin green roof and control roof on the sampling dates are shown in Figure 6-26, with a large spike in sulfate caused by the fertilization coming off of the green roof that lasted for the three months and then returned to normal.

Compared to the thick green roof at Giant Eagle, there was overall fewer sulfates atmospherically deposited at Homestead as indicated from control roof runoff, but there were more sulfates in the green roof runoff which may have come from the thin roof substrate.

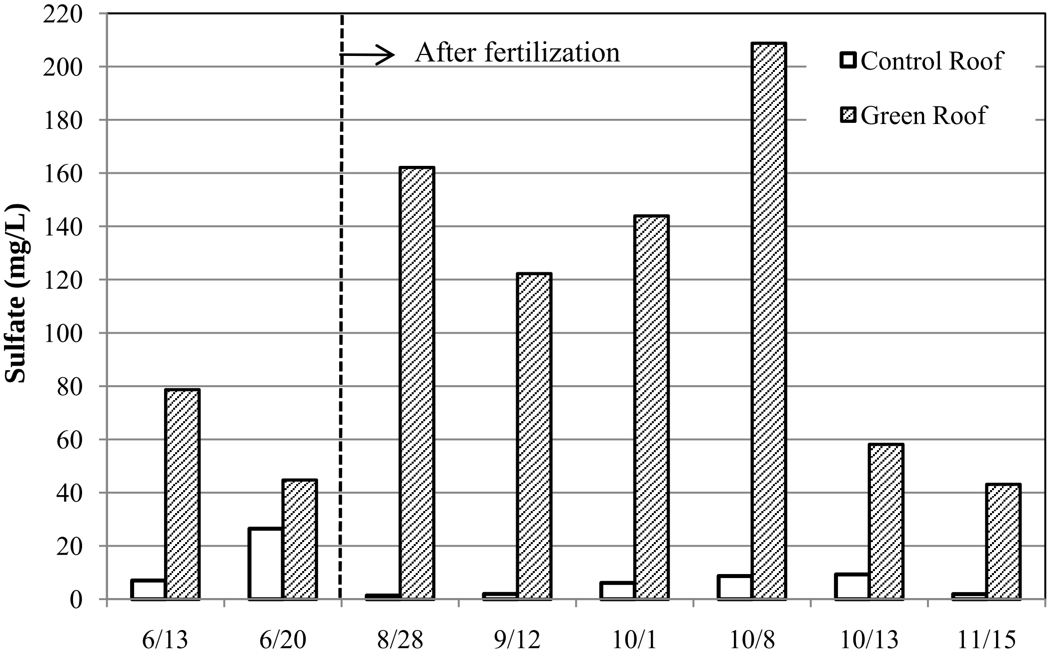

Figure 6-26 Sulfate results (Homestead, 2008)

*Dashed vertical line indicates the date that fertilizer was applied by the building owner to the green roof. Samples were acquired on dates shown.

Total Nitrogen

The nitrogen content of eight samples from Homestead during the 2008-growing season was measured. As shown in Figure 6-27, the first two samples show a significantly higher level than the rest of them. After the building owner fertilized the green roof in July 2008, the concentration of nitrogen in the samples was significantly reduced for both control and green roofs. No clear pattern for nitrogen in the runoff emerged; the nitrogen in the green roof runoff was higher during growing season but lower after mid-October than runoff from the control roof.

The trend of levels of nitrogen in the runoff appears to be opposite that of the trend observed for in sulfate. Nitrogen was depleted in the August samples and present at higher levels in the June and October samples whereas the opposite was true for sulfate. This is most likely due to the rapid growth of the plants after planting.

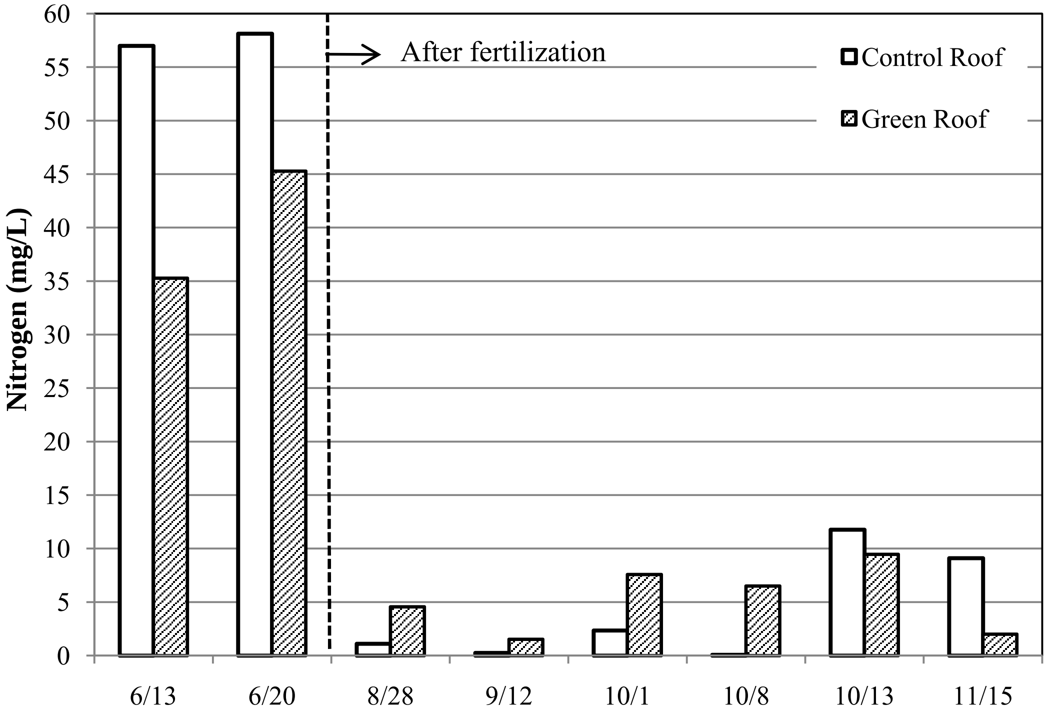

Figure 6-27 Nitrogen results (Homestead, 2008)

*Dashed vertical line indicates the date that fertilizer was applied by the building owner to the green roof. Samples were acquired on dates shown in the figure.

Total Phosphorous (Ortho and Polyphosphate)

The green roof consistently had higher phosphorous levels than the control roof in all runoff samples. Figure 6-28 shows the phosphorous content in the runoff samples from both control and green roof. The green roof had a total phosphate concentration of 10.7 mg/L for the August 28, 2008 sampling, whereas the highest phosphorus in the control roof runoff was 0.9 mg/L on the same day. The fertilization of green roof during July 2008 caused a significant increase in the concentration of phosphorus, which declined over the growing season, only to increase again in the fall.

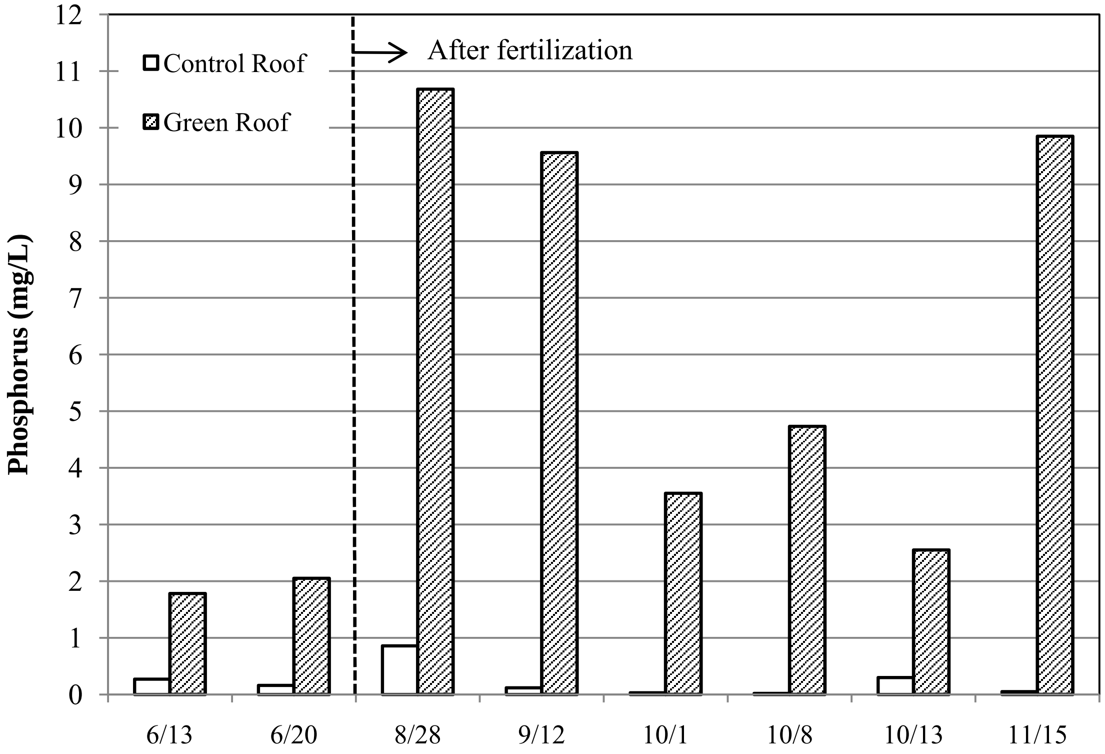

Figure 6-28 Phosphorus results (Homestead, 2008)

*Dashed vertical line indicates the date that fertilizer was applied by the building owner to the green roof. Samples were acquired on dates shown in the figure.

Chemical oxygen demand (COD)

The chemical oxygen demand for both green and control roof runoffs varied significantly. As seen in Figure 6-29, the COD in the Homestead green roof runoff was sometimes higher and sometimes lower than that from the control roof. Prior to fertilization by the building owner, control roof runoff samples had a higher COD concentration than that of the green roof. After fertilization, the green roof runoff had more COD, but it is not clear if the COD increase was caused by the fertilization as the COD from the control roof also varied significantly.

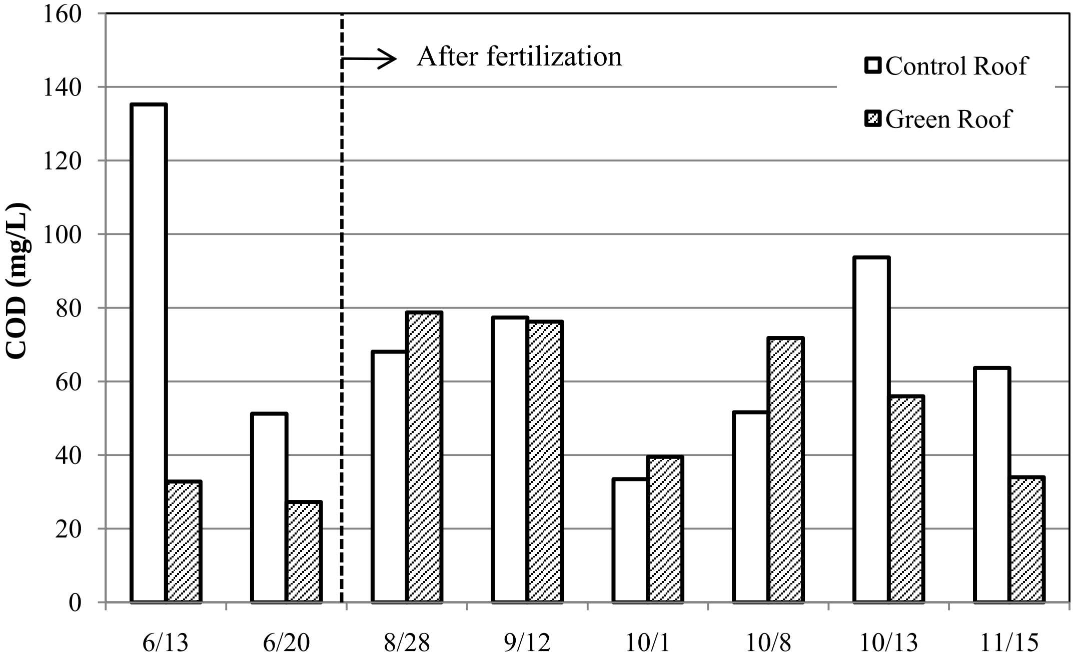

Figure 6-29 COD results (Homestead, 2008)

*Dashed vertical line indicates the date that fertilizer was applied by the building owner to the green roof. Samples were acquired on dates shown in the figure.

Metal ions

Metal ions include Cadmium, Lead and Zinc. However, the results came from the laboratory in Table 6-2 does not show significant features among these metal ions.

6.4.3 **Summary: Runoff samples from Giant Eagle**

Section 4.4 presented details of runoff water quality data from the Giant Eagle site during the course of a storm. The discussion below presents summary data for various runoff parameters so that the thick roof may be better compared to the thin roof.

The parameters utilized to evaluate the green roof runoff quality include pH, turbidity, sulfate, nitrogen, phosphorus and COD. Chemical analysis from samples collected during the course of selected rain events from the Giant Eagle site are reported above. The sulfate, nitrogen, phosphorus, COD measurements were performed on unfiltered and filtered samples. A summary of averaged filtered and unfiltered (*soluble and total*) runoff quality parameters from Giant is presented in Table 6-3 and shown on the figures below.

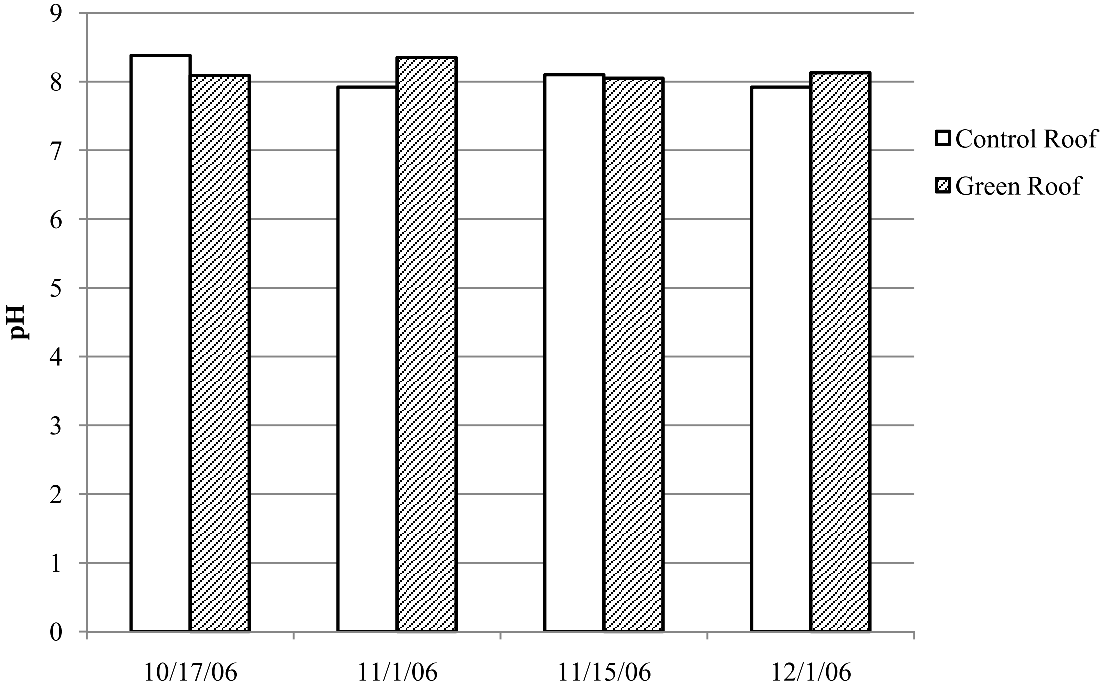

Figure 6-30 pH results (Giant Eagle, 2006)

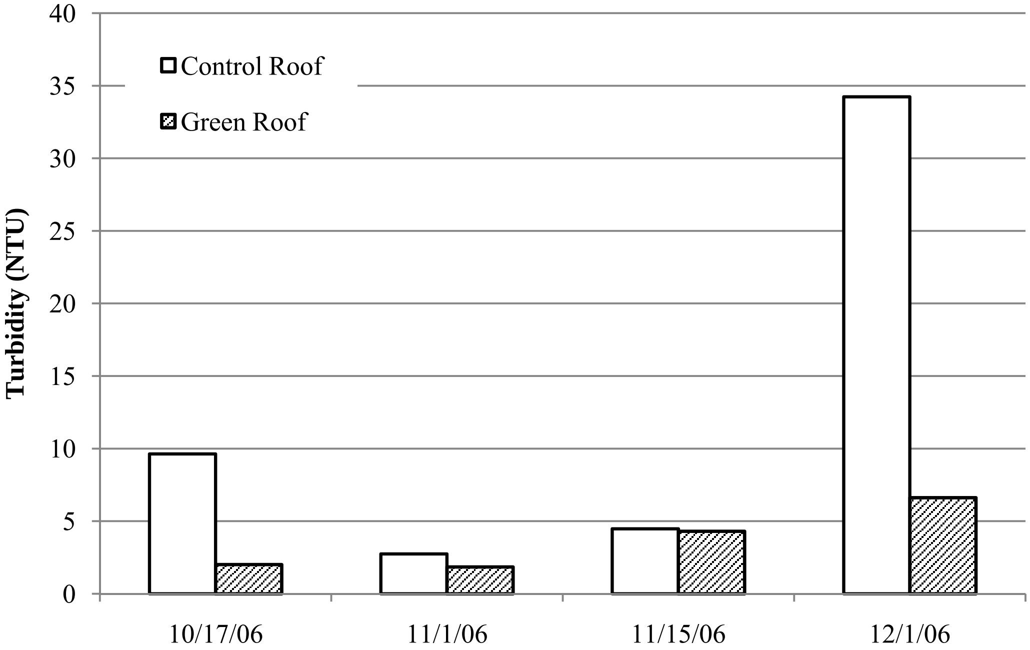

Figure 6-31 Turbidity results (Giant Eagle, 2006)

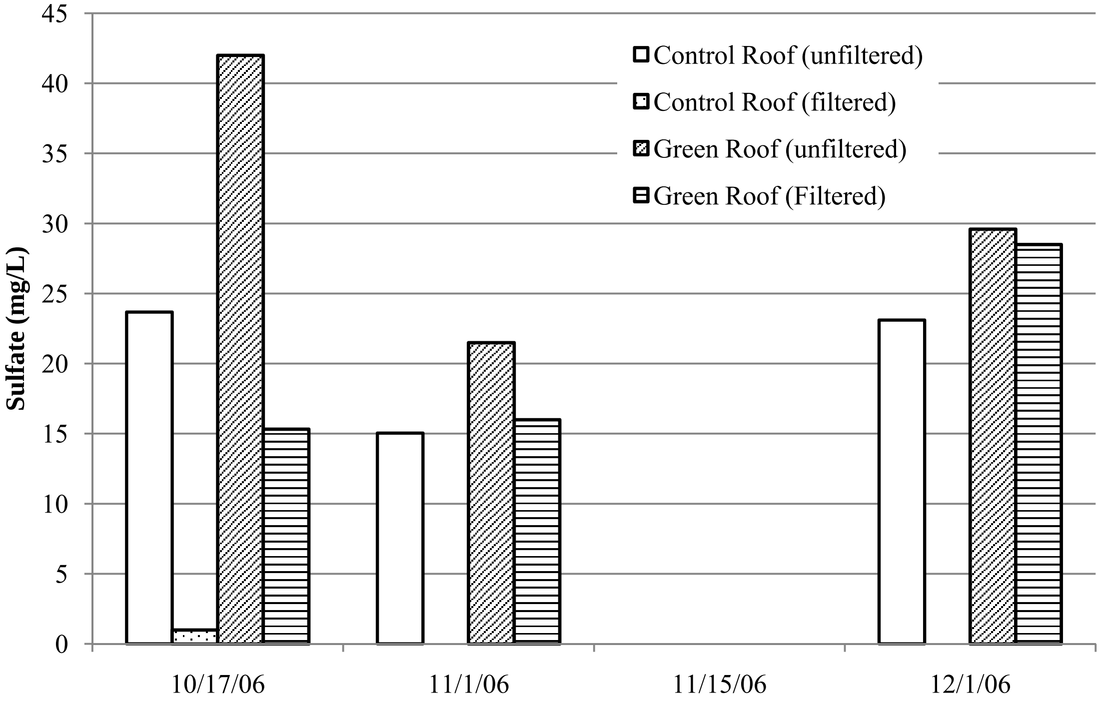

Figure 6-32 Sulfate results (Giant Eagle, 2006)

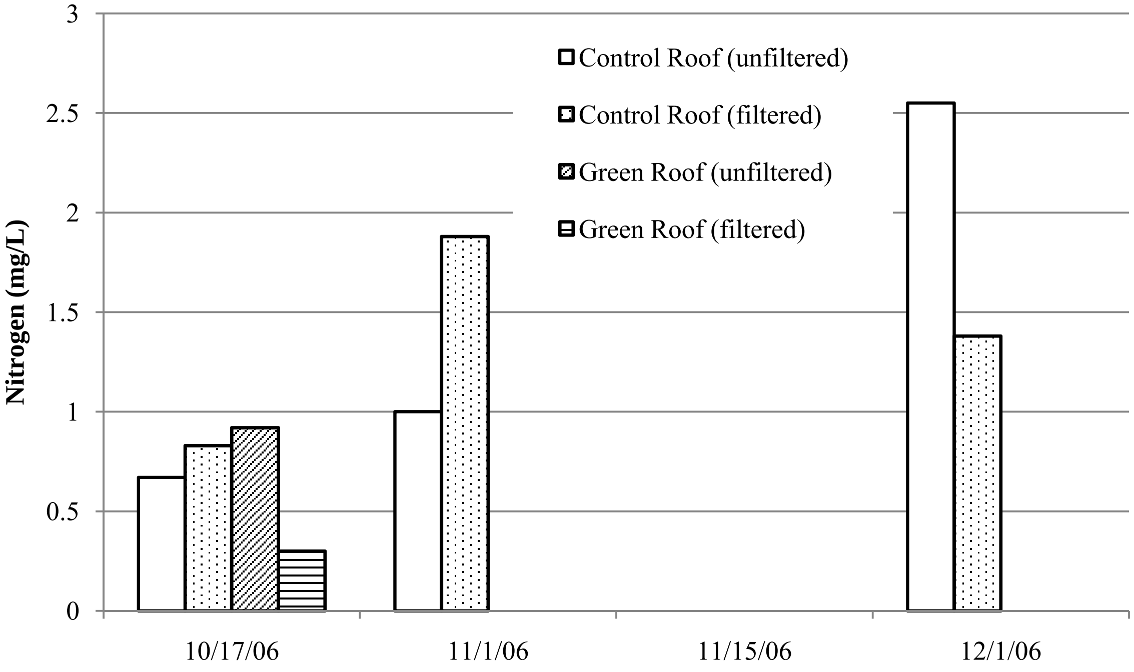

Figure 6-33 Nitrogen results (Giant Eagle, 2006)

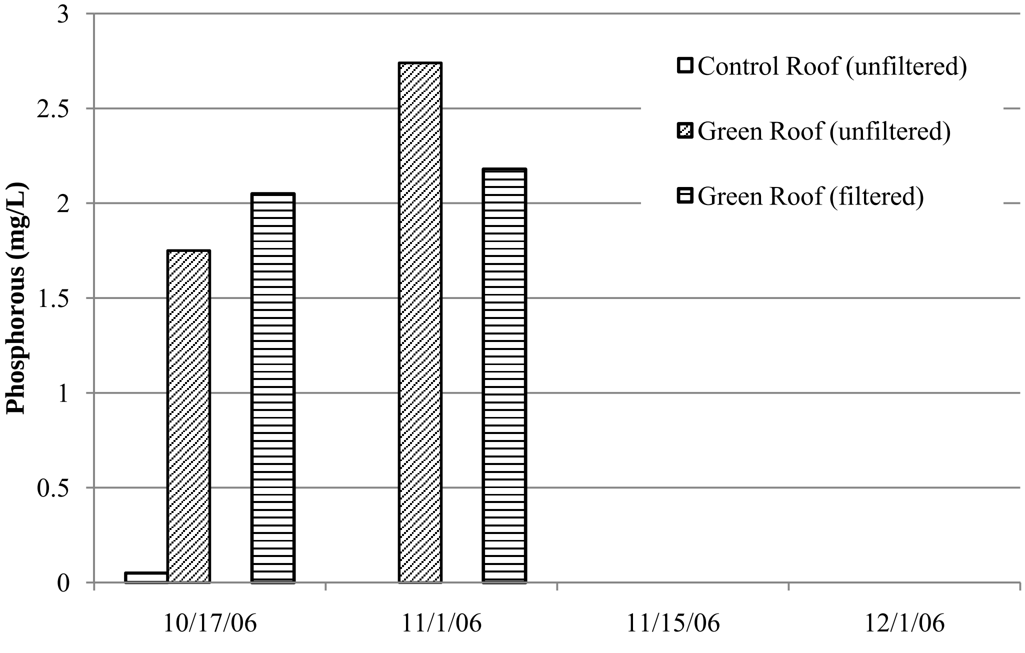

Figure 6-34 Phosphorus results (Giant Eagle, 2006)

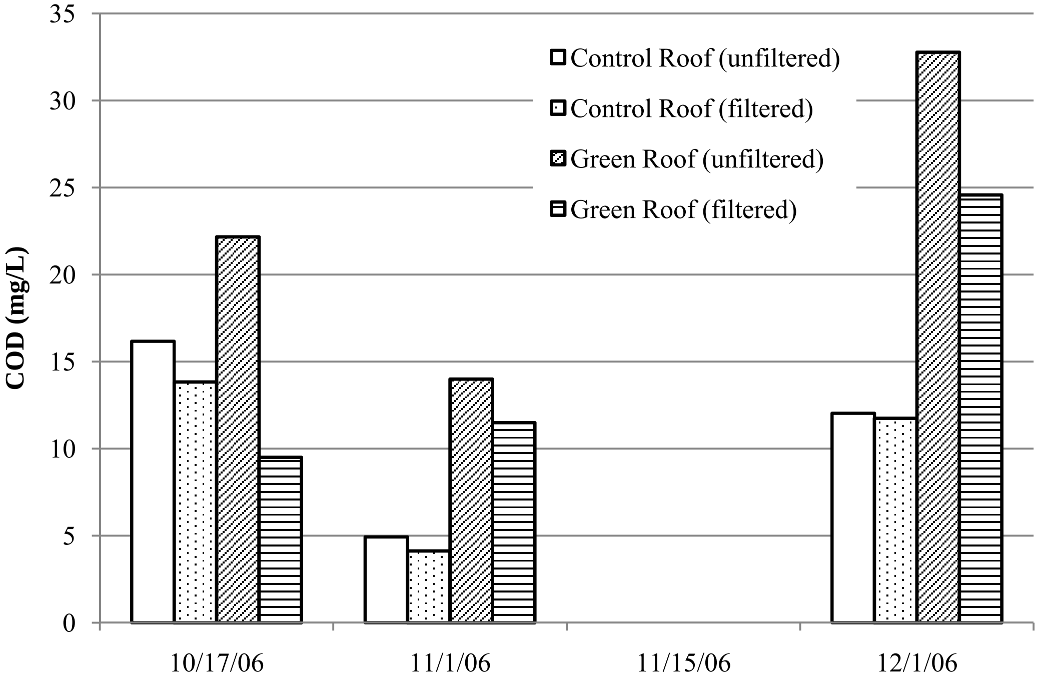

Figure 6-35 COD results (Giant Eagle, 2006)

6.4.4 **Comparative runoff quality**

It is important to know if the average values and standard deviations of runoff water quality are the same or altered by a green roof. To evaluate this question, hypothesis testing t-Test statistics at the 95% confidence level were utilized to compare the evaluated runoff water quality parameters for each green roof compared to its respective the control roof. The mean and standard deviation for each site was calculated and listed in Table 6-2 for the Homestead thin roof and for the Giant Eagle thick roof in Table 6-3. A summary of conclusions showing significant differences is in Table 6-4.

The principle used to identify the statistical differences is the t-value (|t|) and t-critical, which are listed on Table 6-2 and Table 6-3. The null hypothesis is made based on $\mu_{control} \neq \mu_{green}$ (μ is the mean value), as well as the alternative hypothesis is $\mu_{control} = \mu_{green}$. The t-value for two independent samples was calculated by using Minitab statistical software. If the t-value was less than the t-Critical, the results indicate there are significant differences between two samples at the 95% confidence level. If t-Ratio was more than the t-critical, no significant differences are existed between two samples.

As shown on summary Table 6-4, statistical evaluations show that there are a number of significant differences (at the 95% confidence level) that exist in the rainfall runoff quality between the thin green roof and membrane control roof at the Homestead. A similar analysis of the Giant Eagle green roof indicated no significant difference in runoff water quality with the exception of nitrogen and phosphorous.

As seen in Table 6-3, the rainfall runoff from the control roof (typical of rainfall) and runoff pH of the green roof Giant Eagle is alkaline (pH ~ 8.1). On the other hand, while the averaged control roof pH (rainfall pH) at Homestead was 5.3 (suggesting chronic acid rain) and green roof runoff pH was 6.5. This suggests a capability of engineered green roofs to attenuate the acidity resulting from acid rain deposition which occurs in some (but not all) parts of Allegheny County.

Total suspended solids and turbidity measure water quality relating to particulates in the runoff with no differentiation as to chemical properties of particulates. There were statistically significant differences in the Homestead measurements of TSS and turbidity, but not for the Giant Eagle samples (see Table 6-4). The Homestead site exhibited high concentrations of TSS in the runoff sample of control roof (Table 6-2**)**. The analysis shows that there was a significant difference between the green roof and control roof runoff quality with respect to suspended solids. This information strongly suggests that the green roof acts as a filter of atmospherically deposited particles.

There were some statistical differences in the results of sulfate, nitrogen and phosphorus testing at the two sites; however, the fertilization of the Homestead roof by the building owner that was done in July 2008 significantly affected the number of valid results and made drawing conclusions based on statistically significant differences impossible. The results of COD at either Giant Eagle or Homestead do not show any significant differences between the control and green roof. Metals were detected at very low levels in the runoff, such that statistical analysis of the metal ions Cadmium, Lead and Zinc indicate significant differences between control and green roof at both sites for these metals.

Table 6-2 Chemical parameters and t-statistics of runoff for control and green roof at Homestead site (2008)

Chemical parameters	**Roof type**	**6/13/08**	**6/20/08**	**8/28/08**	**9/12/08**	**10/1/08**	**10/8/08**	**10/13/08**	**11/15/08**	**Average**	**Stdev.**	**t-value**	**t-critical**
pH	Control	5.1	5.5	5.3	5.3	5.6	5.2	5.5	5.1	5.3	0.2	10.4	1.8
	Green	6.4	6.3	6.8	6.2	6.8	6.7	6.3	6.3	6.5	0.2		
TSS (mg/L)	Control	133.8	4	34.7	51.8	17.3	37.3	42.1	57.2	47.3	39.0	2.2	
	Green	6	20.3	22	47.9	10.5	8.5	3.1	6.2	15.6	14.7		
Sulfate (mg/L)	Control	7	26.5	1.38	2	6.1	8.7	9.3	1.9	7.9	8.2	4.6	
	Green	78.7	44.8	162.2	122.3	144	208.8	58.2	43.2	107.8	61.1		
Nitrogen (mg/L)	Control	56.98	58.11	1.1	0.25	2.34	0.08	11.77	9.1	17.5	25.1	0.3	
	Green	35.28	45.28	4.56	1.53	7.58	6.51	9.47	2.01	14.0	16.6		
Phosphorus (mg/L)	Control	0.27	0.16	0.86	0.12	0.03	0.02	0.3	0.05	0.2	0.3	4.0	
	Green	1.78	2.05	10.68	9.56	3.55	4.73	2.55	9.85	5.6	3.8		
COD (mg/L)	Control	135.24	51.24	68.04	77.34	33.44	51.61	93.67	63.67	71.8	31.4	1.5	
	Green	32.84	27.24	78.75	76.25	39.53	71.79	56	34	52.1	21.3		
Cd (mg/L)	Control	ND*	ND	0.07	ND	ND	ND	ND	ND	N/A	N/A	N/A	
	Green	ND	ND	0.04	ND	ND	ND	ND	ND				
Pb (mg/L)	Control	ND	ND	ND	ND	ND	ND	ND	ND	N/A	N/A	N/A	
	Green	ND	ND	ND	ND	ND	ND	ND	ND				
Zn (mg/L)	Control	0.08	0.15	0.37	0.53	0.36	0.39	0.59	0.2	0.3	0.2	0.8	
	Green	0.38	0.45	0.04	0.5	0.29	0.25	0.11	0.13	0.3	0.2		

ND: not detected

Dates shown are when the samples were acquired.

Table 6-3 Chemical parameters and t-statistics of runoff for control and green roof at Giant Eagle

Chemical Parameters	Roof Type		10/17/06	11/1/06	11/15/06	12/1/06	Mean	S.D.[9]	t-value	t-Critical
pH	Control		8.4	7.9	8.1	7.9	8.1	0.22	0.59	1.94
	Green		8.1	8.4	8.1	8.1	8.2	0.13		
Turbidity (NTU)	Control		9.6	2.8	4.5	34.2	12.8	14.6	1.23	1.94
	Green		2.0	1.9	4.3	6.6	3.7	2.3		
Sulfate (mg/L)	Unfiltered	Control	24	15.		23	20.6	4.83	1.59	2.13
		Green	42	22		230	31.0	10.32		
	Filtered	Control	23	31		19	24.09	6.12	0.75	2.13
		Green	15	16		29	19.94	7.42		
Nitrogen (mg/L)	Unfiltered	Control	0.7	1		2.6	1.41	1.00	1.68	2.13
		Green	0.9	0		0	0.31	0.53		
	Filtered	Control	0.9	1.9		1.4	1.36	0.53	3.96	2.13
		Green	0.3	0		0	0.15	0.17		
Phosphorus (mg/L)	Unfiltered	Control	0.05	0			0.03	0.04	4.48	2.92
		Green	1.75	2.74			2.25	0.70		
	Filtered	Control	0	0			0.00	0.00	N/A	N/A
		Green	2.05	2.18			2.12	0.09		
COD (mg/L)	Unfiltered	Control	16.2	4.9		12.	11.04	5.68	1.88	2.13
		Green	22.2	14.		32.8	22.98	9.42		
	Filtered	Control	13.8	4.1		11.8	9.90	5.11	0.95	2.13
		Green	9.5	11.5		24.6	15.19	8.19		
Cd (mg/L)	Control		0	0		0	0.00	0.00	N/A	N/A
	Green		0	0		0	0.00	0.00		
Pb (mg/L)	Control		0.08	0.3		0.2	0.19	0.11	0.49	2.13
	Green		0.53	0.07		0.2	0.27	0.24		
Zn (mg/L)	Control		0.09	0.13		0.08	0.10	0.03	0.83	2.13
	Green		0.24	0.22		0.02	0.16	0.12		

Mean values computed before rounding off of individual entries.

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[9] S.D. = Standard deviation

Table 6-4 Summary of Statistical results of runoff quality (Homestead and Giant Eagle)

	Homestead *(thin roof technology)*		**Giant Eagle** *(thick roof technology)*		
Chemical parameters	**Roof type**	**Significant Difference?**	**Roof Type**		**Significant Difference?**
pH	Control	YES	Control		NO
	Green		Green		
TSS (mg/L) - Homestead; Turbidity(NTU) - Giant Eagle	Control	YES	Control		NO
	Green		Green		
Sulfate (mg/L)	Control	YES	Unfiltered	Control	NO
				Green	
	Green		Filtered	Control	NO
				Green	
Nitrogen (mg/L)	Control	NO	Unfiltered	Control	NO
				Green	
	Green		Filtered	Control	YES
				Green	
Phosphorus (mg/L)	Control	YES	Unfiltered	Control	YES
				Green	
	Green		Filtered	Control	ND
				Green	
COD (mg/L)	Control	NO	Unfiltered	Control	NO
				Green	
	Green		Filtered	Control	NO
				Green	
Cd (mg/L)	Control	ND	Control		ND
	Green		Green		
Pb (mg/L)	Control	ND	Control		NO
	Green		Green		
Zn (mg/L)	Control	NO	Control		NO
	Green		Green		

ND: Not detected

The statistical results are based on T-tests conducted at the 95% confidence level and evaluate if there is a significant difference between the green roof and control roof runoff quality.

7. SUMMARY OF EXPERIMENTS

This report presents the use of a green roof compared to a conventional (control) membrane roof using modern construction methods. A green roof has many environmental, economic, and aesthetic benefits over a conventional roof. This study examined the environmental benefits of a thick and a thin green roof, with focus on stormwater management and thermal benefits. The results demonstrated that in comparison to the conventional roofs, green roofs retained significantly more water, moderated temperature increases and decreases of the roof, and had marginal effect on the chemistry of the discharged runoff. Two different technologies of green roofs were analyzed and the enhanced performance of two green roofs over their associated conventional roof was found to depend on soil (roof) thickness. Concise descriptions and major distinctions between a control roof and green roof, and comparisons of thick and thin green roof technologies are summarized in Table 7-1 and Table 7-2 of this summary.

Monitoring systems were developed to capture the water flows and temperature profiles of both the green roof and control roof. The monitoring systems captured electronic data from sensors and transmitted them to the University of Pittsburgh via modem and electronic network. The portion of the roof at Giant Eagle devoted to this research had conventional and green roof segment of sizes 3,520 square feet each while both the conventional and green roofs at Homestead were approximately 2,000 sq. ft. each. The monitoring systems at two sites included (*for green and control roofs*) separate flumes (at Giant Eagle) or weir boxes (at Homestead) ultrasonic sensors; soil moisture sensors, rain gauge, thermocouples, temperature probes, and net radiometers to measure the runoff and thermal performance of the two roof types over time. Runoff water samples from each roof were collected at both sites and tested in the laboratory for water quality characteristics. The system was implemented and environmental data was collected continuously over a first seven-month period from July 2006 through January 2007 at the Giant Eagle location. This phase encompassed periods of summer, fall, and winter climate conditions. A total of 24 storms, ranging from 0.07 inches to 2.2 inches, occurred during that test period, and the chemical data from most storms was captured during the first phase. A second phase of the study was implemented from April 2008 through April 2009 monitoring both the Homestead and Giant Eagle sites. In sum total, the sensors and data loggers at the two sites recorded 95 storms ranging from 0.02 inches to 2.42 inches of precipitation.

Table 7-1 General Characteristics of the Control and Green roof

	Green roof	Control roof
Runoff quantity performances	1% to 100% of overall flow rate reduction (compared to control roof) observed – high percent under light storm and low percent under heavy storm	Usually has a higher peak flow rate than green roof, but became less different for heavy storm and high soil moisture content
	2% to 100% reduction of total runoff volume (compared to control roof) – green roof retained all the stormwater for 100%	Usually in a higher level runoff than the runoff for green roof – more stormwater discharged from control roof
	Comparing with control roof, initial runoff retardation is ranged from 0 to 16.7 hours. Time delay of maximum peak flow is between 0 to 16 hours. Runoff discharge begins after 0.035-0.6 inches of water released from control roof, depending on soil moisture condition.	Runoff water started to discharge in a short time after occurrence of rainfall.
	The soil moisture content, soil thickness as well as the extent of rainfall influenced runoff quantity performances of green roof.	
Thermal performances	Approximately 90°F (or below) of surface temperature observed on a hot summer day	Approximately 100°F (or above) of surface temperature observed on a hot summer day
	Experience less thermal fluctuation from day to night; protect roof membrane and reduce its thermal stress during days with high ambient temperature	Large thermal fluctuation from day to night, particularly during summer. Exposure of the roof membrane to ambient conditions may reduce its usage life
	Solar energy absorbed by the system and for photosynthesis by the vegetation. Water trapped in soil can be evaporated resulting in cooling.	Reflect more solar energy to the atmosphere and may result in an urban heat island effect.
	During the night in summer, the green roof had a slightly higher roof membrane surface temperature than the control roof, which indicates that a green roof releases heat slowly.	
Runoff quality performances	No first flush detected	
	Neutralize the acidic rainfall (Homestead); act as a filter for pollutant particles from atmosphere	No change in water runoff quality. Direct flow to the roof drain.
	Fertilization during the summer of 2008 by the owner of the Homestead green roof influenced the runoff quality results.	

Table 7-2 Characteristic differences between the thin and thick Green roof technologies

<table>
<tr><th></th><th>Thin roof (Homestead)</th><th>Thick roof (Giant Eagle)</th></tr>
<tr><td>General features</td><td>Thickness of soil medium: 1 ½ inches
Manufacturer: Green Living Technology
Type of plants: a mix of sedum kamtschaticum,worm grass sedum and thymus x citriodorus</td><td>Thickness of soil medium: 4 ½ inches.
Manufacturer: The Garland Company.
Type of plants: a mix of sedum acre,album, sexagular, kamtschaticum, etc.</td></tr>
<tr><td rowspan="3">Runoff quantity performance</td><td>For total runoff volume, more stormwater discharged under dry soil condition, due to the limited soil thickness and retention capacity.</td><td>For total runoff volume, large capacity of water retention under dry soil condition, due to an additional 4-inches of soil thickness as compared to the thin roof.</td></tr>
<tr><td>Initial runoff retardation is ranged from 0 to 8.7 hours. Significant retardation of time of maximum peak flow for initially dry soils.</td><td>Initial time of retardation of runoff ranged from 0 to 16.7 hours. Significant retardation of time of maximum peak flow for initially dry soils.</td></tr>
<tr><td colspan="2">For initially wet soils: small differences in time of runoff or retardation of peak flow were observed between thin and thick roofs.</td></tr>
<tr><td rowspan="2">Thermal performances</td><td>Reflect less heat and lower ambient temperature; less insulation effect between the roof surface and roof deck below</td><td>Better insulation effect due to the thicker soil substrate.</td></tr>
<tr><td colspan="2">No significant differences in thermal performance between the two green roofs were found during cold weather months.</td></tr>
<tr><td>Runoff quality performances</td><td colspan="2">The runoff samples from two sites indicated different rainfall pH; however metal constituents were marginally less at Giant Eagle. No statistically significant differences were observed in runoff quality at either green roof except of N & P.</td></tr>
</table>

8. CONCLUSIONS

Part I: Water Quality Results

The results of two green roof studies indicate the potential of green roofs as an effective system in stormwater management. The benefits of a green roof over the conventional membrane "control roof" are as follows:

1. The peak flow rate (normalized as *cubic feet per second of flow per unit roof area*) from the green roof was lower than the control roof in most cases.

In the first study phase, the reduction of the runoff from the thick (Giant Eagle) green roof as compared to the control roof was between 5 to 70%. The peak flow rate reductions during the second study phase were in a ranged from 1% to 100%. The highest comparative reduction in flow rate occurred during light storms while smaller flow rate reductions occurred under heavy storm conditions.

A graphic relationship of the water runoff parameters considered being of importance for this research is shown on the sketch of Figure 8-1. The dashed line represents a typical runoff flow rate of control roof and the solid line represents the green roof runoff flow rate. The designations "A, B and C" are three significant performance parameters of (A) time of initial runoff retardation, (B) time of peak runoff retardation and (C) magnitude of differences in normalized quantities peak runoff flow rates.

For most rainfall events, both the time of occurrence and magnitude of green roof runoff water flow rates are attenuated as compared to control roof flow rates. This observation however was highly dependent on the soil moisture content (relating to time of occurrence of the previous storm event) and overall magnitude of rainfall precipitation. There was virtually no difference between the green roof water retardation of retention capability once the soil reached water saturation (due to heavy and/or prolonged rain fall events).

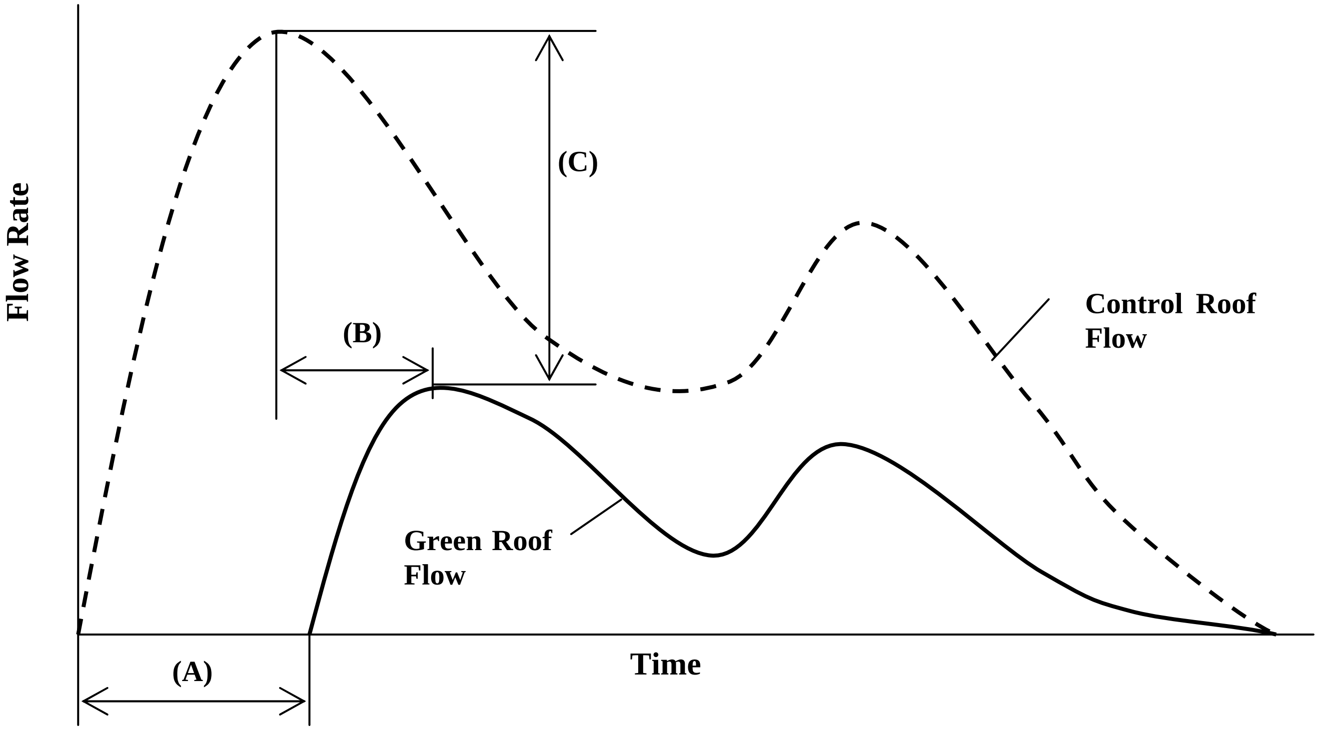

Figure 8-1 Runoff parameters of importance: control and green roof discharges.

(A) Initial runoff retardation: the time difference between which green roof starts discharges stormwater and control roof starts to discharge;

(B) Maximum peak flow retardation: the difference in time between the control roof and the green roof of occurrence of normalized maximum peak flows.

(C) Maximum normalized peak flow rate variation: the difference in maximum peak normalized flow rates between the control roof runoff and green roof runoff.

2. The total quantity of runoff from the green roof was dependent on the soil moisture, the intensity, and duration of the storm. As soil moisture content increased, the capacity of the green roofs to retain water decreased. For heavy storms, the reduction in total flow was less than that under lighter storms, but the reduction was still observable. The reduction observed in both study phases ranged from 100% for the lightest storm to 2% for the heaviest. A reduction of 20% in the total runoff volume was observed in several large storms. For smaller storms (usually less than 0.1 inch of precipitation or slightly higher) where the soil was dry, 100% of reduction of the total runoff volume was often observed. In these cases, the green roof was able to absorb all the stormwater and no runoff was measured.

3. The thickness layer of soil media as well as soil moisture of the green roof impacts the capacity of stormwater retention. Under dry soil conditions, the thick roof (at the Giant Eagle site) retained more water than the thin roof (at the Homestead site). A larger mass of dry soil (from a thicker soil layer) has more available capacity (field capacity) for water retention. However, as the soils became saturated, any

additional water that fell on the green roof soil was discharged and little differences in further water retention are observed.

The water cup reservoir specifically incorporated into the thin roof technology is designed to retain part of the stormwater and may yield additional water storage capacity, but this effect was minimally observable. The water cup reservoir, however, can provide moisture during prolonged drought conditions for the plants on the thin roof, and thus has an important benefit.

4. The time of initial discharge from green roof was significantly delayed relative to the initial time of discharge from the control roof. The average retardation time for green roof runoff under dry soil condition was 3 hours behind the control roof runoff and only 1.5 hours under wet soil condition.

It was observed that towards the end of a storm, the runoff from green roof has a prolonged tail consisting of a very low flow rate that did not occur for the control roof. This tailing of flow occurred for a significant amount of time after rain ceased and the runoff from the control roof stopped.

Part II: Temperature Profile Results

There are significant benefits in reduced heat gain and loss that are observed to be a function of roof type and thickness. The most significant results are:

1. The temperature profile shows the stone ballast covering the "rubber" membrane on the control roof at Giant Eagle cannot protect the membrane from the ambient conditions and incoming radiation. Despite the light color of the stone ballast on the roof surface, that membrane surface reached extreme temperatures on a hot summer day. During summer time, the control roof surface reached a temperature above 100°F when the ambient temperature is close to 90°F. The green roof surface temperature remained at or below 90°F during the day, which was about the same as ambient temperature.

The green roof provided protection to the roof membrane and reduced the thermal stress on the roof membrane during days with ambient temperatures greater than 75°F. During summer nights, the green roof temperature closely followed the ambient temperature. These observations suggest that the green roof has the ability to absorb and release of energy that it was exposed to during the day.

2. Temperature profiles show that the wintertime surface temperature of the green roof and control roof exhibited little difference during the day when the sun shines. During the night, however, the green roof was able to retain a portion of the heat it absorbed during the day. Although the temperature profiles suggest that the thermal benefits of the green roof in winter is not as significant as it is the summer, the green roof was able to save a small amount of energy by showing reduced heat loss in comparison to the control roof.

3. The net radiation at the site was observed to influence the roof performance. In the summer and fall when the roof is exposed to 400-800 $W*m^{-2}$ net of incoming radiation throughout the day, the control roof easily stores this energy, while the soil and plants on the green roof store and use that energy. The data from the summer and fall indicate that the green roof shows slightly higher positive radiation during the day, meaning the green roof is reflecting less energy during the day, and slightly higher negative radiation at night, meaning the green roof is releasing less energy at night. This suggests there is significant potential for green roofs in mitigating the urban heat island effect. During the winter the two roofs perform nearly the same as the short days, lower sun, and shading by the apartment building greatly limited the energy transfer during the day.

Part III: Water Quality Considerations

Runoff water quality results for the green roof and associated control roof are compared. In addition, T-statistics at the 95% confidence level are utilized to evaluate if the green roof and control roof runoff water quality concentration differences are statistically significant. This is done for both locations. The major conclusions drawn from this information are:

1. No "first flush" effect (*elevation in contaminant level during the initial water runoff)* for the green roof was observed for any test parameter. The "first flush" effect was noticeable for the control roof.

2. There was a significant difference between the green roof and control roof pH at the Homestead site indicating the ability of that green roof to neutralize acidic stormwater (*from acid rain falling at that location*).

3. There is a statistically significant difference in total suspended solids (TSS) between the control and green runoff samples at Homestead, with a relatively lower concentration coming from the green roof. There was not such a difference observed at the Giant Eagle site for TSS.

4. The results of Chemical Oxygen Demand (COD) at Giant Eagle or Homestead sites do not show any significant differences between the control and green roof. Metal ions were not detected at significant levels from runoff samples with the exception of zinc.

5. Chemical fertilization of the Homestead green roof by the building owner during the latter part of the project period was observed to influence green roof runoff water quality. All nutrient contaminants in runoff waters from the Homestead green roof show a significant increase in concentration after fertilization; however, the foliage appeared beautiful.

In summary, green roof technology is an effective and practical way to improve the stormwater management, thermal performance, as well as stormwater quality. The body of the report document provides supporting data and analysis leading to technical insights for the use of this "green" technology for urban stormwater management.

9. SUGGESTIONS FOR FURTHER STUDIES

The results of this project demonstrate a methodology for the quantitative collection of engineering and performance-verification information for the application of green roof technologies. Implementation of green roof technologies can contribute to helping resolve the "combined sewer overflow" issue in many urban areas in addition to contributing to esthetic and heat island improvements.

During the course of research, several suggestions for improvement for future investigators became apparent.

- If possible, measurements of water flows using flumes (as at Giant Eagle) are preferable to the use of weir boxes (as at Homestead). Weir boxes inherently have standing water which flumes do not. Furthermore, weir boxes can readily overflow and spill water at high storm intensities resulting in loss of flow measurements.

  (Loss of water under these conditions is noted in Table I-1 where negative values in the column of "V_G/V_C" are shown.)

- Vendors of green roofs inherently provide irrigation systems (or sprinklers) to assure plant growth, and to avoid possible desiccation. This research was able to determine runoff due to such irrigation, however, better means of communication regarding periods of irrigation should be done for future researchers.

- Fertilization on a research monitored green roof should be avoided if a stormwater quality study is involved, since the components of the fertilizer will influence the results of some chemical parameters.

- Field and roof monitoring equipment that is exposed to year-round weather elements for several consecutive years need superior protection against rain, snow and extreme heat and possible vandalism (*vandalism was not noted during this research*). In addition, periodic metal wire corrosion was observed and contributed to instruments malfunctioning and added maintenance. Weatherproofing of all electrical signal contacts is essential.

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APPENDICES

In the section, tables and graphs for runoff and thermal performance from both Homestead and Giant Eagle site are exhibited, which were not presented in the main body of the report. The appendix is divided into two subsections, including runoff performances and temperature profiles for both control and green roof.

APPENDIX I. STORMWATER RUNOFF DATA

Control and green roof runoff data acquired during the time period from April 20, 2008 to April 30, 2009 for individual storm events from both Homestead and Giant Eagle locations are presented in the following tables and graphs.

Table I-1 Flow Rate and runoff volumes for individual rainfall events

				Maximum Peak Flow Rate (cf/s)			Maximum Peak Flow retardation (hr)	Initial runoff retardation (hr)	Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		Water Retained (%)
	Location	Rainfall (in)	Soil Condition	Control	Green	% Reduc.			Control	Green	V_G/V_R	V_G/V_C	
4/20/2008	Homestead	0.57	Dry	0.0058	0.0035	40%	5	2.0	42.52	23.37	49%	55%	51%
	Giant Eagle		Dry	0.0116	0.0082	29%	3	4.0	62.28	26.79		43%	
4/28/2008	Homestead	1.04	Dry	0.0107	0.0084	21%	3	3.5	83.68	68.76	79%	82%	21%
5/7-5/8, 2008	Homestead	0.43	Dry	0.0091	0.0044	52%	0	8.7	32.65	6.23	17%	19%	83%
	Giant Eagle		Dry	0.0125	0.0022	82%	1	6.9	45.83	3.72		8%	
5/9-5/10, 2008	Homestead	1.25	Wet	0.0130	0.0117	10%	0	2.7	101.77	82.47	79%	81%	21%
	Giant Eagle		Wet	0.0251	0.0214	15%	0	1.3	92.21	83.18		90%	
5/11-5/12, 2008	Homestead	0.57	Wet	0.0135	0.0034	75%	0	3.1	44.79	19.76	42%	44%	58%
	Giant Eagle		Wet	0.0121	0.0096	21%	0	0	46.01	36.67		80%	
5/17/2008	Homestead	0.12	Dry	0.0234	0.0034	85%	0	3.0	10.00	1.71	11%	17%	89%
	Giant Eagle	0.2	Dry	0.0046	0.0024	48%	0	1.7	7.04	2.99	18%	42%	82%
5/18/2008	Homestead	0.18	Wet	0.0129	0.0057	56%	0	0	11.84	6.63	21%	56%	79%
	Giant Eagle	0.47	Wet	0.0096	0.0085	12%	0	0	32.85	27.87	71%	85%	29%
5/31/2008	Homestead	0.3	Dry	0.0075	0.0011	85%	1	1.7	25.00	2.06	8%	8%	92%
	Giant Eagle	0.17	Dry	0.0030	0	100%			6.10	0	0	0	100%
6/3-6/4, 2008	Homestead		Dry	0.0038	0.0019	51%	16	1.3	20.29	3.10		15%	
	Giant Eagle	0.98	Dry	0.0145	0.0029	80%	1	16.7	65.07	3.71	5%	6%	95%
6/5/2008	Homestead	0.15	Wet	0.0035	0.0022	38%	0	0.6	12.50	2.06	16%	16%	84%
	Giant Eagle	0.15	Wet	0.0084	0.0032	61%	0	0	11.27	4.21	34%	37%	66%
6/13-6/14, 2008	Homestead	2.25	Dry	0.0333	0.0174	48%	10	0	68.81	55.42	30%	81%	70%
	Giant Eagle	1.65	Dry	0.0208	0.0096	54%	16	10.3	91.92	36.11	26%	39%	74%

Table I-1 (continued)

				Maximum Peak Flow Rate (cf/s)			Maximum Peak Flow retardation (hr)	Initial runoff retardation (hr)	Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		Water Retained (%)
	Location	Rainfall (in)	Soil Condition	Control	Green	% Reduc.			Control	Green	V_G/V_R	V_G/V_C	
6/16/2008	Homestead	0.16	Wet	0.0077	0.0003	96%	0	0	13.33	0.18	1%	1%	99%
	Giant Eagle	0.16	Wet	0.0014	0	100%			1.83	0	0%	0%	100%
6/20/2008	Homestead	0.25	Dry	0.0166	0.0023	86%	0	2.1	20.83	1.67	8%	8%	92%
6/21/2008	Homestead	0.21	Wet	0.0042	0	100%			17.50	0	0%	0%	100%
	Giant Eagle	0.11	Dry	0	0				0	0			100%
6/22-6/23, 2008	Homestead	0.56	Wet	0.0114	0.006729	41%	0	0	46.67	12.87	28%	28%	72%
	Giant Eagle		Wet	0.0260	0.00167	94%	1	0	33.77	2.55	4%	8%	96%
6/26-6/27, 2008	Homestead	1.39	Dry	0.0256	0.0091	64%	0	1.9	43.66	35.36	28%	81%	72%
	Giant Eagle		Dry	0.0258	0.0207	20%	0	1.8	122.46	92.73		76%	
6/28/2008	Homestead	0.37	Wet	0.0244	0.0077	69%	0	0	30.83	7.76	25%	25%	75%
	Giant Eagle		Wet	0.0156	0.0087	44%	0	0	23.69	14.11	35%	60%	65%
6/29/2008	Homestead	0.49	Wet	0.0257	0.0151	41%	0	0	40.83	22.06	54%	54%	46%
	Giant Eagle	0.4	Wet	0.0075	0.0061	19%	0	0	16.88	11.41	34%	68%	66%
6/30-7/1, 2008	Homestead	2.16	Wet	0.0407	0.0367	10%	0	0	106.00	136.79	76%	-29%	24%
	Giant Eagle	0.69	Wet	0.0132	0.0123	7%	0	0	35.90	29.79	52%	83%	48%
7/3/2008	Homestead		Wet	0.0042	0.0038	9%	0	0	23.74	9.24		39%	
	Giant Eagle	0.35	Wet	0.0064	0	100%			17.79	0	0%	0%	100%
7/4/2008	Giant Eagle	0.05	Wet	0	0				0	0			100%
7/7/2008	Giant Eagle	0.69	Dry	0.0217	0.0143	34%	0	0	32.71	20.91	36%	64%	64%
7/8-7/9, 2008	Giant Eagle	0.56	Wet	0.0207	0.0123	40%	0	0	28.58	20.06	43%	70%	57%

Table I-1 (continued)

	Location	Rainfall (in)	Soil Condition	Maximum Peak Flow Rate (cf/s)			Maximum Peak Flow retardation (hr)	Initial runoff retardation (hr)	Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		Water Retained (%)
				Control	Green	% Reduc.			Control	Green	V_G/V_R	V_G/V_C	
7/20/2008	Homestead	0.54	Dry	0.0402	0.0147	64%	0	6.9	27.06	12.99	60%	48%	40%
	Giant Eagle	0.09	Dry	0	0				0	0	0%	0%	100%
7/21/2008	Homestead	0.27	Wet	0.0309	0.0078	75%	0	0	15.31	5.75	31%	38%	69%
	Giant Eagle	0.22	Dry	0.0045	0	100%			5.35	0	0%	0%	100%
7/22/2008	Homestead	0.09	Wet	0.0013	0	100%			0.96	0	0%	0%	100%
	Giant Eagle	0.08	Wet	0.0035	0	100%			6.23	0	0%	0%	100%
7/23/2008	Homestead	0.28	Wet	0.0155	0.0030	81%	0	7.6	11.24	2.00	9%	18%	91%
	Giant Eagle	0.33	Wet	0.0084	0	100%			12.39	0	0%	0%	100%
7/27/2008	Homestead	0.02	Dry	0.0022	0	100%			0.68	0	0%	0%	100%
7/30/2008	Homestead	0.47	Dry	0.0496	0.0054	89%	0	0	23.07	7.44	19%	32%	81%
	Giant Eagle	0.84	Dry	0.0720	0.0068	90%	0	0	43.72	7.44	11%	17%	89%
8/5/2008	Homestead	0.08	Dry	0	0				0	0	0%	0%	100%
	Giant Eagle	0.49	Dry	0.0131	0	100%			30.19	0	0%	0%	100%
8/6/2008	Homestead	0.14	Dry	0.0096	0	100%			5.10	0	0%	0%	100%
	Giant Eagle	0.3	Wet	0.0175	0.0059	66%	0	0	19.16	5.98	24%	31%	76%
8/8/2008	Homestead	0.04	Wet	0.0047	0	100%			1.32	0	0%	0%	100%
	Giant Eagle		Wet	0.0052	0	100%			5.36	0	0%	0%	100%
8/9-8/10, 2008	Homestead	0.44	Wet	0.0227	0.0012	95%	0	0	13.27	0.51	1%	4%	99%
	Giant Eagle		Wet	0.0018	0	100%			2.84	0	0%	0%	100%
8/14/2008	Homestead	0.23	Dry	0.0054	0.0005	90%	0	0.7	7.19	0.19	1%	3%	99%
	Giant Eagle		Dry	0.0236	0.0065	73%	3	0	48.44	19.61		40%	

Table I-1 (continued)

	Location	Rainfall (in)	Soil Condition	Maximum Peak Flow Rate (cf/s)			Maximum Peak Flow retardation (hr)	Initial runoff retardation (hr)	Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		Water Retained (%)
				Control	Green	% Reduc.			Control	Green	V_G/V_R	V_G/V_C	
8/25/2008	Homestead	0.04	Dry	0.0024	0	100%			0.67	0	0%	0%	100%
8/27-8/28, 2008	Homestead	0.88	Wet	0.0086	0.0084	1%	0	0.7	22.43	23.58	32%	-5%	68%
	Giant Eagle	0.63	Dry	0.0181	0	100%			50.62	0	0%	0%	100%
9/9/2008	Homestead	0.17	Dry	0.0028	0	100%			3.15	0	0%	0%	100%
	Giant Eagle	0.12	Dry	0.0013	0	100%			1.83	0	0%	0%	100%
9/12/2008	Homestead	1.83	Dry	0.0327	0.0219	33%	0	1.9	69.01	79.06	52%	-15%	48%
	Giant Eagle	2.42	Dry	0.0972	0.0350	64%	0	0	161.57	69.01	34%	43%	66%
9/13/2008	Homestead	0.29	Wet	0.0067	0.0019	72%	0	0	6.77	2.49	10%	37%	90%
	Giant Eagle	0.25	Wet	0.0033	0.0016	51%	0	10.3	15.31	2.44	12%	16%	88%
10/1/2008	Homestead	0.25	Dry	0.0109	0.0046	58%	0	2.6	9.41	4.66	22%	50%	78%
10/8/2008	Homestead	0.28	Dry	0.0016	0	100%			1.90	0	0%	0%	100%
	Giant Eagle	0.28	Dry	0.0053	0	100%			21.15	0	0%	0%	100%
10/24-10/25, 2008	Homestead	1.32	Dry	0.0110	0.0043	61%	0	6.6	33.53	36.41	33%	-9%	67%
	Giant Eagle	1.16	Dry	0.0196	0.0108	45%	3	4.7	95.56	61.00	63%	64%	37%
11/15/2008	Homestead	0.79	Dry	0.0035	0.0020	43%	1	0	9.70	10.03	15%	-3%	85%
	Giant Eagle	0.61	Dry	0.0104	0.0081	22%	1	1.1	46.15	34.35	91%	74%	9%
11/30/2008	Homestead	0.35	Dry	0.0029	0.0007	74%	0	7.2	2.10	0.56	2%	27%	98%
	Giant Eagle		Dry	0.0043	0.0033	24%	0	1.2	32.75	24.21		74%	
2/10/2009*	Homestead	0.07	Wet	0.0019	1.58E-05	99%	0	0	0.60	0.02	0.3%	3%	97%
	Giant Eagle	0.38	Wet	0.0110	0.0025	77%	1	0.7	24.85	20.49	65%	82%	18%
2/18-2/19, 2009*	Homestead	0.34	Wet	0.0035	0.0005	87%	0	5.7	5.37	0.98	3%	18%	82%
	Giant Eagle	0.32	Wet	0.0085	0.0047	45%	0	5.6	20.57	11.96	42%	58%	42%

Table I-1 (continued)

	Location	Rainfall (in)	Soil Condition	Maximum Peak Flow Rate (cf/s)			Maximum Peak Flow retardation (hr)	Initial runoff retardation (hr)	Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		Water Retained (%)
				Control	Green	% Reduc.			Control	Green	V_G/V_R	V_G/V_C	
3/8-3/9, 2009	Homestead	0.38	Dry	0.0044	0	100%			4.75	0	0%	0%	100%
	Giant Eagle	0.29	Dry	0.0091	0.0027	70%	0	0.6	13.71	4.18	17%	31%	83%
3/25/2009	Giant Eagle	0.36	Dry	0.0112	0	100%			26.84	0	0%	0%	100%
3/26/2009	Giant Eagle	0.48	Wet	0.0097	0.0075	23%	1	0.5	41.19	28.65	72%	70%	28%
3/27-3/28, 2009	Giant Eagle	0.14	Wet	0.0023	0	100%			5.00	0	0%	0%	100%
3/29/2009	Giant Eagle	0.33	Wet	0.0111	0.0062	44%	0	0	21.76	13.90	51%	64%	49%
4/3/2009	Giant Eagle	1.36	Dry	0.0323	0.0193	40%	0	0	95.69	76.83	68%	80%	32%
4/14-4/15, 2009	Giant Eagle	0.5	Dry	0.0064	0.0020	69%	10	9.8	32.08	6.82	16%	21%	84%
4/20/2009	Giant Eagle	0.41	Dry	0.0063	0.0020	68%	5	8.1	36.43	5.78	17%	16%	83%
4/28/2009	Giant Eagle	0.29	Dry	0.0072	0	100%			15.52	0	0%	0%	100%
4/30/2009	Giant Eagle	0.16	Wet	0.0032	0	100%			5.76	0	0%	0%	100%

1. Retardation (Δt)=Time of initial flowing of control roof - Time of initial flowing for green roof
2. V_G: Cumulative runoff volume of green roof (cf/1000sf); V_C: cumulative runoff of control roof (cf/1000sf); V_R: cumulative rainfall of each rainfall Event
3. Considering the possibility of melted snow, the soil condition for the rainfall events on 2/10, 2009 and 2/18-2/19, 2009 were presumed as wet.
4. %Reduc. =1- (max. peak flow rate of control roof/max. peak flow rate of green)
5. Water Retained (%) = 1- V_G/V_C

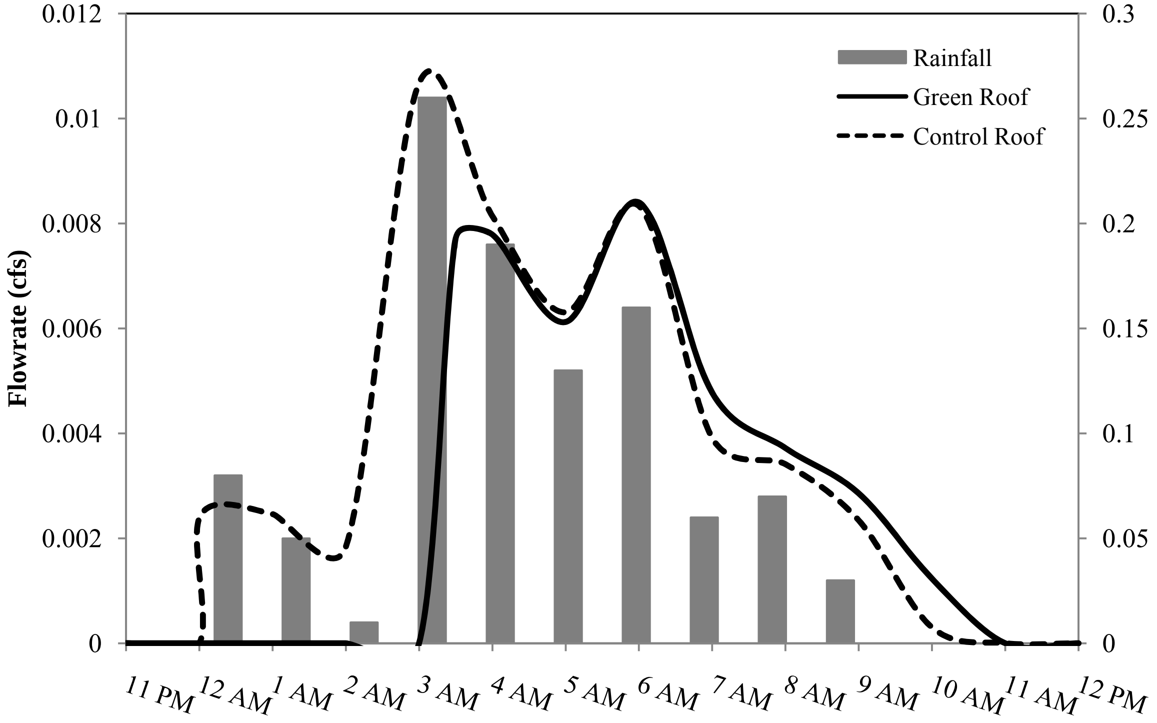


Figure I-1 Runoff Flow Rates and Rainfall intensity – April 28, 2008 Storm (Homestead)

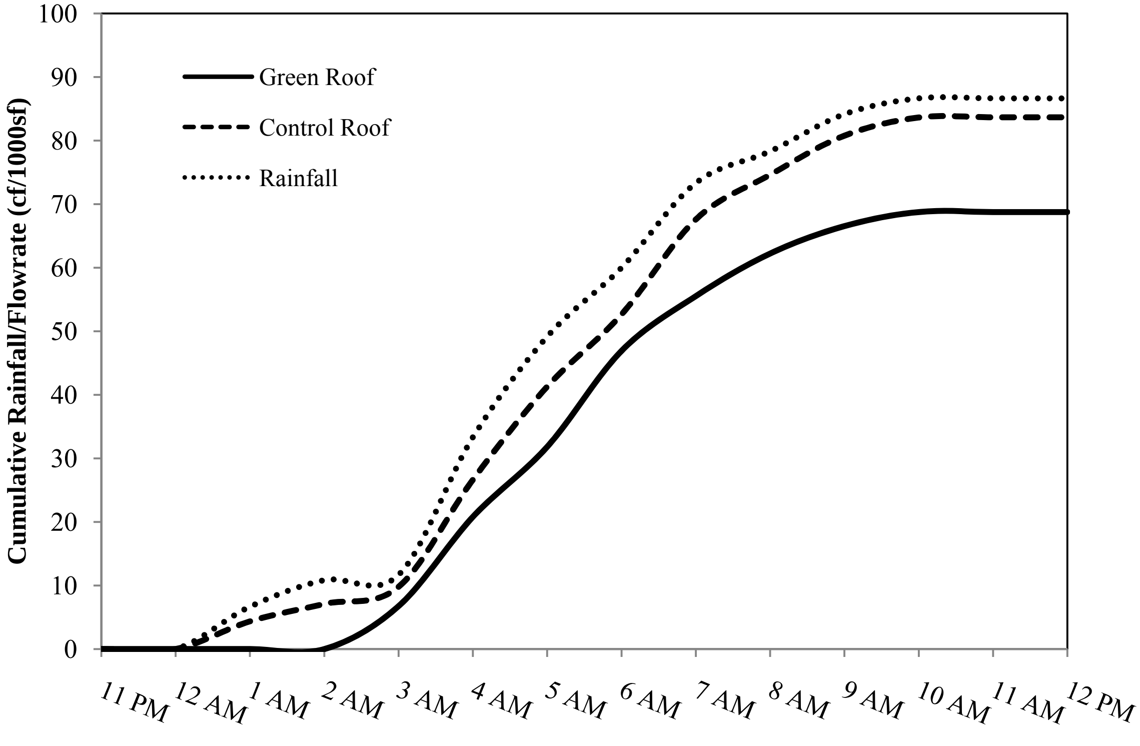


Figure I-2 Runoff and rainfall volumes – April 28, 2008 Storm (Homestead)

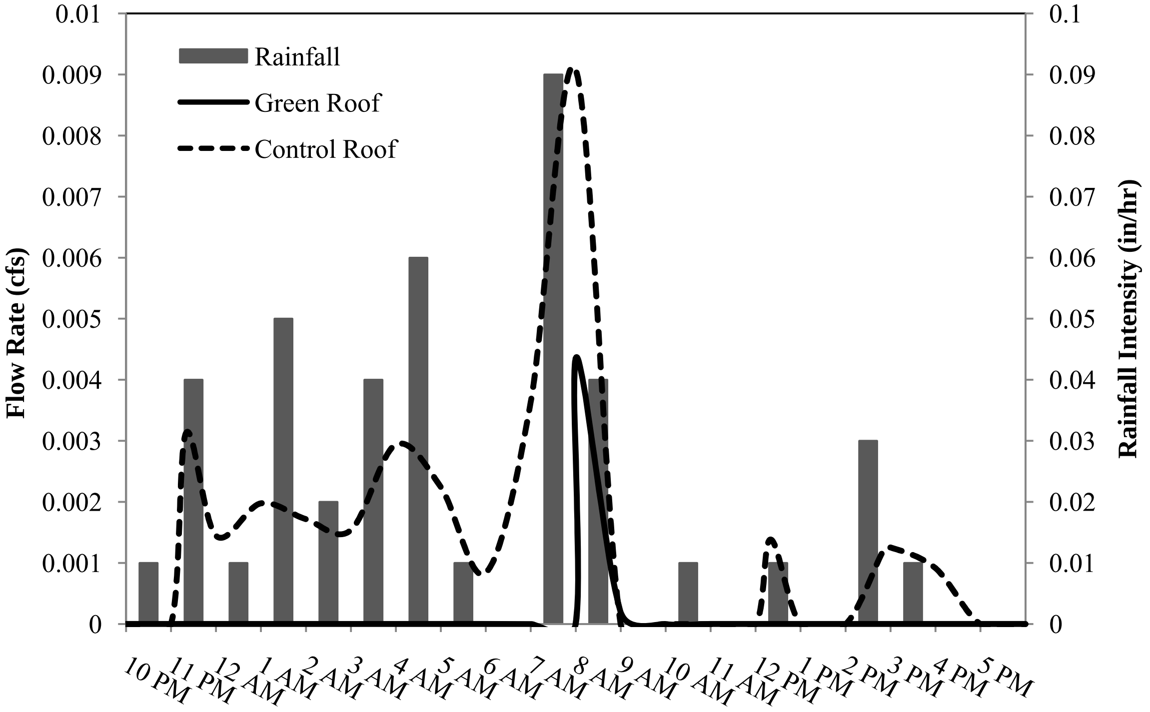


Figure I-3 Runoff Flow Rates and Rainfall intensity – May 7-8, 2008 Storm (Homestead)

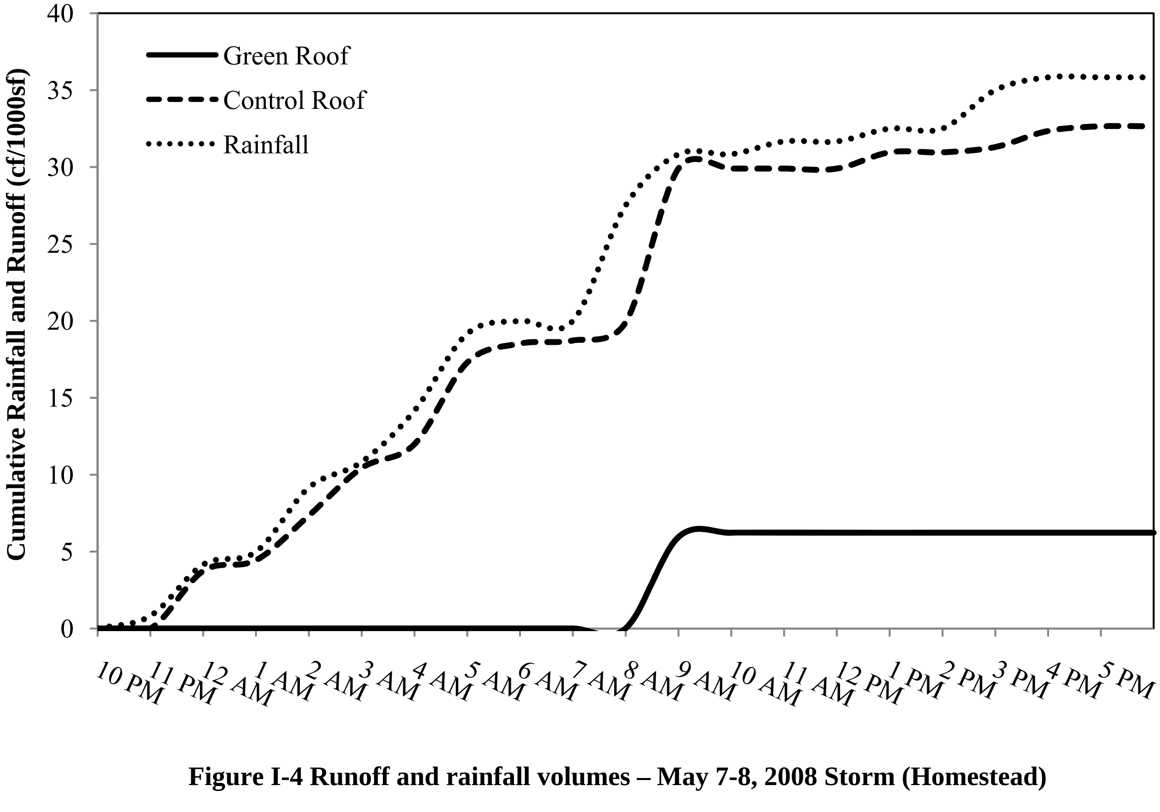


Figure I-4 Runoff and rainfall volumes – May 7-8, 2008 Storm (Homestead)

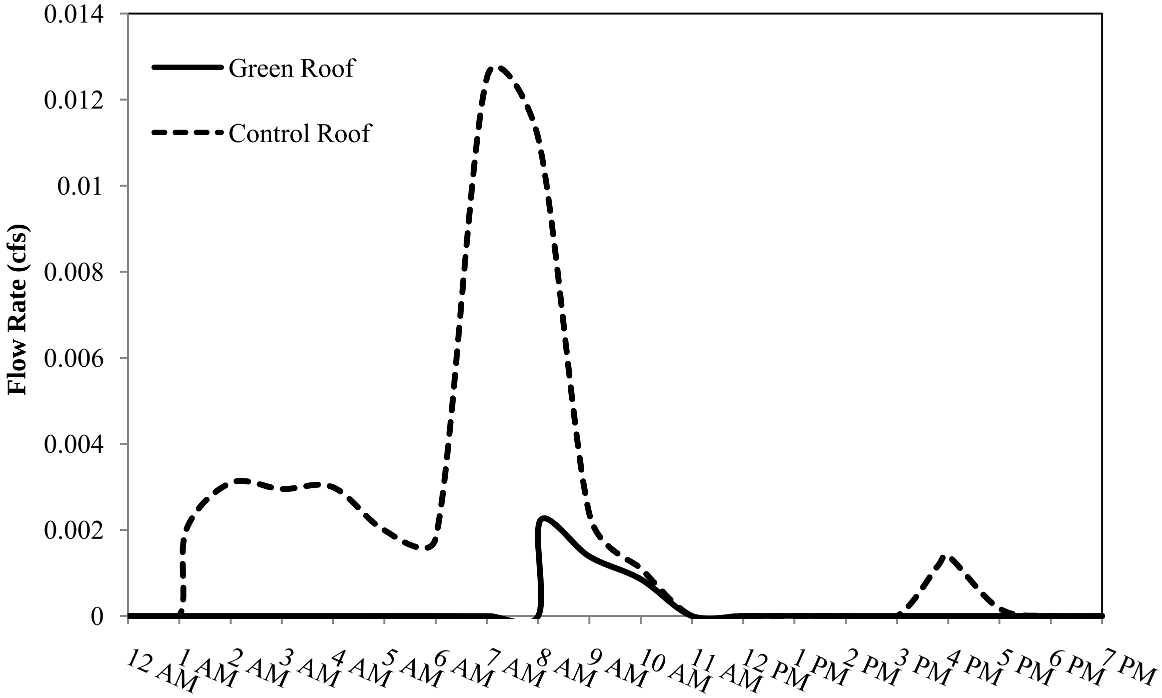


Figure I-5 Runoff flow Rates – May 7-8, 2008 Storm (Giant Eagle)

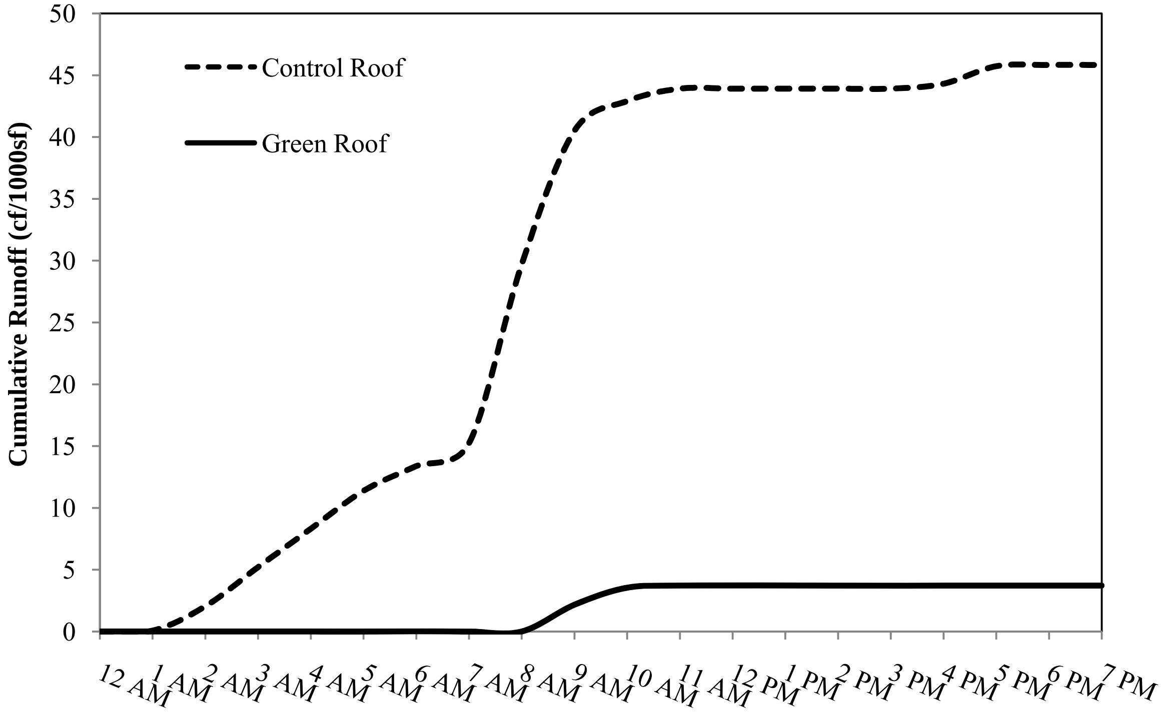


Figure I-6 Runoff Volumes – May 7-8, 2008 Storm (Giant Eagle)

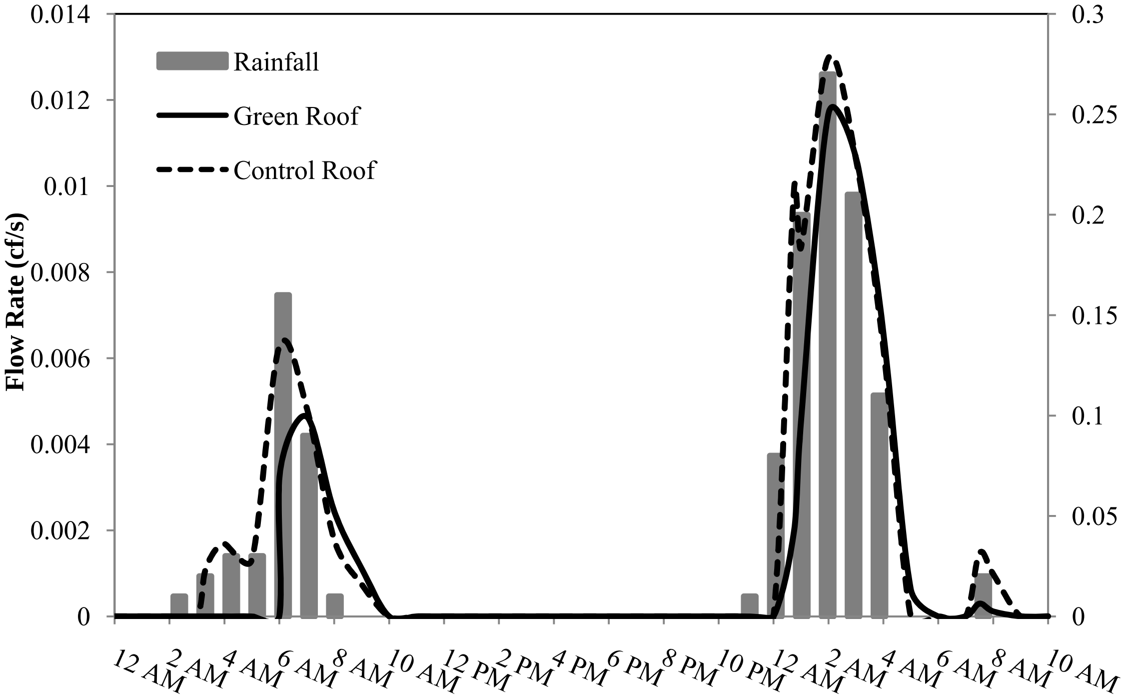


Figure I-7 Runoff Flow Rates and Rainfall intensity – May 9-10, 2008 Storm (Homestead)

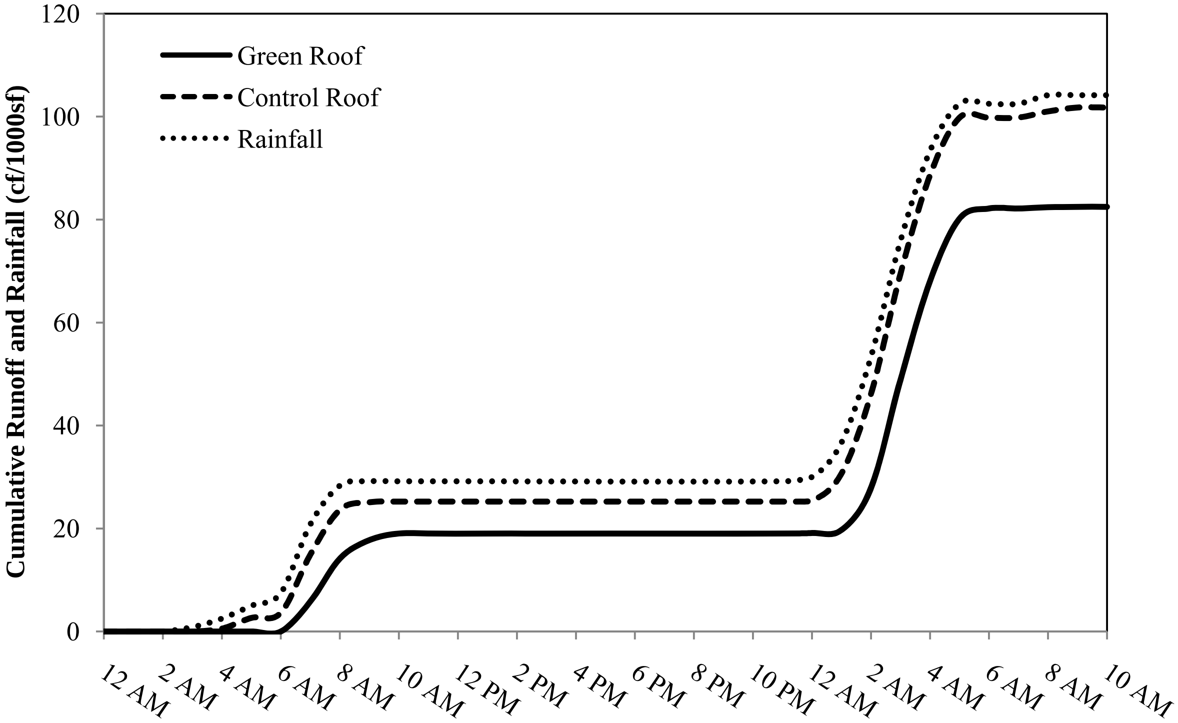


Figure I-8 Runoff and rainfall volumes – May 9-10, 2008 Storm (Homestead)

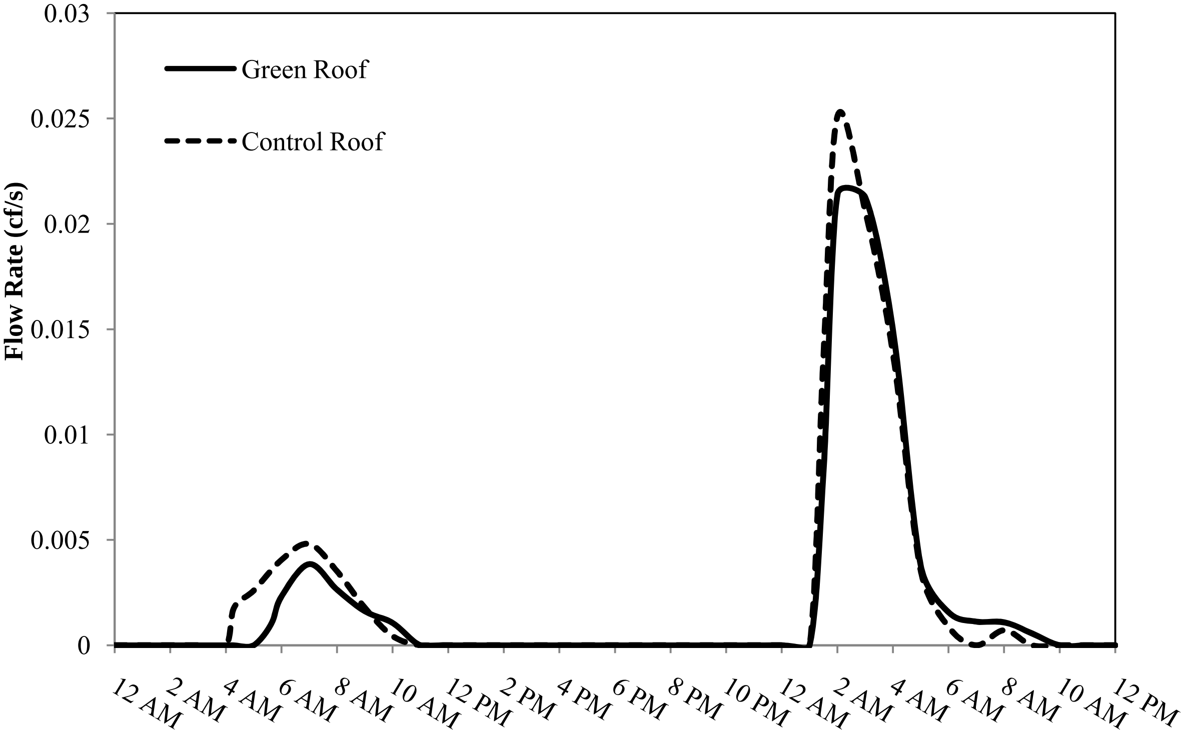


Figure I-9 Runoff flow Rates – May 9-10, 2008 Storm (Giant Eagle)

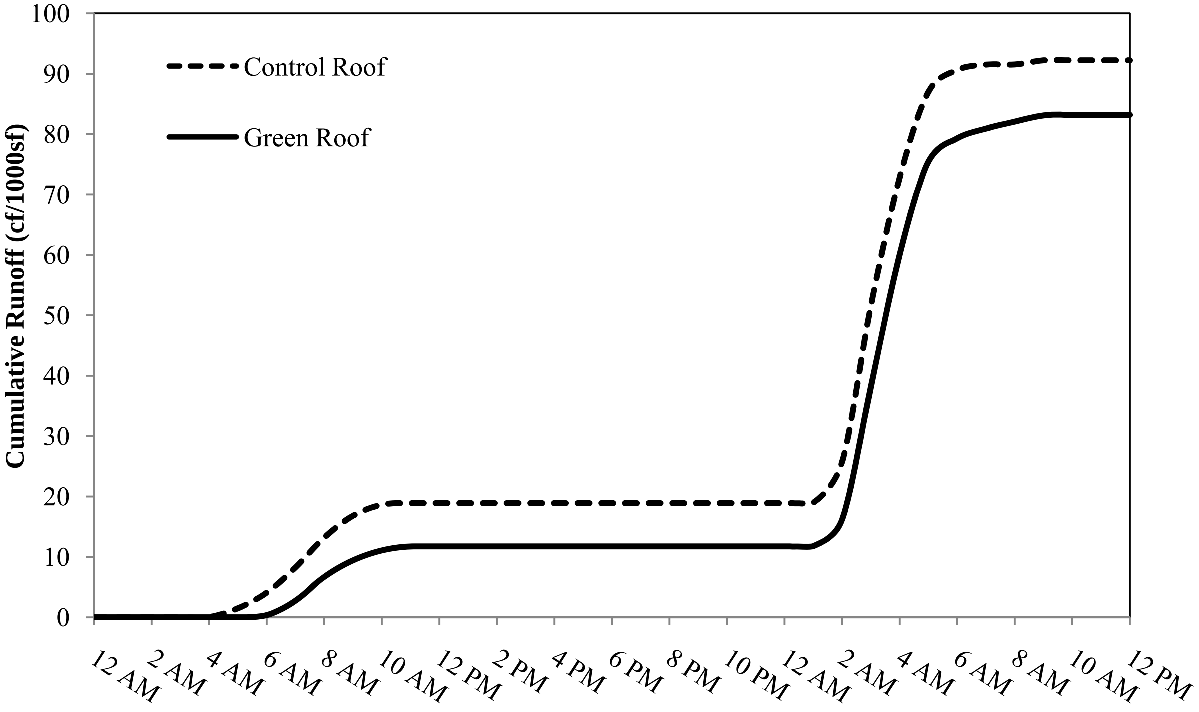


Figure I-10 Runoff Volumes – May 9-10, 2008 Storm (Giant Eagle)

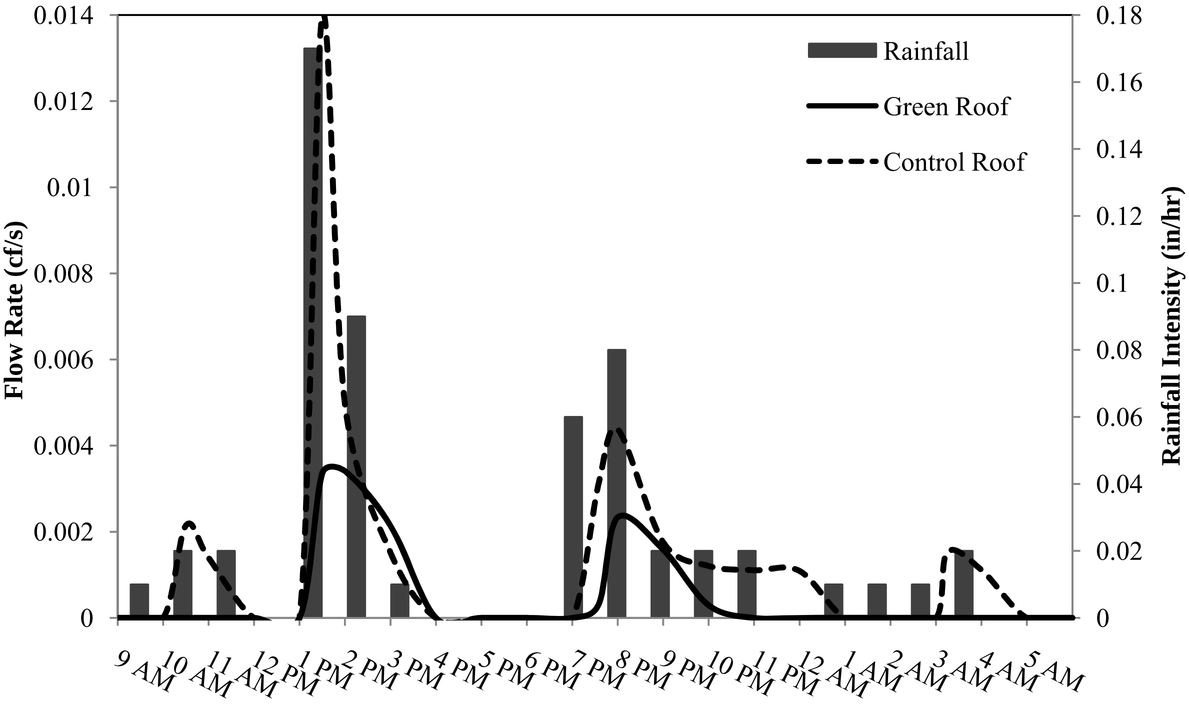


Figure I-11 Runoff Flow Rates and Rainfall intensity – May 11-12, 2008 Storm (Homestead)

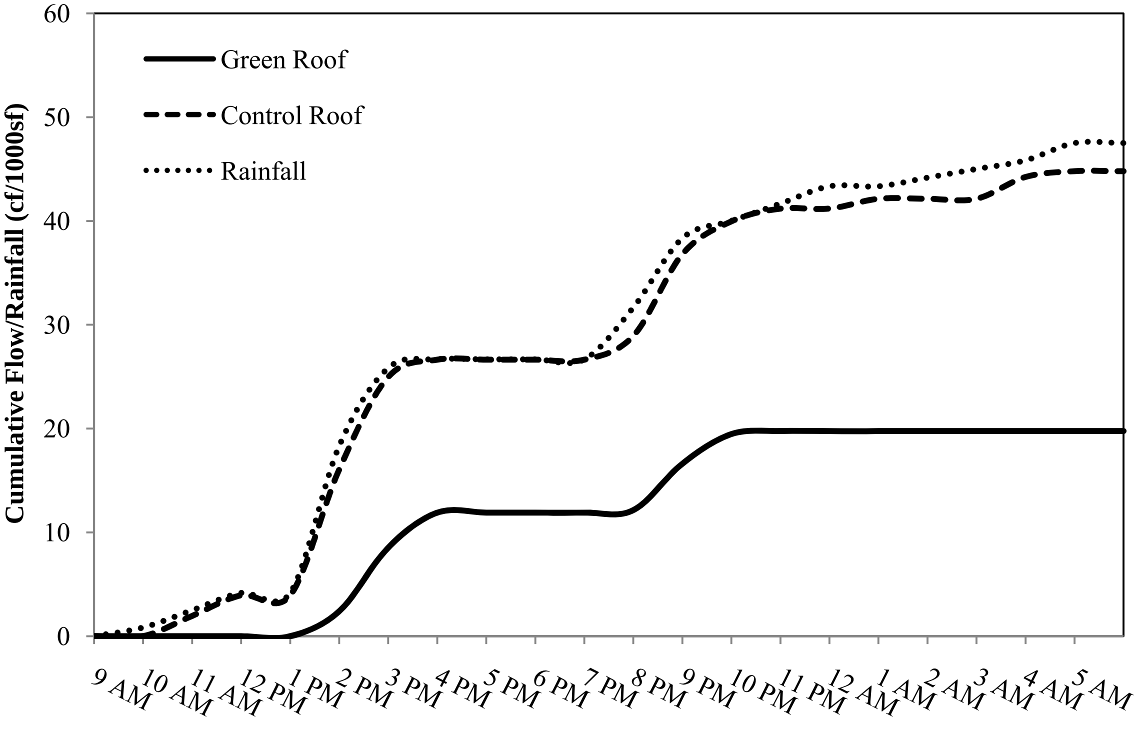


Figure I-12 Runoff and rainfall volumes – May 11-12, 2008 Storm (Homestead)

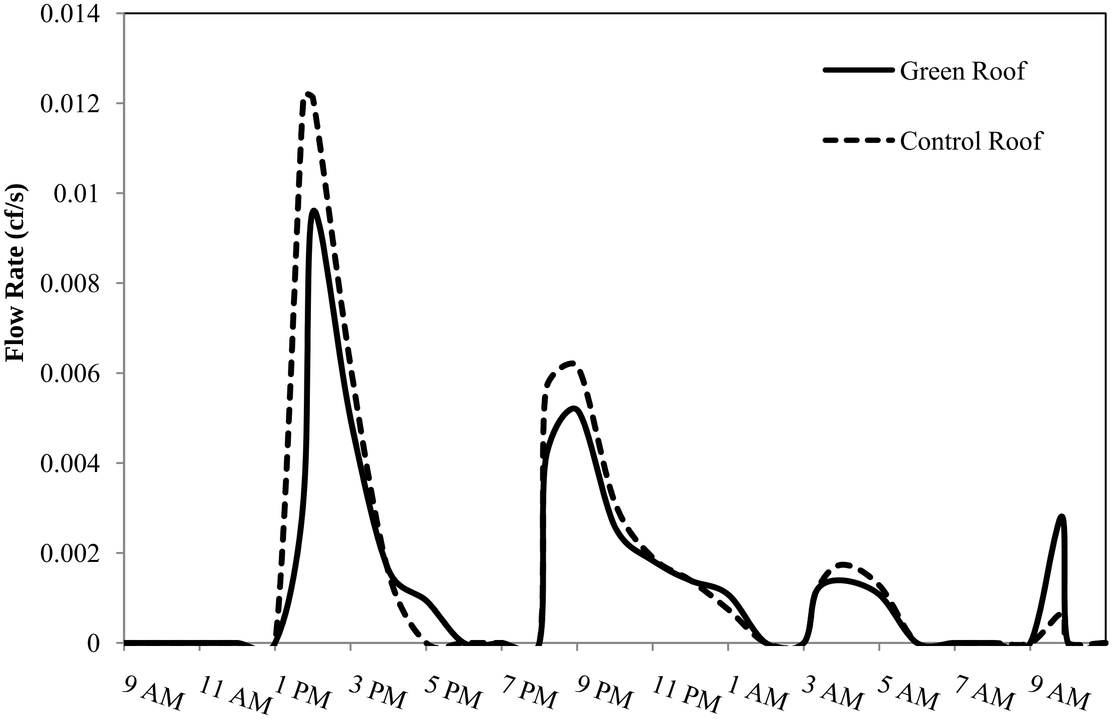


Figure I-13 Runoff flow Rates – May 11-12, 2008 Storm (Giant Eagle)

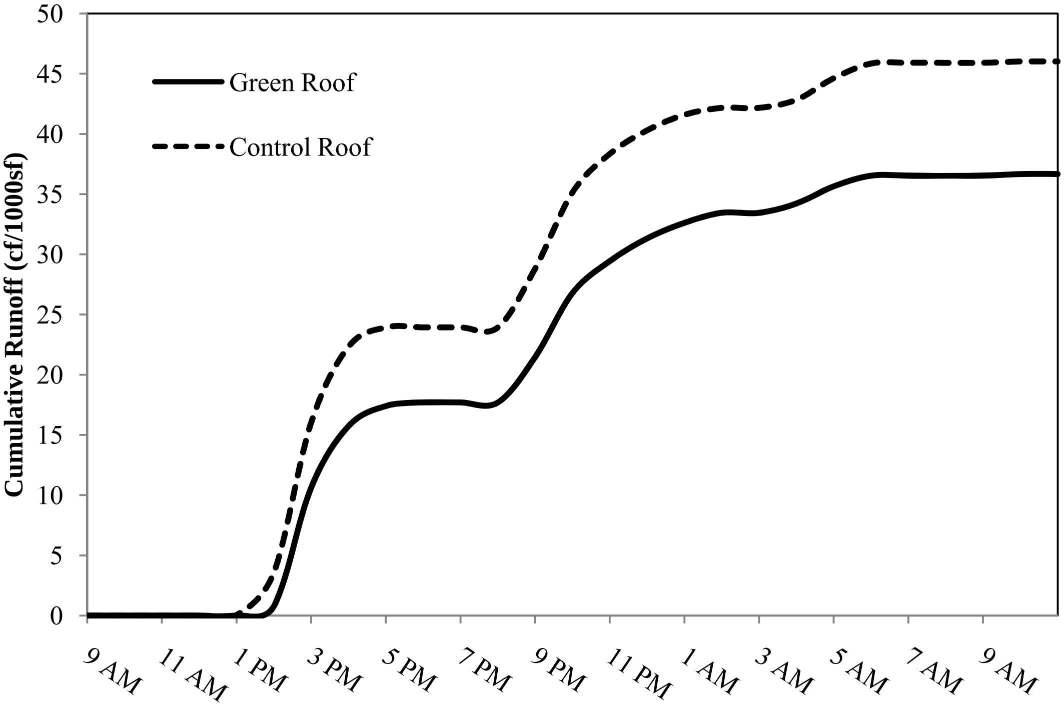


Figure I-14 Runoff Volumes – May 11-12, 2008 Storm (Giant Eagle)

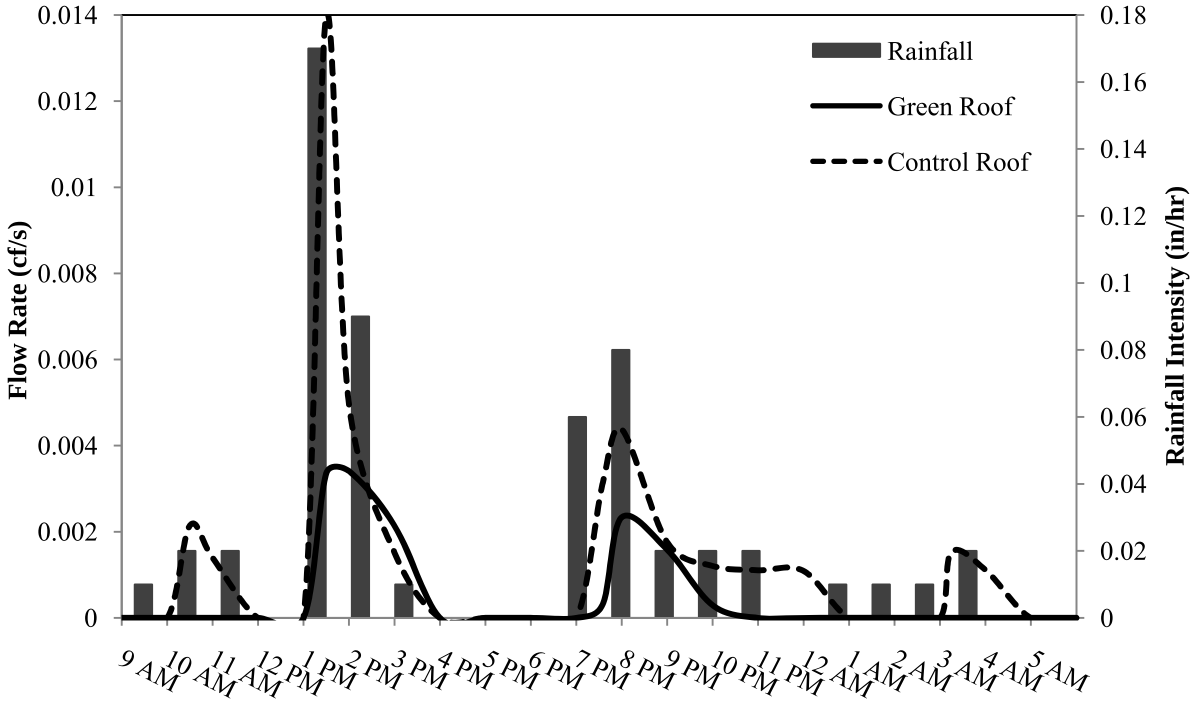


Figure I-15 Runoff Flow Rates and Rainfall intensity – May 11-12, 2008 Storm (Homestead)

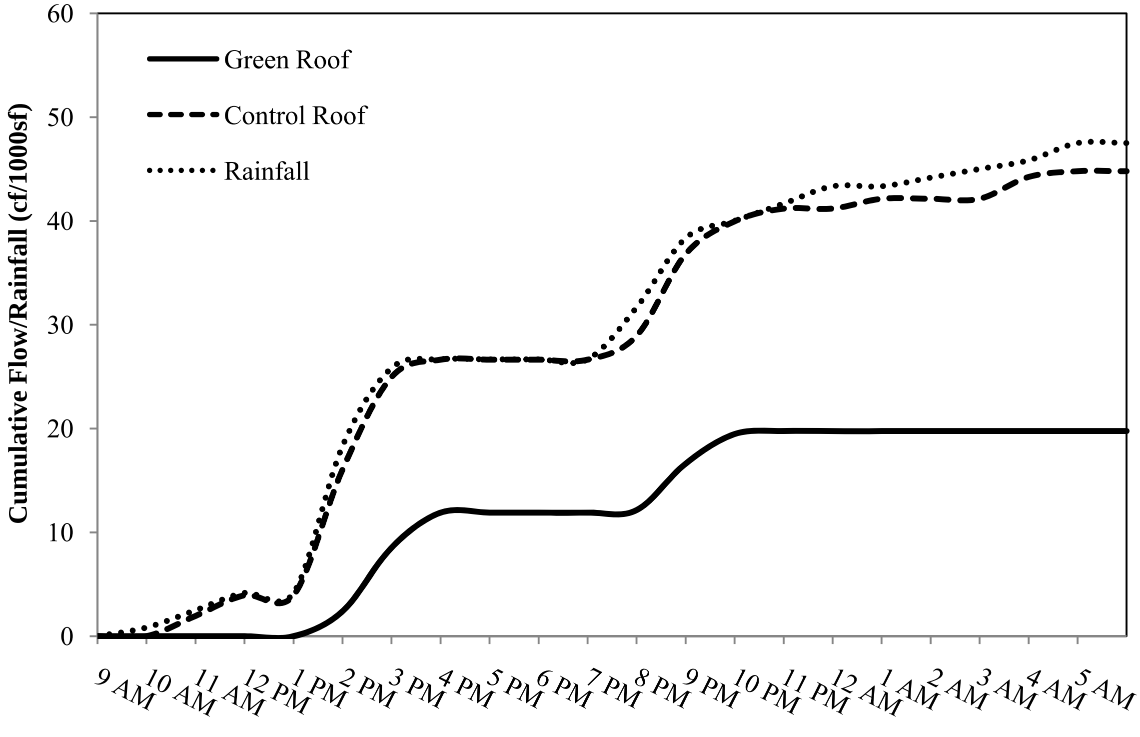


Figure I-16 Runoff and rainfall volumes – May 11-12, 2008 Storm (Homestead)

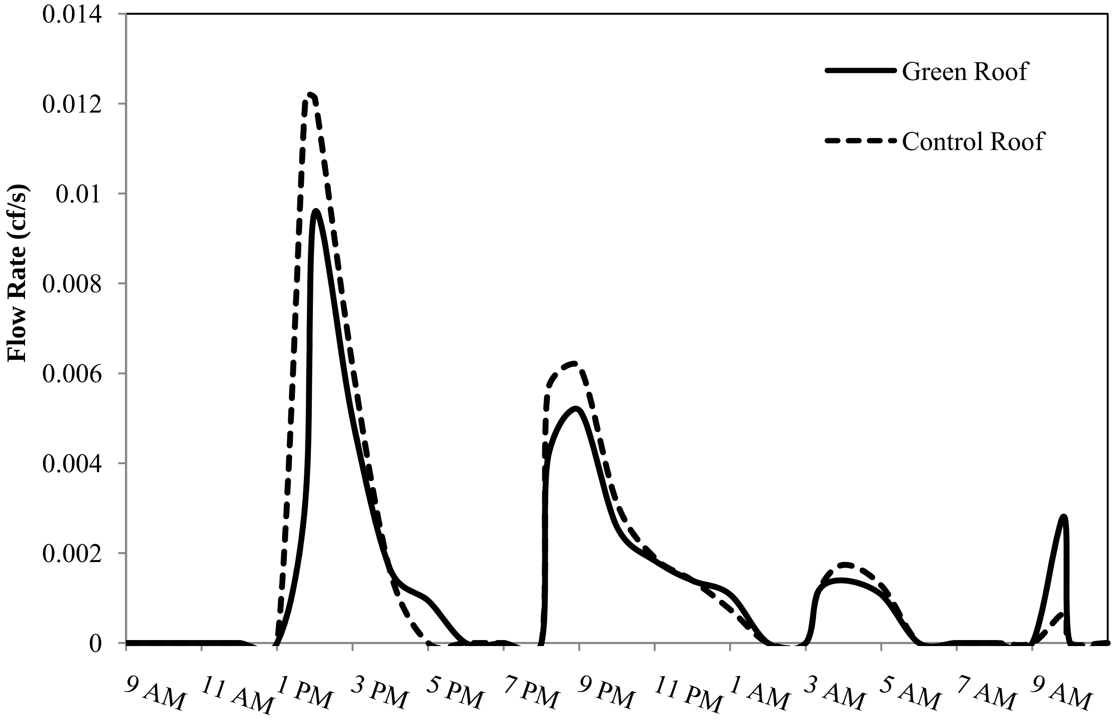


Figure I-17 Runoff flow Rates – May 11-12, 2008 Storm (Giant Eagle)

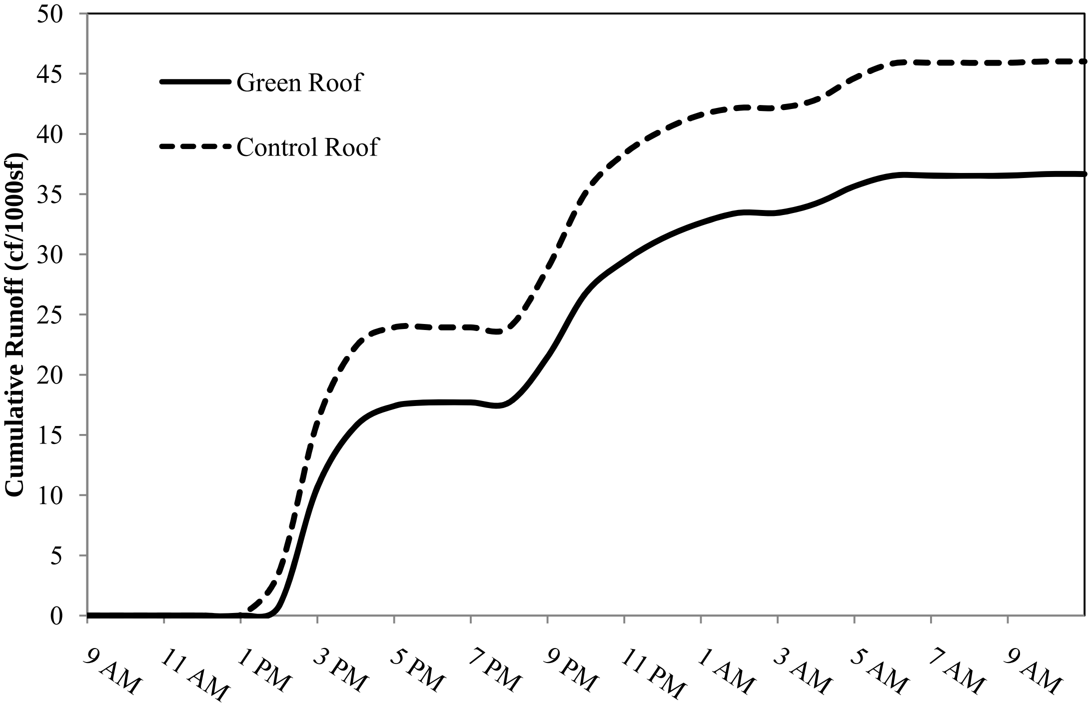


Figure I-18 Runoff Volumes – May 11-12, 2008 Storm (Giant Eagle)

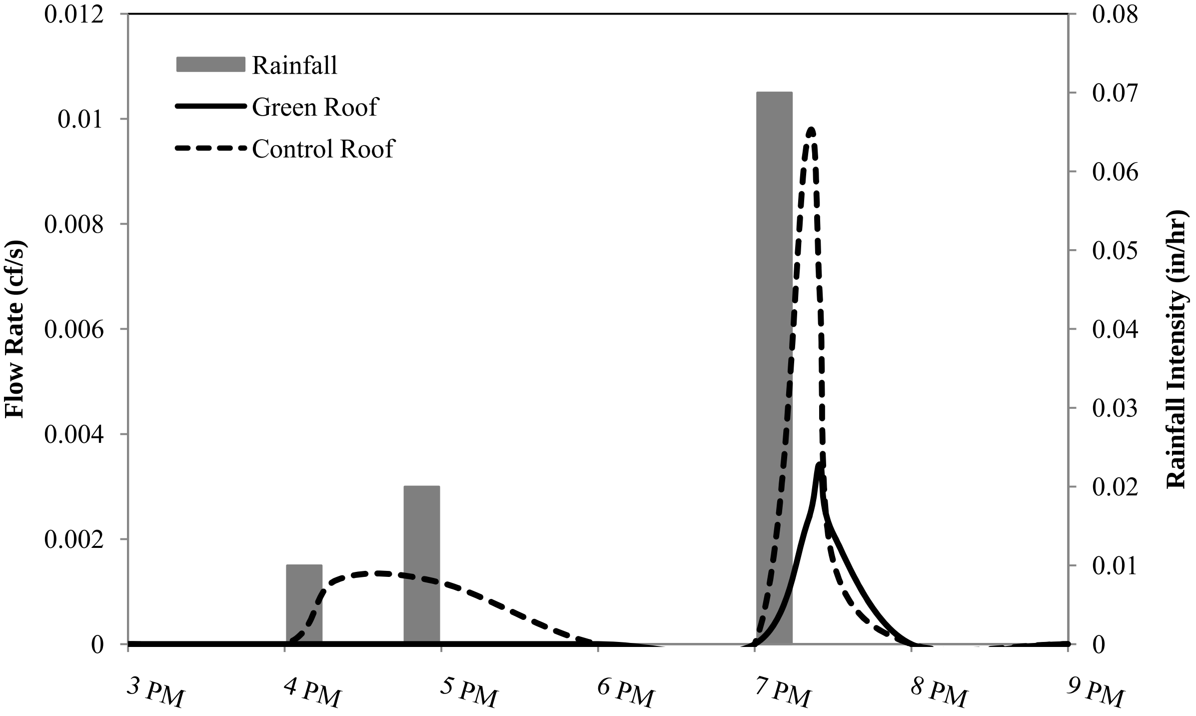


Figure I-19 Runoff Flow Rates and Rainfall Intensity – May 17, 2008 Storm (Homestead)

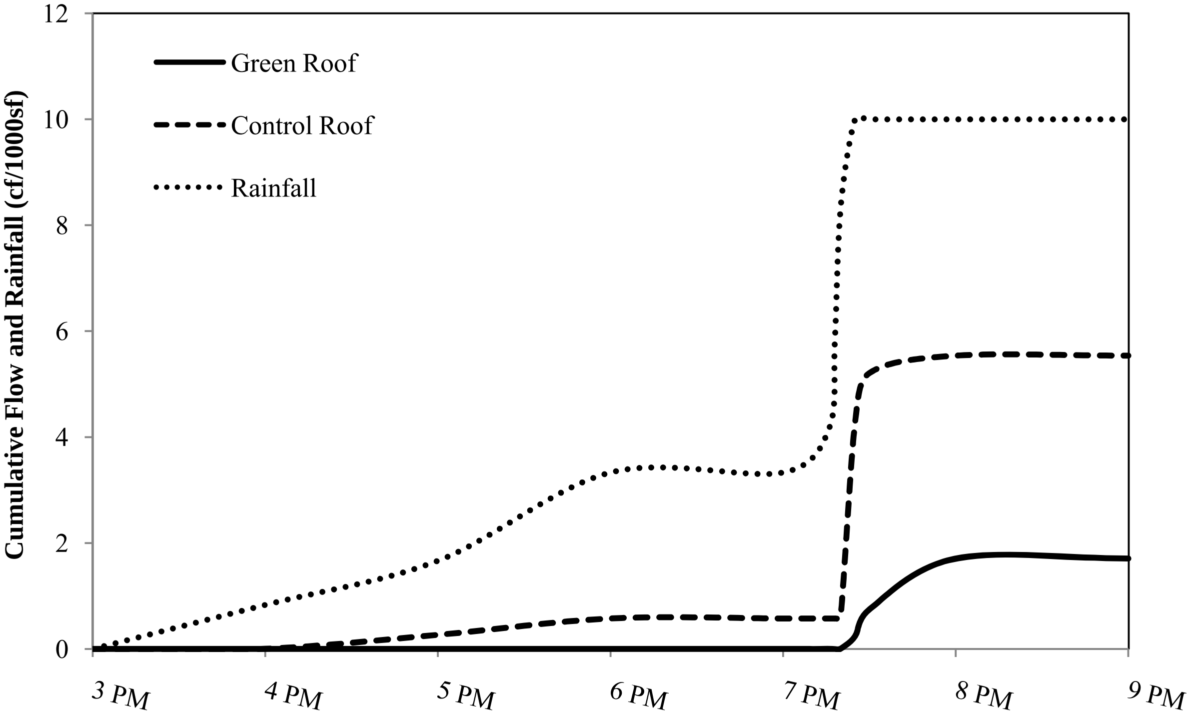


Figure I-20 Runoff and Rainfall Volumes – May 17, 2008 Storm (Homestead)

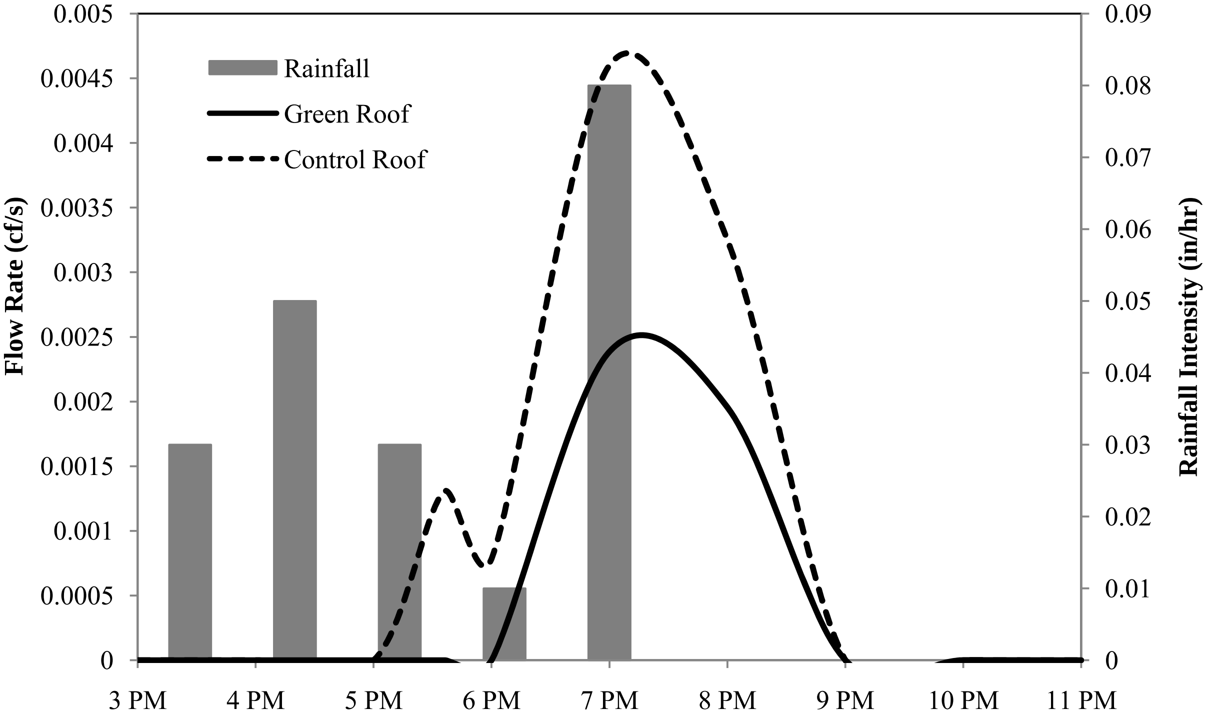


Figure I-21 Runoff Flow Rates and Rainfall intensity – May 17, 2008 Storm (Giant Eagle)

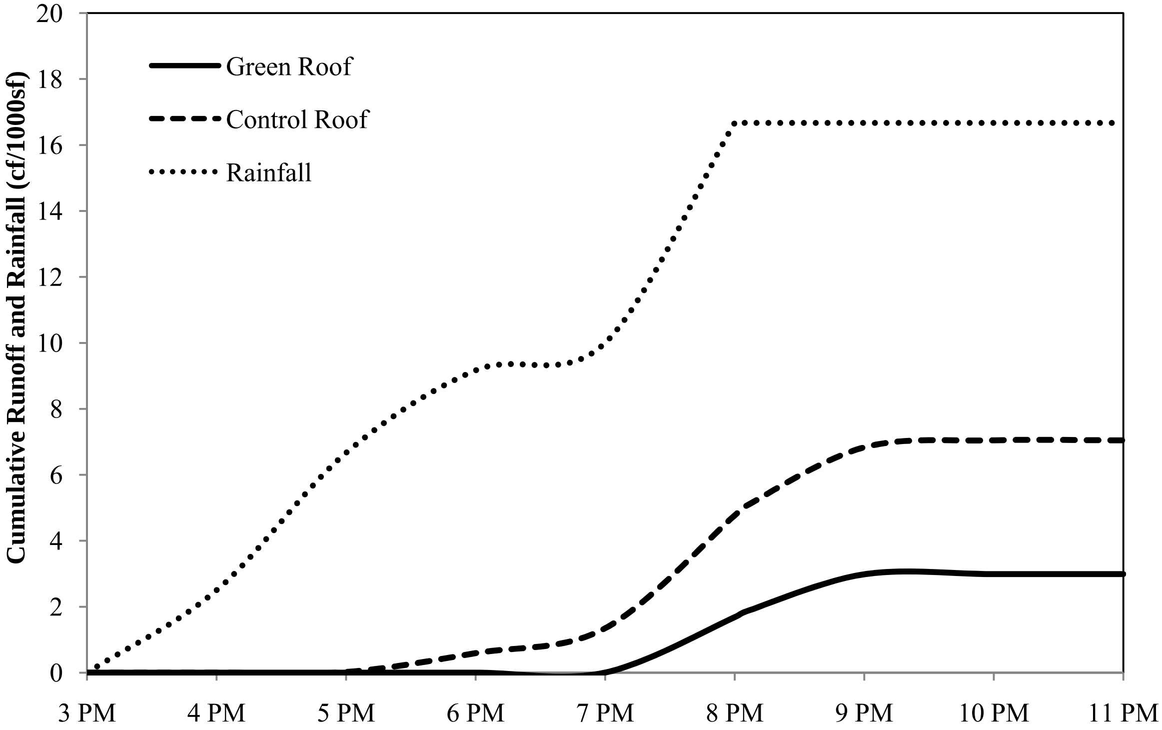


Figure I-22 Runoff and Rainfall Volumes – May 17, 2008 Storm (Giant Eagle)

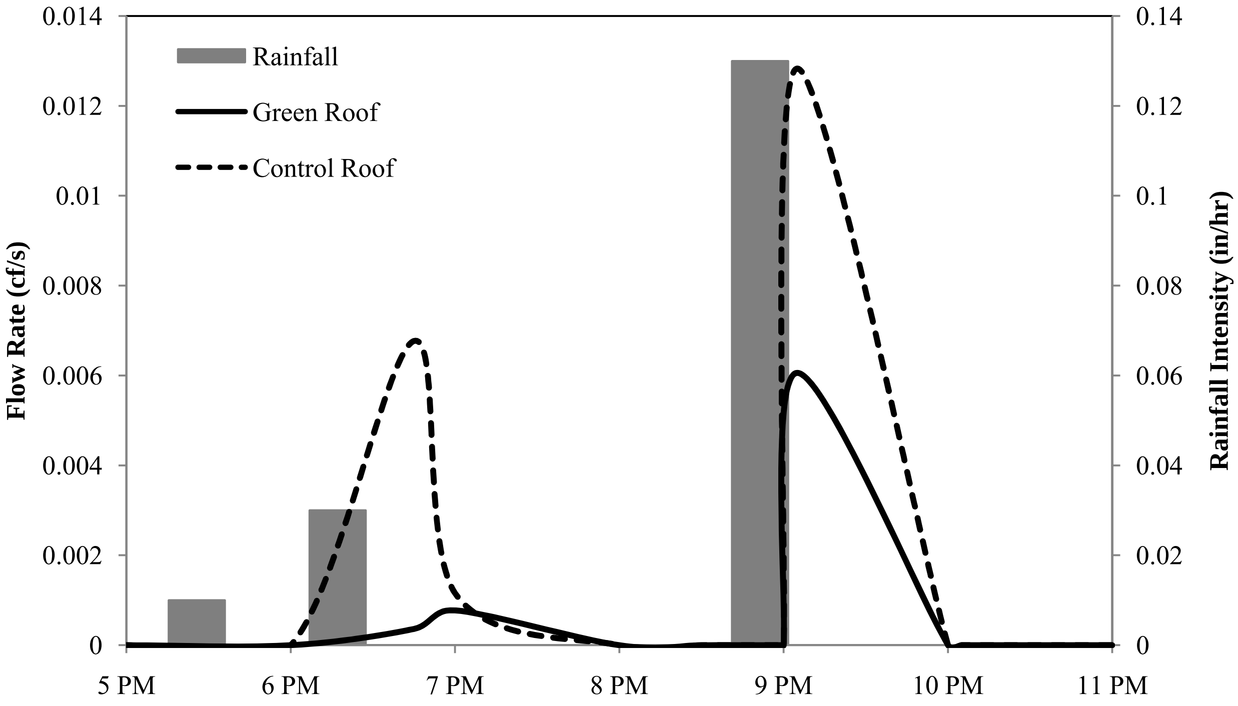


Figure I-23 Runoff Flow Rates and Rainfall Intensity – May 18, 2008 Storm (Homestead)

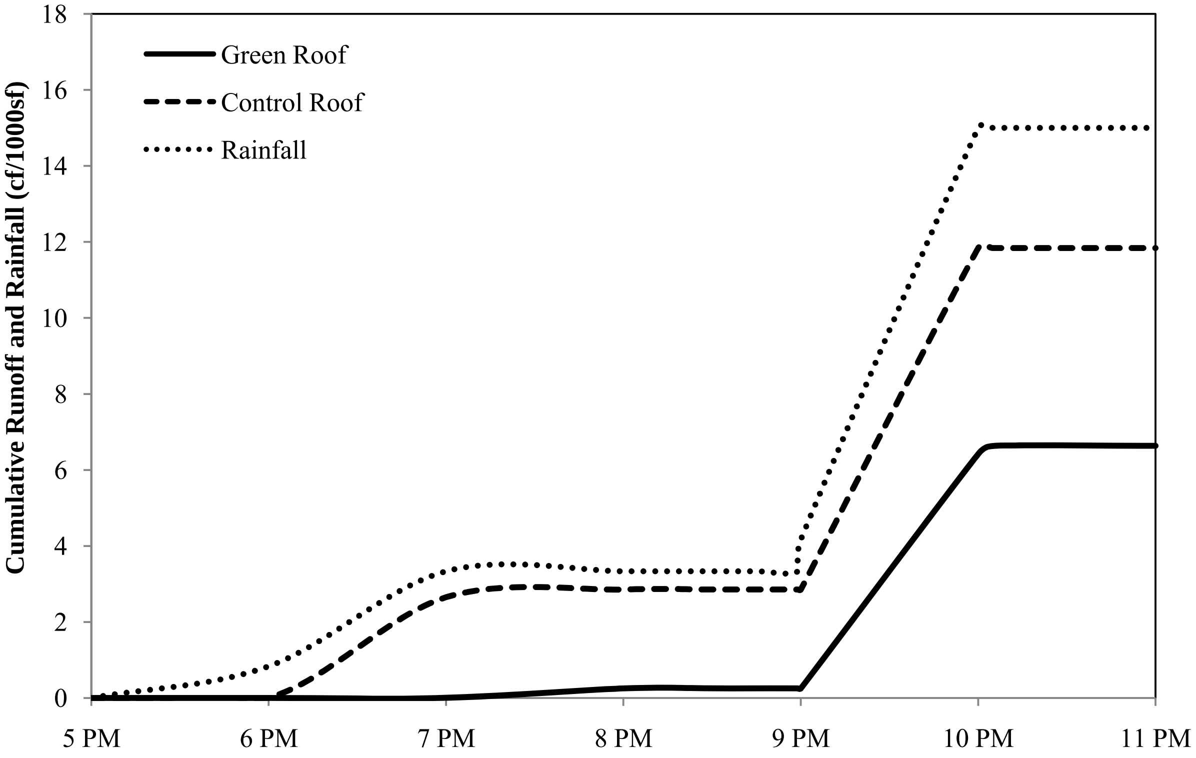


Figure I-24 Runoff and Rainfall Volumes – May 18, 2008 Storm (Homestead)

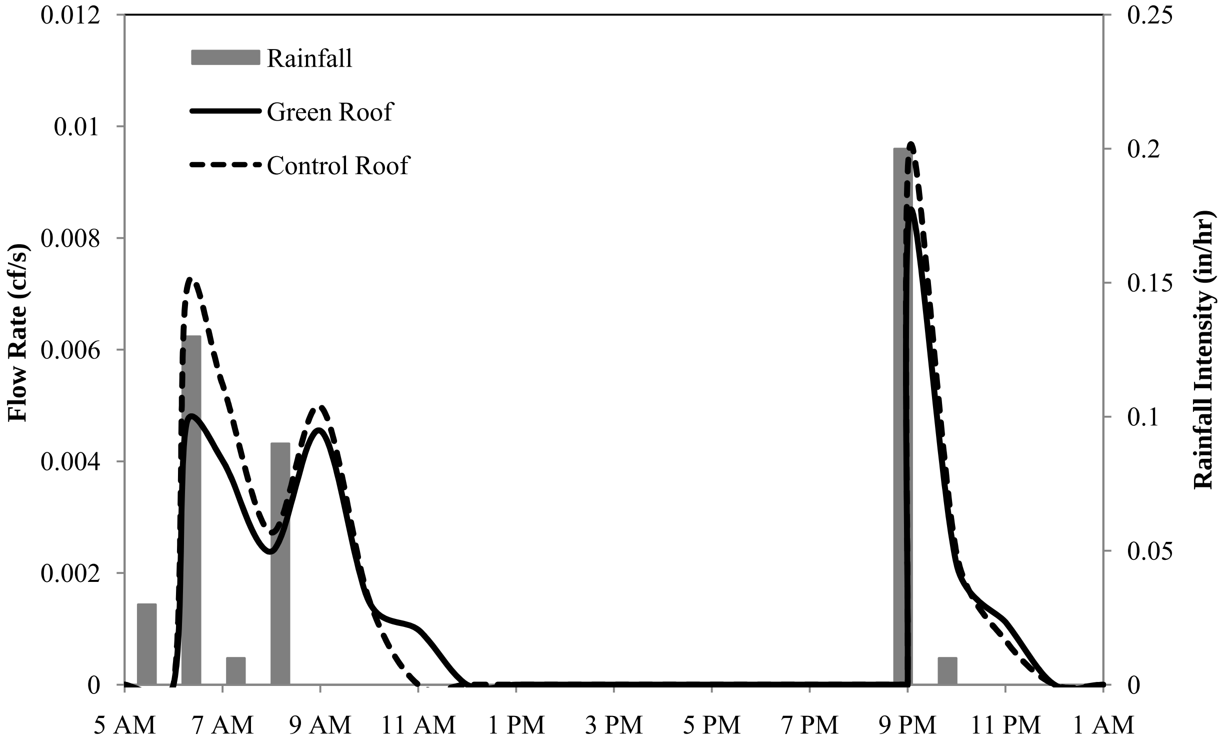


Figure I-25 Runoff Flow Rates and Rainfall intensity – May 18, 2008 Storm (Giant Eagle)

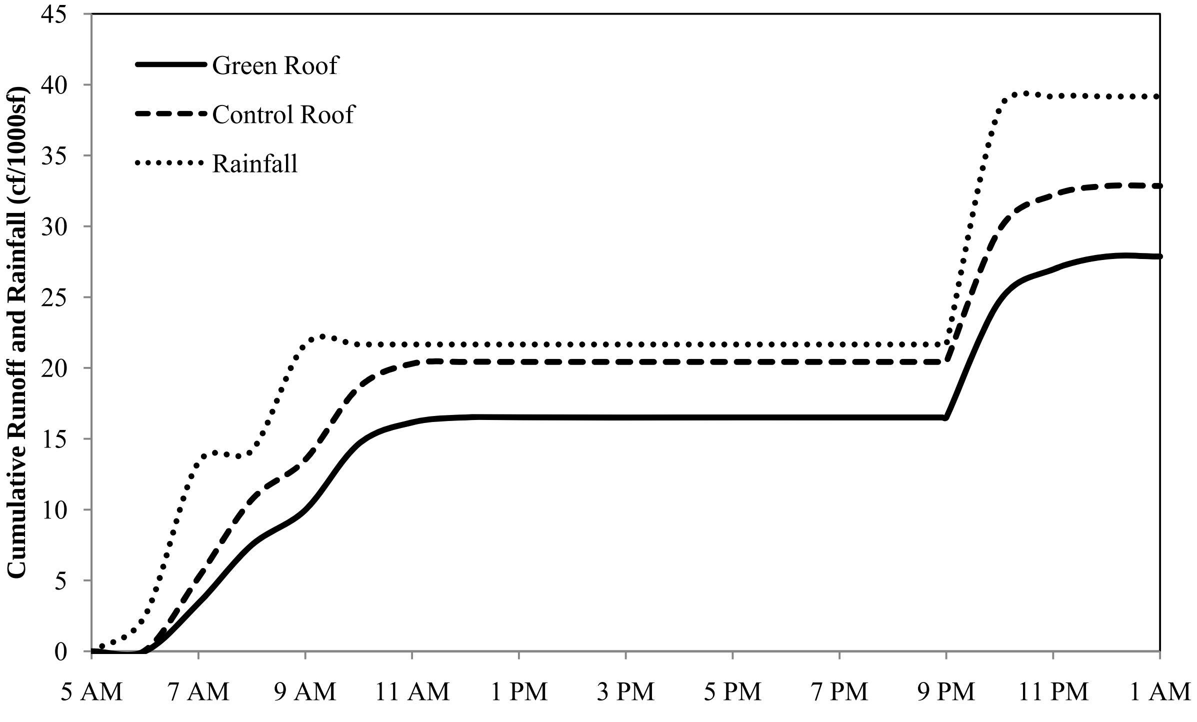


Figure I-26 Runoff and Rainfall Volumes – May 18, 2008 Storm (Giant Eagle)

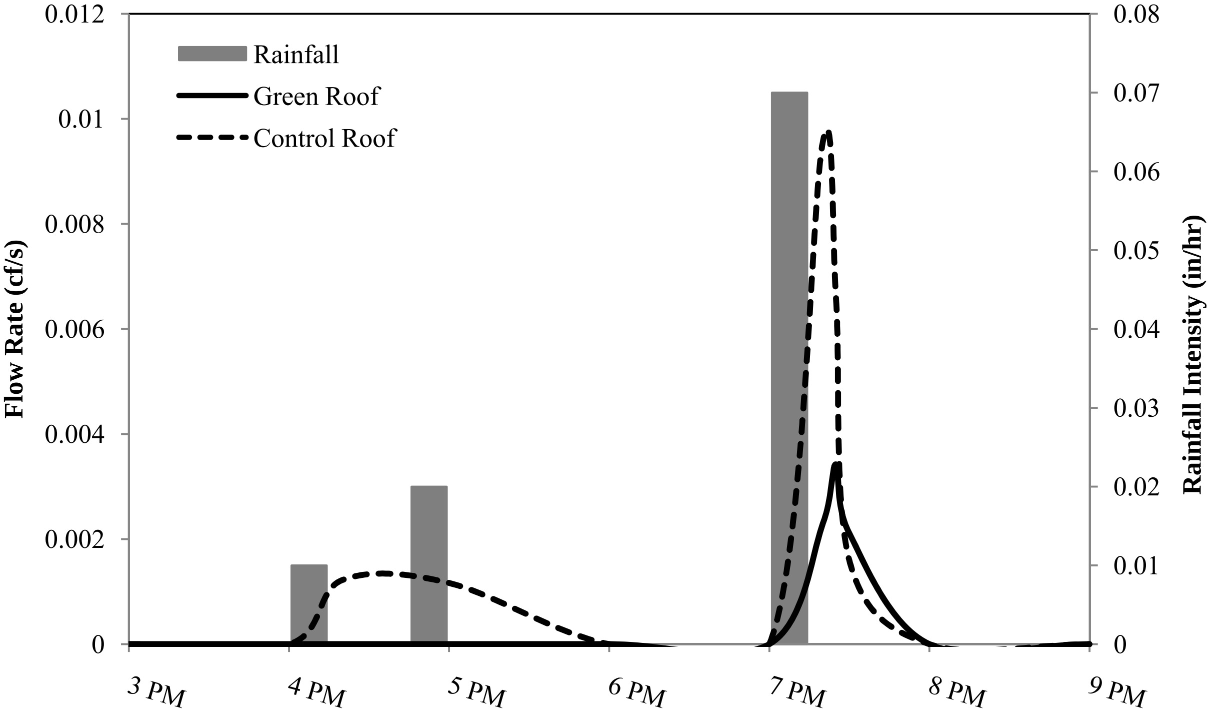


Figure I-27 Runoff Flow Rates and Rainfall Intensity – May 17, 2008 Storm (Homestead)

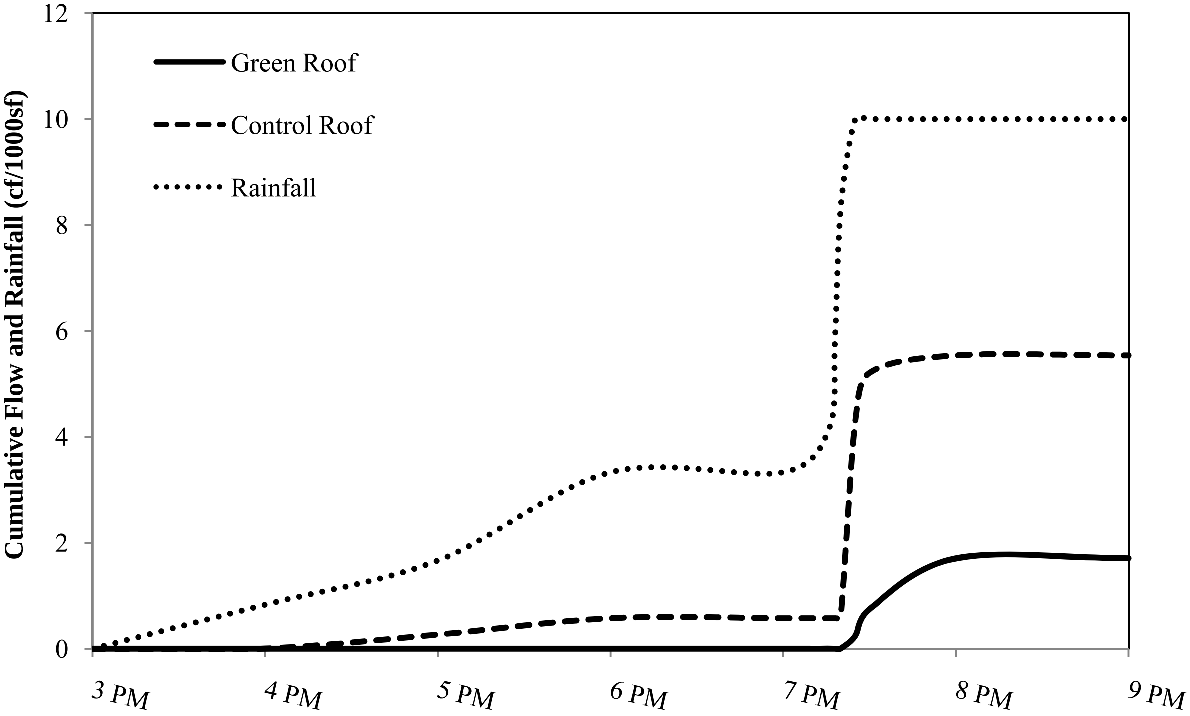


Figure I-28 Runoff and Rainfall Volumes – May 17, 2008 Storm (Homestead)

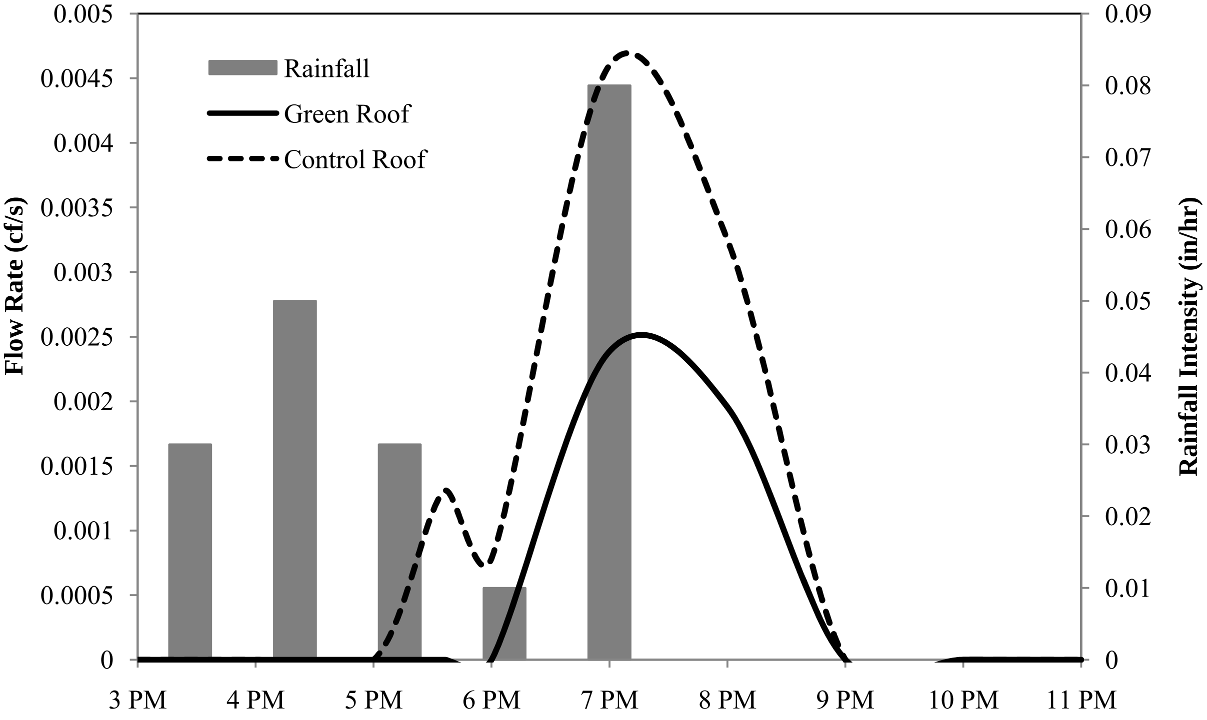


Figure I-29 Runoff Flow Rates and Rainfall intensity – May 17, 2008 Storm (Giant Eagle)

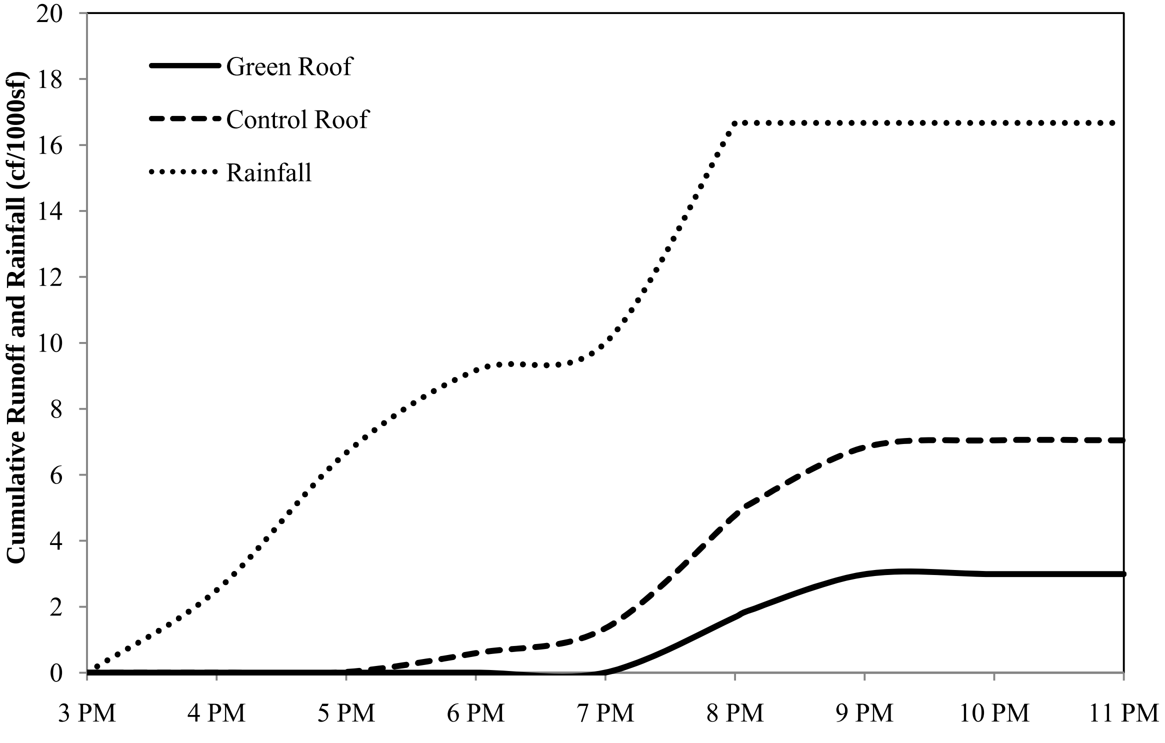


Figure I-30 Runoff and Rainfall Volumes – May 17, 2008 Storm (Giant Eagle)

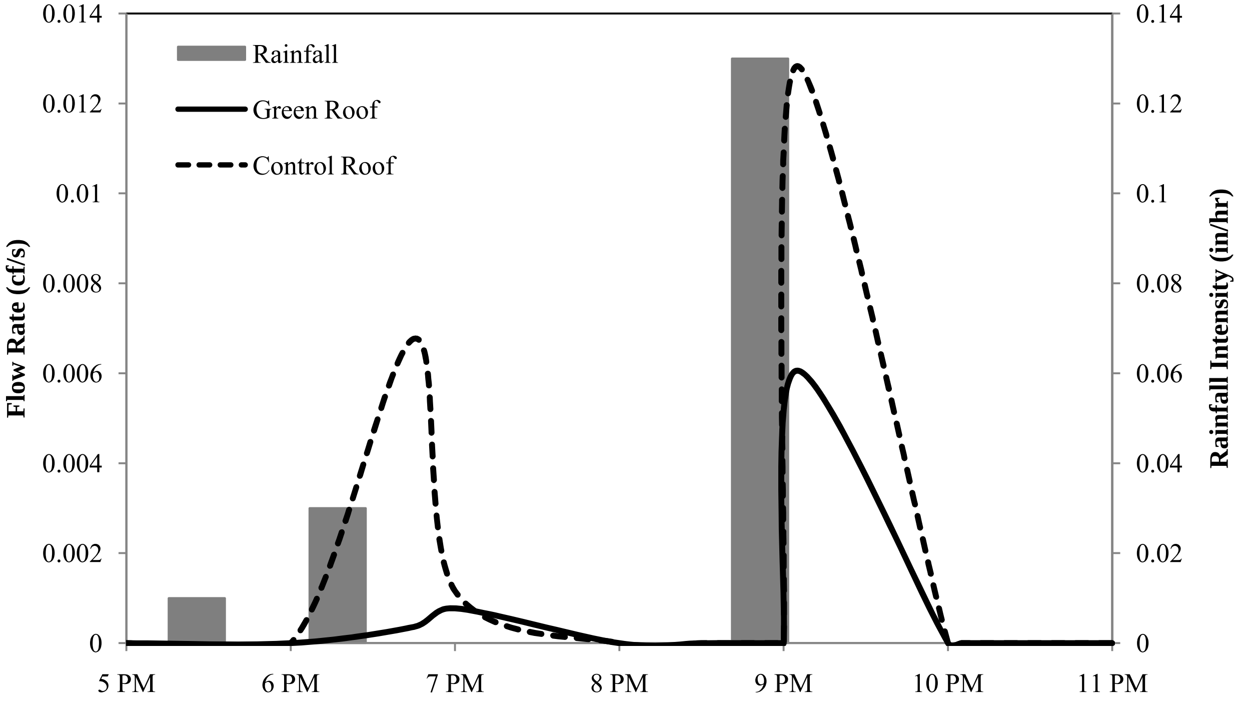


Figure I-31 Runoff Flow Rates and Rainfall Intensity – May 18, 2008 Storm (Homestead)

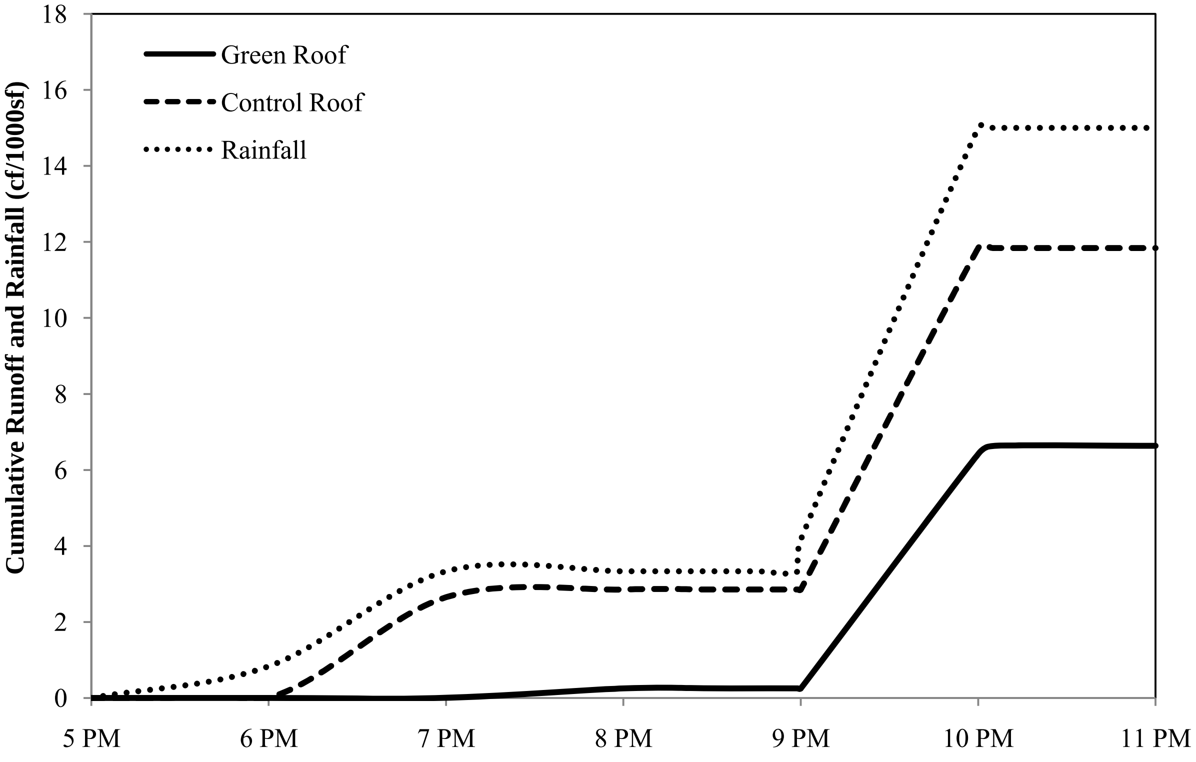


Figure I-32 Runoff and Rainfall Volumes – May 18, 2008 Storm (Homestead)

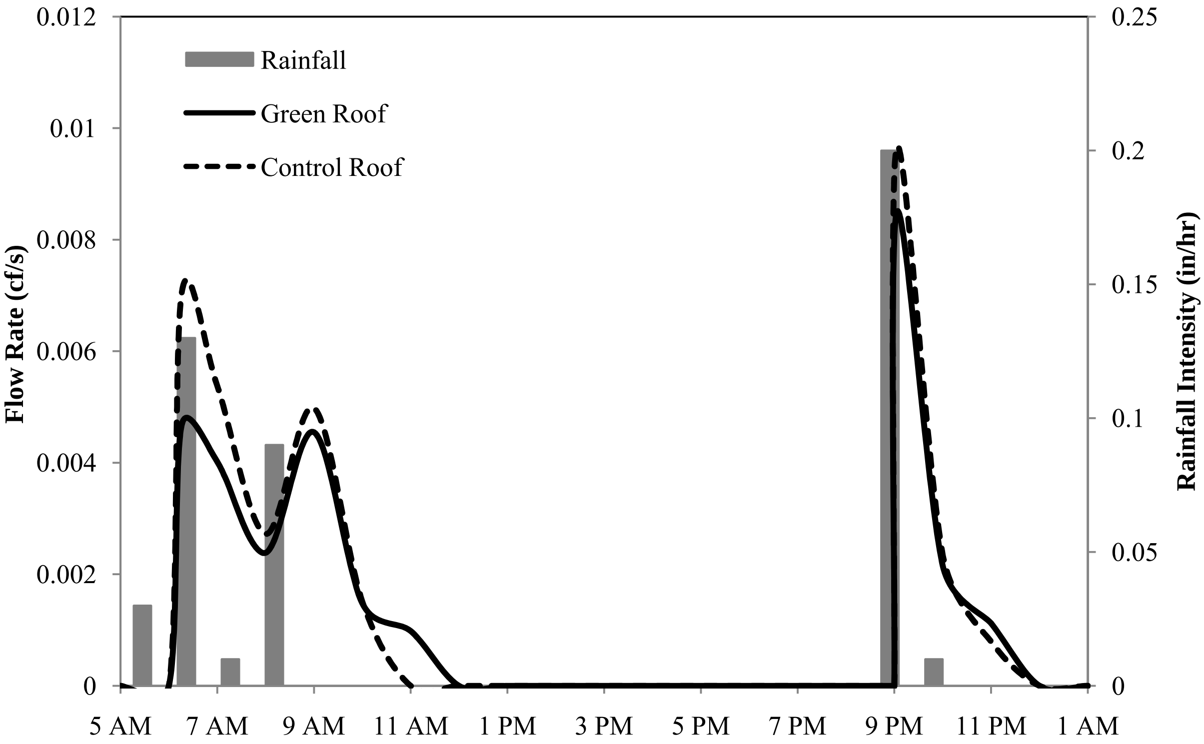


Figure I-33 Runoff Flow Rates and Rainfall intensity – May 18, 2008 Storm (Giant Eagle)

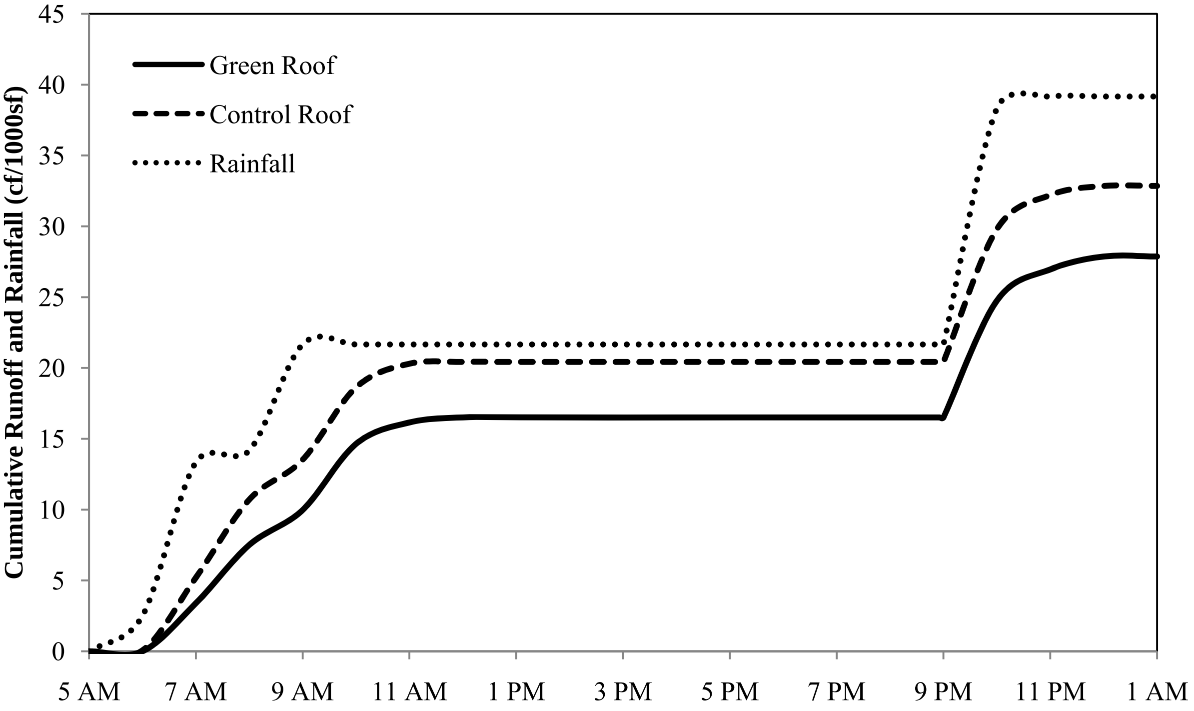


Figure I-34 Runoff and Rainfall Volumes – May 18, 2008 Storm (Giant Eagle)

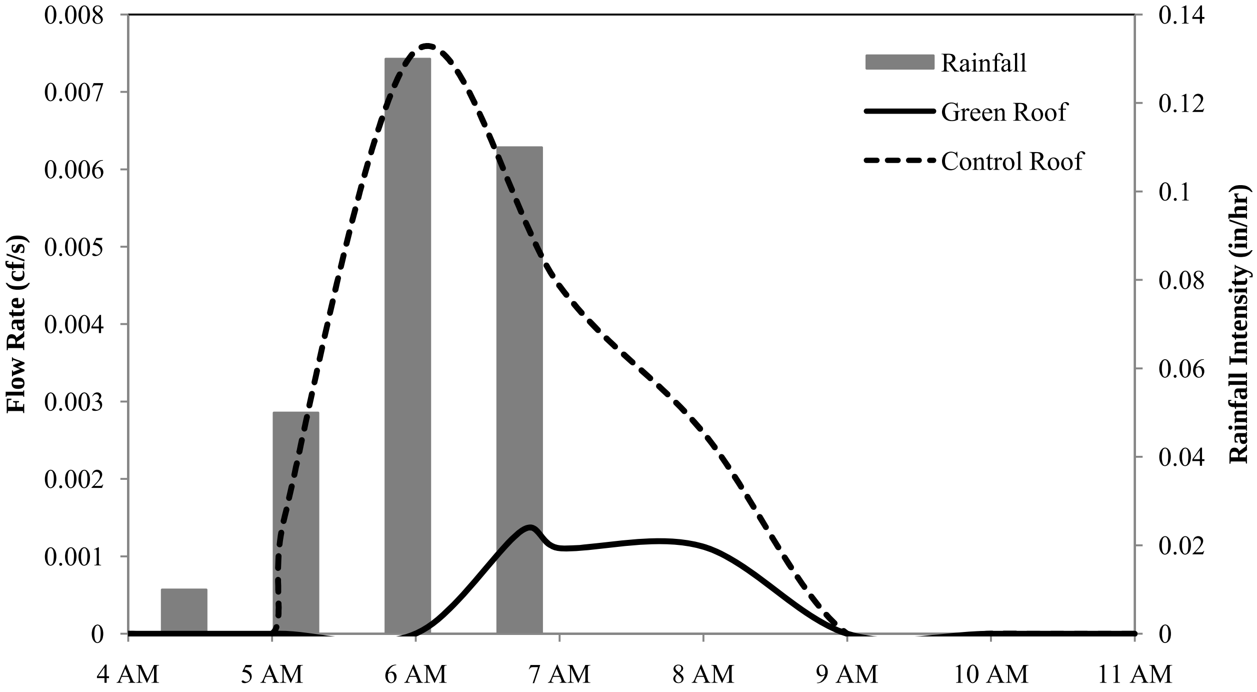


Figure I-35. Runoff Flow Rates and Rainfall Intensity – May 31, 2008 Storm (Homestead)

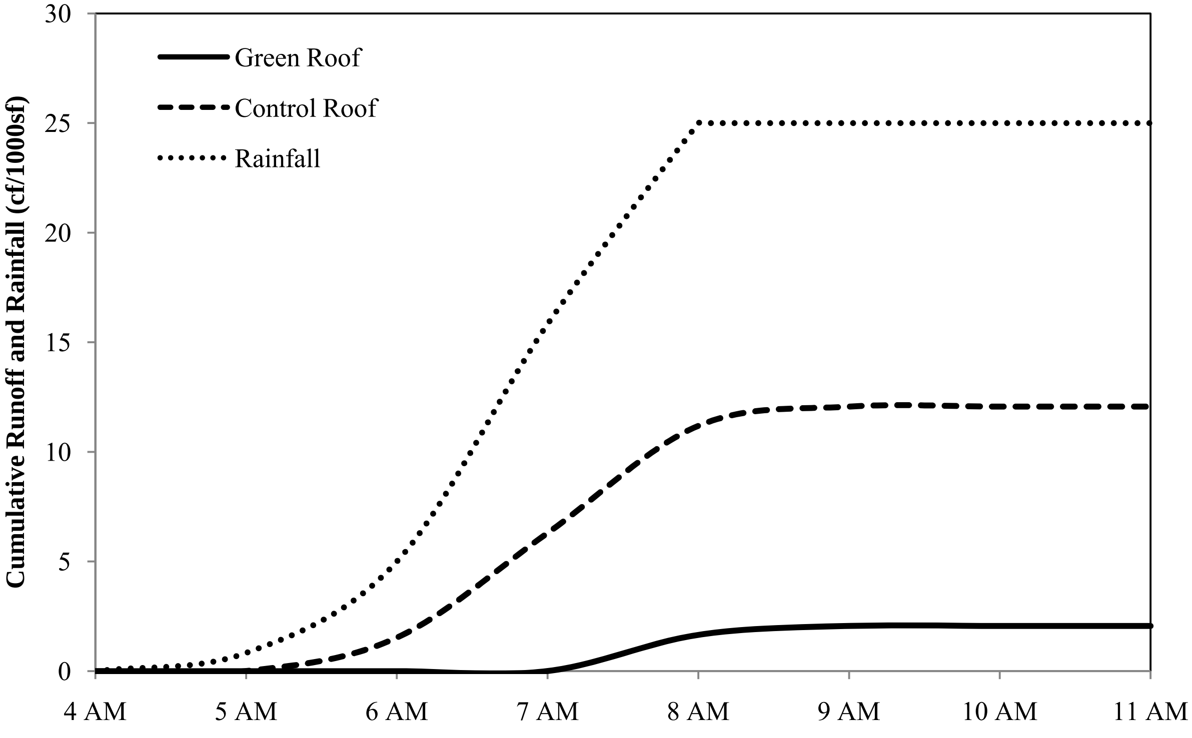


Figure I-36 Runoff and Rainfall Volumes – May 31, 2008 Storm (Homestead)

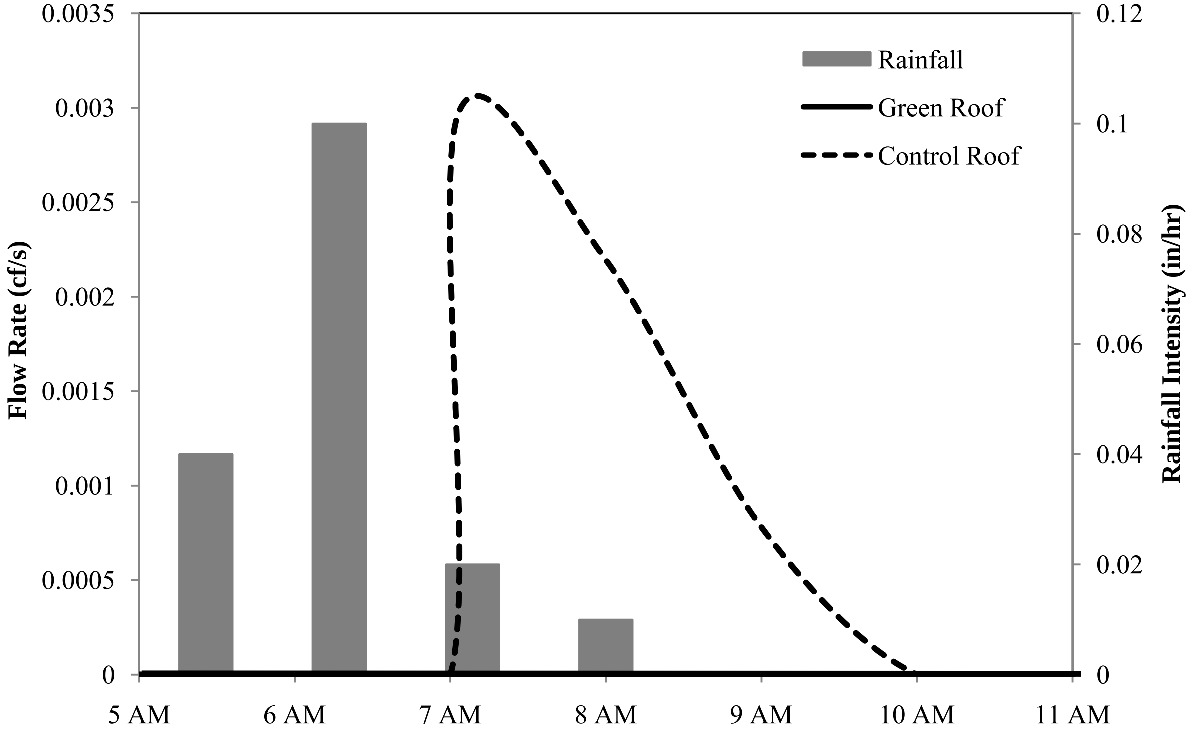


Figure I-37 Runoff Flow Rates and Rainfall intensity – May 31, 2008 Storm (Giant Eagle)

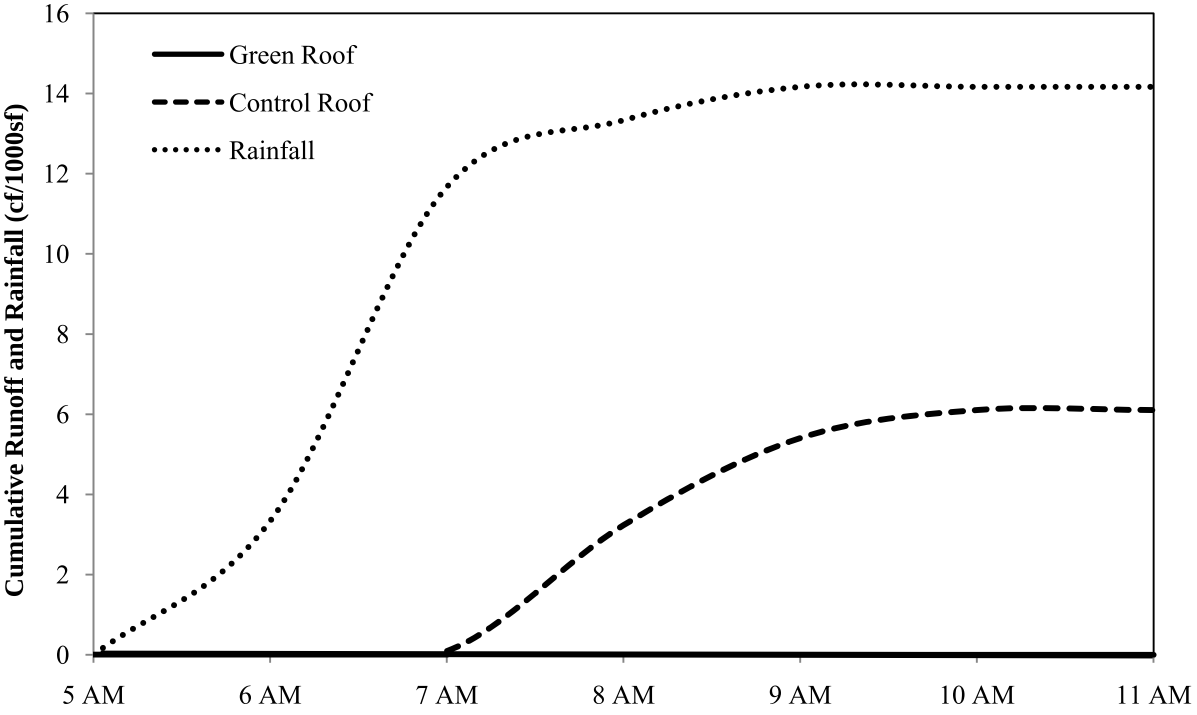


Figure I-38 Runoff and Rainfall Volumes – May 31, 2008 Storm (Giant Eagle)

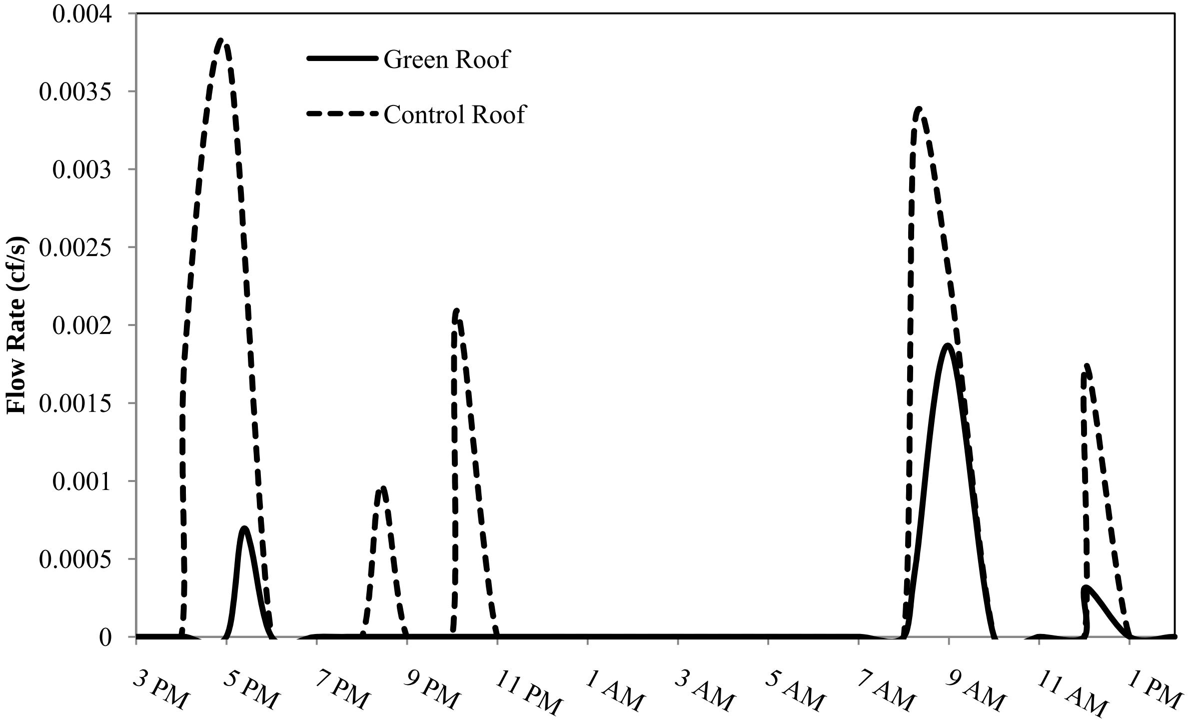


Figure I-39 Runoff Flow Rates – June 3-4, 2008 Storm (Homestead)

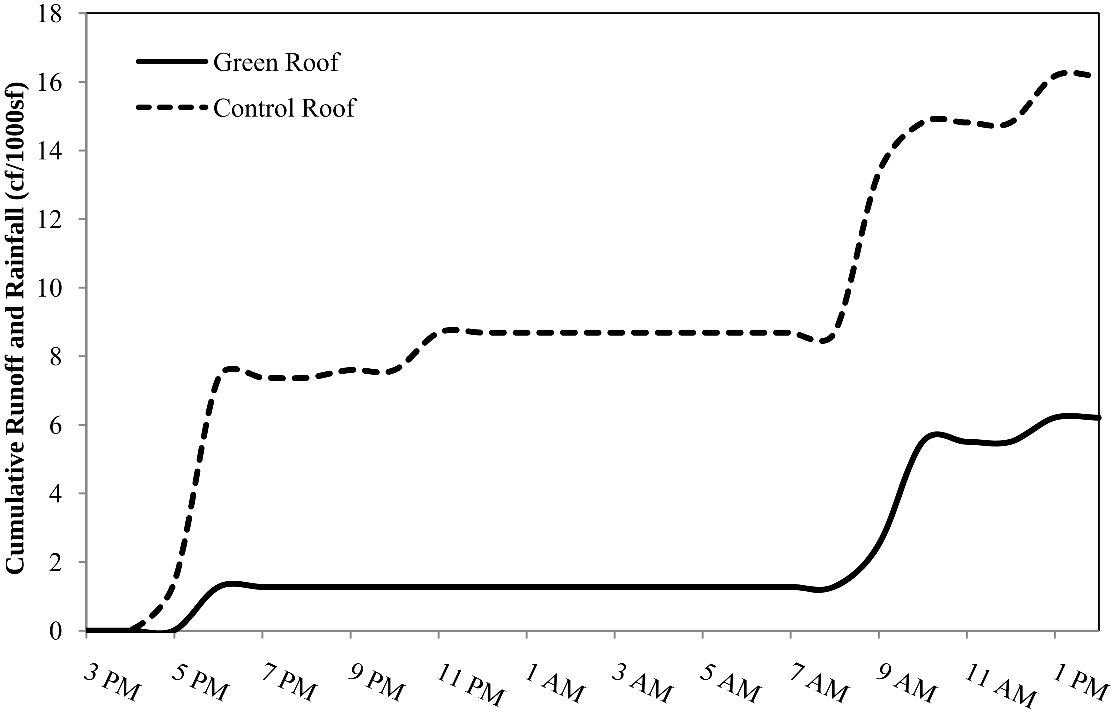


Figure I-40 Runoff Volumes – June 3-4, 2008 Storm (Homestead)

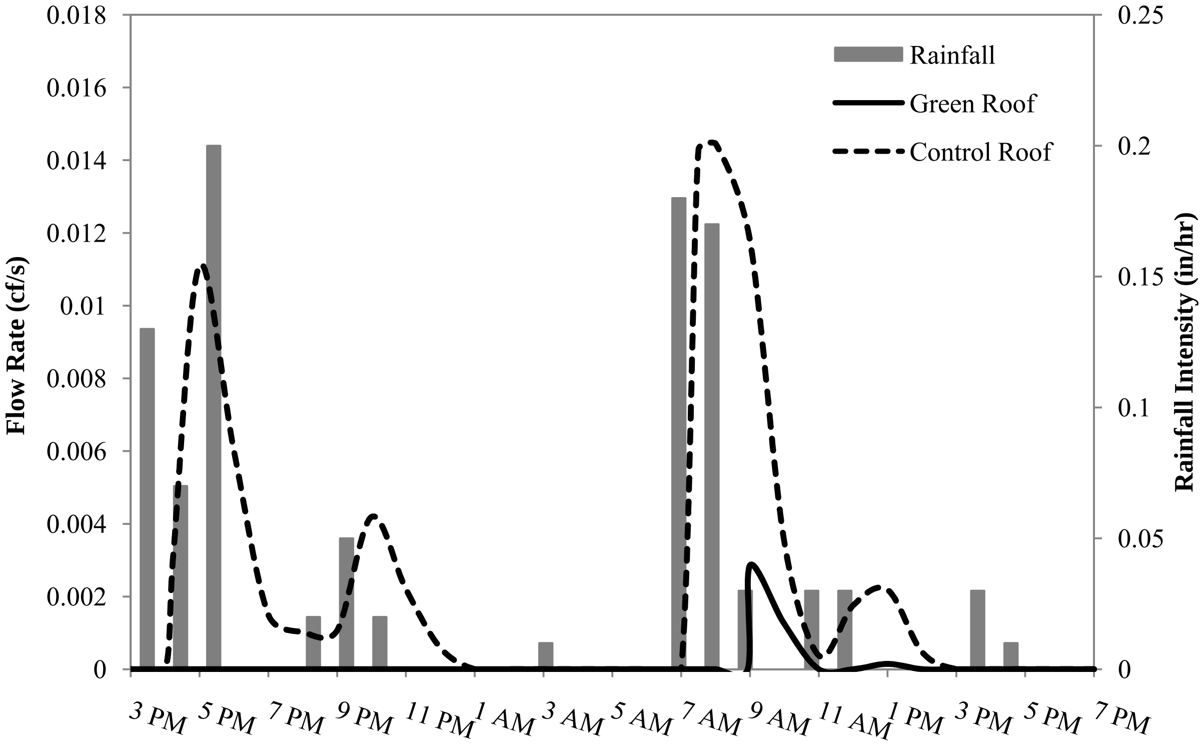


Figure I-41 Runoff Flow Rates and Rainfall intensity – June 3-4, 2008 Storm (Giant Eagle)

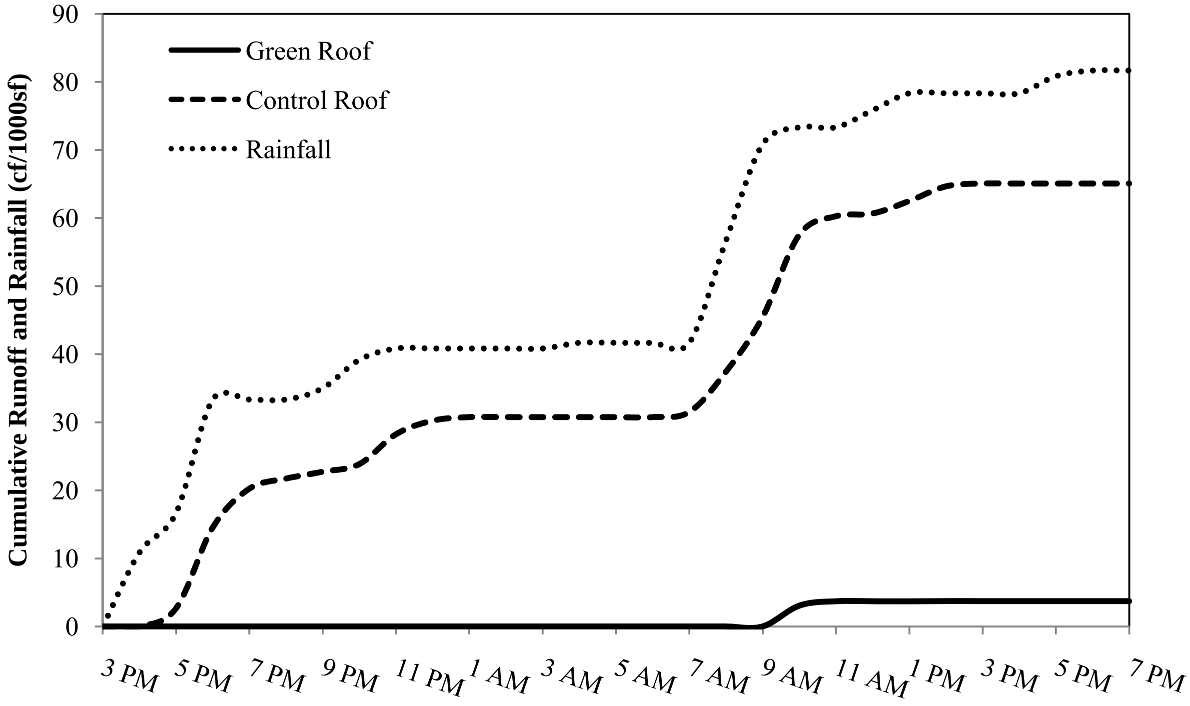


Figure I-42 Runoff and Rainfall Volumes – June 3-4, 2008 Storm (Giant Eagle)

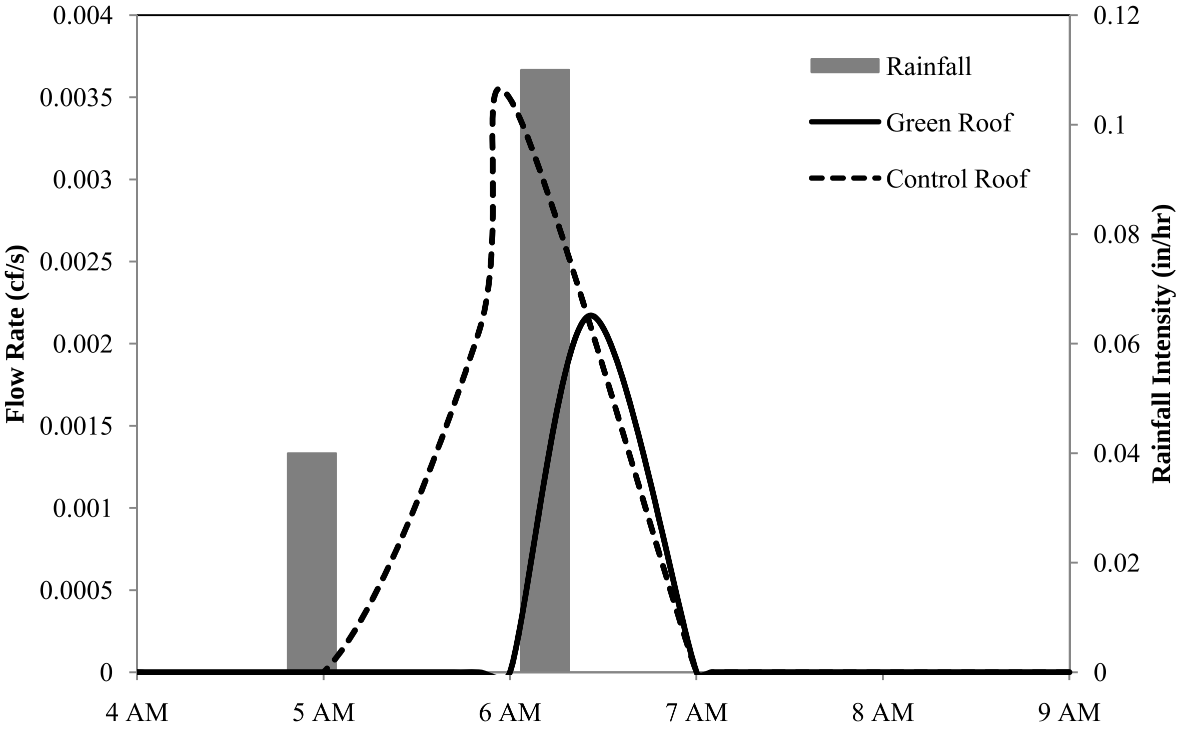


Figure I-43 Runoff Flow Rates and Rainfall Intensity – June 5, 2008 Storm (Homestead)

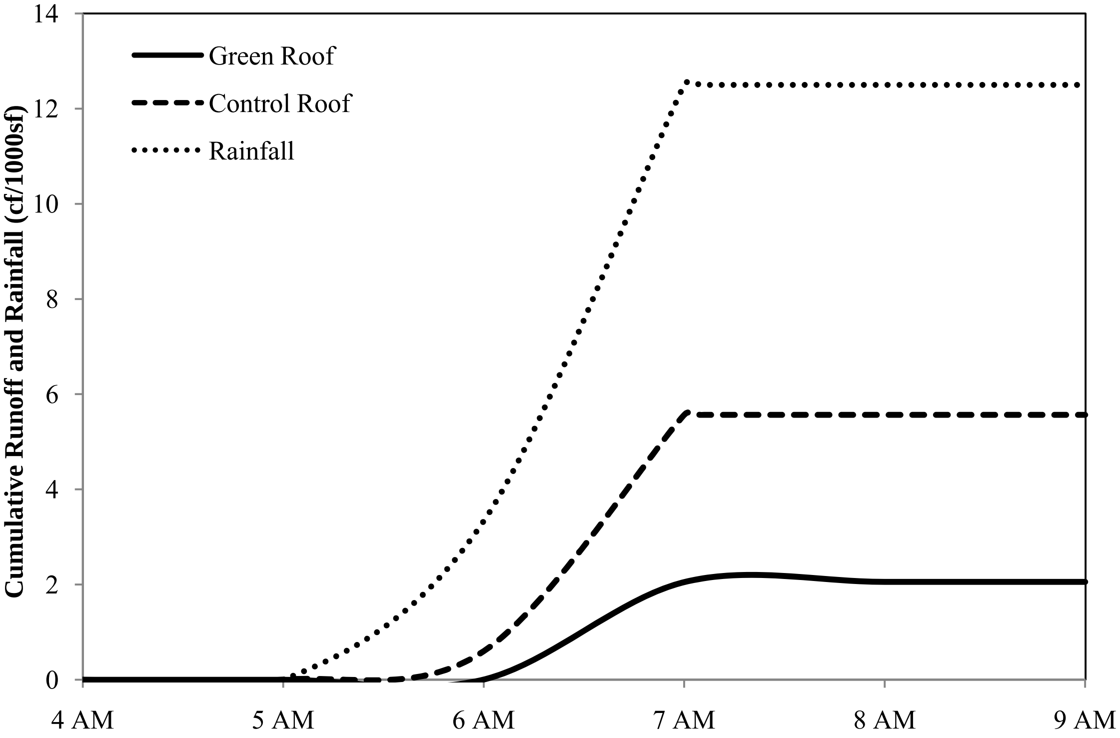


Figure I-44 Runoff and Rainfall Volumes – June 5, 2008 Storm (Homestead)

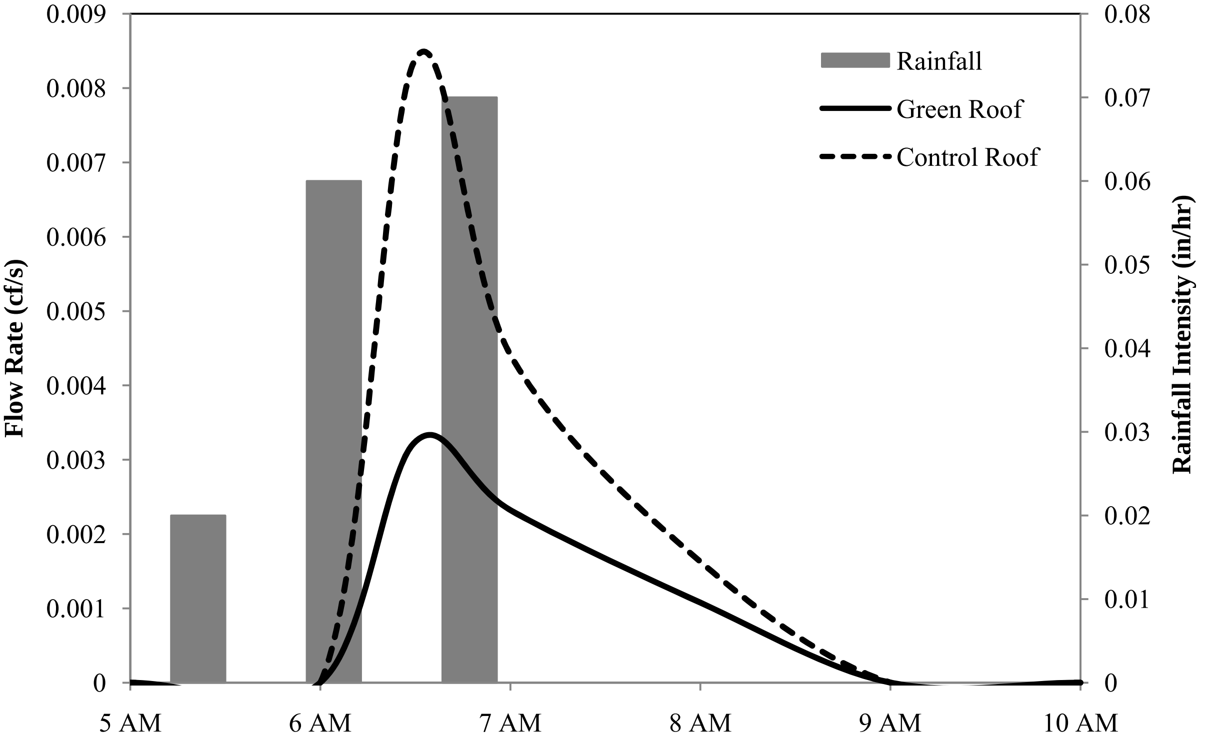


Figure I-45 Runoff Flow Rates and Rainfall intensity – June 5, 2008 Storm (Giant Eagle)

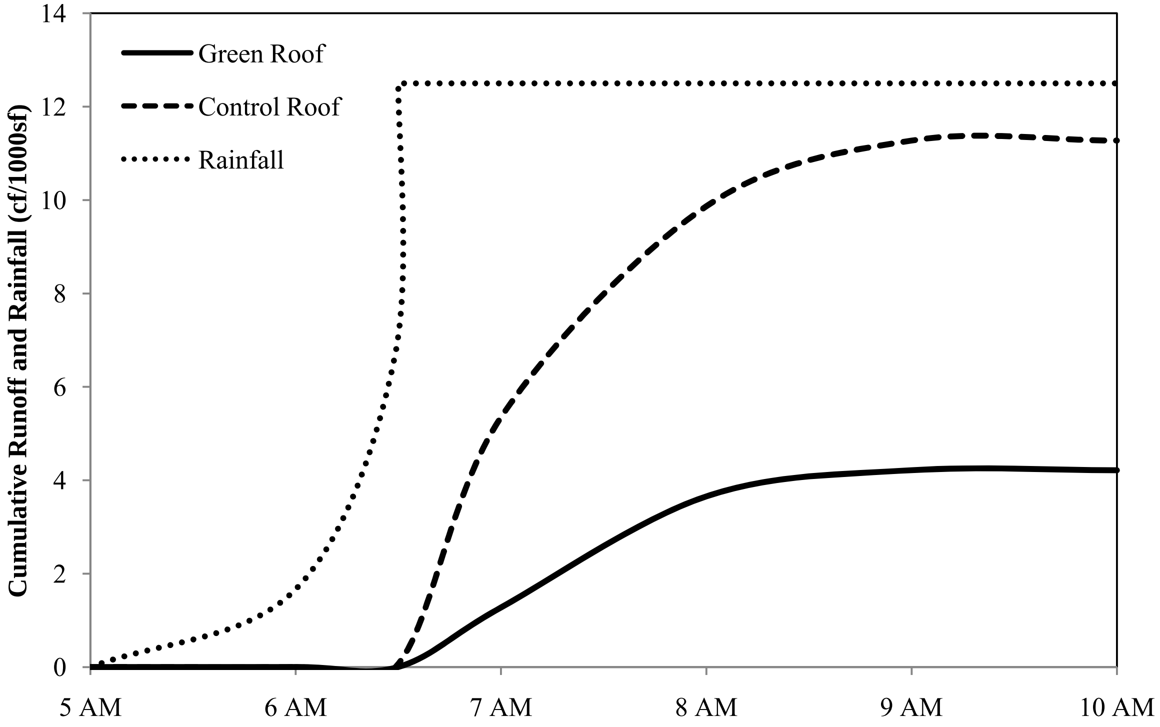


Figure I-46 Runoff and Rainfall Volumes – June 5, 2008 Storm (Giant Eagle)

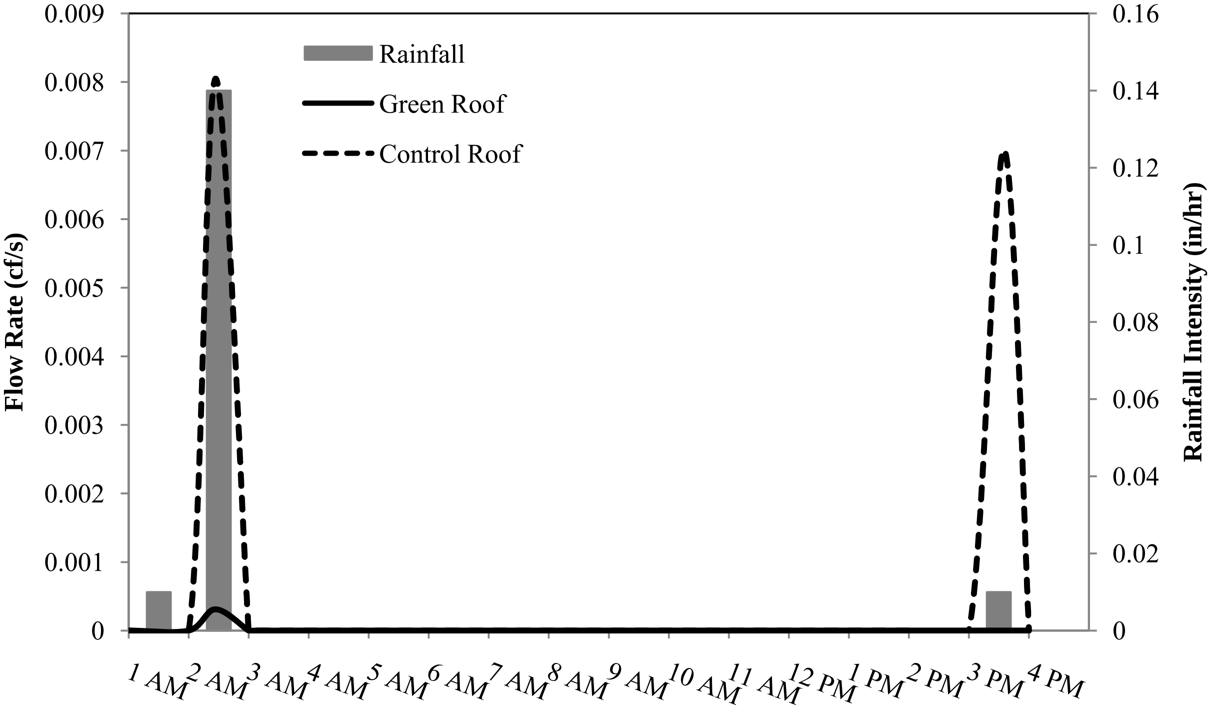


Figure I-47 Runoff Flow Rates and Rainfall Intensity – June 16, 2008 Storm (Homestead)

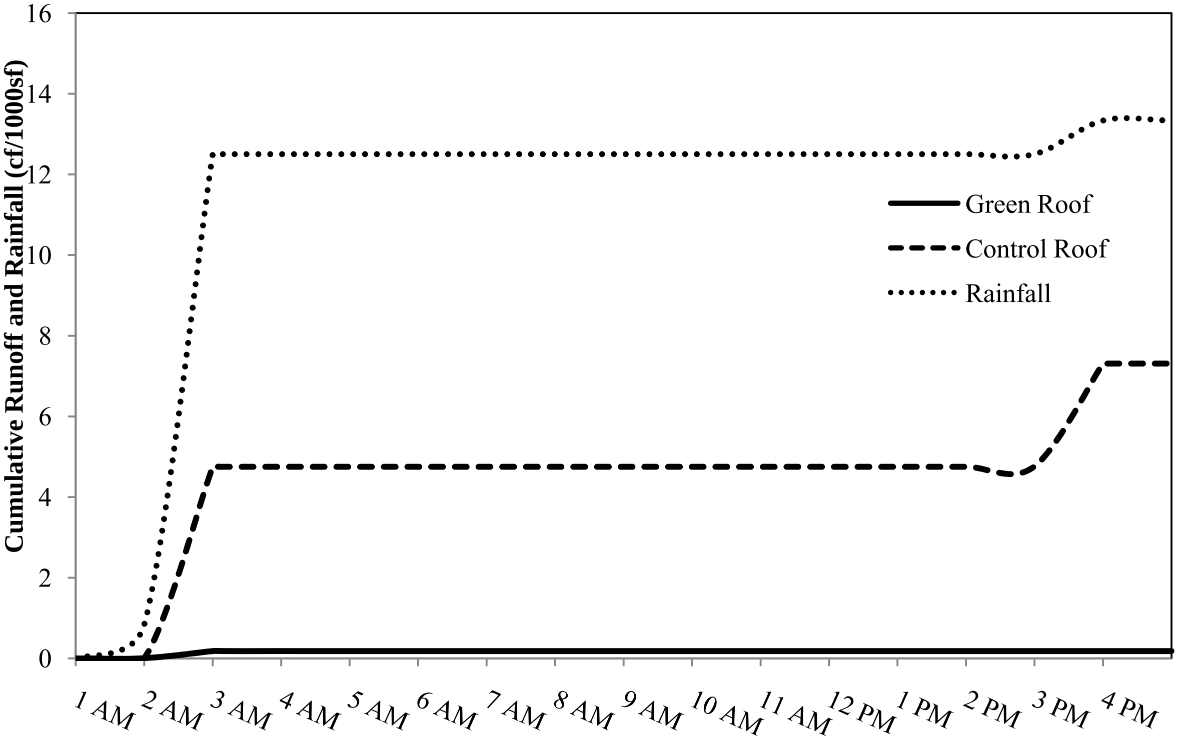


Figure I-48 Runoff and Rainfall Volumes – June 16, 2008 Storm (Homestead)

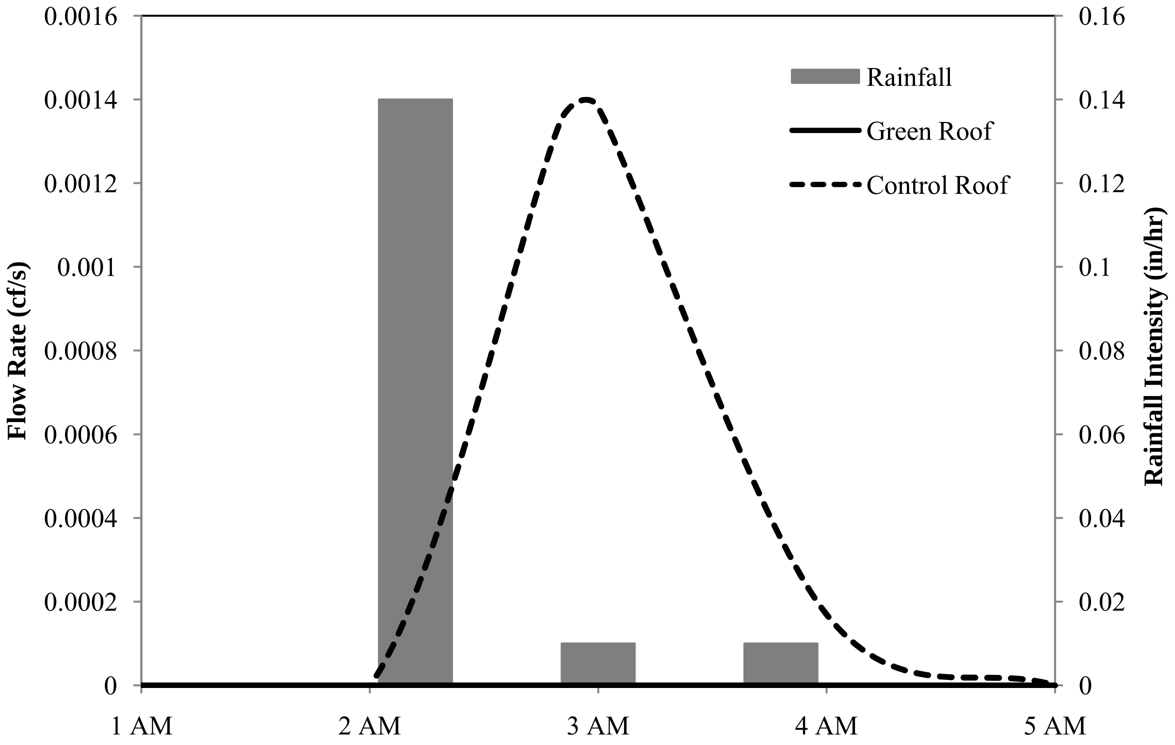


Figure I-49 Runoff Flow Rates and Rainfall intensity – June 16, 2008 Storm (Giant Eagle)

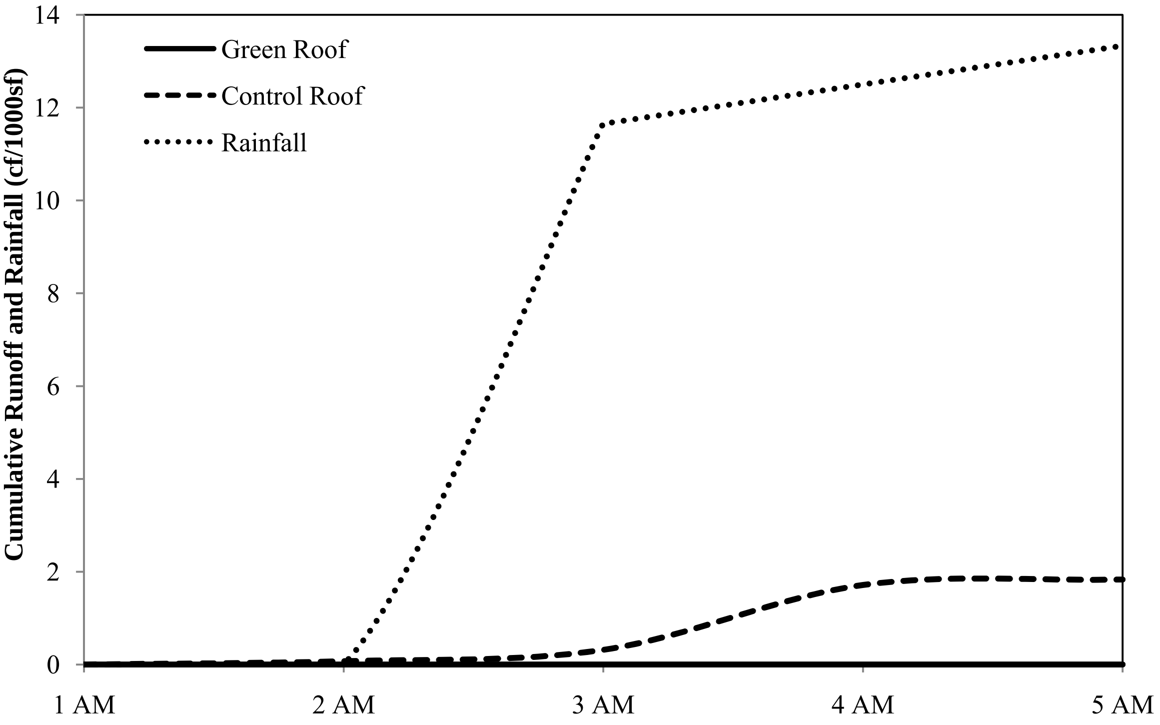


Figure I-50 Runoff and Rainfall Volumes – June 16, 2008 Storm (Giant Eagle)

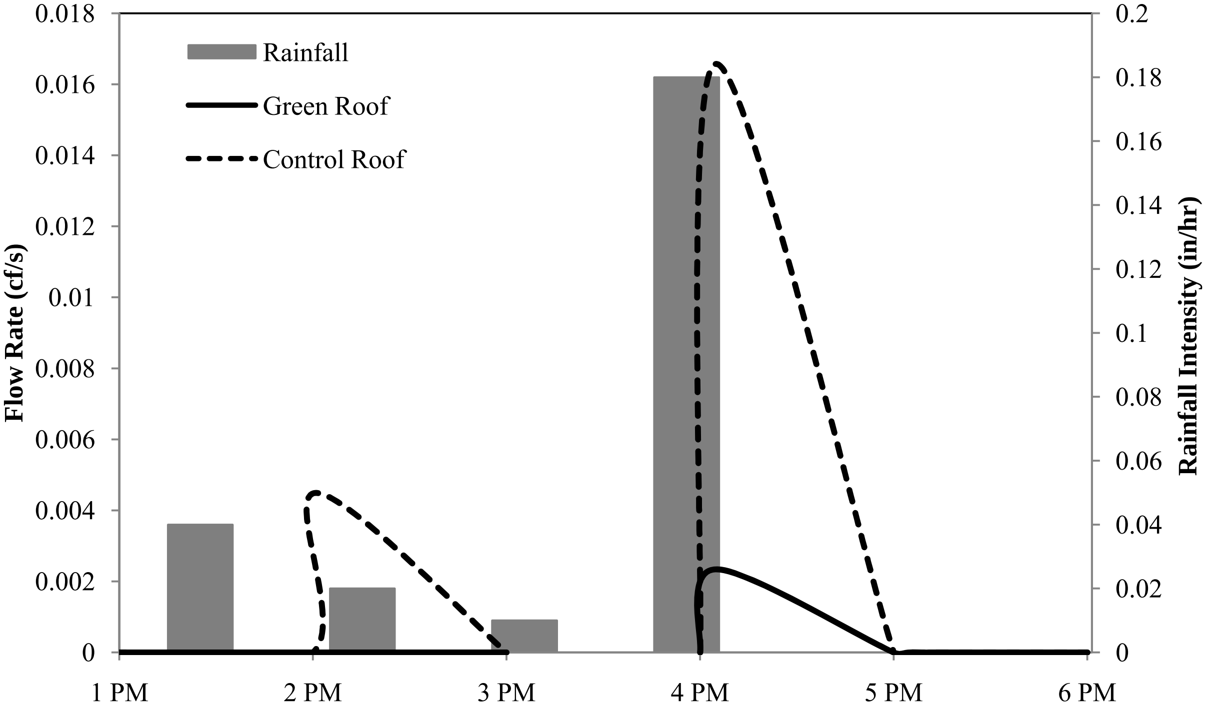


Figure I-51 Runoff Flow Rates and Rainfall Intensity – June 20, 2008 Storm (Homestead)

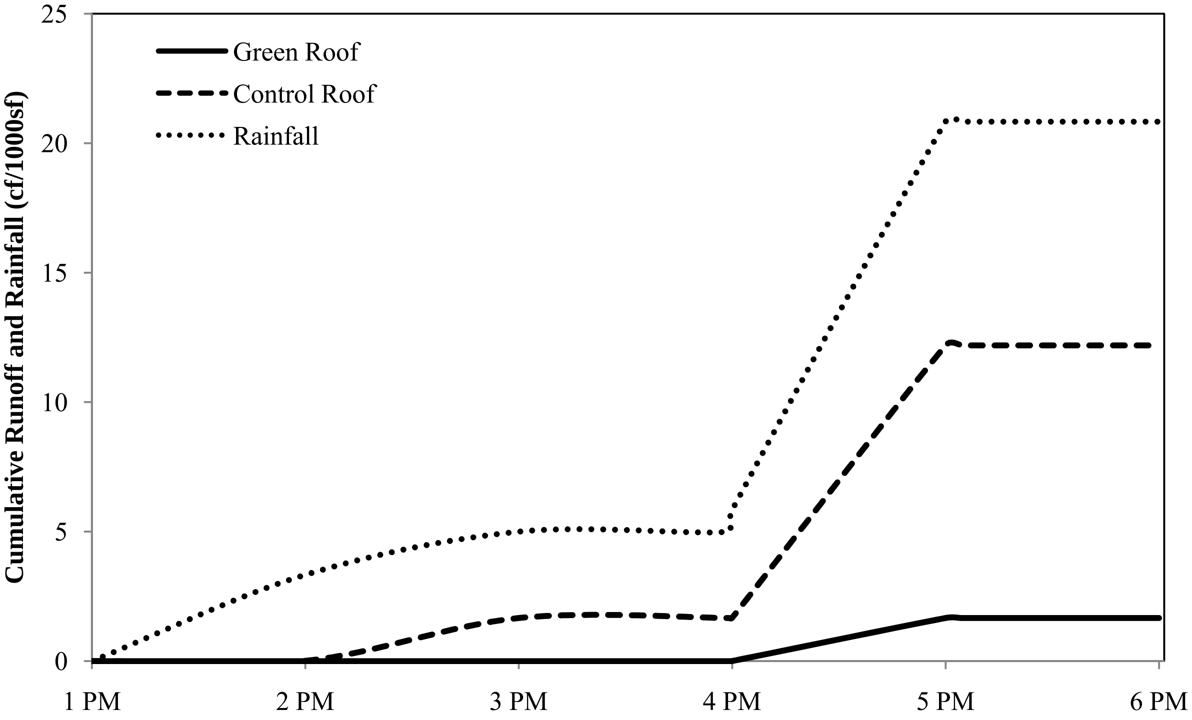


Figure I-52 Runoff and Rainfall Volumes – June 20, 2008 Storm (Homestead)

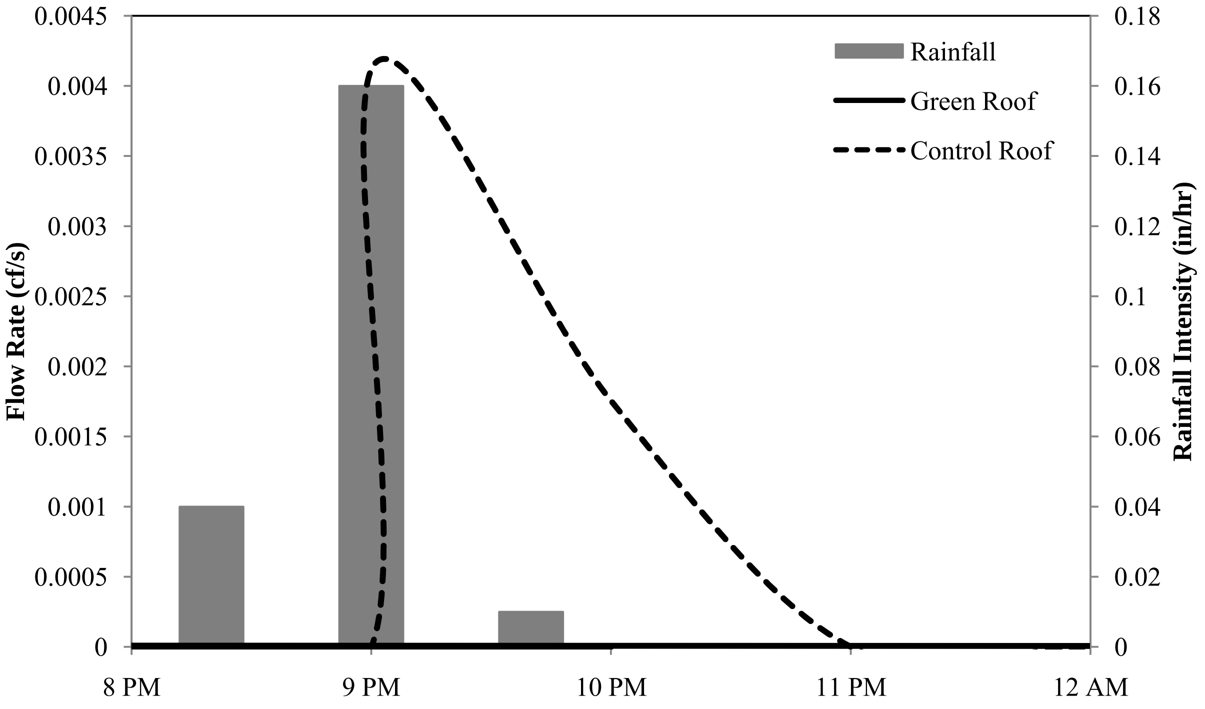


Figure I-53 Runoff Flow Rates and Rainfall Intensity – June 21, 2008 Storm (Homestead)

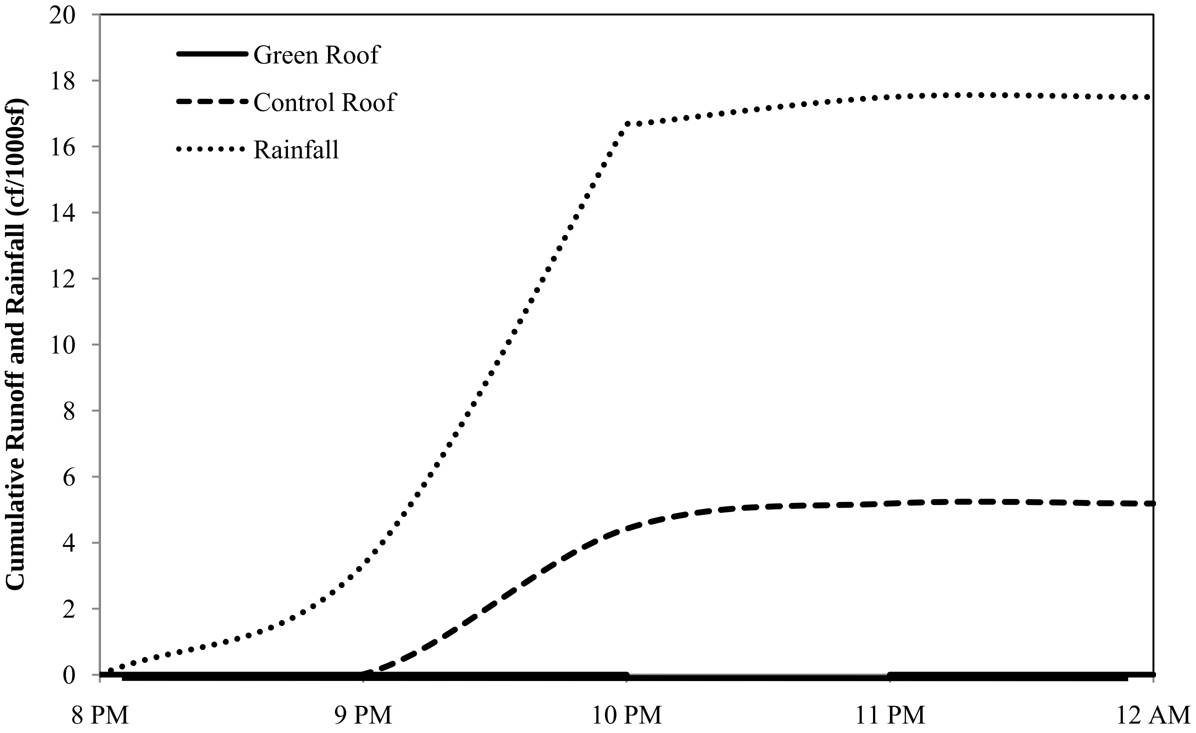


Figure I-54 Runoff and Rainfall Volumes – June 21, 2008 Storm (Homestead)

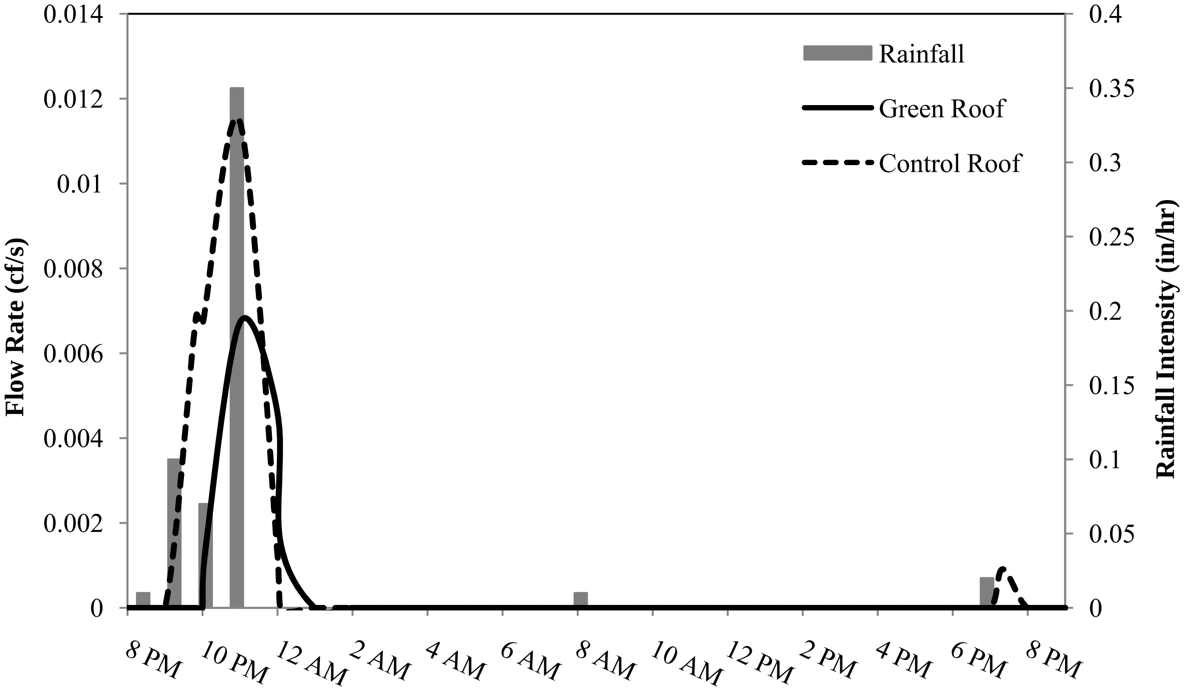


Figure I-55 Runoff Flow Rates and Rainfall Intensity – June 22-23, 2008 Storm (Homestead)

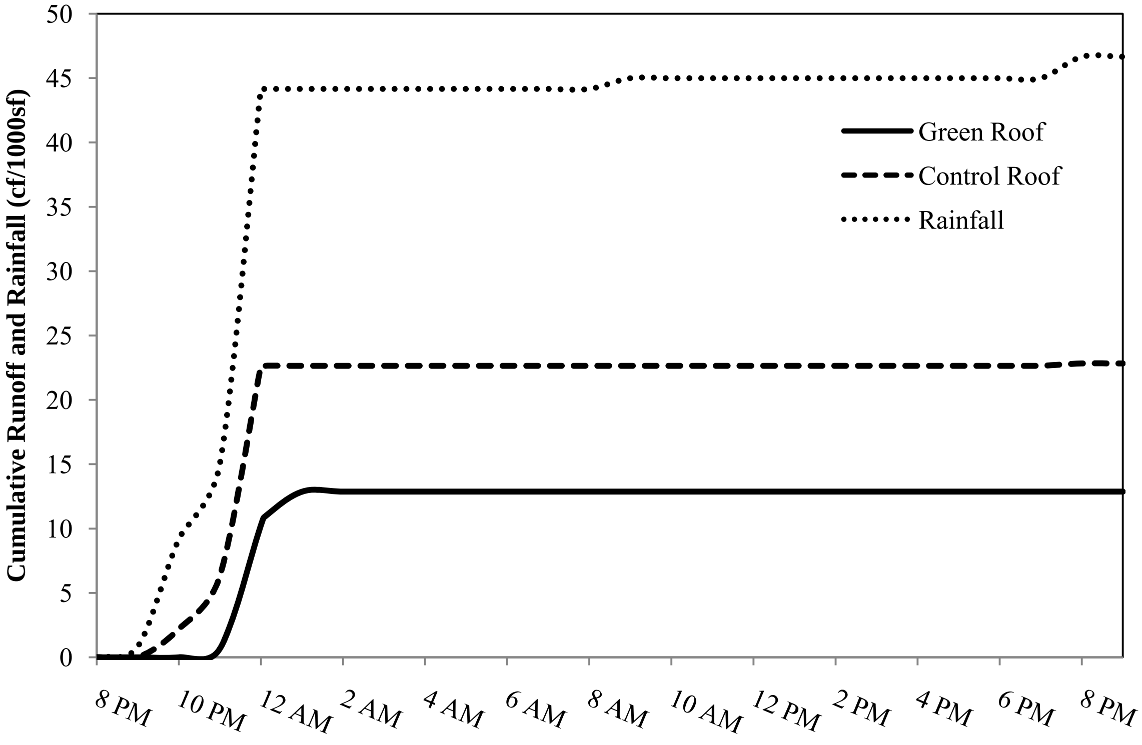


Figure I-56 Runoff and Rainfall Volumes – June 22-23, 2008 Storm (Homestead)

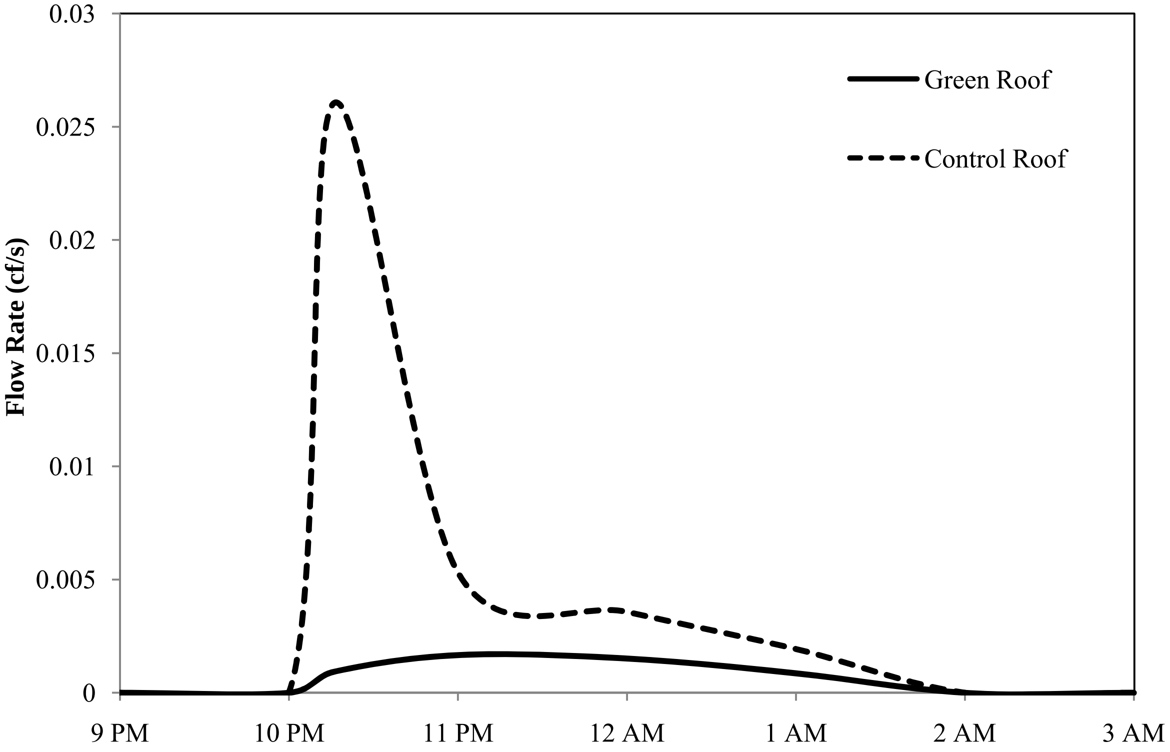


Figure I-57 Runoff Flow Rates – June 22-23, 2008 Storm (Giant Eagle)

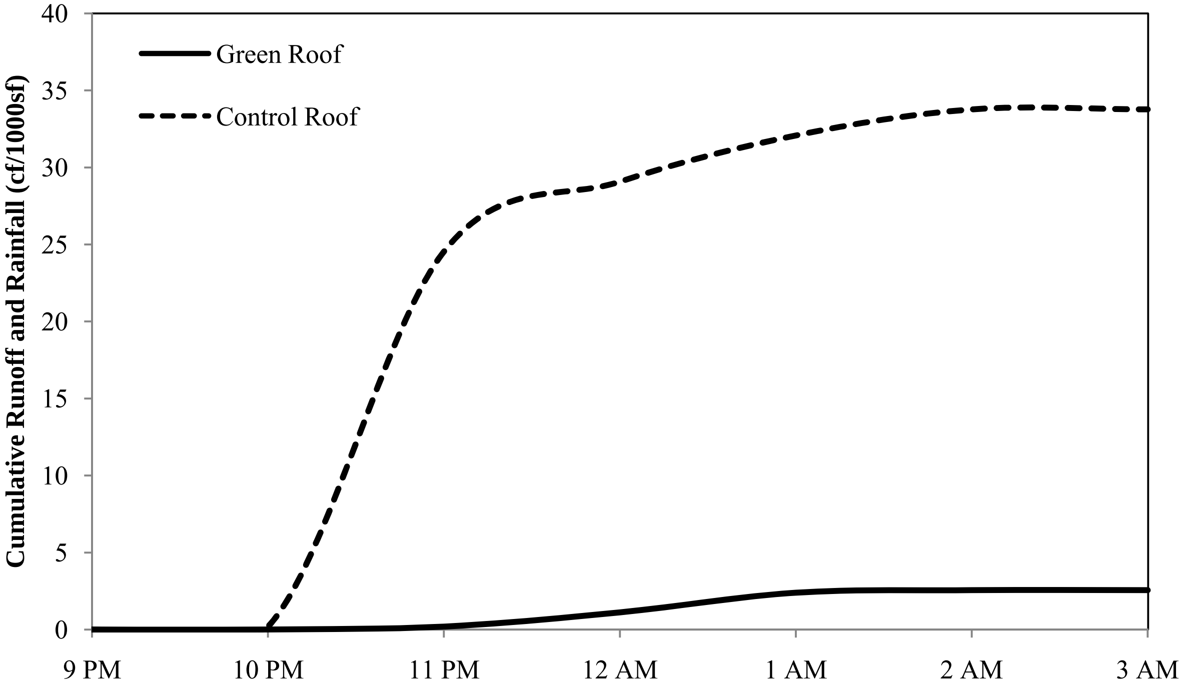


Figure I-58 Runoff Volumes – June 22-23, 2008 Storm (Giant Eagle)

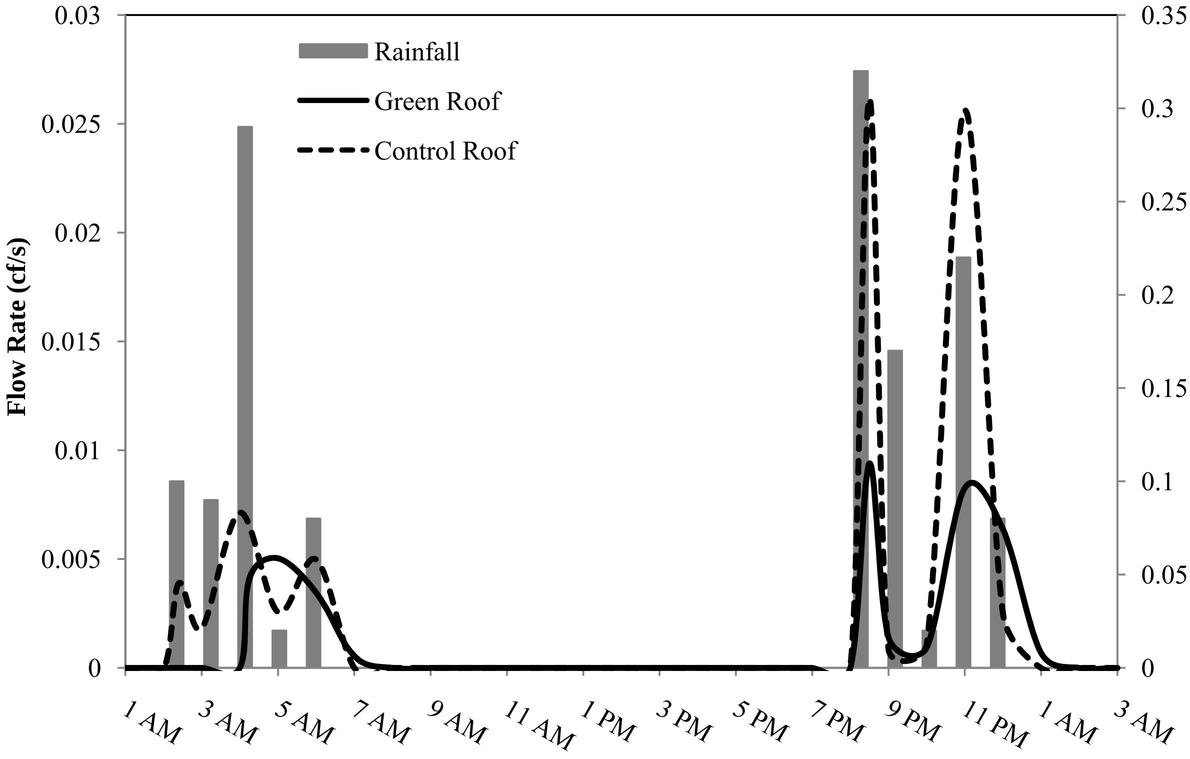


Figure I-59 Runoff Flow Rates and Rainfall Intensity – June 26-27, 2008 Storm (Homestead)

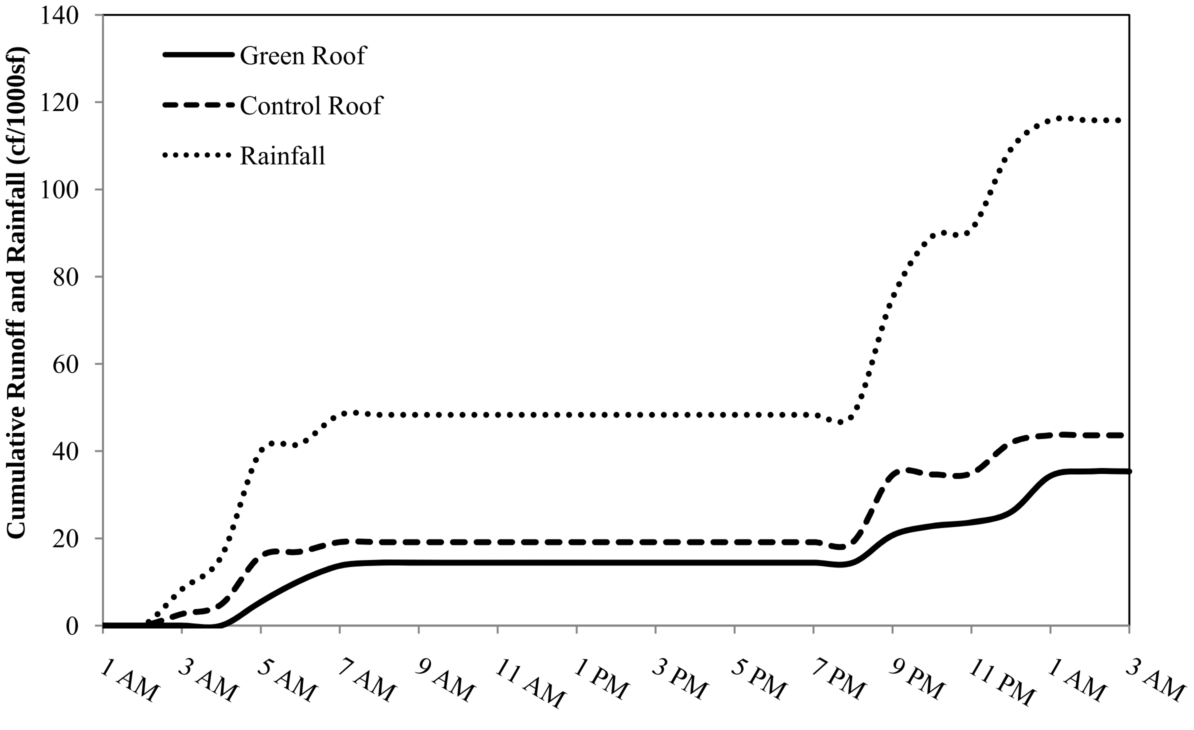


Figure I-60 Runoff and Rainfall Volumes – June 26-27, 2008 Storm (Homestead)

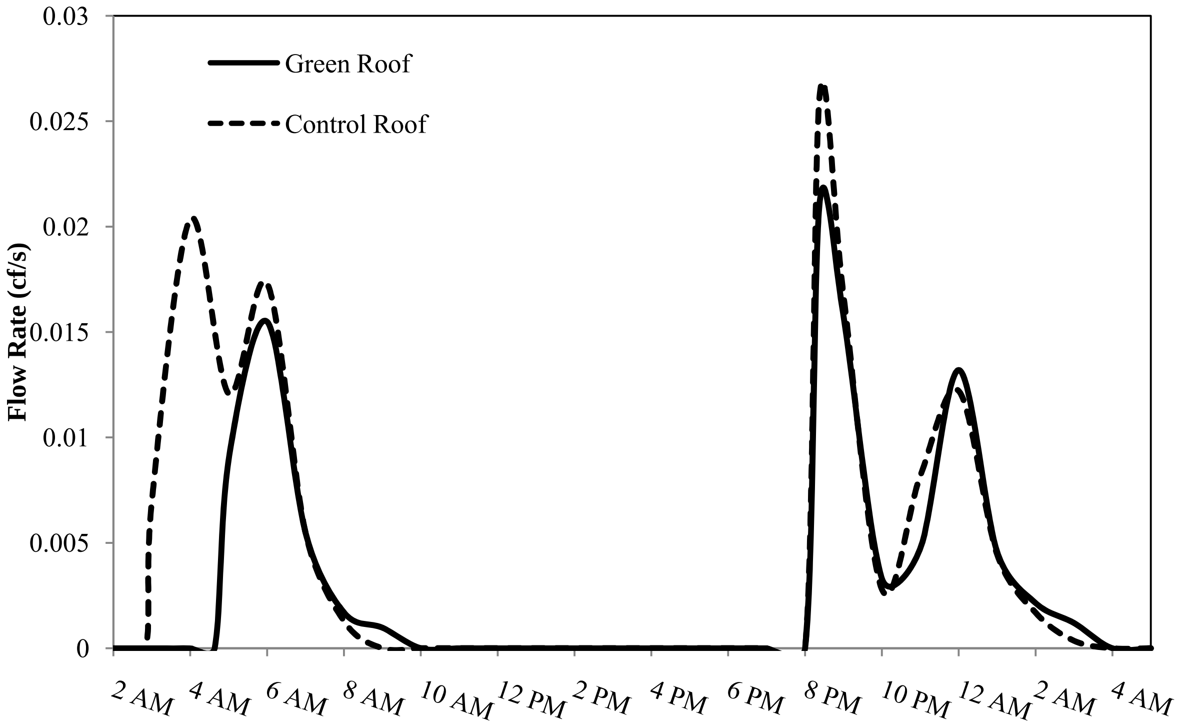


Figure I-61 Runoff Flow Rates – June 26-27, 2008 Storm (Giant Eagle)

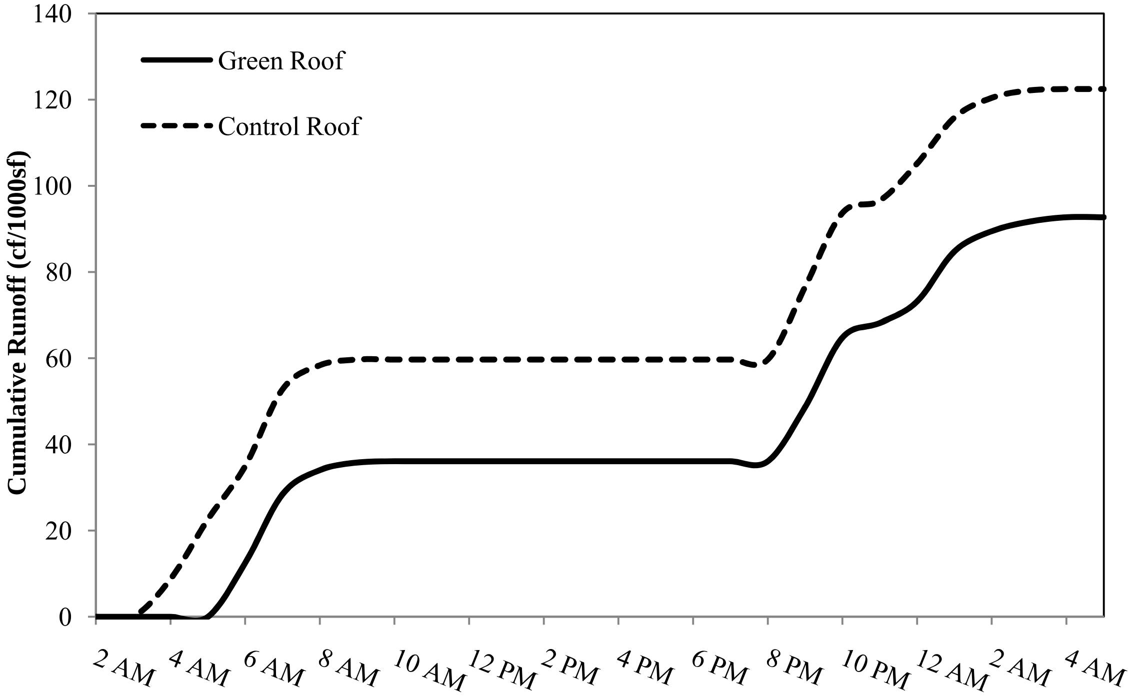


Figure I-62 Runoff Volumes – June 26-27, 2008 Storm (Giant Eagle)

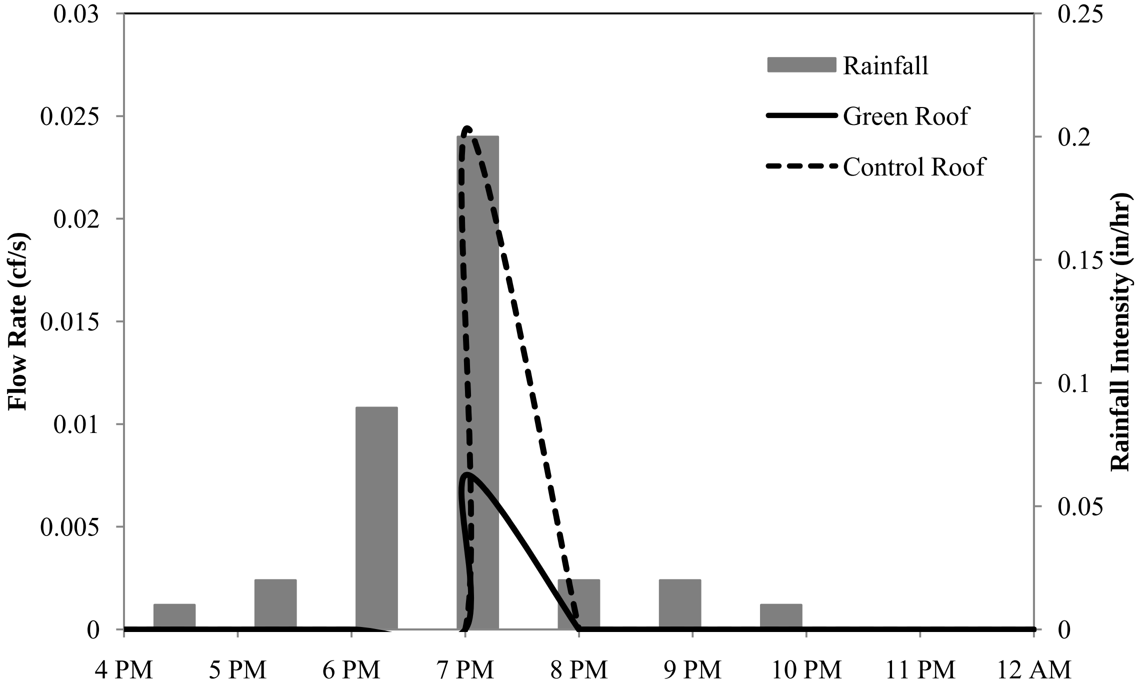


Figure I-63 Runoff Flow Rates and Rainfall Intensity – June 28, 2008 Storm (Homestead)

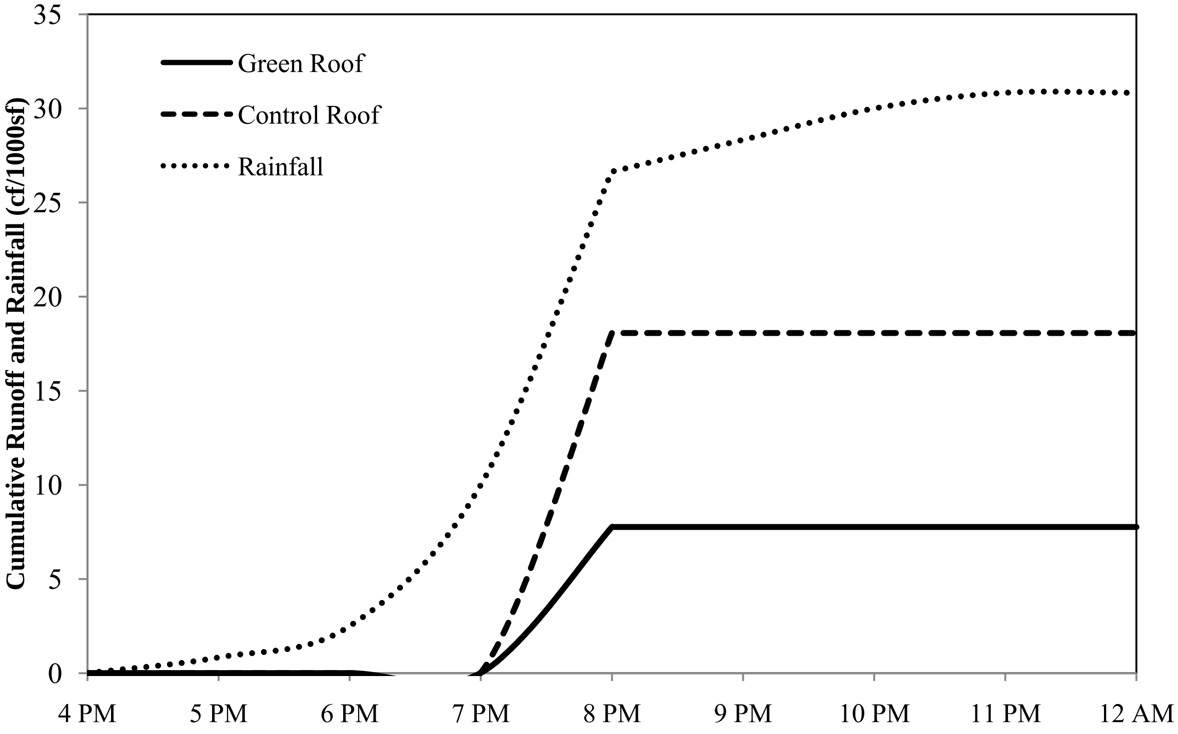


Figure I-64 Runoff and Rainfall Volumes – June 28, 2008 Storm (Homestead)

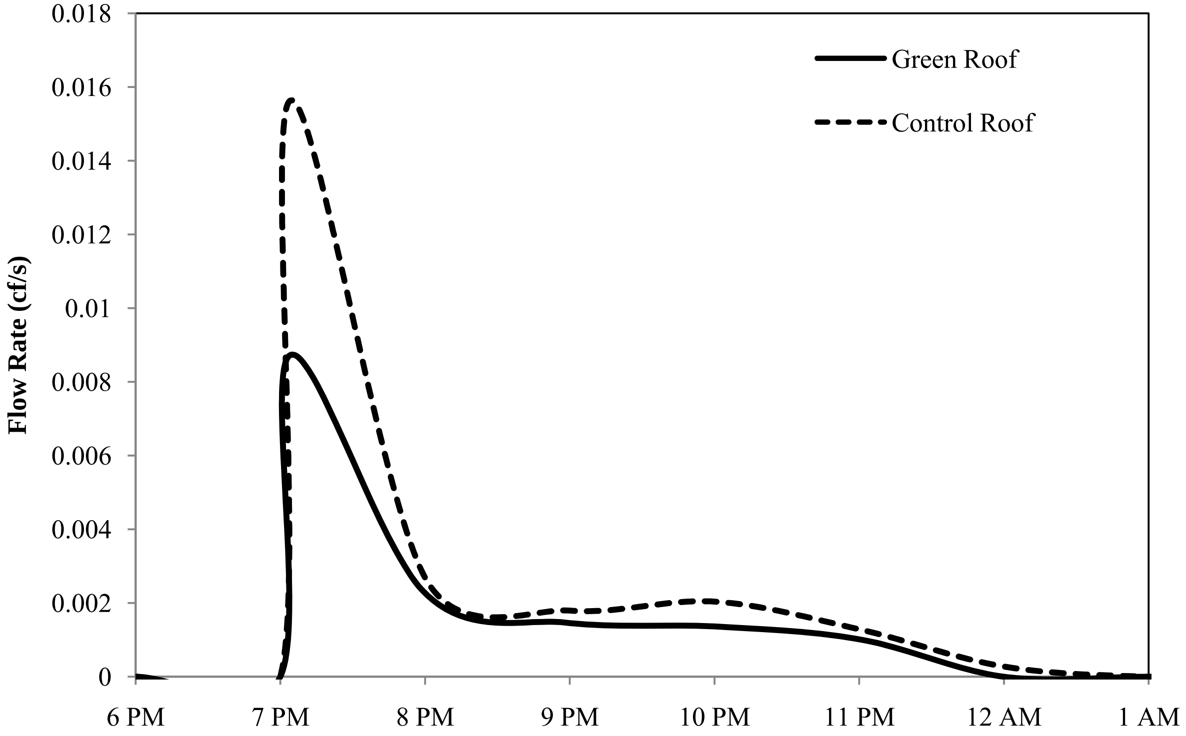


Figure I-65 Runoff Flow Rates – June 28, 2008 Storm (Giant Eagle)

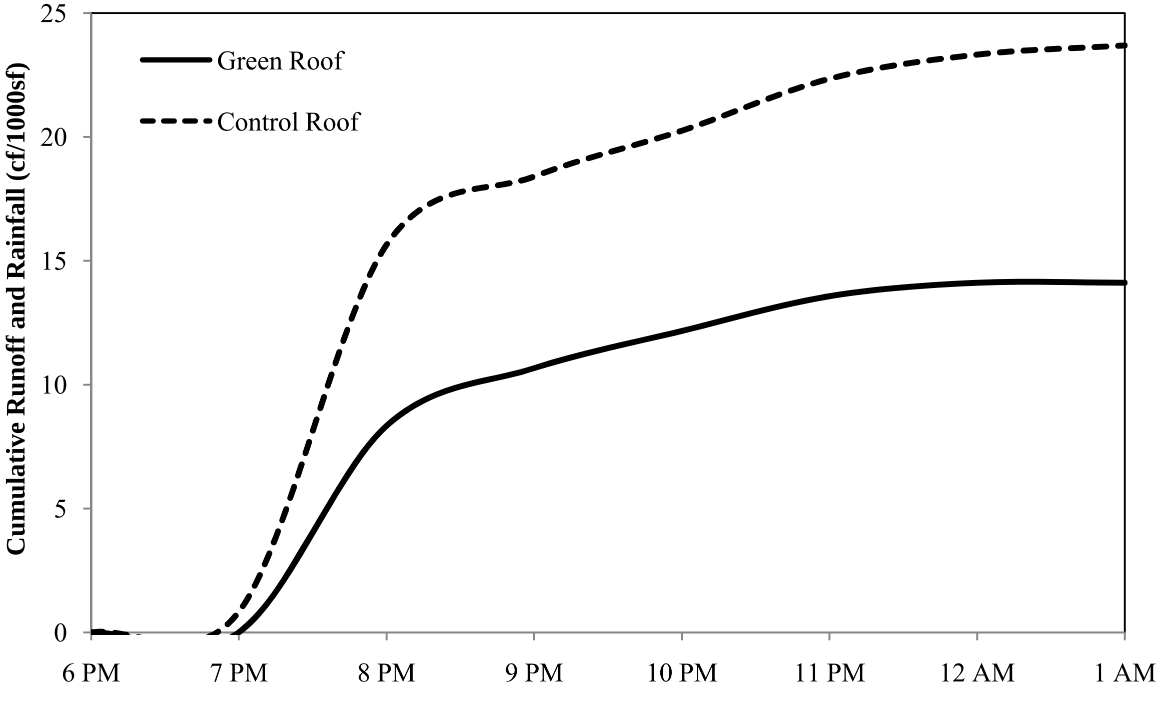


Figure I-66 Runoff Volumes – June 28, 2008 Storm (Giant Eagle)

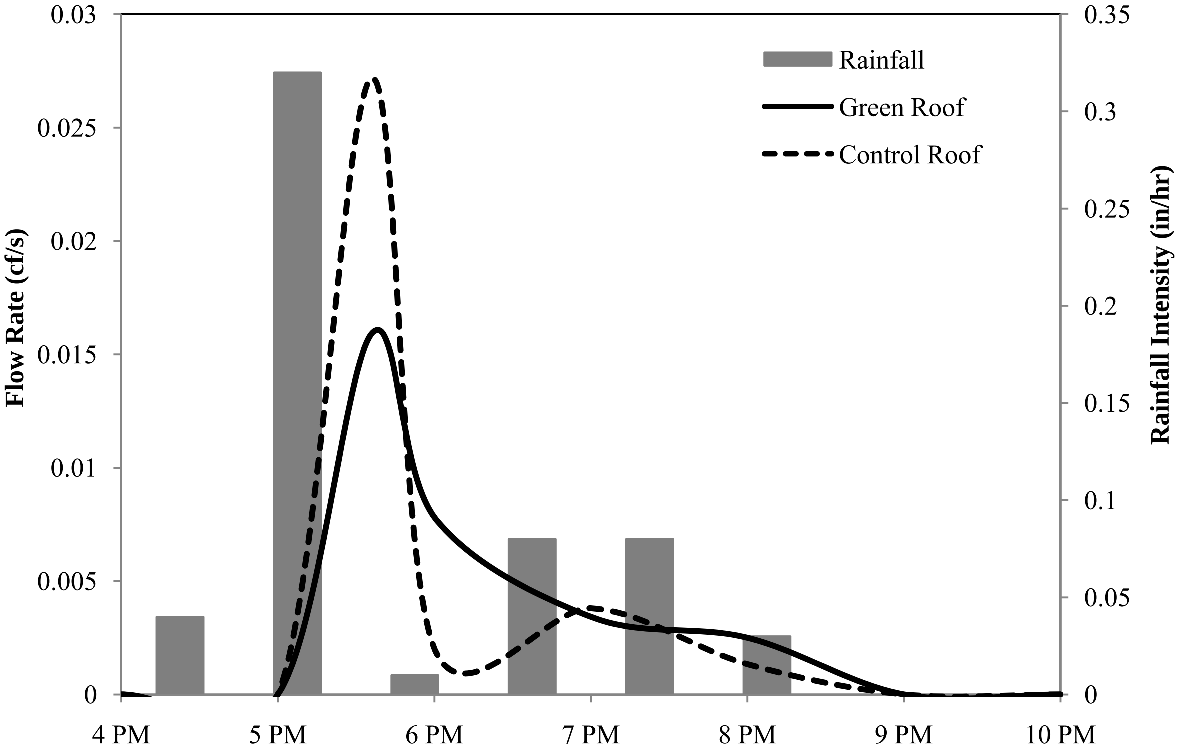


Figure I-67 Runoff Flow Rates and Rainfall Intensity – June 29, 2008 Storm (Homestead)

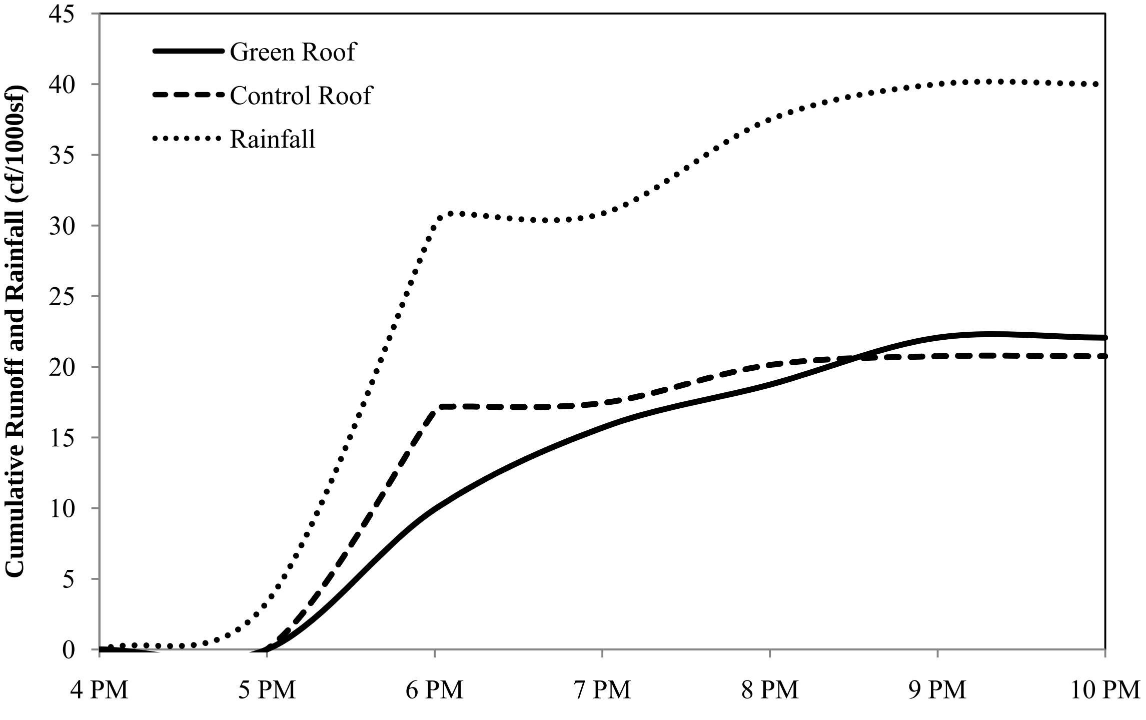


Figure I-68 Runoff and Rainfall Volumes – June 29, 2008 Storm (Homestead)

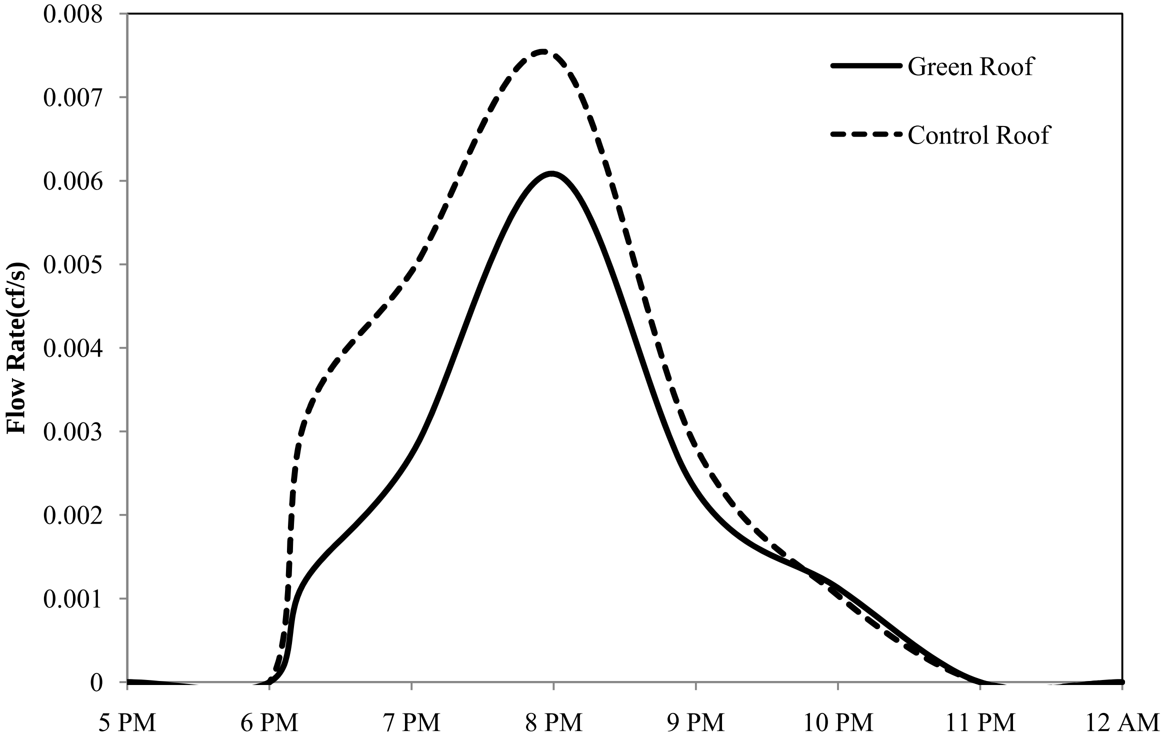


Figure I-69 Runoff Flow Rates – June 29, 2008 Storm (Giant Eagle)

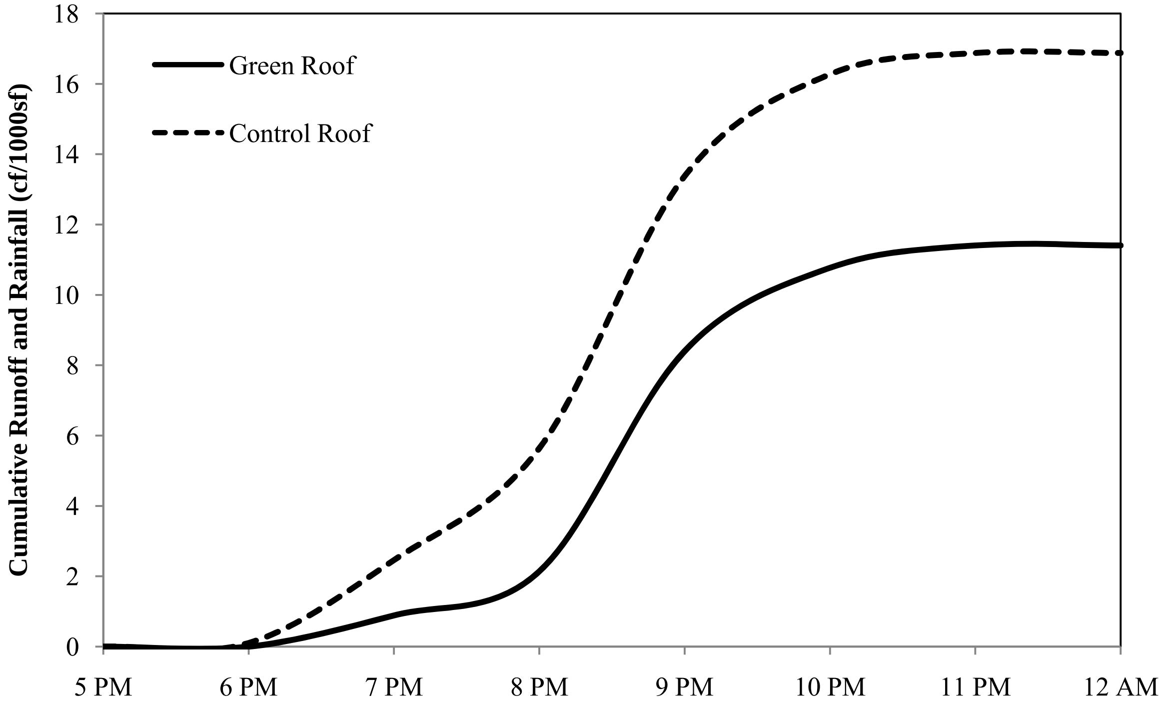


Figure I-70 Runoff Volumes – June 29, 2008 Storm (Giant Eagle)

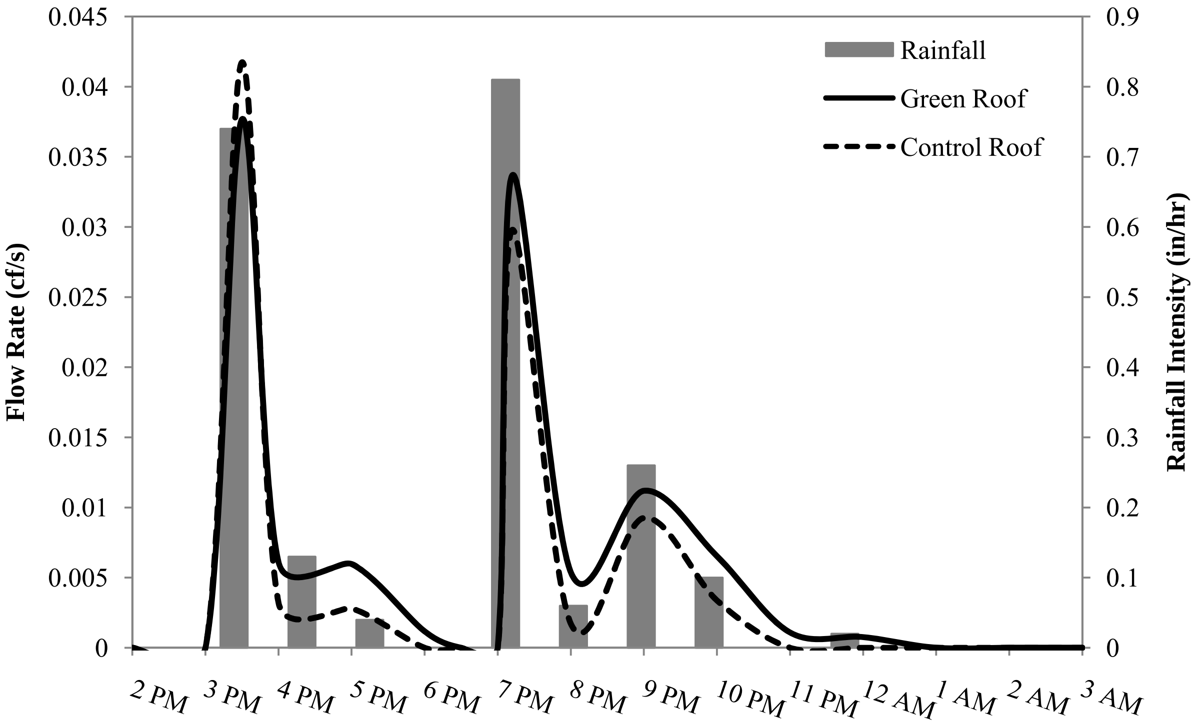


Figure I-71 Runoff Flow Rates and Rainfall Intensity – June 30-July1, 2008 Storm (Homestead)

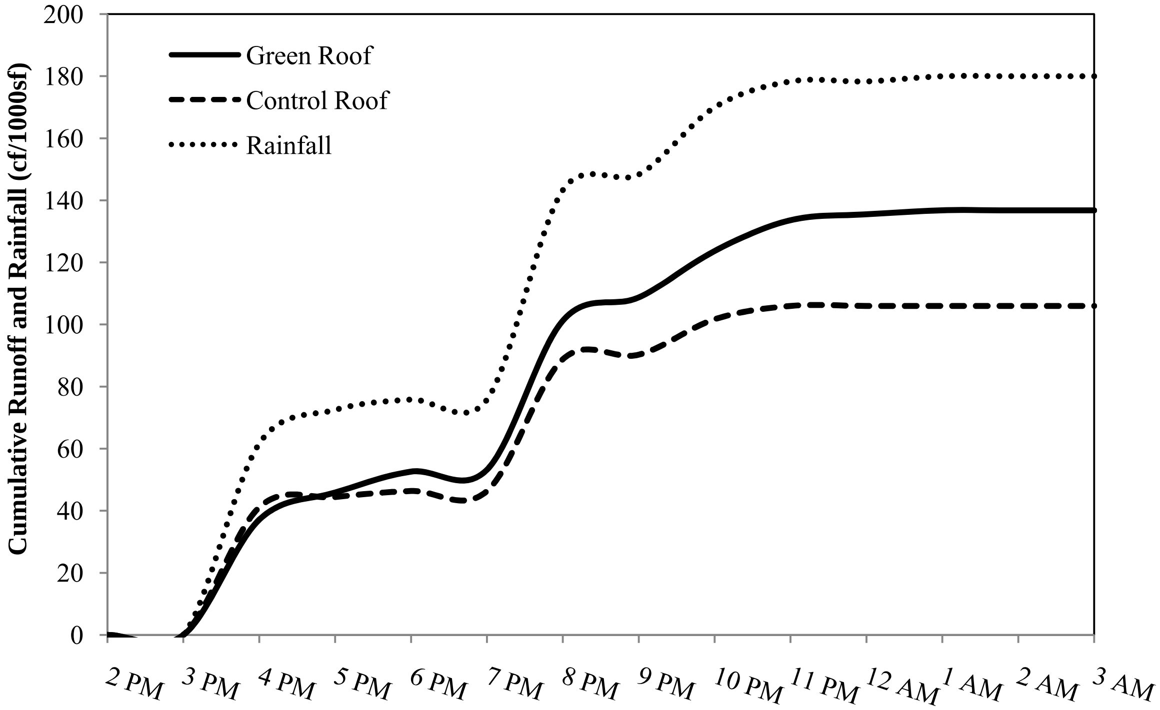


Figure I-72 Runoff and Rainfall Volumes – June 30-July 1, 2008 Storm (Homestead)

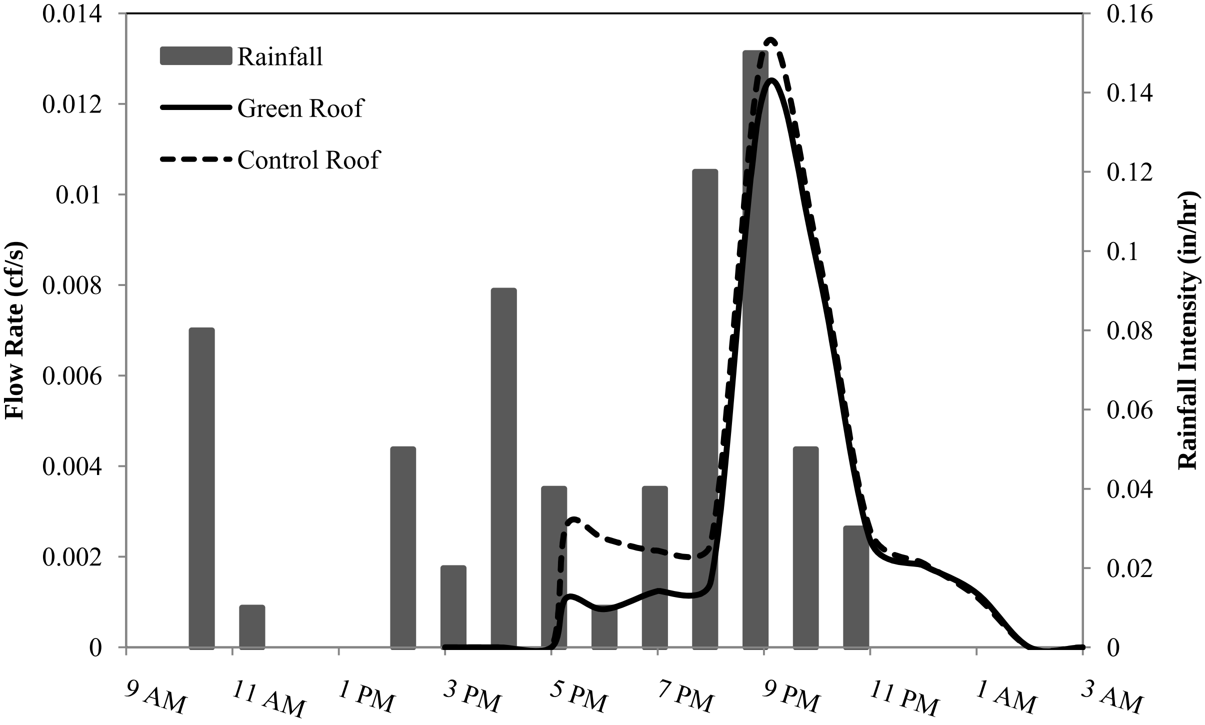


Figure I-73 Runoff Flow Rates and Rainfall intensity – June 30-July 1, 2008 Storm (Giant Eagle)

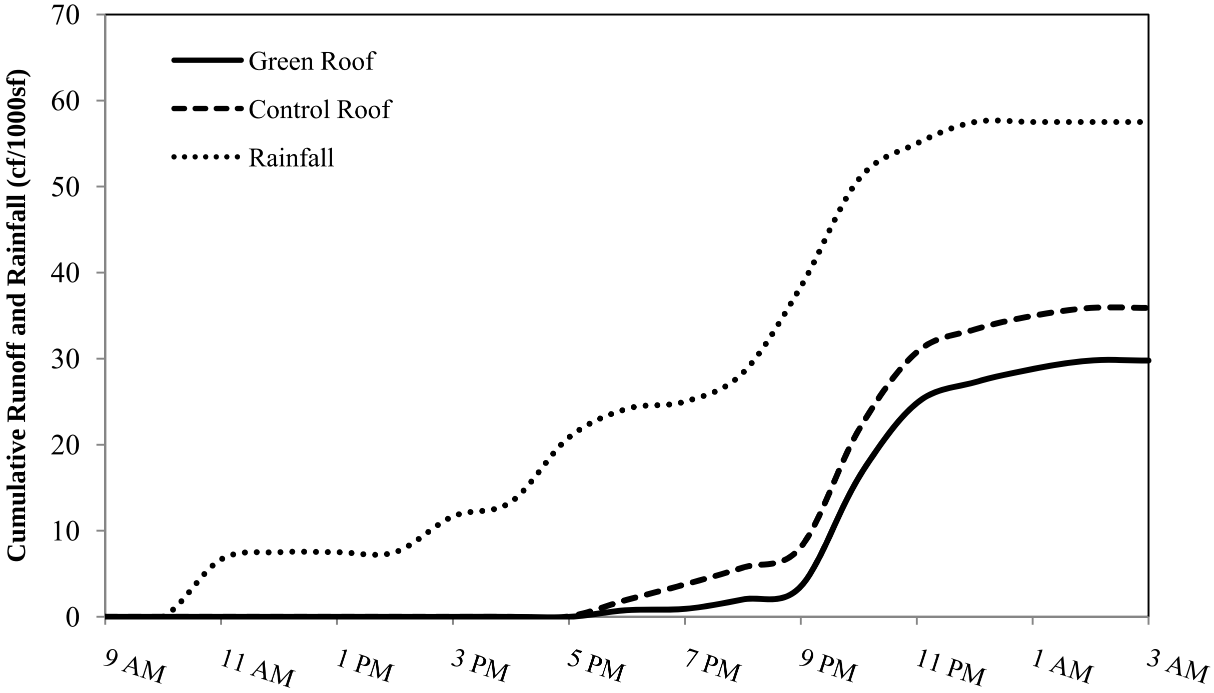


Figure I-74 Runoff and Rainfall Volumes – June 30-July 1, 2008 Storm (Giant Eagle)

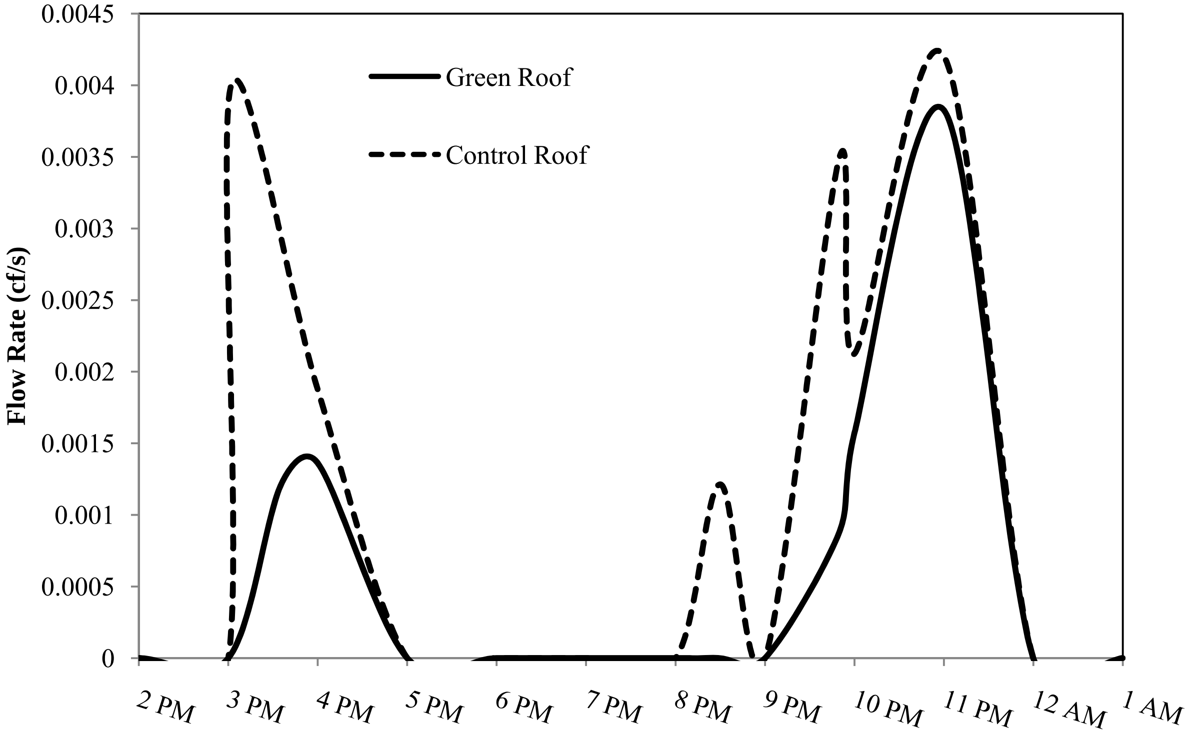


Figure I-75 Runoff Flow Rates – July 3, 2008 Storm (Homestead)

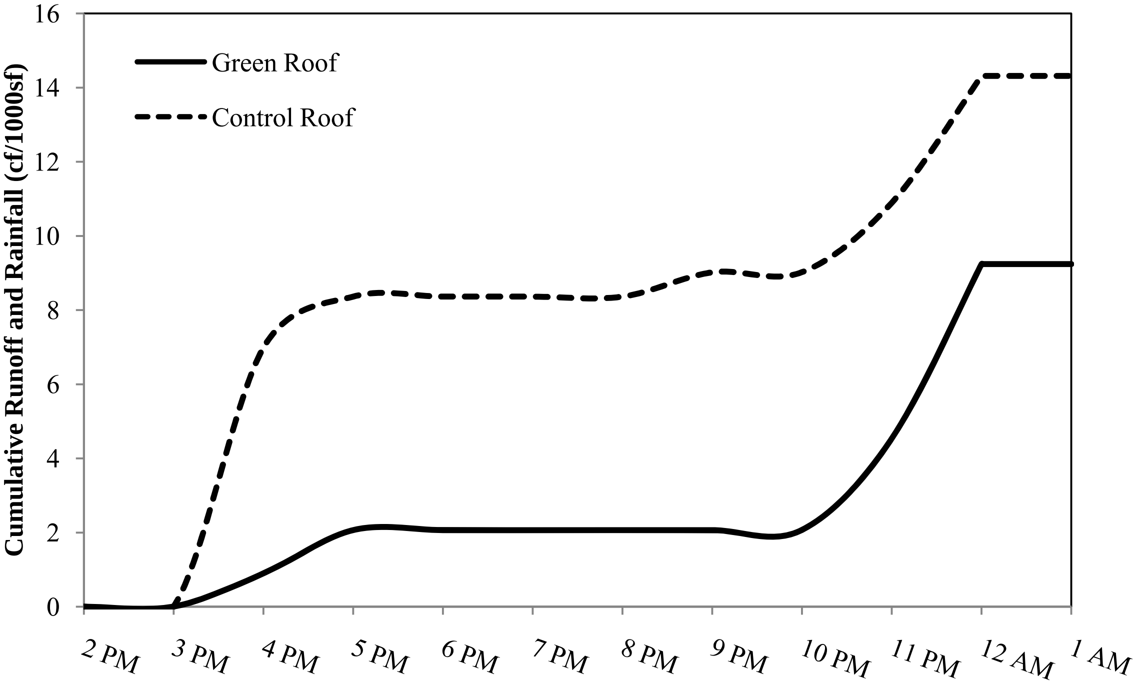


Figure I-76 Runoff Volumes – July 3, 2008 Storm (Homestead)

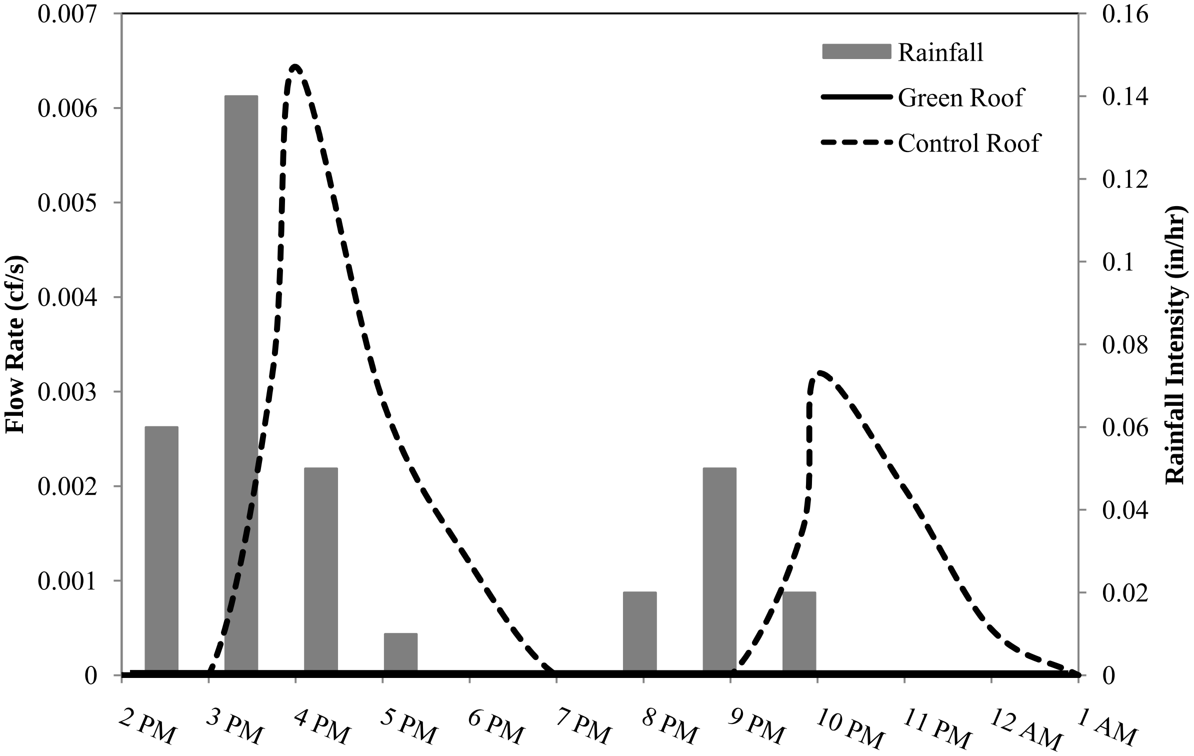


Figure I-77 Runoff Flow Rates and Rainfall intensity – July 3, 2008 Storm (Giant Eagle)

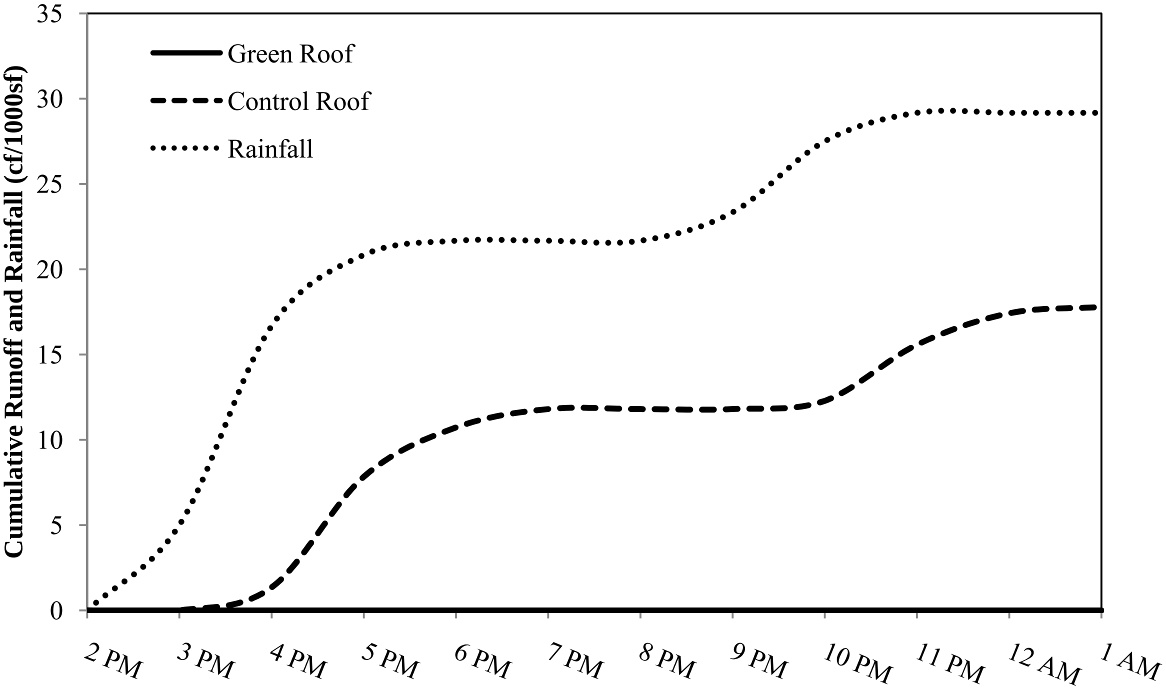


Figure I-78 Runoff and Rainfall Volumes – July 3, 2008 Storm (Giant Eagle)

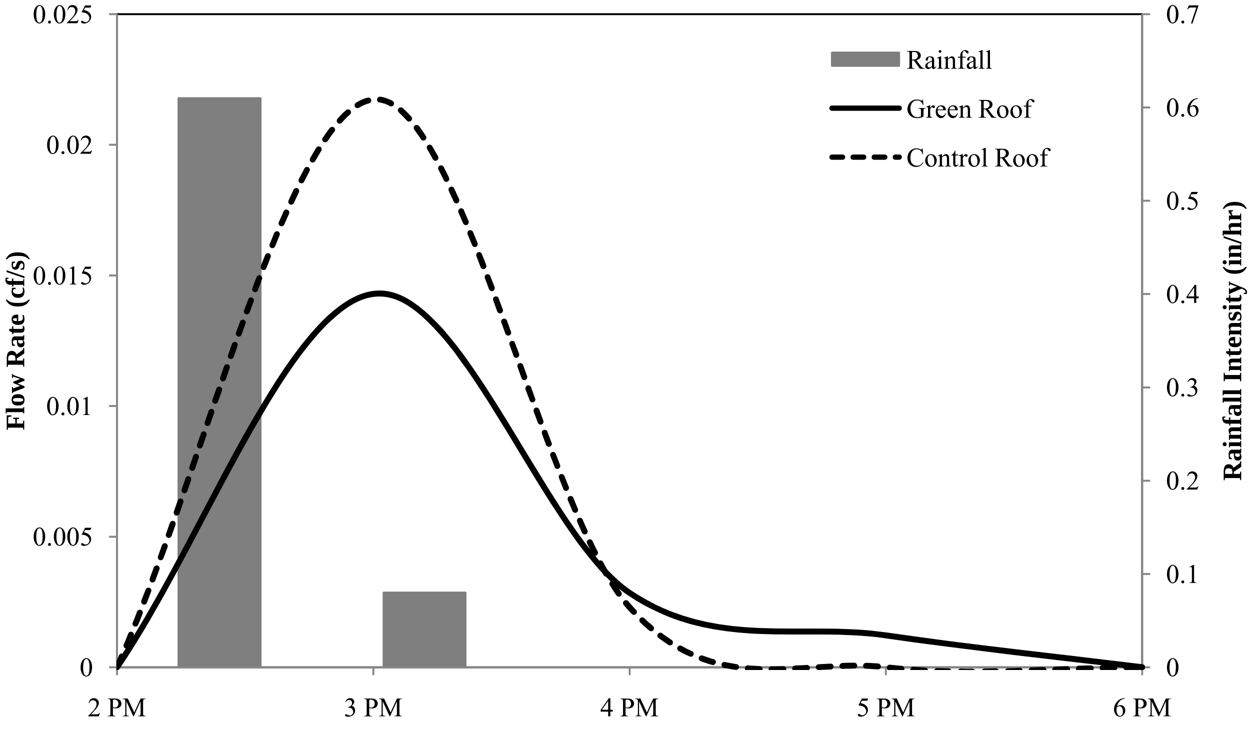


Figure I-79 Runoff Flow Rates and Rainfall intensity – July 7, 2008 Storm (Giant Eagle)

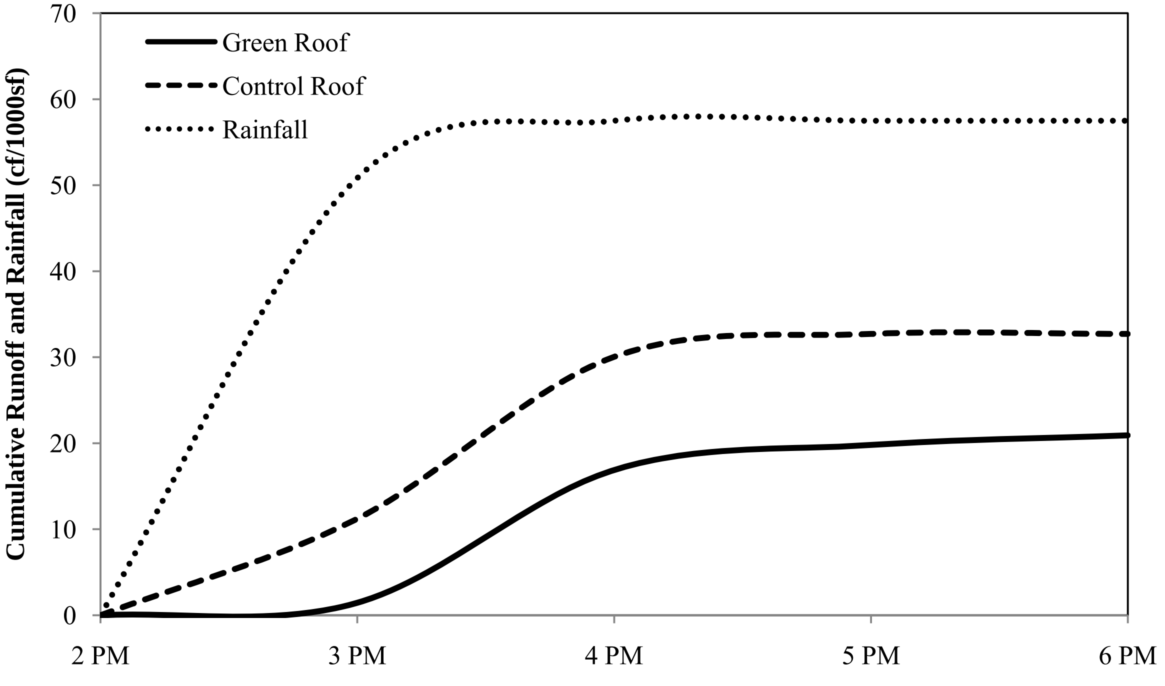


Figure I-80 Runoff and Rainfall Volumes – July 7, 2008 Storm (Giant Eagle)

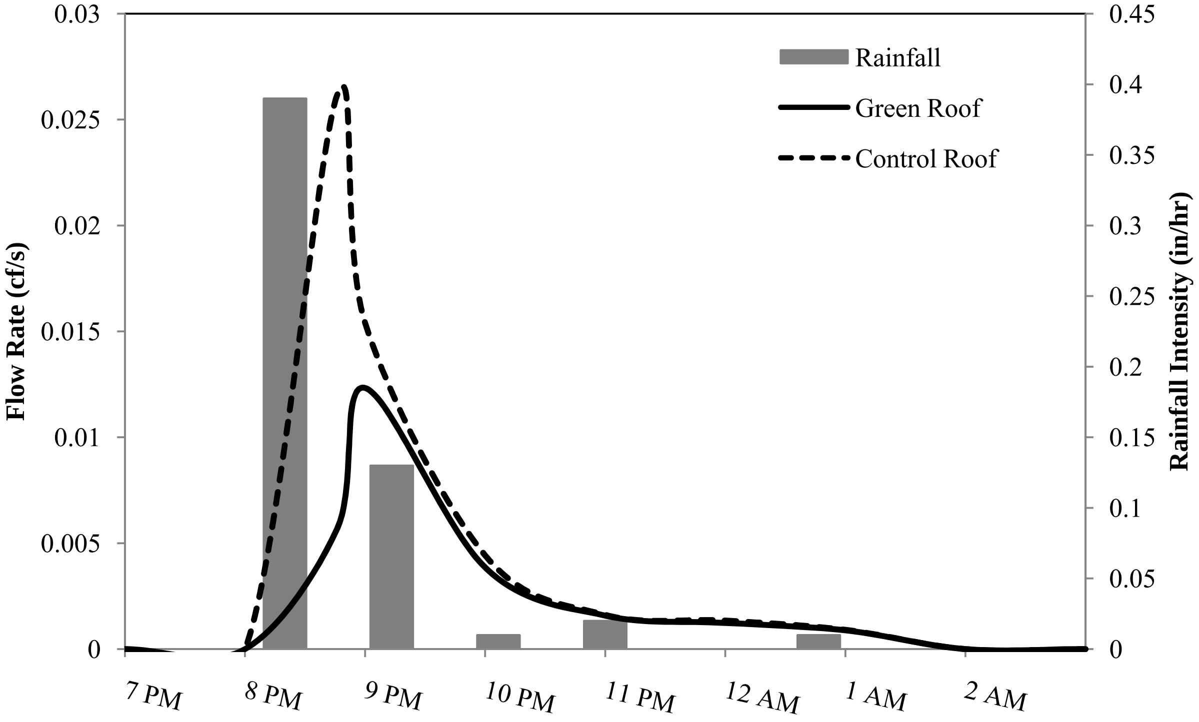


Figure I-81 Runoff Flow Rates and Rainfall intensity – July 8-9, 2008 Storm (Giant Eagle)

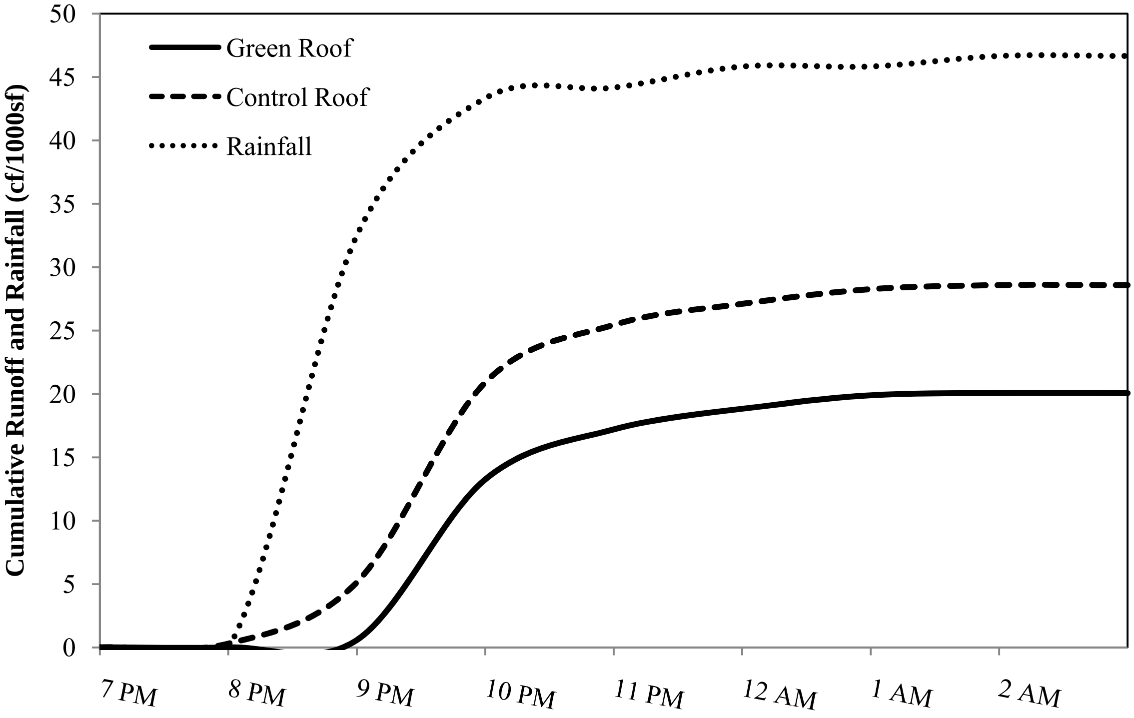


Figure I-82 Runoff and Rainfall Volumes – July 8-9, 2008 Storm (Giant Eagle)

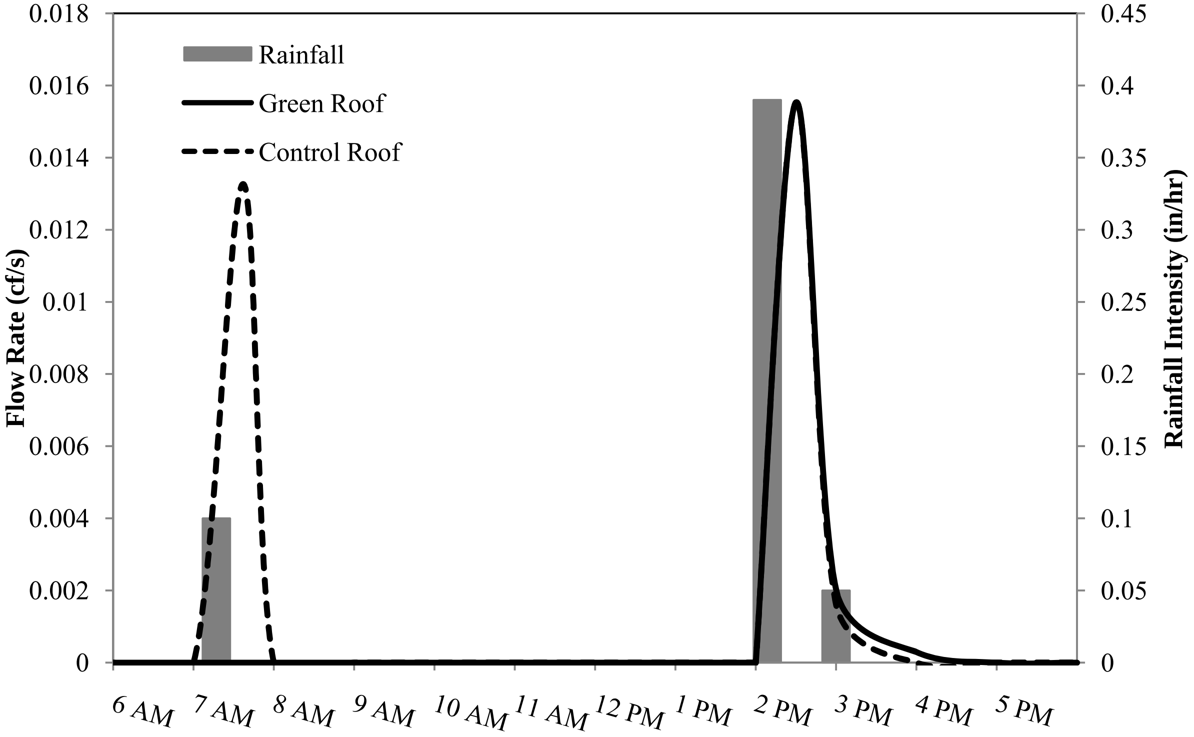


Figure I-83 Runoff Flow Rates and Rainfall Intensity – July 20, 2008 Storm (Homestead)

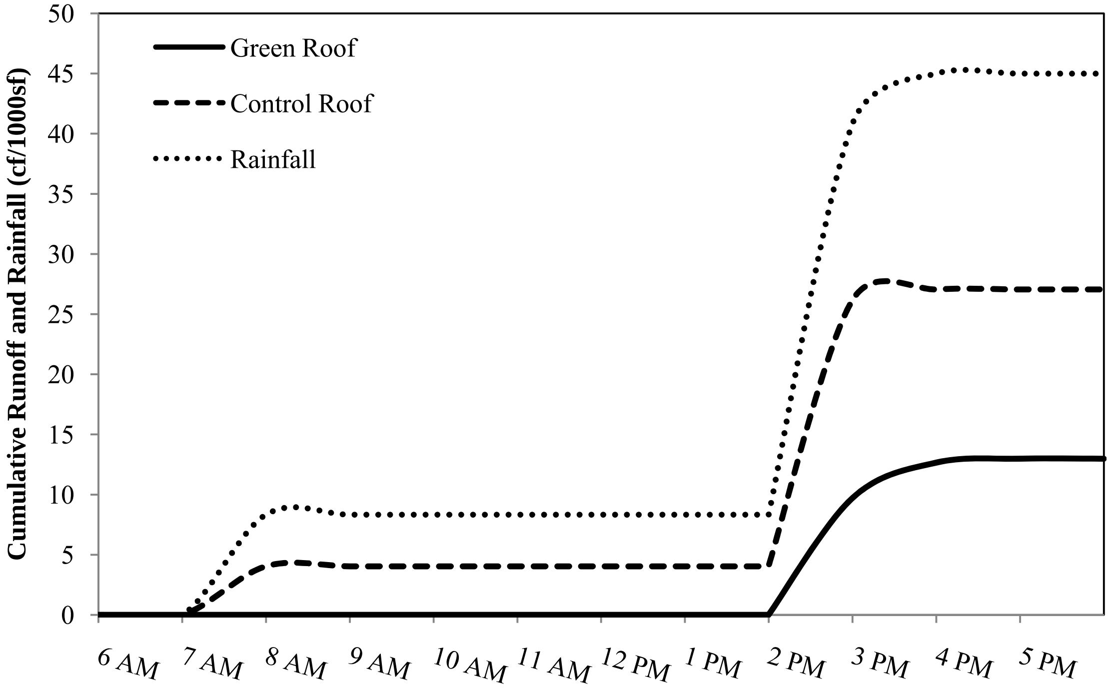


Figure I-84 Runoff and Rainfall Volumes – July 20, 2008 Storm (Homestead)

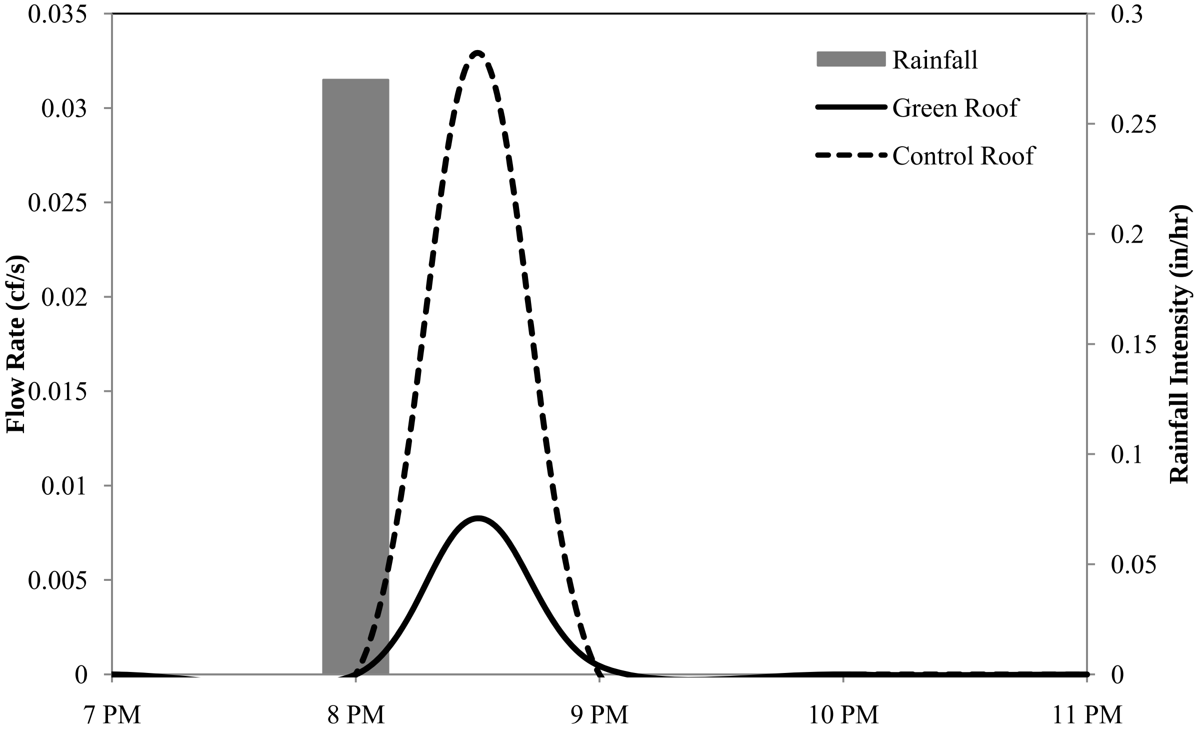


Figure I-85 Runoff Flow Rates and Rainfall Intensity – July 21, 2008 Storm (Homestead)

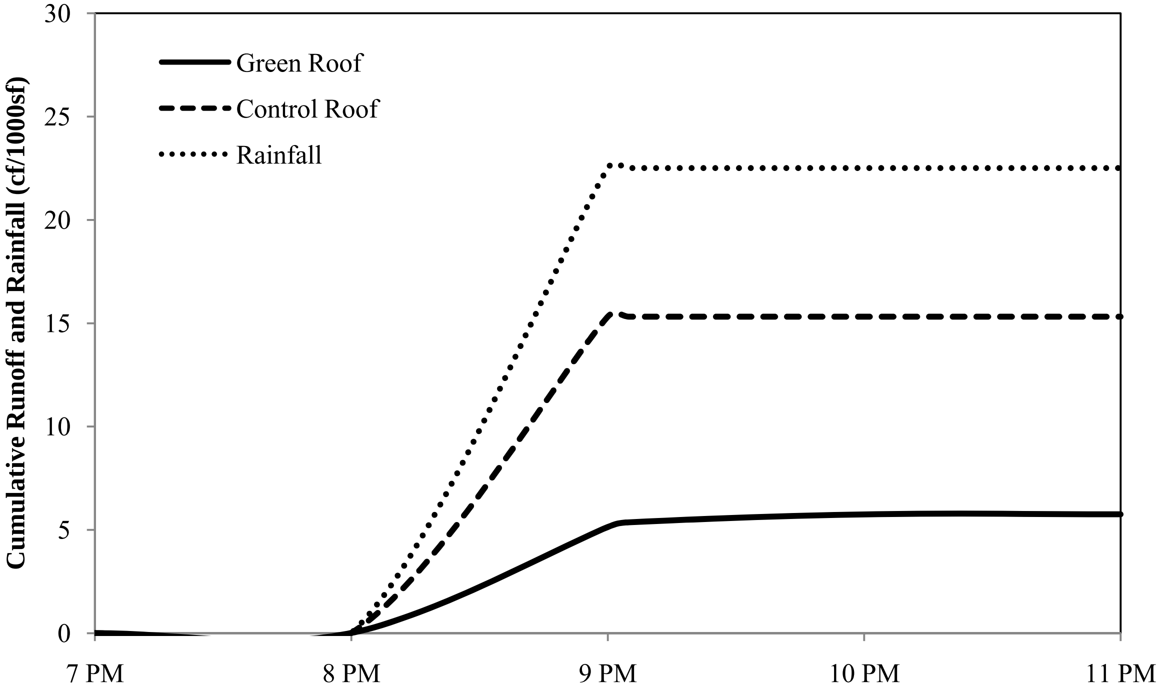


Figure I-86 Runoff and Rainfall Volumes – July 21, 2008 Storm (Homestead)

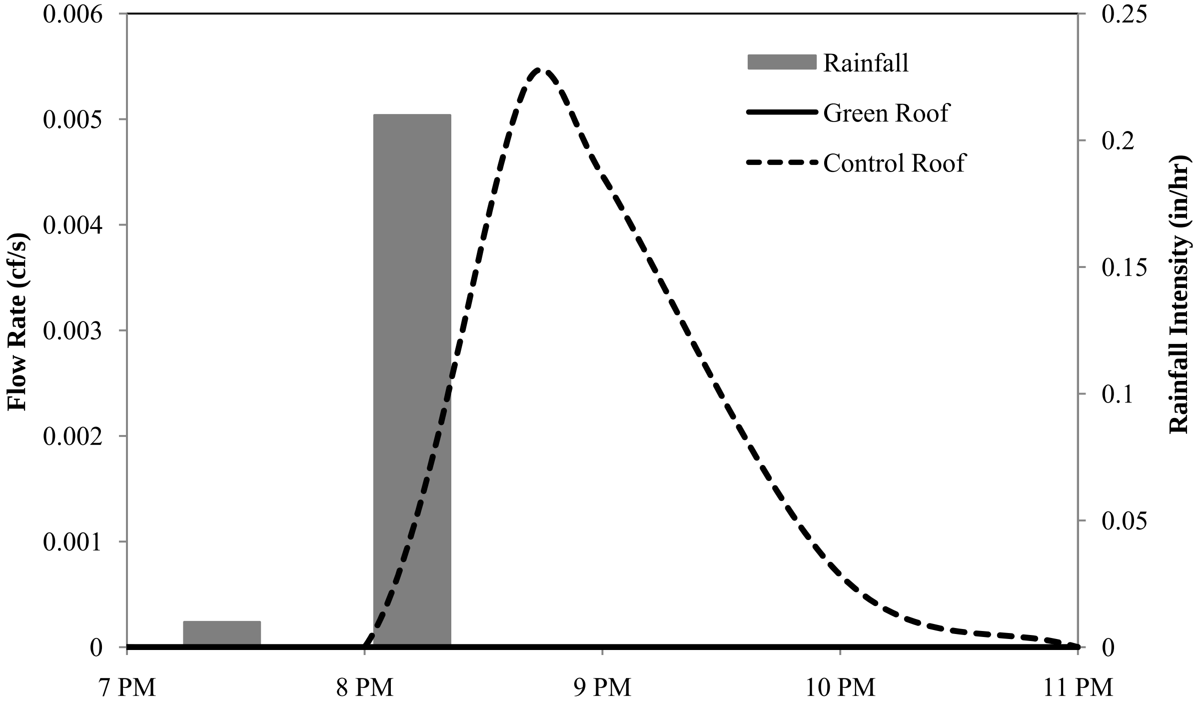


Figure I-87 Runoff Flow Rates and Rainfall intensity – July 21, 2008 Storm (Giant Eagle)

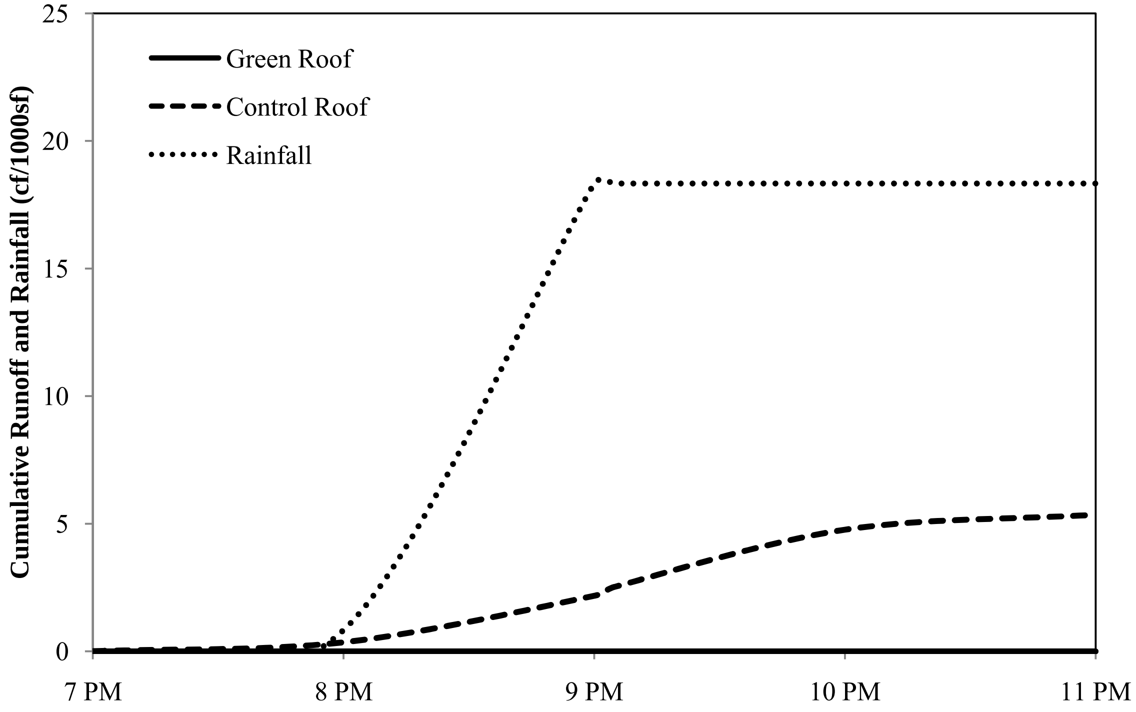


Figure I-88 Runoff and Rainfall Volumes – July 21, 2008 Storm (Giant Eagle)

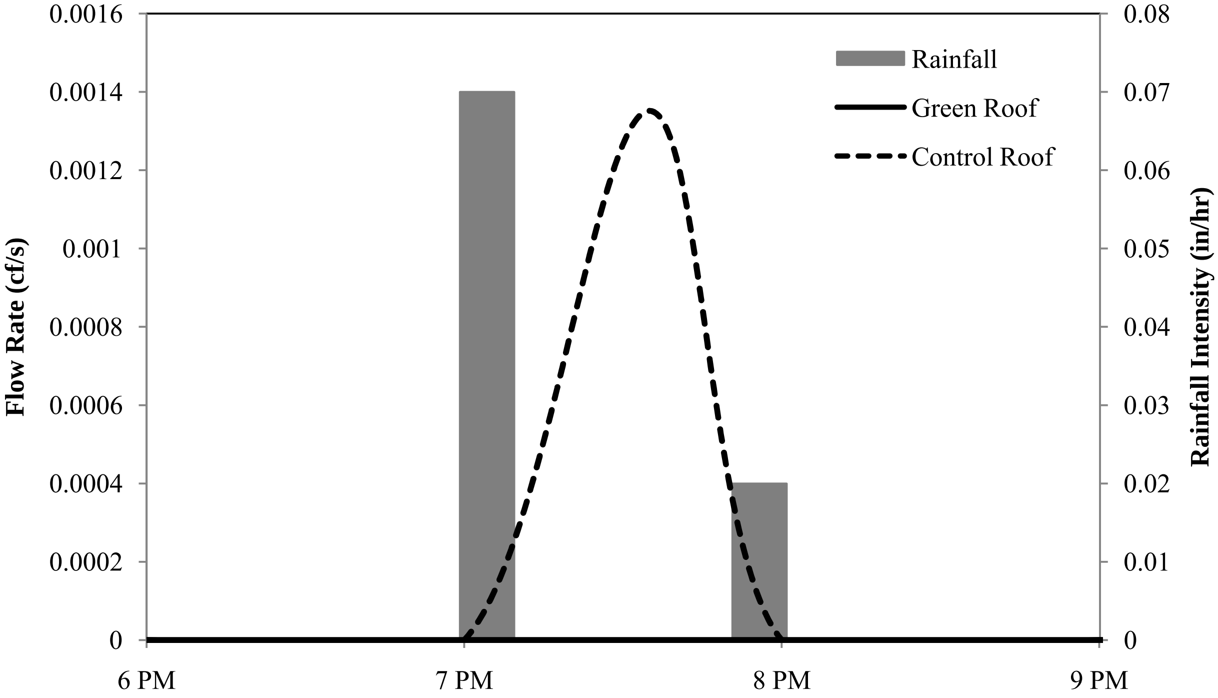


Figure I-89 Runoff Flow Rates and Rainfall Intensity – July 22, 2008 Storm (Homestead)

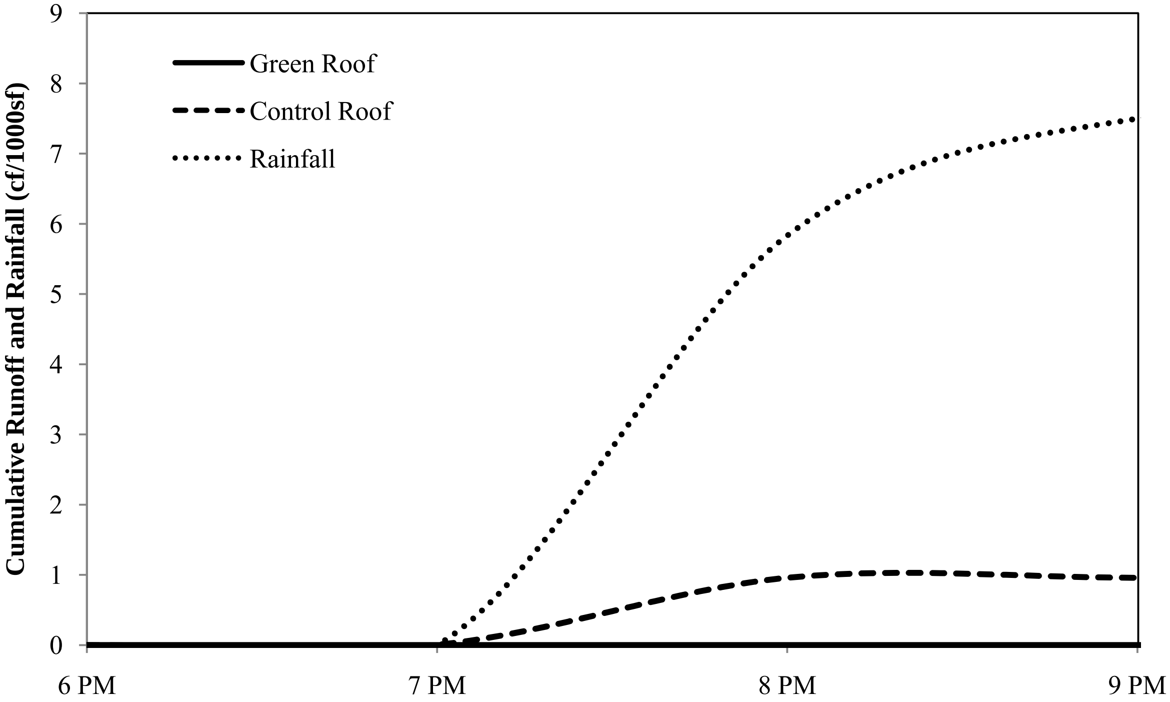


Figure I-90 Runoff and Rainfall Volumes – July 22, 2008 Storm (Homestead)

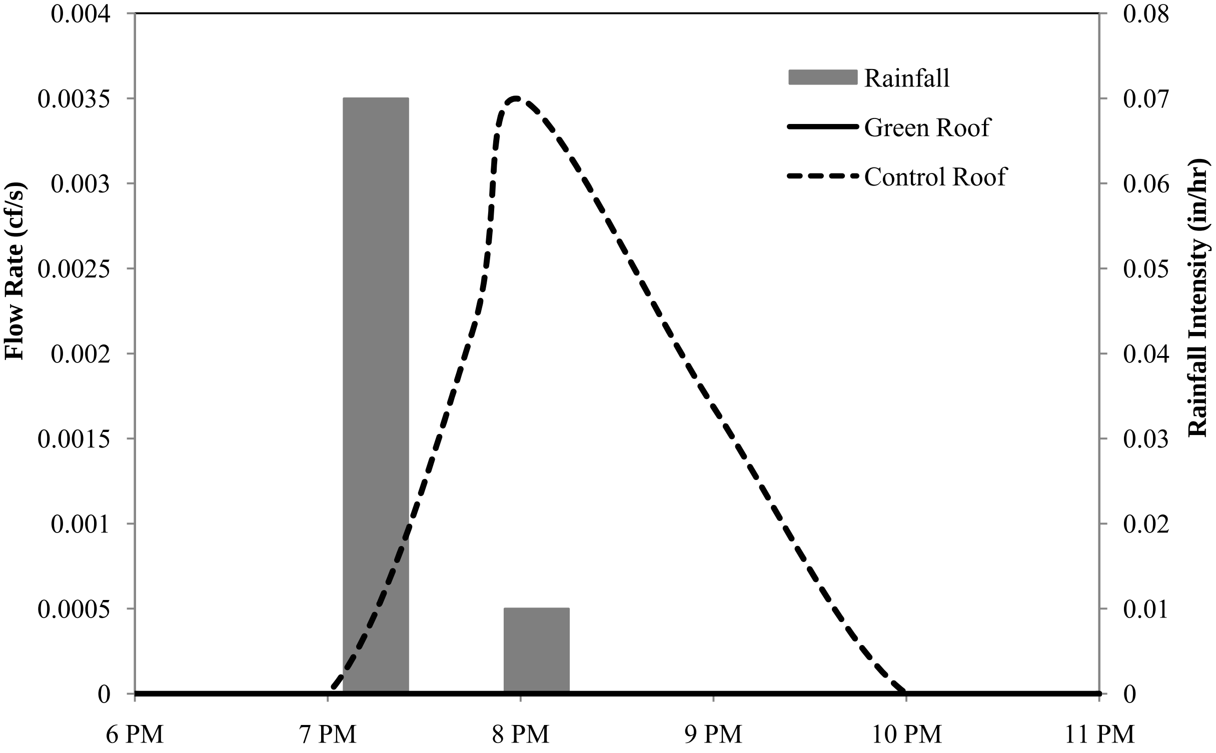


Figure I-91 Runoff Flow Rates and Rainfall intensity – July 22, 2008 Storm (Giant Eagle)

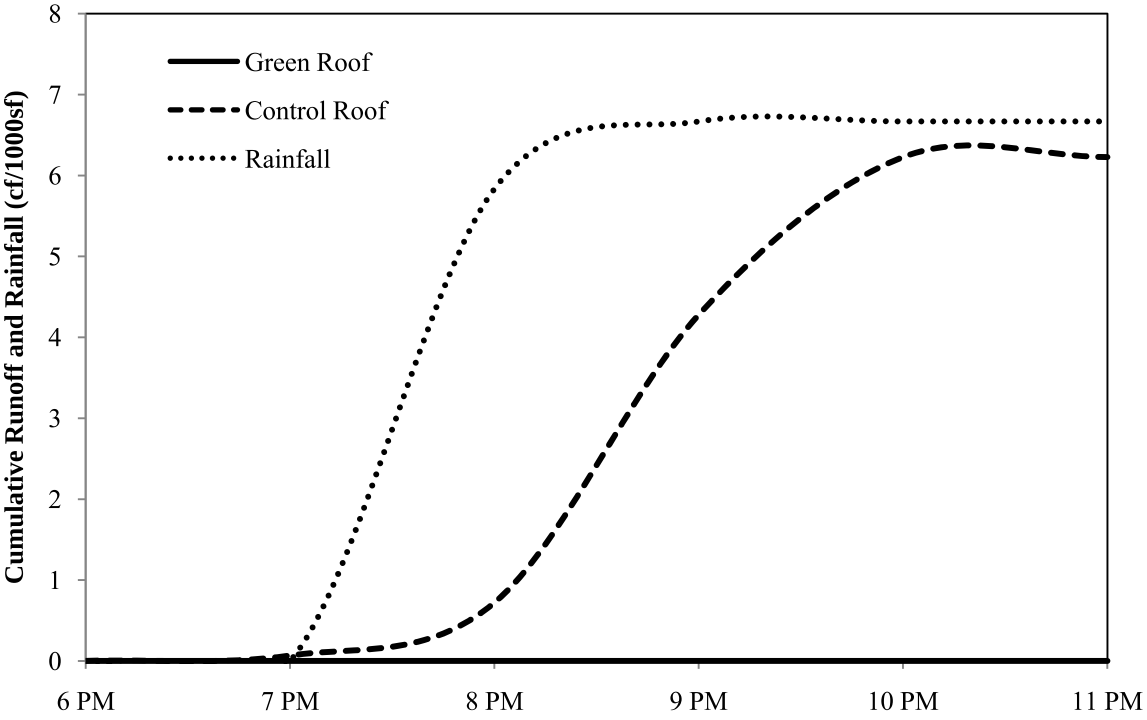


Figure I-92 Runoff and Rainfall Volumes – July 22, 2008 Storm (Giant Eagle)

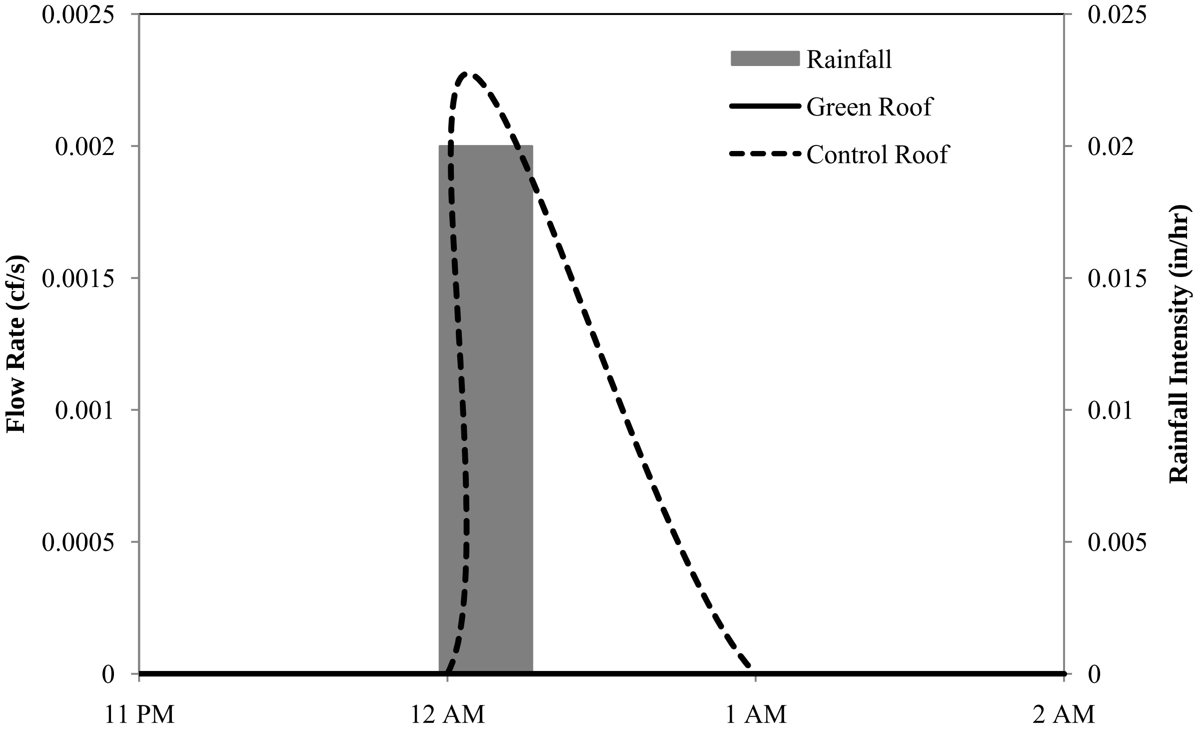


Figure I-93 Runoff Flow Rates and Rainfall Intensity – July 27, 2008 Storm (Homestead)

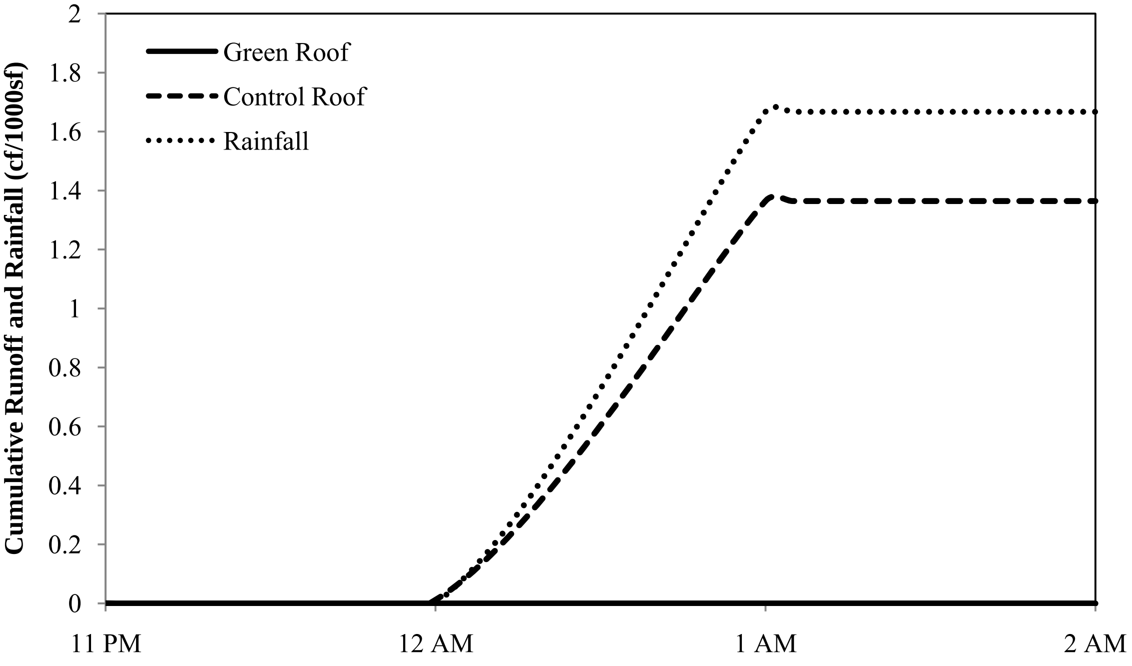


Figure I-94 Runoff and Rainfall Volumes – July 27, 2008 Storm (Homestead)

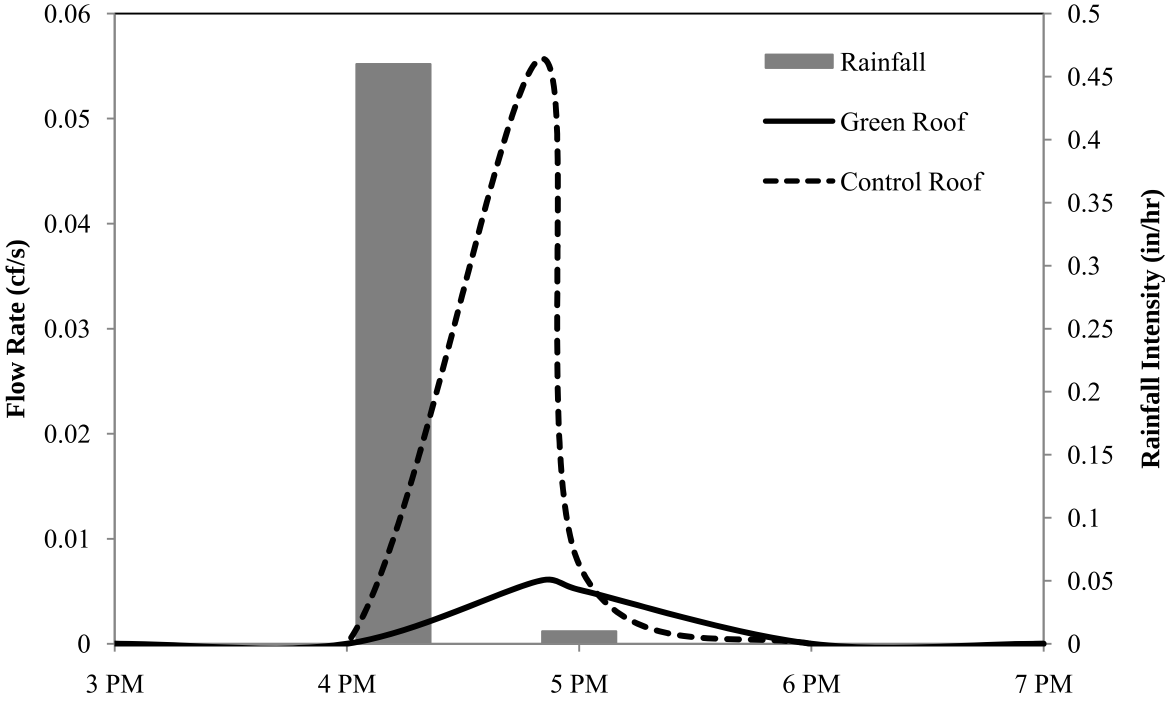


Figure I-95 Runoff Flow Rates and Rainfall intensity – July 30, 2008 Storm (Homestead)

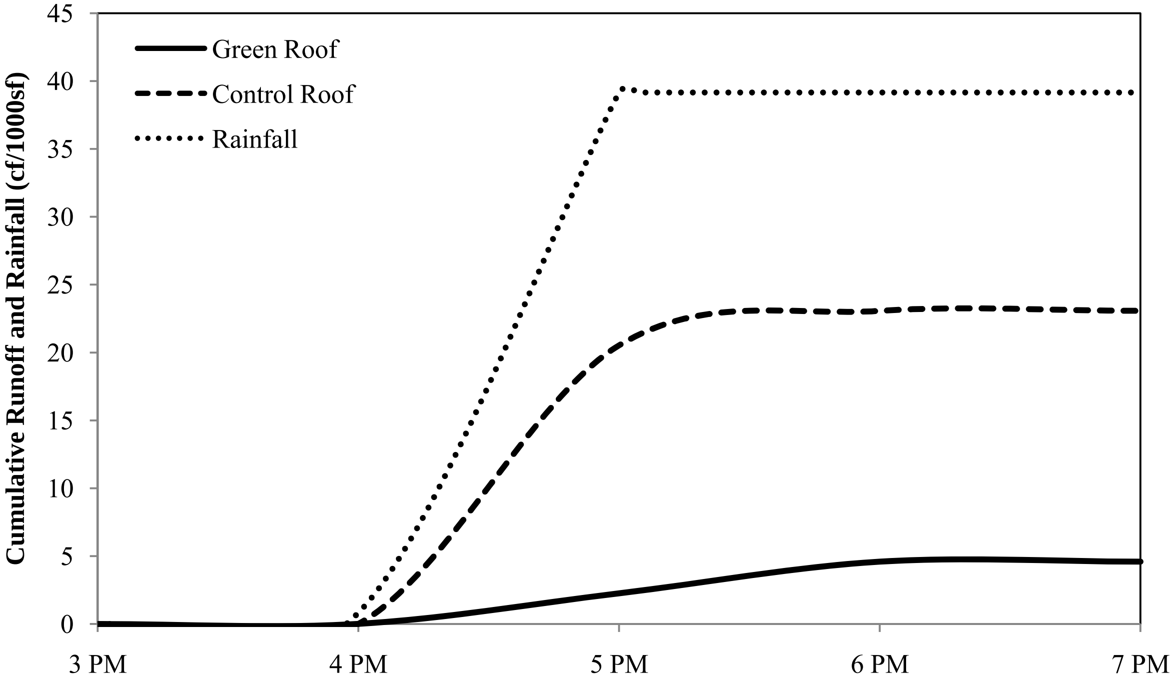


Figure I-96 Runoff and Rainfall Volumes – July 30, 2008 Storm (Homestead)

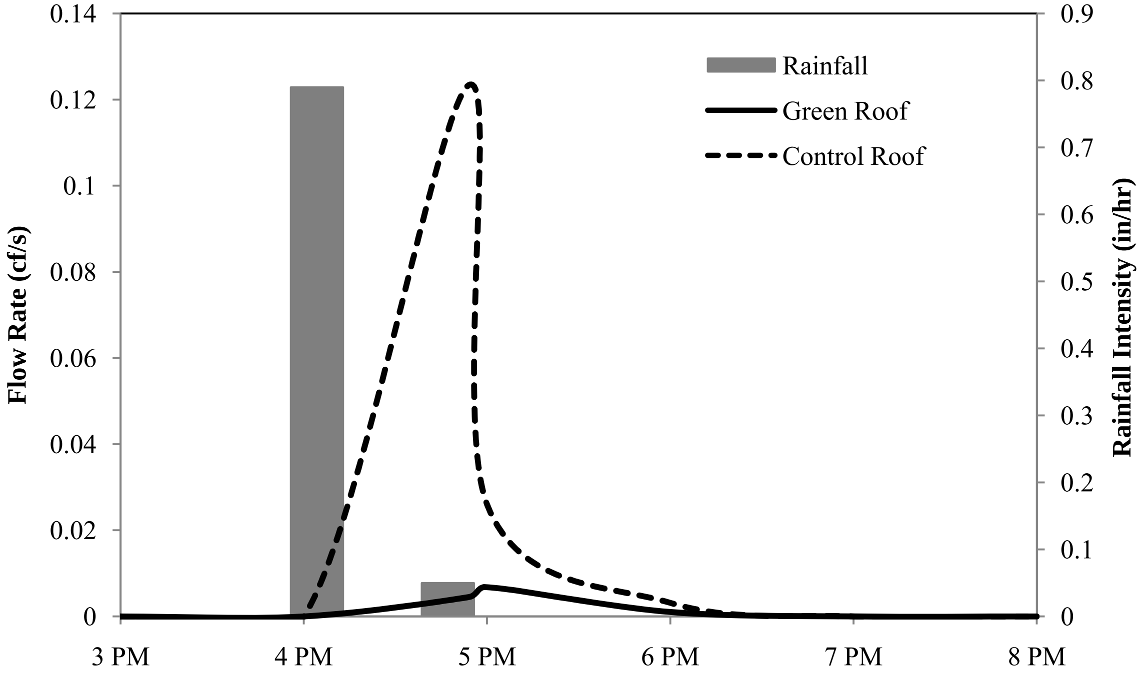


Figure I-97 Runoff Flow Rates and Rainfall intensity – July 30, 2008 Storm (Giant Eagle)

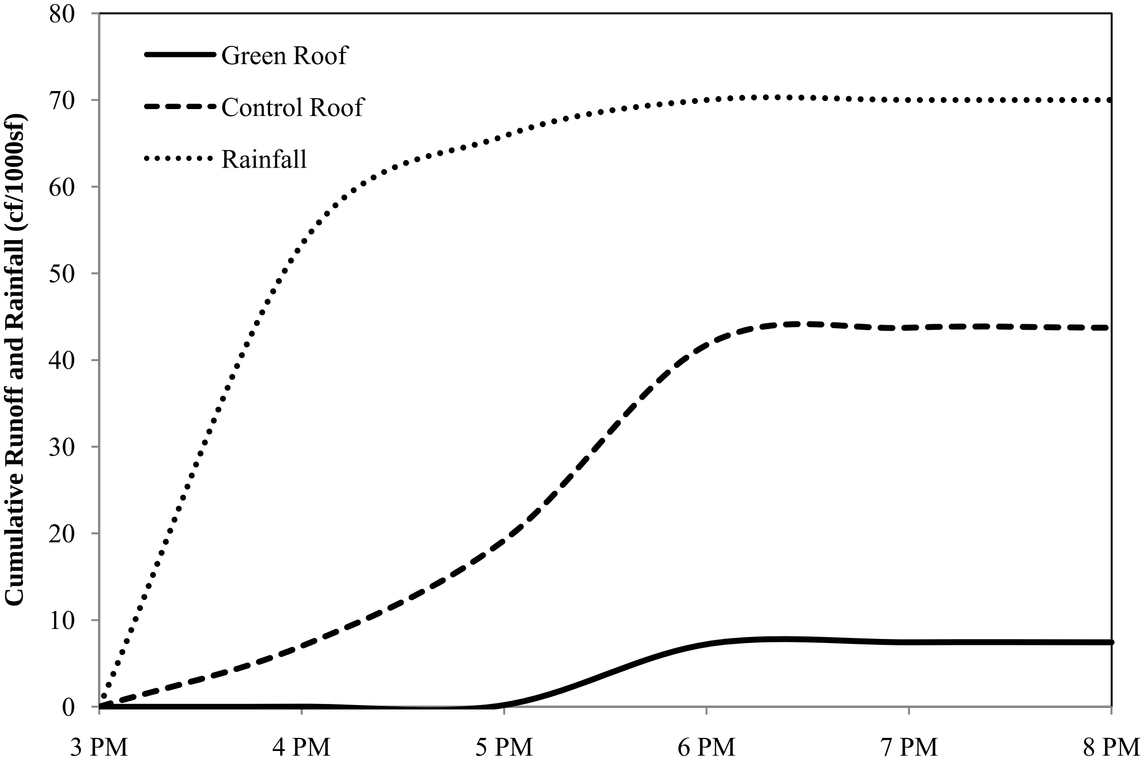


Figure I-98 Runoff and Rainfall Volumes – July 30, 2008 Storm (Giant Eagle)

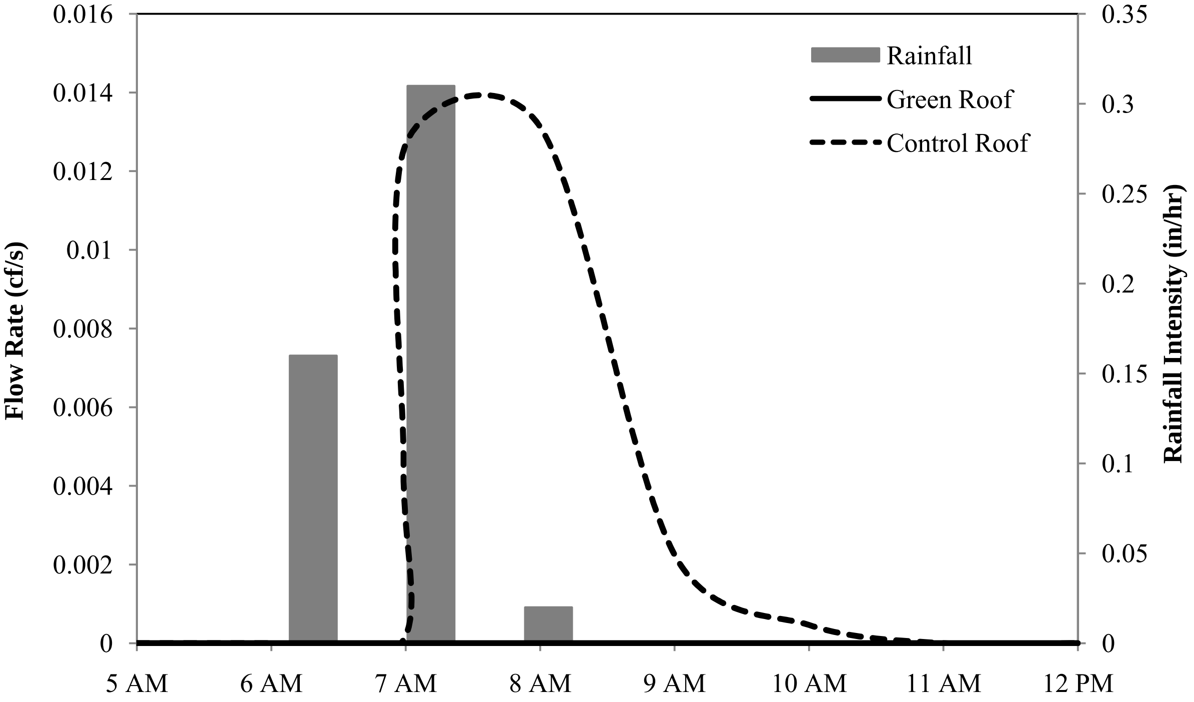


Figure I-99 Runoff Flow Rates and Rainfall intensity – August 5, 2008 Storm (Giant Eagle)

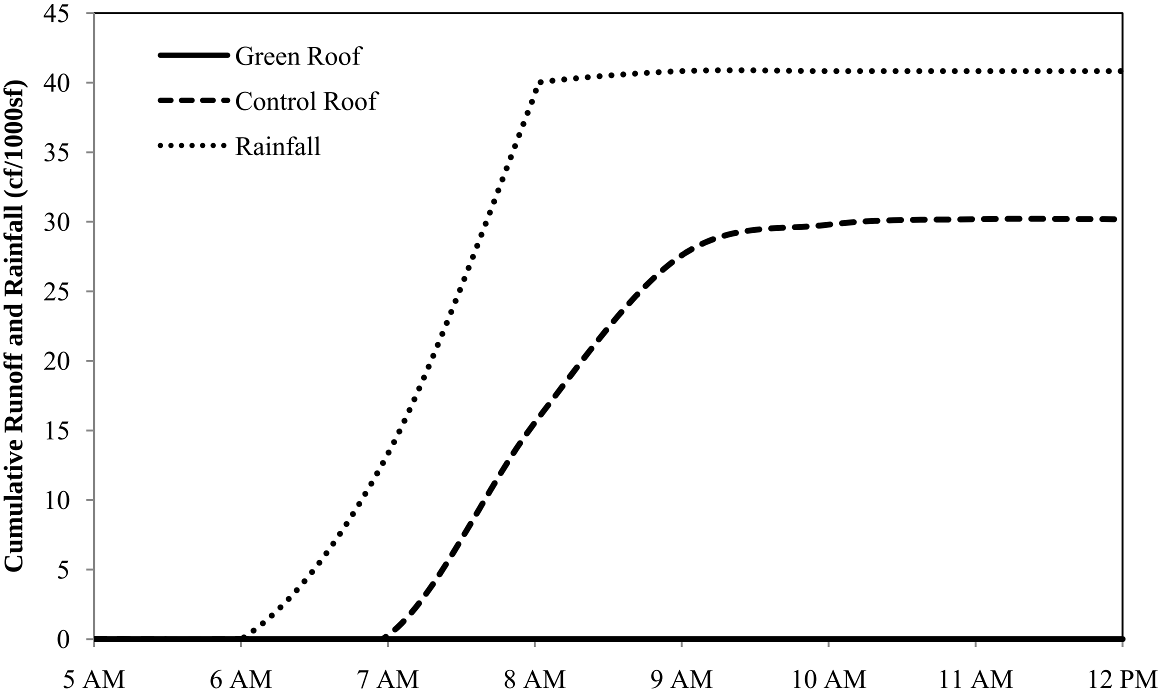


Figure I-100 Runoff and Rainfall Volumes – August 5, 2008 Storm (Giant Eagle)

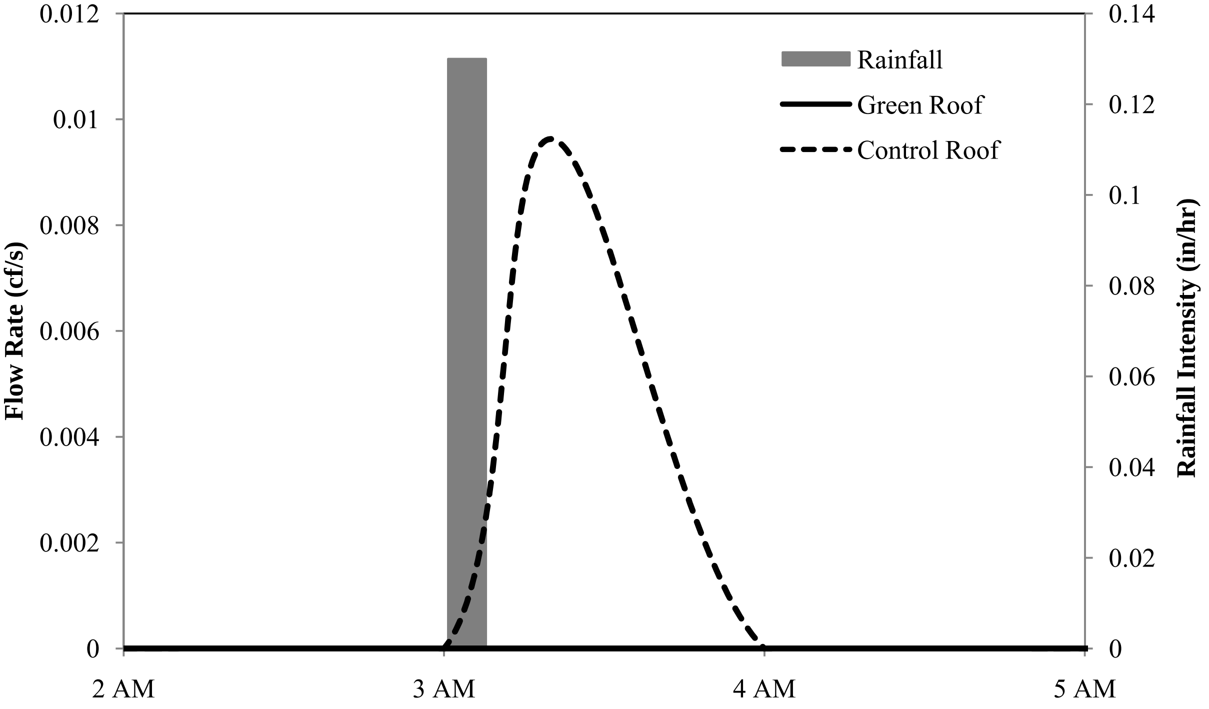


Figure I-101 Runoff Flow Rates and Rainfall Intensity – August 6, 2008 Storm (Homestead)

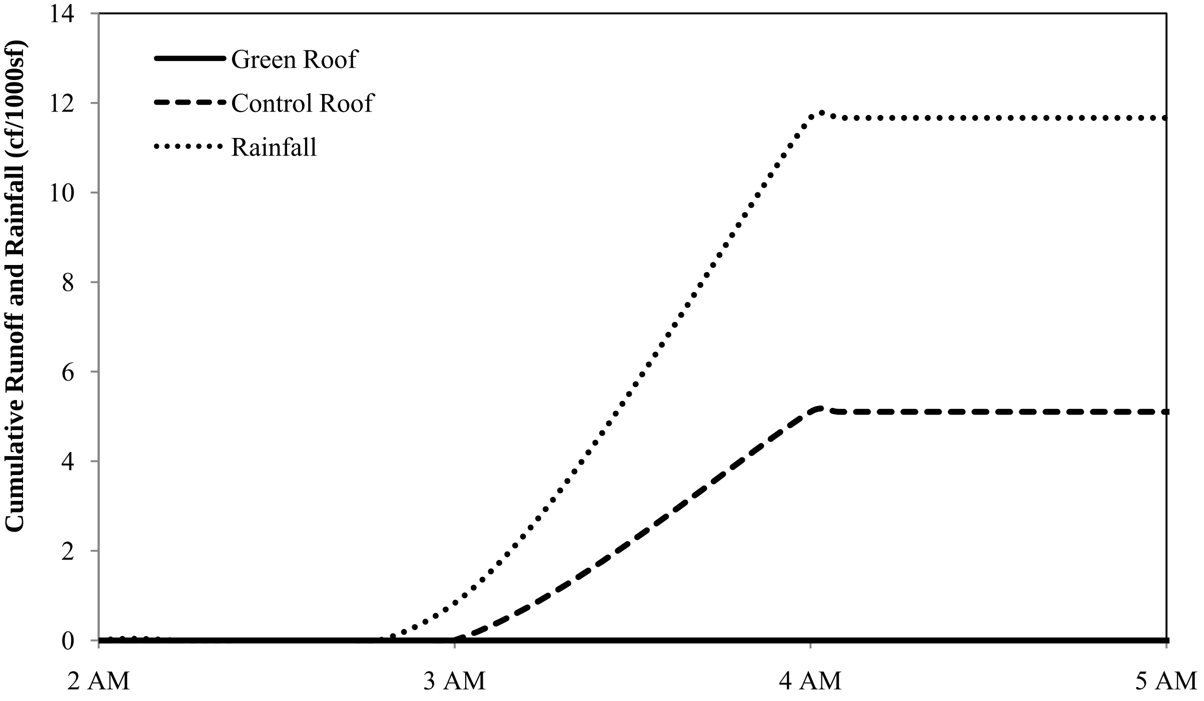


Figure I-102 Runoff and Rainfall Volumes – August 6, 2008 Storm (Homestead)

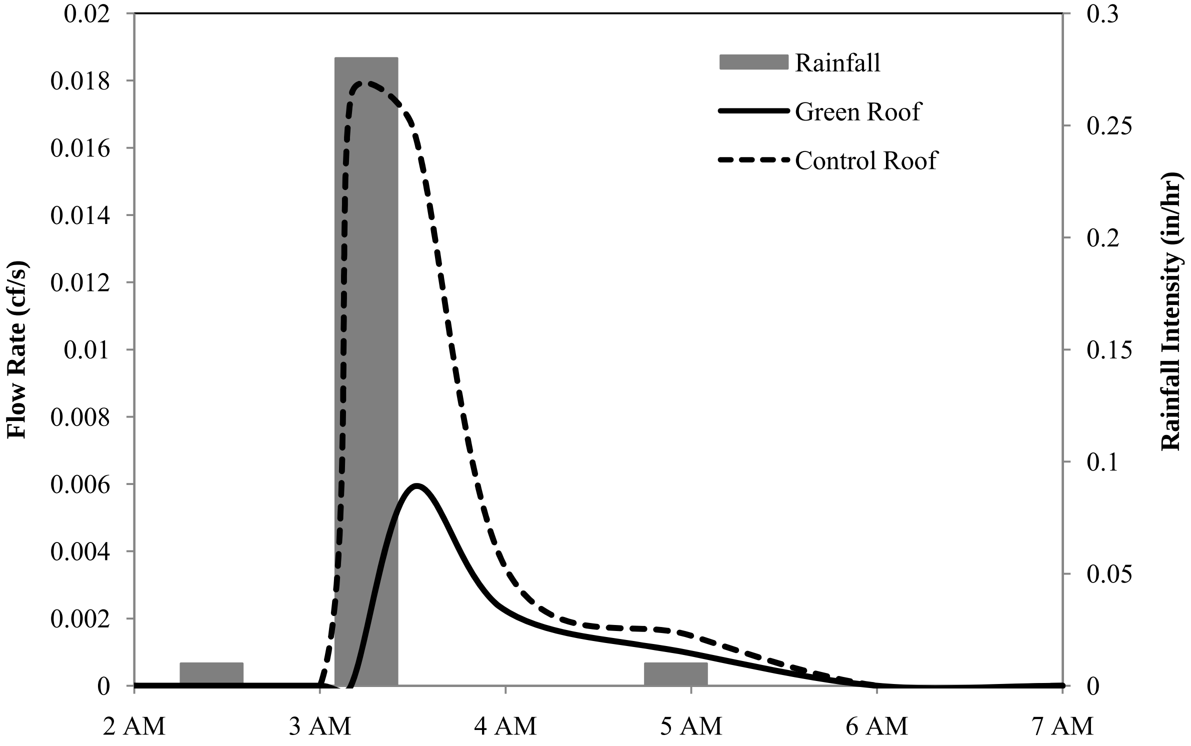


Figure I-103 Runoff Flow Rates and Rainfall intensity – August 6, 2008 Storm (Giant Eagle)

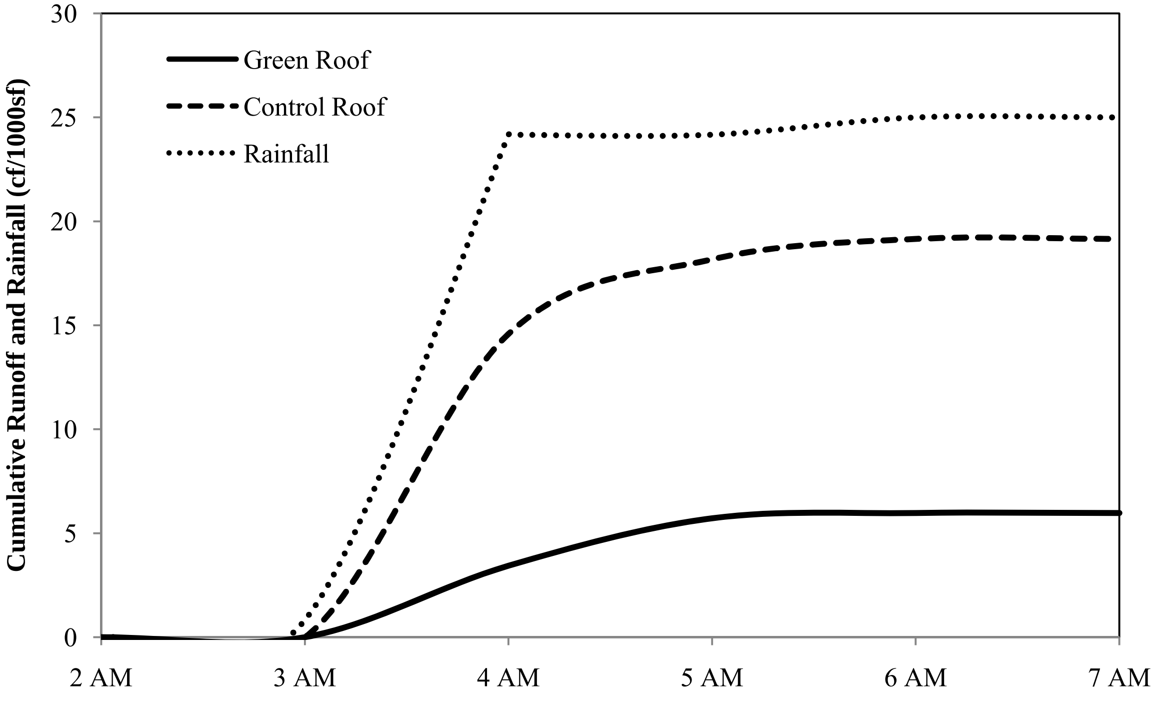


Figure I-104 Runoff and Rainfall Volumes – August 6, 2008 Storm (Giant Eagle)

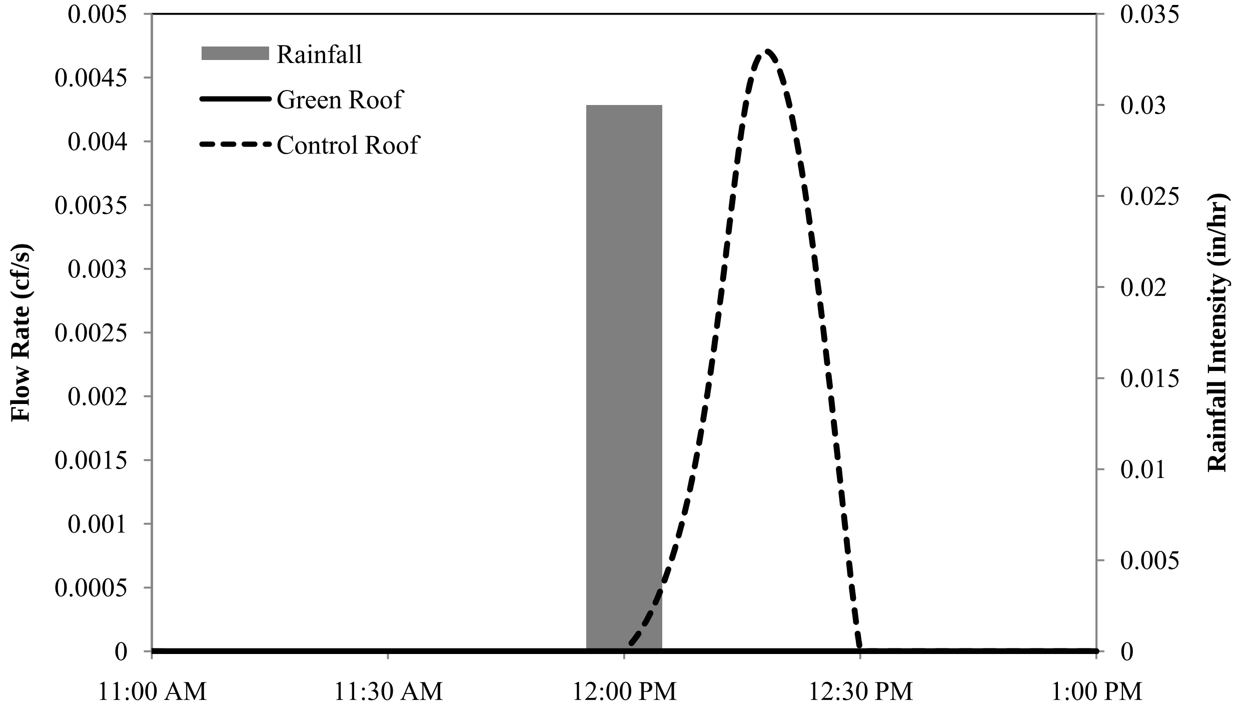


Figure I-105 Runoff Flow Rates and Rainfall Intensity – August 8, 2008 Storm (Homestead)

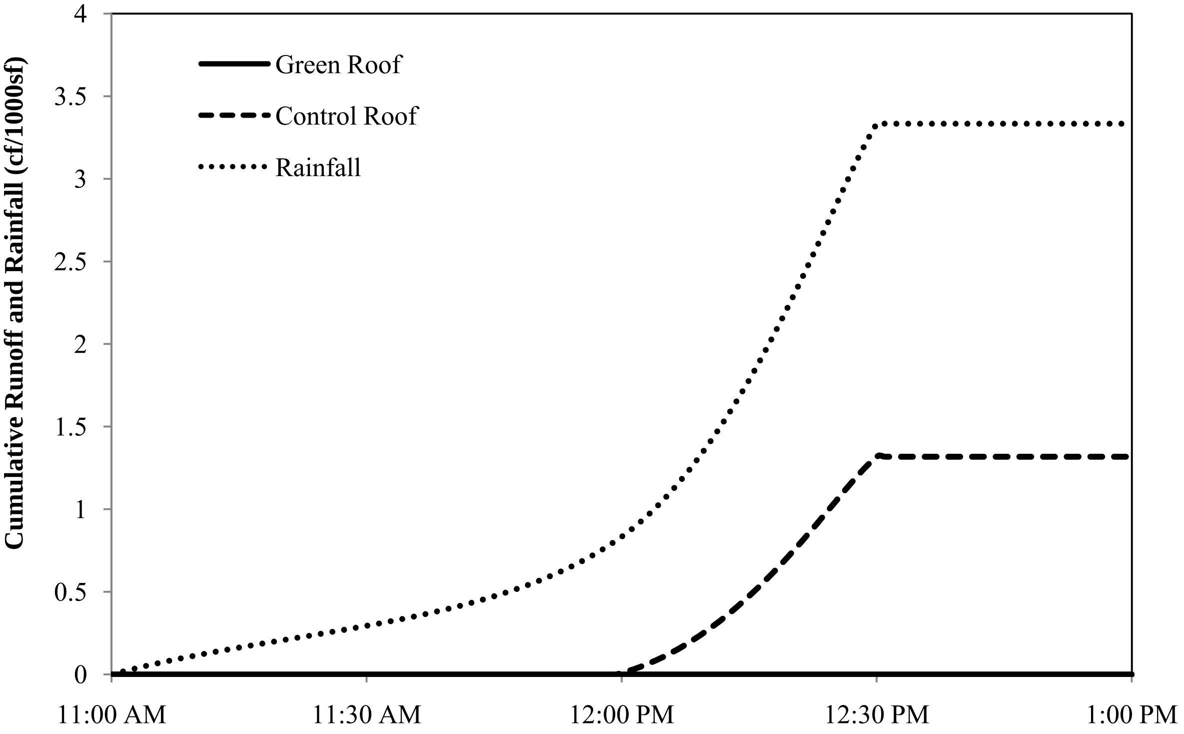


Figure I-106 Runoff and Rainfall Volumes – August 8, 2008 Storm (Homestead)

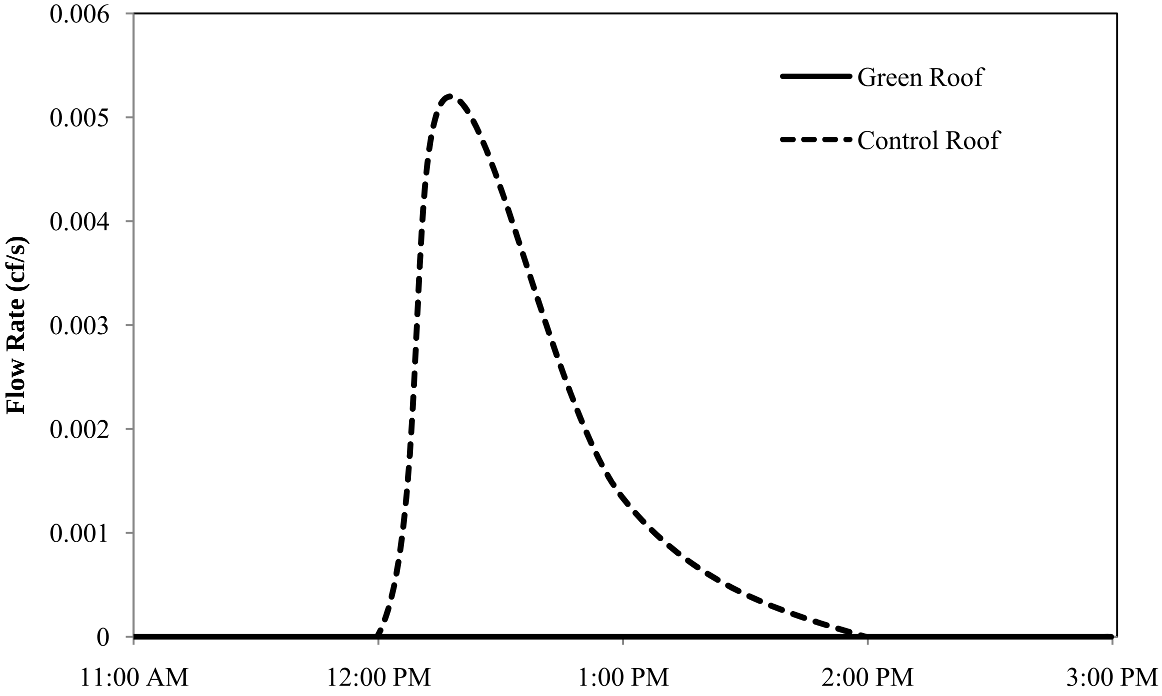


Figure I-107 Runoff Flow Rates – August 8, 2008 Storm (Giant Eagle)

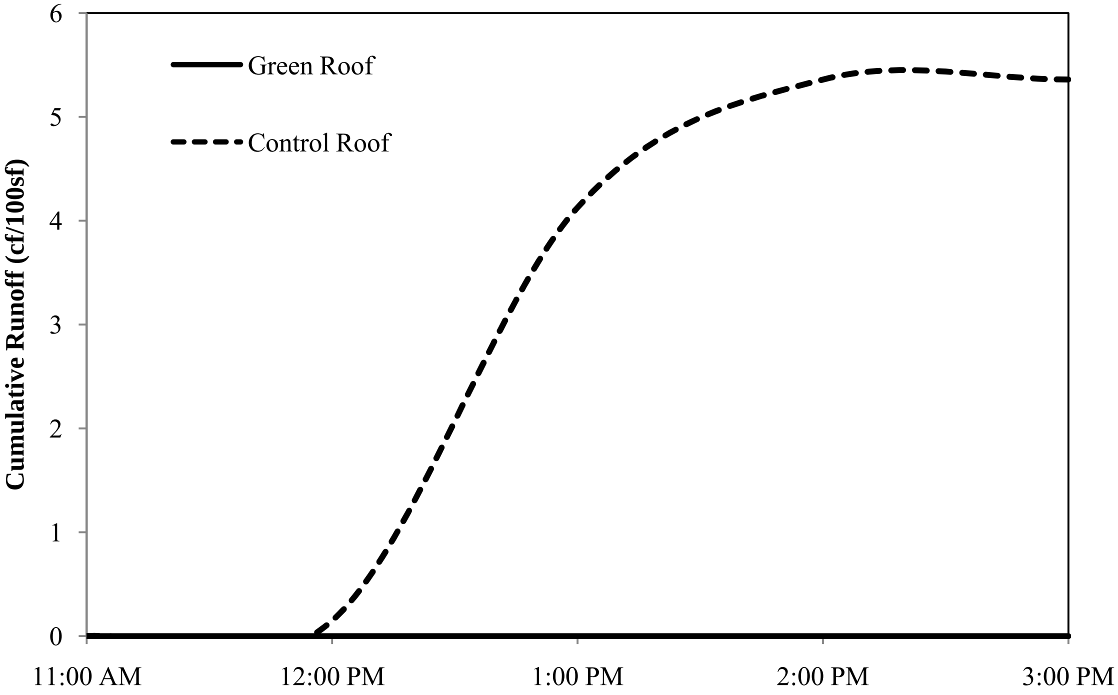


Figure I-108 Runoff Volumes – August 8, 2008 Storm (Giant Eagle)

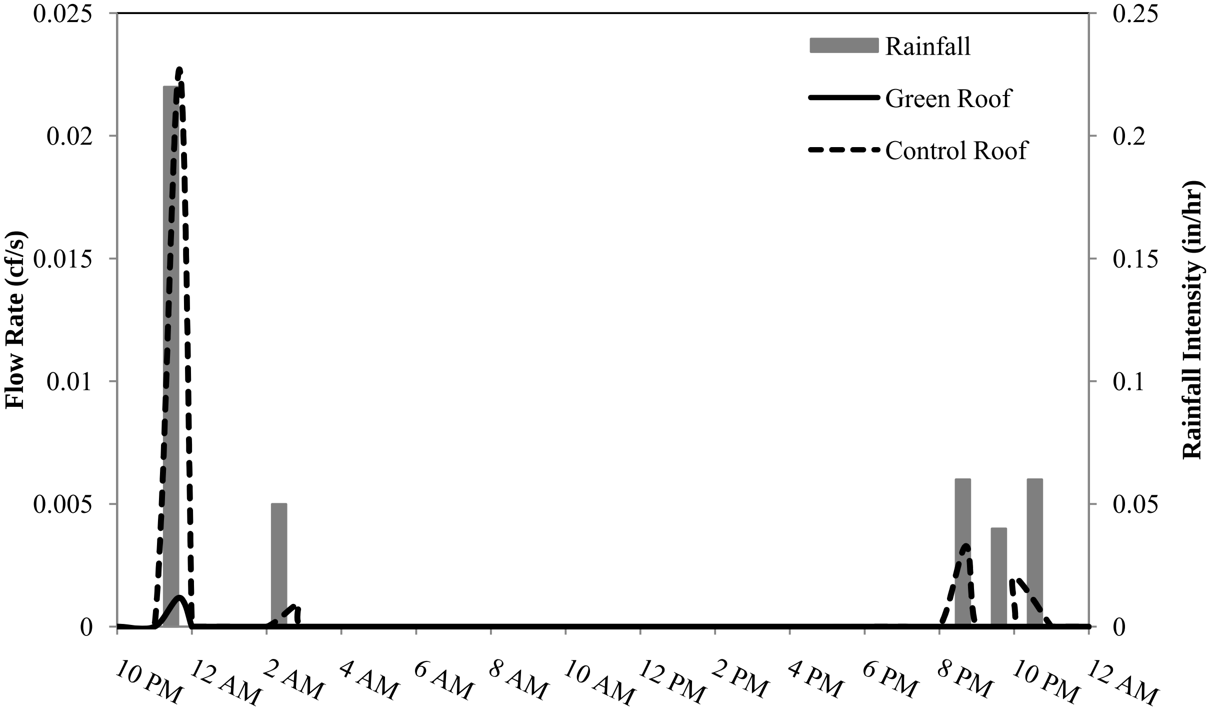


Figure I-109 Runoff Flow Rates and Rainfall Intensity – August 9-10, 2008 Storm (Homestead)

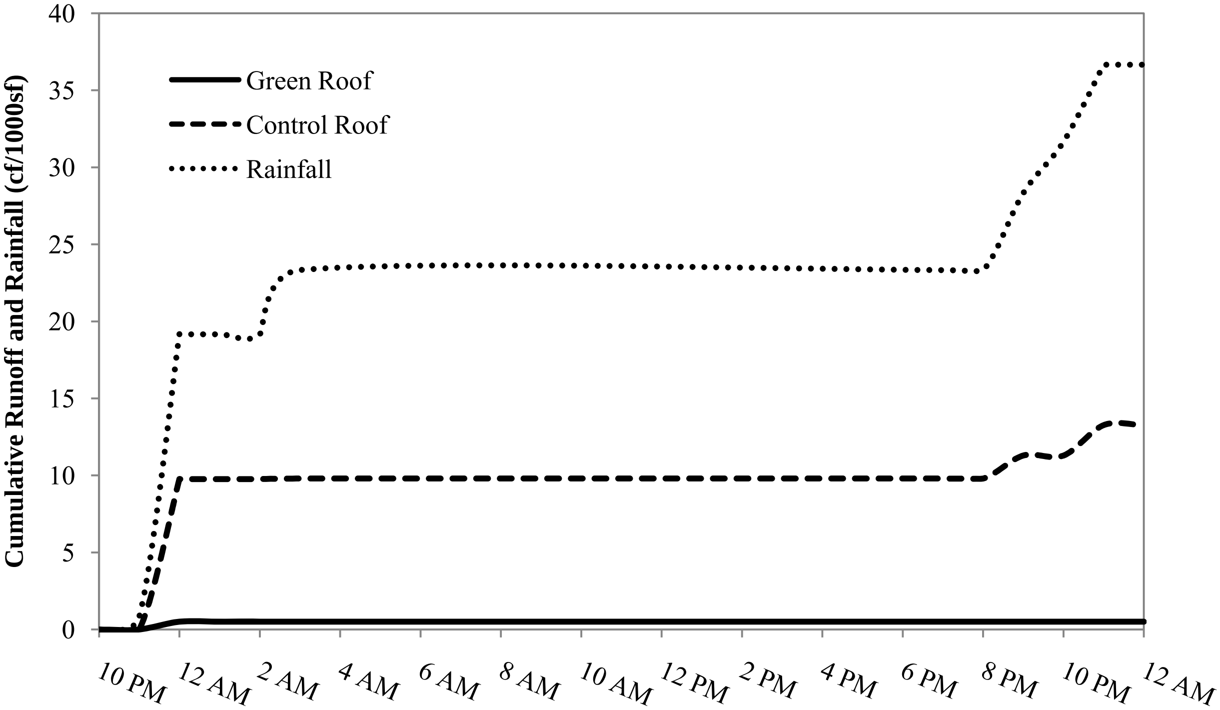


Figure I-110 Runoff and Rainfall Volumes – August 9-10, 2008 Storm (Homestead)

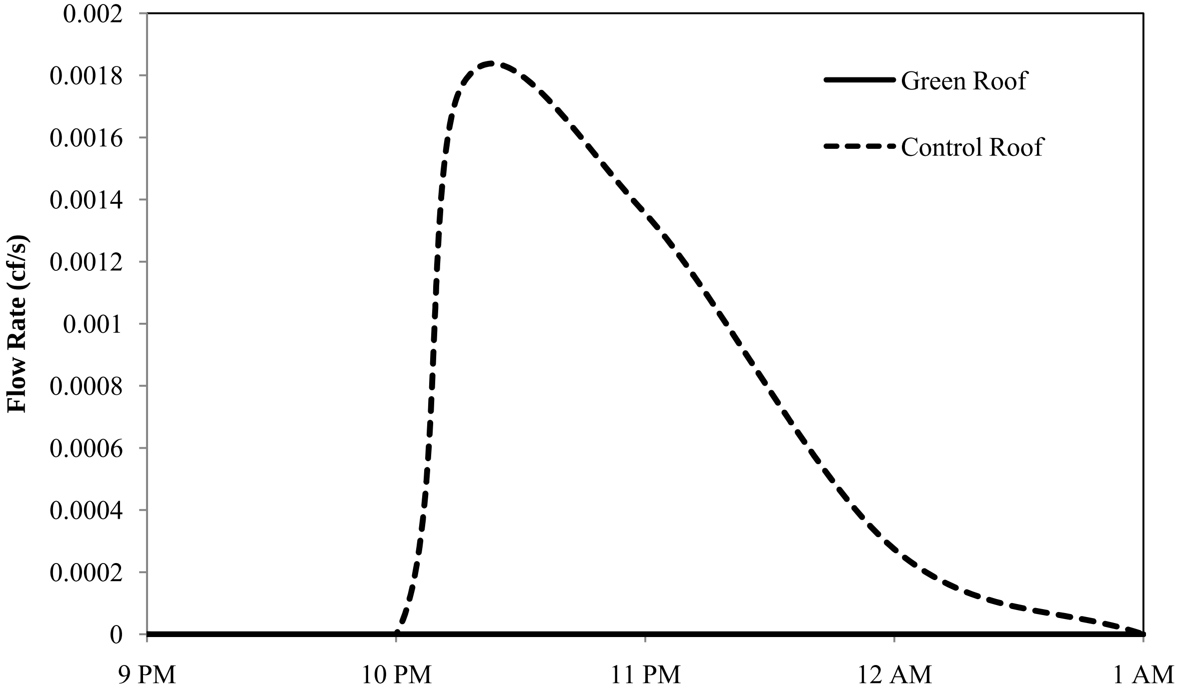


Figure I-111 Runoff Flow Rates – August 10, 2008 Storm (Giant Eagle)

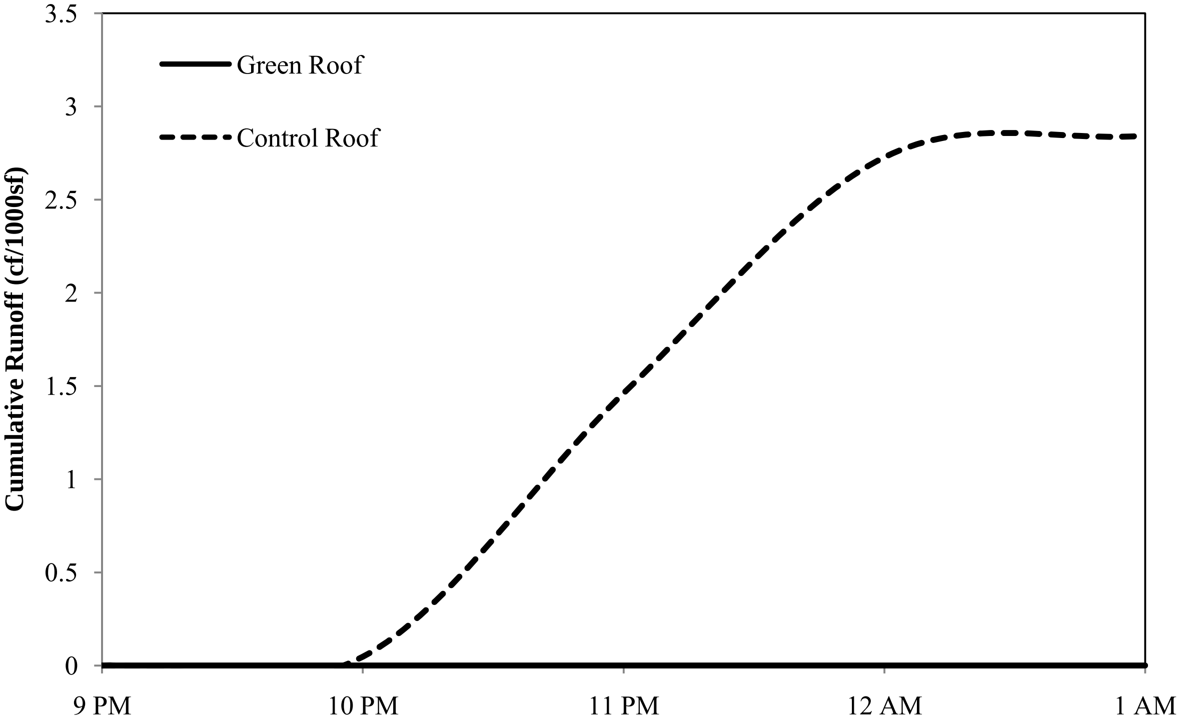


Figure I-112 Runoff Volumes – August 10, 2008 Storm (Giant Eagle)

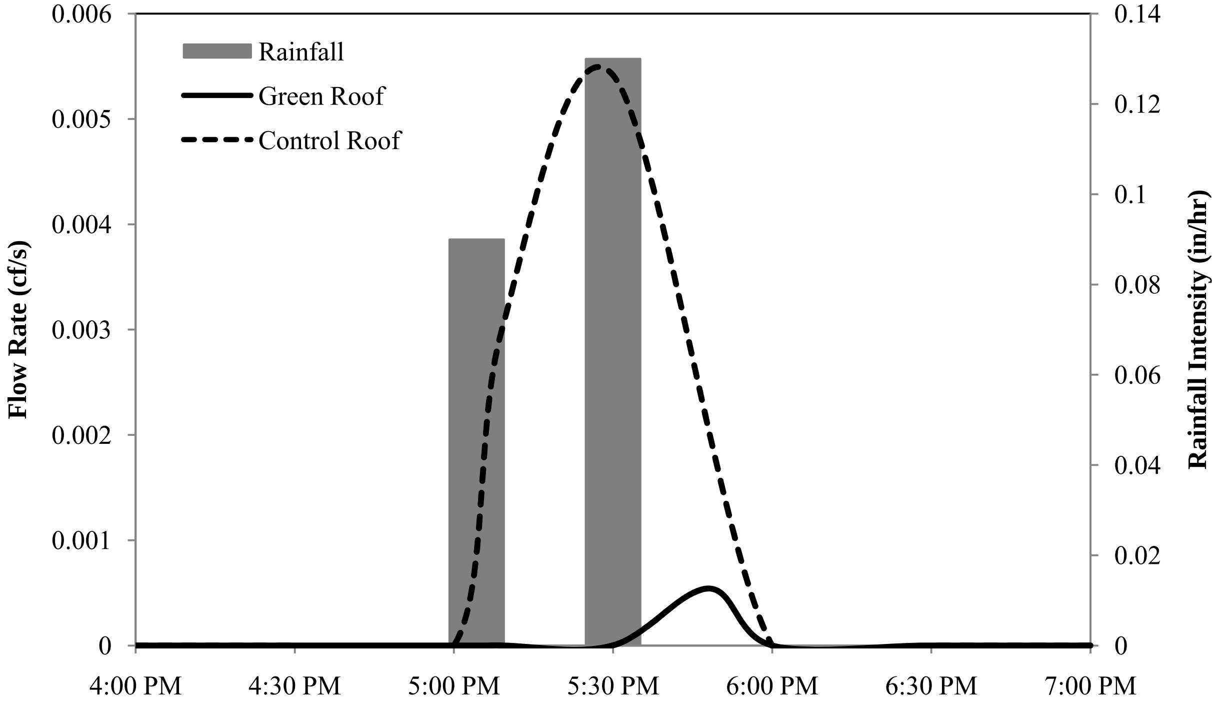


Figure I-113 Runoff Flow Rates and Rainfall Intensity – August 14, 2008 Storm (Homestead)

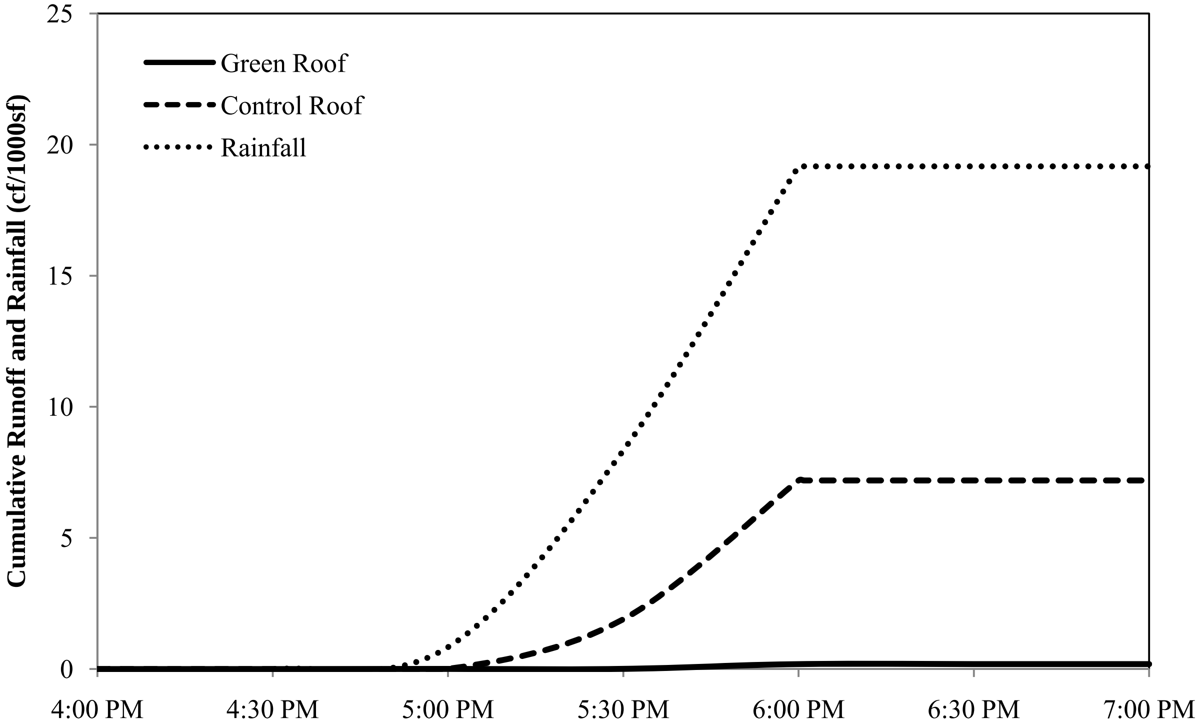


Figure I-114 Runoff and Rainfall Volumes – August 14, 2008 Storm (Homestead)

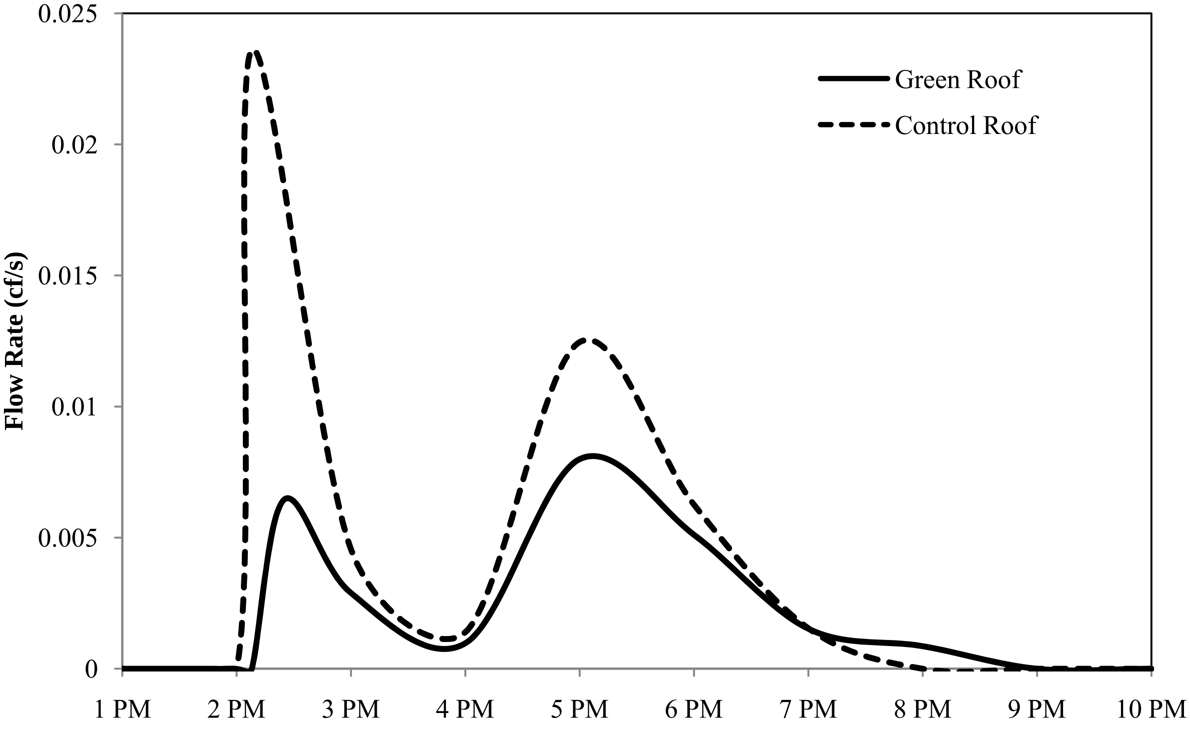


Figure I-115 Runoff Flow Rates – August 14, 2008 Storm (Giant Eagle)

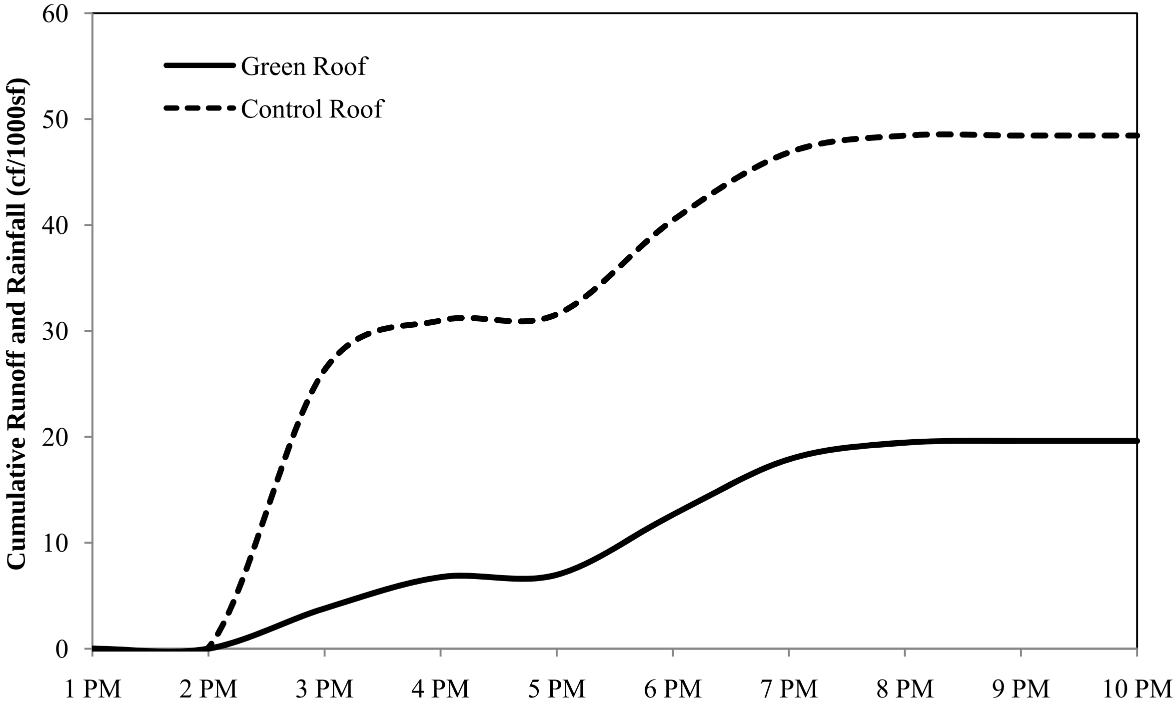


Figure I-116 Runoff Volumes – August 14, 2008 Storm (Giant Eagle)

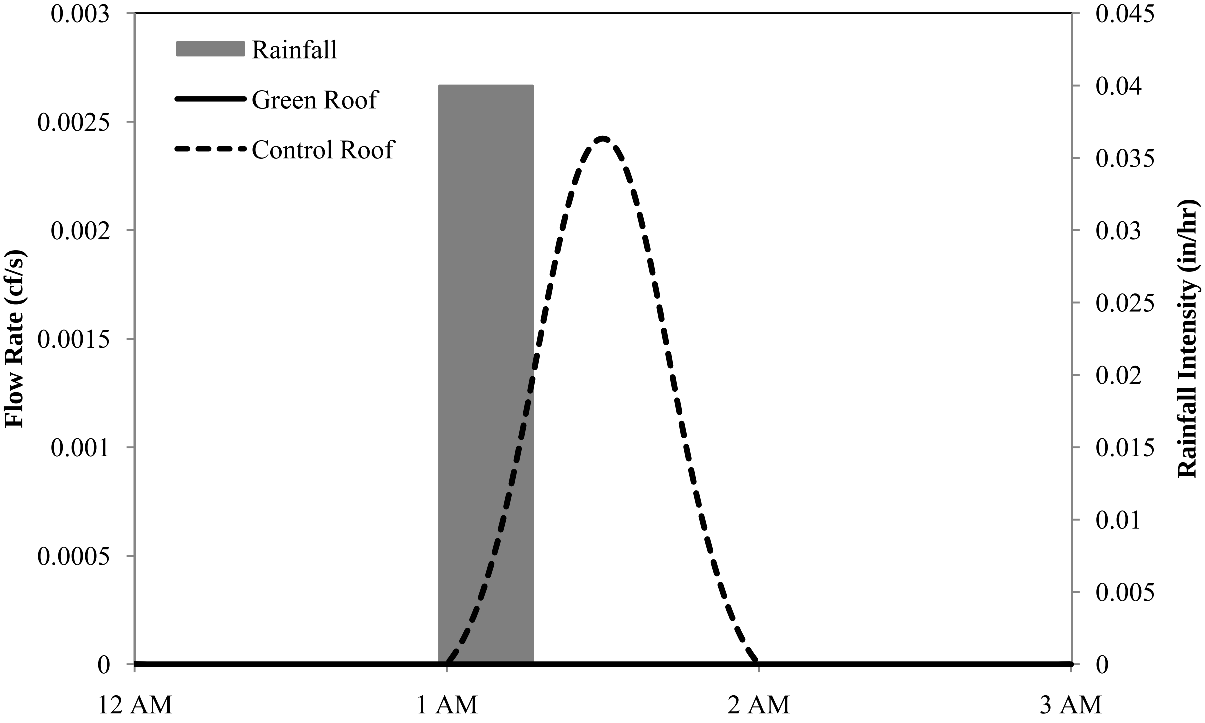


Figure I-117 Runoff Flow Rates and Rainfall Intensity – August 25, 2008 Storm (Homestead)

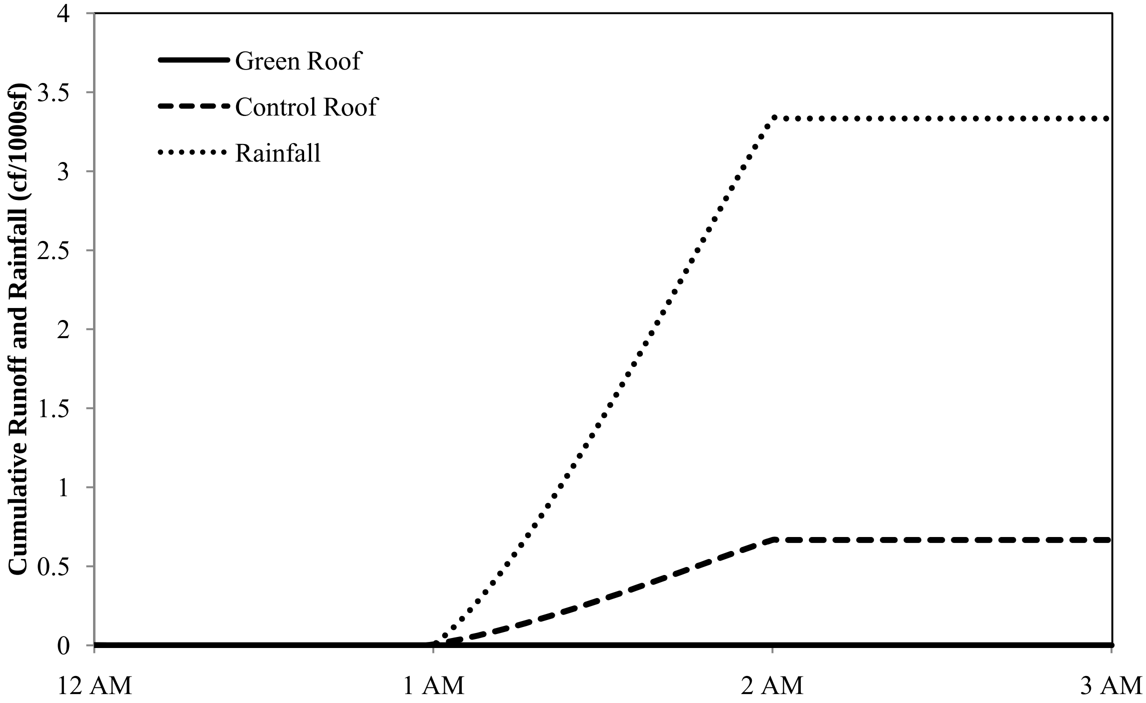


Figure I-118 Runoff and Rainfall Volumes – August 25, 2008 Storm (Homestead)

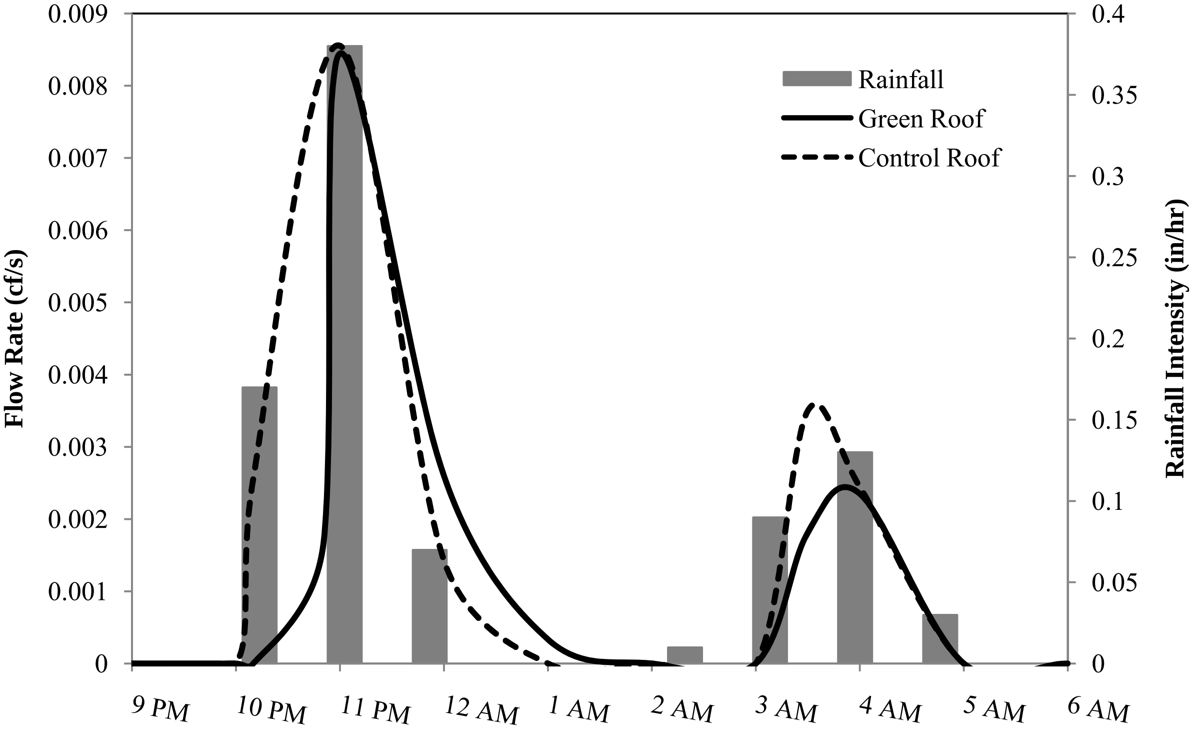


Figure I-119 Runoff Flow Rates and Rainfall Intensity – August 27-28, 2008 Storm (Homestead)

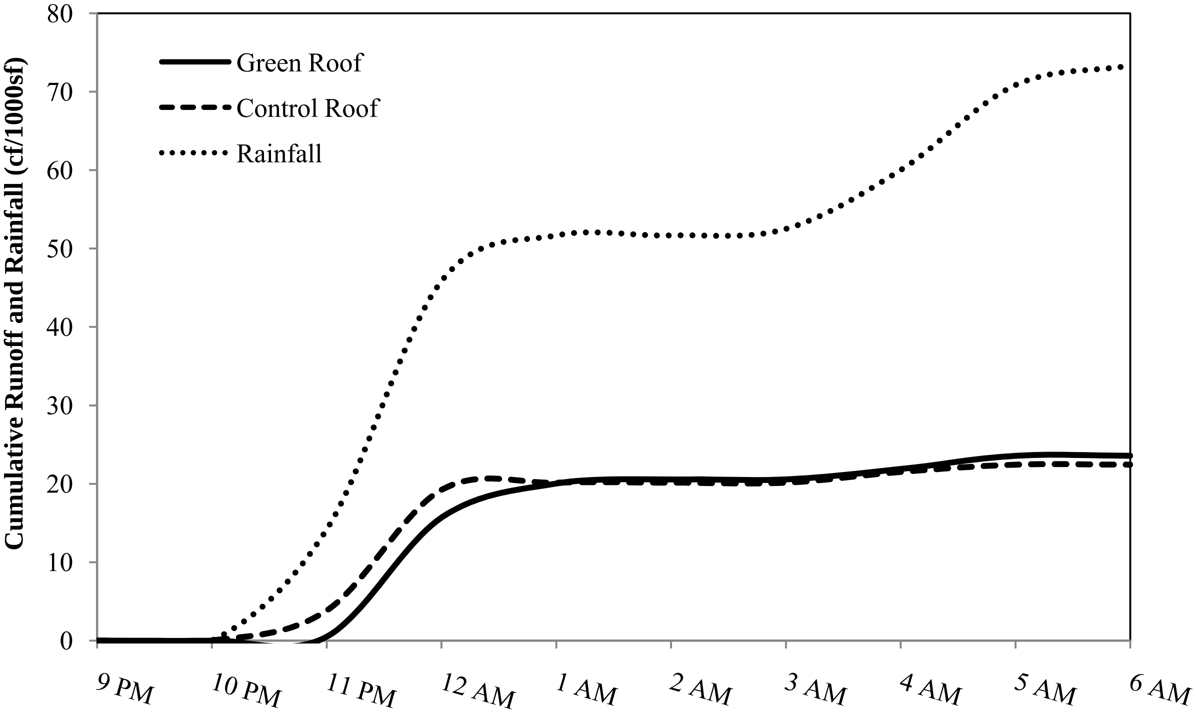


Figure I-120 Runoff and Rainfall Volumes – August 27-28, 2008 Storm (Homestead)

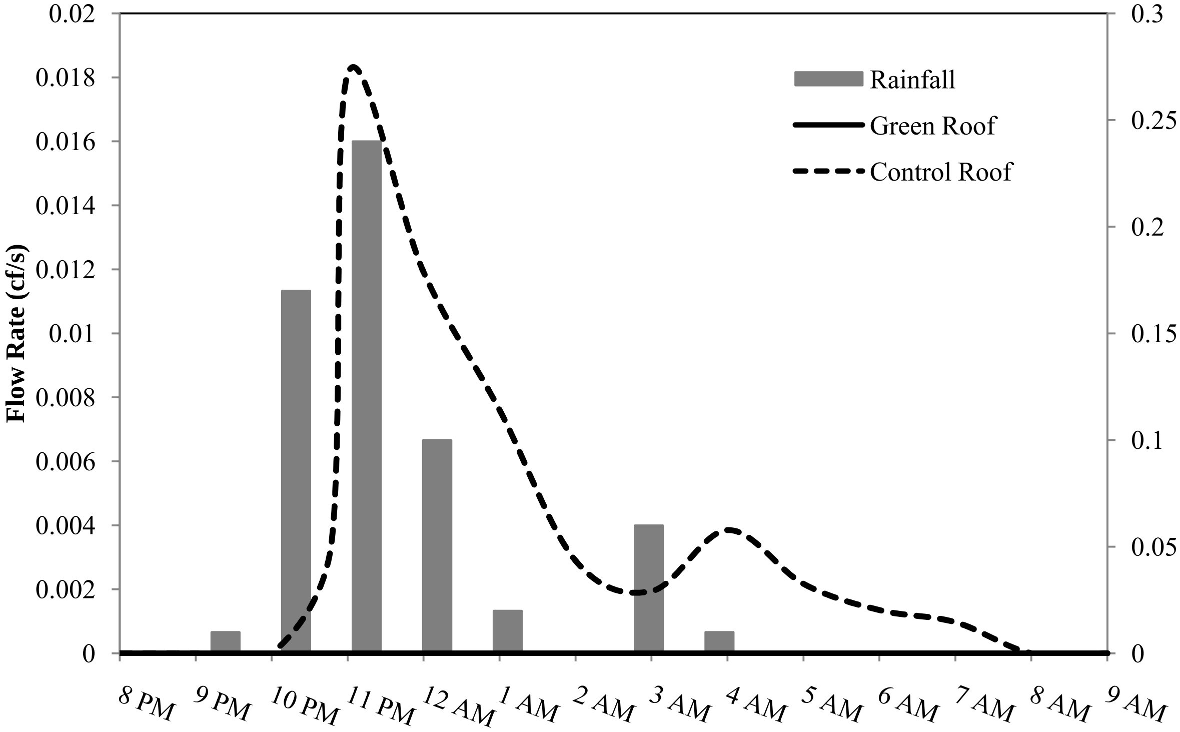


Figure I-121 Runoff Flow Rates and Rainfall intensity – August 27-28, 2008 Storm (Giant Eagle)

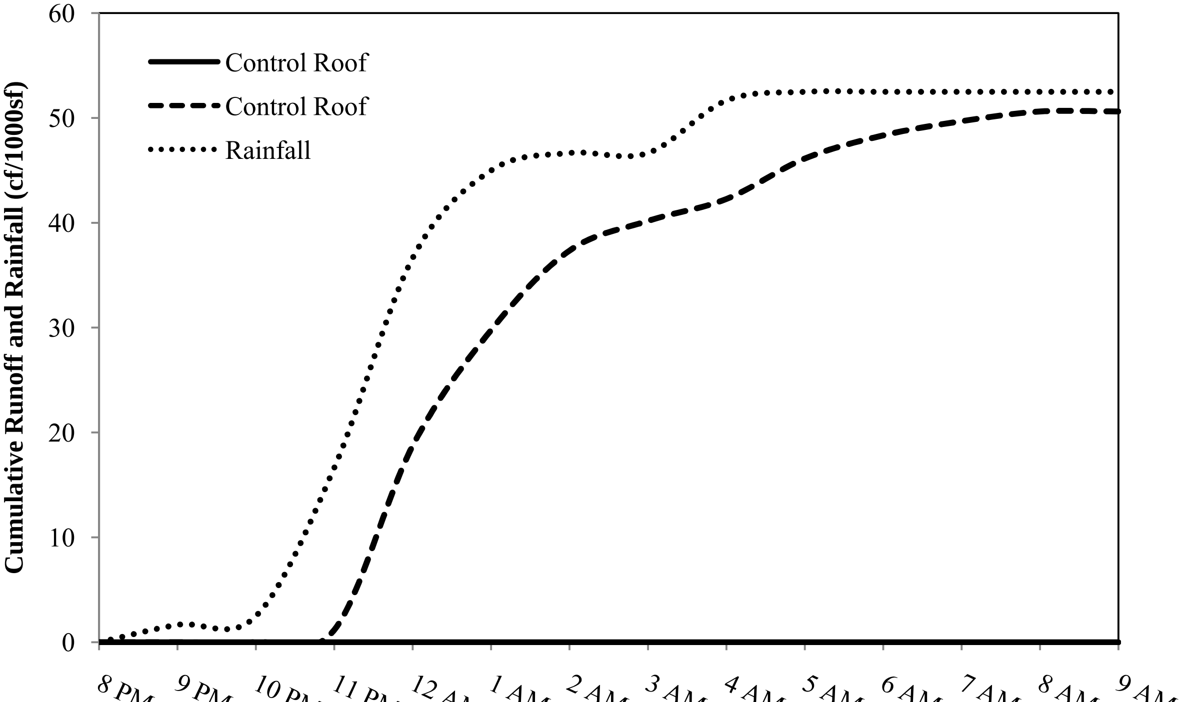


Figure I-122 Runoff and Rainfall Volumes – August 27-28, 2008 Storm (Giant Eagle)

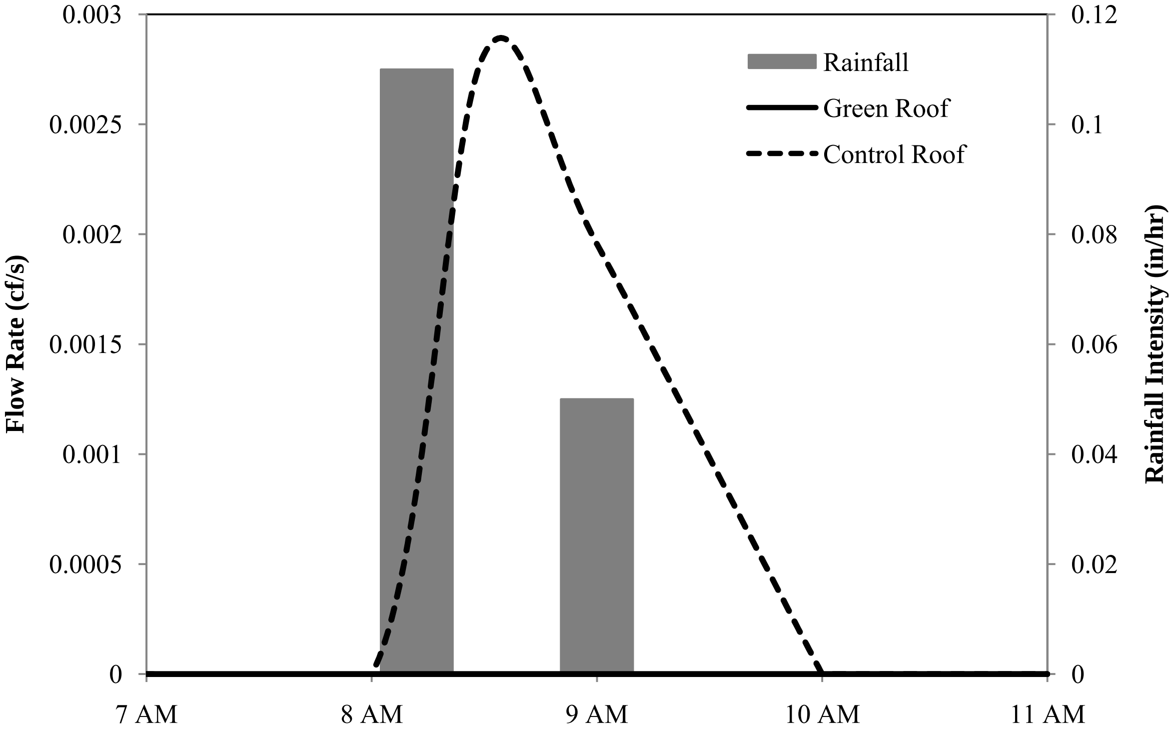


Figure I-123 Runoff Flow Rates and Rainfall Intensity – September 9, 2008 Storm (Homestead)

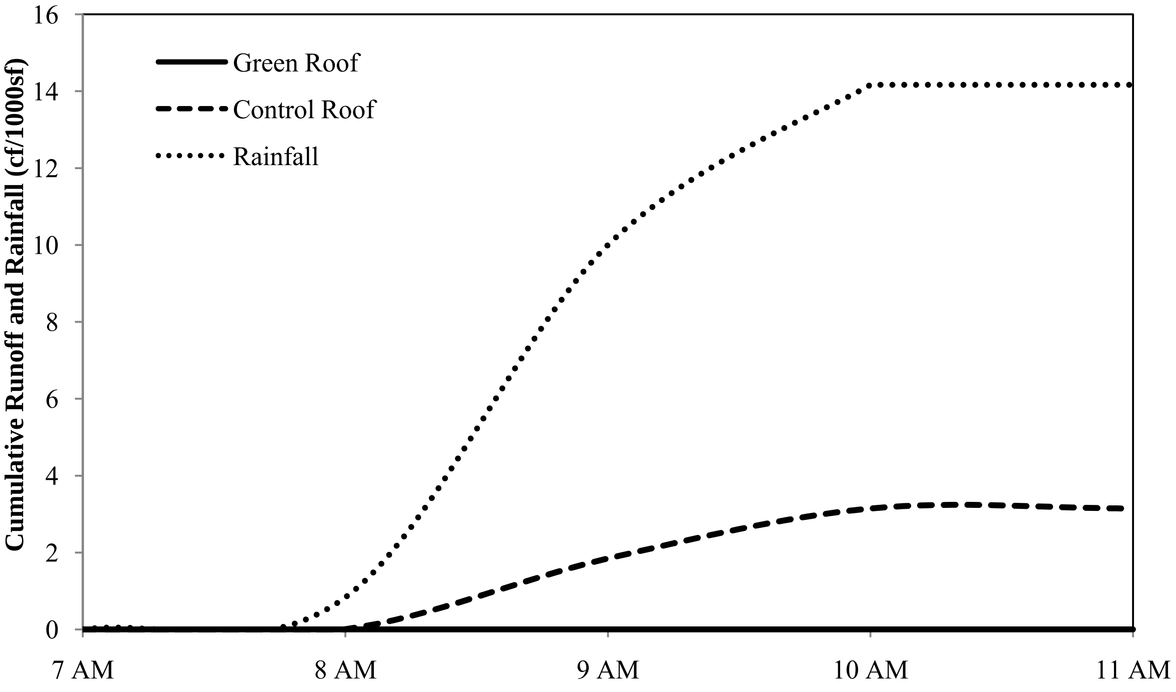


Figure I-124 Runoff and Rainfall Volumes – September 9, 2008 Storm (Homestead)

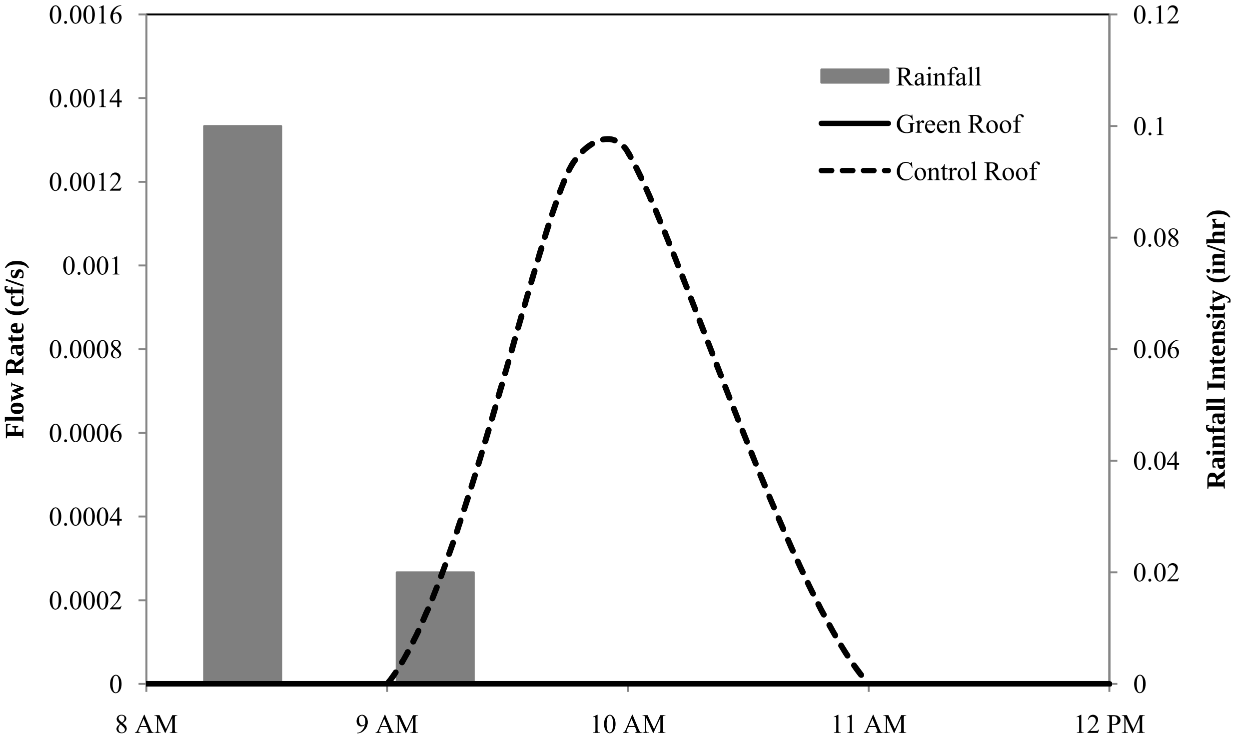


Figure I-125 Runoff Flow Rates and Rainfall intensity – September 9, 2008 Storm (Giant Eagle)

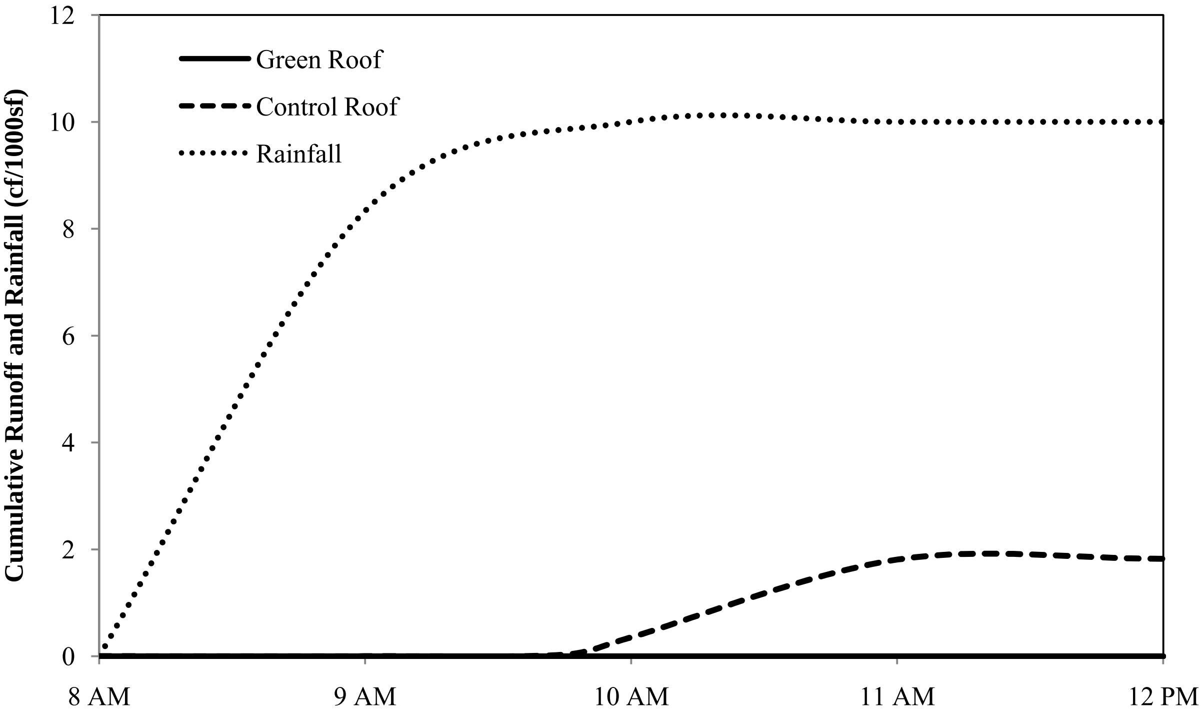


Figure I-126 Runoff and Rainfall Volumes – September 9, 2008 Storm (Giant Eagle)

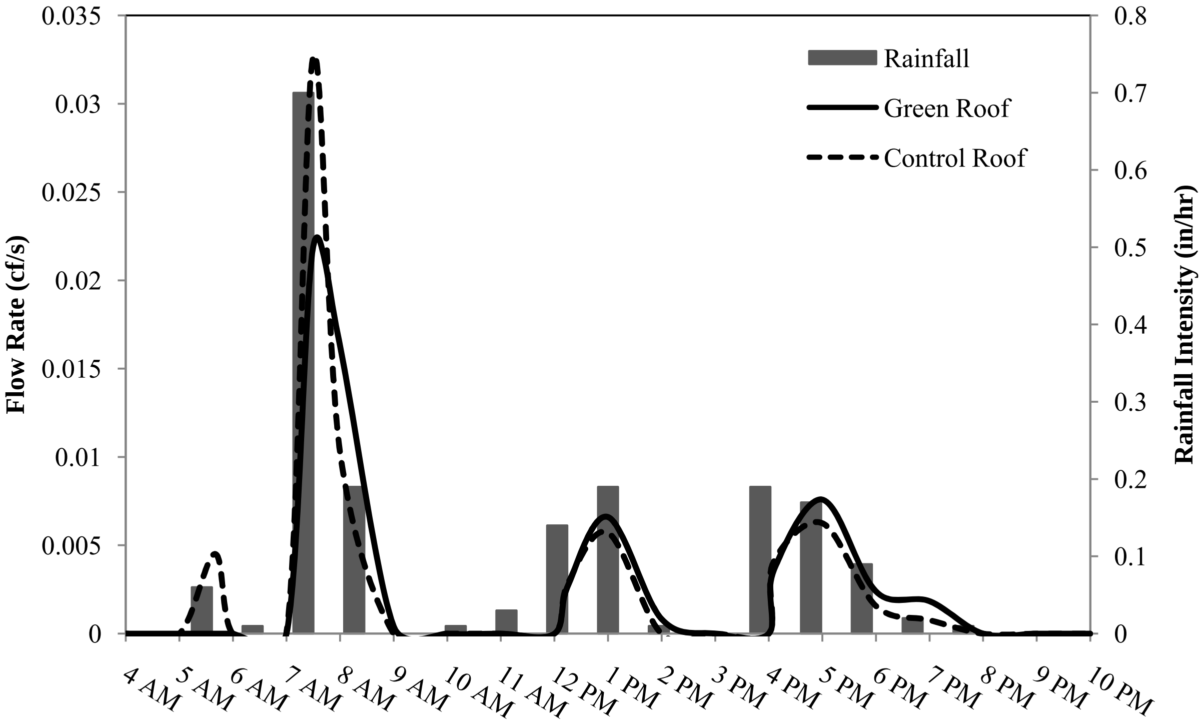


Figure I-127 Runoff Flow Rates and Rainfall Intensity – September 12, 2008 Storm (Homestead)

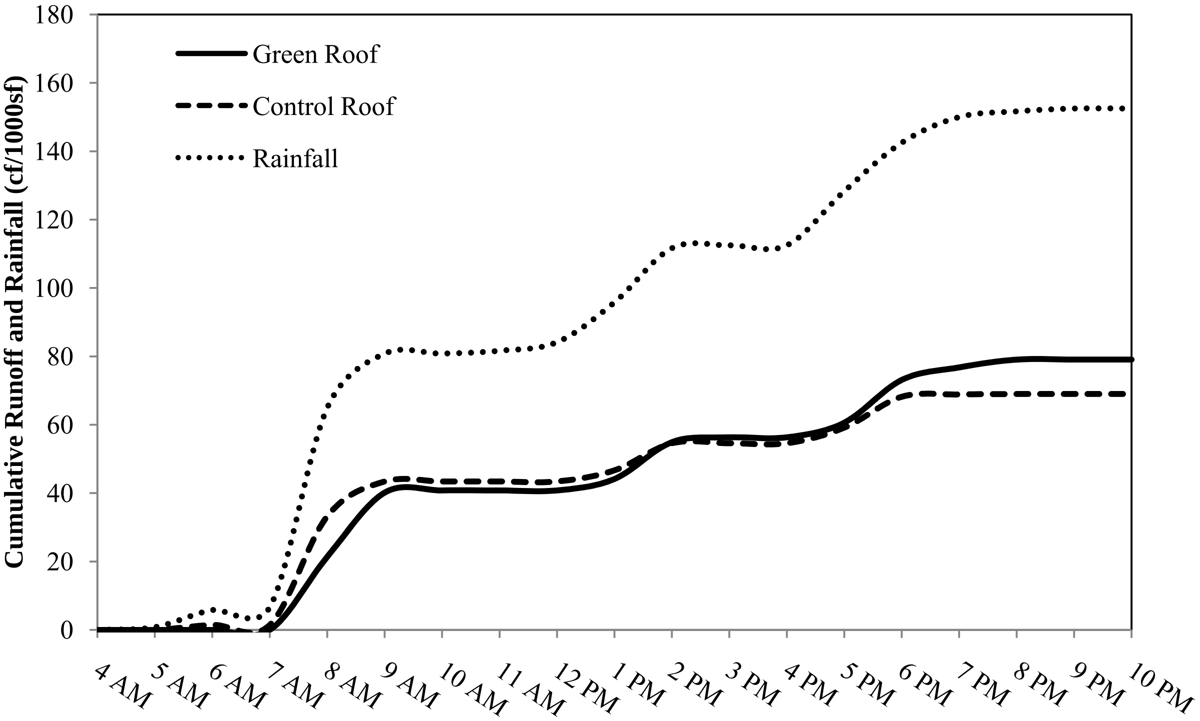


Figure I-128 Runoff and Rainfall Volumes – September 12, 2008 Storm (Homestead)

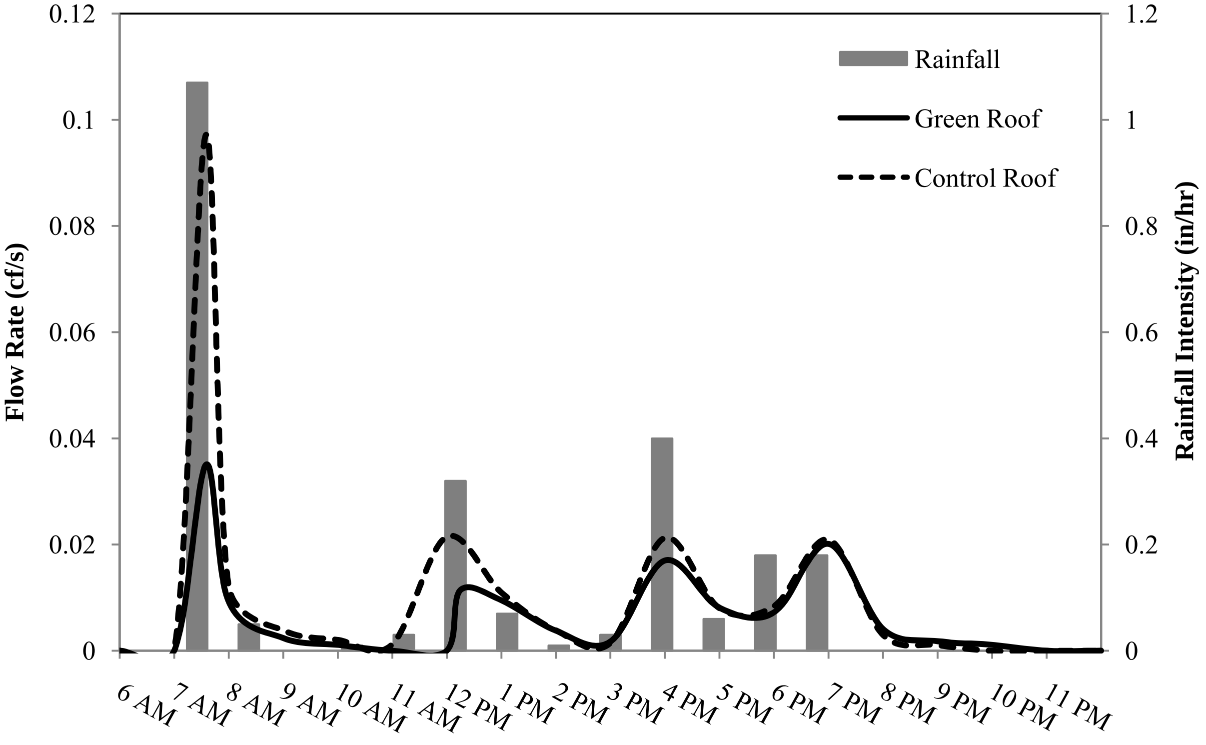


Figure I-129 Runoff Flow Rates and Rainfall intensity – September 12, 2008 Storm (Giant Eagle)

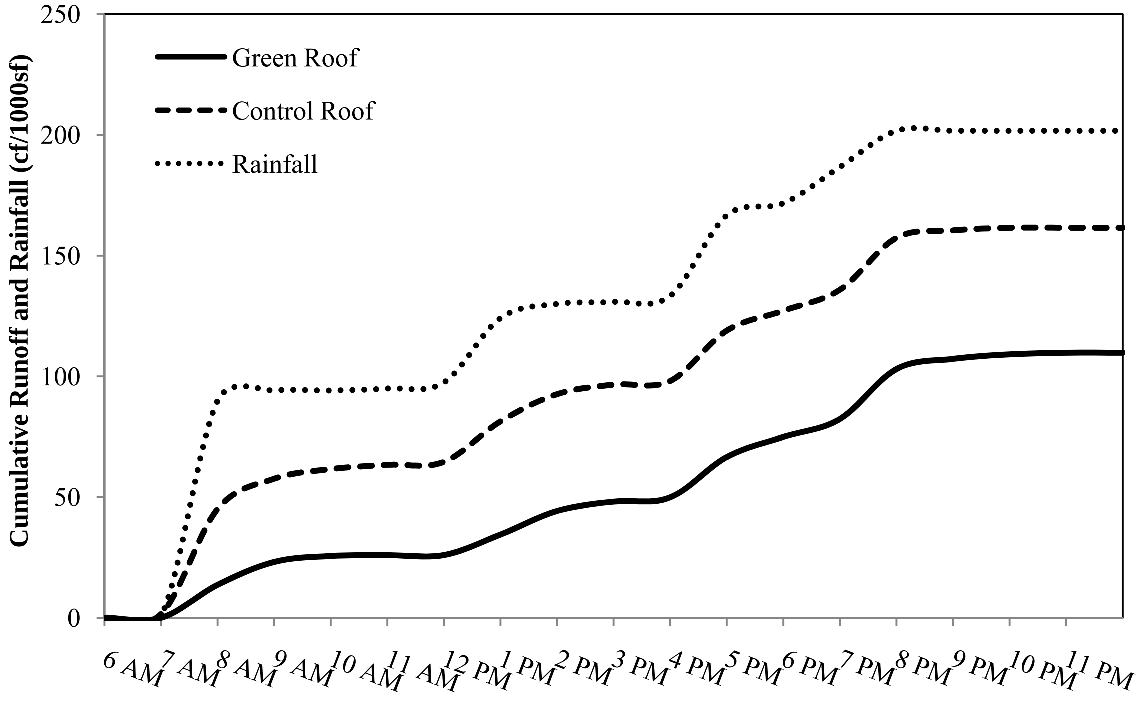


Figure I-130 Runoff and Rainfall Volumes – September 12, 2008 Storm (Giant Eagle)

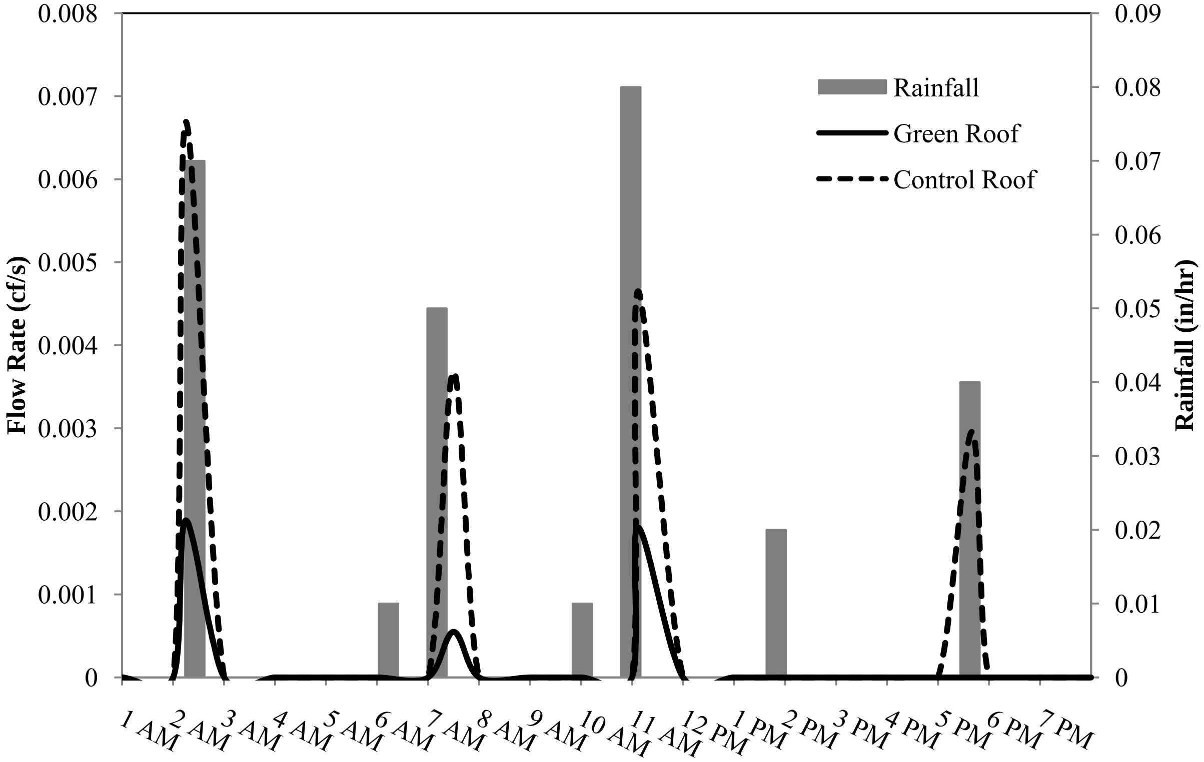


Figure I-131 Runoff Flow Rates and Rainfall Intensity – September 13, 2008 Storm (Homestead)

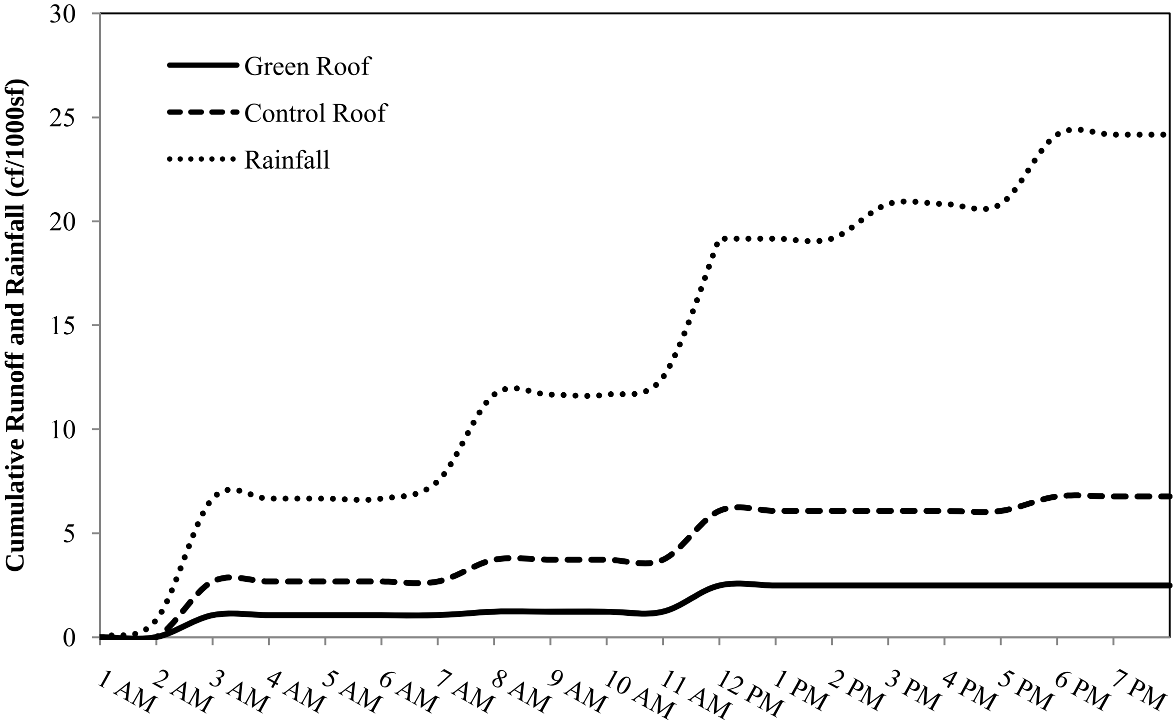


Figure I-132 Runoff and Rainfall Volumes – September 13, 2008 Storm (Homestead)

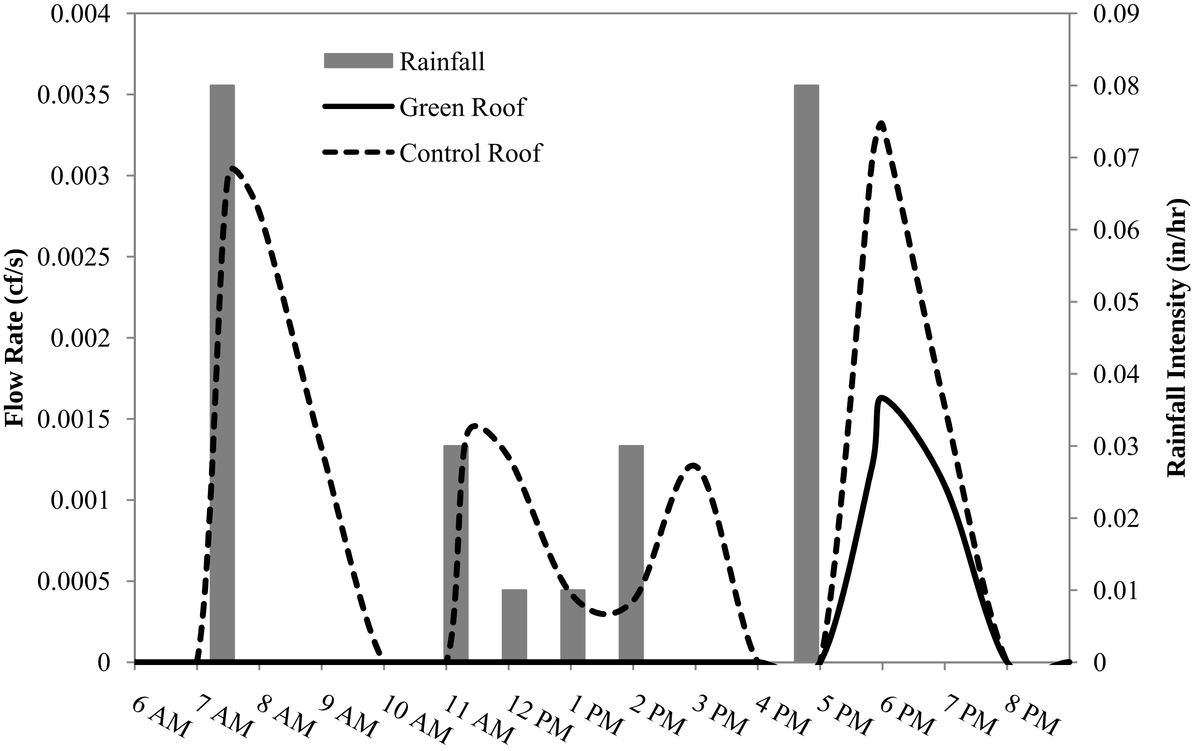


Figure I-133 Runoff Flow Rates and Rainfall intensity – September 13, 2008 Storm (Giant Eagle)

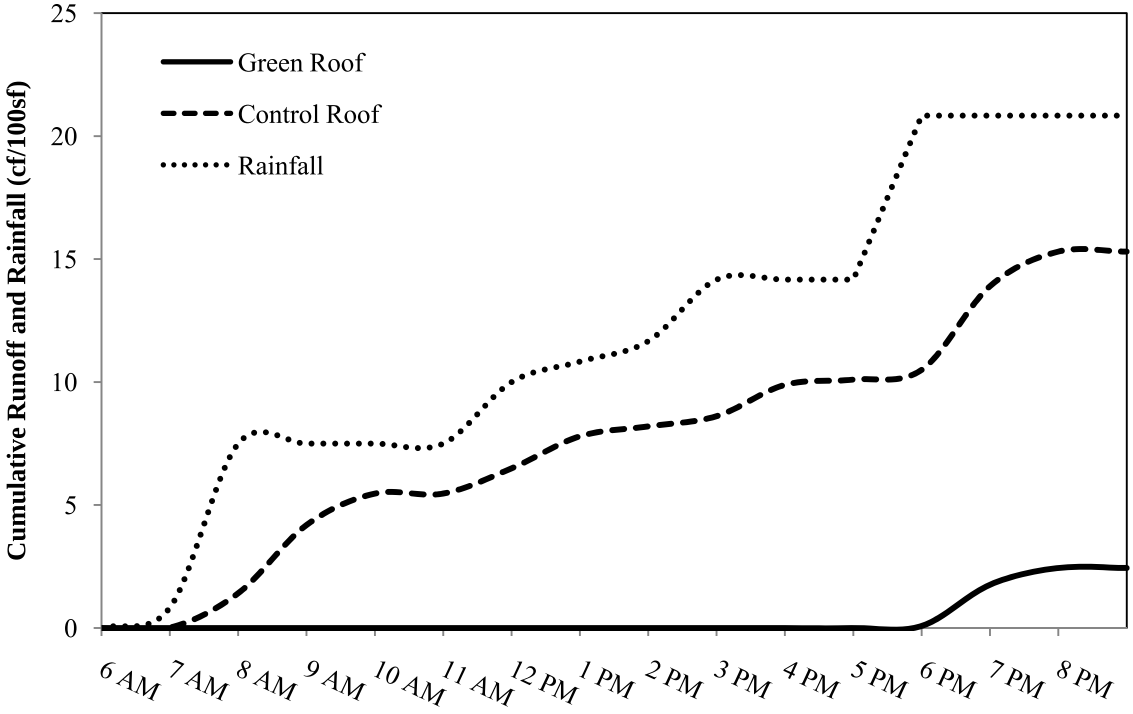


Figure I-134 Runoff and Rainfall Volumes – September 13, 2008 Storm (Giant Eagle)

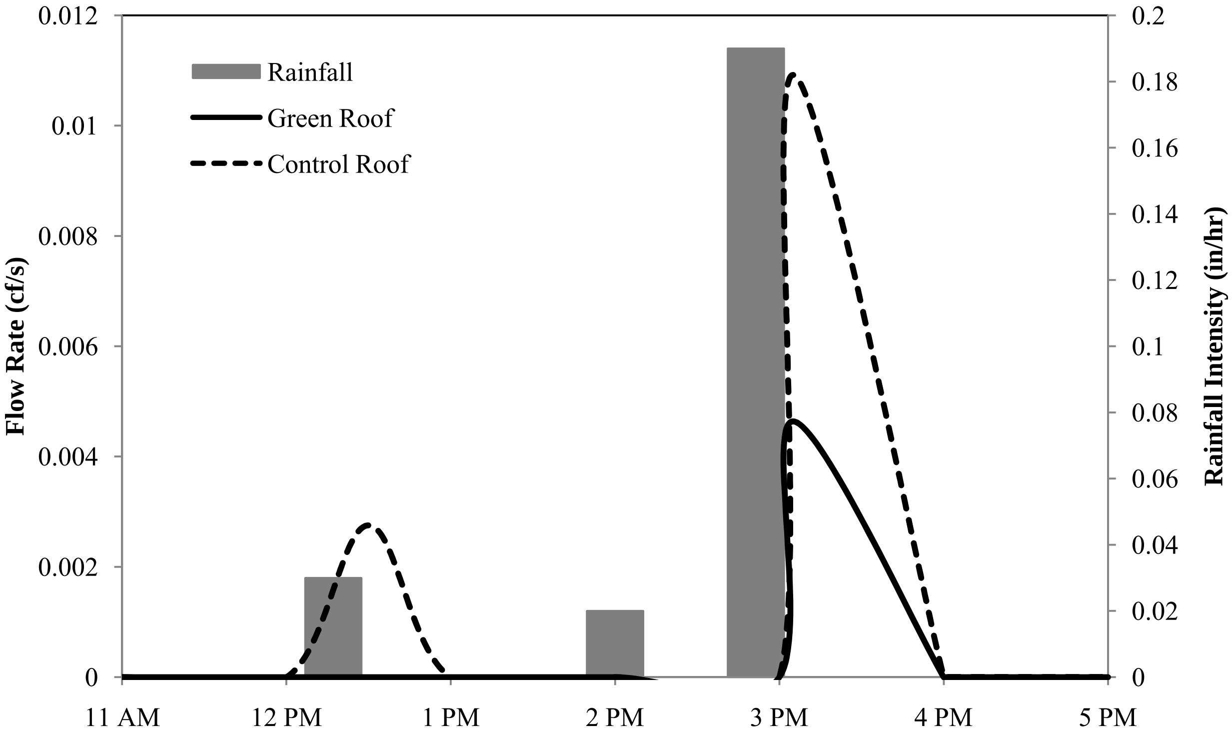


Figure I-135 Runoff Flow Rates and Rainfall Intensity – October 1, 2008 Storm (Homestead)

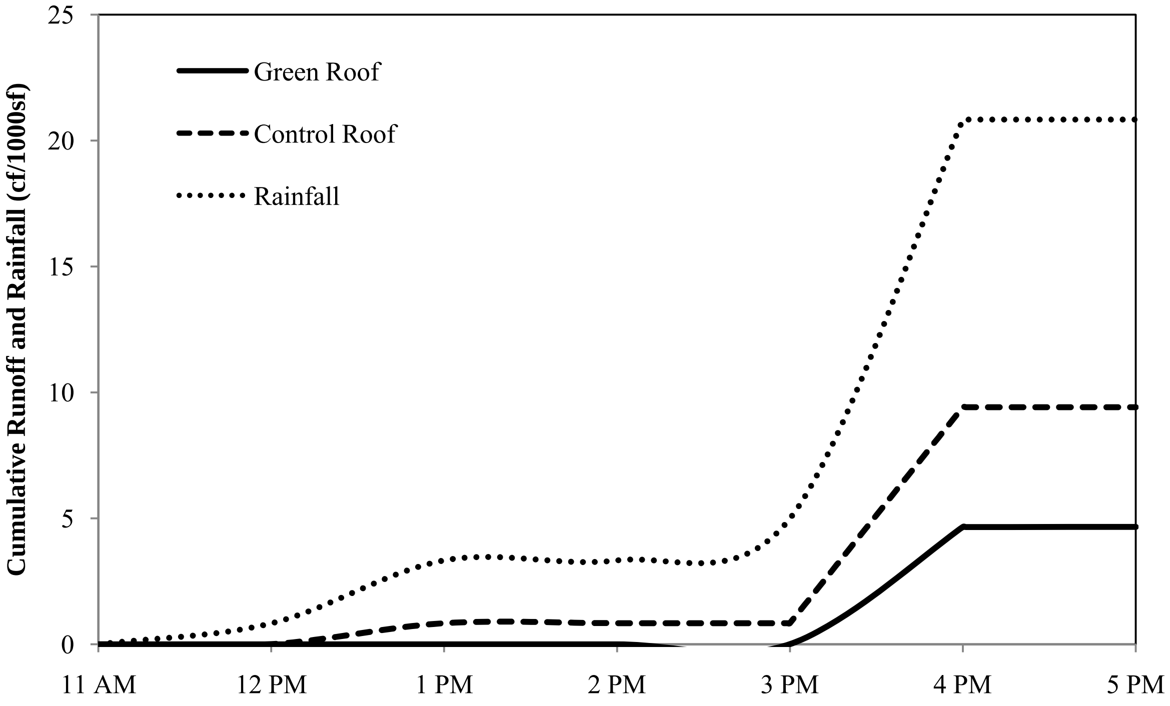


Figure I-136 Runoff and Rainfall Volumes – October 1, 2008 Storm (Homestead)

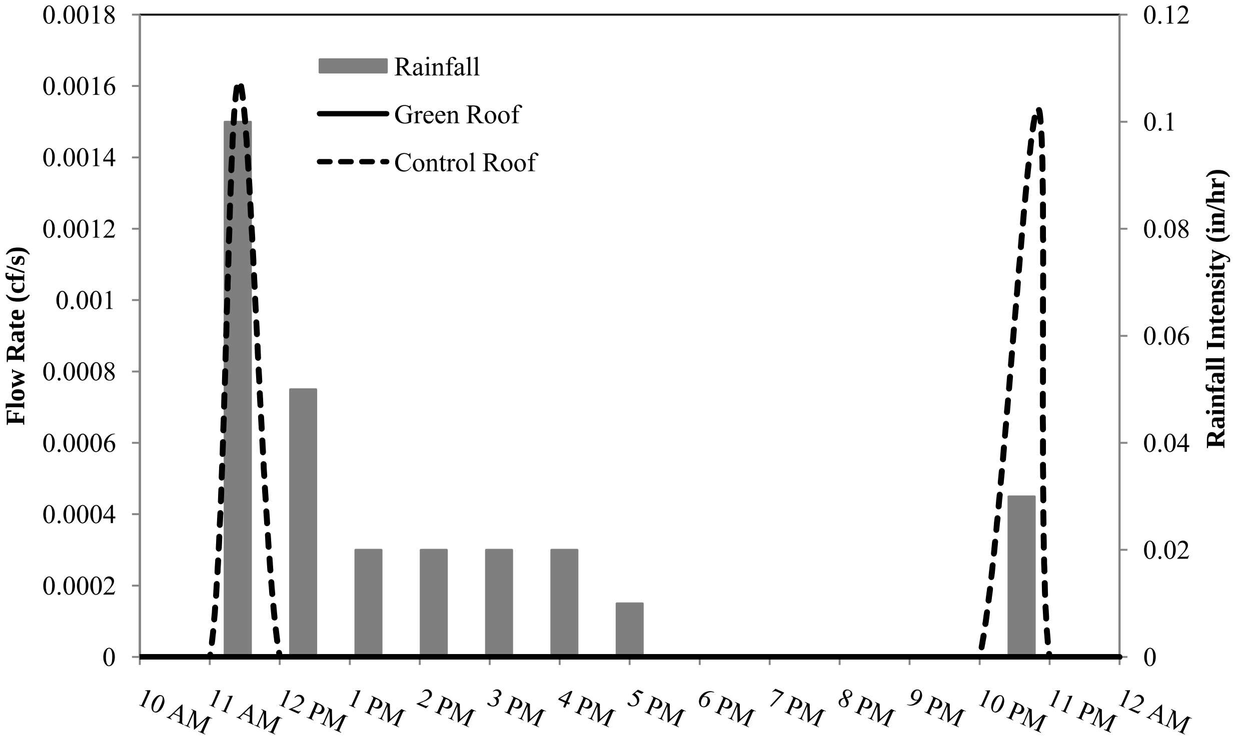


Figure I-137 Runoff Flow Rates and Rainfall Intensity – October 8, 2008 Storm (Homestead)

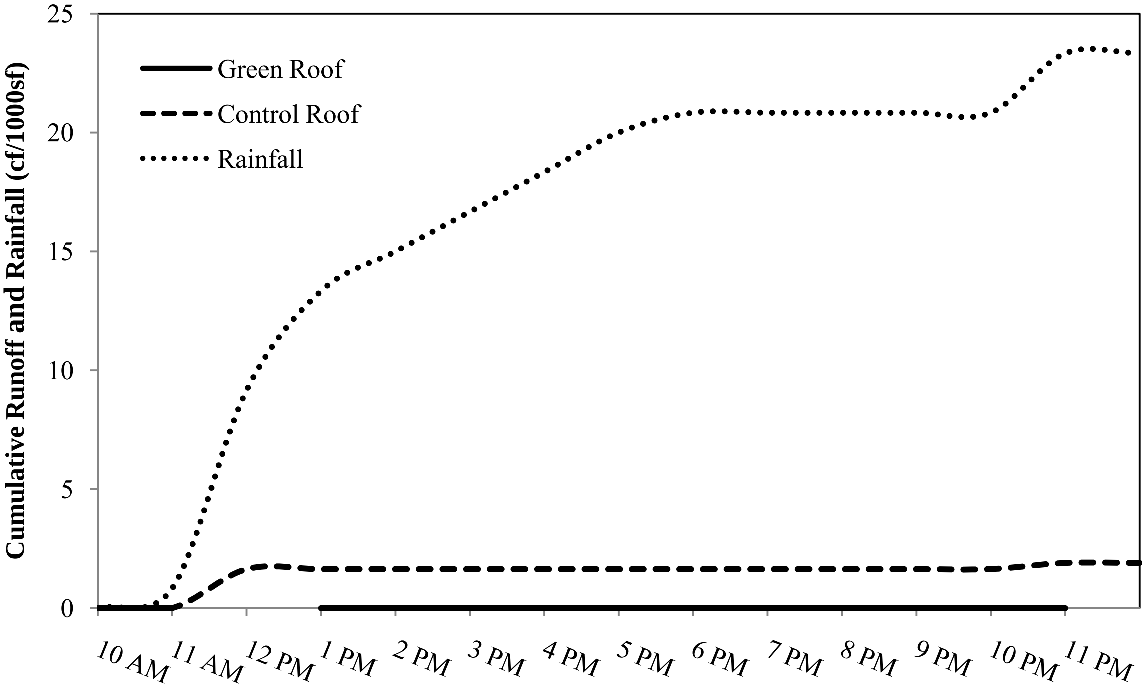


Figure I-138 Runoff and Rainfall Volumes – October 8, 2008 Storm (Homestead)

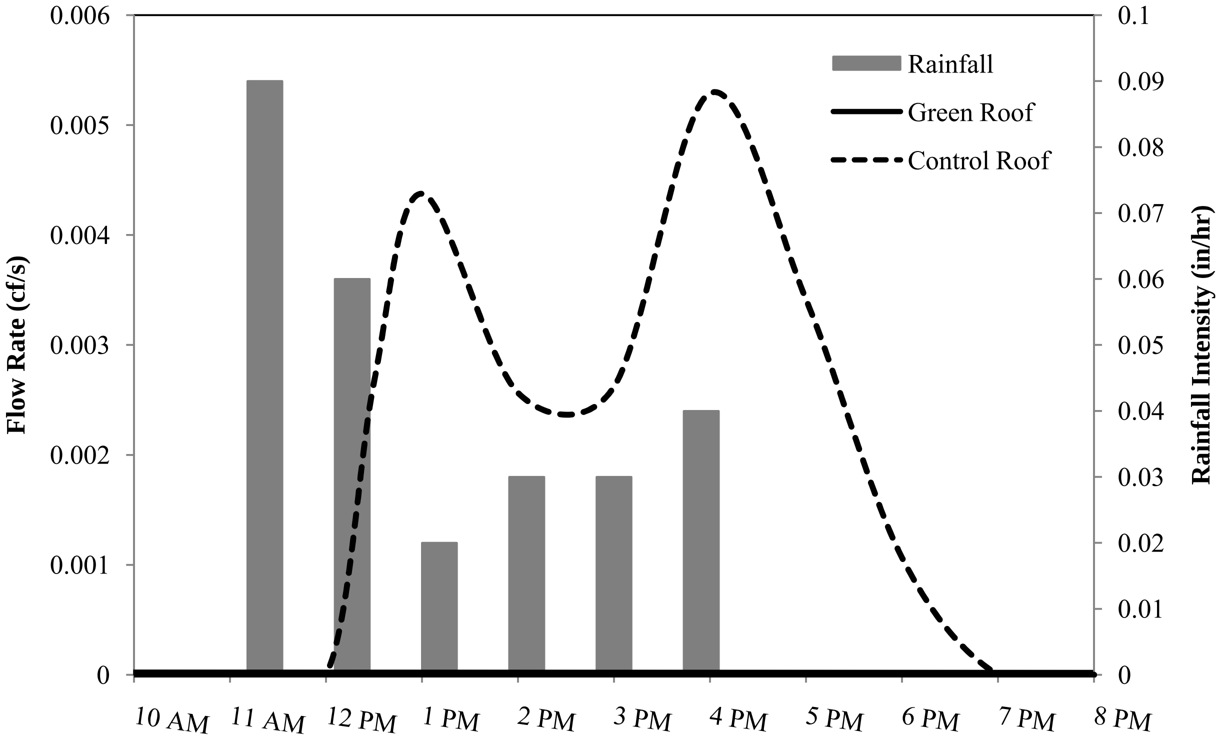


Figure I-139 Runoff Flow Rates and Rainfall intensity – October 8, 2008 Storm (Giant Eagle)

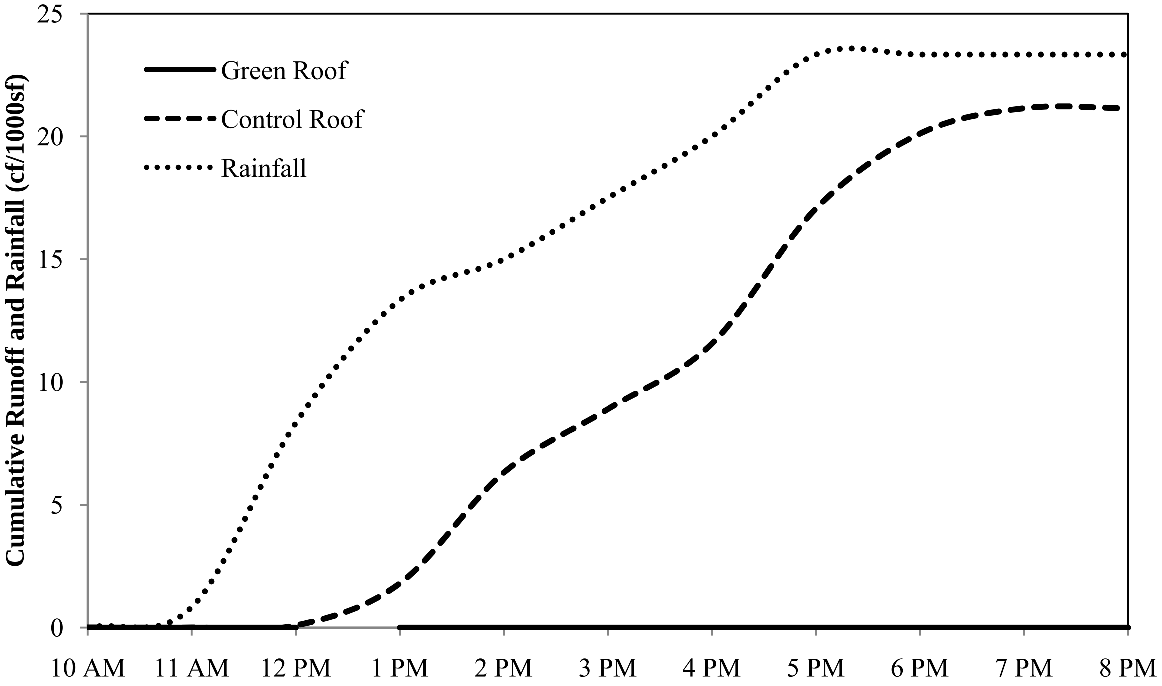


Figure I-140 Runoff and Rainfall Volumes – October 8, 2008 Storm (Giant Eagle)

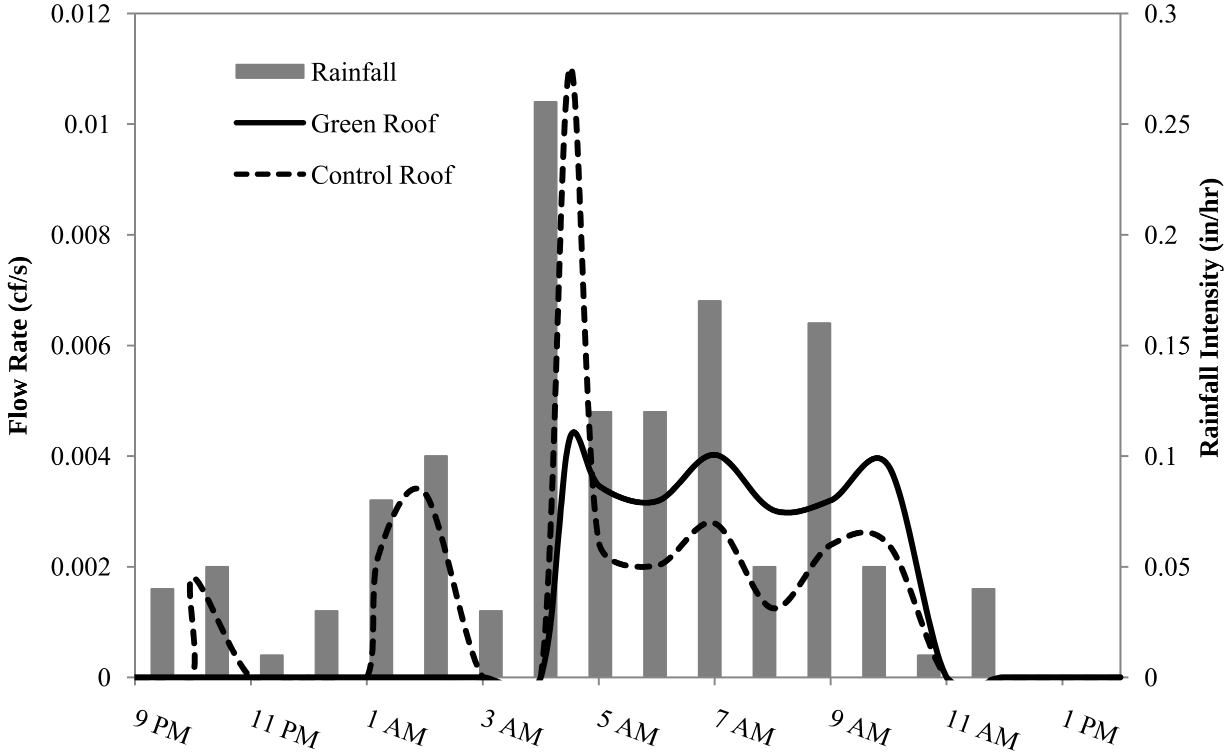


Figure I-141 Runoff Flow Rates and Rainfall Intensity – October 24-25, 2008 Storm (Homestead)

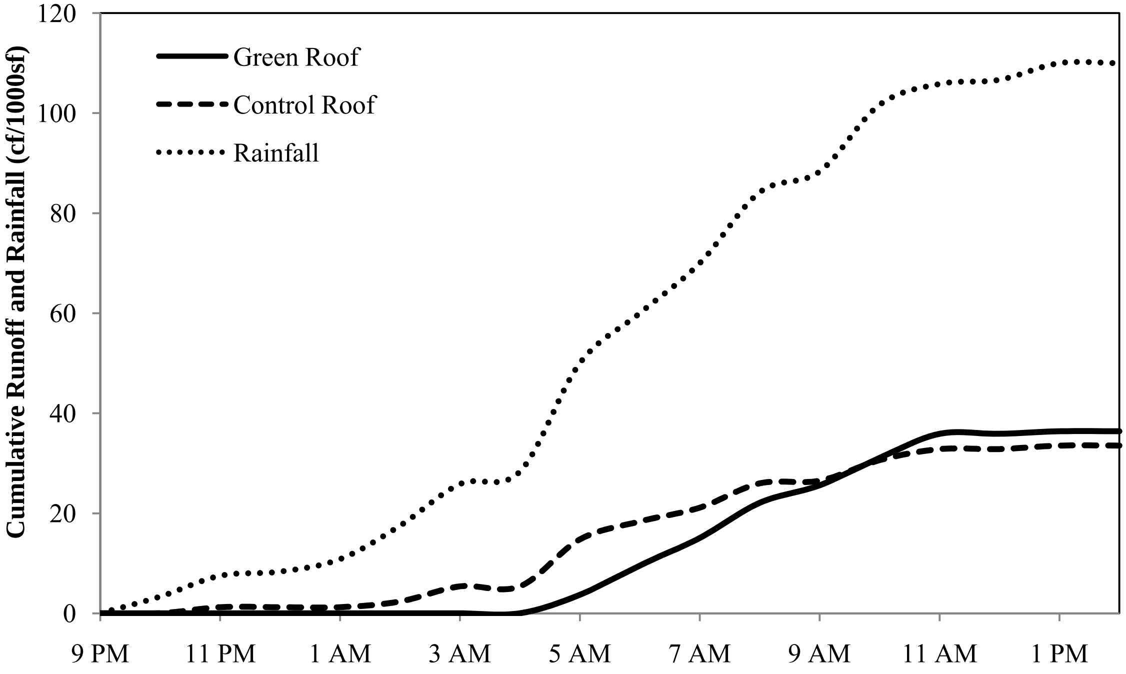


Figure I-142 Runoff and Rainfall Volumes – October 24-25, 2008 Storm (Homestead)

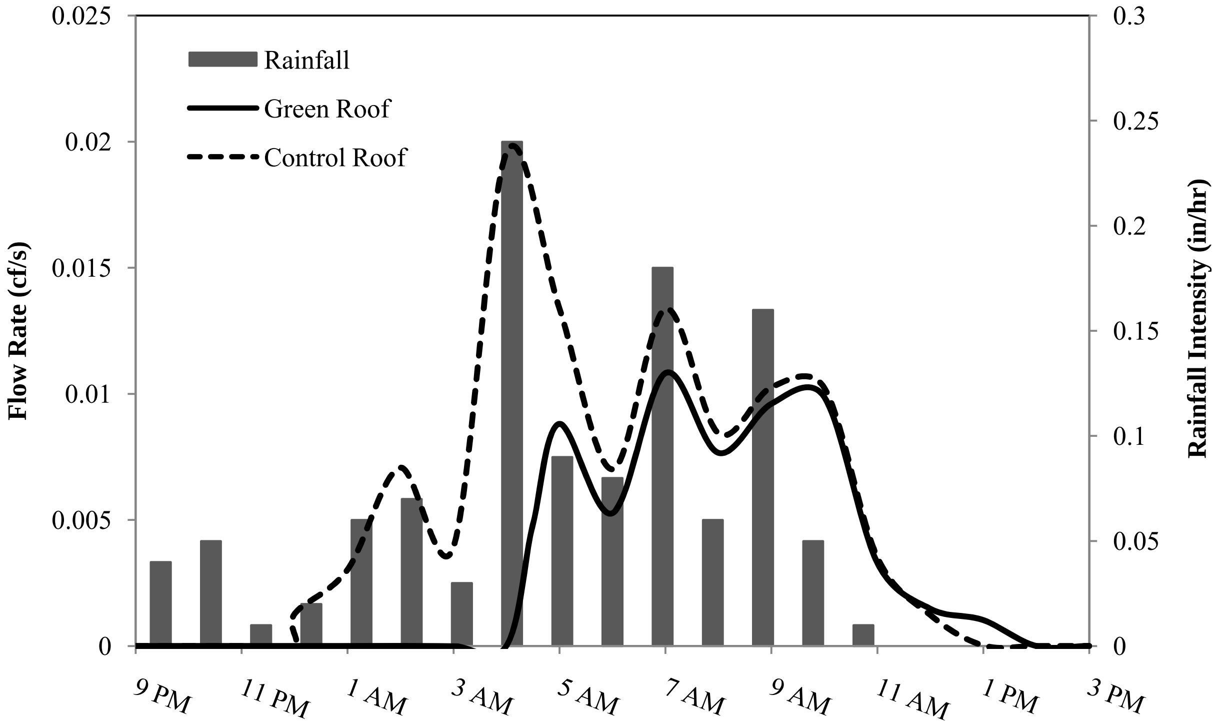


Figure I-143 Runoff Flow Rates and Rainfall intensity – October 24-25, 2008 Storm (Giant Eagle)

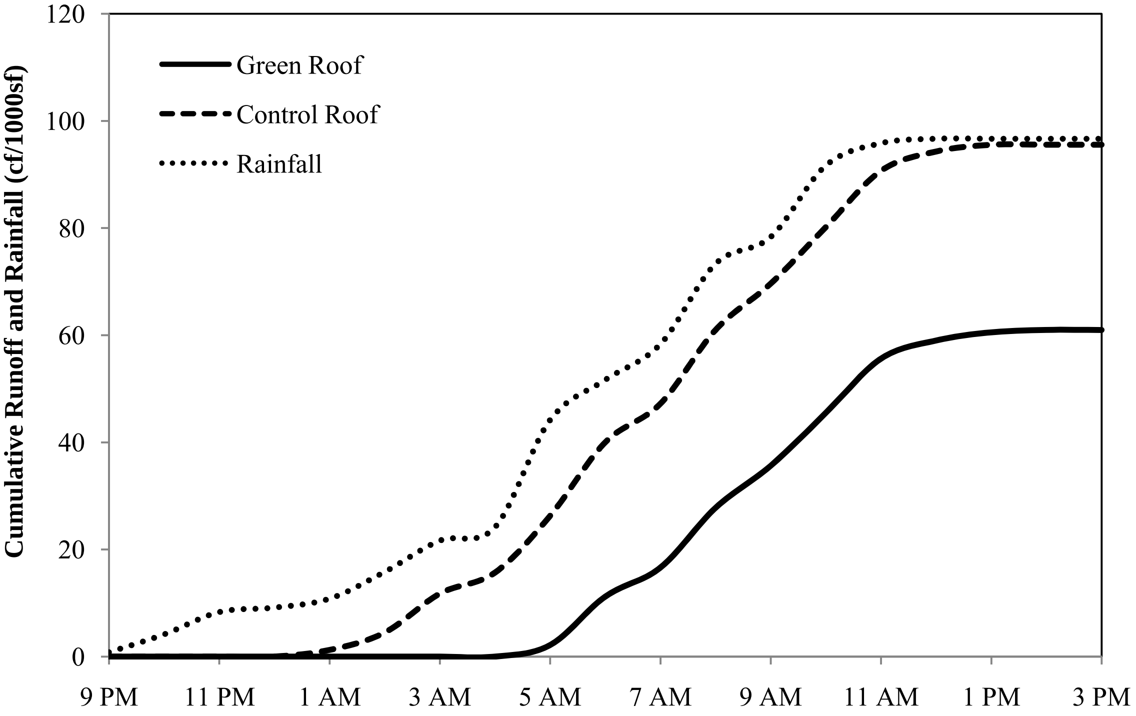


Figure I-144 Runoff and Rainfall Volumes – October 24-25, 2008 Storm (Giant Eagle)

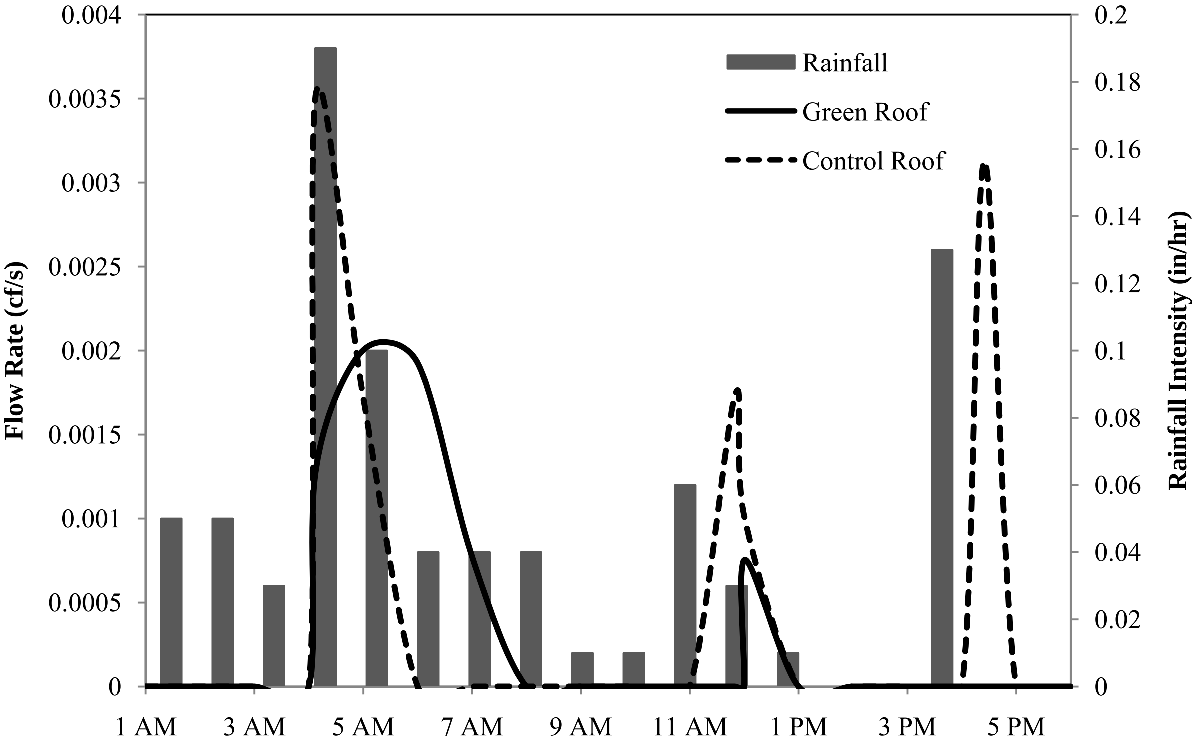


Figure I-145 Runoff Flow Rates and Rainfall Intensity – November 15, 2008 Storm (Homestead)

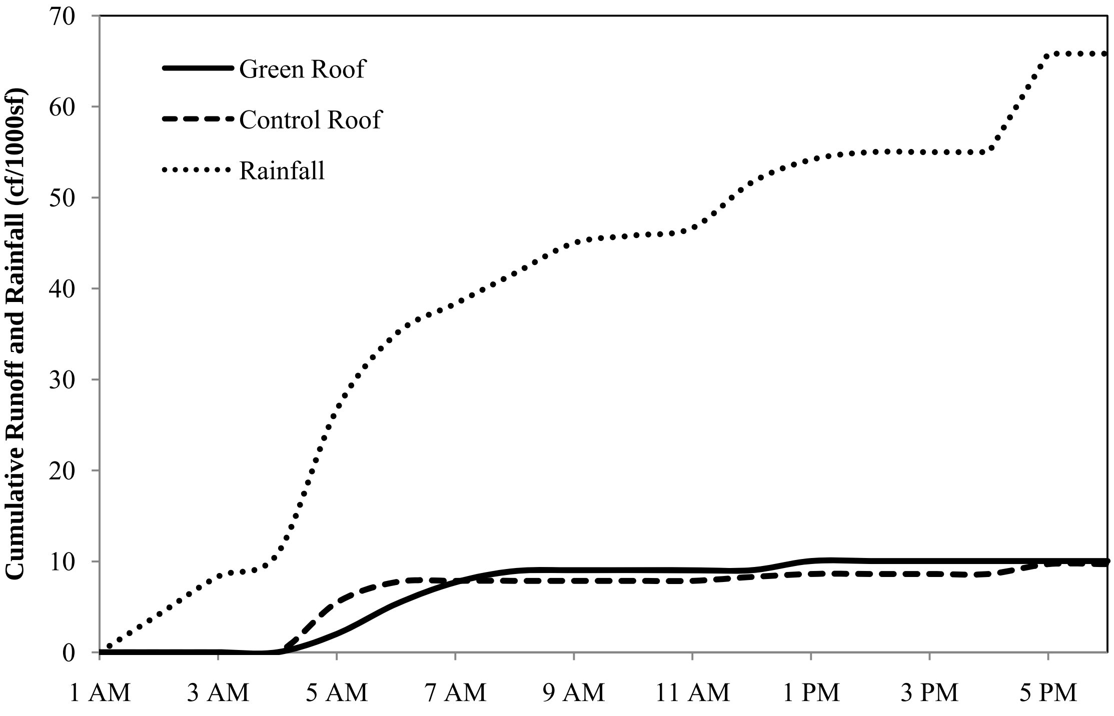


Figure I-146 Runoff and Rainfall Volumes – November 15, 2008 Storm (Homestead)

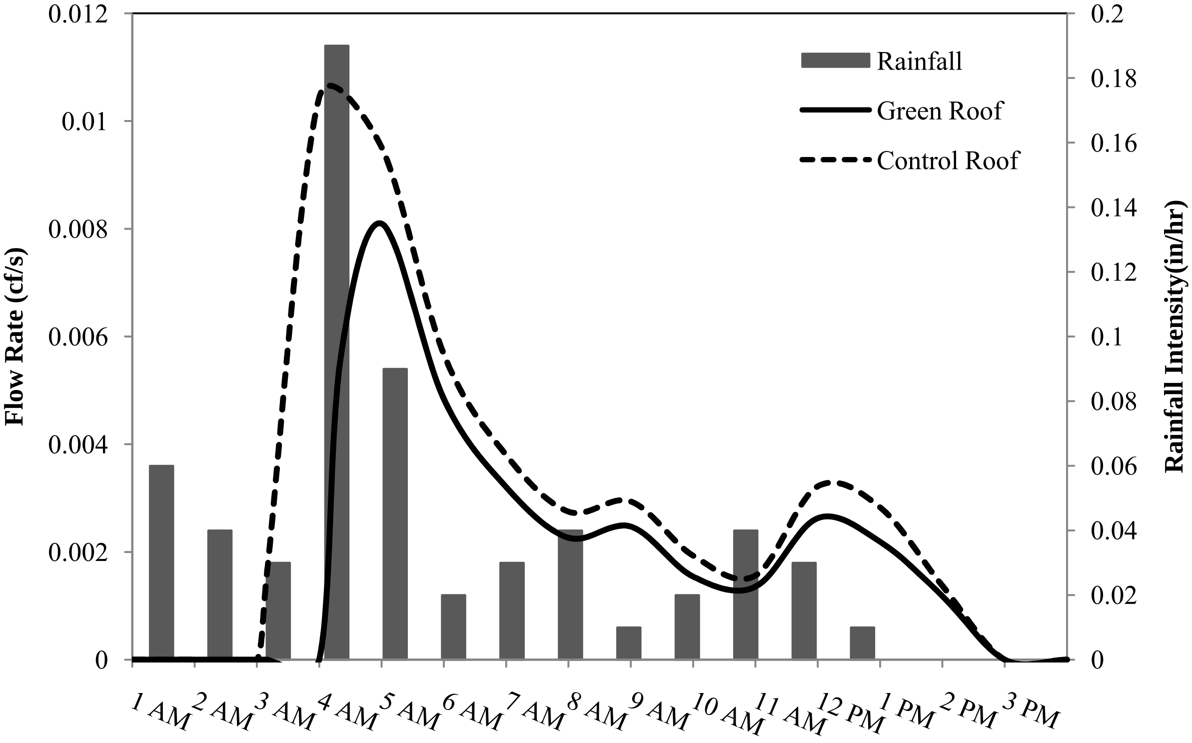


Figure I-147 Runoff Flow Rates and Rainfall intensity – November 15, 2008 Storm (Giant Eagle)

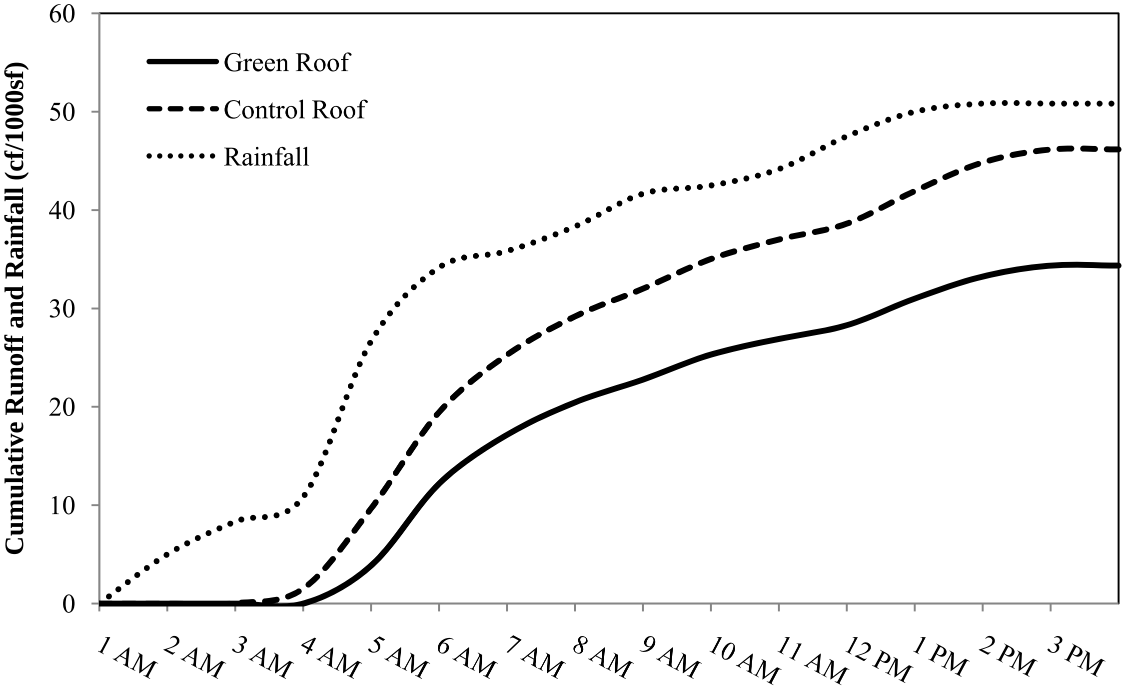


Figure I-148 Runoff and Rainfall Volumes – November 15, 2008 Storm (Giant Eagle)

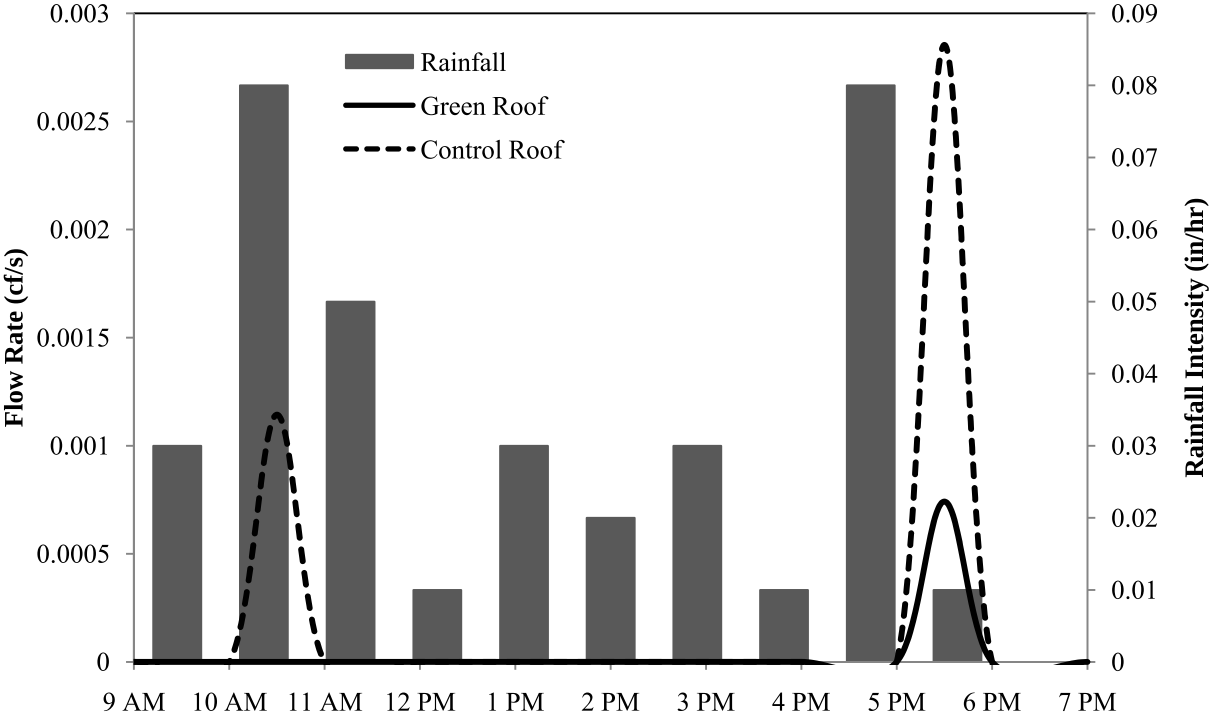


Figure I-149 Runoff Flow Rates and Rainfall Intensity – November 30, 2008 Storm (Homestead)

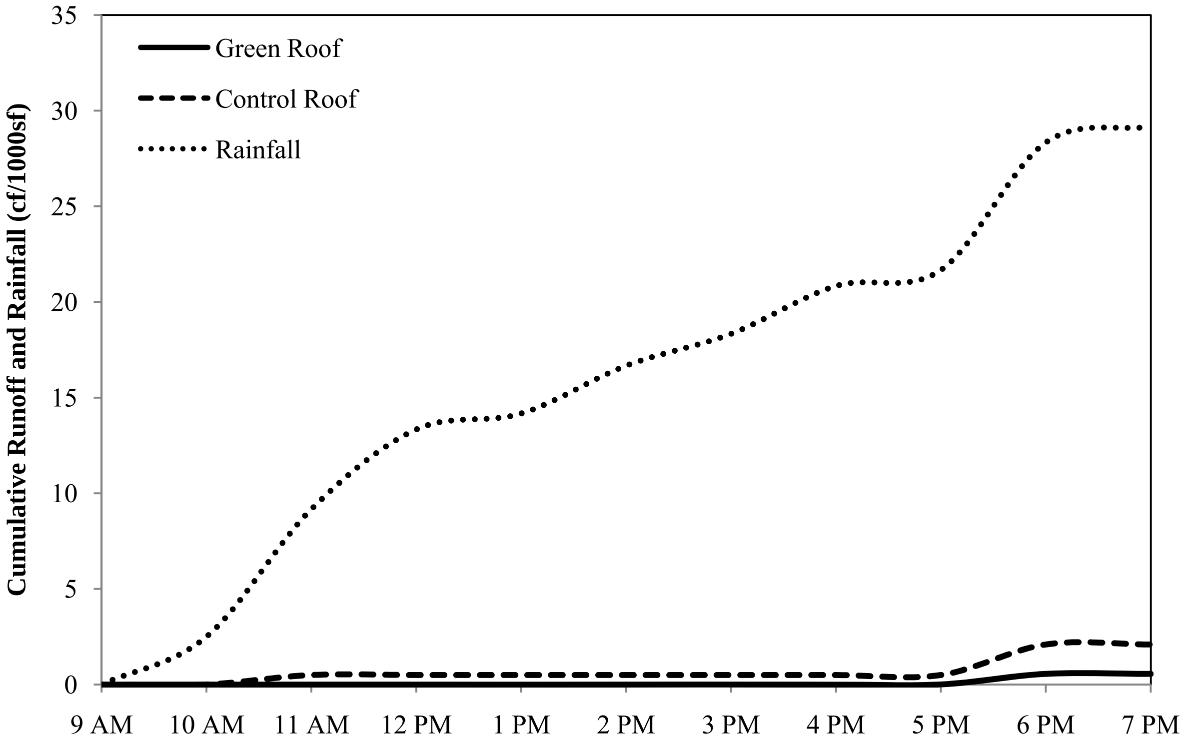


Figure I-150 Runoff and Rainfall Volumes – November 30, 2008 Storm (Homestead)

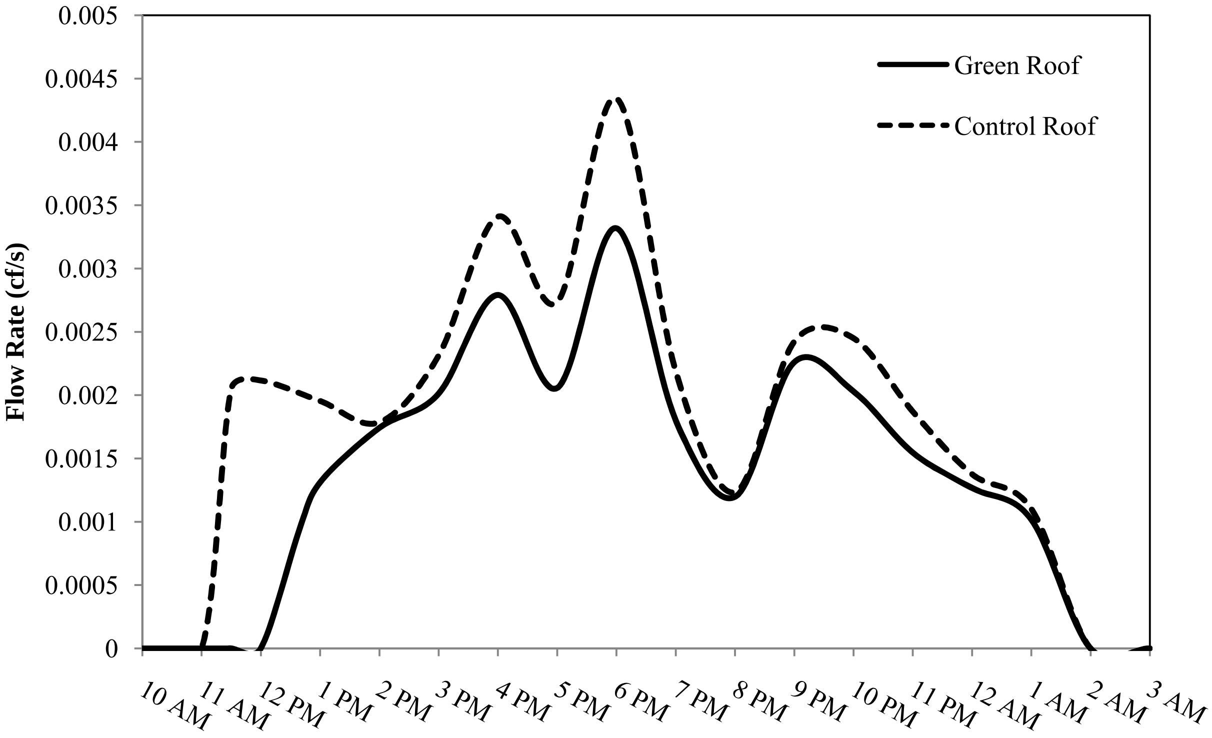


Figure I-151 Runoff Flow Rates– November 30-December 1, 2008 Storm (Giant Eagle)

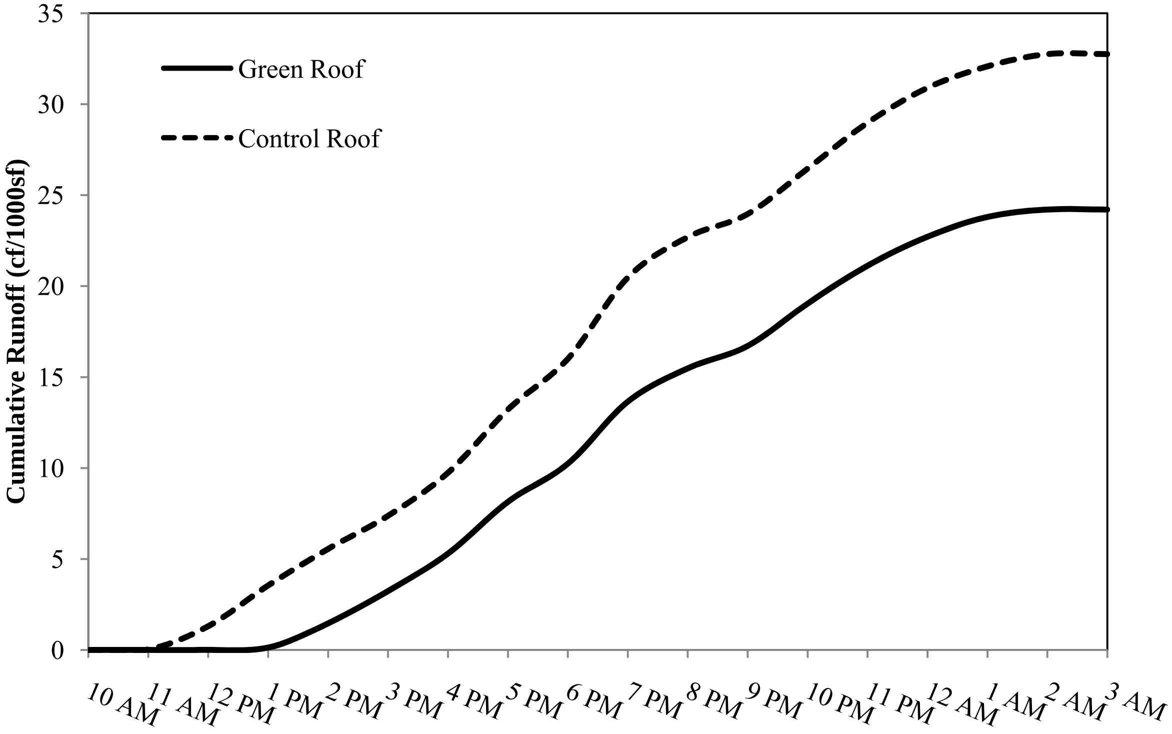


Figure I-152 Runoff Volumes – November 30-December 1, 2008 Storm (Giant Eagle)

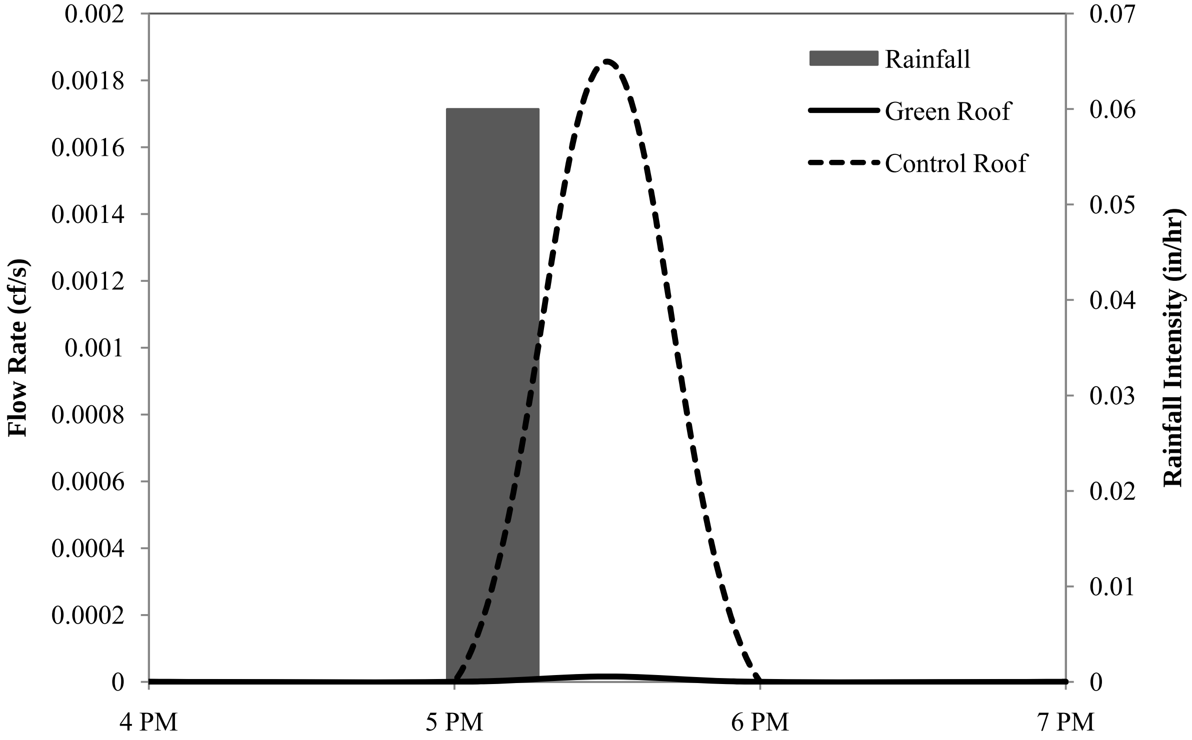


Figure I-153 Runoff Flow Rates and Rainfall Intensity – February 10, 2009 Storm (Homestead)

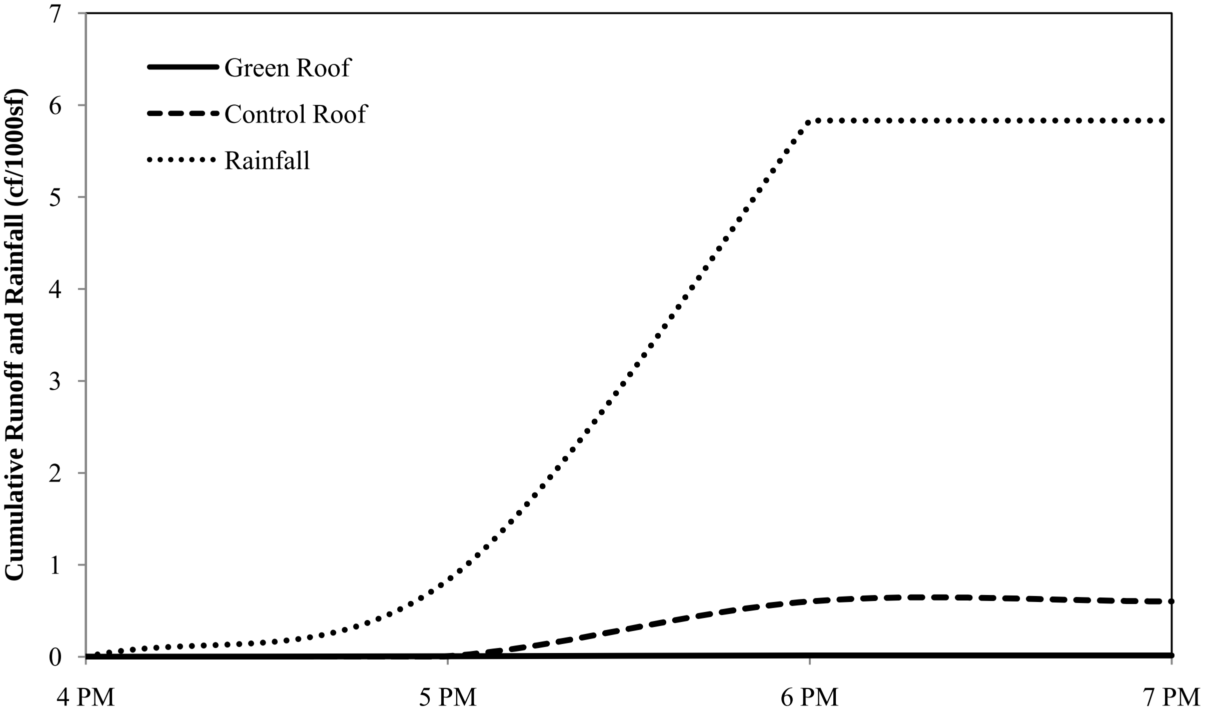


Figure I-154 Runoff and Rainfall Volumes – February 10, 2009 Storm (Homestead)

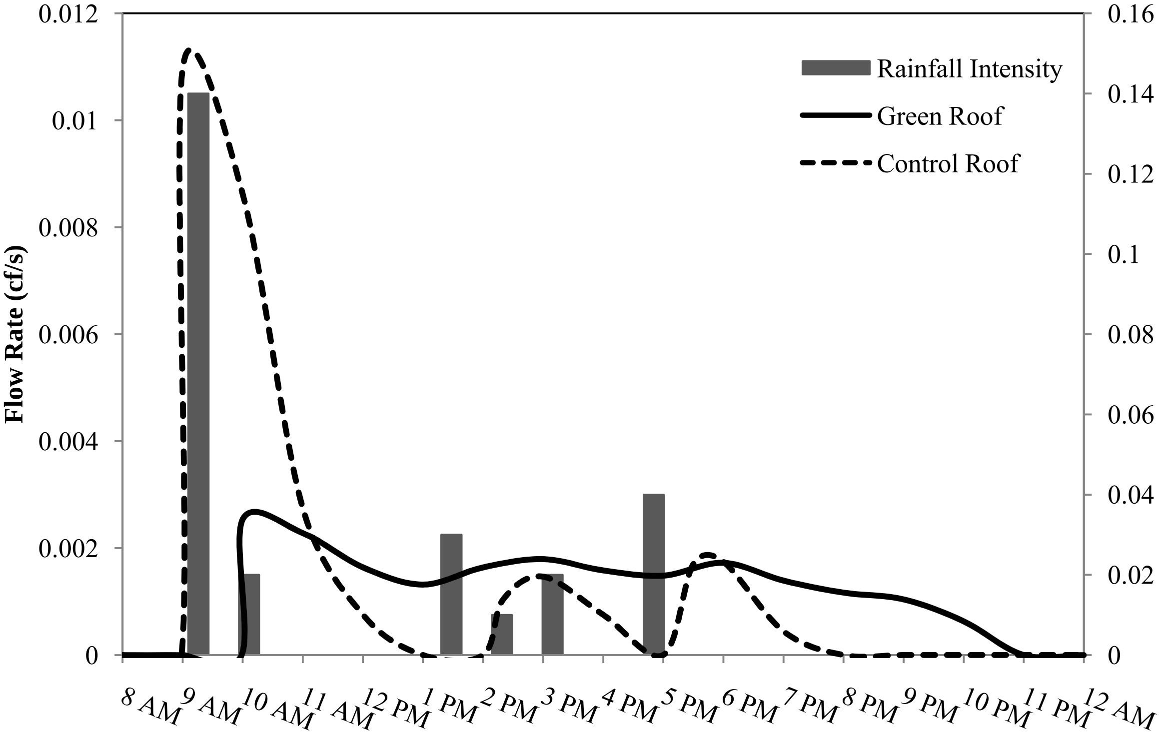


Figure I-155 Runoff Flow Rates and Rainfall intensity – February 10, 2009 Storm (Giant Eagle)

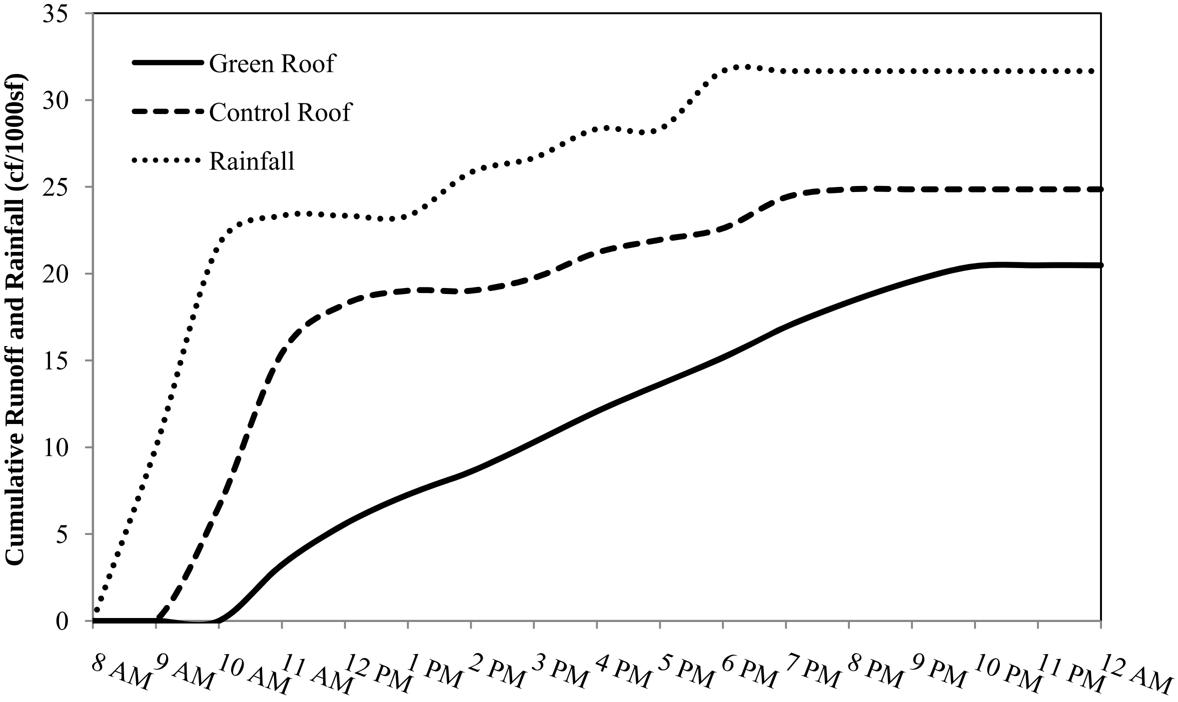


Figure I-156 Runoff and Rainfall Volumes – February 10, 2009 Storm (Giant Eagle)

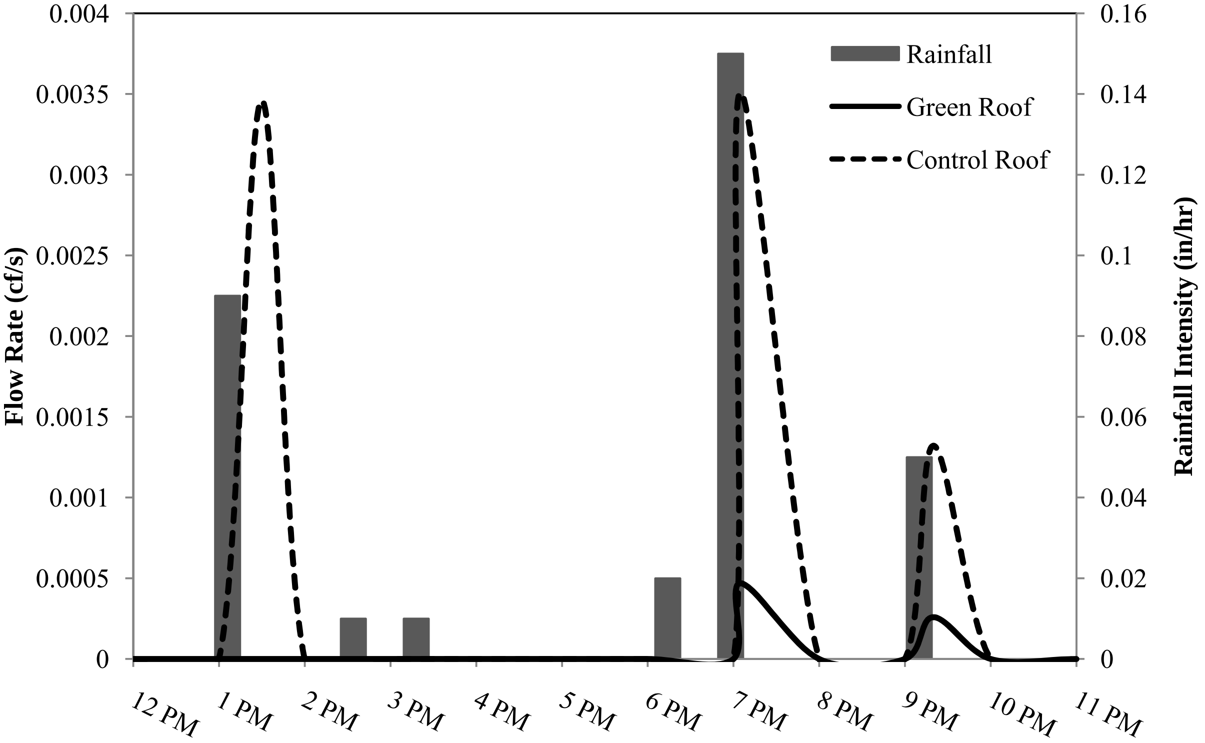


Figure I-157 Runoff Flow Rates and Rainfall Intensity – February 18, 2009 Storm (Homestead)

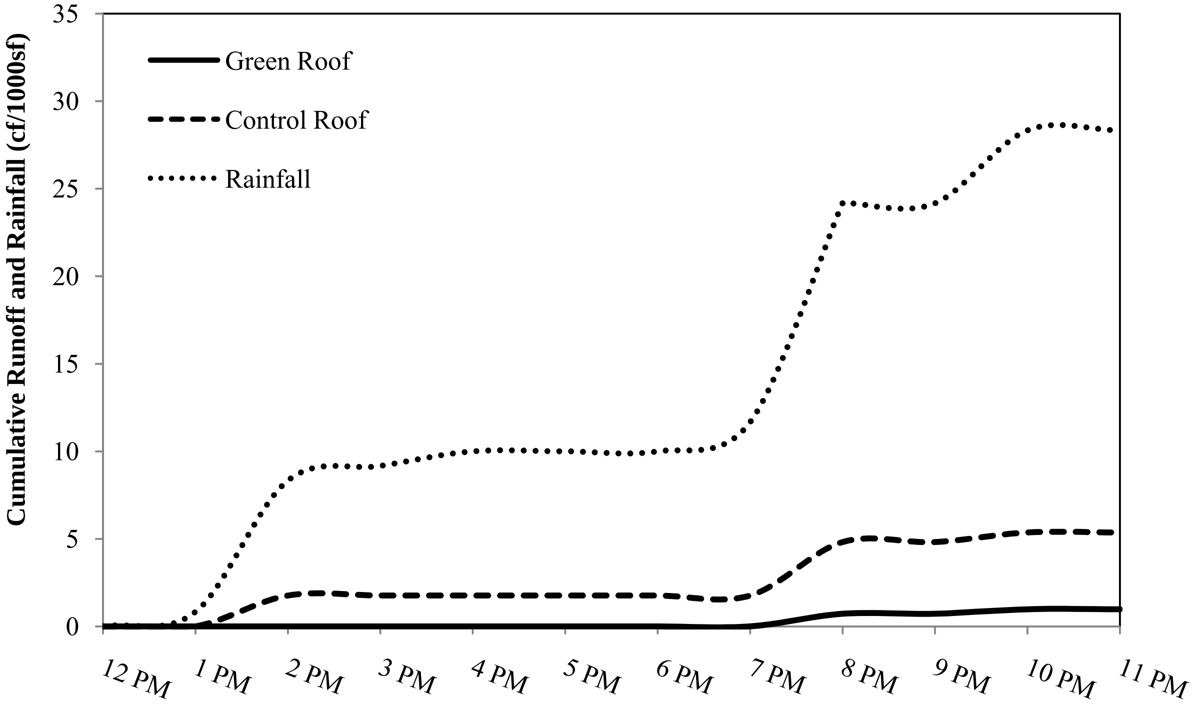


Figure I-158 Runoff and Rainfall Volumes – February 18, 2009 Storm (Homestead)

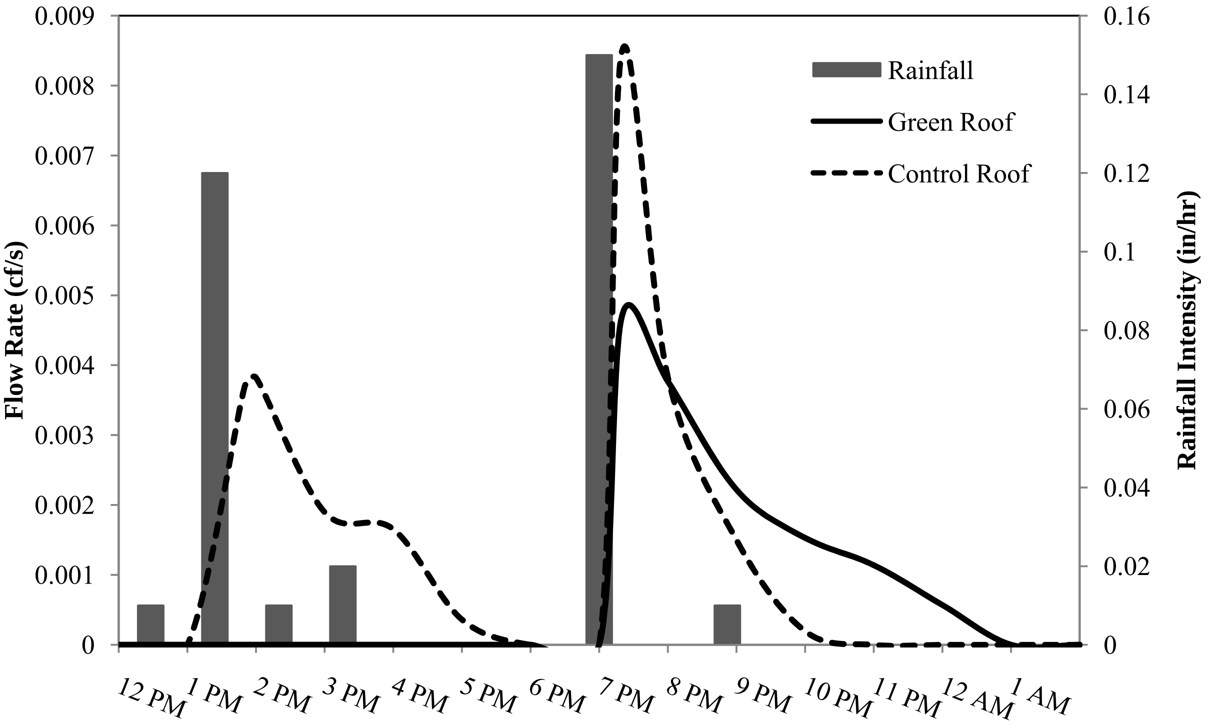


Figure I-159 Runoff Flow Rates and Rainfall intensity – February 18-19, 2009 Storm (Giant Eagle)

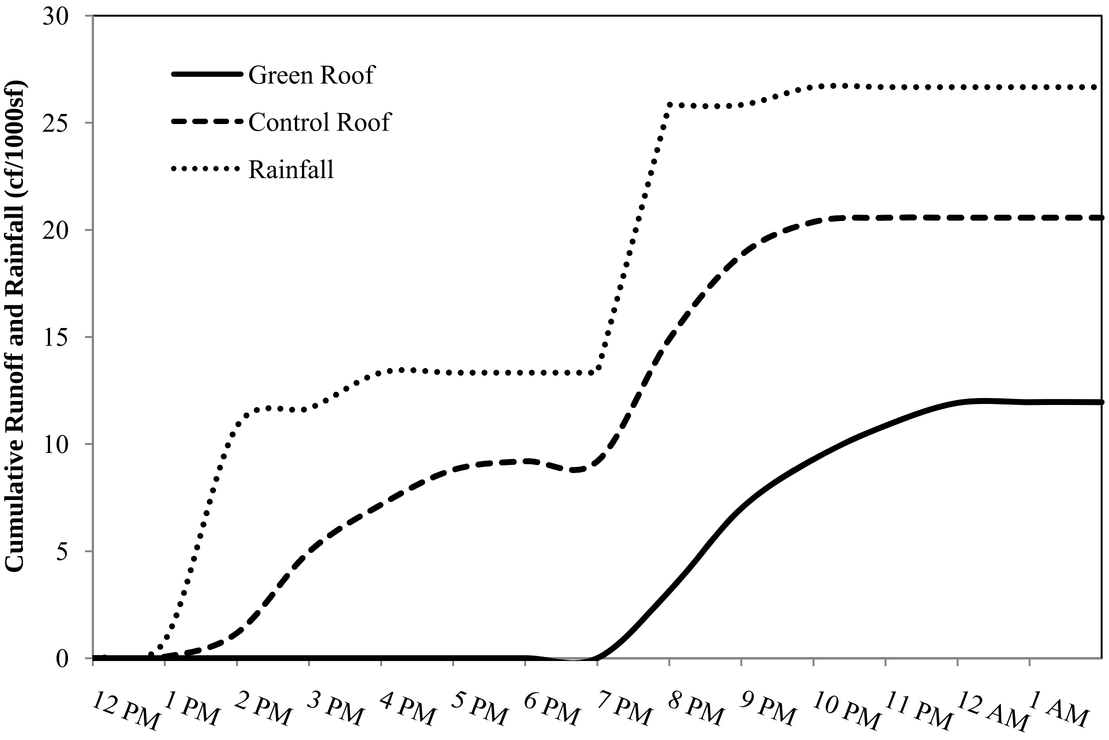


Figure I-160 Runoff and Rainfall Volumes – February 18-19, 2009 Storm (Giant Eagle)

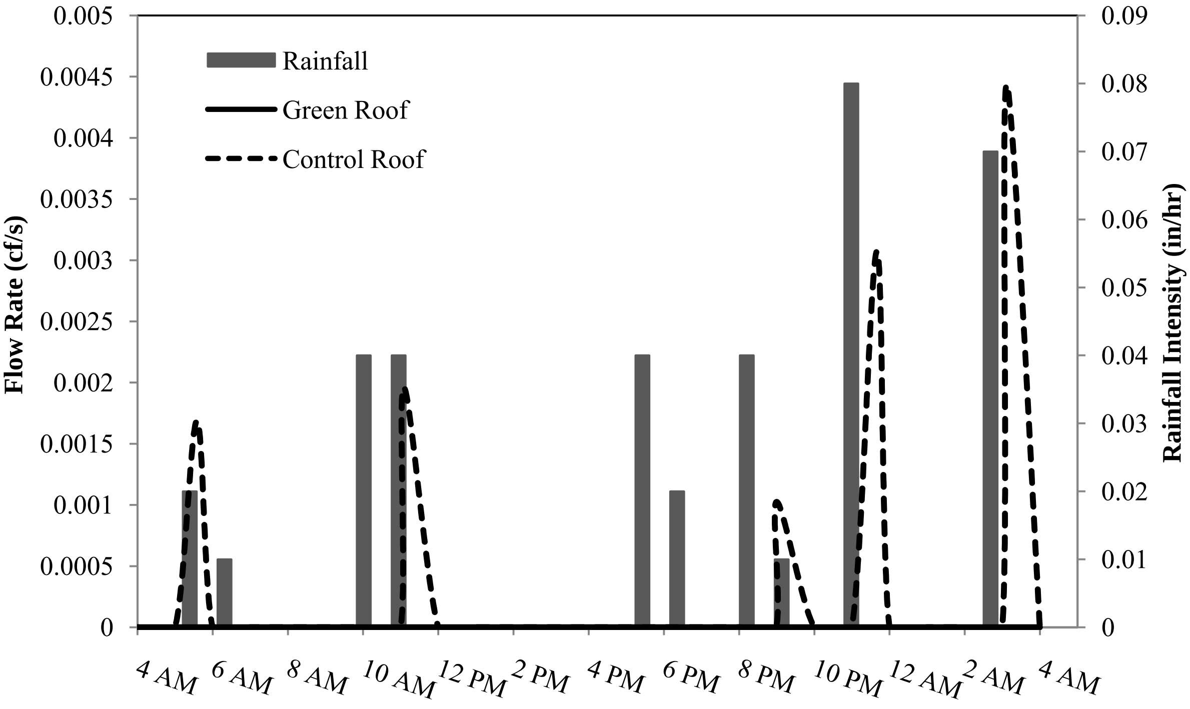


Figure I-161 Runoff Flow Rates and Rainfall Intensity – March 8-9, 2009 Storm (Homestead)

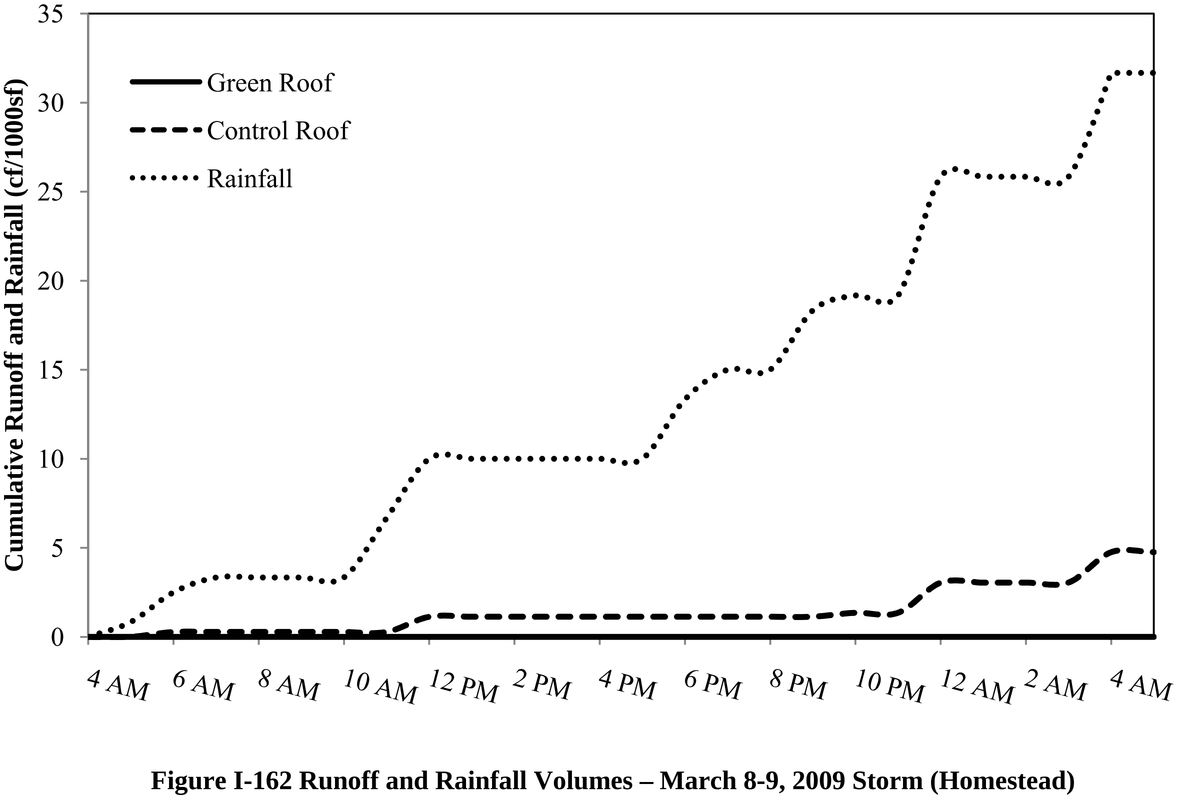


Figure I-162 Runoff and Rainfall Volumes – March 8-9, 2009 Storm (Homestead)

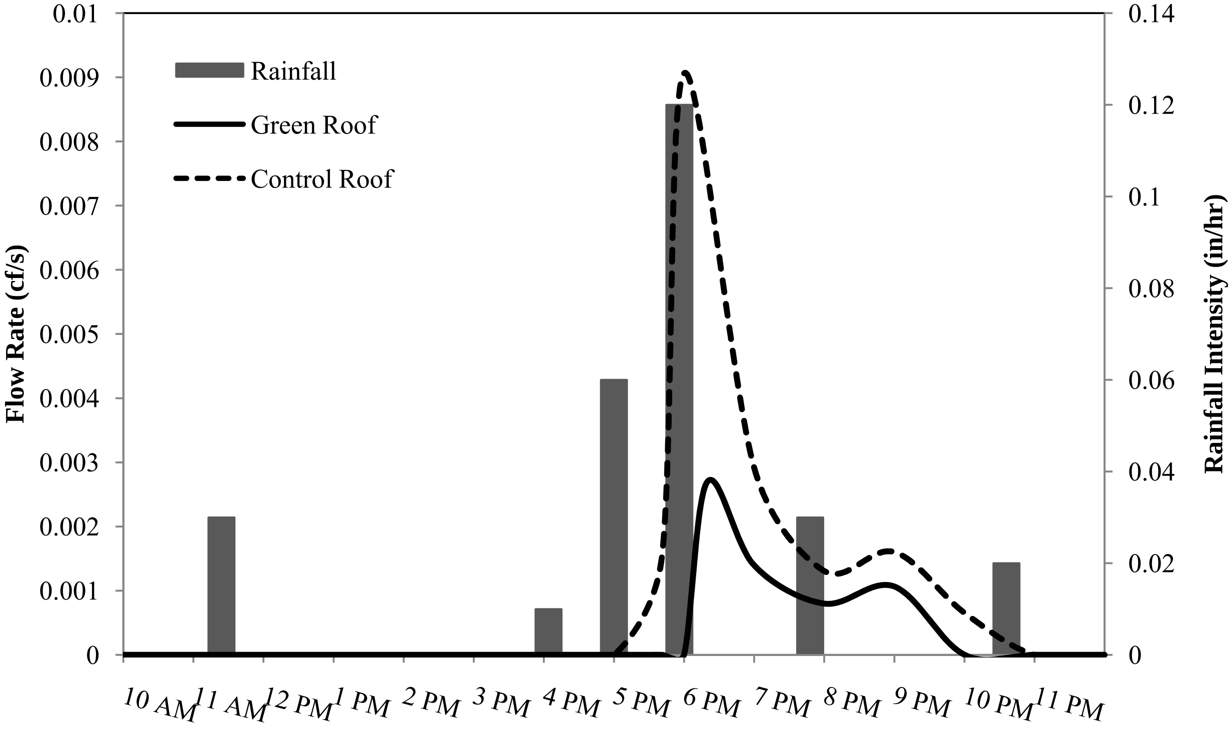


Figure I-163 Runoff Flow Rates and Rainfall intensity – March 8, 2009 Storm (Giant Eagle)

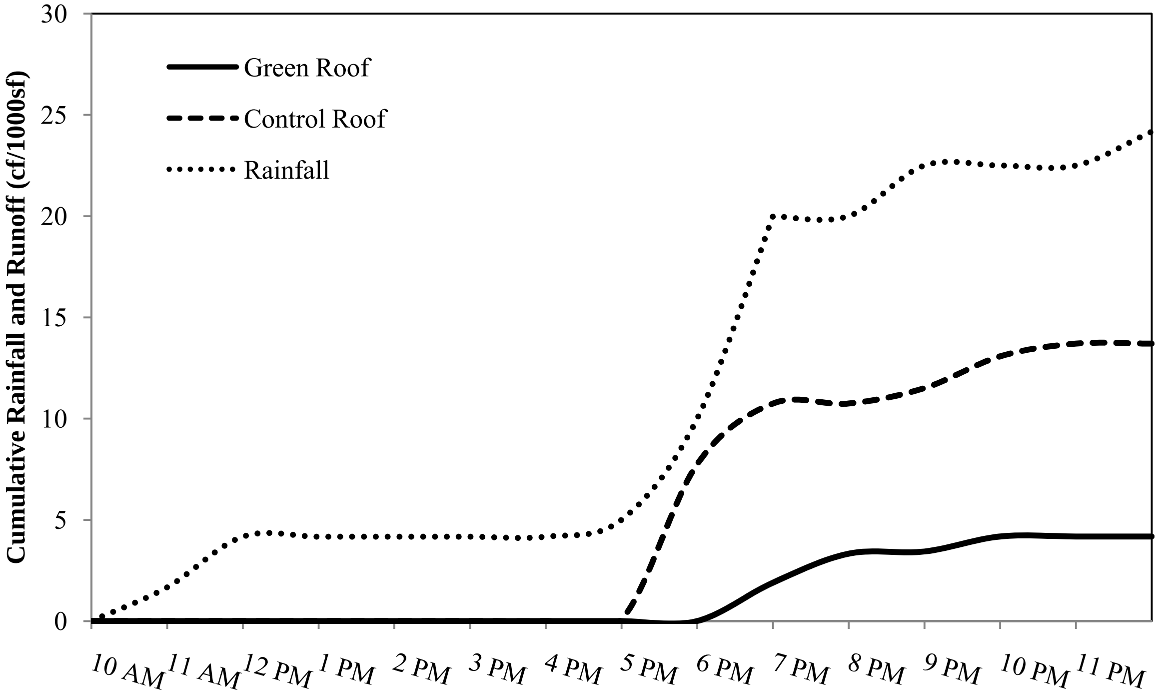


Figure I-164 Runoff and Rainfall Volumes – March 8, 2009 Storm (Giant Eagle)

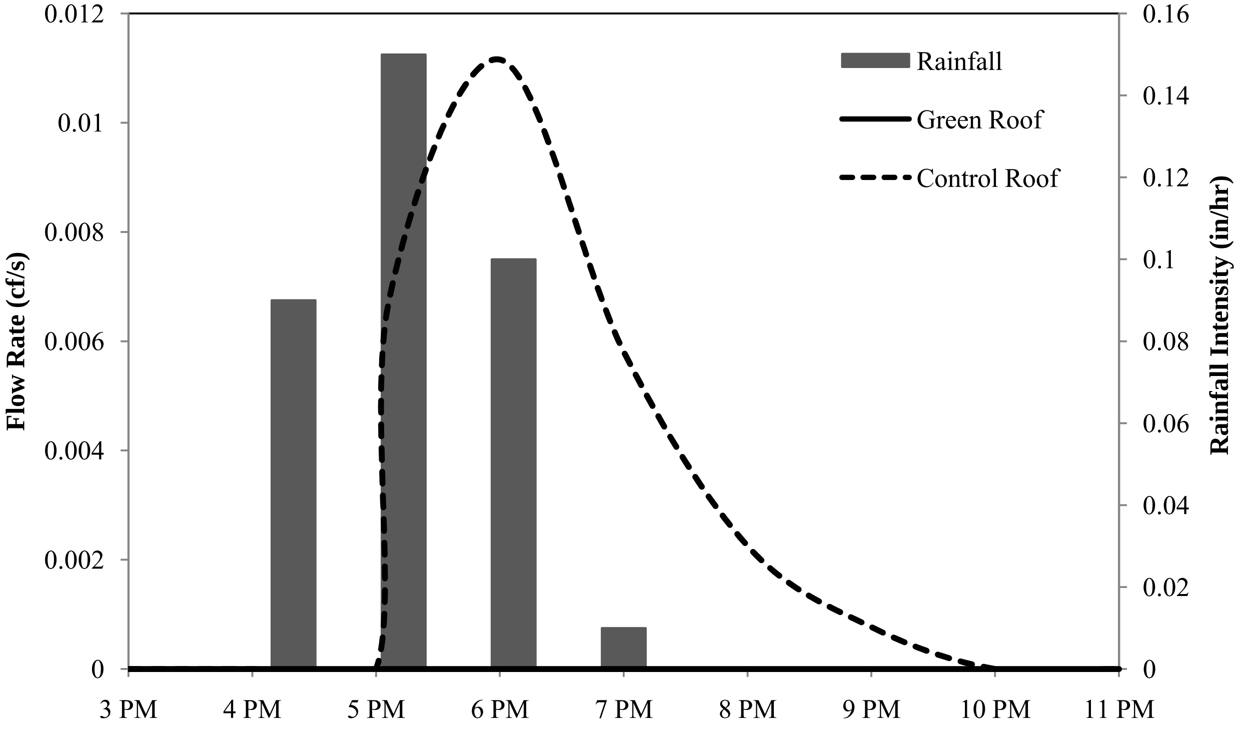


Figure I-165 Runoff Flow Rates and Rainfall intensity – March 25, 2009 Storm (Giant Eagle)

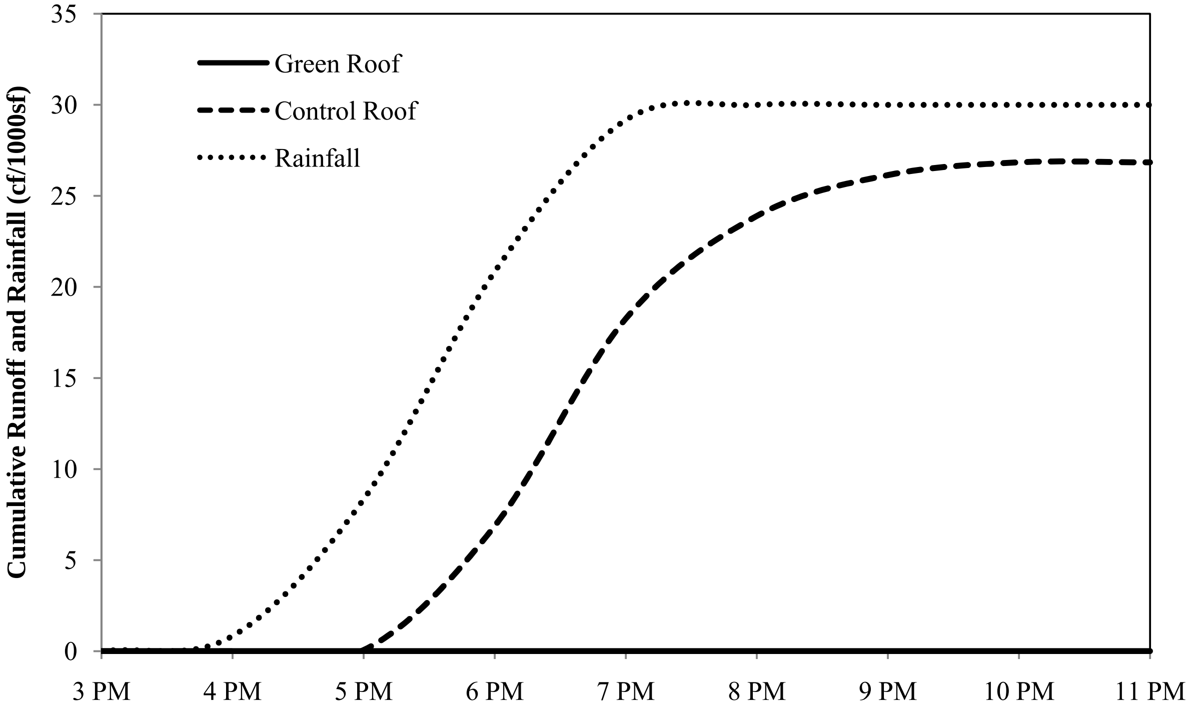


Figure I-166 Runoff and Rainfall Volumes – March 25, 2009 Storm (Giant Eagle)

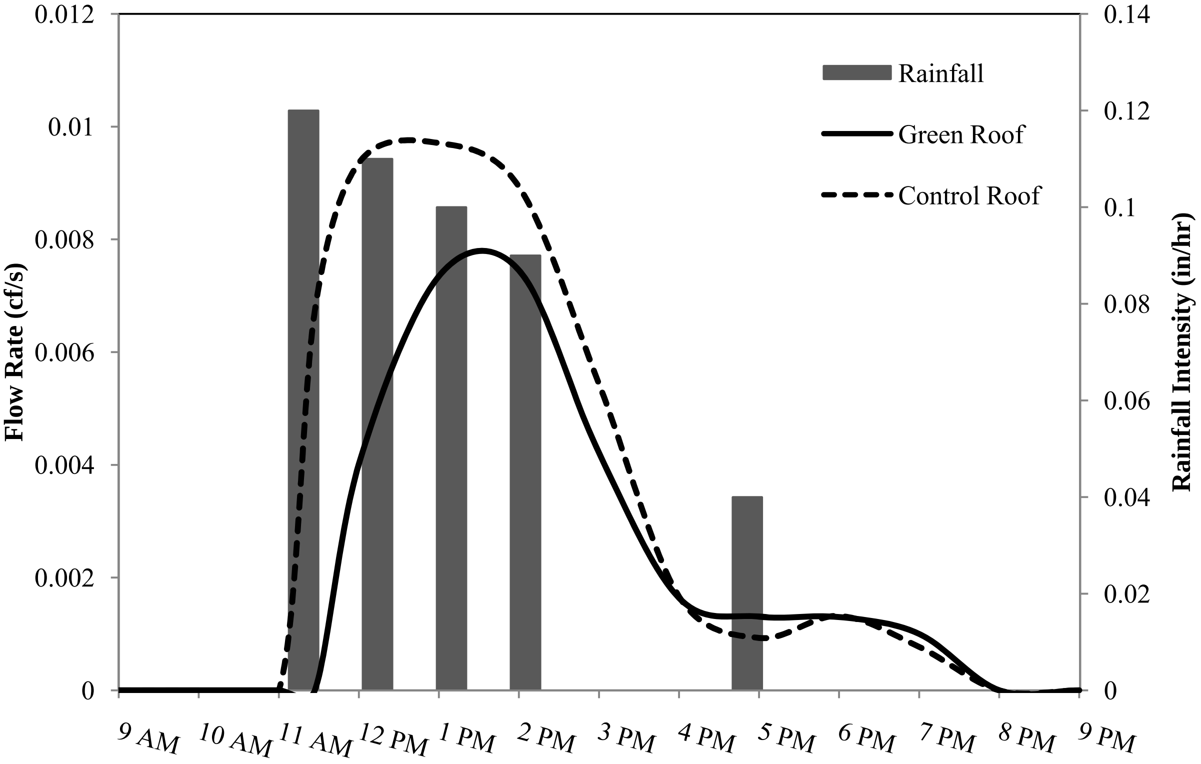


Figure I-167 Runoff Flow Rates and Rainfall intensity – March 26, 2009 Storm (Giant Eagle)

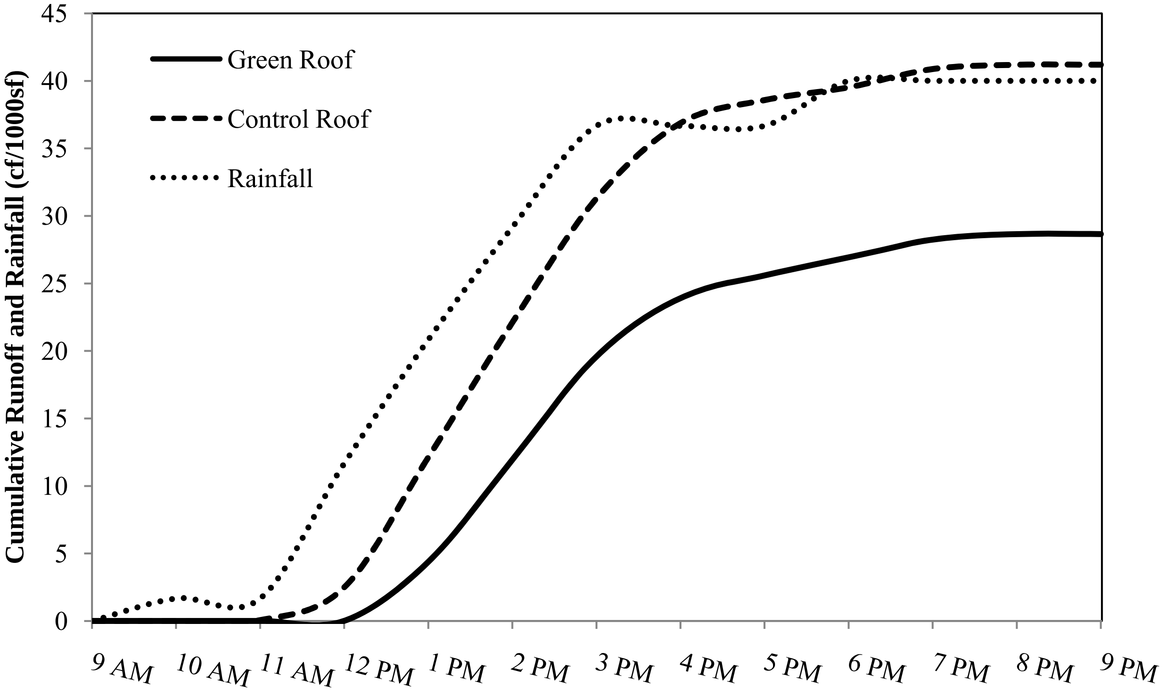


Figure I-168 Runoff and Rainfall Volumes – March 26, 2009 Storm (Giant Eagle)

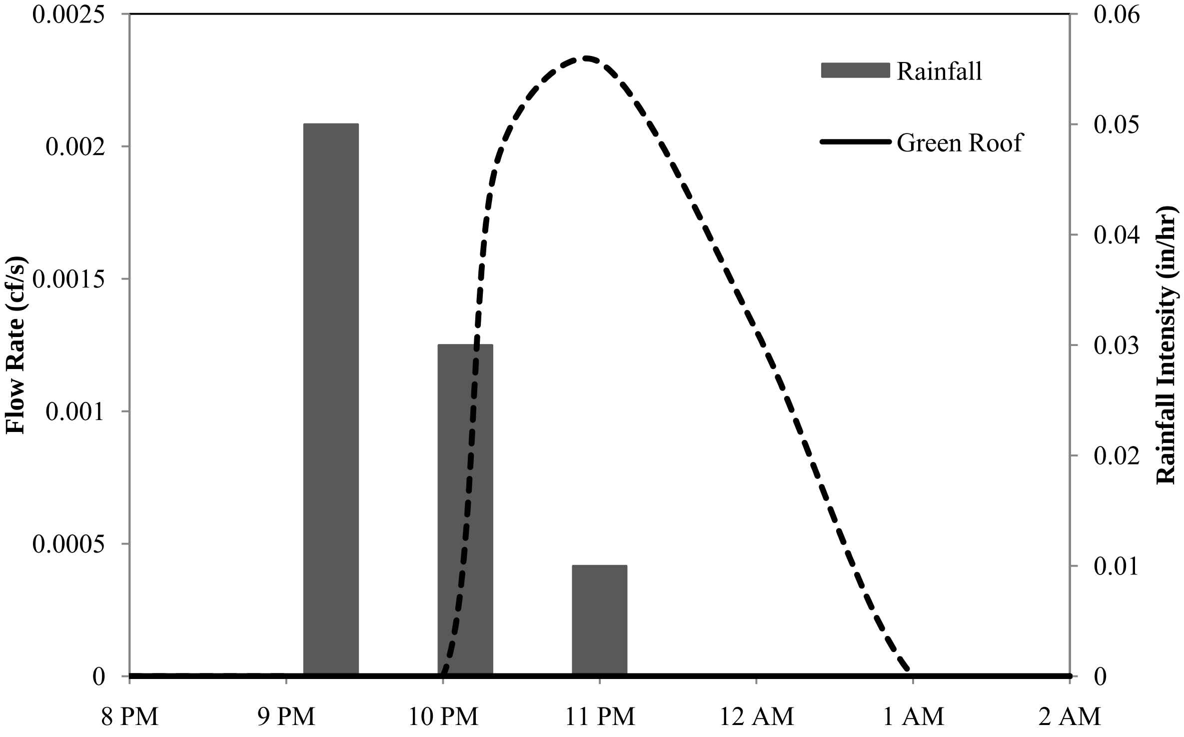


Figure I-169 Runoff Flow Rates and Rainfall intensity – March 27-28, 2009 Storm (Giant Eagle)

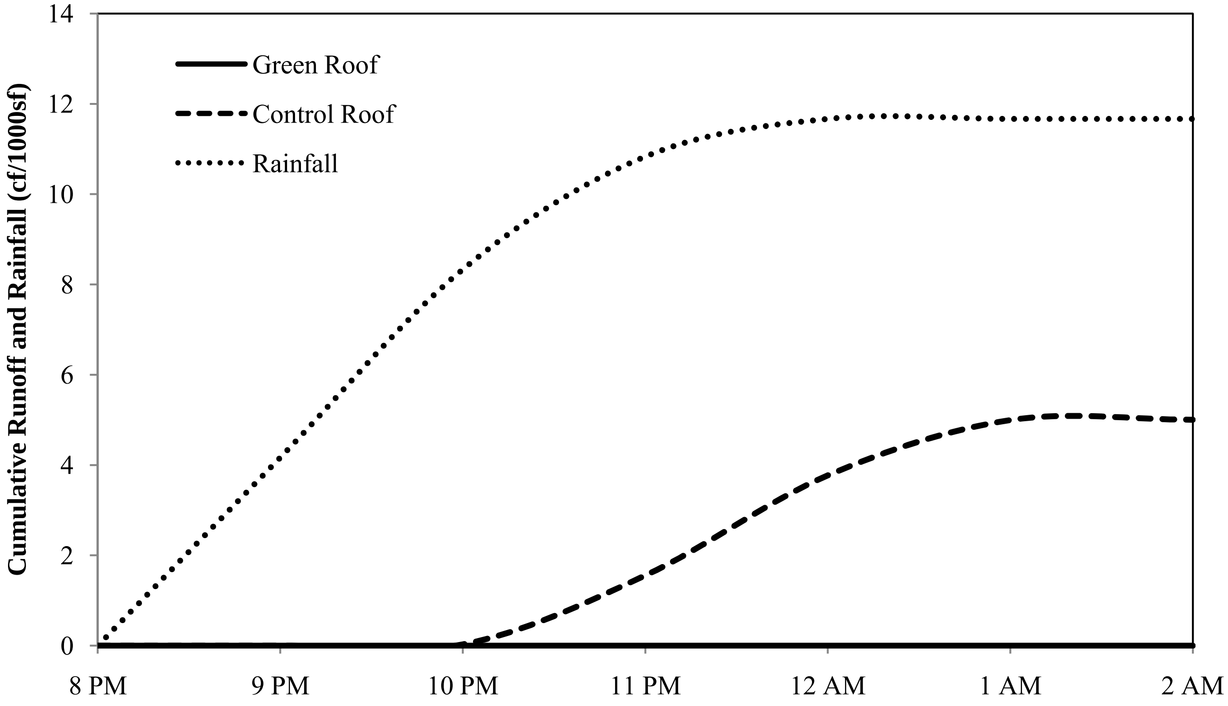


Figure I-170 Runoff and Rainfall Volumes – March 27-28, 2009 Storm (Giant Eagle)

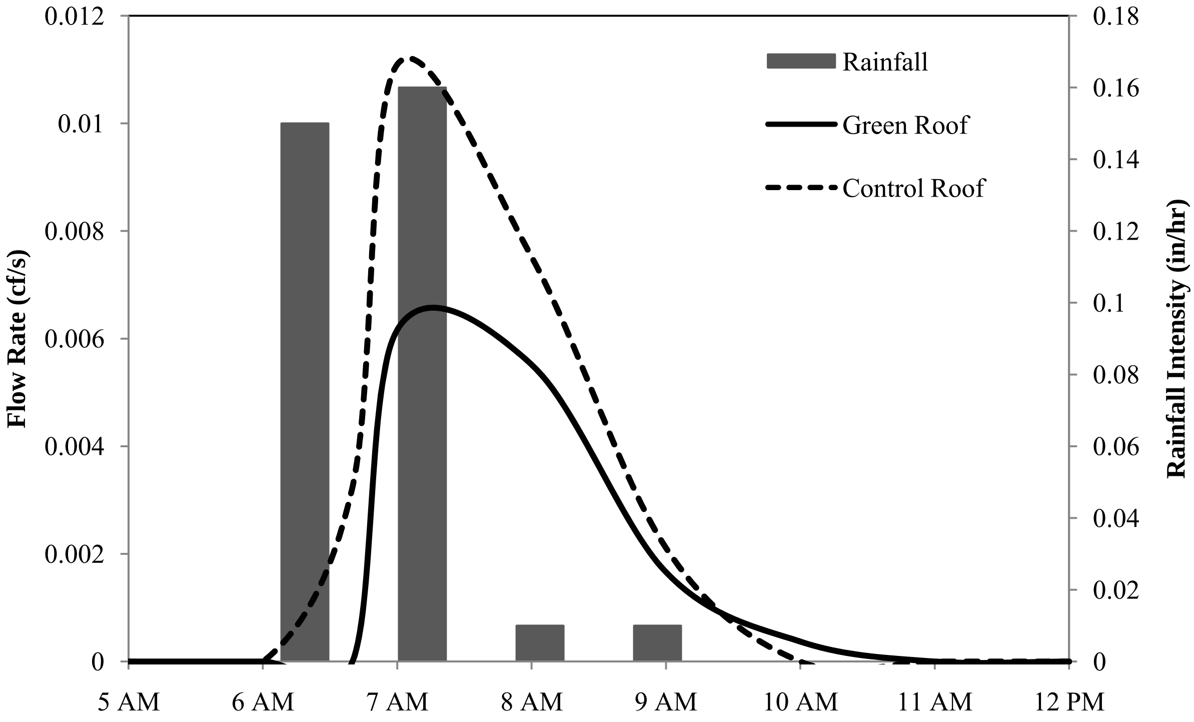


Figure I-171 Runoff Flow Rates and Rainfall intensity – March 29, 2009 Storm (Giant Eagle)

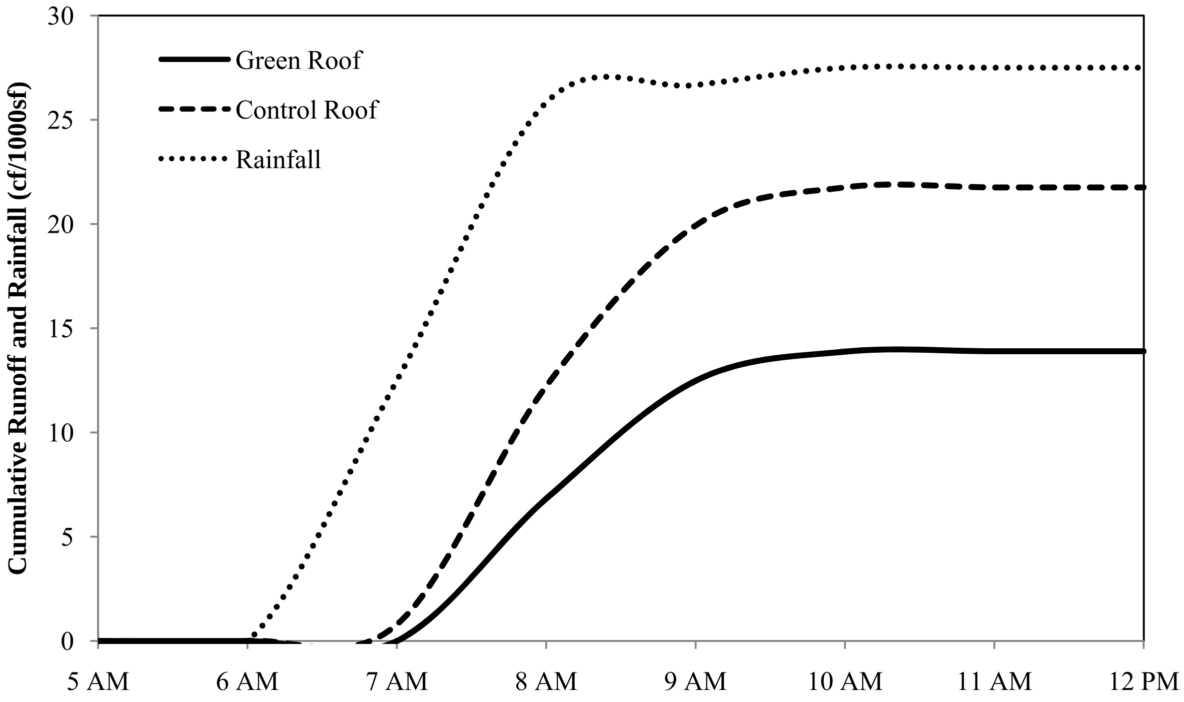


Figure I-172 Runoff and Rainfall Volumes – March 29, 2009 Storm (Giant Eagle)

APPENDIX II. TEMPERATURE PROFILES

Temperature profile data are presented in tables and graphs. Data is shown on a monthly averaged basis for the Homestead site from January 2008 to March 2009 and from January 2008 to April 2009 at the Giant Eagle site.

Table II-1 Day-time temperature data of ambient, roof and soil surface

Month	Homestead *(thin roof)*					Giant Eagle (*thick roof*)				
	Average ambient temperature upon green roof	Average ambient temperature upon control roof	Temperature at roof/soil surface			Average ambient temperature upon green roof	Average ambient temperature upon control roof	Temperature at roof/soil surface		
			Green	Control	Δt			Green	Control	Δt
Jan	33.6	33.7	29.8	32.9	3.1	33.4	32.7	33.3		
Feb	36.5	36.5	38.7	36.9	-1.8	32.3	32.3	31.9		
Mar	44.3	43.8	45.2	47.4	2.2	43.2	43.9	42.9		
Apr	66.0	68.9	69.9	77.0	7.0	64.9	65.2	66.2		
May	65.4	67.4	71.9	82.5	10.6	65.9	64.0	67.4		
Jun	80.8	83.0	87.6	100.3	12.6	80.7	79.2	81.2	99.4	18.2
Jul	86.1	88.4	91.3	101.9	10.6	85.0	83.8	85.4	106.9	21.5
Aug	81.6	84.1	88.8	92.8	4.0	80.5	80.3	80.8	101.5	20.7
Sep	76.4	77.8	80.4	81.9	1.5	74.3	75.2	73.7	89.8	16.1
Oct	60.4	60.2	62.9	61.7	-1.2	57.7	58.8	56.1	67.4	11.3
Nov	46.4	45.8	46.8	44.5	-2.3	44.2	44.6	43.4	47.9	4.5
Dec	39.6	39.7	38.2	37.8	-0.4	38.6	38.1	40.6	37.5	-3.1
Jan	26.2	26.0	25.6	26.7	1.1	25.0	24.9	26.2	25.2	-1.0
Feb	38.0	37.9	38.5	38.1	-0.4	36.3	37.1	35.4	41.2	5.8
Mar	47.2	47.6	50.5	49.7	-0.8	48.0	48.9	50.3	59.6	9.3
Apr						58.5	59.4	62.3	70.9	8.6

The unit of temperature is Fahrenheit in Table II-1.

Δt = temperature at roof surface (control roof) – temperature at soil surface (green roof)

The ambient temperature is the average temperature for the measuring points above the soil/roof surface.

Table II-2 Night-time temperature data of ambient, roof and soil surface

Month	Homestead (*thin roof*)					Giant Eagle (*thick roof*)				
	Average ambient temperature upon green roof	Average ambient temperature upon control roof	Temperature at roof/soil surface			Average ambient temperature upon green roof	Average ambient temperature upon control roof	Temperature at roof/soil surface		
			Green	Control	Diff.			Green	Control	Diff.
Jan	28.5	28.3	22.3	23.8	1.5	29.9	29.3	30.0		
Feb	31.3	31.3	33.7	28.6	-5.1	29.8	28.8	29.4		
Mar	37.5	36.3	33.5	32.6	-0.9	37.7	37.6	38.0		
Apr	51.0	49.8	48.2	42.2	-6.0	53.0	52.7	53.5		
May	53.8	53.3	45.9	40.5	-5.4	56.1	55.1	55.8		
Jun	66.4	66.2	63.8	60.9	-2.9	68.1	67.1	67.4	63.6	-3.8
Jul	70.5	70.3	68.8	64.6	-4.2	72.2	71.3	72.0	67.5	-4.5
Aug	66.8	66.6	64.8	60.9	-3.9	67.9	67.1	67.5	62.8	-4.7
Sep	63.1	62.5	61.1	57.1	-4.0	67.2	64.1	63.9	59.6	-4.2
Oct	48.2	47.8	45.6	42.1	-3.6	50.0	49.5	48.9	44.8	-4.1
Nov	38.3	38.0	36.5	34.7	-1.8	39.2	38.4	39.0	35.5	-3.5
Dec	37.5	37.3	35.1	33.5	-1.7	37.8	36.5	36.3	34.2	-2.1
Jan	19.8	19.8	22.1	21.1	-1.0	21.1	19.9	23.5	18.9	-4.6
Feb	30.2	29.6	28.6	25.5	-3.2	31.1	30.3	30.8	26.9	-3.9
Mar	38.5	38.1	36.1	33.6	-2.5	40.4	39.8	38.9	36.3	-2.6
Apr						50.2	49.5	48.3	46.6	-1.7

The unit of temperature is Fahrenheit in Table II-2.
Δt = temperature at roof surface (control roof) – temperature at soil surface (green roof)

The ambient temperature is the average temperature for the measuring points above the soil/roof surface.

Table II-3 Day-time temperature data of soil surface and below the roof deck

Month	Homestead *(thin roof)*			Giant Eagle (*thick roof)*		
	Temperature at soil surface	Temperature below (green) roof deck	Δt	Temperature at soil surface	Temperature below (green) roof deck	Δt
Jan	29.8	54.5	-24.7	33.3	60.0	-26.6
Feb	38.7	54.7	-16.0	31.9	62.7	-30.8
Mar	45.2	55.6	-10.3	42.9	65.4	-22.5
Apr	69.9	65.0	5.0	66.2	73.1	-6.9
May	71.9	67.1	4.8	67.4	72.5	-5.0
Jun	87.6	81.4	6.3	81.2	79.7	1.6
Jul	91.3	83.2	8.1	85.4	81.4	4.0
Aug	88.8	80.5	8.3	80.8	79.1	1.7
Sep	80.4	75.8	4.6	73.7	76.0	-2.3
Oct	62.9	65.2	-2.3	56.1	68.9	-12.8
Nov	46.8	65.0	-18.2	43.4	65.4	-21.9
Dec	38.2	68.1	-29.9	40.6	63.1	-22.5
Jan	25.6	61.1	-35.5	26.2	58.9	-32.6
Feb	38.5	60.5	-21.9	35.4	62.5	-27.1
Mar	50.5	62.3	-11.8	50.3	66.4	-16.1
Apr				62.3	70.0	-7.7

The unit of temperature is Fahrenheit in Table II-3.

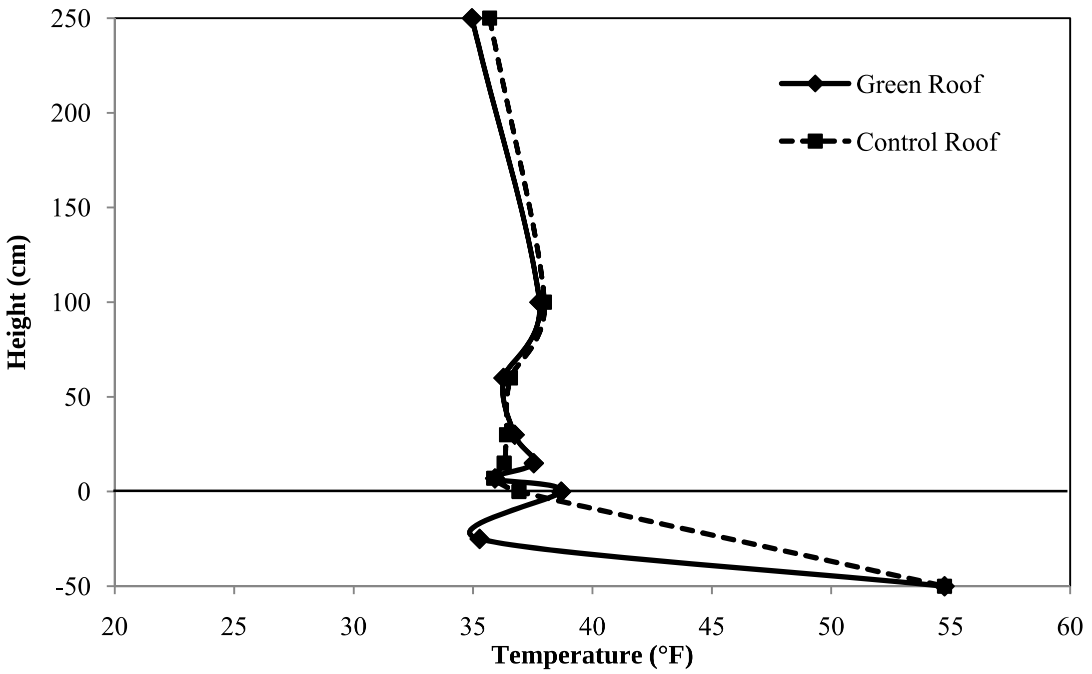
Δt = temperature at soil surface – temperature below (green) roof deck

Table II-4 Night-time temperature data of soil surface and roof deck underneath

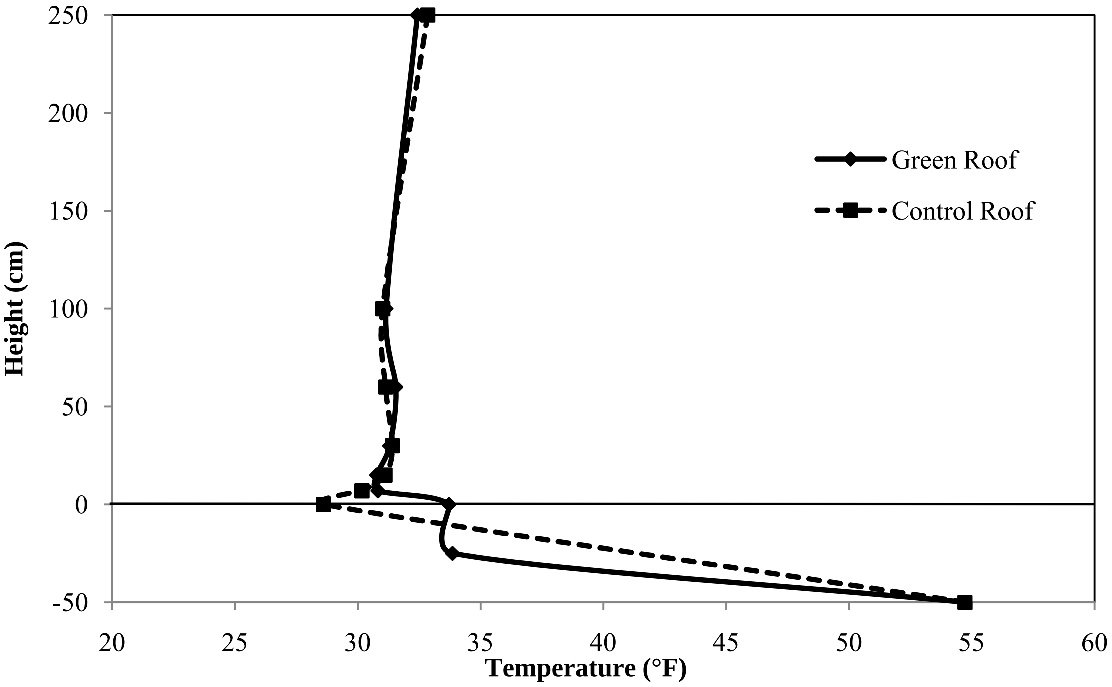
Month	Homestead *(thin roof)*			Giant Eagle (*thick roof*)		
	Temperature at soil surface	Temperature below (green) roof deck	Δt	Temperature at soil surface	Temperature below (green) roof deck	Δt
Jan	22.3	54.6	-32.3	30.0	58.5	-28.5
Feb	33.7	54.7	-21.0	29.4	61.2	-31.8
Mar	33.5	55.8	-22.3	38.0	63.3	-25.3
Apr	48.2	66.0	-17.8	53.5	68.6	-15.2
May	45.9	68.0	-22.1	55.8	69.3	-13.5
Jun	63.8	82.2	-18.4	67.4	75.6	-8.1
Jul	68.8	84.1	-15.3	72.0	77.4	-5.4
Aug	64.8	81.3	-16.5	67.5	75.1	-7.6
Sep	61.1	76.4	-15.3	63.9	73.2	-9.3
Oct	45.6	65.9	-20.3	48.9	66.9	-18.0
Nov	36.5	65.7	-29.1	39.0	63.7	-24.7
Dec	35.1	69.0	-33.9	36.3	62.6	-26.2
Jan	22.1	61.4	-39.3	23.5	57.5	-34.0
Feb	28.6	60.8	-32.2	30.8	60.8	-30.0
Mar	36.1	63.0	-26.9	38.9	64.1	-25.3
Apr				48.3	66.9	-18.6

The unit of temperature is Fahrenheit in Table II-4.

Δt = temperature at soil surface – temperature below (green) roof deck

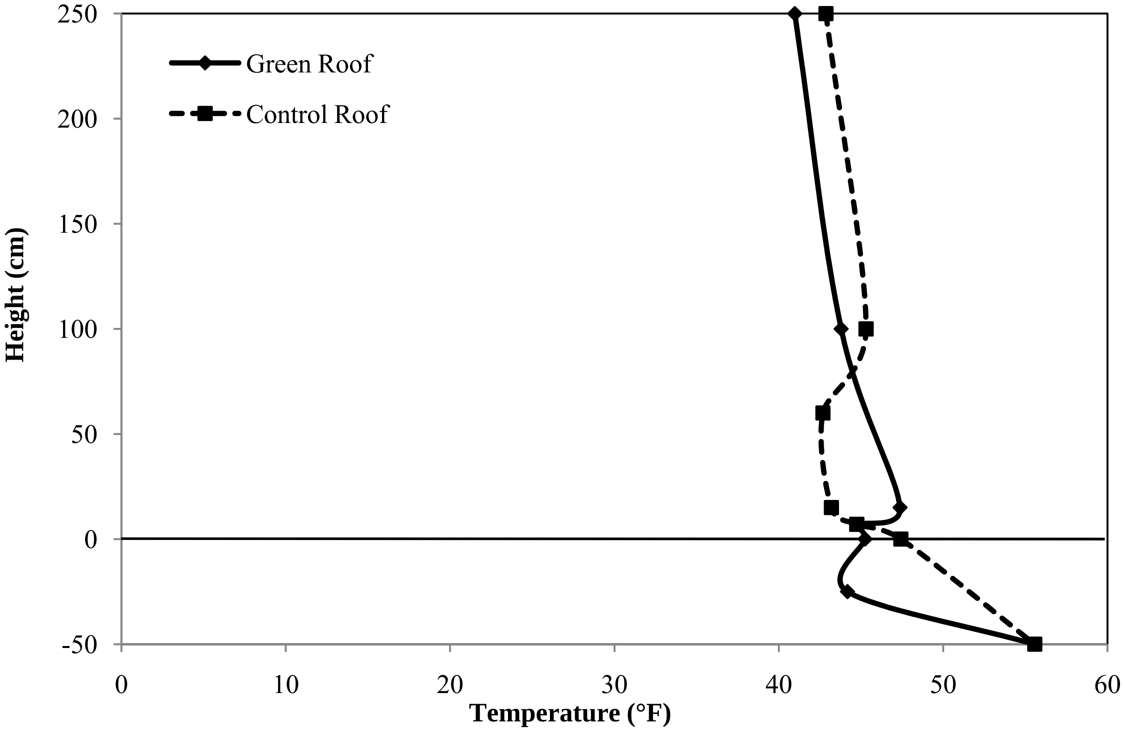


(a) Day-time temperature profile

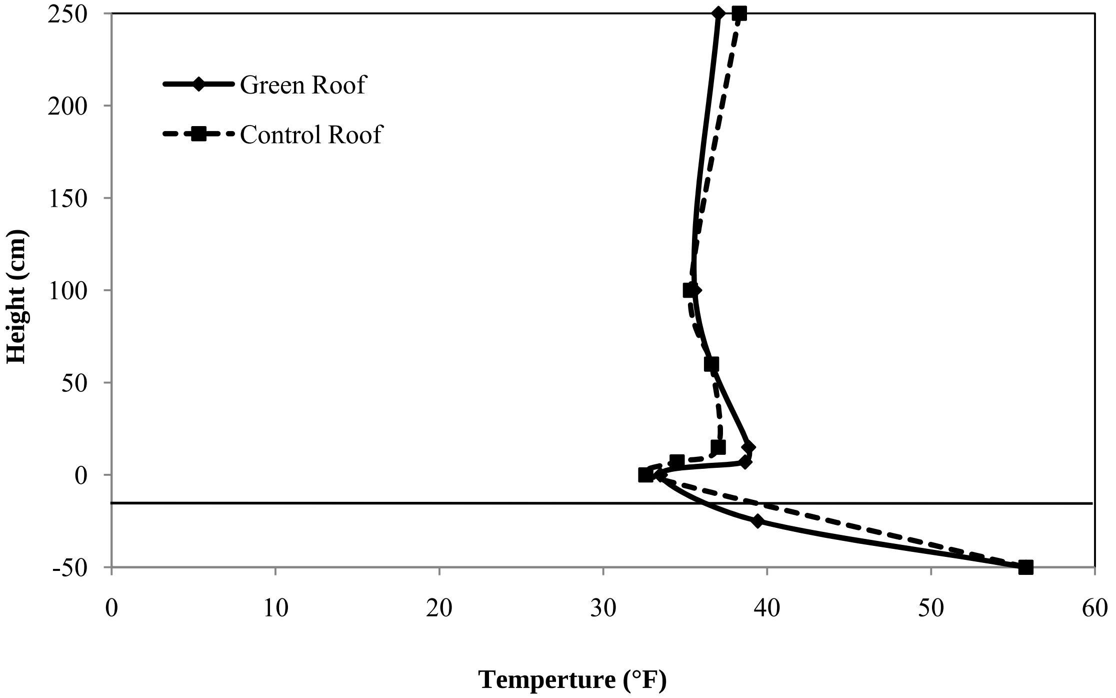


(b) Night-time temperature profile

Figure II-1 February, 2008 temperature profile at Homestead

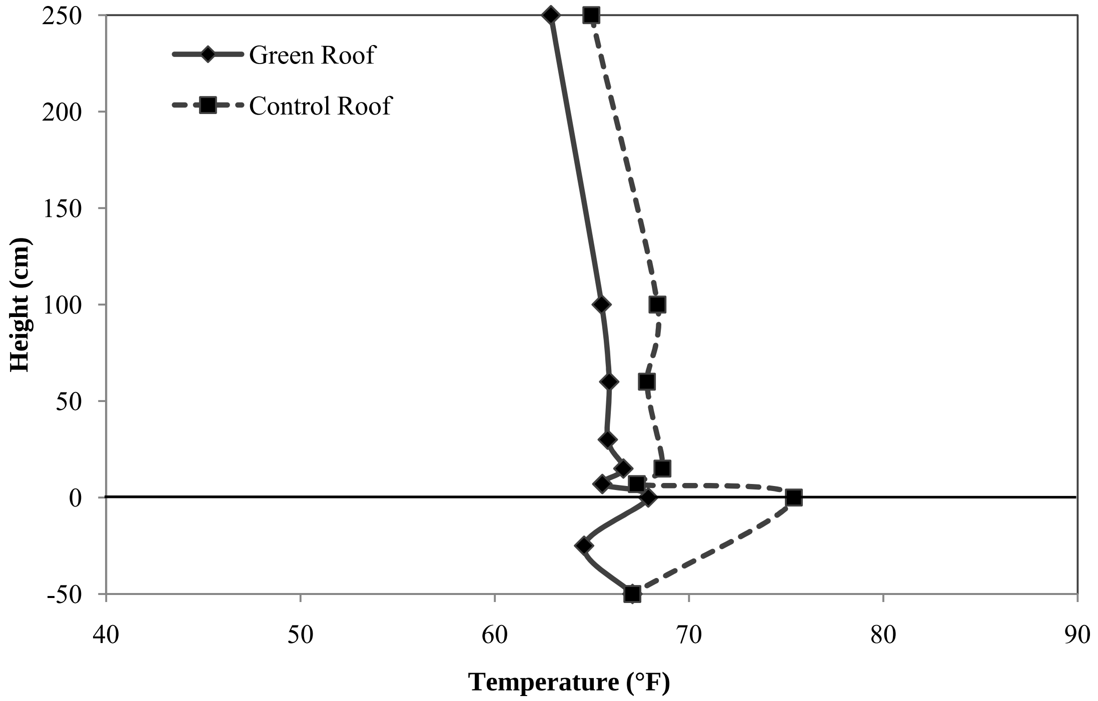


(a) Day-time temperature profile

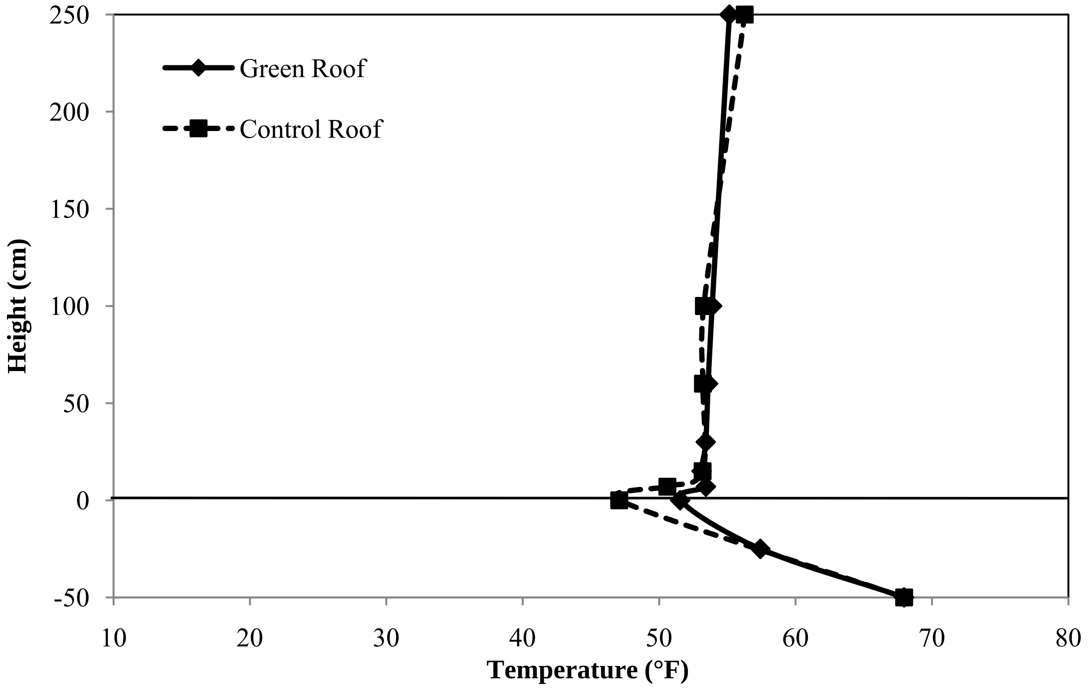


(b) Night-time temperature profile

Figure II-2 March, 2008 temperature profile at Homestead

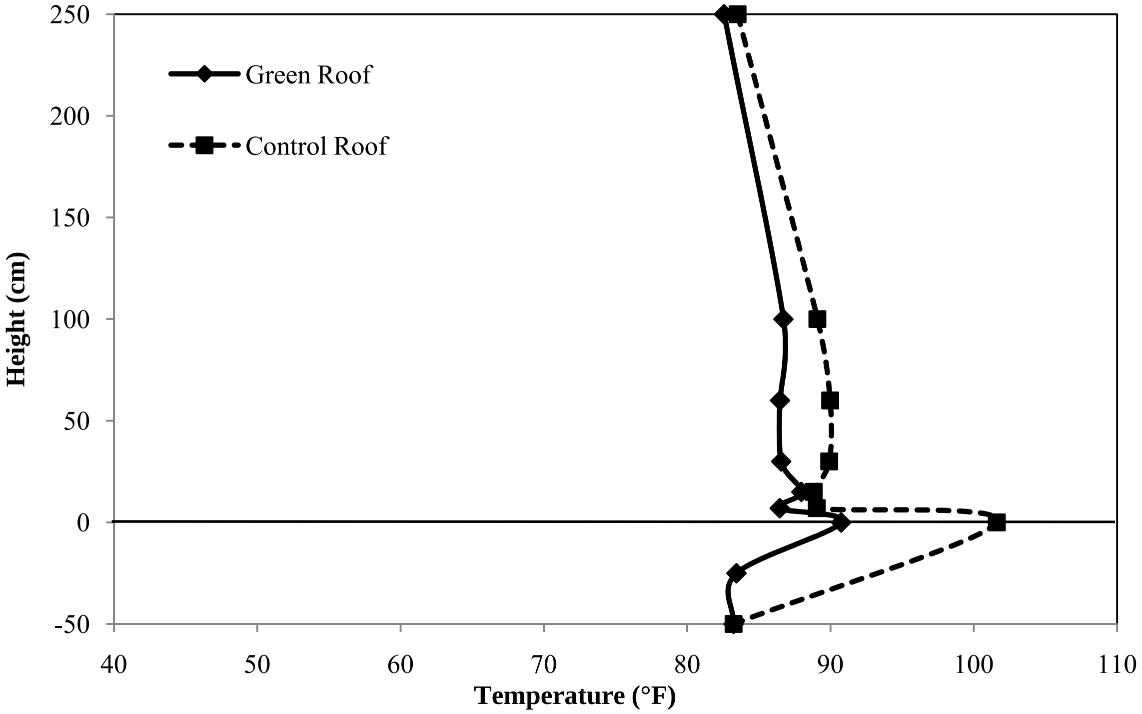


(a) Day-time temperature profile

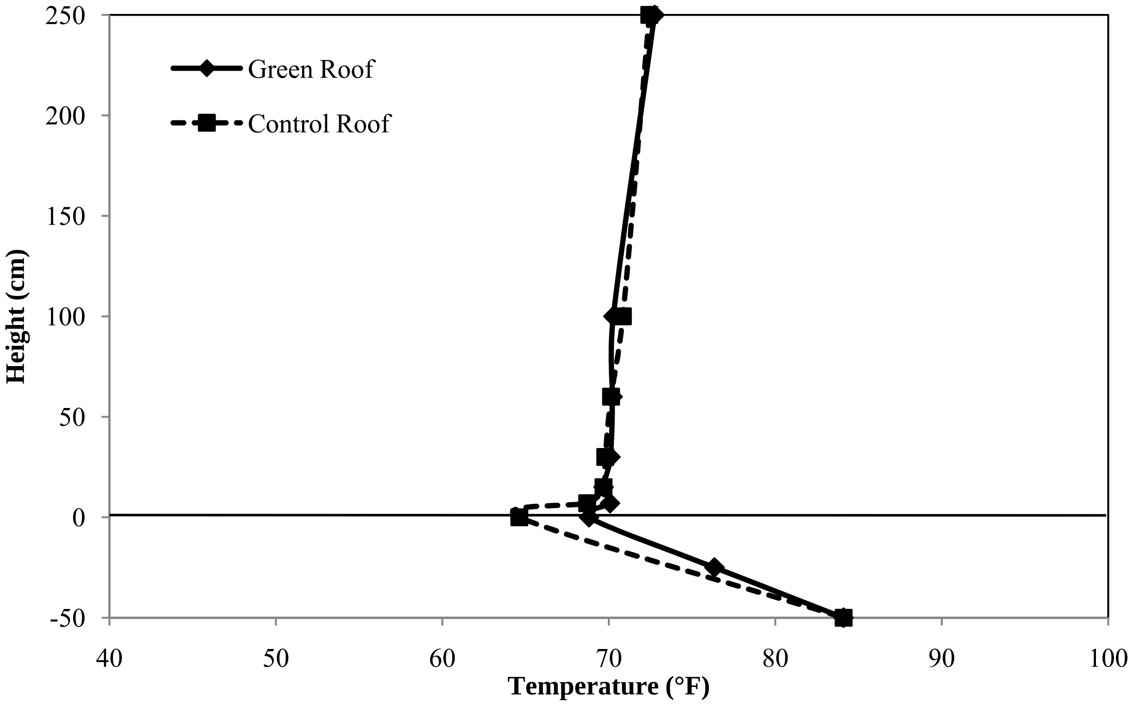


(b) Night-time temperature profile

Figure II-3 May, 2008 temperature profile at Homestead

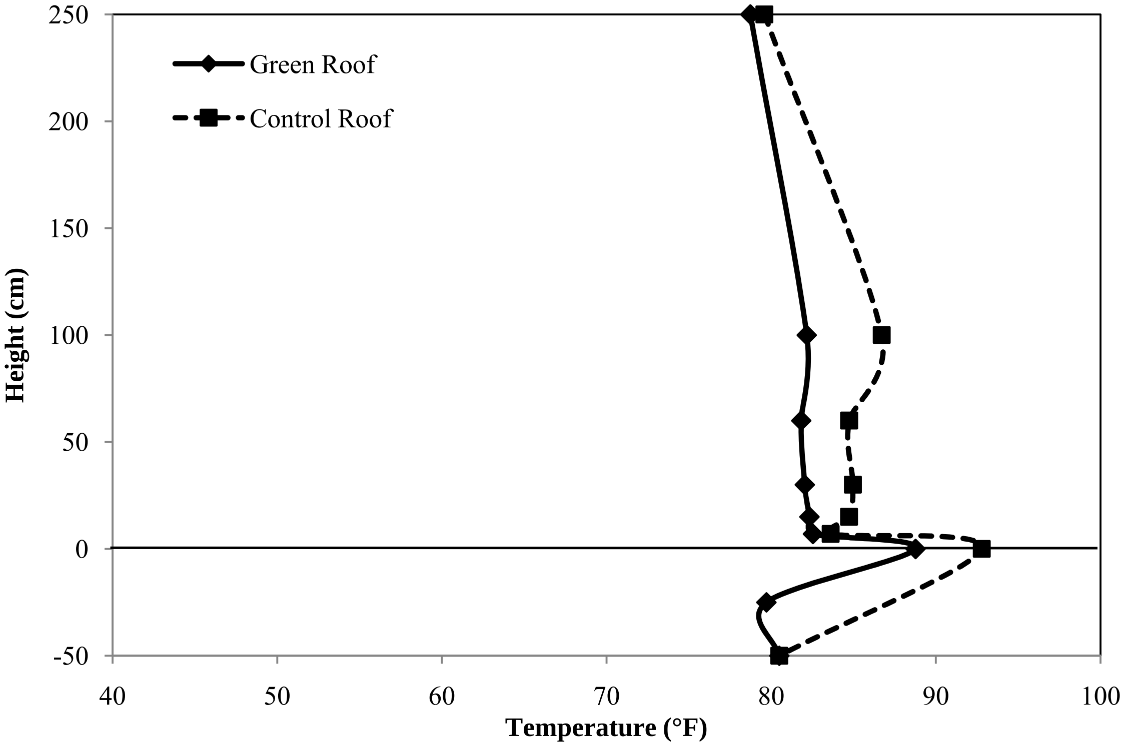


(a) Day-time temperature profile

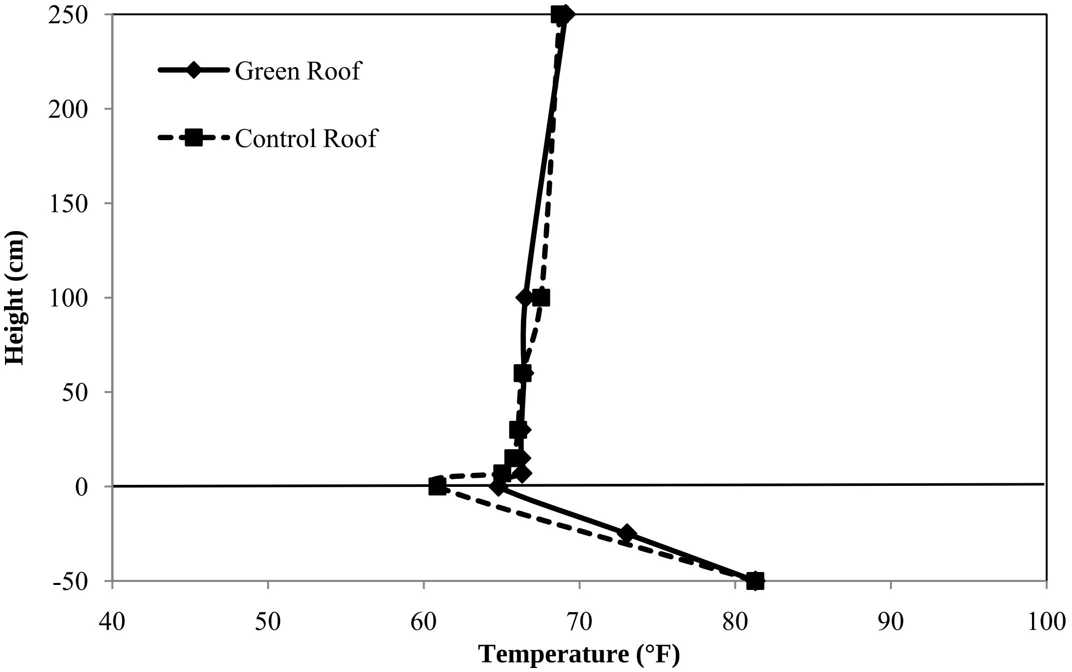


(b) Night-time temperature profile

Figure II-4 July, 2008 temperature profile at Homestead

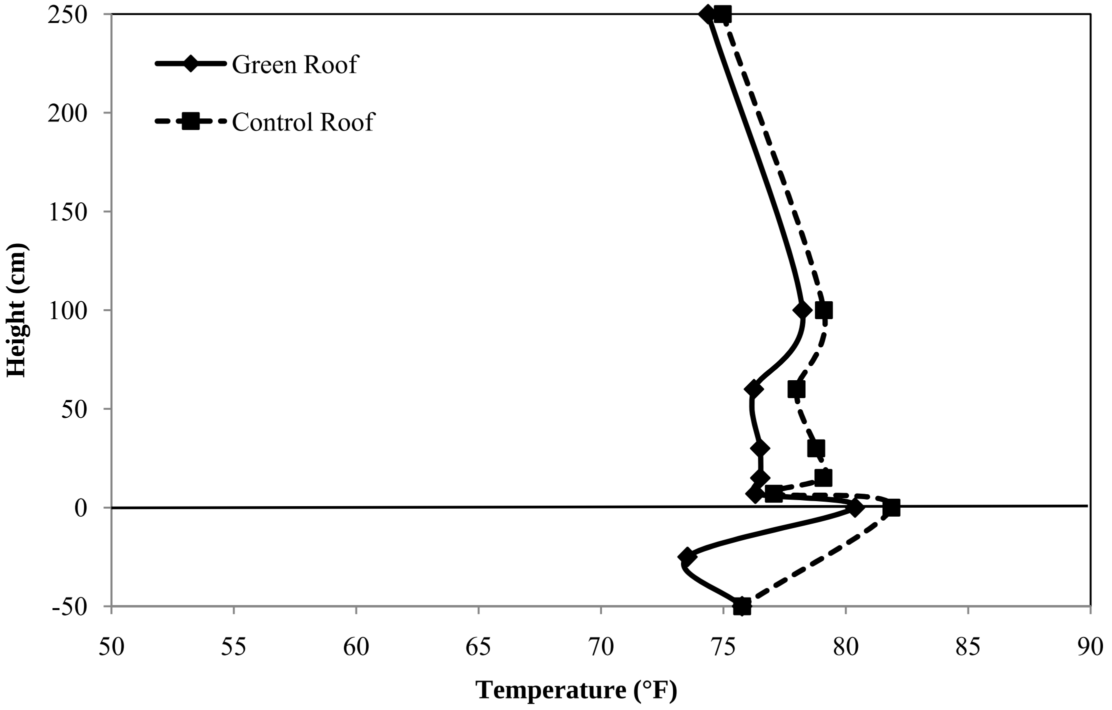


(a) Day-time temperature profile

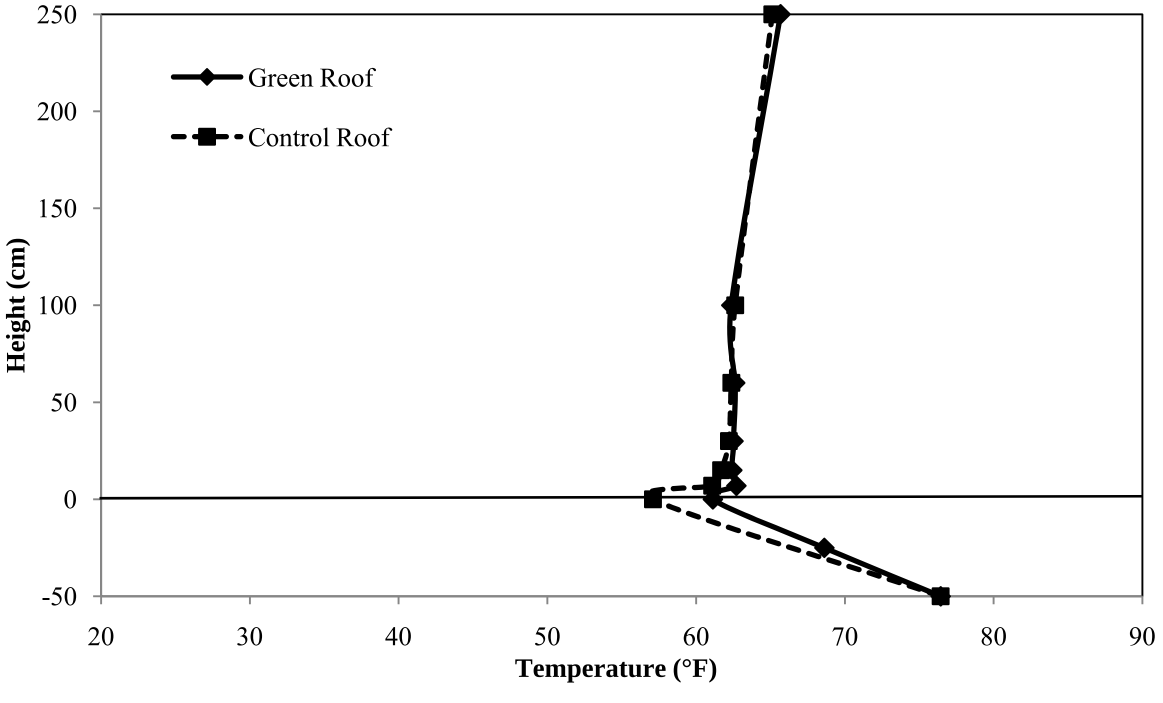


(b) Night-time temperature profile

Figure II-5 August, 2008 temperature profile at Homestead

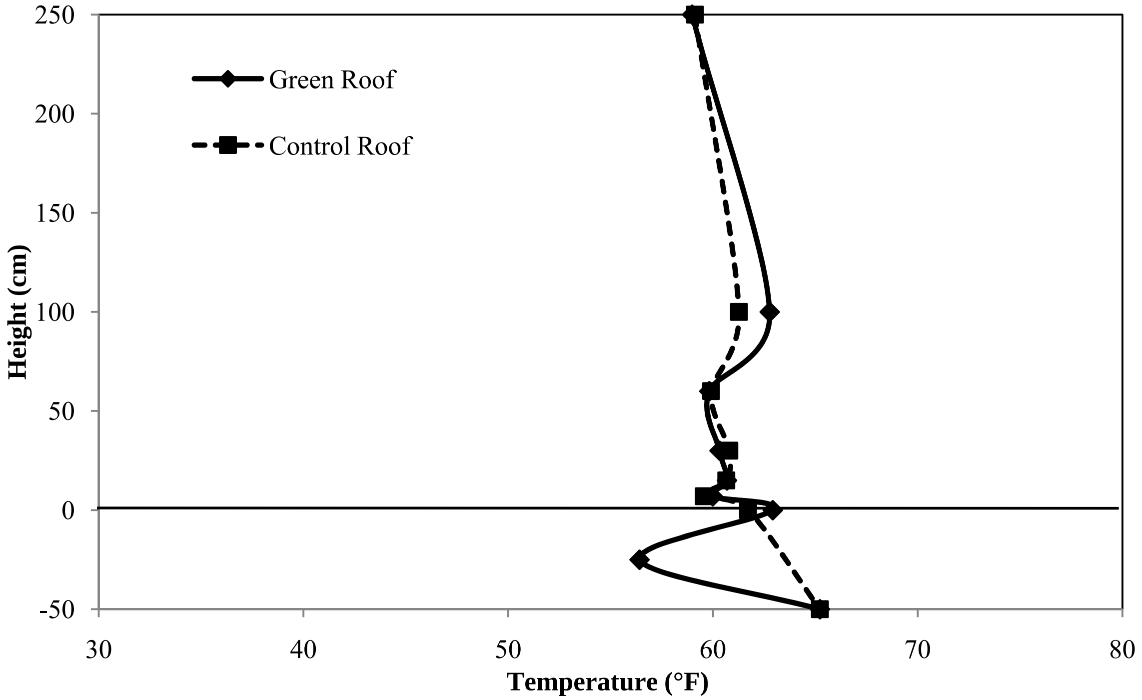


(a) Day-time temperature profile

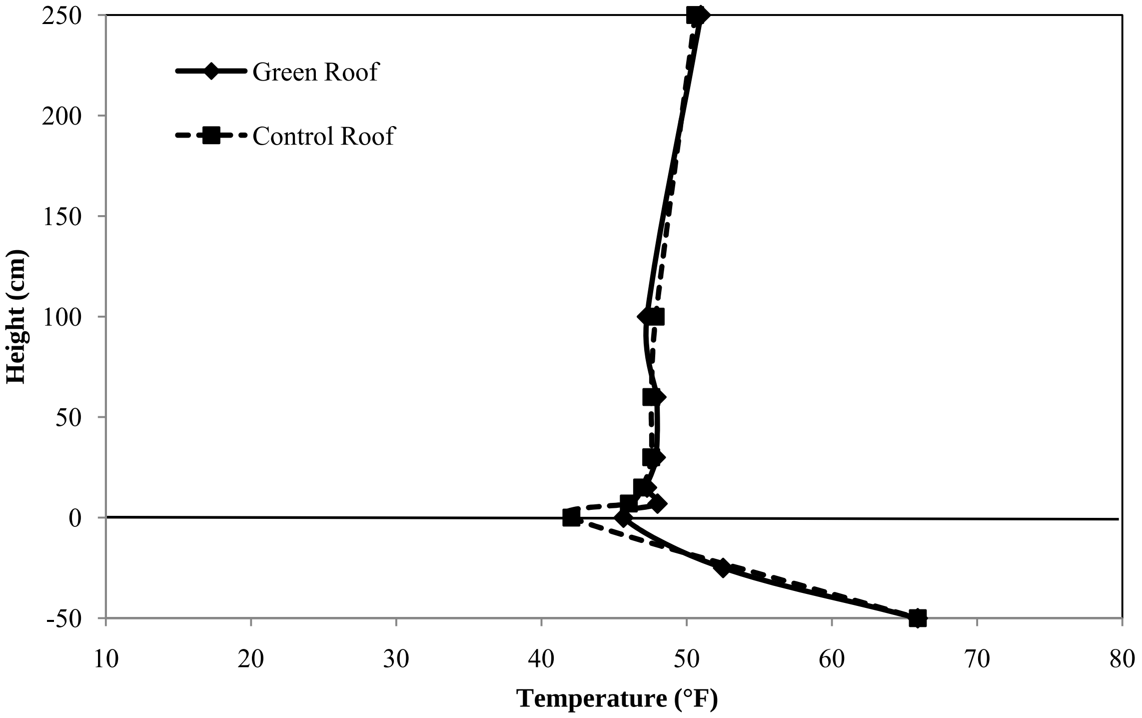


(b) Night-time temperature profile

Figure II-6 September, 2008 temperature profile at Homestead

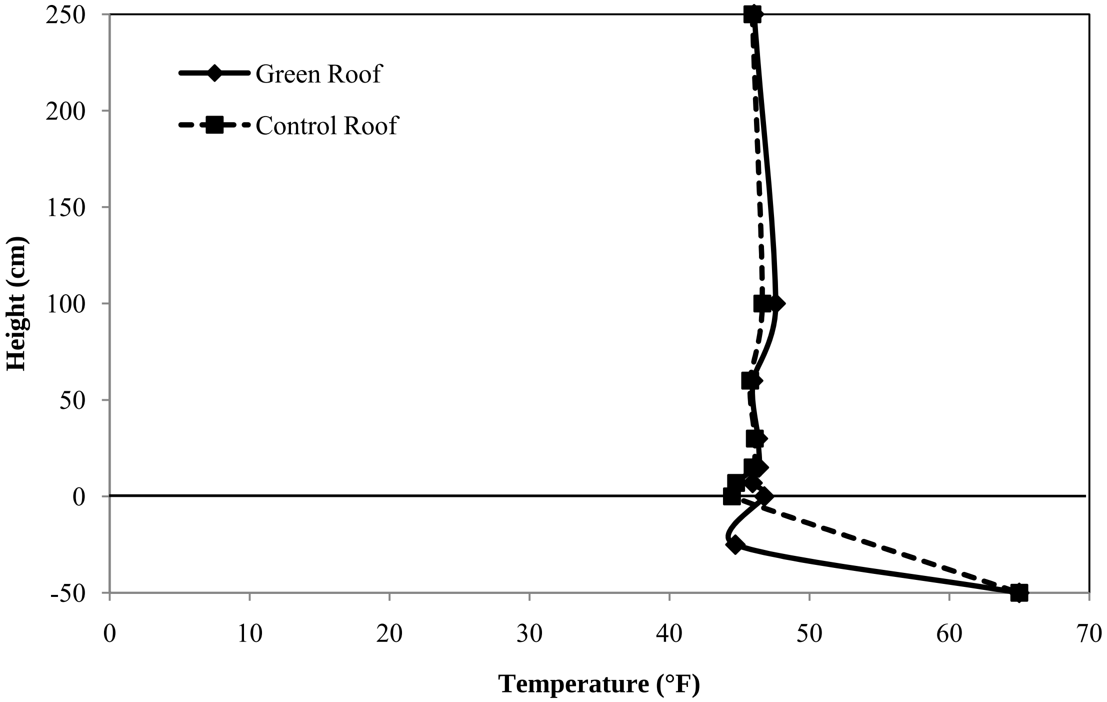


(a) Day-time temperature profile

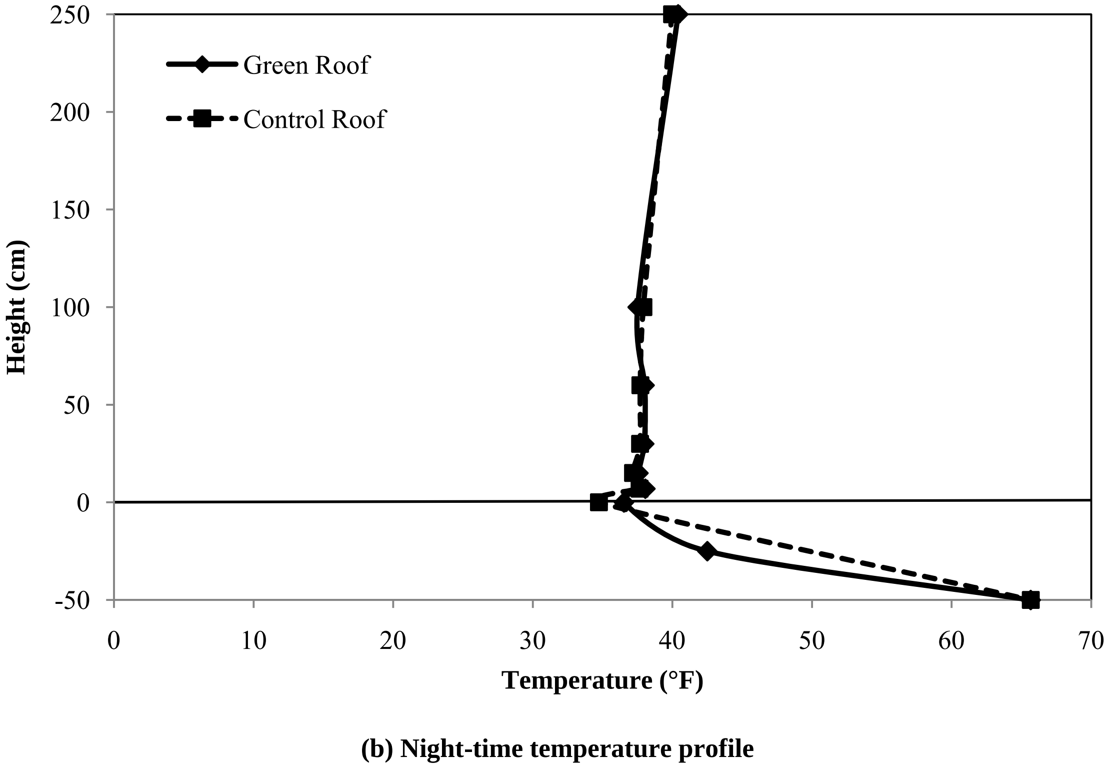


(b) Night-time temperature profile

Figure II-7 October, 2008 temperature profile at Homestead

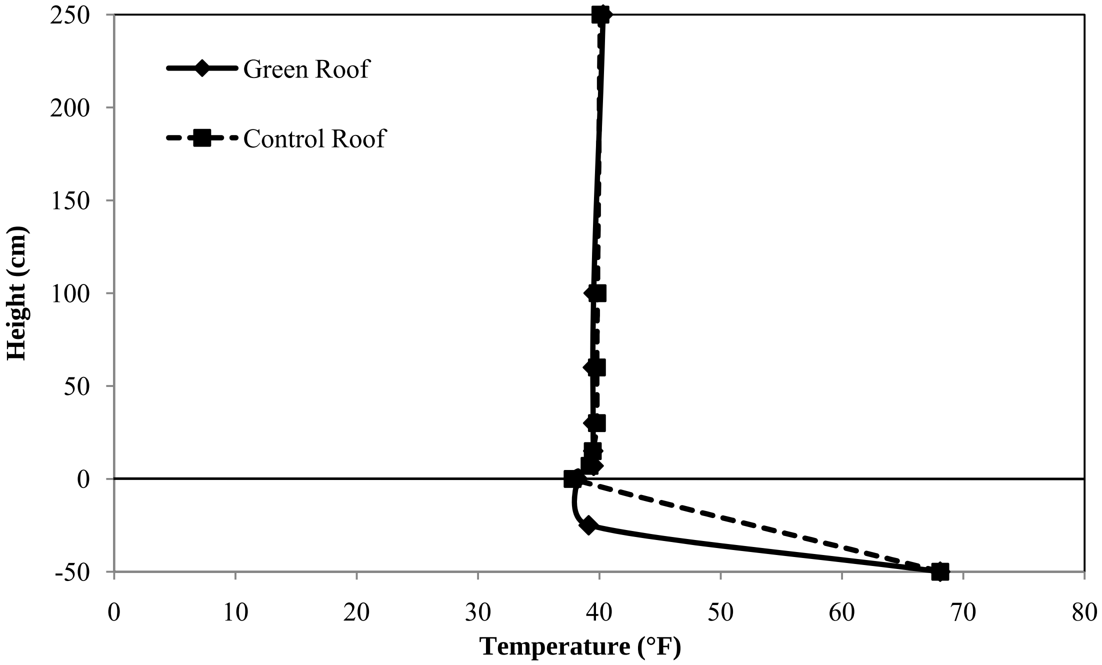


(a) Day-time temperature profile

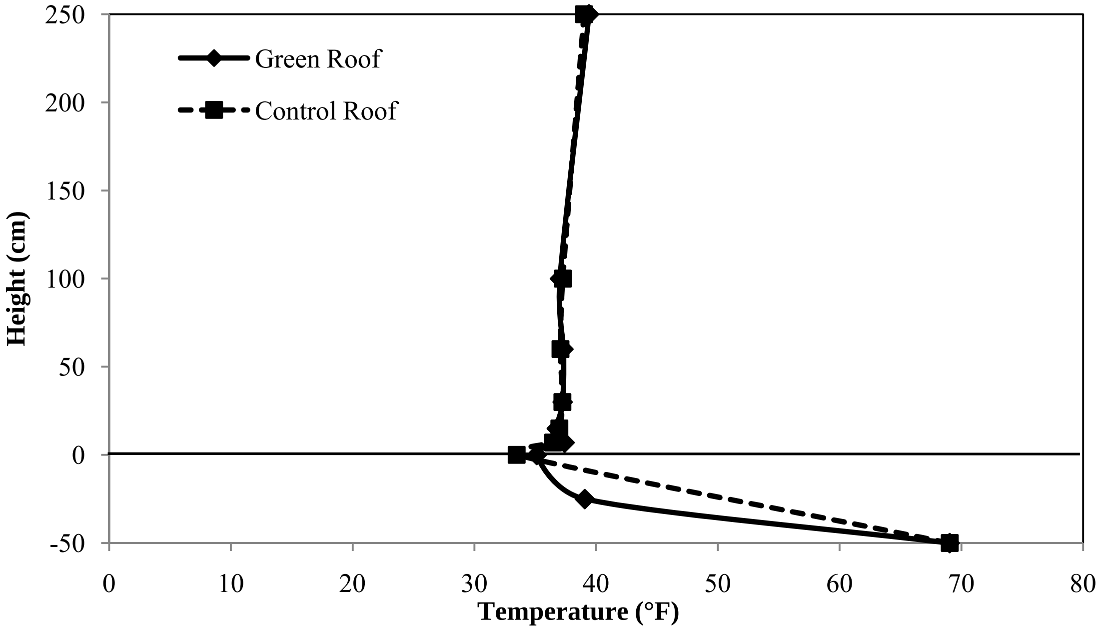


(b) Night-time temperature profile

Figure II-8 November, 2008 temperature profile at Homestead



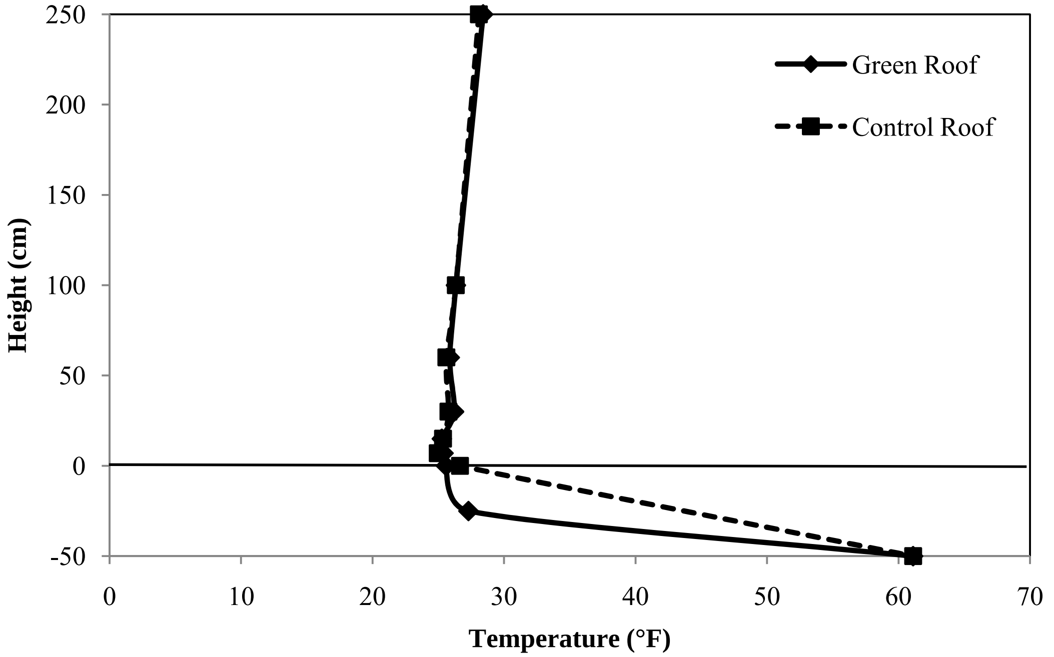
(a) Day-time temperature profile



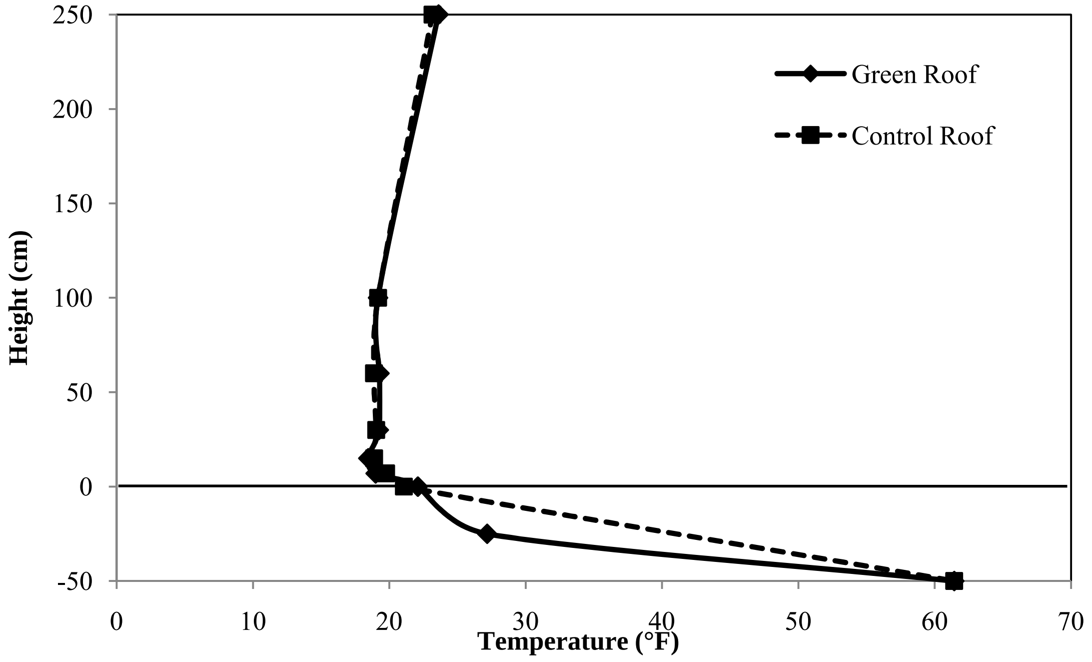
(b) Night-time temperature profile

Figure II-9 December, 2008 temperature profile at Homestead

Note: Only one day (December 1, 2008) was recorded for December temperature profile, due to the crash of the computer program.

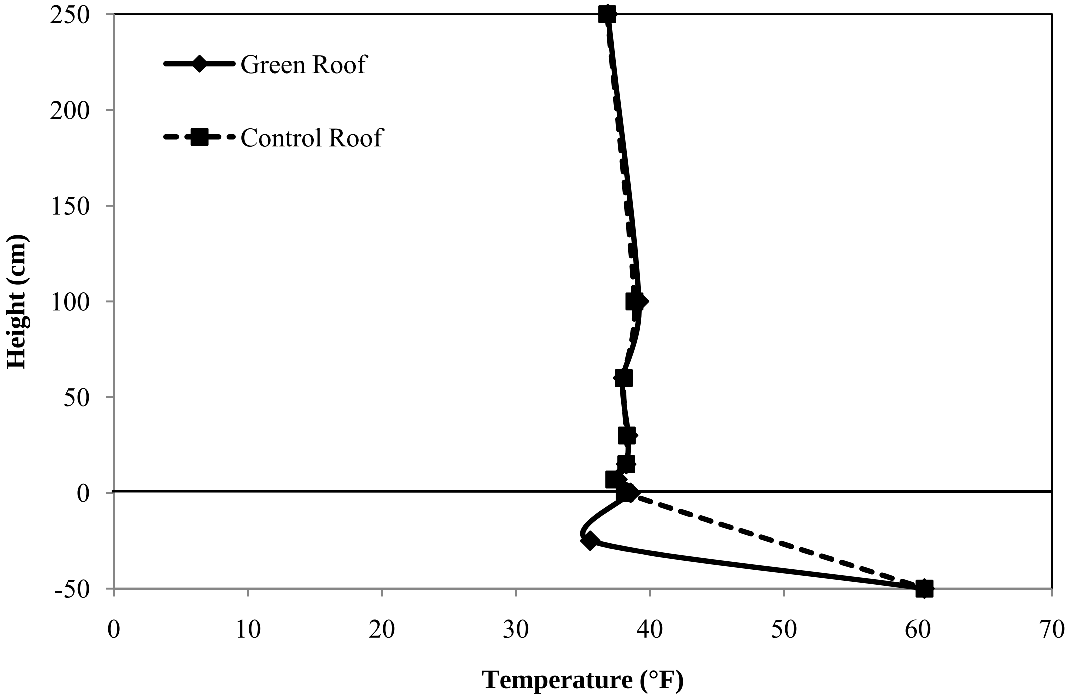


(a) Day-time temperature profile

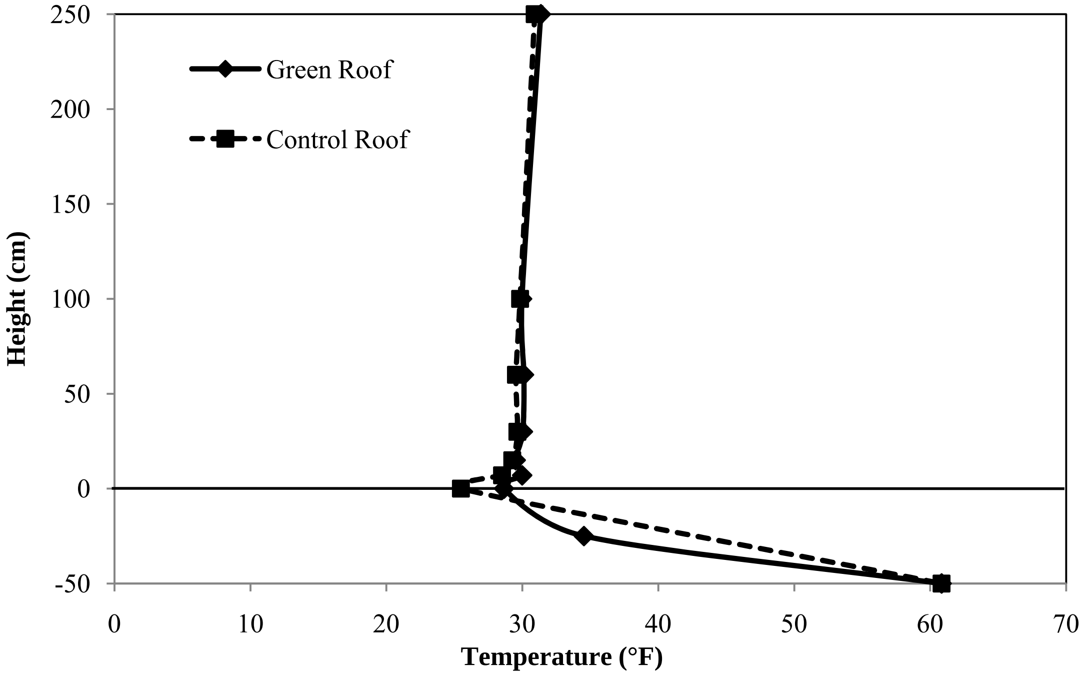


(b) Night-time temperature profile

Figure II-10 January, 2009 temperature profile at Homestead

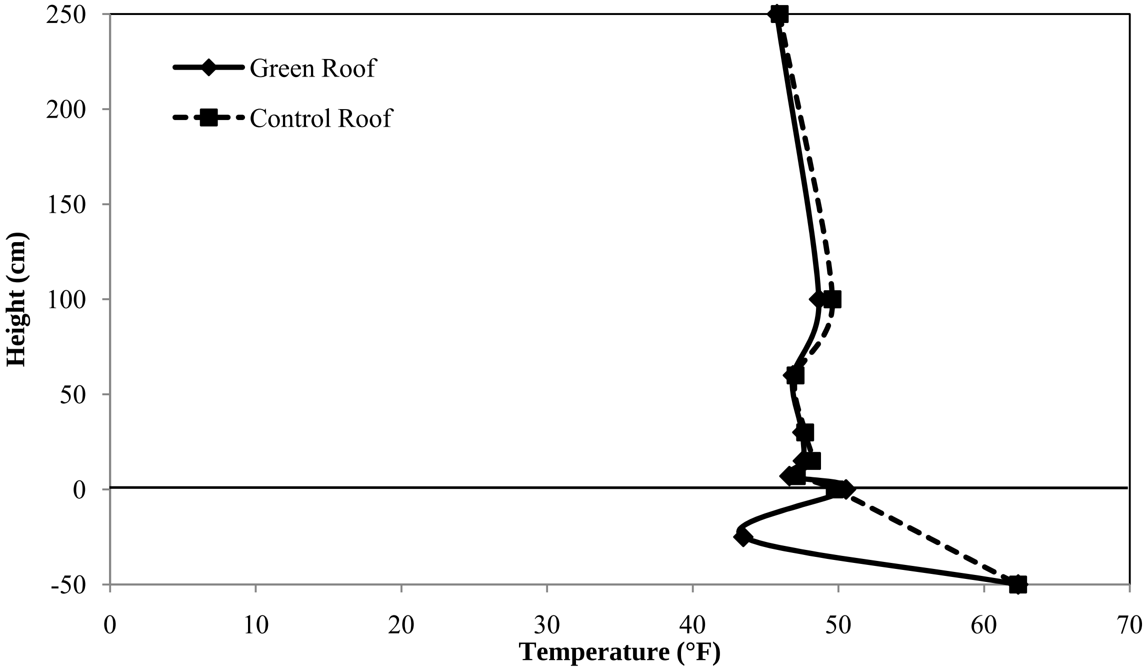


(a) Day-time temperature profile

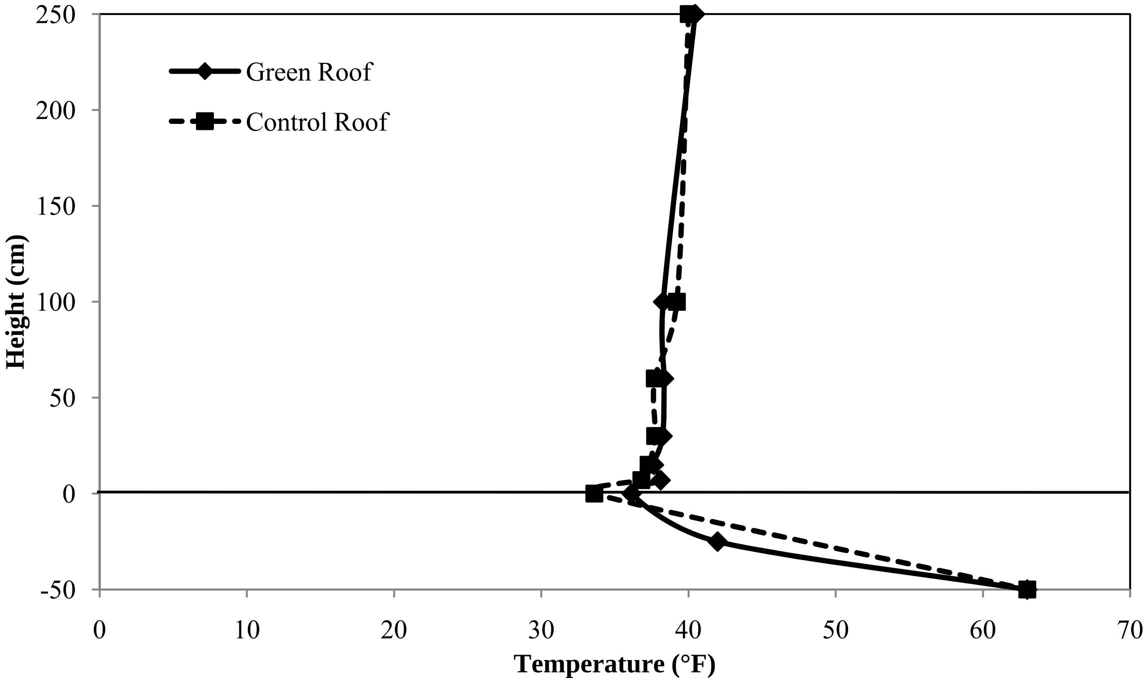


(b) Night-time temperature profile

Figure II-11 February, 2009 temperature profile at Homestead



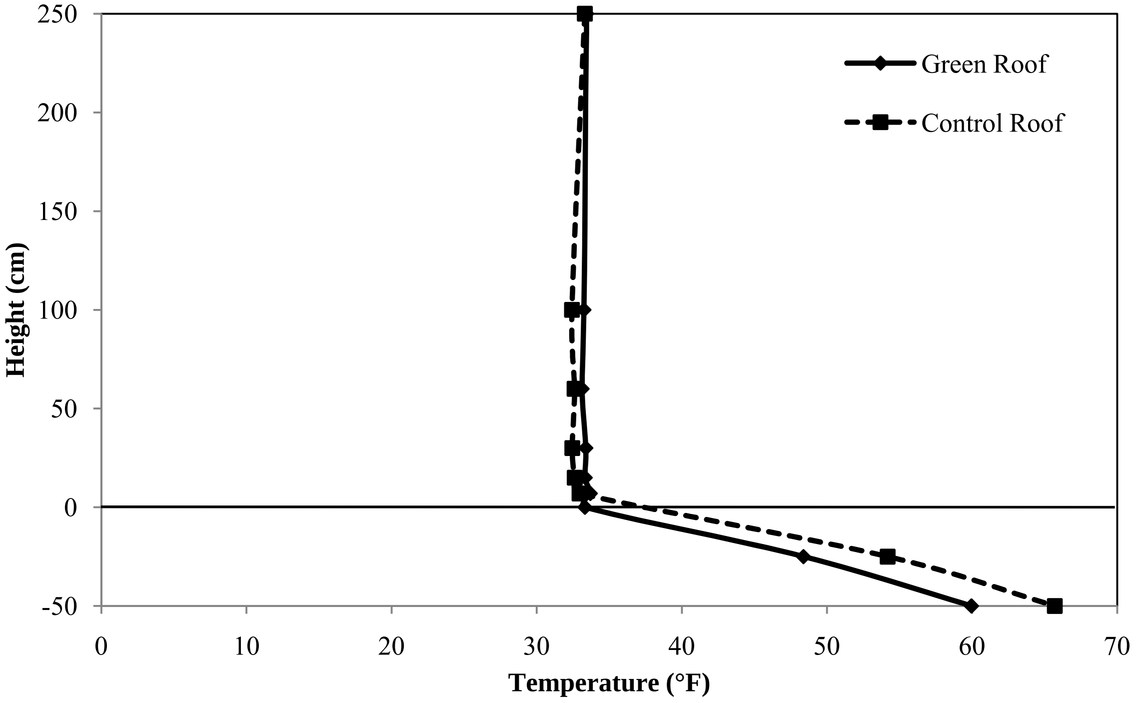
(a) Day-time temperature profile



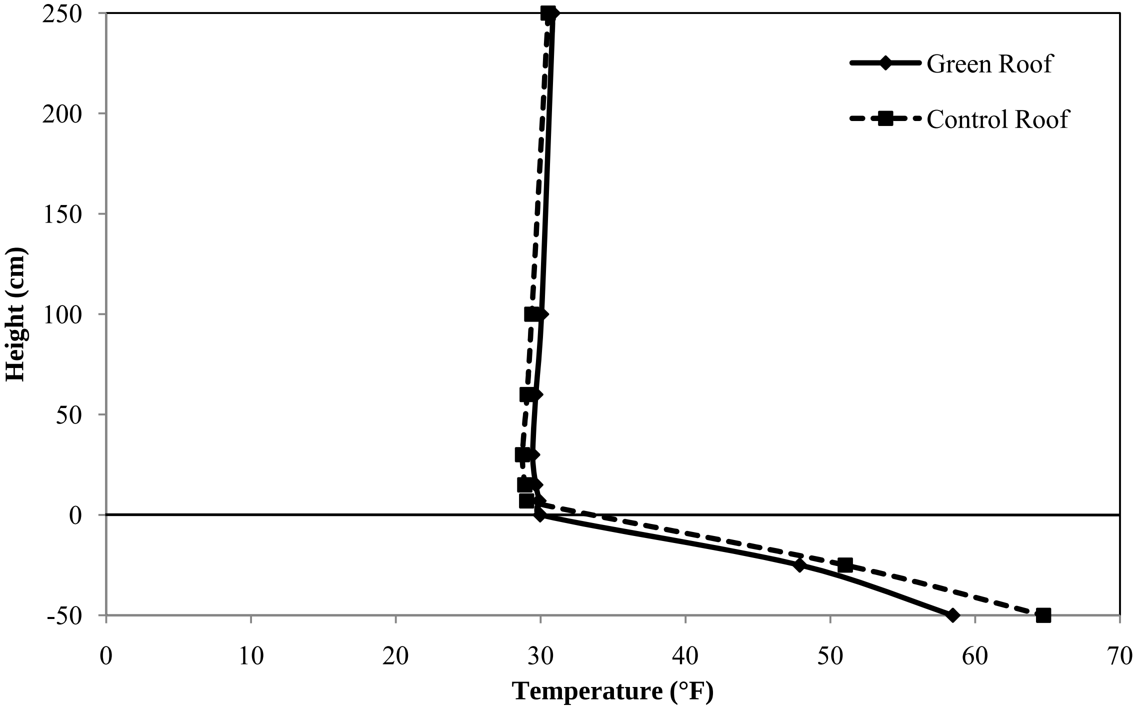
(b) Night-time temperature profile

Figure II-12 March, 2009 temperature profile at Homestead

Note: The temperature profile in March, 2009 at Homestead only includes the data from March 1, 2009 to March 10, 2009.

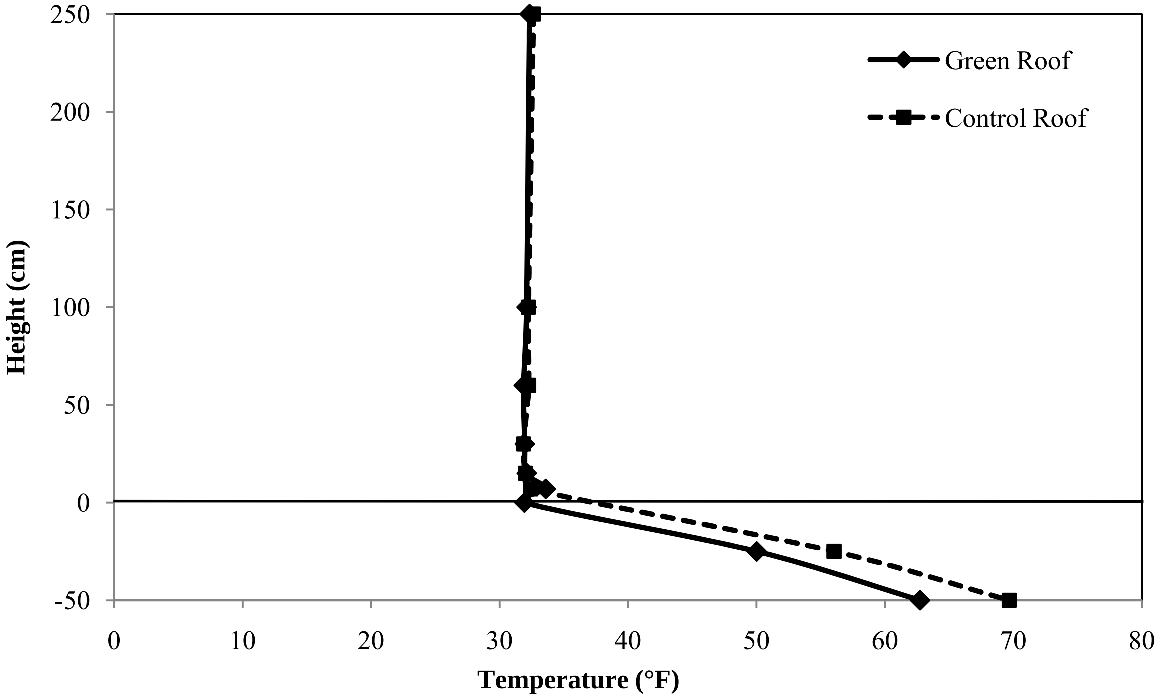


(a) Day-time temperature profile

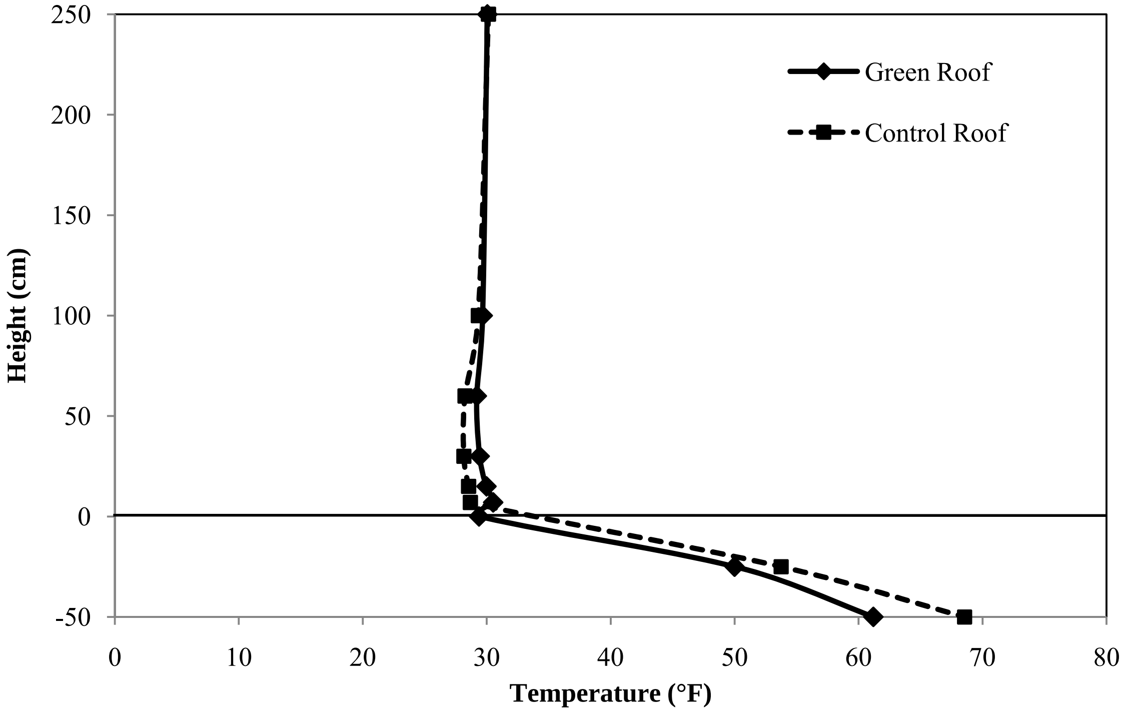


(b) Night-time temperature profile

Figure II-13 January, 2008 temperature profile at Giant Eagle

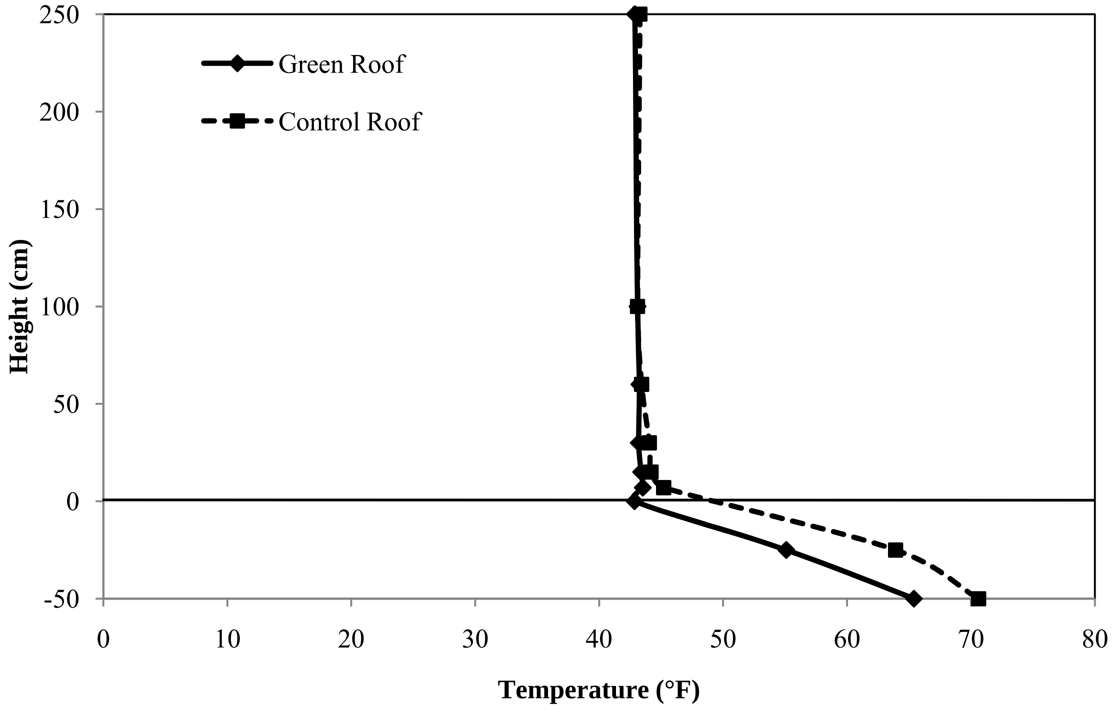


(a) Day-time temperature profile

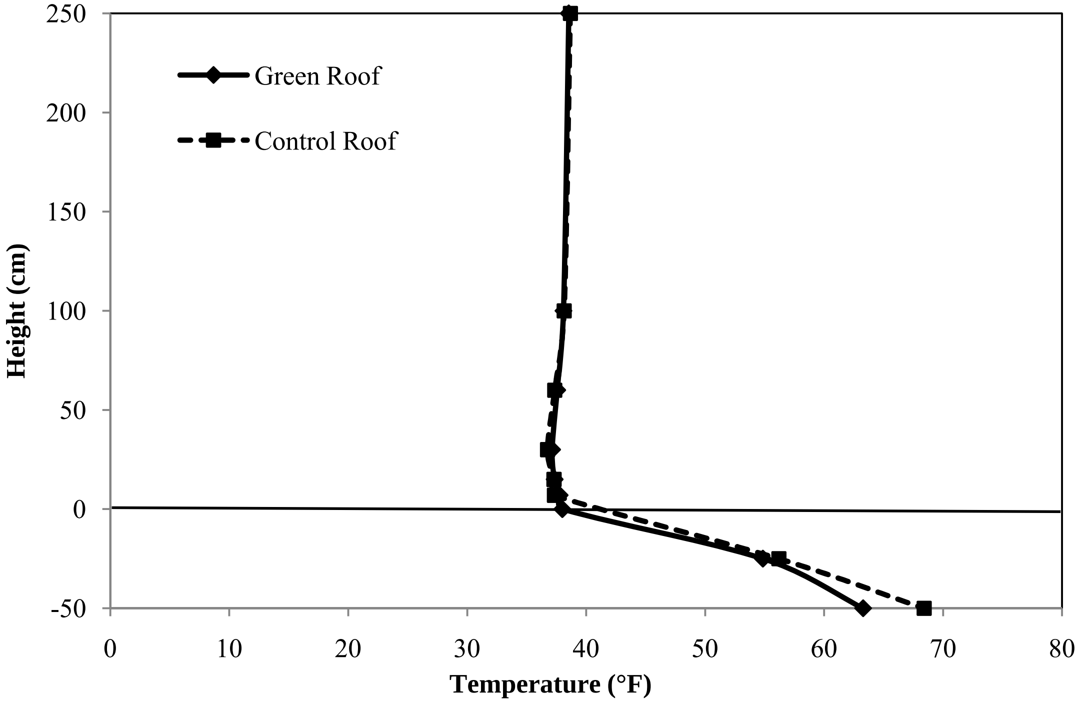


(b) Night-time temperature profile

Figure II-14 February, 2008 temperature profile at Giant Eagle

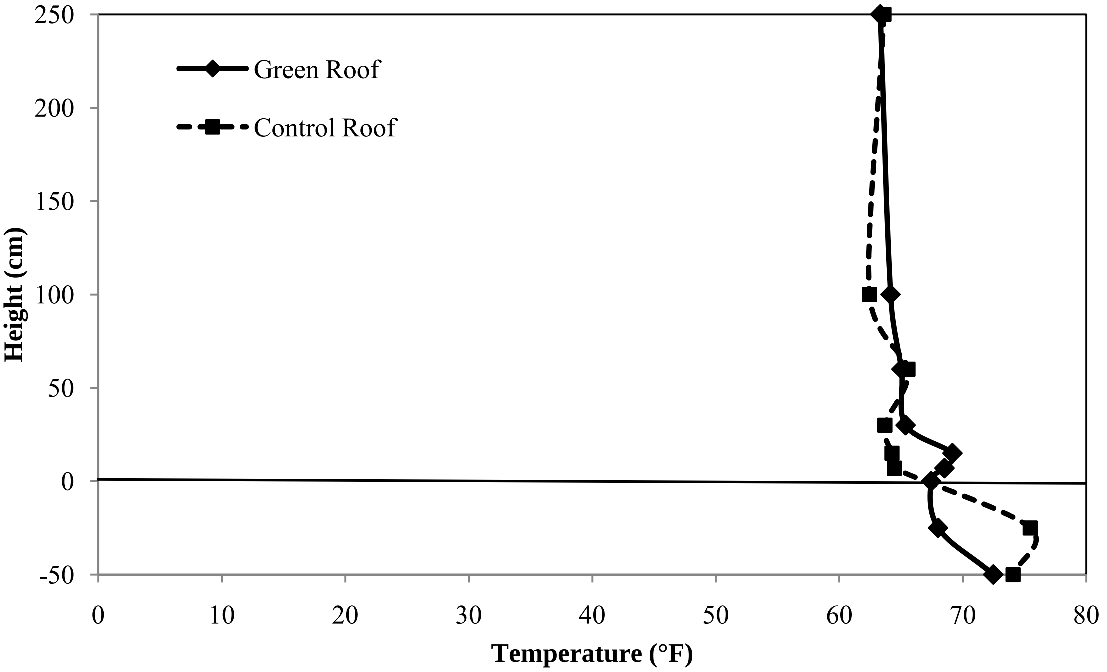


(a) Day-time temperature profile

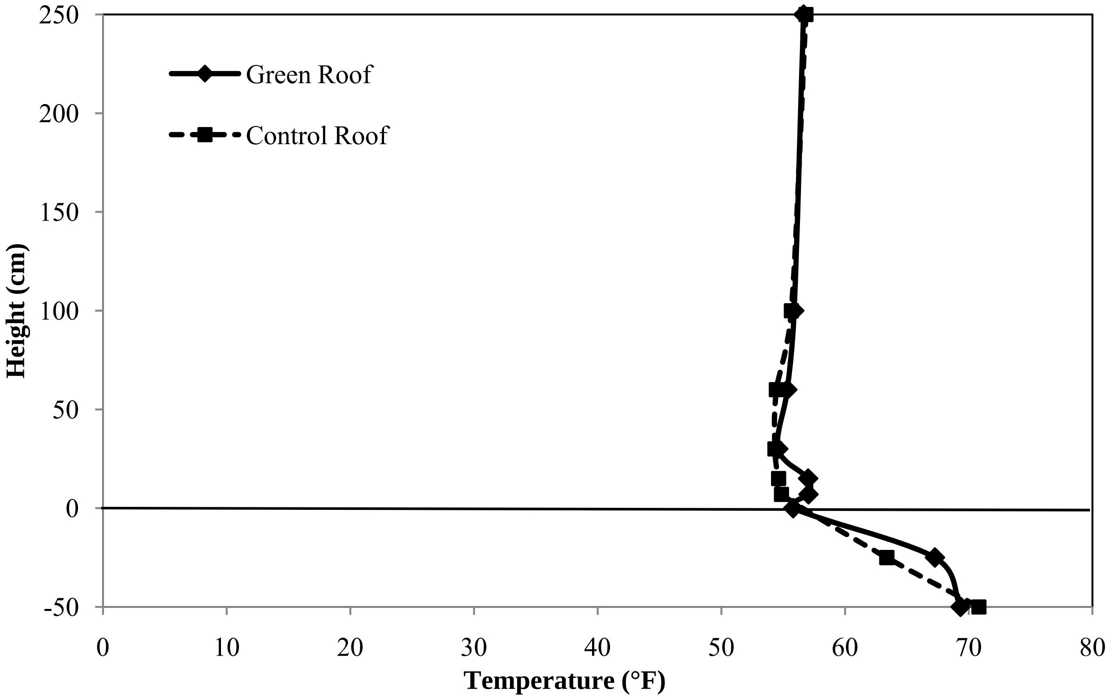


(b) Night-time temperature profile

Figure II-15 March, 2008 temperature profile at Giant Eagle

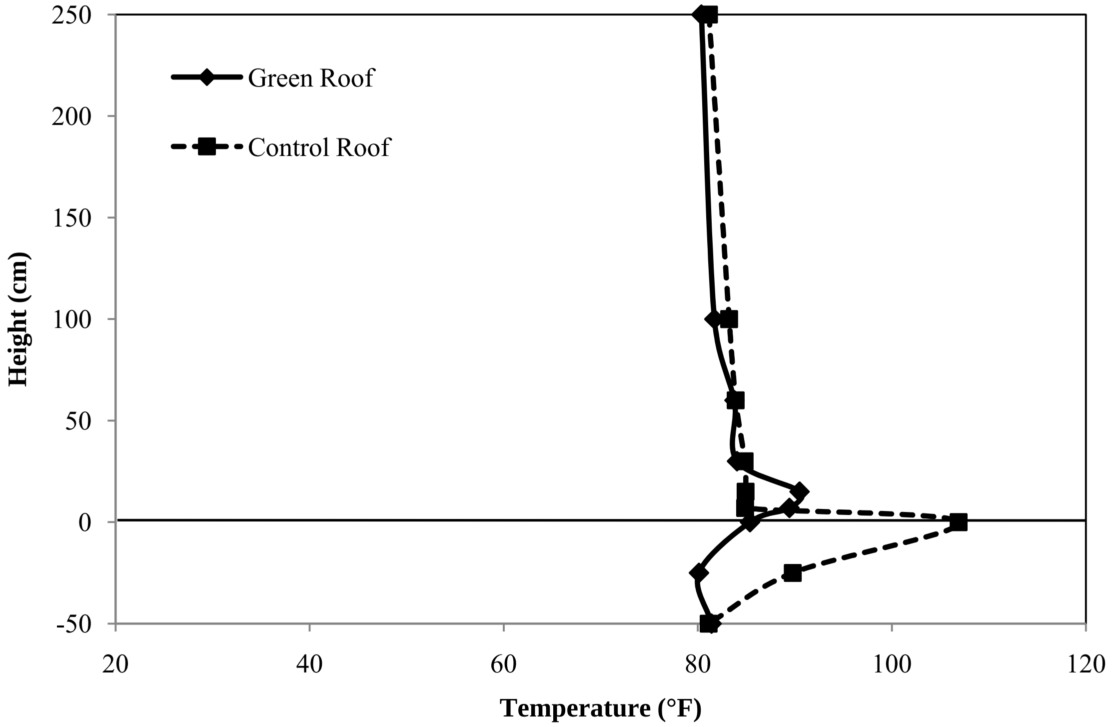


(a) Day-time temperature profile

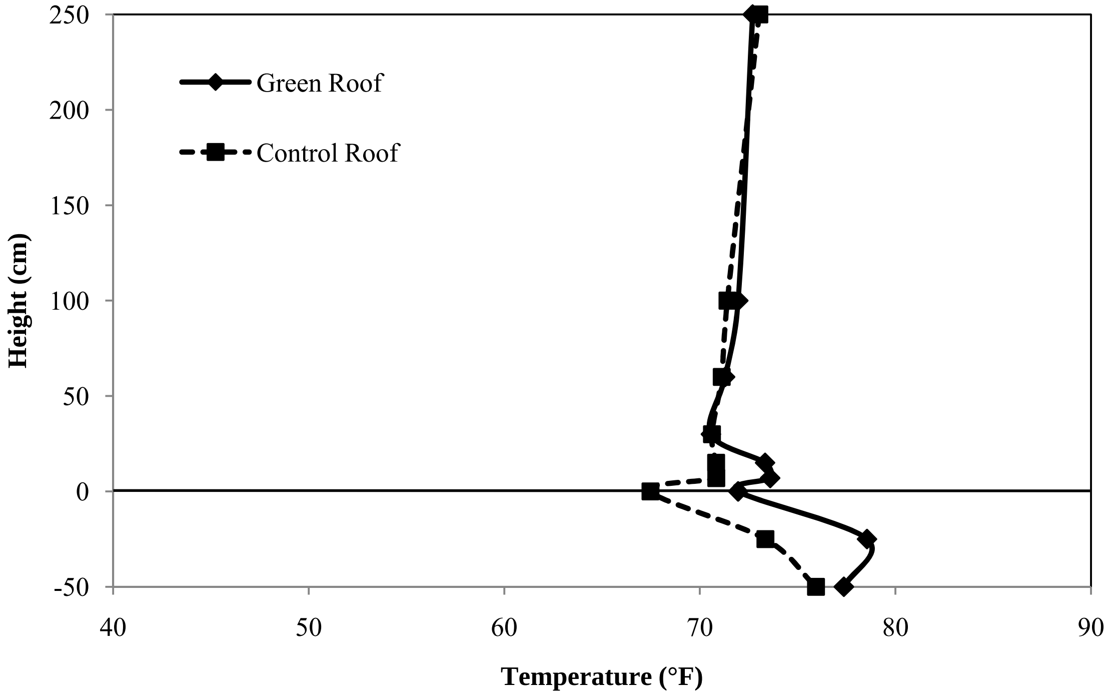


(b) Night-time temperature profile

Figure II-16 May, 2008 temperature profile at Giant Eagle

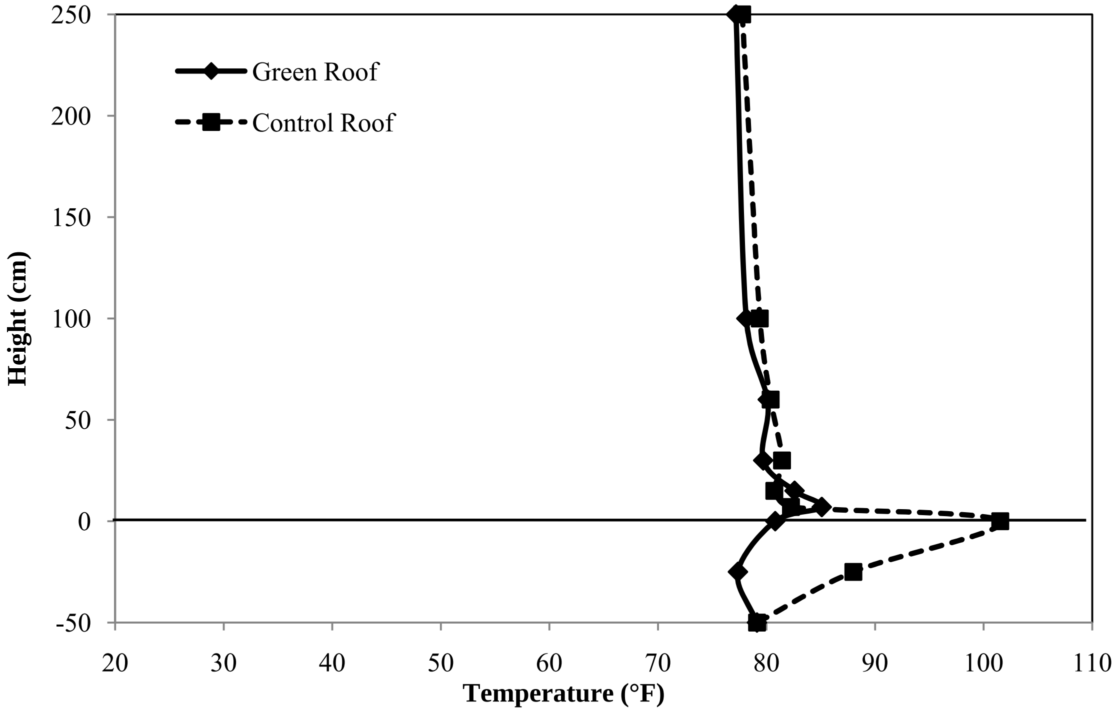


(a) Day-time temperature profile

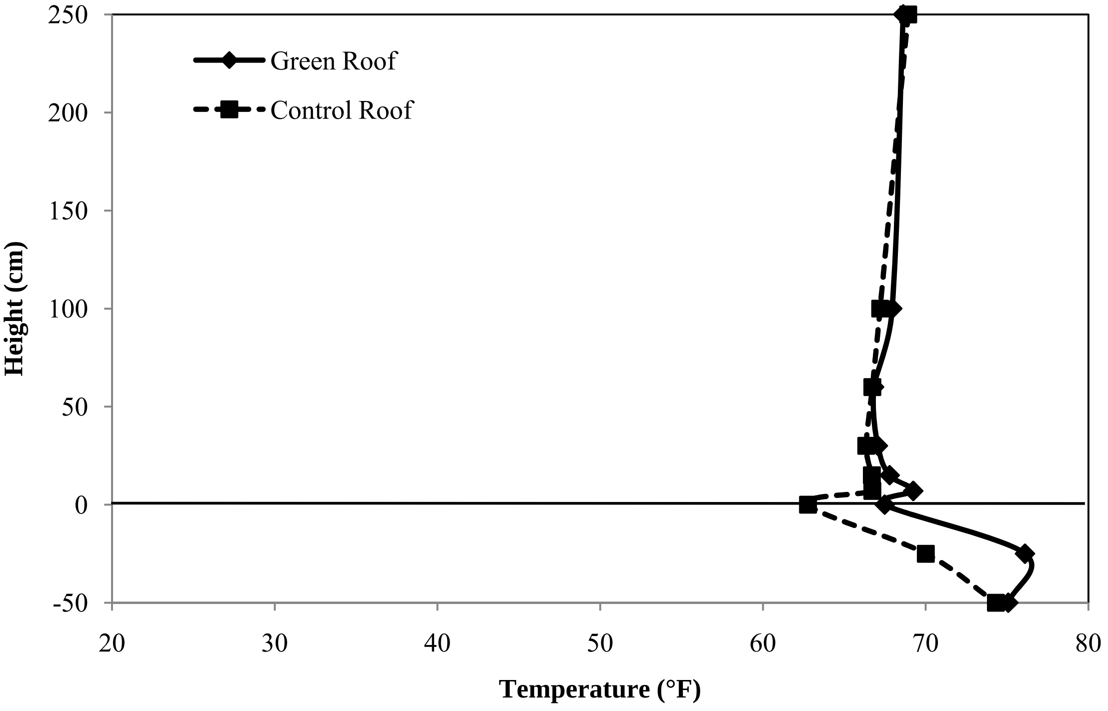


(b) Night-time temperature profile

Figure II-17 July, 2008 temperature profile at Giant Eagle

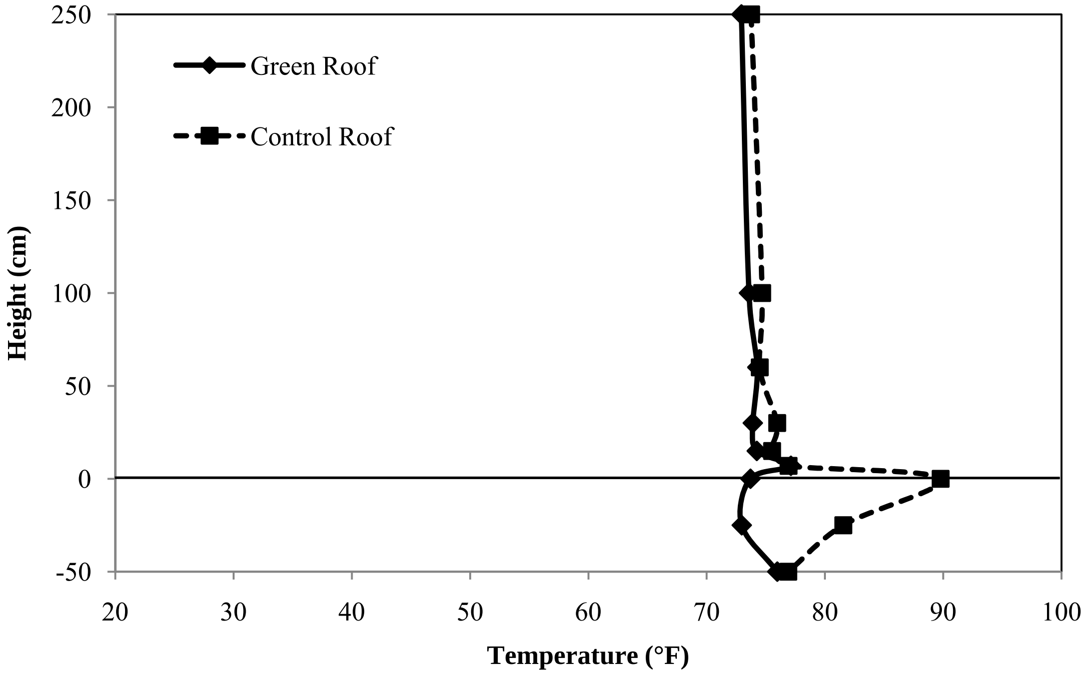


(a) Day-time temperature profile

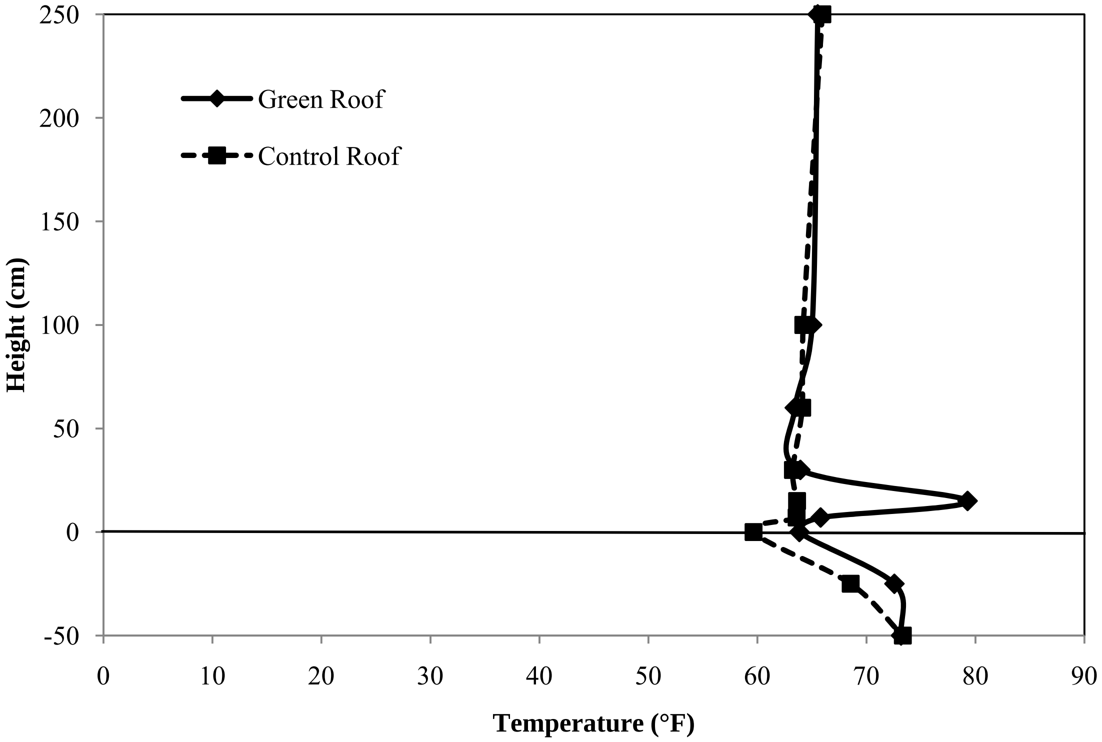


(b) Night-time temperature profile

Figure II-18 August, 2008 temperature profile at Giant Eagle

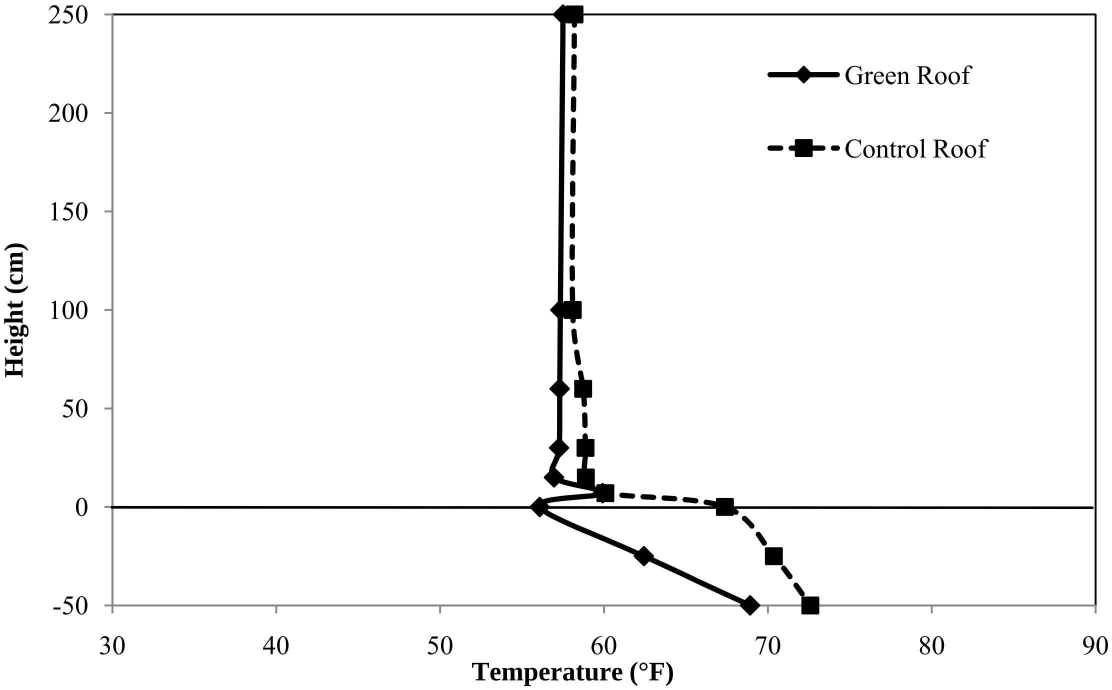


(a) Day-time temperature profile

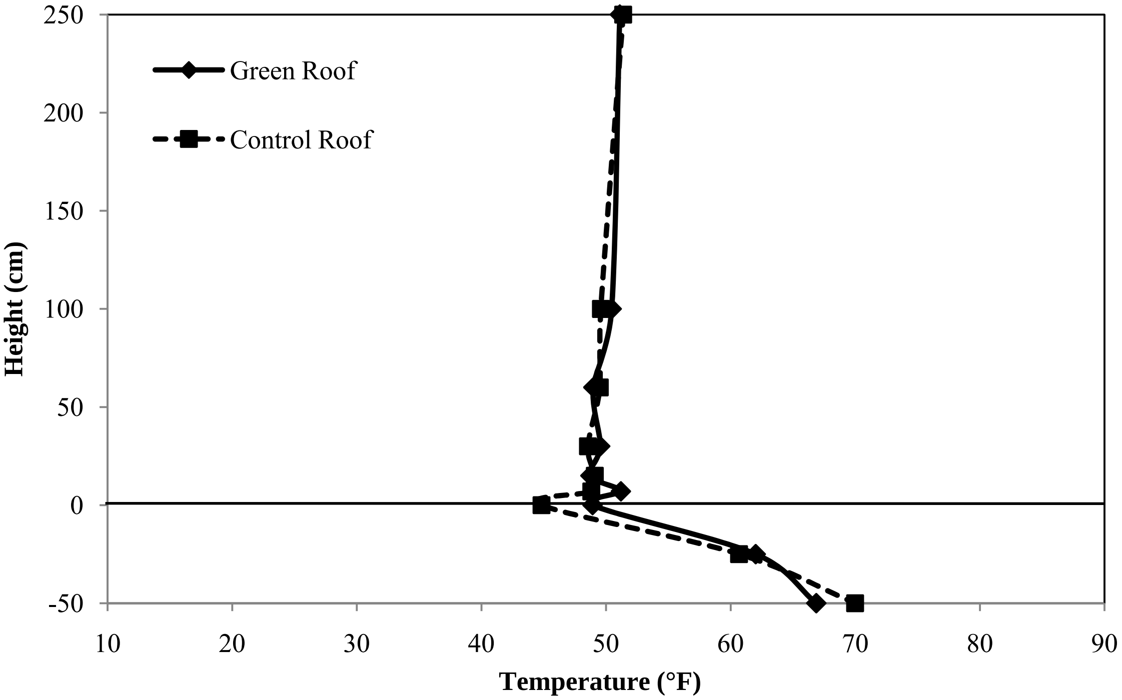


(b) Night-time temperature profile

Figure II-19 September, 2008 temperature profile at Giant Eagle

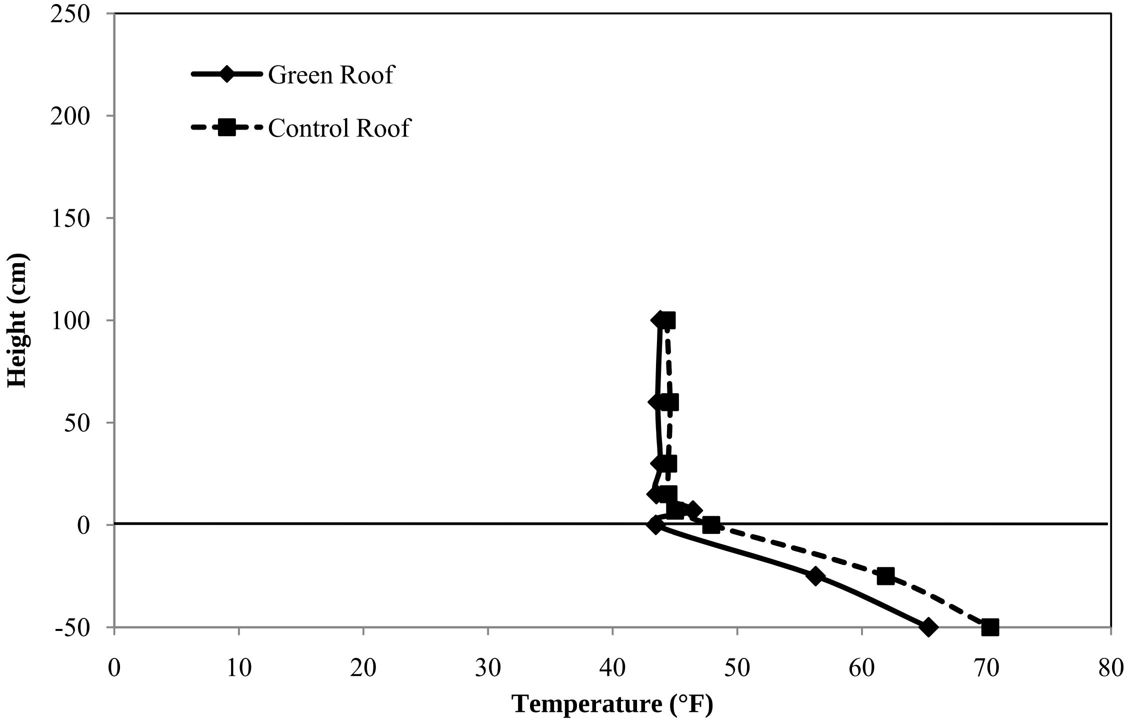


(a) Day-time temperature profile

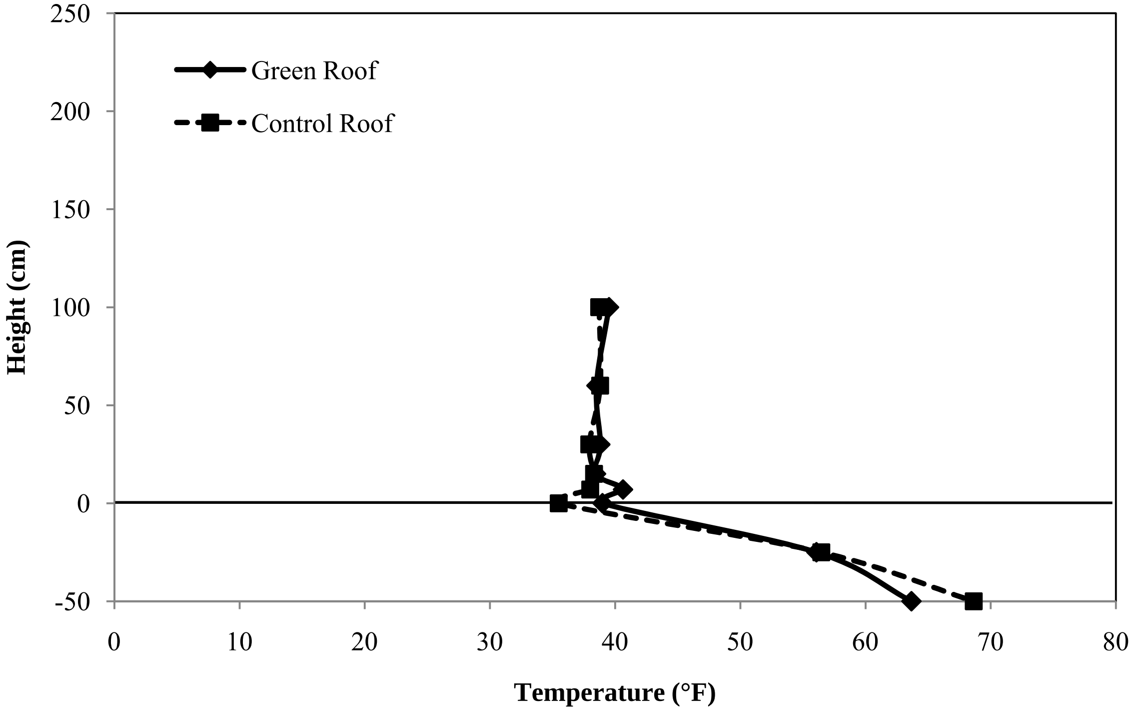


(b) Night-time temperature profile

Figure II-20 October, 2008 temperature profile at Giant Eagle

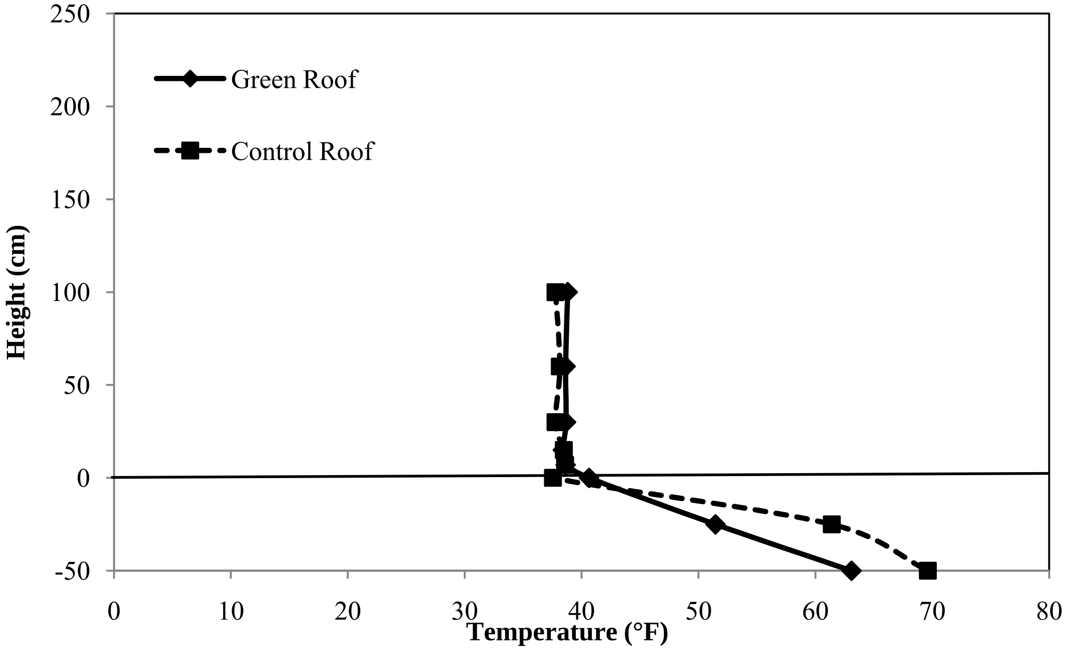


(a) Day-time temperature profile

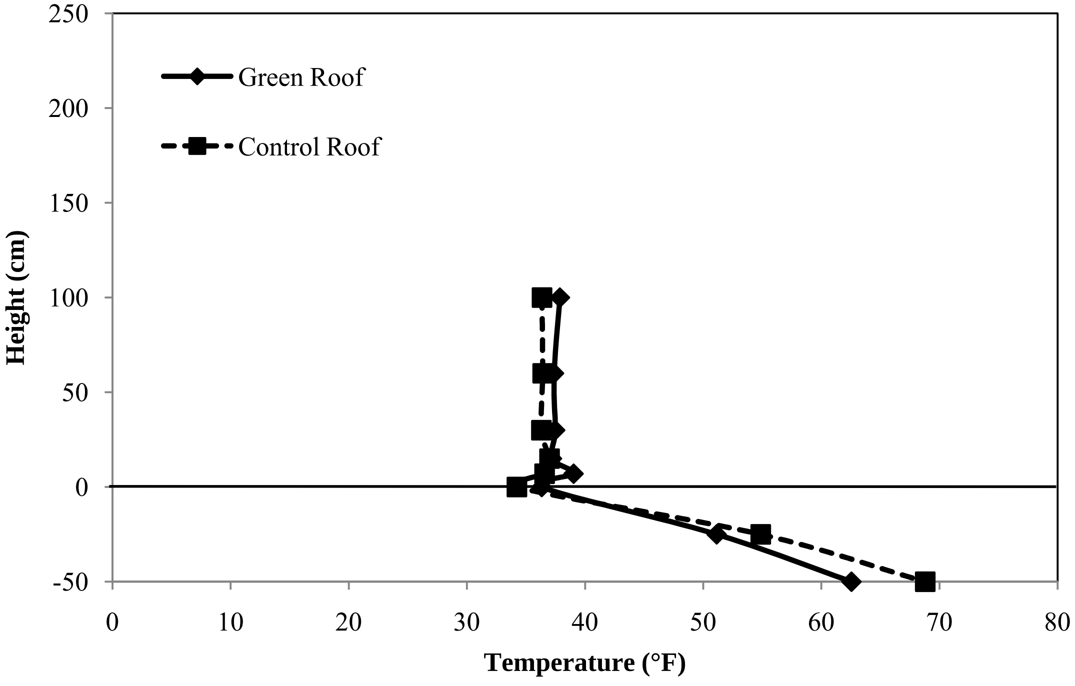


(b) Night-time temperature profile

Figure II-21 November, 2008 temperature profile at Giant Eagle



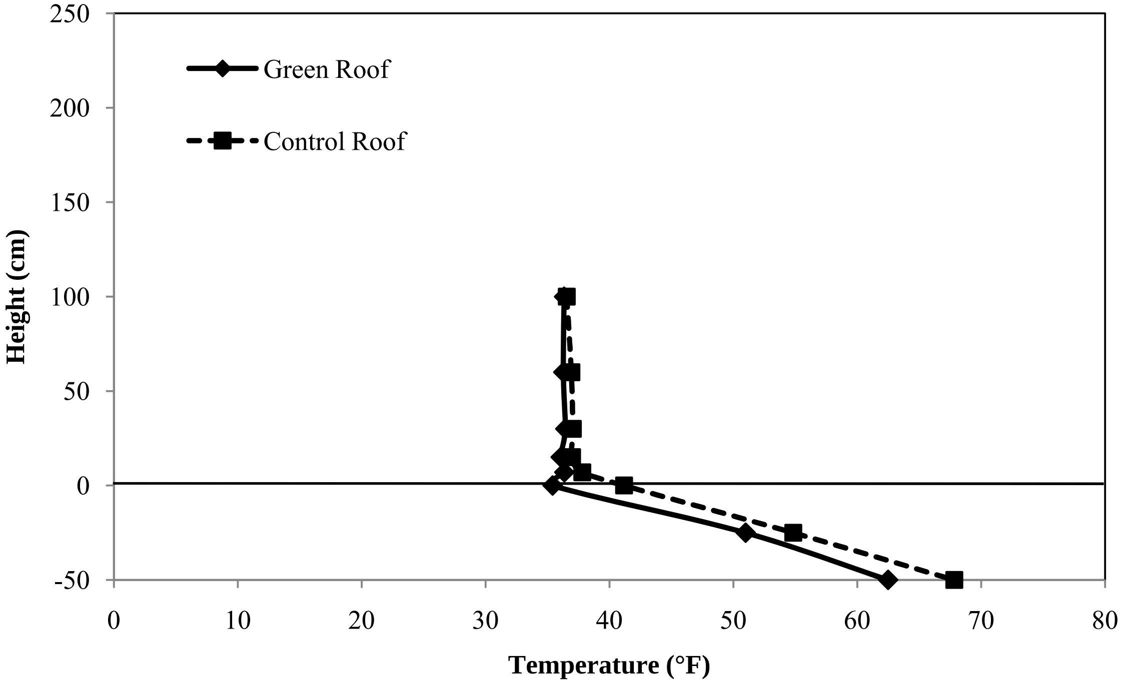
(a) Day-time temperature profile



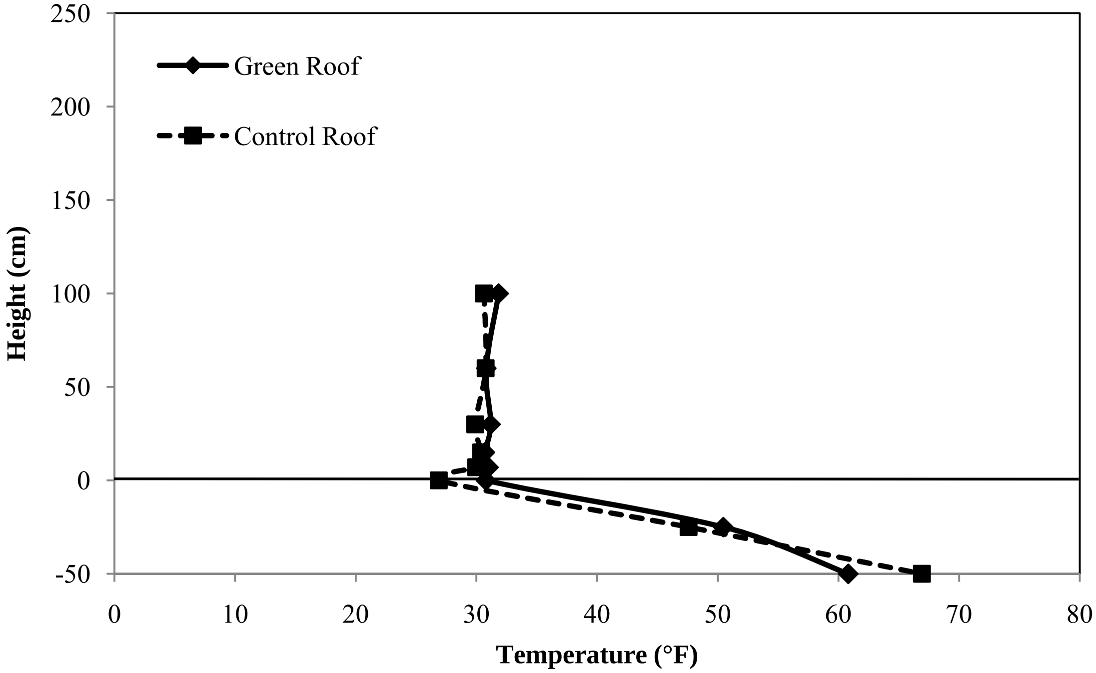
(b) Night-time temperature profile

Figure II-22 December, 2008 temperature profile at Giant Eagle

Note: Only one day (December 1, 2008) was recorded for December temperature profile, due to the crash of the computer program.

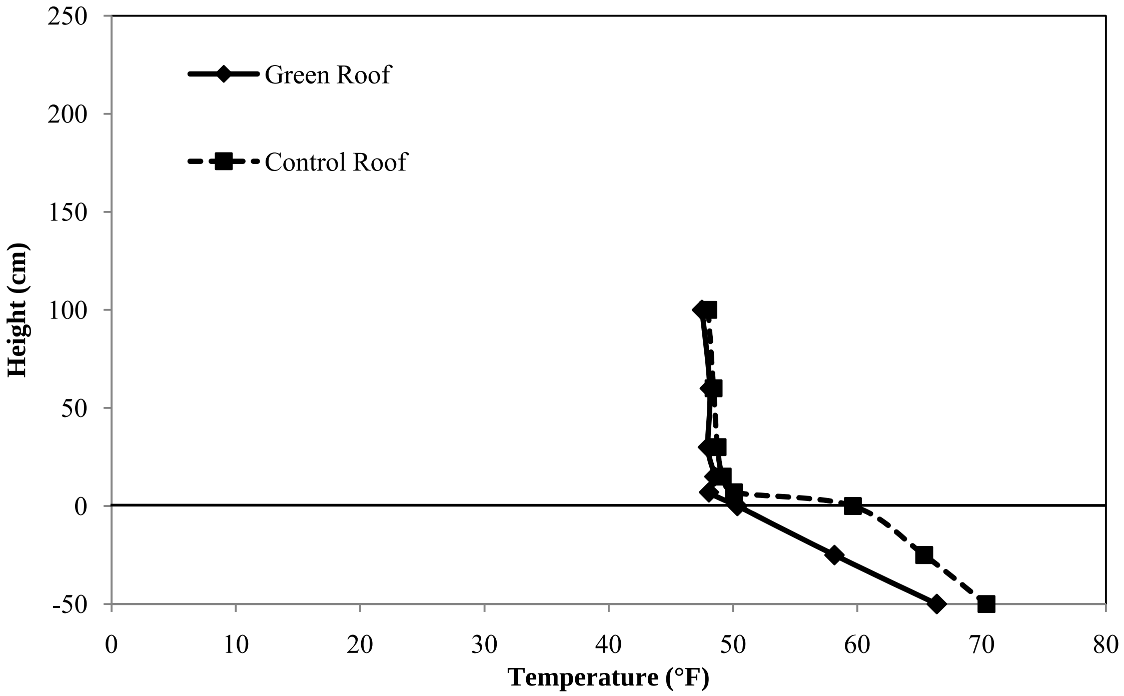


(a) Day-time temperature profile

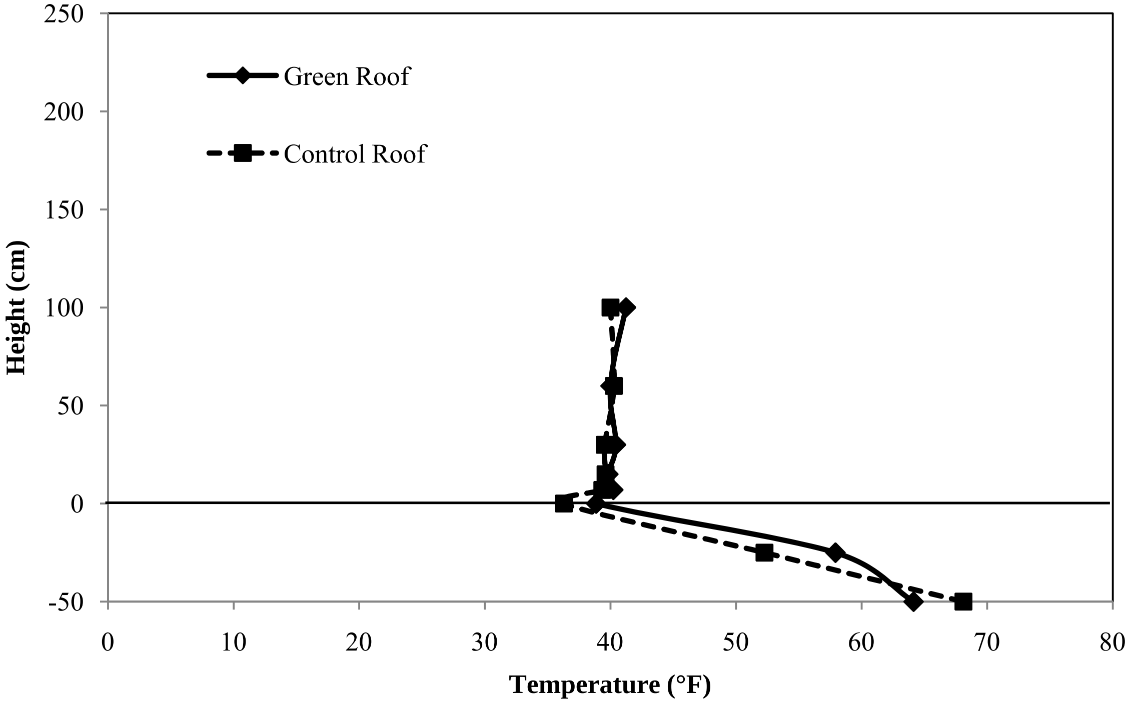


(b) Night-time temperature profile

Figure II-23 February, 2009 temperature profile at Giant Eagle

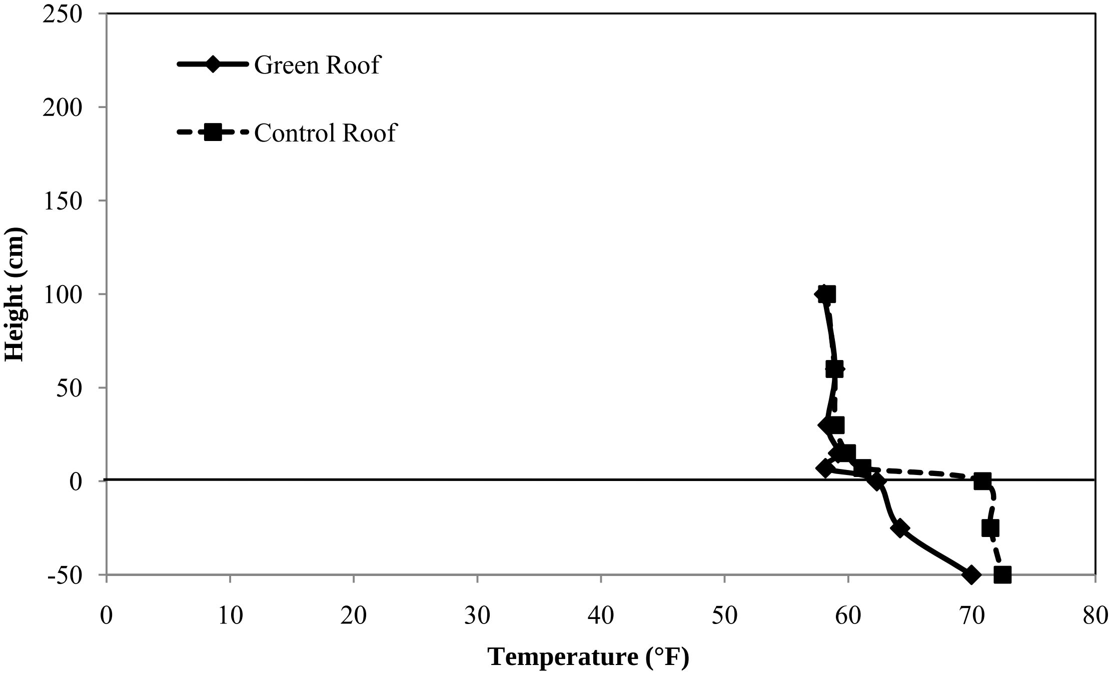


(a) Day-time temperature profile

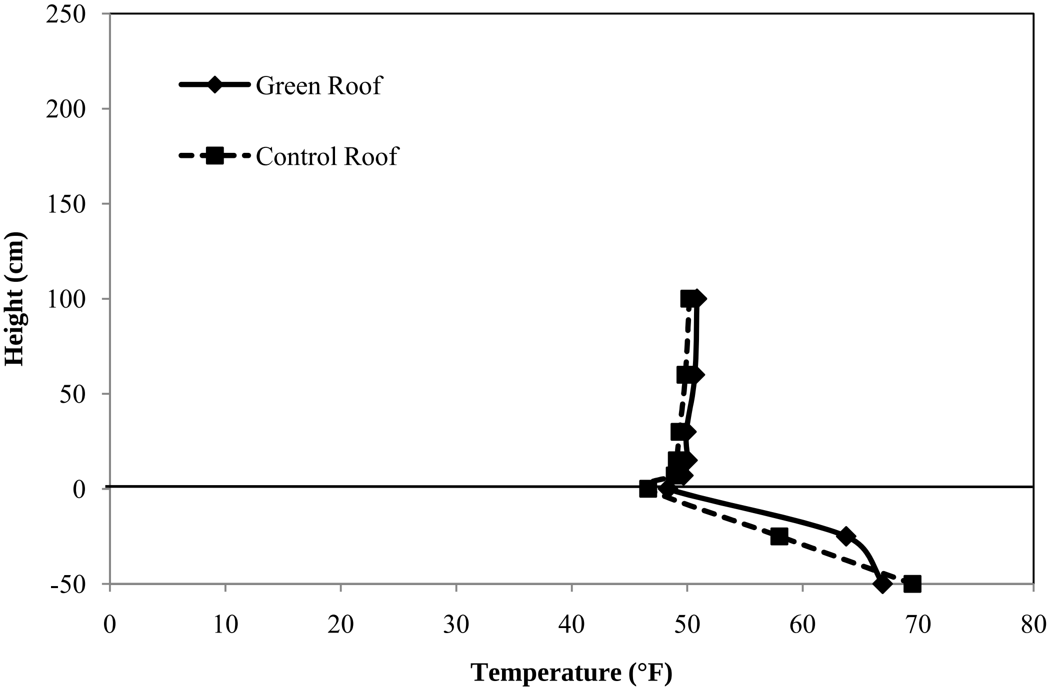


(b) Night-time temperature profile

Figure II-24 March, 2009 temperature profile at Giant Eagle



(a) Day-time temperature profile



(a) Night-time temperature profile

Figure II-25 March, 2009 temperature profile at Giant Eagle

Additional Giant Eagle temperature profiles, from June 2007 to December 2007:

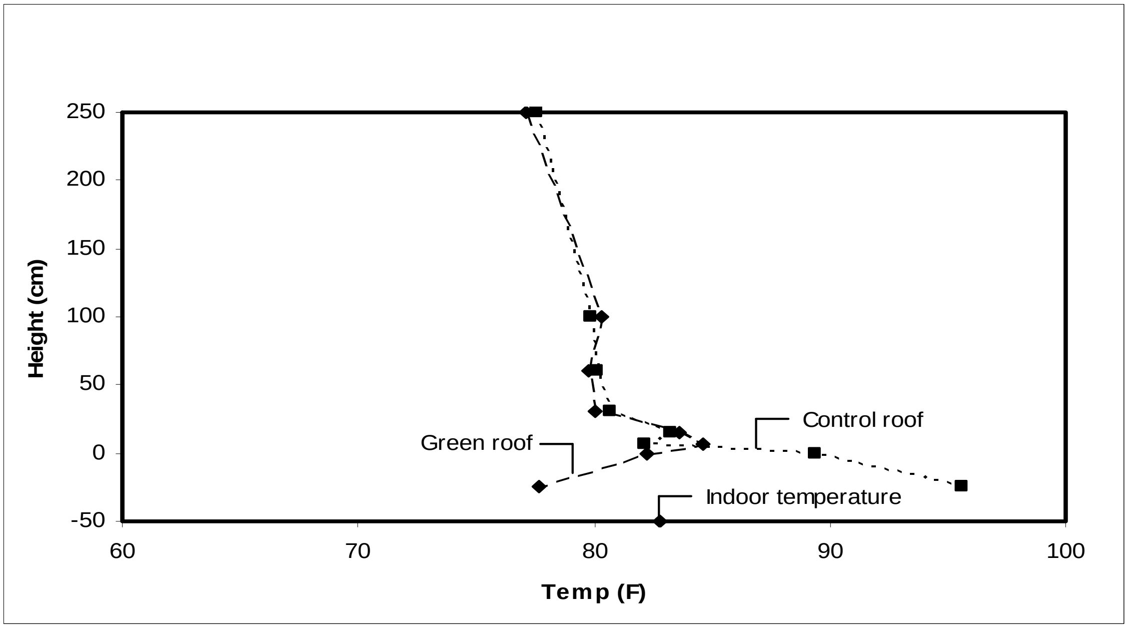


Figure II-26 June, 2007 temperature profile at Giant Eagle

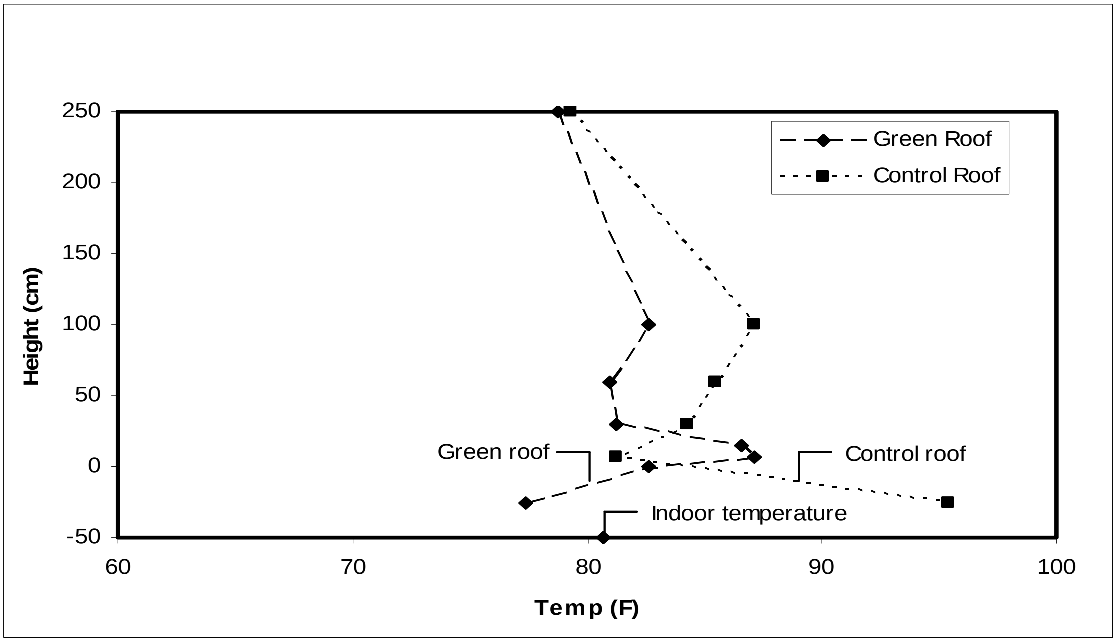


Figure II-27 July, 2007 temperature profile at Giant Eagle

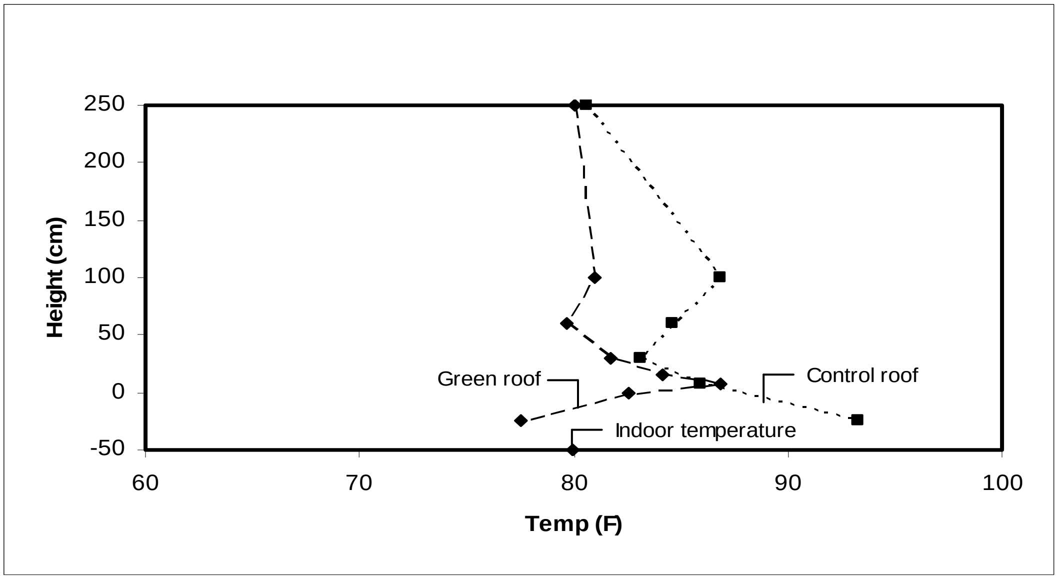


Figure II-28 August, 2007 temperature profile at Giant Eagle

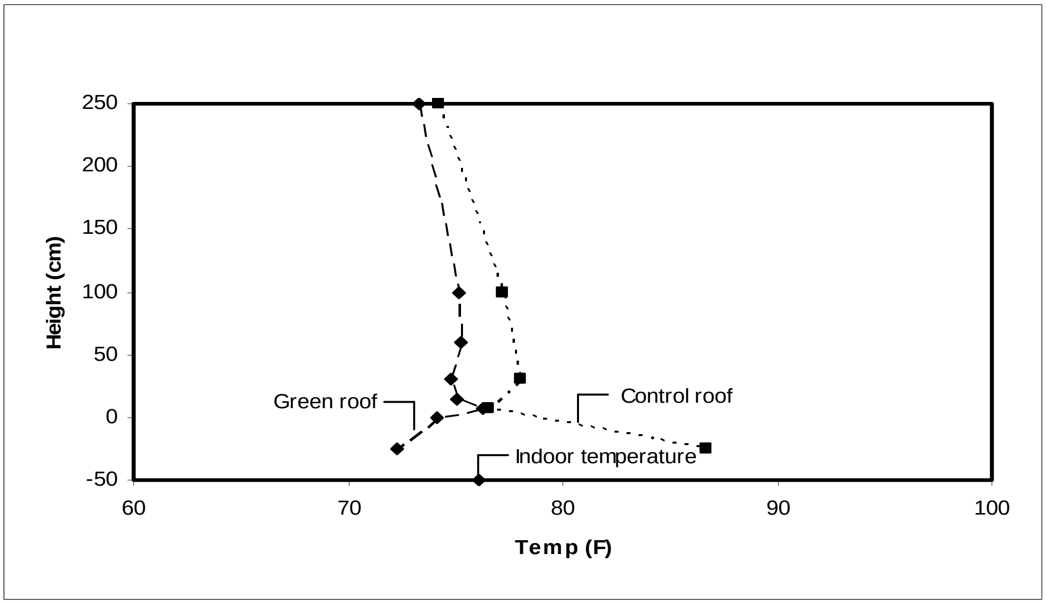


Figure II-29 September, 2007 temperature profile at Giant Eagle

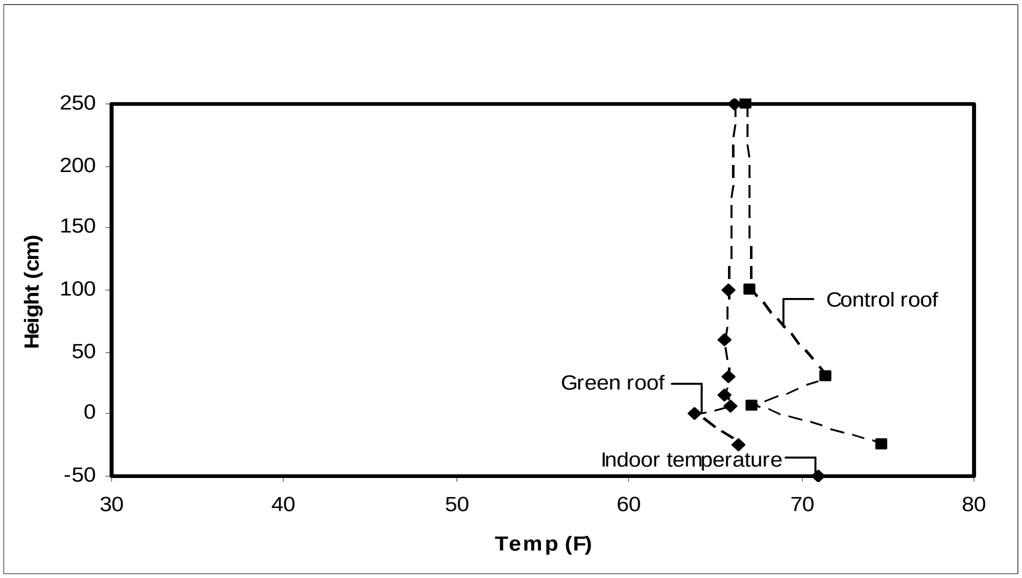


Figure II-30 October, 2007 temperature profile at Giant Eagle

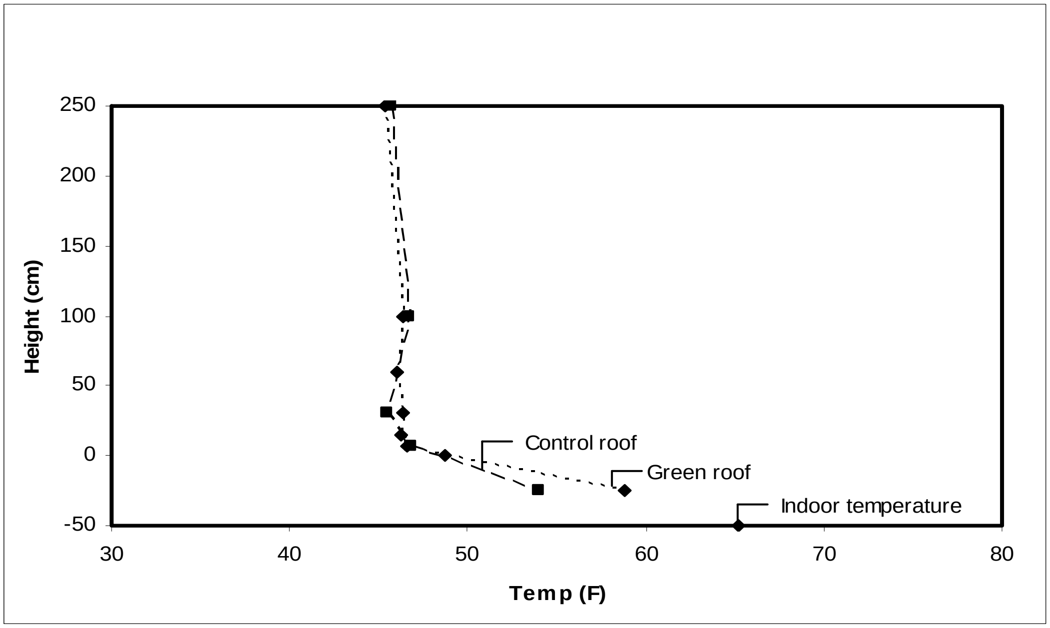


Figure II-31 November, 2007 temperature profile at Giant Eagle

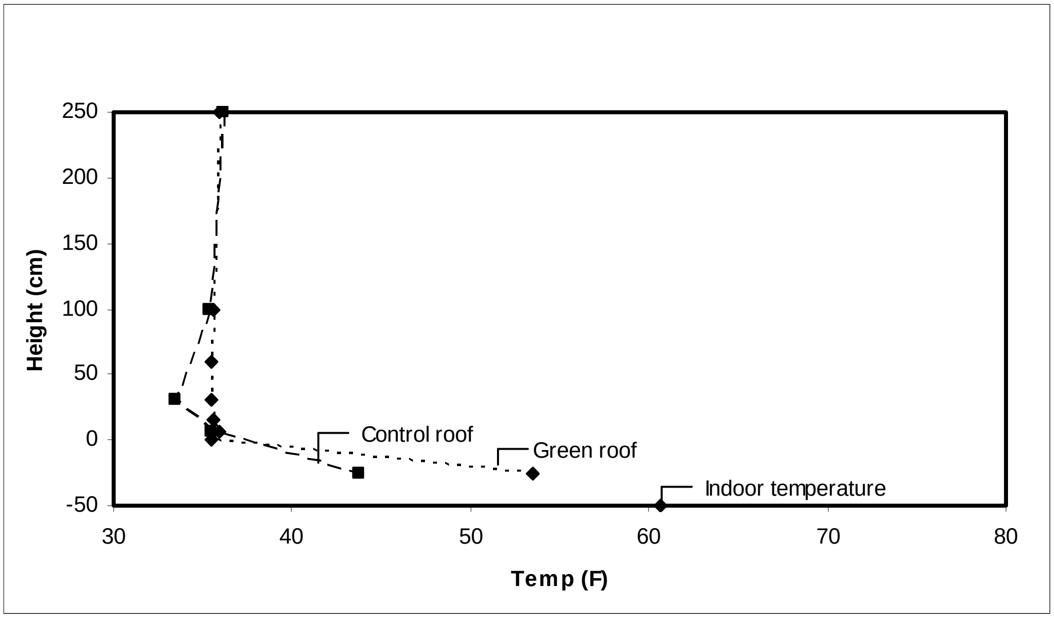


Figure II-32 December, 2007 temperature profile at Giant Eagle