GREEN ROOF STUDY: STORMWATER QUANTITY, QUALITY AND THERMAL PERFORMANCE

by

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GREEN ROOF STUDY: EFFECTS OF STORMWATER QUANTITY, QUALITY AND THERMAL IMPACT

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This thesis presents the use of green roofs compared to conventional (control) roofs using modern construction methods. The green roof is aesthetically and environmentally superior to the control roof, which improves the city landscape and reduces the burden to environment. Two green roofs involved in the study are located at Shadyside of Pittsburgh and Homestead, PA, respectively. Additionally, a control roof is established and monitored next to each of the green roofs. The green roof study primarily focused on stormwater runoff (quantity and quality) and thermal performance. The results demonstrated that green roofs, on the contrary to the conventional roofs, retain significantly more water, attenuate temperature fluctuations for a roof membrane, and attenuate environmental contaminants to the discharged runoff. Two different technologies of green roofs were analyzed. Soil medium thickness and soil moisture content are controlling variables.

Several benefits of the green roof in comparison to the control roof were observed. Data acquired during the 95 storms at the two study locations revealed that green roofs delayed the time for runoff from the roof to begin as well as when the peak flow occurred and greatly reduced the hourly flow rate and total runoff volume in comparison to the control roofs. The delay time for runoff onset from a green roof ranged from minutes to hours, and depends on the soil moisture content prior to the storm. Temperature profiles suggest that a green roof provides better insulation and decreased temperature variations for all parts of the roof, particularly the waterproofing membrane, during warm weather. The soil medium over the green roof is able to neutralize the acidic rainfall and retain pollutant solids, preventing the unfiltered rainfall from directly discharging to the sewage system.

KEY WORDS: green roof, vegetated roof, combined sewer overflow technology, CSO, rainfall runoff, water retention, thermal performance, green infrastructure, runoff pollution mitigation.

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1.0 INTRODUCTION

With the development of urban area, the buildings, highways and many infrastructures create a large amount of city's impervious surfaces, which are largely made of concrete, asphalt and gravel. In the United State, it is estimated that 10% of residential developments and 71% to 95% of industrial areas and shopping centers are covered with impervious surfaces (Ferguson, 1998).

These impervious surfaces contribute to two key problems – the urban heat island effect and urban storm water runoff – and both effect the consumption of energy and water as well as the demand of energy and water system (FEMP, 2006). In another aspect, during the period of heavy rainfall, the combined sewer systems in many old cities may cause overflow occasionally and discharge excess wastewater directly to nearby streams, rivers, or other water bodies, which is called combined sewer overflows (CSO).

Because of their many energy-saving and environmental benefits, green roofs are a promising technology for energy-efficient buildings. In a green roof, a layer of vegetation covers the surface of a roof to provide shade, cool indoor and outdoor temperatures, stormwater management, and more. The main components of green roof are waterproofing, soil, and plants (FEMP, 2006). The soil and plants upon the green roof are able to mitigate the stormwater runoff, preventing the stormwater directly discharging to the sewer system without any filtration. In the case of thermal performance, the measureable direct benefits of green roofs are lower roof temperatures and reduced heat transfer through the roof deck.

The city of Pittsburgh is facing the problem of combined sewer overflows. The system in Pittsburgh is decades old, deteriorated and undersized for the current wet weather stormwater runoff. While adequate during dry weather, very little stormwater runoff is needed to cause an overflow event. The average depth of rainfall for a storm in Pittsburgh is approximately one-quarter of an inch, yet only one-tenth of an inch of rain can cause overflows of the combined sewer system. Raw sewage is frequently deposited into the city's three rivers as a result of rain events (Bliss, 2007).

1.1 STUDY OBJECTIVES

Two green roofs were constructed in Pittsburgh and Homestead, Pennsylvania, respectively. The former one is located on the top of the Giant Eagle supermarket at Shadyside area of Pittsburgh, and the latter is located on the roof of a 3-story residential building at Homestead. The two locations are not far away from each other, which have a distance of approximately 4 miles.

This study is not only to demonstrate the benefits of green roof, but also to compare the features in the aspect of green roofs with different soil medium thickness. The comparison concerns about the runoff quantity, quality and temperature performance. Some of the data, including the stormwater runoff and temperature, will be referred from previous study results at Shadyside, which were described in Bliss (2007) and Kosareo (2007).

Additionally, to compare and prove the superiority of the green roofs, two conventional (control) roofs were established next to their respective green roofs on both sites. Monitoring systems are instrumented on both green and control roofs at two locations, respectively. The devices installed on the sites are used to quantify the stormwater runoff and temperature change.

The following sections would discuss the typical characteristics of green roof, as well as demonstrate the experimental procedures and results from the data recorded. In the end of this thesis, some conclusive points are able to be drawn from the demonstration and comparison of green and control roofs, and two different green roofs as well.

2.0 BACKGROUND ON GREEN ROOF TECHNOLOGY

The importance of implementing green roof systems in urban area is becoming recognized worldwide. Initially inspired by the sod roofs seen in rural Iceland over several centuries, green roofs have been adopted by municipalities as a pragmatic means of improving environmental impacts in a way of stormwater management and energy-saving effect.

Composed of a drainage layer, a solid matrix “soil” layer, and vegetation, green roofs reduce the thermal gain directly beneath the roof (Lazzarin 2005) and improve the water balance between evaportranspiration and runoff (Villarreal 2004). As a result, green roofs act as buffering between rainfall and sewage pipes, and insulation between the solar radiation and interior building spaces as well. In addition, the plants on the green roofs reduce the greenhouse gas emissions in the surrounding air by the process of photosynthesis.

The ecosystem created by a green roof’s interacting components mimics several key properties of ground-level vegetation that are absent from a conventional roof. Green roofs, like other constructed ecosystems (e.g., sewage treatment wetlands, bioswales for stormwater management, or living walls), mimic natural ecosystems to provide ecosystem services (Oberndorfer et al. 2007). Furthermore, compared to these stormwater treatment facilities, green roofs are more economical in themselves that they do not construct on the ground surface area and, therefore, are effective in reducing urban congestion.

2.1 HISTORY OF GREEN ROOFS

Roof gardens, the precursors of contemporary green roofs, have ancient roots. The earliest documented roof gardens were the hanging gardens of Semiramis in what is now Syria, considered one of the seven wonders of the ancient world (Oberndorfer et al. 2007). In the 1600s to 1800s, Norwegians covered roofs with soil for insulation and then planted grasses and other species for stability. Early American settlers of the Great Plains also used this technique in the late 1800s because of a lack of timber (Osmundson 1999).

The modern green roof originated at the turn of the 20th century in Germany, where vegetation was installed on roofs to mitigate the damaging physical effects of solar radiation on the roof structure. Early roofs were also employed as fire retardant structures (Kohler 2003). In 1880s, Germany experienced rapid industrialization and urbanization. Inexpensive housing was often built with highly flammable tar as the roofing material. A roofer named H. Koch developed a method to reduce the fire hazard by covering the tar with sand and then gravel. Seeds naturally colonized these roofs eventually to form meadows. As of 1980, 50 of these roofs were still intact and still completely waterproof (Kohler and Keeley, 2005).

The Great Depression and World War II led to a general lull in roof greening. However, Britain benefited from the camouflaging capabilities of green roofs by using them to cover military airfield hangars in the form of turf during the 1930s (Firth and Gedge, 2005). Despite the failing economy during the depression, the first prominent US modern green roof was built at the Rockefeller Center in New York City during that time (Osmundson, 1999). Today in the United States, green roofs are becoming less of novelty, although other countries are far more advanced in the adoption of this technology. In Germany, it is estimated that 14% of all flat roofs are green (Kohler and Keeley, 2005).

2.2 TYPES OF GREEN ROOFS

Generally speaking, there are two types of green roof: intensive and extensive, depending on the planting material and the planned usage for the roof area. The intensive green roofs, known for their deep substrates and variety of plantings, have the appearance of conventional ground-level gardens, and they can augment living and recreation space in densely populated urban areas. Extensive green roofs are a modern modification of the roof-garden concept. They typically have shallower substrates, require less maintenance, and are more strictly functional in purpose than intensive living roofs or roof gardens (Oberndorfer et al. 2007). The two green roofs discussed in this thesis are both extensive types, with low-growing vegetation on them.

2.2.1 Intensive green roofs

Intensive green roofs are more complex than extensive types, and they require more maintenance. They feature deeper soil (usually more than 12 inch in depth) and more diverse plants, such as shrubs and trees (FEMP 2006). Figure 1 shows a picture of a typical intensive green roof.

Intensive green roofs can be distinguished from the popular roof garden of container-filled plants by the continuous underlying greenroofing layer system. Ideally, these green roofs have relatively flat roof surfaces (1 - 1.5%) or mild roof slope percentages of up to 3% (Greenroofs .com 2009).

Different growth media types and depths allow for a larger selection of plants, including flowering shrubs and trees. Typical soil depths start at 6 - 8 inches and can reach 15 feet or more - the limiting factors here are the roof loads and perhaps the client's budget. Pathways, terraces, water fountains, ponds, and other architectural features result in beautiful and dramatic spaces. Depending on the plant selection, additional water collection cisterns, reservoir boards, irrigation, fertilization and/or maintenance may be necessary, just as it would be for a traditional garden (Greenroofs.com 2009).

Intensive green roofs typically require substantial investments in plant care. Furthermore, they emphasize the active use of space and carry higher aesthetic expectations than “extensive” green roofs, which generally have shallower soil and low-growing ground cover (Oberndorfer et al. 2007). Usually, the intensive green roofs are more expensive and require high-level maintenance.

Figure 1. An intensive green roof on the top of Waldspirale, a residential building complex in Darmstadt, Germany (image by flickr user Bockstark Knits)

2.2.2 Extensive green roofs

Extensive green roofs are a modern modification of the roof-garden concept. They typically have shallower substrates, require less maintenance, and are more strictly functional in purpose than intensive living roofs or roof gardens (Dunnett and Kingsbury 2004). A picture of typical extensive green roof is exhibited in Figure 2.

Generally, extensive green roofs can be constructed on roofs with slopes up to 33%, and can be retrofitted onto existing structures with little, or most often, no additional structural support. The average weight of a fully saturated minimum extensive green roof is 17 pounds per square foot, which is comparable to the weight of gravel ballast placed on many conventional roofs. These roofs are not intended for recreation, or to accommodate the weights of people, larger shrubs nor trees. Extensive green roofs are less costly due to single or double layer construction (Greenroof.com 2009).

The extensive green roofs contain shallow soil and low-growing, horizontally spreading plants. These plants are primary succulents that can thrive in the somewhat alpine conditions of many rooftops. In other words, there is not much water or soil, but the roof does experience a significant amount of exposure to the sun and wind (FEMP 2006).

Contrary to the intensive type, the extensive green roofs are less complex and more environmentally effective. The two green roofs being described in this thesis are both extensive types. Table 1 shows a series of comparative features of intensive and extensive green roofs.

Figure 2. Typical extensive green roof (Soka-Bau green roof case study 2009)

Table 1. A comparison of extensive and intensive green roofs (Oberndorfer et al. 2007)

Characteristics	Extensive roof	Intensive roof
Purpose	Functional; storm-water management, thermal insulation, fireproofing	Functional and aesthetic; increased living space
Structural requirements	Typically within standard roof weight-bearing parameters; additional 70 to 170kg per m^2 (Dunnett and Kingsbury 2004)	Planning required in designing phase or structural improvements necessary; additional 290 to 970 kg per m^2
Substrate type	Lightweight; high porosity, low organic matter	Lightweight to heavy; high porosity, low organic matter
Average substrate depth	2 to 20 cm	20 or more cm
Plant communities	Low-growing communities of plants and mosses selected for stress-tolerance	No restriction other than those imposed by substrate depth, climate, building height and exposure, and irrigation facilities
Irrigation maintenance	Most require little or no irrigation Little or no maintenance required; some weeding or mowing as necessary	Often require irrigation Same maintenance requirements as similar garden at ground level
Cost (above waterproofing membrane)	\$10 to \$30 per ft^2	\$20 or more per ft^2
Accessibility	Generally functional rather than accessible; will need basic accessibility for maintenance	Typically accessible; bylaw consideration

2.3 COMPONENTS OF GREEN ROOFS

The green roof is a green space created by adding layers of growing medium and plants on top of a traditional roofing system. In very simple term, to achieve this all green roofs are composed of at least two layers: the vegetation itself and the media or substrate within which the plants are growing. In addition most commercial green roof system will also have a drainage layer, and in all cases there must be a mechanism by which the building below is protected from the twin damage from plant roots and leaking of water from the above (Dunnett and Kingsbury 2004). The construction of green roof, supplied by the manufacturers, may have different approaches or procedures. The green roof systems for construction may vary, depending on the manufacturers' choice and structural roof condition. Although with different options on green roof systems, the main components of green roofs consist of four layers: growing medium, drainage and filter, root protection barrier, and waterproofing membrane. Figure 3 illustrates a typical cross section of a green roof containing these major layers.

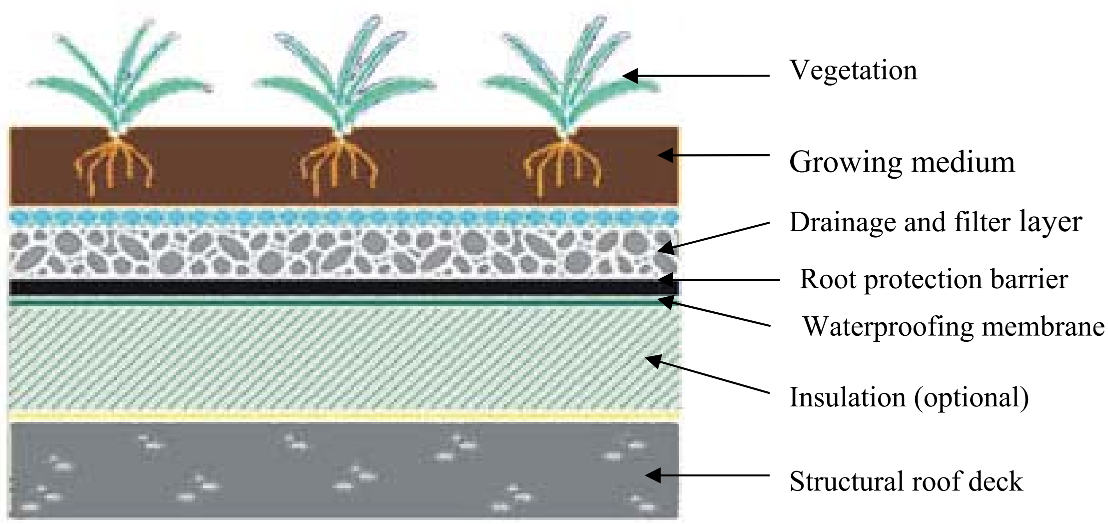

Figure 3. Cross section of a typical green roof (image from greenroofs.com)

2.3.1 Growing medium or substrate

The ideal substrate has to achieve the seemingly miraculous combination of being highly efficient at absorbing and retaining water while at the same time having free-draining properties. It should also be able to absorb and supply nutrients and retain its volume over time, as well as provide anchorage for the plants of the green roof. This is generally achieved by granular mineral materials that absorb water and create pore space, mixed with fine articles (in relatively small proportion) to which water will cling (Miller 2003). In addition, unless the roof is of the intensive type, the substrate must be lightweight so that the weight imposed on the roof is kept to a minimum. German research indicates that the ideal growing medium will comprise 30-40 percent substrate and 60-70 percent pore space. This will ensure good moisture retention capacity as well as aeration to the roots of the plants. If the pore space is saturated on a long-term basis, that is, continuously less than 15 percent of the substrate containing air-filled pore space, then poor plant growth will result (Hitchmough 1994).

General garden soil or topsoil is not suitable for non-intensive green roofs because it is both too heavy and too fertile. High fertility is not desirable because it encourages vigorous lush growth that is susceptible to environmental stress, whether this be from extreme cold or drought. Medium to low fertility is to prevent dominance by vigorous aggressive species (Dunnett and Kingsbury 2004).

For plants growth artificial soils can be superior to many natural soils provided they are tailored for the specific type of vegetation they are to support. Examples of natural mineral materials include sand and lava (Hithmough 1994).

The composition and character of green-roof vegetation depend on many factors. To a large extent, substrate depth dictates vegetation diversity and the range of possible species.

Shallow substrate depths between 2 and 5 cm have more rapid rates of desiccation and are more subject to fluctuations in temperature, but can support simple sedum-moss communities. Substrate depths of 7 to 15 cm can support more diverse mixtures of grasses, geophytes, alpines, and drought-tolerant herbaceous perennials, but are also more hospitable for undesirable weeds (Oberndorfer et al. 2007).

2.3.2 Drainage and filter layer

Maintaining proper drainage on a green roof is extremely important for several reasons. First is the protection of the waterproof membrane. If drainage is inadequate on a flat green roof, then damage to the roof membrane may ensue because of continuous contact with water or wet soil. Because green roof vegetation, particularly of the extensive type, is selected to be drought-resistant and tolerant of dry, free-draining soils, prolonged saturation of the soil is likely to cause plant failure, rotting, and sour, anaerobic conditions. A permanently wet green roof also will lose its thermal insulation properties.

Green roofs turn our normal interpretation of rainfall runoff on its head. The water that escapes a green roof is actually underflow, or percolated water. Surface runoff should not occur at all on a well-designed green roof (Miller 2003). The function of the drainage layer is to remove excess water or underflow as rapidly as possible to prevent over-long saturation. The drainage layer in some instances may also double up as a means of introducing irrigation. In some case the drainage layer may also provide the means of irrigating the green roof and providing additional nutrients or fertilizer (Dunnett and Kingsbury 2004).

The filter layer separates the drainage and substrate layer. Its primary role of the filter layer is to hold the engineered soil in place and still prevent small media particles, such as plant debris and fines, from entering the clogging the drainage layer below. Air and water are thus permitted to flowing through while the drainage layer and the actual drains are protected. The filter may be made of a geocomposite drain mat or board (Greenroofs.com 2009). It is particularly necessary to install a filter layer when substrate/soil is very fine. However, on roofs at an angle of over 10°, it is not recommended to use a filter layer on the entire roof as it will act as a slip layer. Instead, it should be installed around the roof perimeters/outlets.

2.3.3 Root protection barrier

If the waterproofing membrane on a roof upon which a green roof is be installed contains bitumen, asphalt, or any other organic material, it is crucial that a continuous separation is maintained between the waterproofing membrane and the plant layer because the membrane will be susceptible to root penetration and the activity of micro-organisms ─ these organic oil-based materials are not rot proof. If the roof is not completely flat, then any pockets of collecting water can also form the basis of plant growth on a roof ─ again there must be protection from root damage (Dunnett and Kingsbury 2004).

Root protection membranes are usually composed of rolls of PVC (varying in thickness from 0.8 mm [0.03 in] to more than 1.0 mm [0.04 in] in thickness) and laid out over the weatherproofed roof deck or surface (Dunnett and Kingsbury 2004).

The membrane must be raised up beyond the surface of the planting medium at the edges and around all projections such as chimneys and vents. The membrane sheets are welded together to form a complete seal ─ it is essential that the welding is effective because any gaps or weaknesses will be exploited by the plant roots (Dunnett and Kingsbury 2004).

2.3.4 Waterproofing membrane

An effective waterproofing membrane to the roof is an essential prerequisite for all green roofs and it is laid directly on the roof decking. There are three main types of membrane: the built-up, the single-ply membrane, and the fluid-applied membrane (Osmundson 1999).

The membrane should be a minimum 80 mil or greater in thickness for best durability and performance. The waterproofing membrane must also be impenetrable by roots and resist the growth of algae and other organisms. Leak detection systems can often be installed to make any leakage easy to detect and locate. The waterproofing layer used upon the roof should at least have slope of 1.5%, in order to ensure the drainage capacity (Greenroof.com 2009).

2.4 BENEFITS OF GREEN ROOFS

Green roofs are considered to be a form of low-impact development, and they are becoming more accepted as sustainable planning and design practices. Today, green roofs technology is anchored in the U.S. Green Building Council's Leadership in Energy & Environmental Design (LEED) building rating system because of the ways that green roofs help to minimize the environmental footprint of buildings and mitigate the impacts of urban runoff and urban heat islands (FEMP 2006).

Therefore, green roofs are important to consider in designing a sustainable facility. The following sections provide more detailed information for the benefits of green roofs, which contribute to several key aspects: stormwater management, thermal impact and quality of stormwater runoff. All of them have the effect on the energy and water system, which are essential to urban and environmental development.

2.4.1 Stormwater management

Because an impervious surface cannot absorb precipitation this water flows off surfaces and reduces infiltration into groundwater. In forest, 95% of rainfall is absorbed, whereas only about 25% is absorbed in cities (Scholz-Barth, 2001). Excessive volume of stormwater can overwhelm municipal sewer system. When stormwater exceeds capacity, the combined sewage can overflow into relief points, resulting into raw waster being dumped into our rivers. Thus, a combined sewage overflow (CSO) will occur. In New York City, CSO events dump 40 billion gallons of untreated waters annually (Cheney, 2005).

Green roofs are ideal for urban stormwater management because they make use of existing roof space and prevent runoff before it leaves the lot. Green roofs store water during rainfall events, delaying runoff until after peak rainfall and returning precipitation to the atmosphere through evapotranspiration (Mentens 2005, Moran et al. 2005).

Depending on the intensity of rainfall, the growing season, and the soil moisture content at the site, an extensive green roof can eliminate runoff from a building and reduce the peak flow rate and volume of the sewer system. For example, a layer of soil 3 to 4 inches deep in an extensive green roof can absorb about 1 inch of water. Green roofs are estimated to absorb, filter, retain, and store an average of about 75 percent of the annual precipitation that fall on them. This applies to most areas in the United States (FEMP 2006). Green roofs may reduce runoff by 60% to 100%, depending on the type of green roof system. Water retention depends on design factors such as substrate depth, composition, and plant species, as well as weather factors such as intensity and duration of rainfall (Getter and Rowe 2006). A green roof study at North Carolina indicated that green roof retained approximately the first 15 mm (0.6 in.) of rainfall and an average of 62%-63% of the total recorded rainfall were retained by the green roof. Average peak flow reduction from the green roof is 83% (Moran et al. 2004). Liu (2002) reported that the green roof delayed runoff by 45 minutes and absorbed at least 2 mm (0.1 in.) of it before runoff occurred. It reduced the runoff rate by 75% during the first event and retained 45 percent of the rain with a relatively moist growing medium.

Because green roofs retain stormwater, they can mitigate the effects of impervious surface runoff. For example, if 6% of the roof surface were green, Peck (2005) estimated that the impact on stormwater retention would be equal to building a $60 million (CAD) storage tunnel. Deutsch and colleagues (2005) calculated that if 20% of all buildings in Washington, D.C., that could support a green roof had one, that they would add more than 71 million L to the city's stormwater storage capacity and store 958 million L of rainwater in an average year (Getter and Rowe 2006).

2.4.2 Thermal impact

Green roofs represent a unique, unconventional approach to increasing the energy performance of buildings through shading, insulation, evapotranspiration, and thermal mass (FEMP 2006), resulting in energy savings and mitigation of the urban heat island effect (Getter and Rowe 2006).

Many impervious surfaces tend to be heat-absorbing structures. The albedo of a surface is a measure of the incoming solar radiation that is reflected off the surface and thus is not absorbed and transformed into heat energy. The albedo of urban surfaces is generally 10% lower than the albedo of rural surfaces (Oliver 1973). Green roofs have a high albedo (ranging, from 0.7-0.85), depending on water availability (Gaffin 2005). Other cool-roof technologies, such as white roofs, may start with an albedo of 0.8, but reflectivity can decline up to 11% from dust and debris accumulation. Conventional roof surfaces have much lower albedo, ranging from 0.05 to 0.25 (USEPA 2005). The effect of urban heat island can be reduced by increasing albedo or by increasing vegetation cover with sufficient soil moisture for evaportranspiration. A regional simulation model using 50% green-roof coverage distributed evenly throughout Toronto showed temperature reductions as great as 2°C in some areas (Bass 2002).

Media depth, shade from plant material, and transpiration can reduce solar energy gain by up to 90% compared with nonshaded buildings. Green roofs have reduced indoor temperature 3°C to 4°C (37°F to 39°F) when outdoor temperatures were between 25°C and 30°C (77°F to 86°F) (Peck 1999). Every decrease in internal building air temperature of 0.5°C (33°F) may reduce electricity use for air-conditioning up to 8% (Dunnett and Kingsbury 2004).

The growing medium and plants on the green roofs act as a thermal mass, which effectively damped the thermal fluctuations going through the roofing system. A green roof study in Ottawa, Canada indicated that the average daily energy demand for space conditioning of the reference roof was 6.0-7.5 kWh (20,500-25,600 BTU), whereas the green roof reduced the energy demand to less than ─ a reduction of more than 75 percent (Liu 2002).

The reduction in energy consumption for space cooling is a significant factor in reducing life cycle environmental impacts of the residential building. Research showed that a green roof is estimated to reduce annual energy consumption by over 1%, with 16% of the building's exposed surface area covered with green plants. Also, greater energy reduction would be achieved with a larger roof-to-envelope ratio, such as with a low-rise building (Saiz et al 2006).

Most energy savings from green roof will occur during the summer months. This is because the insulation properties of the substrate are greater when air space exists in the pores as opposed to when they are saturated, which is normally the case during winter. However, if energy saving were the only reason for installing a green roof, it would be much less expensive to install additional insulation when constructing the building rather than installing a green roof (Getter and Rowe 2006).

2.4.3 Quality of stromwater runoff

Green roofs can affect runoff quality in a number of ways. Because any runoff is filtered through the media and the plants there is potential for both cleansing and contamination. The media and plants act as a particle trap for dust and airborne particulates removing them from the runoff when it rains. The media also acts as a cation exchange filter for charged ions (nutrients and metals) in the rain water. What this means is that if there is a high concentration of an ion in the rain the roof can retain a portion of the ion lowering the concentration in runoff. On the other hand, if the concentration of an ion in the incoming rain is substantially lower than the concentration in the soil (media) solution and on the media cation exchange, then some of the ion will be removed from the soil (media) exchange and the runoff will have a higher concentration of the ion than the rain. But if the concentration of a nutrient ion in the runoff is the same or is greater from a green than from a non-green roof, the total amount of that nutrient released to the environment may be substantially less from a green roof because the total quantity of the runoff is reduced (Berghage et al. 2009).

Nitrogen and phosphorus stemming from atmospheric deposition become fixed in the soil and serve as plant fertilizer. Sediments are trapped as water slowly percolates through the soil medium. Green roofs reduce this non-point-source pollution, and any runoffs thus cooler and cleaner than it would be if it came from conventional roof (FEMP 2006). However, some research demonstrates that green-roof runoff includes increased levels of nitrogen and phosphorus due to leaching from the substrate (Dunnett and Kingsbury 2004, Moran et al. 2005). Research on more inert substrates, and on integrated gray-water reuse systems, may lead to mitigation of the effect. Reducing the fertilization of green roof vegetation should also improve runoff water quality but may reduce plant growth or survival. Selecting plants that optimize the uptake of nutrients and contaminants may help to reduce pollutants in runoff while promoting plant survival.

3.0 GREEN ROOF CASE STUDY – CHICAGO CITY HALL ROOFTOP GARDEN RETROFIT

The city of Chicago is one five U.S. cities selected by the EPA to participate in the Urban Heat Island Pilot Project. The goal of the pilot study is to measure elevated ambient air temperatures in a metropolitan area and study the benefits of cooling urban heat islands to improve air quality. Figure 4 shows two pictures of the green roof on the top of the Chicago City Hall (FEMP 2006).

The Chicago city hall shares a 12-story building in downtown Chicago with Cook Country's administrative offices. The city hall roof measures about 38,800 square feet and a semi-extensive green roof was constructed atop the city hall with 22,000 square feet of the total and consists of 156 plant varieties. The soil layer of the Chicago City Hall green roof was designed to have a variety of depths, ranging from 3- to 4-inch layers to semi-intensive layers of about 8 to 10 inches. Two small intensive areas contain one tree each (FEMP 2006).

Data loggers were used to monitor ambient air temperature over City Hall's green roof and over the adjacent Cook County Building's black tar roof. In August 2001, the temperature of ambient air over the County Building's black tar measured 114°F (45.5°C), and the temperature over City Hall's green roof measured 107°F (41.6°C). The air over the green roof was thus cooler by 7°F (3.9°C) than that over the black tar roof (FEMP 2006).

The roof temperatures shown below were taken with an infrared thermometer on August 9, 2001 (FEMP 2006).

City Hall green roof paved surfaces: 126°F - 130°F (52.2°C – 54.5°C)

City Hall green roof surface: 91°F - 119°F (32.7°C – 48.3°C)

County Building black tar roof: 169°F (76°C)

The average temperature difference between the city’s and country’s roof surfaces was thus found to be 64°F (35.5°C). This indicates the potential of green roofs to efficiently lower ambient air temperature (FEMP 2006). Additionally, the projected avoided energy cost is $3,600 per year. The total direct savings are estimated to be 9,272 kWhr per year and the corresponding savings in natural gas for heating are 7,372 therms per year (cityofchicago.org 2009).

(a) An overview of the green roof on the Chicago City Hall

(b) Plants upon the Chicago City Hall's green roof

Figure 4. Pictures of the green roof on the Chicago City Hall (images by www.cityofchicago.org)

4.0 GREEN ROOF STUDY IN PITTSBURGH AREA

The Allegheny County is facing the problem of the untreated sewage and stormwater overflowing into the region's waterways, which the solution is complicated to be derived and may need a series of study and research. The 3 Rivers Wet Weather Demonstration Program (3RWWDP) is committed to providing the cost-effective and sustainable methods to improve the quality of Allegheny County's water resources (3RWW “Mission statement” 2009).

3 Rivers Wet Weather (3RWW) has begun funding Stormwater Best Management Practice (BMP) demonstration projects, focusing on lot-level or Low-Impact Development (LID) projects. LID is a highly effective strategy for controlling urban stormwater runoff. The primary goals for the LID is, firstly, to reduce runoff volume through infiltration, retention, and evaporation; secondly, to find beneficial uses for water rather than exporting it as a waste product down storm sewers (3RWW “Green roof demonstration project” 2009)

The green roof demonstration project granted by 3RWW is primarily aimed at the issue of stormwater management. As a result, some green roof projects were awarded grants to study the benefits of green roofs and its future perspective. The green roof projects at Shadyside Giant Eagle and Homestead are two of them, which are to study the green roof in the case of stormwater runoff and thermal behavior. As for the green roof project at Shadyside Giant Eagle, the stormwater runoff performance has been compiled by Bliss (2007) in his thesis and Kosareo (2007) has described the thermal behavior of the green roof in her thesis as well.

This thesis continues the study on the green roof at Shadyside Giant Eagle. Meanwhile, a green roof at Homestead was added to further investigate the features of the green roof. The results of this further study not only compared the green roofs with control (conventional) roofs in their runoff and thermal aspect, as well as two green roofs with different soil medium thickness at two locations.

4.1 SITES DESCRIPTION

4.1.1 Shadyside Giant Eagle site

The Shadyside Giant Eagle supermarket is located on the east side of Pittsburgh. In addition, a two-story parking garage was built beneath the structure and seventy-eight condos occupy five-stories built above the rear of the supermarket (Bliss 2007).

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). 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 (Bliss 2007).

Figure 5 is the overall layout of Giant Eagle roof, including the placement of monitoring stations, rain gauge and dataloggers. Total four tripods for the monitoring the temperature were located at both green and control roof, two tripods for each roof. As seen in Figure 5, two tripods at location A and B are for green roof, while the other two tripods for control roof are located at

C and D. 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 6 and Figure 7 are site overviews of the green and control roof, respectively. One of the tripods located at green roof is shown in Figure 8, and Figure 9 is one of the tripods located at control roof. In addition, two flumes (Figure 10) were disposed outside the building and used for runoff drainage from the green and control roof. Two separate rooftop drains drain similar 3,530 square foot drainage areas of the control roof and green roof, which are directly connected to the flumes.

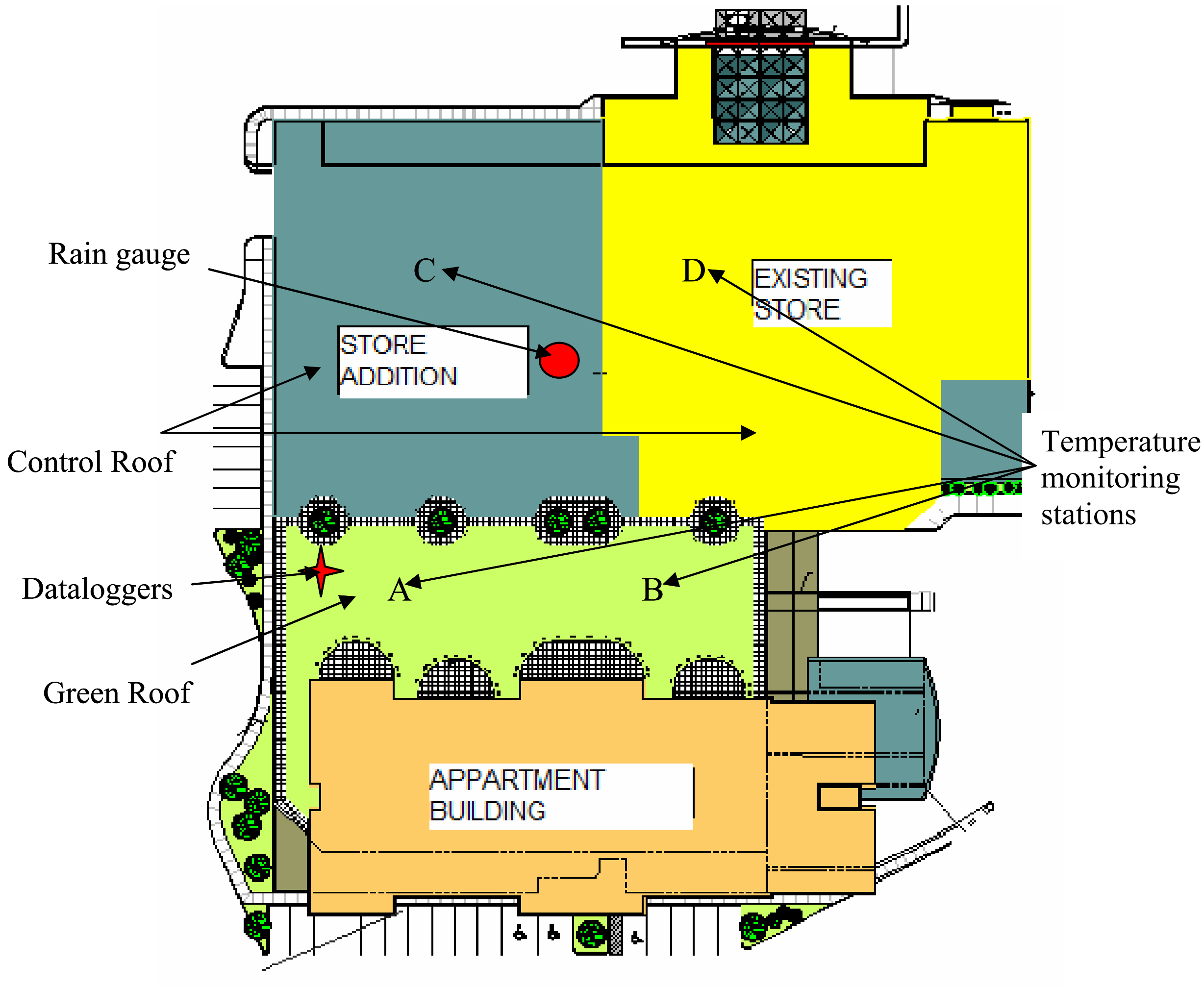

Figure 5. Layout of Giant Eagle roof and monitoring locations

Figure 6. Green roof on the top of the Shadyside Giant Eagle supermarket

Figure 7. Control roof on the top of the Shadyside Giant Eagle supermarket

Figure 8. One of the Tripods for monitoring temperature at green roof side (Giant Eagle)

Figure 9. One of the Tripods for monitoring temperature at control roof side (Giant Eagle)

Figure 10. Flumes for runoff drainage at Giant Eagle site

Inside one is for the control roof and outside one is for the green roof

4.1.2 Homestead site

The Homestead green roof is located on a 98-year-old, four-story building in the historic district of Homestead, Pennsylvania, which 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 11. 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 interconncected with 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 12.

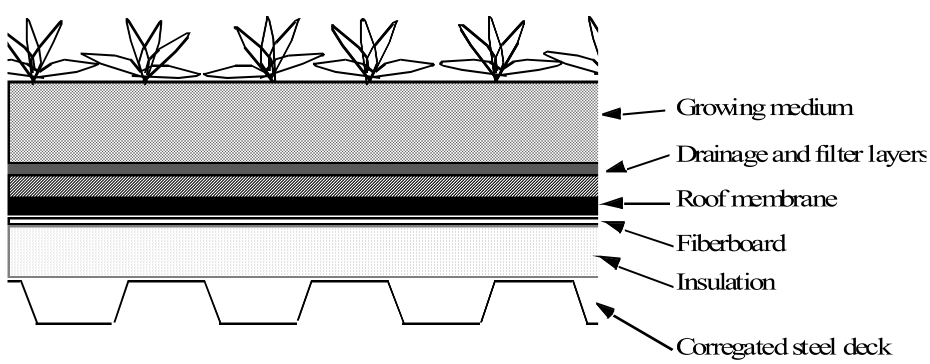

Figure 11. Typical Green Roof Cross-Section (similar to Giant Eagle green roof)

Figure 12. Typical GLT Green Roof system Cross-Section (similar to Homestead)
(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.

The rooftop layout at Homestead site is shown in Figure 13, including the position of monitoring locations. Photographs of green roof and control roof located at Homestead are shown in Figure 14 and Figure 15 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.

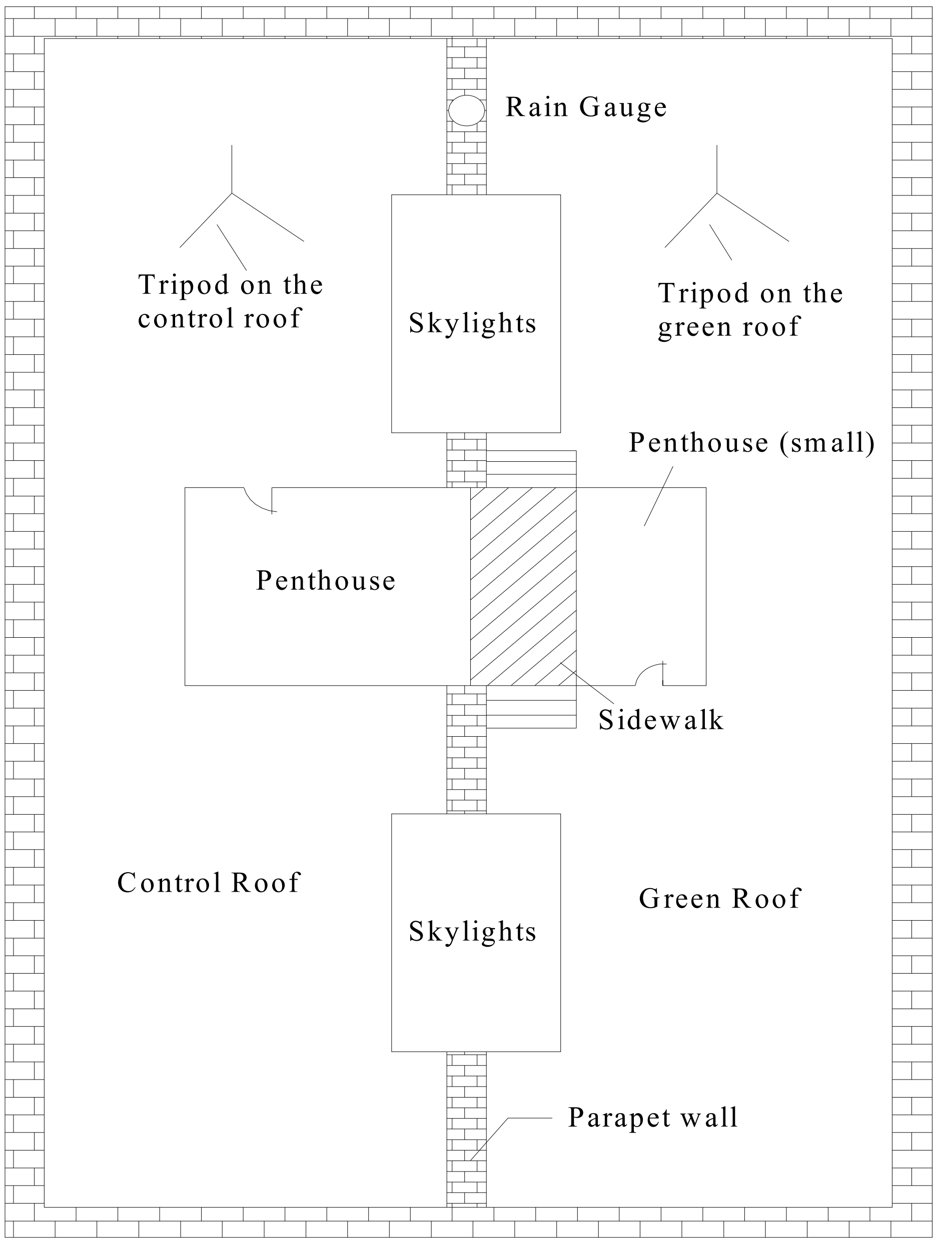

Figure 13. Layout of the rooftop at Homestead site

Figure 14. GLT Green roof at Homestead site

Figure 15. Control roof at Homestead site

Two monitoring locations, one on each roof, were installed for the Homestead roof. There are fewer stations at this site than at the Giant Eagle roofs because both the Homestead roofs, at 2000 sq. ft., are considerably smaller. For runoff monitoring, two separate drains conducted all the runoff from the two roofs to the basement (Figure 16). In the basement, two weir boxes (V-notch at thirty degrees angle) were installed to receive the runoff.

Figure 16. Drainage system at Homestead Site

Two weir boxes are located at the basement of the building. The one next to the wall is used for the green roof and the other one is for the control roof.

4.1.3 Monitoring instruments and technologies

The most frequently used instruments at two sites during the project period are rain gauge, ultrasonic sensor, valves, thermocouples and temperature and relative humidity probe. However, there are some instruments, such as net radiometer, soil moisture sensor and wind direction and speed sensor, are not used any more, due to its malfunction or unavailability. As a result, these unavailable instruments will not be described in the following sections.

4.1.3.1 Rain gauge

The rain gauge is used to determine the amount of rainfall reaching the rooftop. A Hydrologic Services RG703 8 inch Tipping Bucket Rain Gauge (Figure 17) was used to accomplish this. A siphon mechanism allows the gauge to measure all rainfall intensities. After each one hundredth of an inch of rain falls, the bucket tips (Figure 18) and sends a reading to the datalogging system, which will be discussed in detail later. The rain gauge not only takes a measurement on the rainfall volume that falls on the roof, but also rate of rainfall. The rainfall data was used to calculate both the total volume of water that reaches the roof and the rate. Along with runoff data, this will show the affect the green roof has on reducing runoff. Similarly, the rainfall rate will show the delay in runoff accumulation from each roof (Bliss 2007). The types of rain gauges used for Giant Eagle and Homestead site are identical.

Figure 17. Rain gauge installed on the roof

Figure 18. Tipping bucket (silver) inside the rain gauge

4.1.3.2 Ultrasonic sensor

To measure the runoff created by each roof, the Greyline Instruments LIT25 (Level Indicating Transmitter) Ultrasonic sensors. These sensors send a sound wave into the flume, which then bounces back. The time that the wave takes to return allows the equipment to measure the depth of water in the flume at that point. From the depth of water, the flow rate and cumulative volume of runoff are calculated (Bliss 2007). Same types of the ultrasonic sensors were installed at both Giant Eagle and Homestead site. Figure 19 and Figure 20 show the ultrasonic sensors at Giant Eagle and Homestead, respectively, but with different mounting techniques.

Figure 19. Ultrasonic sensors installed at Giant Eagle site

Figure 20. Ultrasonic sensor installed at Homestead site

4.1.3.3 Valves

The valves are used for runoff samples collection system and to control the volume of samples. Solenoid valves are used at both sites, but with different runoff sample collection systems. The valves at Giant Eagle were removed after the first phase of the project, but the valves at Homestead are operational. Runoff samples collected from the Homestead will be compared with the sample results from Bliss (2007). Picture is still available for the sample collection system at Giant Eagle site, as seen in Figure 21, six solenoid valves were attached with the collection pipe for each flume. These solenoid valves are normally closed and are opened when energized. Each of the valves was connected to a 500 mL low density polyethylene sample bottle. The valves are wired to the datalogger located on the roof, which controls when the valves are opened. Each of the six valves is programmed to open at a set value of cumulative runoff. Since runoff can start at different times and flow at different rates on the green and control roofs, this allows the samples to be matched from both roofs. Additionally, the series of valves allows for samples to be taken at six different points during a storm. With samples taken in this manner, the first flush effect can be studied. Less specifically, it lets the changes in water quality throughout the storm be measured. The 500 mL of sample provided enough water to complete the series of water quality tests in the protocol. The valves were programmed to stay open for as short a time as possible to allow the sample bottles to fill while minimizing overflows.

The sample collection system at Homestead has differences to the one at Giant Eagle, as seen in Figure 22. Since only one valve was installed for each trap system, the operation of the valves was simpler than the one at Giant Eagle site; for the Homestead roofs, each valve is programmed to open and close automatically 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. The data obtained from runoff samples collected at Homestead site are presented in section 6.0 .

Figure 21. Solenoid Valves and Sample bottles at Giant Eagle site (Bliss 2007)

Figure 22. Solenoid valves (circled) and sample bottles at Homestead site

4.1.3.4 Thermocouples, temperature and relatively humidity sensors

The temperature measurements were taken with a combination of thermocouple wire (Figure 23), HMP 45C Relative Humidity and Temperature Probes (Figure 24), and Model 107AT Temperature Probes. These sensors will provide a temperature profile vertically throughout the green and conventional roof structures. The thermocouples exposed to the outside environment will need to be shielded from solar radiation. A simple, open-air shelter, protect each above surface monitoring point. Additional soil temperature measurements will be obtained with the temperature probes. These model 107 temperature probes are buried 3 inches into the soil substrate on the green roof. The ambient air temperature is monitored by the RH probes, a dual function probe, which is protected in a radiation shield (Kosareo 2007).

Both two sites are using the same methods of temperature monitoring technology, while there are two different points regarding the installation of the thermocouples at two sites. Firstly, the monitoring locations (tripod) at Giant Eagle are two more than the one at Homestead; secondly, the amount of the thermocouples installed between the roof surface and structural deck is significantly different at two sites.

At Giant Eagle, two monitoring stations are located at each roof due to the large area of the rooftop. The thermocouples will be 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 (Kosareo 2007).

Whereas, only one monitoring station is located at each roof at Homestead since the rooftop area is small. 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 in an 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 installations of thermocouples above the roof surface are similar to the one at Giant Eagle.

Figure 23. Temperature and Relatively Humidity probe

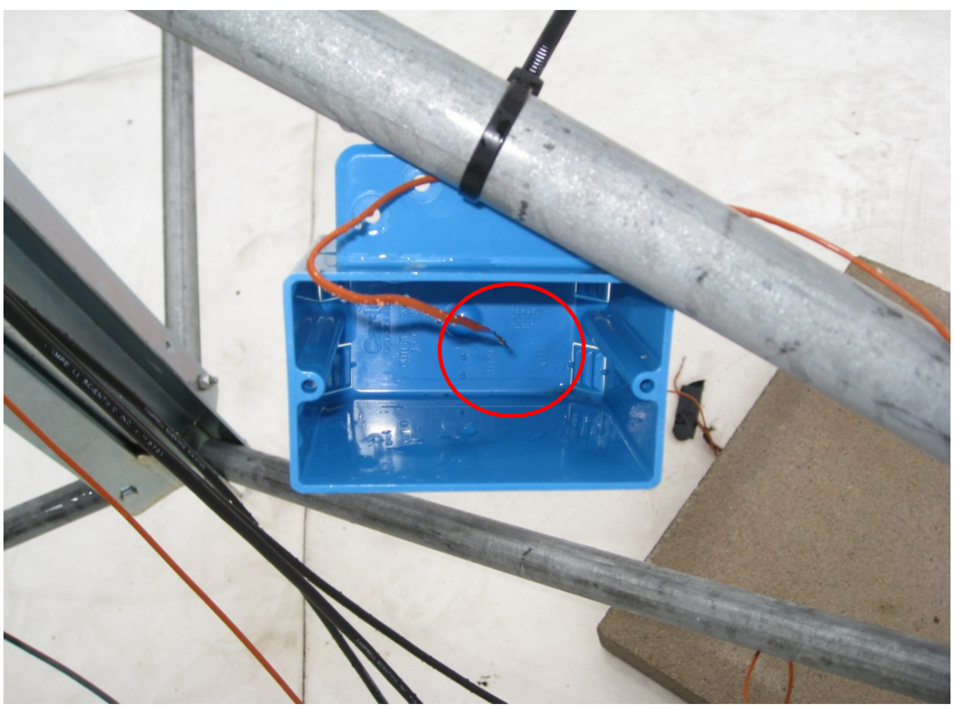

Figure 24. Thermocouple (circled) fixed on the tripod

4.1.3.5 Dataloggers and programming

A National Instruments Fieldpoint datalogging system was used to record data for the project and operate all the equipment. The Fieldpoint system is comprised of modular units that each accepts different types of inputs. Two banks of modules were used for this project. Both banks contained a power supply (PS-4 module) and a network module (FP-2000). The network module contains an Ethernet port that allows the bank of Fieldpoint units to communicate with computers, both directly and over the internet. They also contain a small computer, which allows simple programs to be run on the 106 unit as well as host web pages. Through communication with the network modules, the data that is received from the other units can be stored, displayed and studied. The Fieldpoint units are connected inline, with the network module in the first position (Bliss 2007).

Two Fieldpoint banks (Figure 25) were established at Giant Eagle site. First bank of modules contain five FP-TC-120 units, each of them accepts eight thermocouples. One FP-CTR-502 counter module records the rainfall. Each time one hundredth of an inch of rain falls, the rain gauge tips and sends a reading to the counter module to be recorded. A FP-DO-401 digital output module was used to control the opening and closing of the solenoid valve (not used currently). The second Fieldpoint bank contains two FP-AI-100 analog input modules. These units acquire data for all of the equipment on the roof, with the exception of the thermocouples, rain gauge and solenoid valves. The analog input modules are able to accept both voltages and currents that are output by the equipment. This bank also includes a FP-DO-401. The majority of the equipment on this bank is able to draw its power constantly, which is done from the analog input modules. Finally, there is one thermocouple module for the last eight thermocouples on the roof (Bliss 2007).

Since less monitoring locations were deployed at Homestead, only one Fieldpoint bank was installed and the same National Instruments datalogging system was used at Homestead. Figure 26 is an overview of the datalogging system at Homestead, with eight units of modules. In addition to a power supply (PS-4 module) and a network module (FP-2000), the one bank of modules contains two FP-TC-120 units, with total fourteen channels accepting thermocouples. Two FP-AI-100 modules next to the FP-TC-120 are functioned identically as the one at Giant Eagle, but with some measuring parameters unavailable. One FP-CTR-502 counter module is wiring with the rain gauge, recording the data of rainfall. The last one in the bank is the FP-DO-401, which is used to control solenoid valves in the basement.

To control the equipment, a program was written in National Instruments' LabVIEW 8.0 programming language. First, the program acquires data from the Fieldpoint units. As most of the data is in units such as volts, it is then converted to a usable form. The data are stored in a computer at the campus of University of Pittsburgh. Another program of National Instruments' DIAdem is used to extract the available data and switch it into Microsoft Excel file type.

Figure 25. National Instrument Fieldpoint Dataloggers at Giant Eagle site (Bliss, 2007)

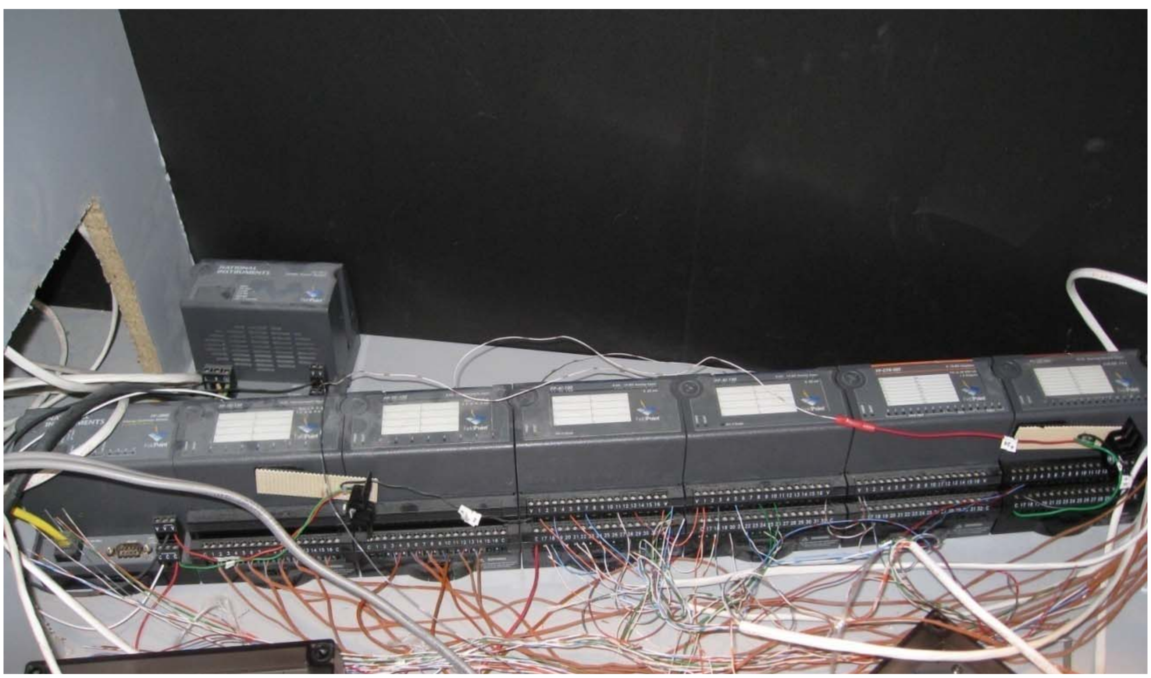

Figure 26. National Instrument Fieldpoint Dataloggers at Homestead site

4.1.4 Summary of site description

A summary of the major physical parameters, such as rooftop drainage area, data recording techniques, runoff sample collection system, etc., are used to compare the differences between two green roof technologies and listed in Table 2.

Table 2. Comparative features of Giant Eagle and Homestead site

	Giant Eagle	**Homestead**
Rooftop drainage area	Green roof: 3530 sq. ft. Control roof: 3530 sq. ft.	Green roof: 2000 sq. ft. Control roof: 2000 sq. ft.
Depth of the planting medium	5 ½ inches	1 ½ inches
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, raingauge, 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)	

5.0 RUNOFF QUANTITY ANALYSIS AND RESULTS

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 4.1.3. 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 9 in Appendix A. Appendix A 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. These are used to illustrate the differences in performance between the roof types under multiple conditions.

5.1 RUNOFF QUANTITY DATA FOR 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.

5.1.1 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 27. The cumulative volumes of water received (rainfall) and discharged (runoff) are presented in Figure 28. 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 27. 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.

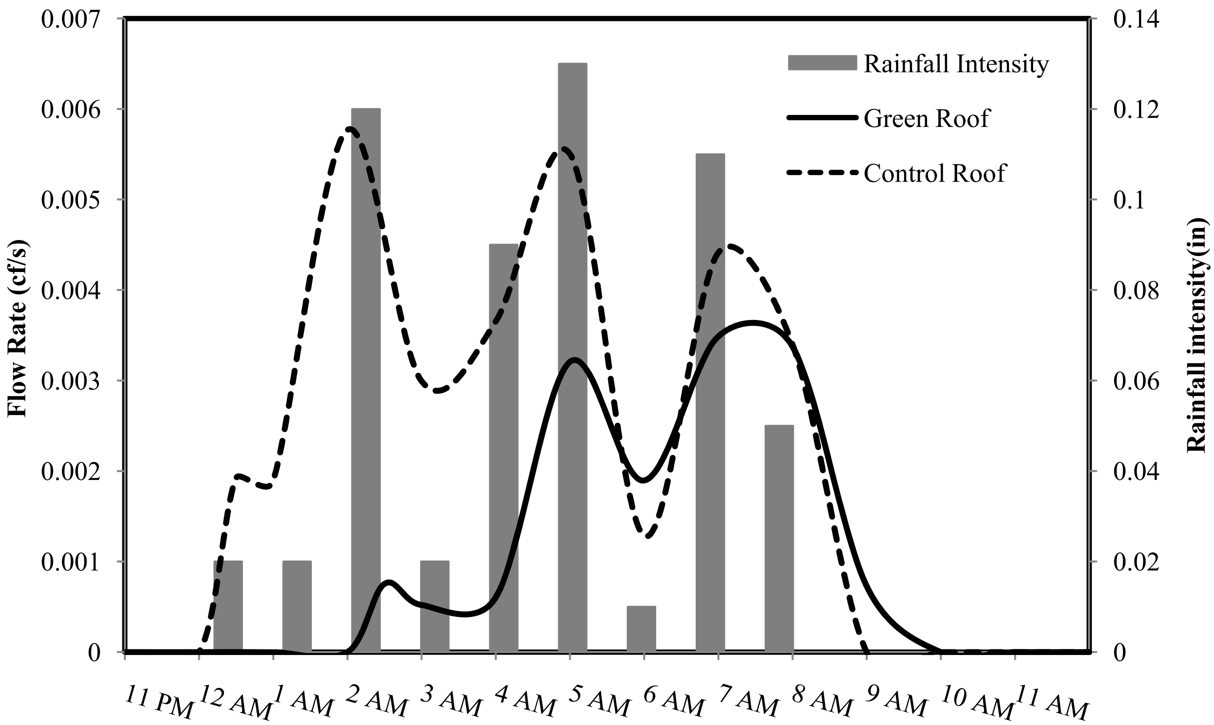

Figure 27. Runoff Flow Rates and Rainfall intensity – April 20, 2008 Storm (Homestead)

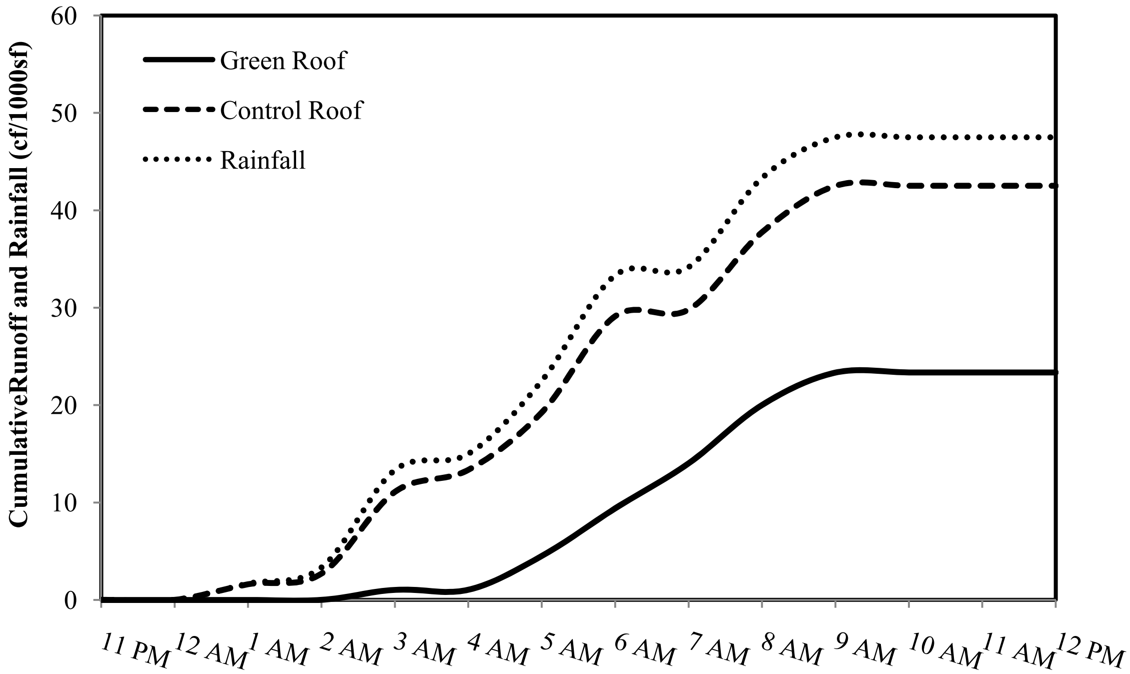

Figure 28. Runoff and rainfall volumes – April 20, 2008 Storm (Homestead)

5.1.2 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 29, and Figure 30 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 30). 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 30). 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 29, 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 30) from the green roof was 30% of the total equivalent rainfall volume, leaving 70% of stormwater retained by the green roof.

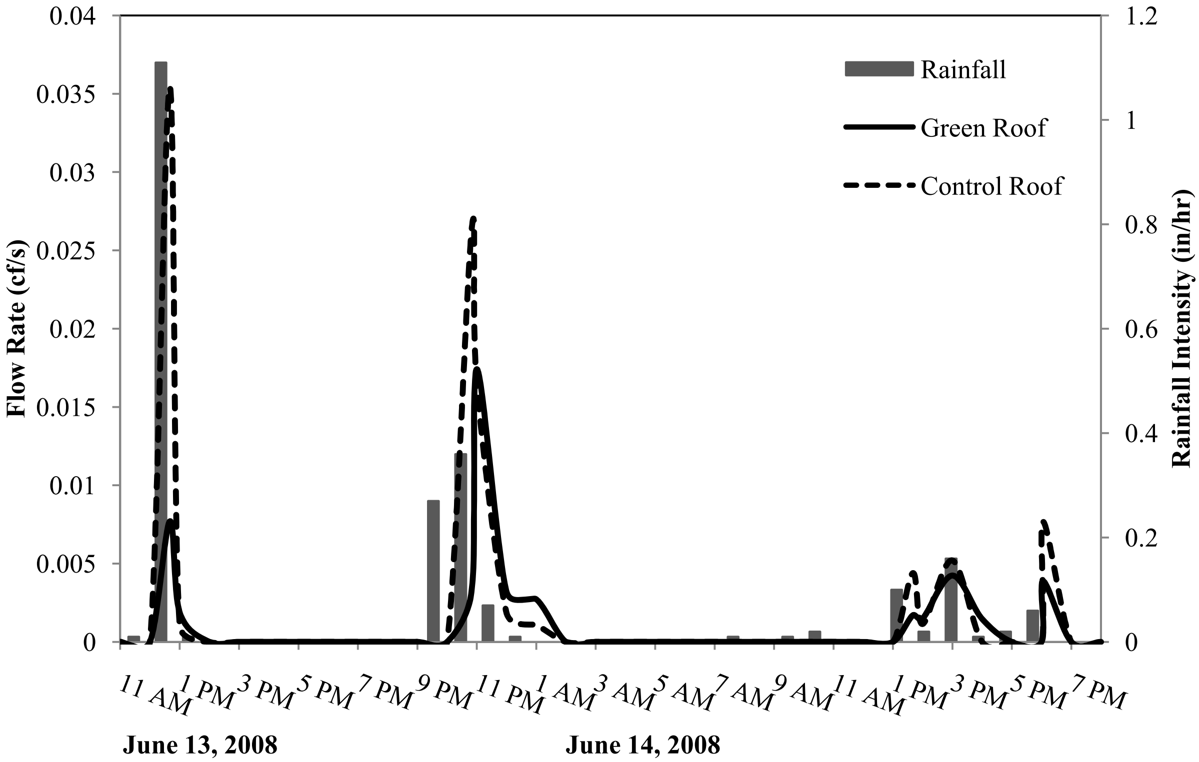

Figure 29. Runoff Flow Rates and Rainfall intensity – June 13-14, 2008 Storm (Homestead)

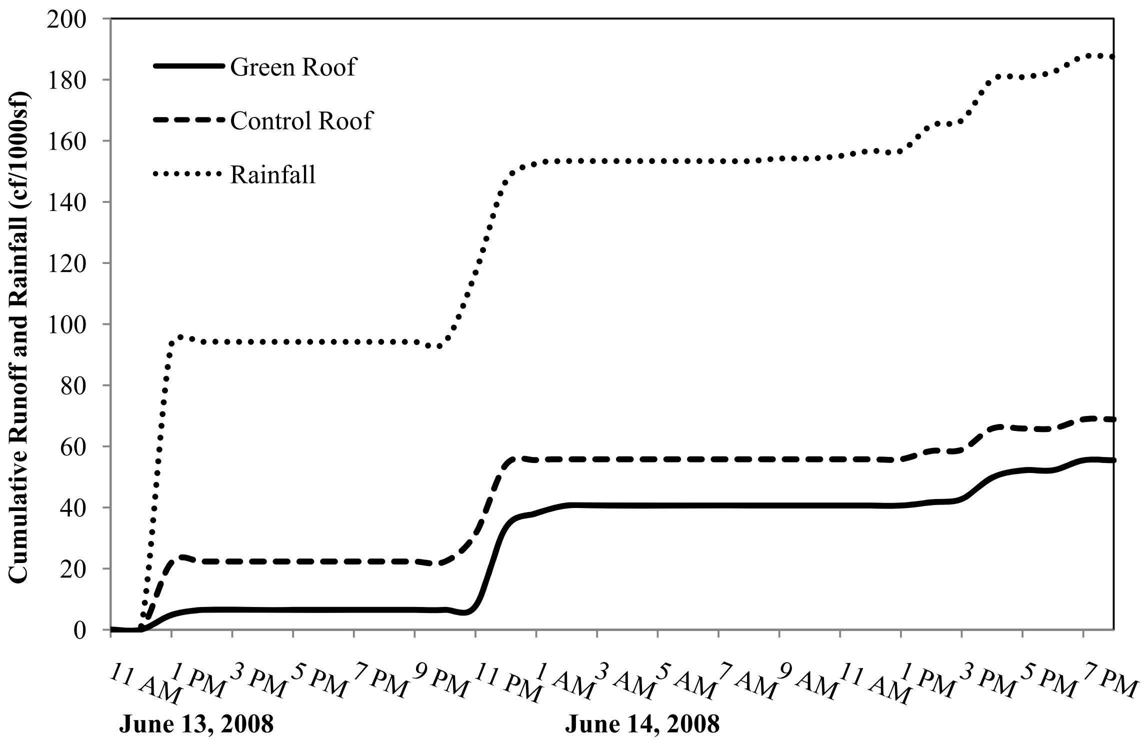

Figure 30. Runoff and Rainfall Volumes – June 13-14, 2008 Storm (Homestead)

5.1.3 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 31, 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 on Figure 5-6.

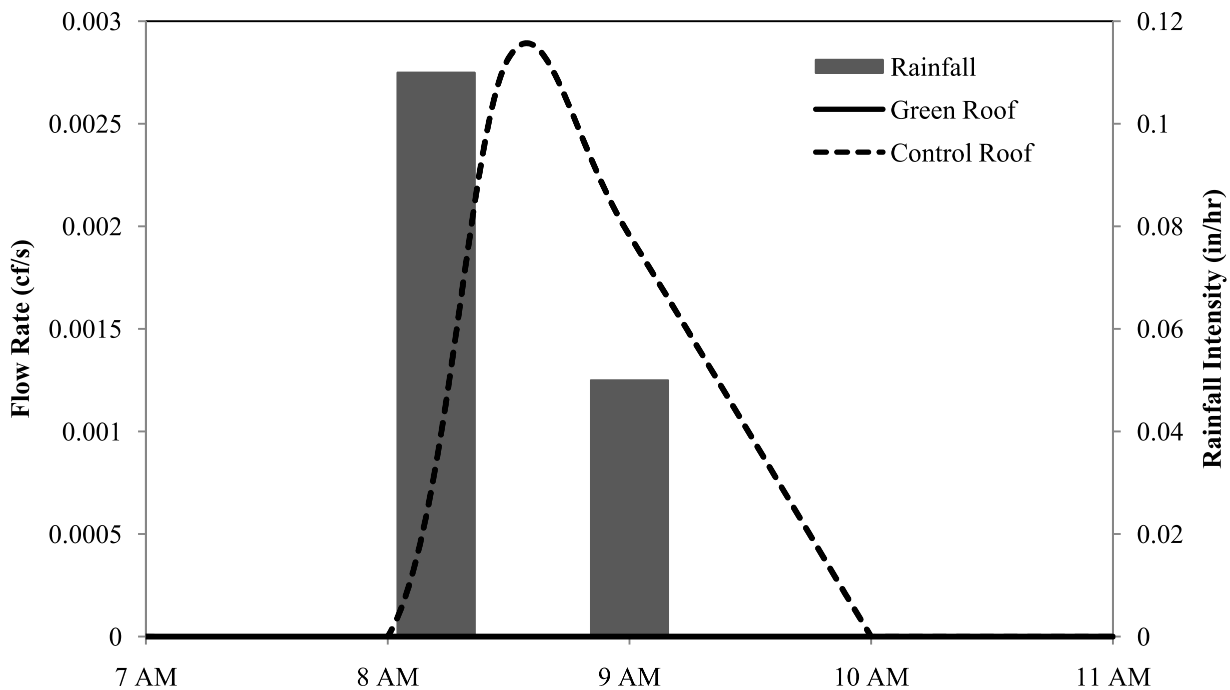

Figure 31. Runoff Flow Rates and Rainfall Intensity – September 9, 2008 Storm (Homestead)

During this light storm, the green roof absorbed all rainfall.

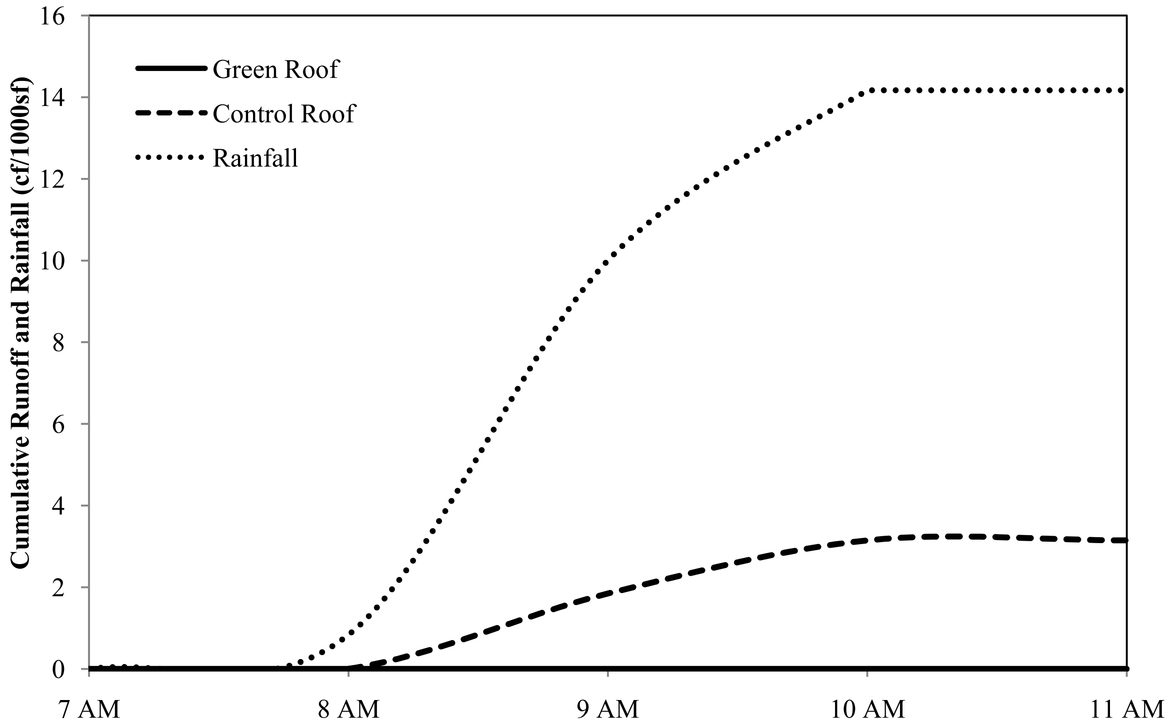

Figure 32. Runoff and Rainfall Volumes – September 9, 2008 Storm (Homestead)

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

5.1.4 February 18, 2008 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 33). 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 34) was 3% and 18% of the total equivalent rainfall and control roof, respectively.

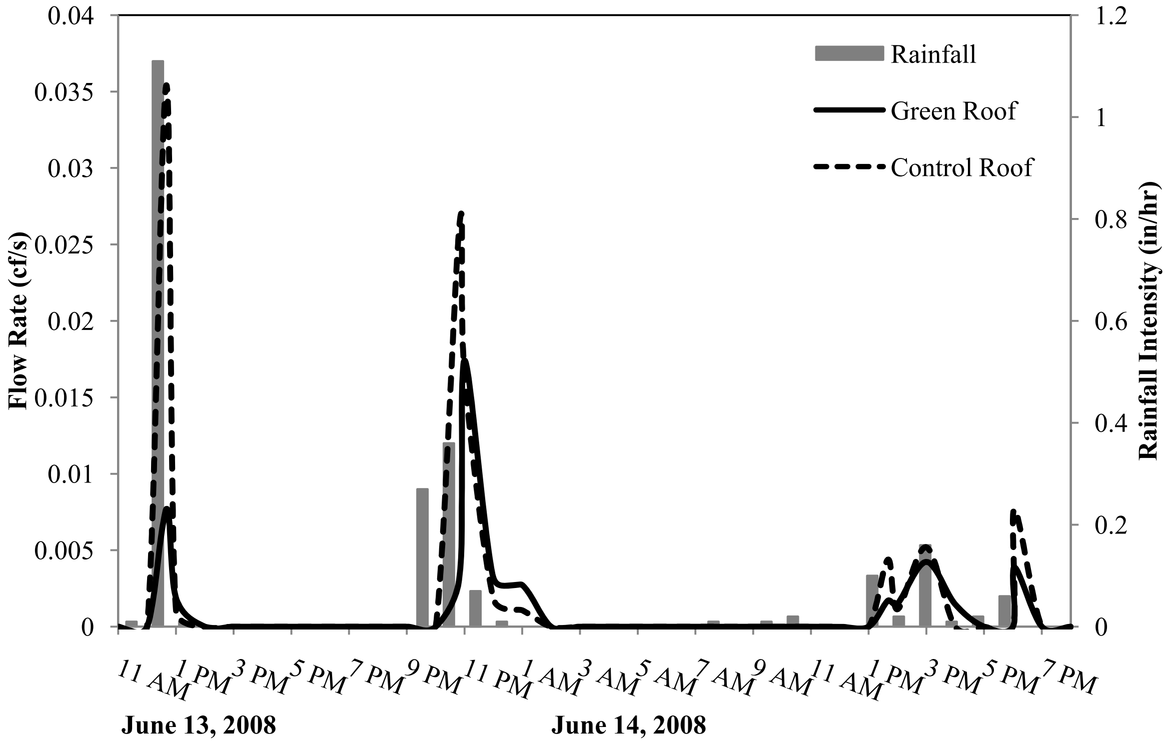

Figure 33. Runoff Flow Rates and Rainfall Intensity – June 13-14, 2008 Storm (Homestead)

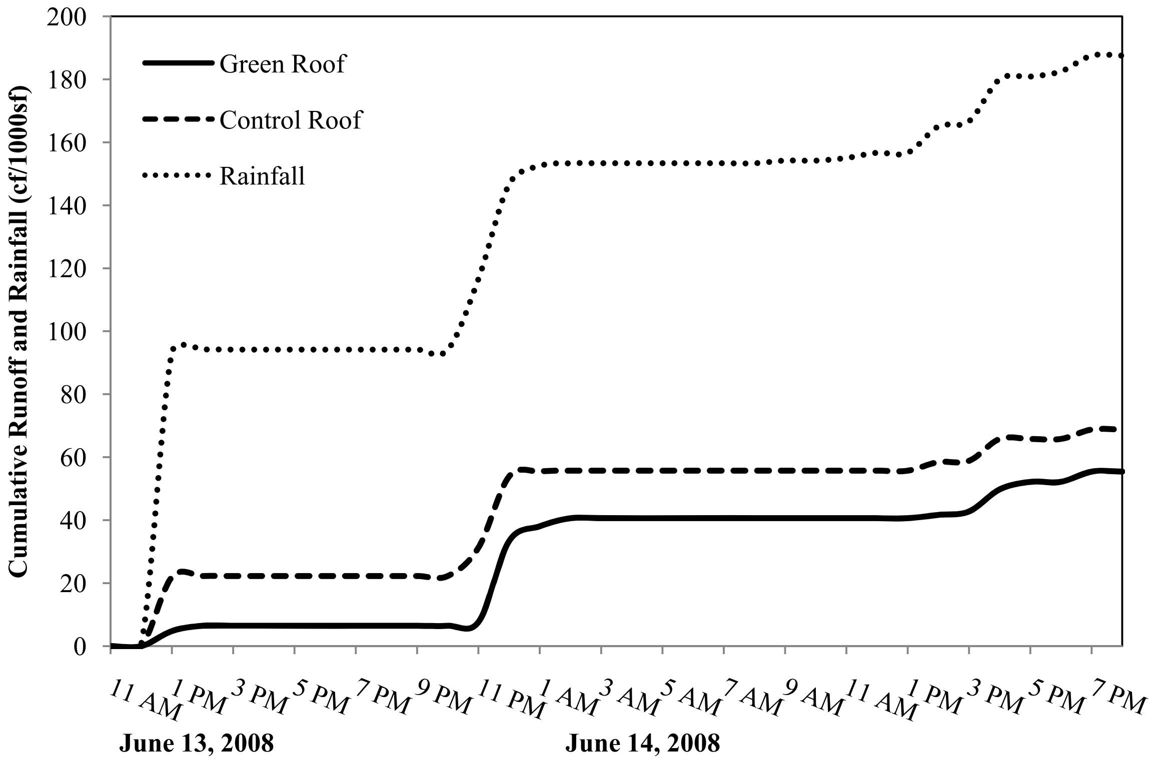

Figure 34. Runoff and Rainfall Volumes – June 13-14, 2008 Storm (Homestead)

5.2 RUNOFF QUANTITY DATA FOR GIANT EAGLE SITE

Individual rainfall events occurring at Giant Eagle site are presented in this section, and evaluated by comparing rainfall, runoff flow rate and volume.

5.2.1 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 35, Figure 36).

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.

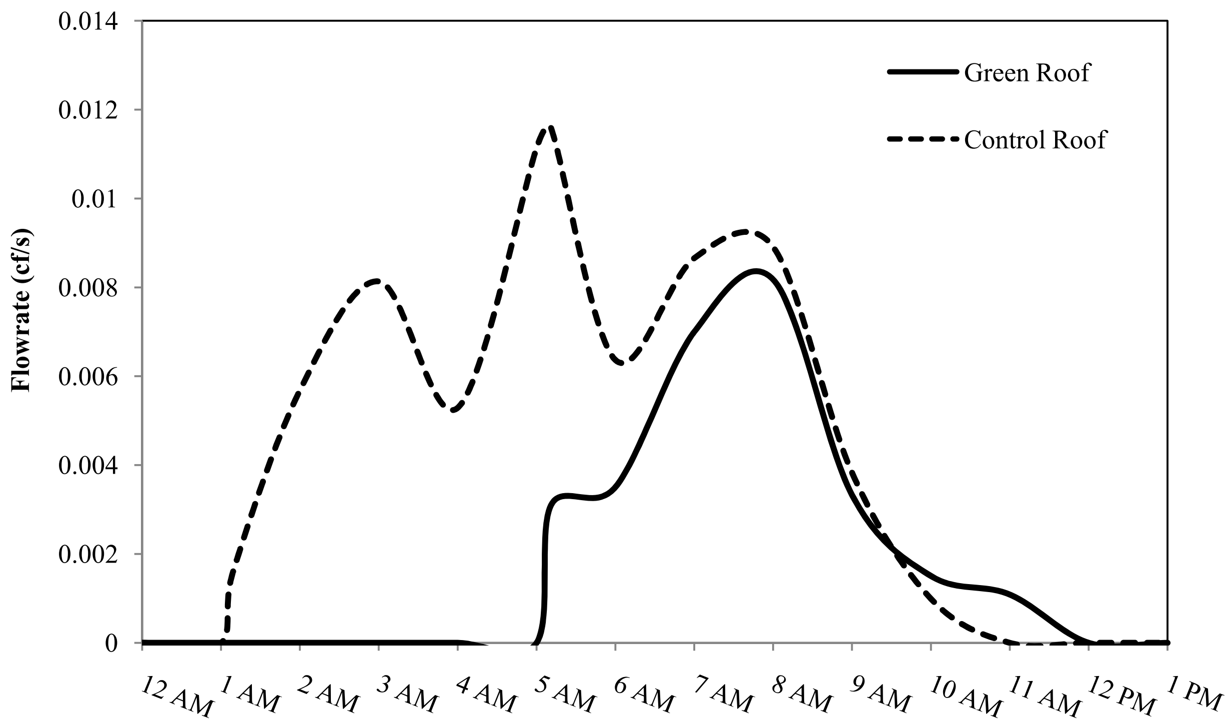

Figure 35. Runoff Flow Rates – April 20, 2008 Storm (Giant Eagle)

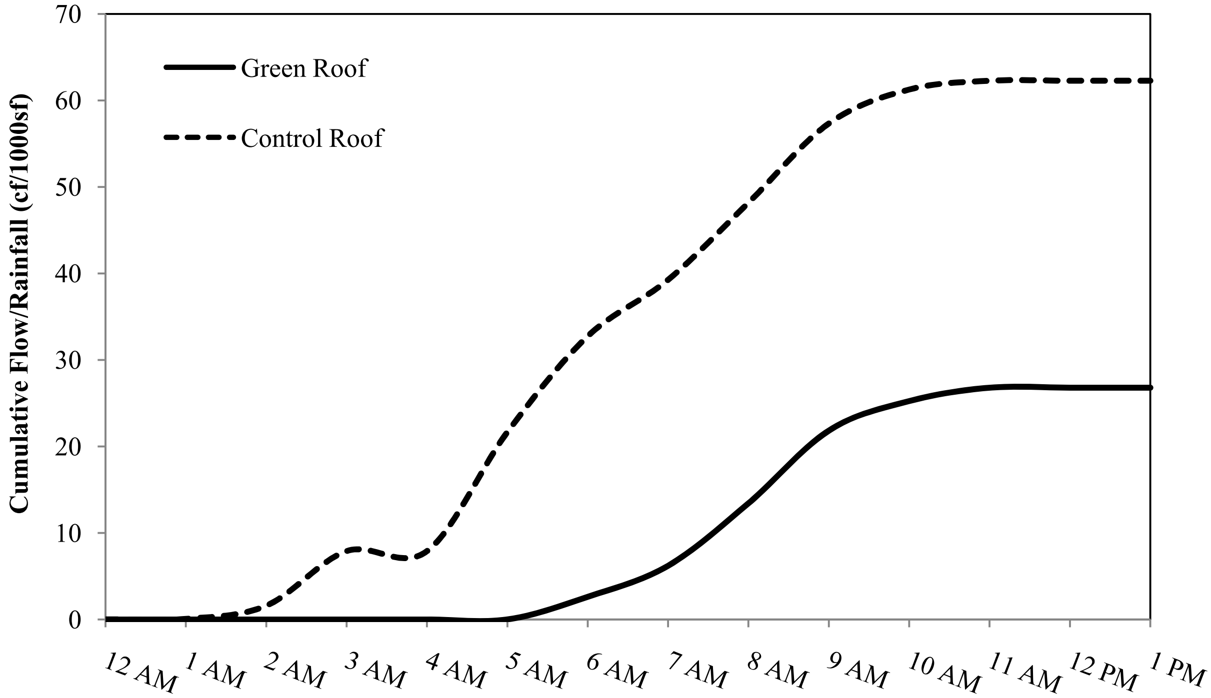

Figure 36. Cumulative Runoff Volumes – April 20, 2008 Storm (Giant Eagle)

5.2.2 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 37. 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 38) at a much higher level of discharge than the green roof runoff for all periods of rain.[1]

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 37). The total runoff volume was lower for the green roof, with 74% of total rainfall being withheld. As shown in Figure 38, runoff from the green roof equals 39% of the runoff from the control roof and 26% of the total rainfall.

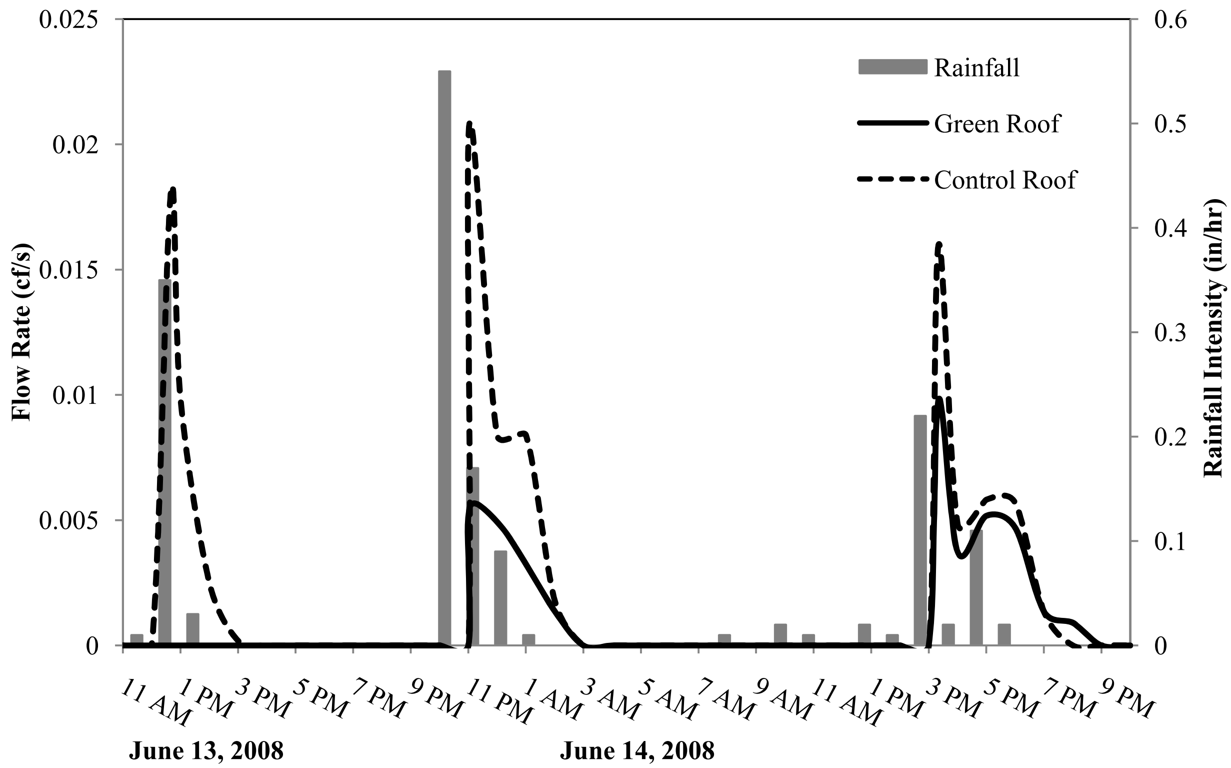

Figure 37. Runoff Flow Rates and Rainfall Intensity – June 13-14, 2008 Storm (Giant Eagle)

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

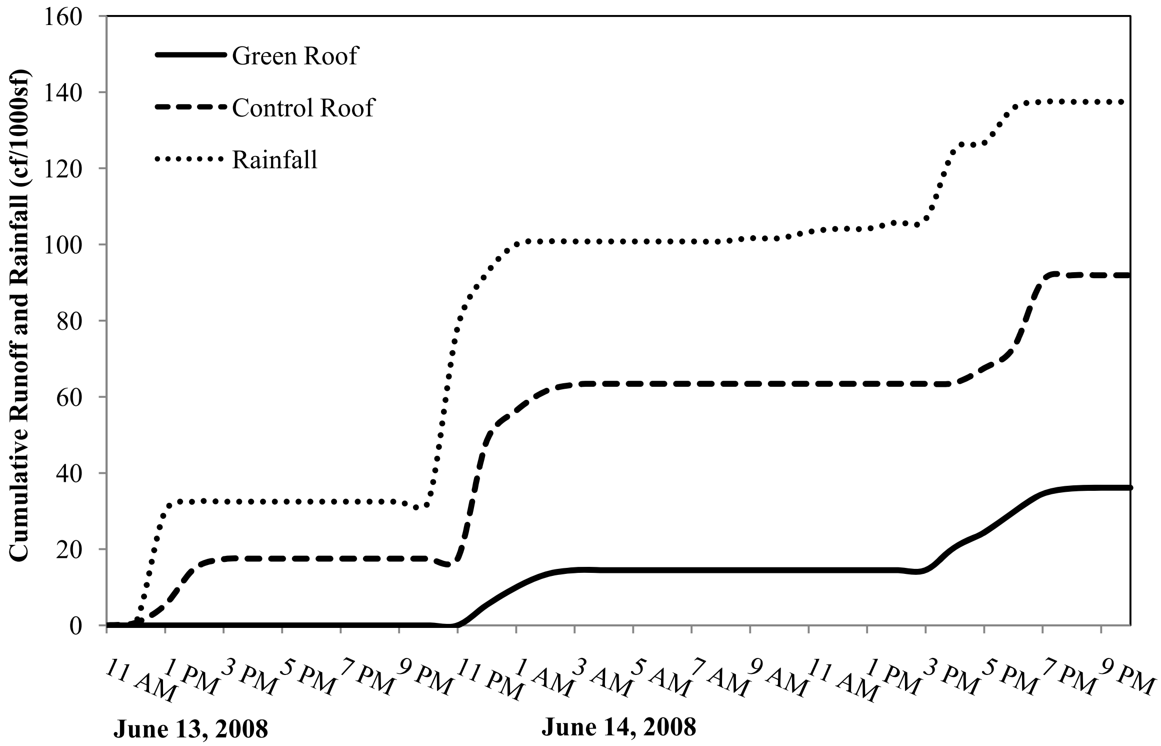

Figure 38. Runoff and Rainfall Volumes – June 13-14, 2008 Storm (Giant Eagle)

5.2.3 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 39). The normalized total runoff volume from the control roof (Figure 40) 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.

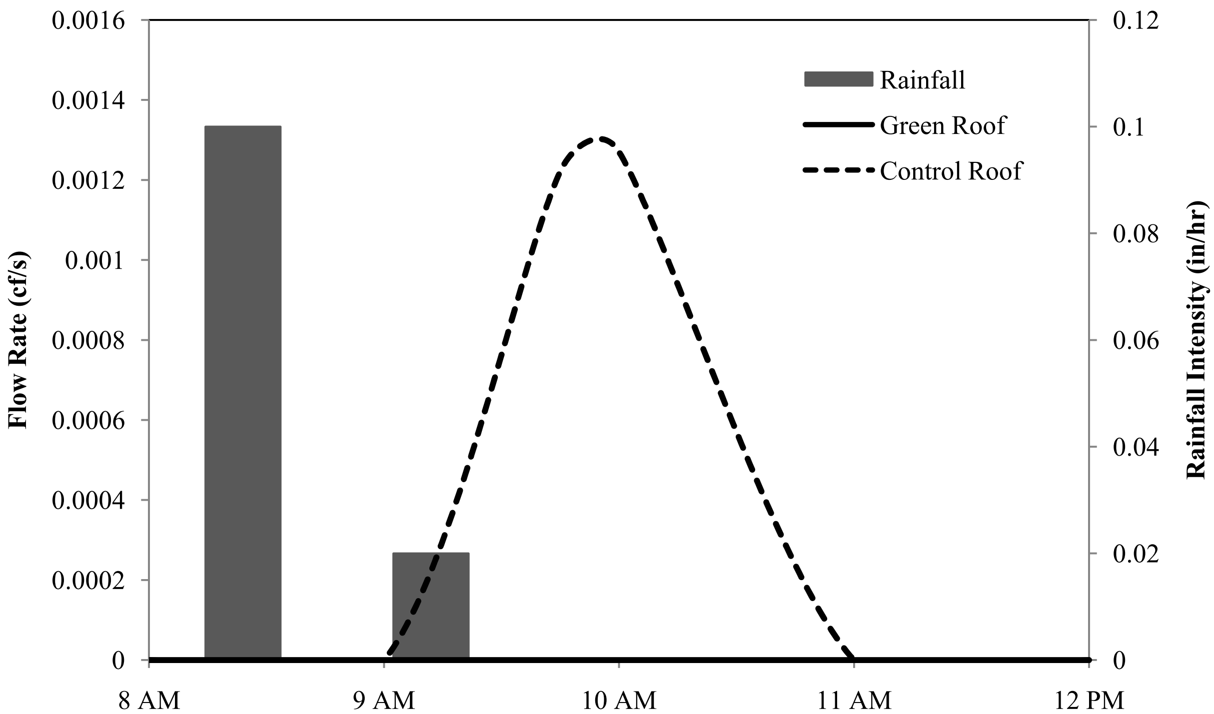

Figure 39. Runoff Flow Rates and Rainfall Intensity – September 9, 2008 Moderate Storm (Giant Eagle)

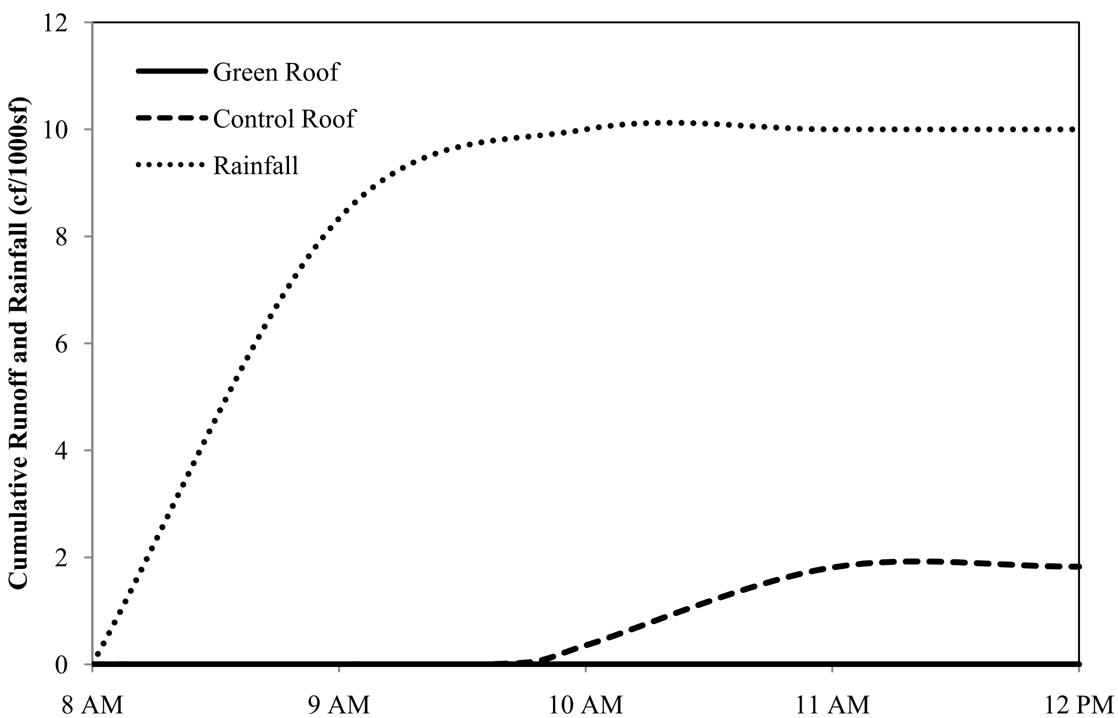

Figure 40. Runoff and Rainfall Volumes – September 9, 2008 Moderate Storm (Giant Eagle)

5.2.4 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 41). 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 42.

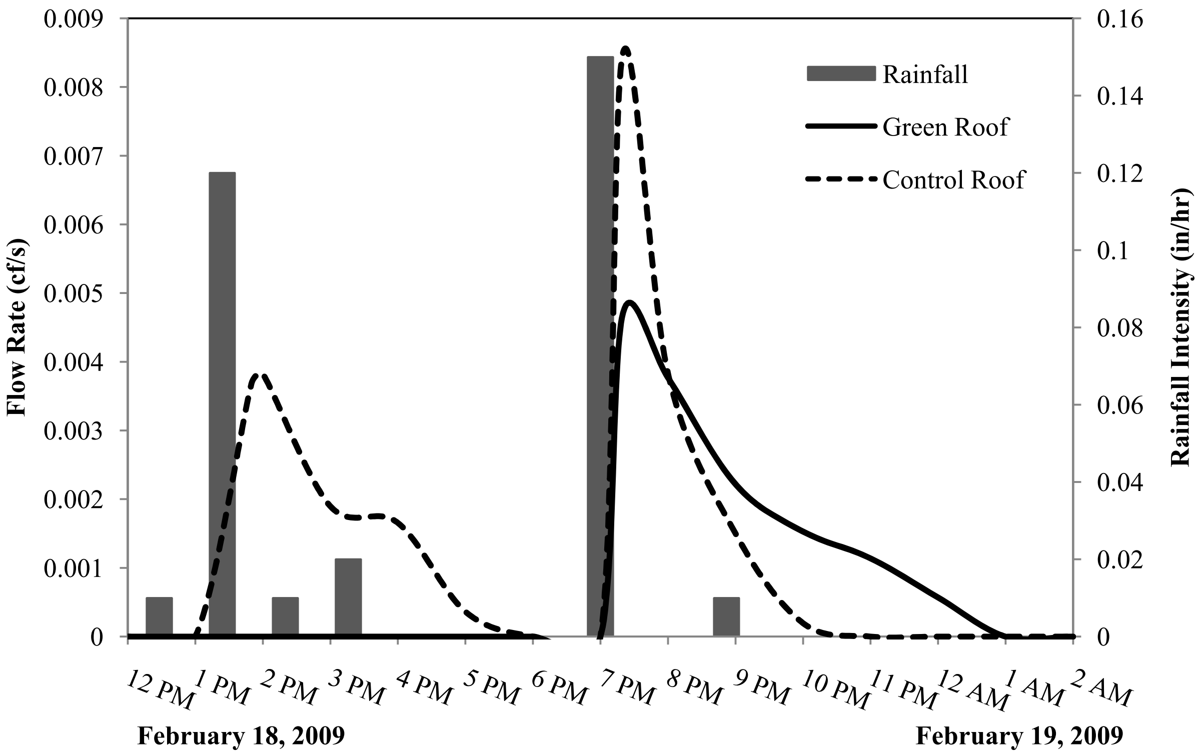

Figure 41. Runoff Flow Rates and Rainfall Intensity – February 18-19, 2009 Storm (Giant Eagle)

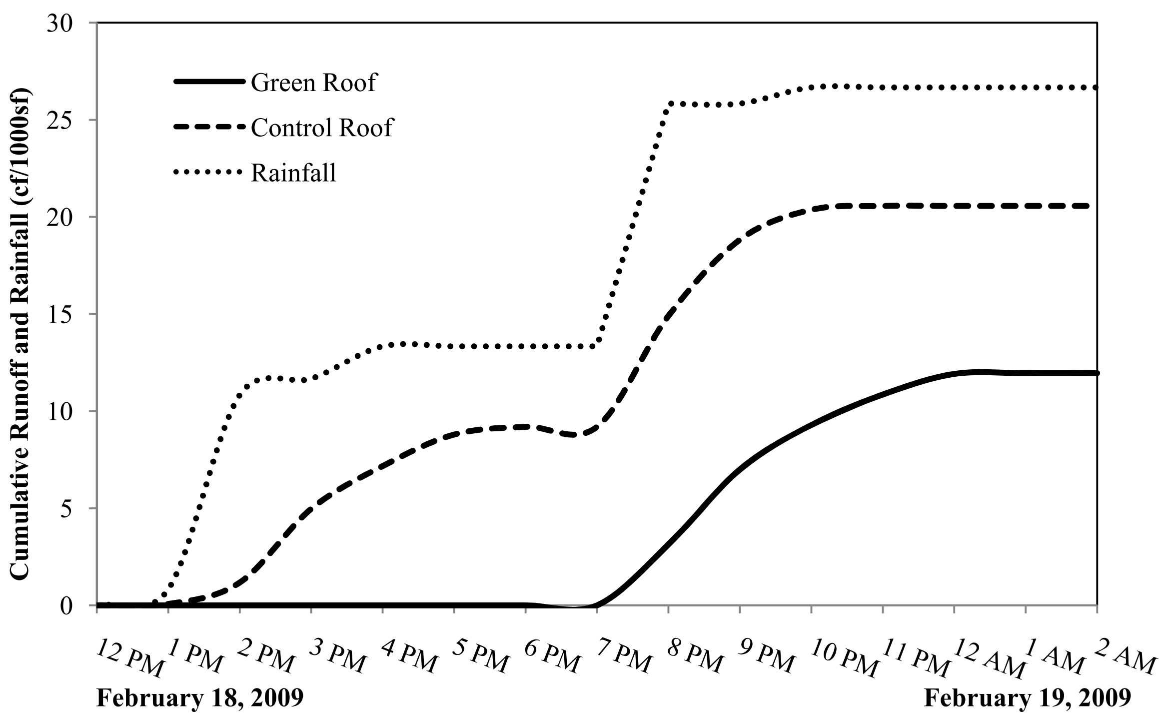

Figure 42. Runoff and Rainfall Volumes – February 18-19, 2009 Storm (Giant Eagle)

5.3 DISCUSSION AND ANALYSIS: COMPARATIVE RUNOFF QUANTITY

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 A (Table 9). 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 A Table 9 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 43.

5.3.1 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 43 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 43. 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.

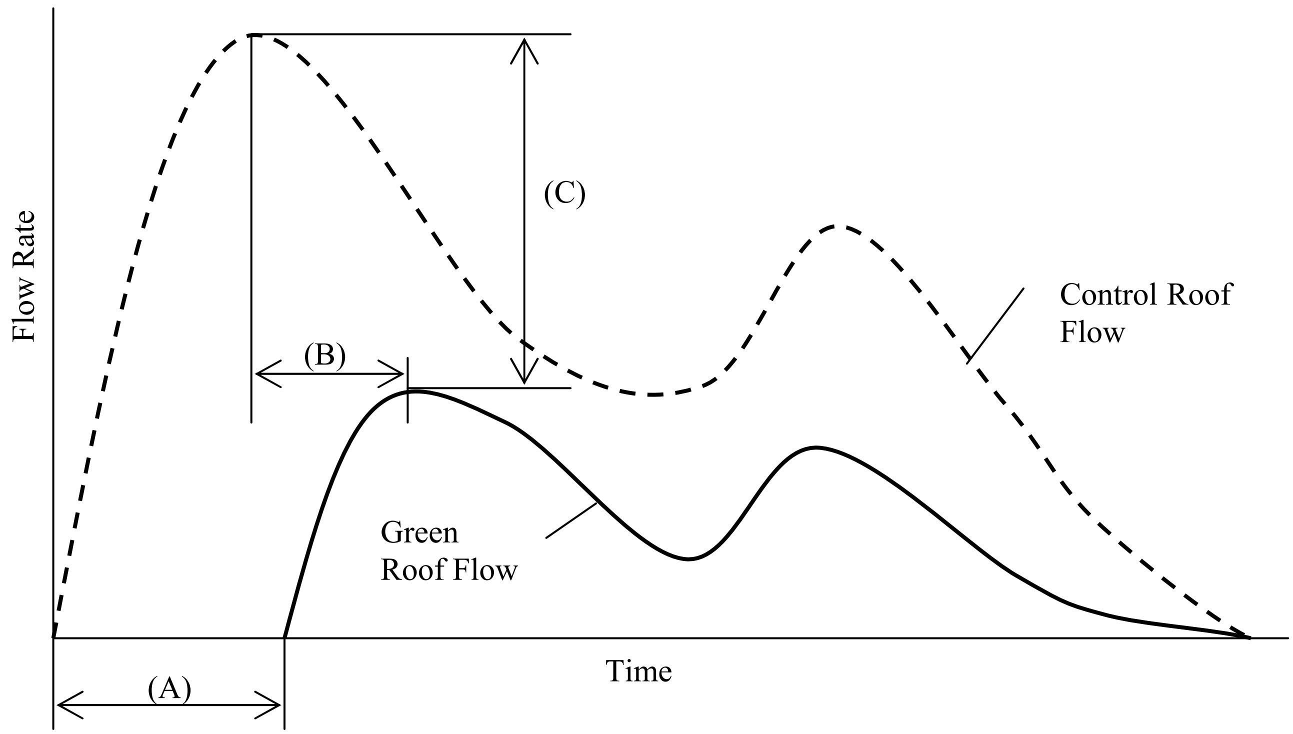

Figure 43. Different measuring parameters related to green and control roof runoff flow rate

(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 43. 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 44, 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.

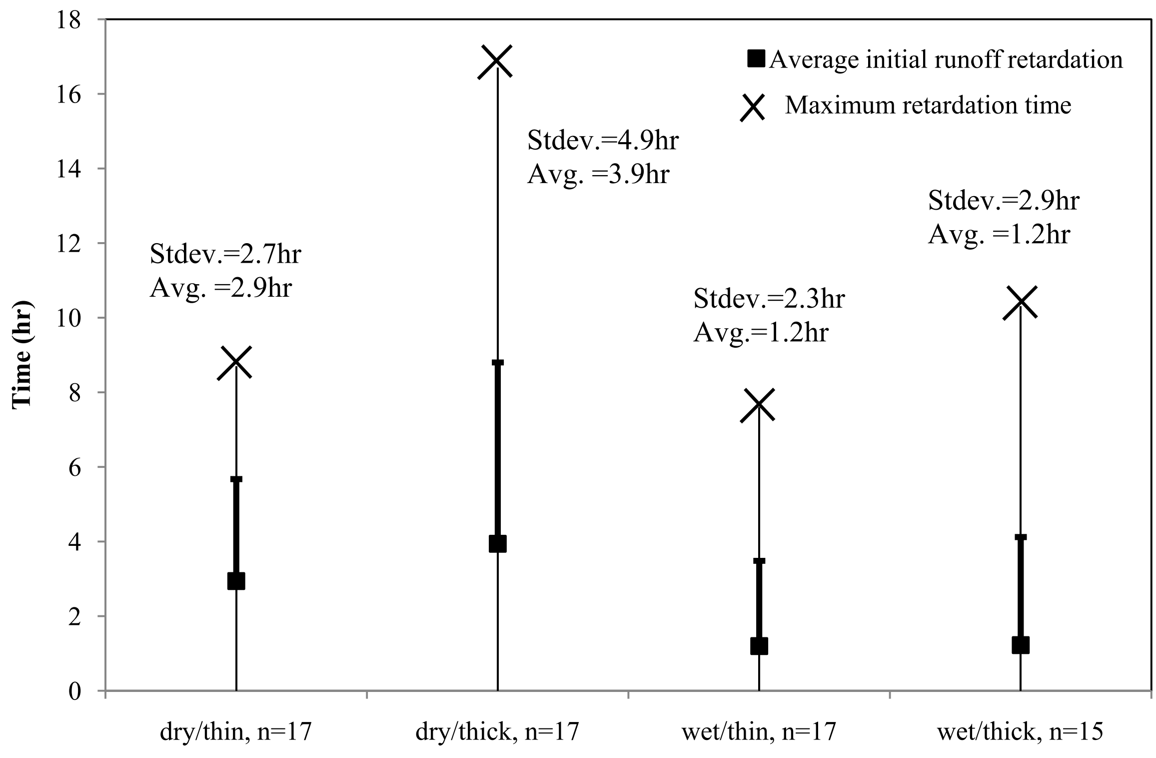

Figure 44. Time of initial runoff retardation under different soil condition and thickness

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 43. 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 45 compares the time of maximum peak flow retardation for thick and thin and wet and dry soils.

For the dry soils, the maximum 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 maximum time retardation of thick roof however was 1 hour.

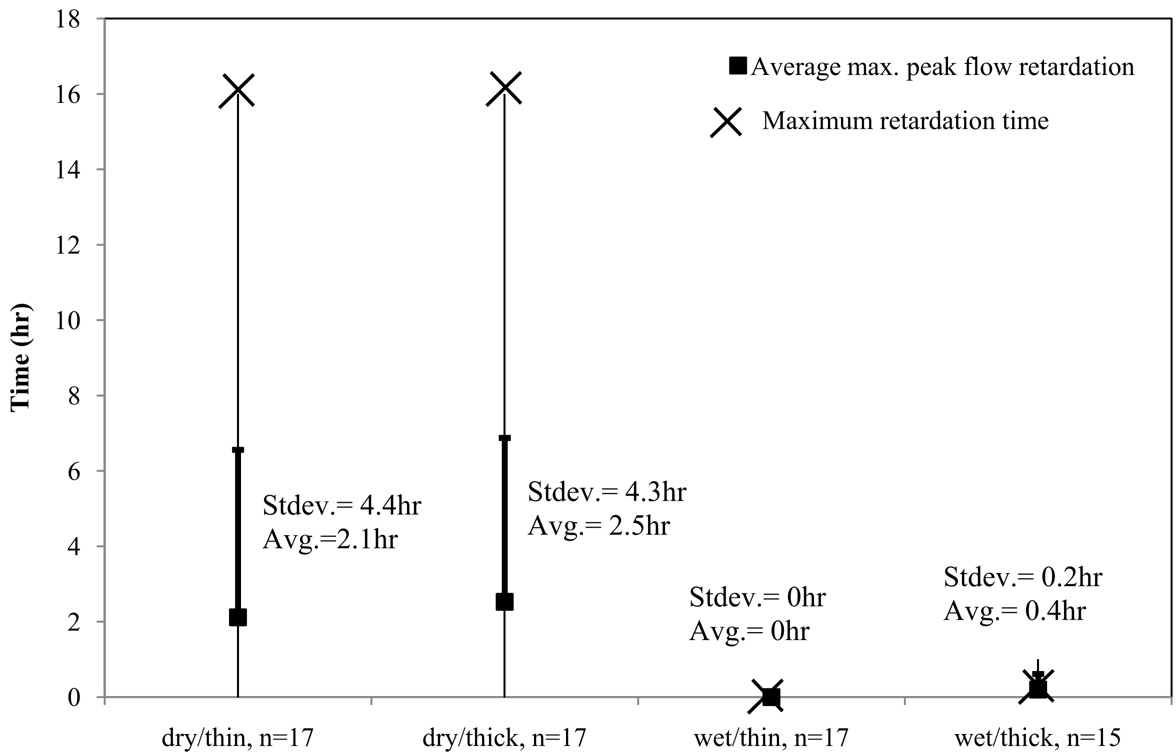

Figure 45. Retardation of occurrence (hr) of maximum peak flow with wet/dry & thick/thin soils

Figure 46 and Figure 47 show the cumulative probability of occurrence of maximum peak flow rate under dry and wet soil condition (parameter C from Figure 43). 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 46, 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 47, 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.

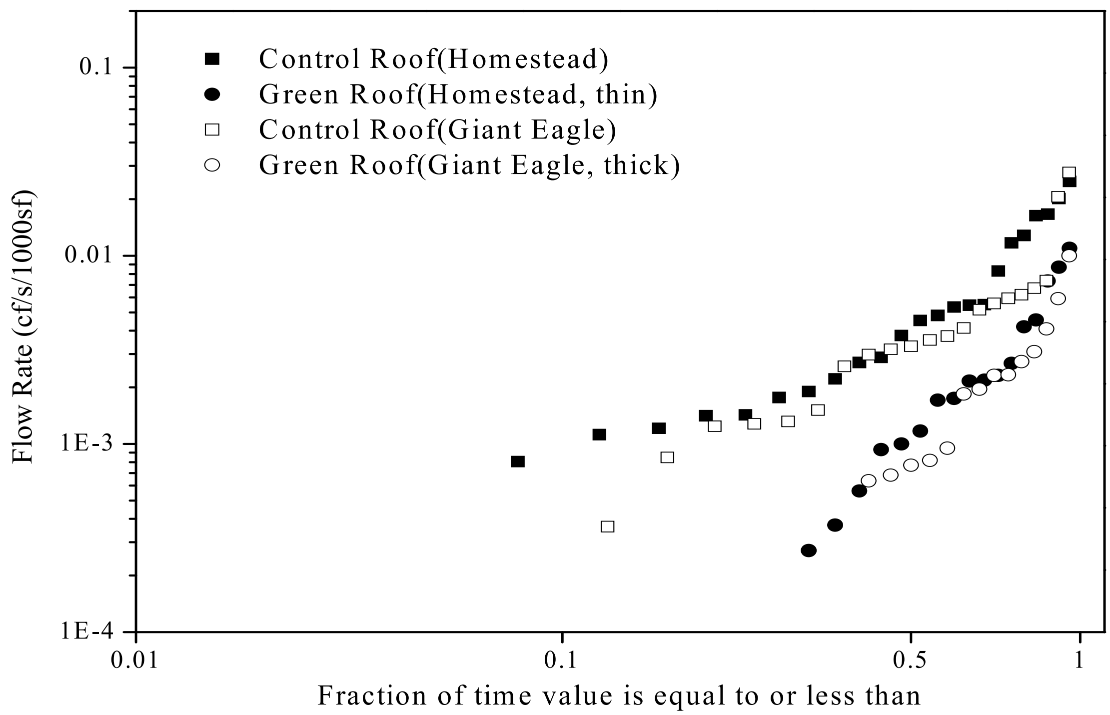

Figure 46. Probability of occurrence of maximum peak flow rate under dry soil condition

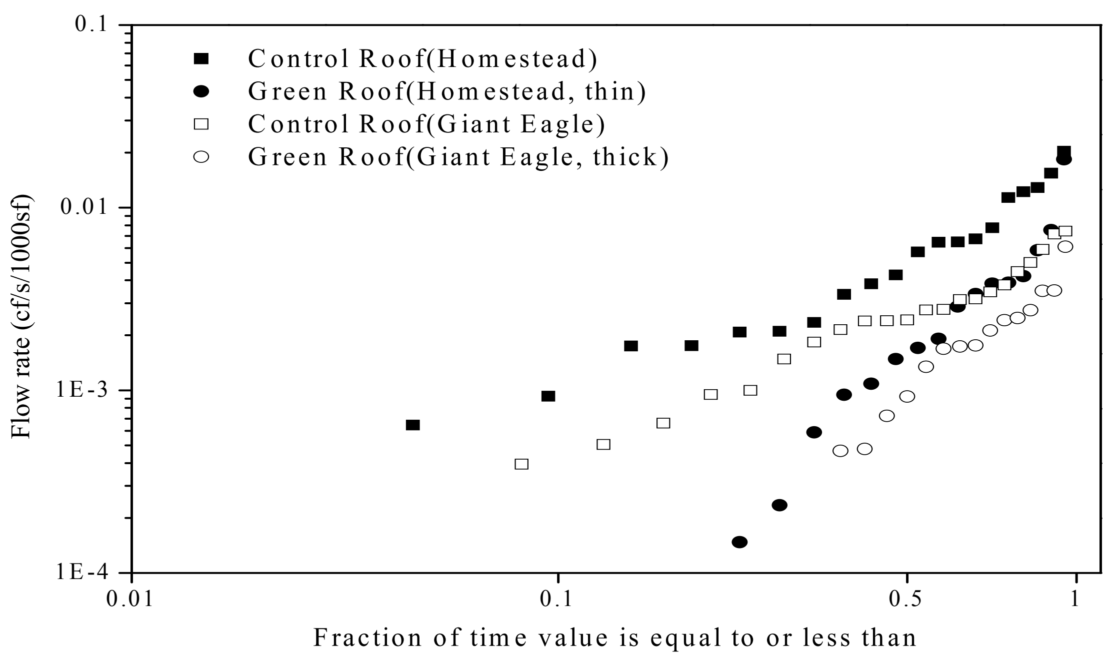

Figure 47. Probability of occurrence of maximum peak flow rate under wet soil condition

The Figure 48 and Figure 49 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[2] . 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 48 and Figure 49, 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. Envelops in the figures involve most of data points which green roof had runoff discharged. As a good approximation, the thin 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 wet soil conditions, runoff started sooner. The green roof was able to usually retain water at about 0.09 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 50 and Figure 51. As a good approximation, the thick green roof, with initially dry soil conditions (Figure 50), was able to usually retain water at about 0.6 inch of rain or less (measured as control roof runoff, inches of water). Similarly, the thick green roof, with initially wet soil conditions (Figure 51) was able to usually retain water at about 0.15 inches of rain or less (measured as control roof runoff, inches of water) water released from control roof.

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

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.

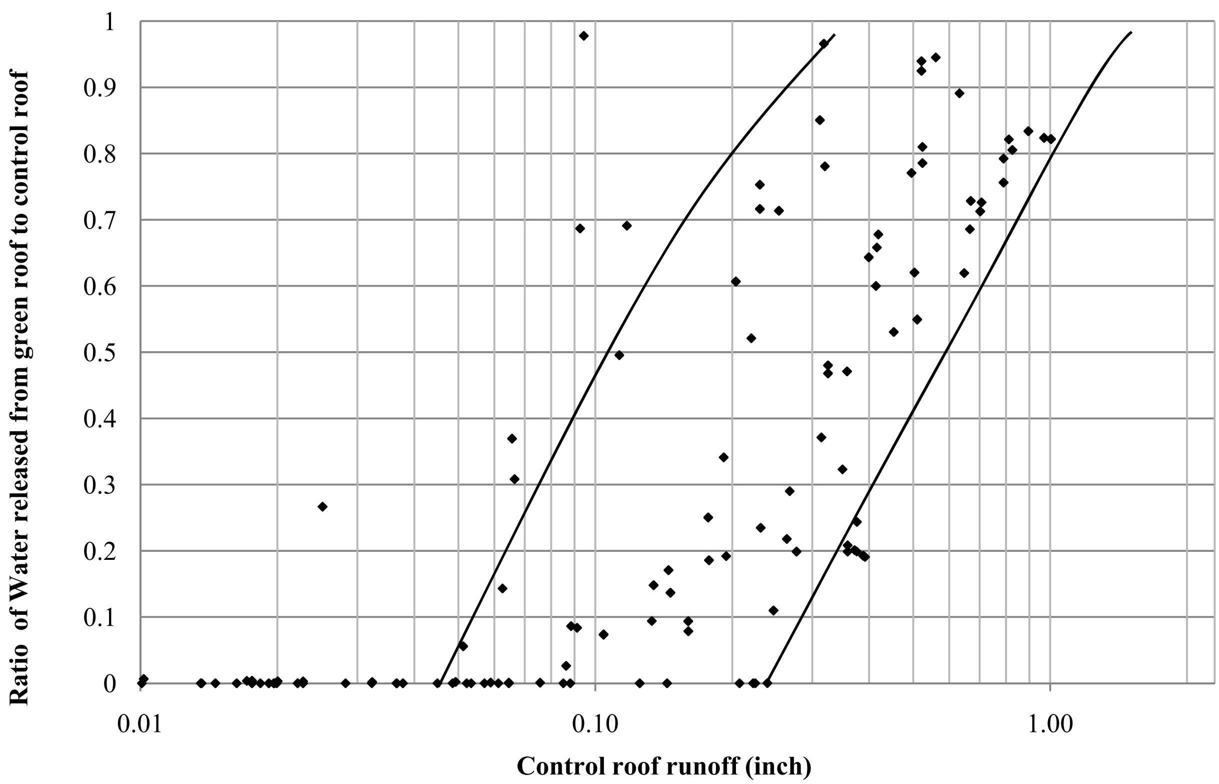

Figure 48. Ratio of water released from green roof to control roof vs. control roof runoff: thin roof at Homestead with dry soils (140 data points in total)

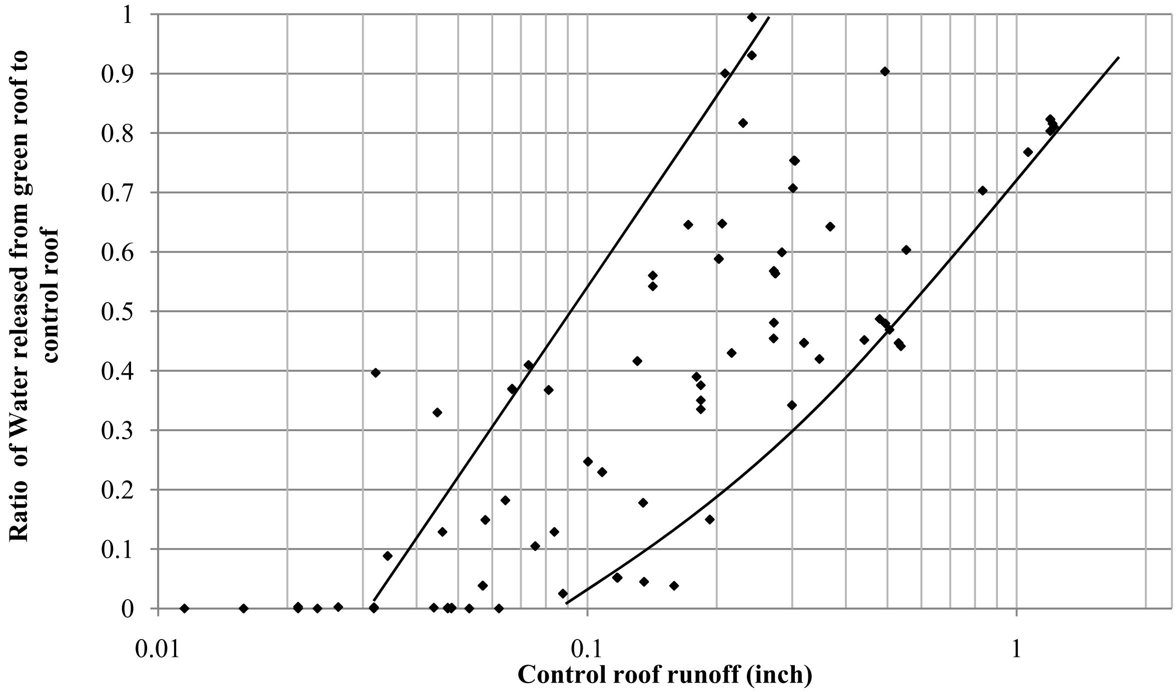

Figure 49. Ratio of water released from green roof to control roof vs. control roof runoff: thin roof at Homestead with wet soils (104 data points in total)

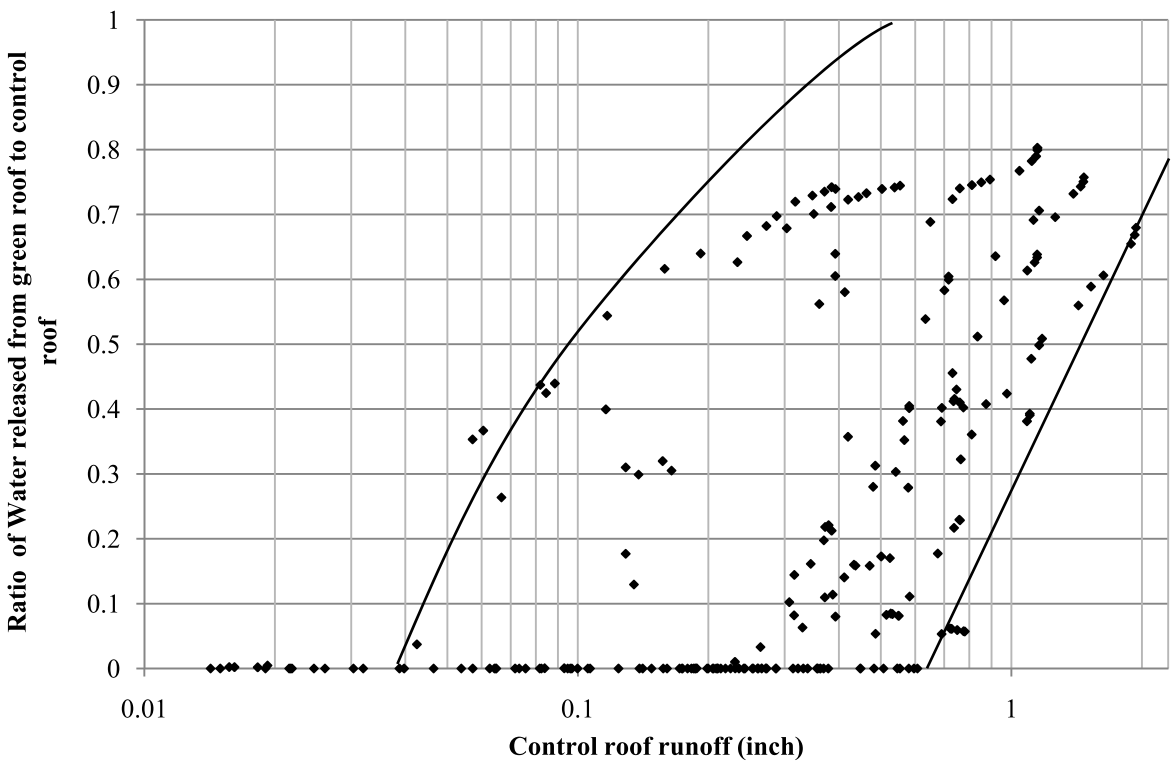

Figure 50. Ratio of water released from green roof to control roof vs. control roof runoff: thick roof at Giant Eagle with dry soils (258 data points in total)

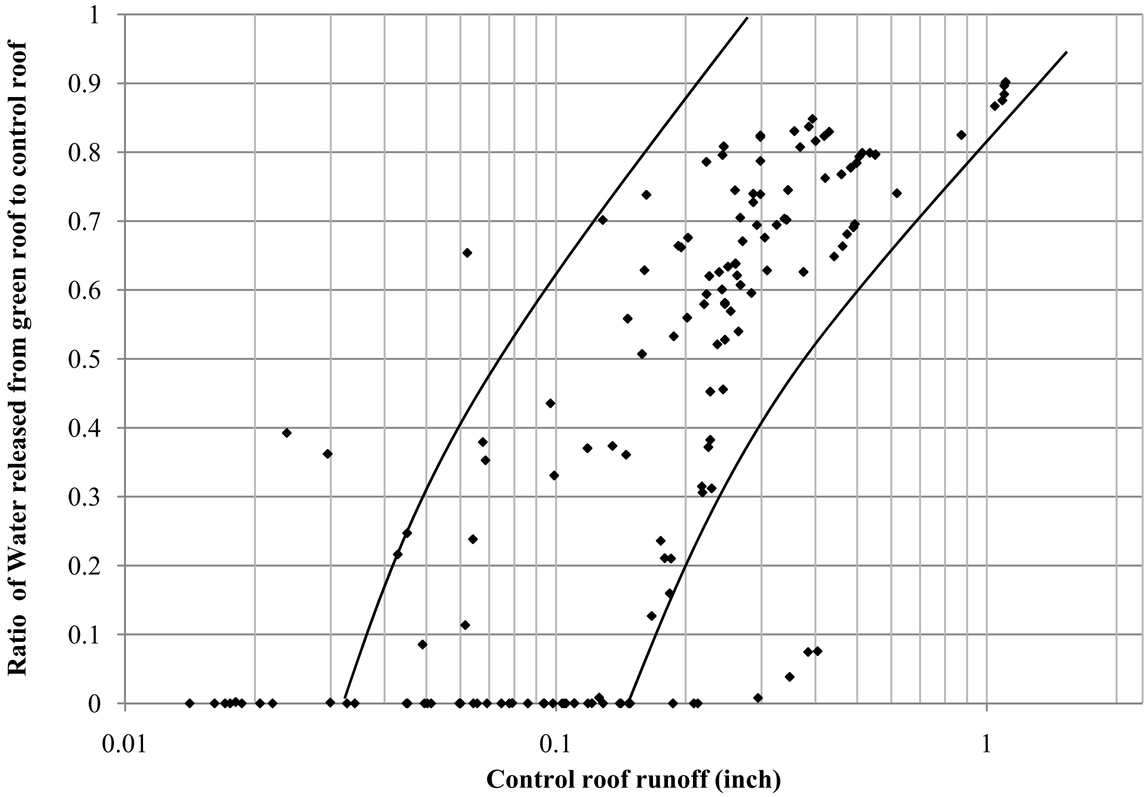

Figure 51. Ratio of water released from green roof to control roof vs. control roof runoff: thick roof at Giant Eagle with wet soils (179 data points in total)

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.*

5.3.2 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 9 in Appendix A). 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 52a. 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 [3]. 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

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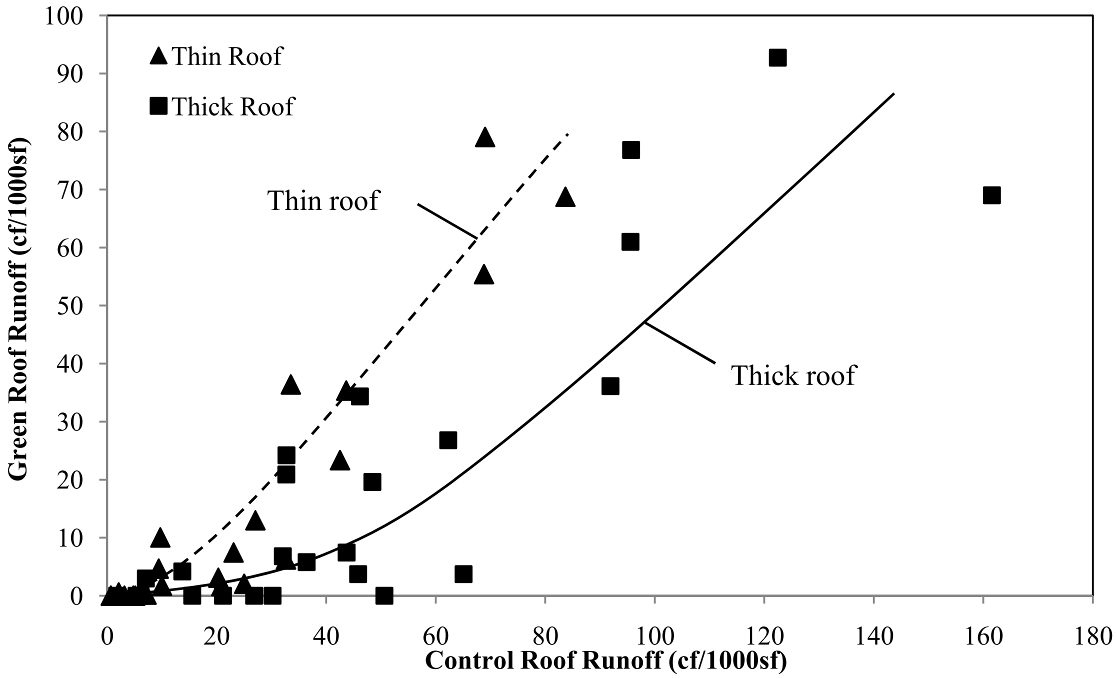
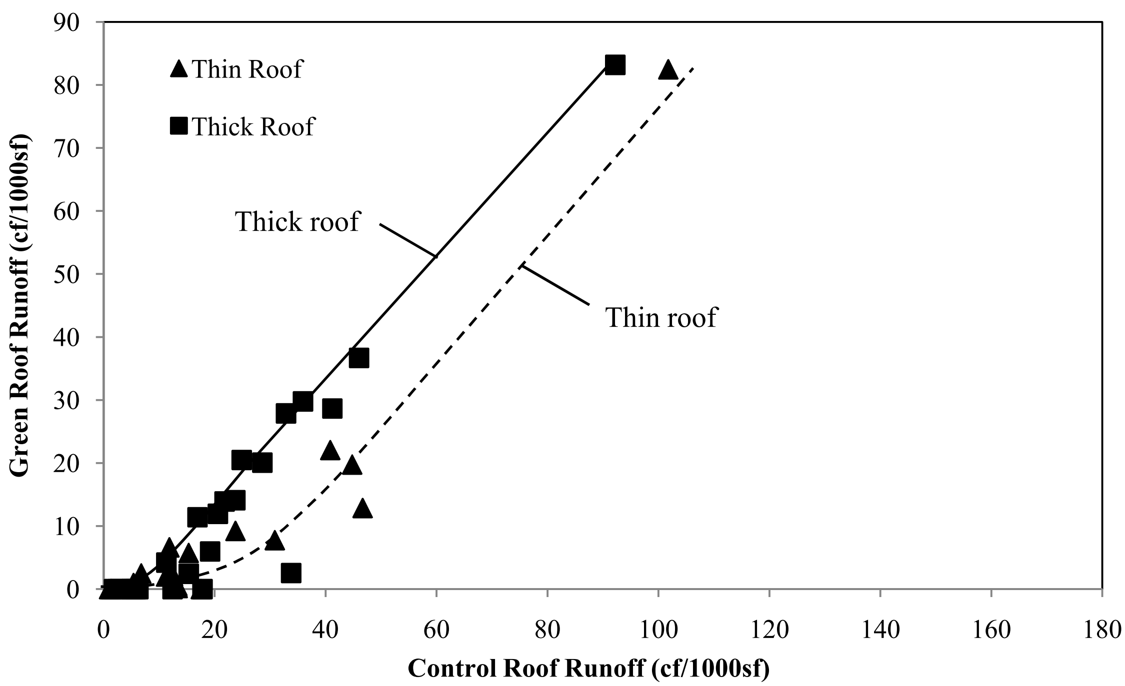
[3] data was plotted only when data from both sites was available

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 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 52. Comparative runoff performance of thin and thick green roofs for wet and dry soils

6.0 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 3 and locations graphically shown on Figure 53.

Table 3. 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[4]	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

[4] 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 53.

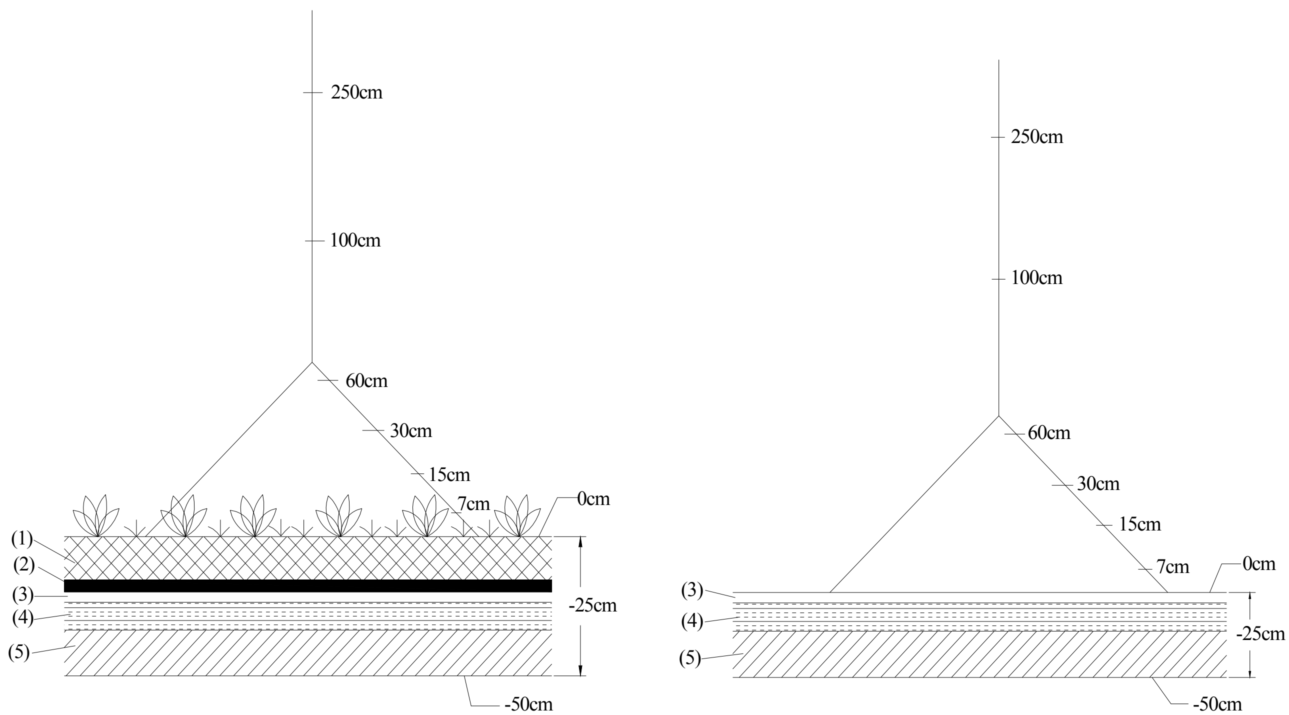


Figure 53. Vertical Layout of temperature monitoring positions of green (left) and control (right) roof

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.

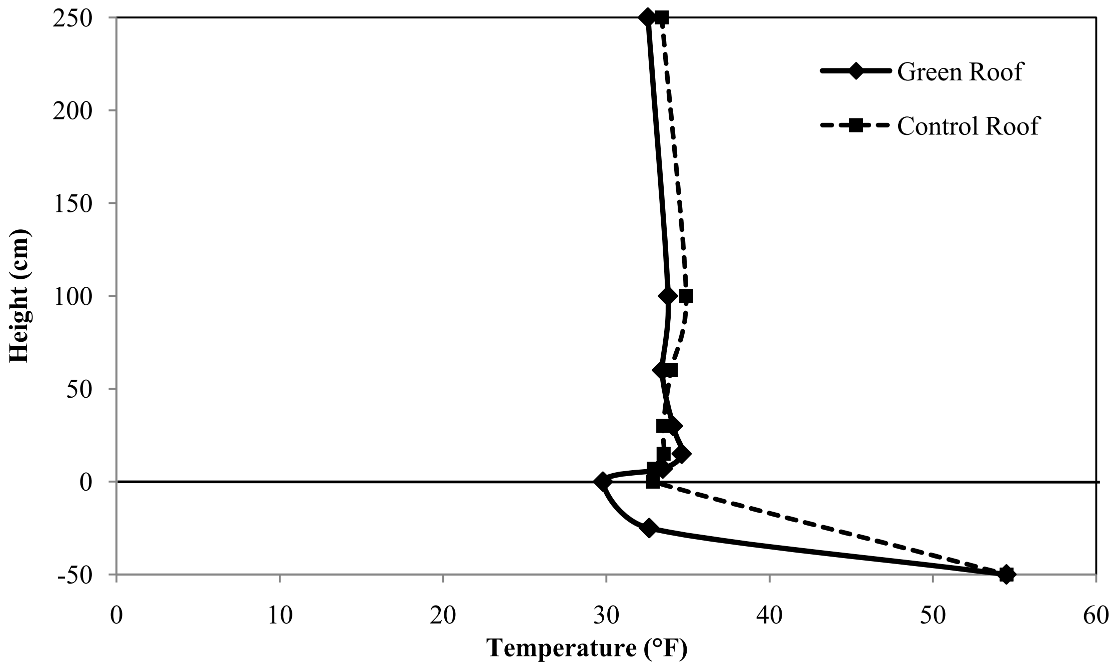
6.1 SEASONAL THERMAL PERFORMANCES FOR HOMESTEAD SITE

The thermal performances at Homestead site for both control and green roof are presented in this section. Seasonal thermal performances are evaluated and classified by cold, moderate and hot weather.

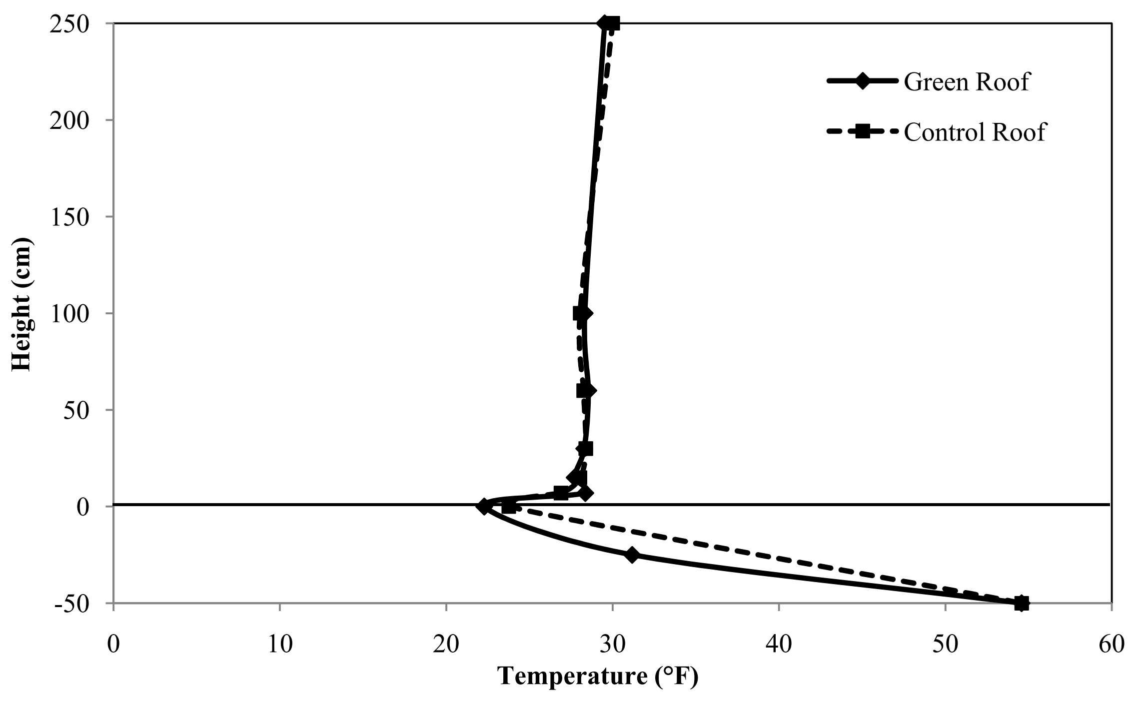
6.1.1 Winter Thermal performance (cold weather condition)

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 B. 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 54a. 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 54(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

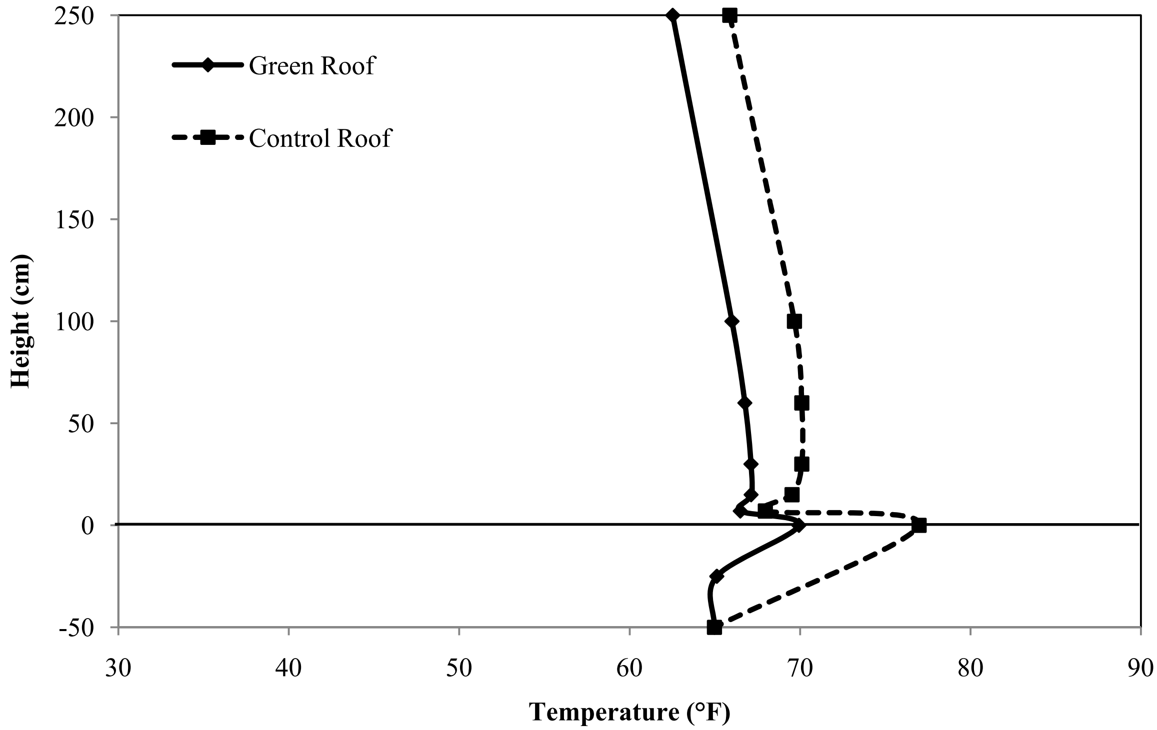
Figure 54. January, 2008 temperature profile at Homestead. There is no temperature differences measured between the green and control roofs in cold weather conditions.

6.1.2 Spring and Autumn Thermal performance (moderate weather conditions)

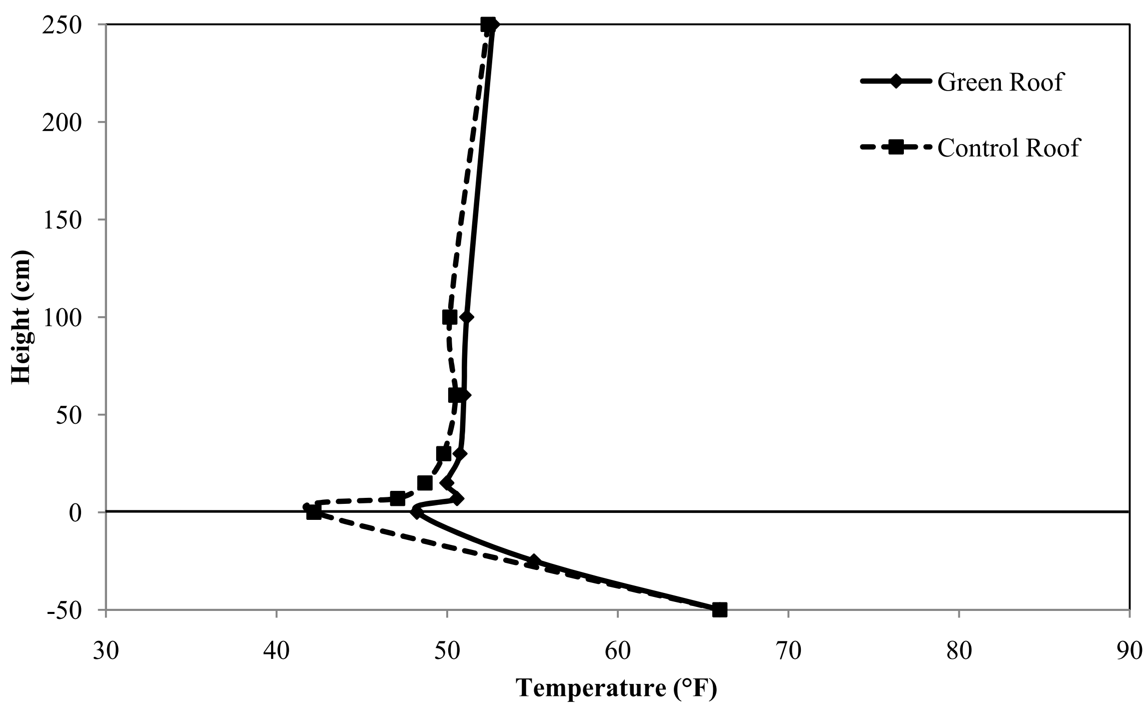
The temperature profile for April 2008 was chosen to be representative for moderate weather conditions. Temperature profiles for addition time periods with moderate weather conditions are in the in Appendix B. The temperature data was divided into day as shown on Figure 55(a) and night time as shown on Figure 55(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 55a). 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 55b), 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

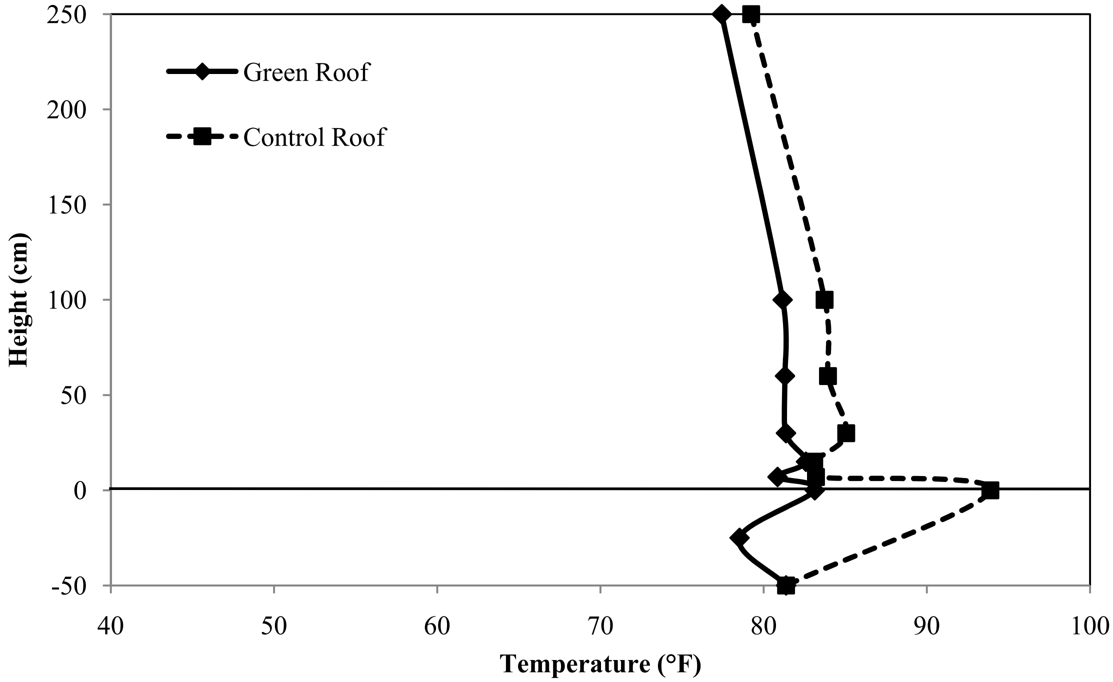
Figure 55. April, 2008 temperature profile at Homestead. Moderate weather conditions

6.1.3 Summer Thermal performance (hot weather condition)

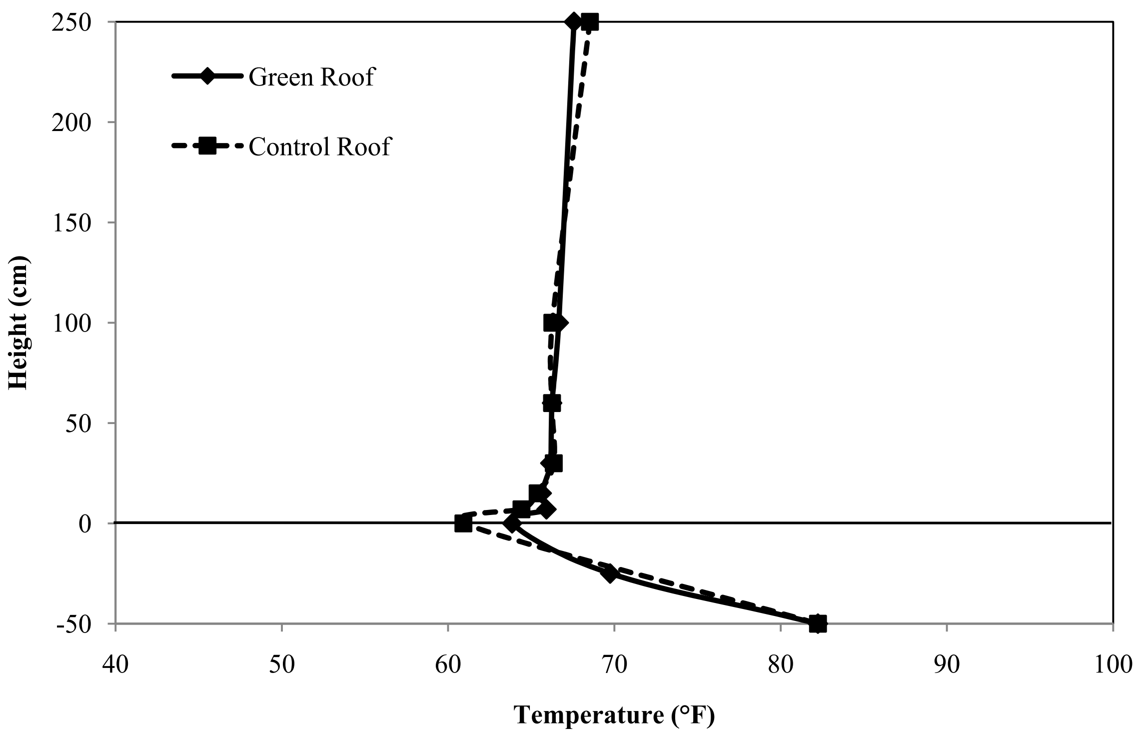
The temperature profile for June 2008 was chosen to be representative for hot weather conditions. Temperature profiles for other time periods during hot weather conditions are in Appendix B. The temperature data was divided into day (Figure 56a) and nighttime (Figure 56b) segments. As an overall observation, 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 56a, 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 56. June, 2008 temperature profile at Homestead Summer (hot) weather conditions

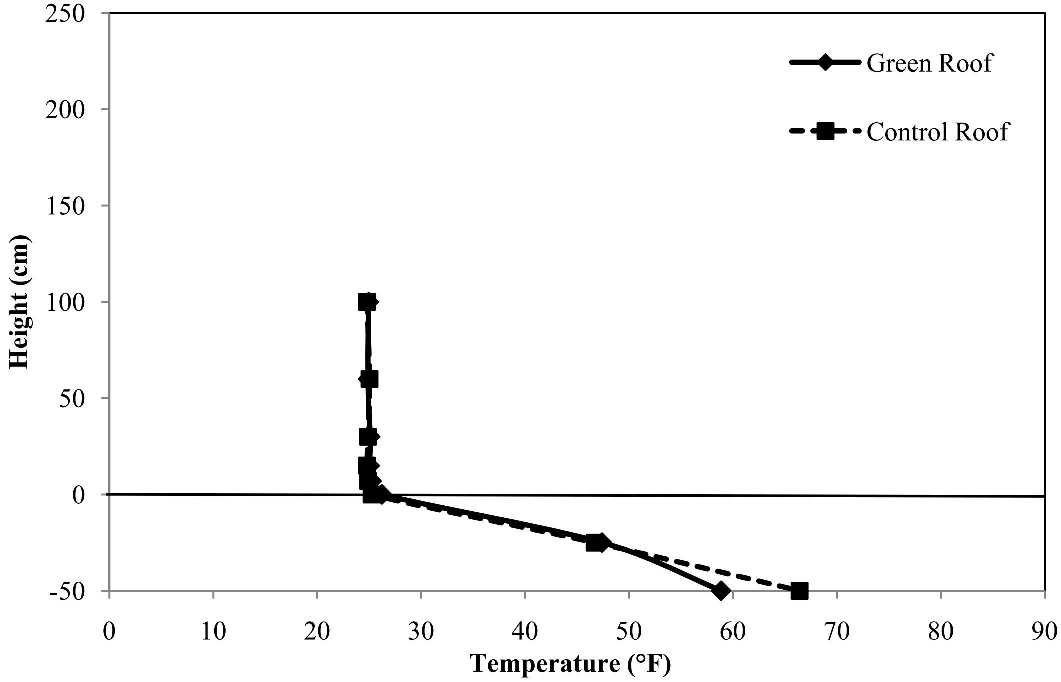
6.2 SEASONAL THERMAL PERFORMANCES FOR GIANT EAGLE SITE

The thermal performances at Giant Eagle site for both control and green roof are presented in this section. Seasonal thermal performances are evaluated and classified by cold, moderate and hot weather.

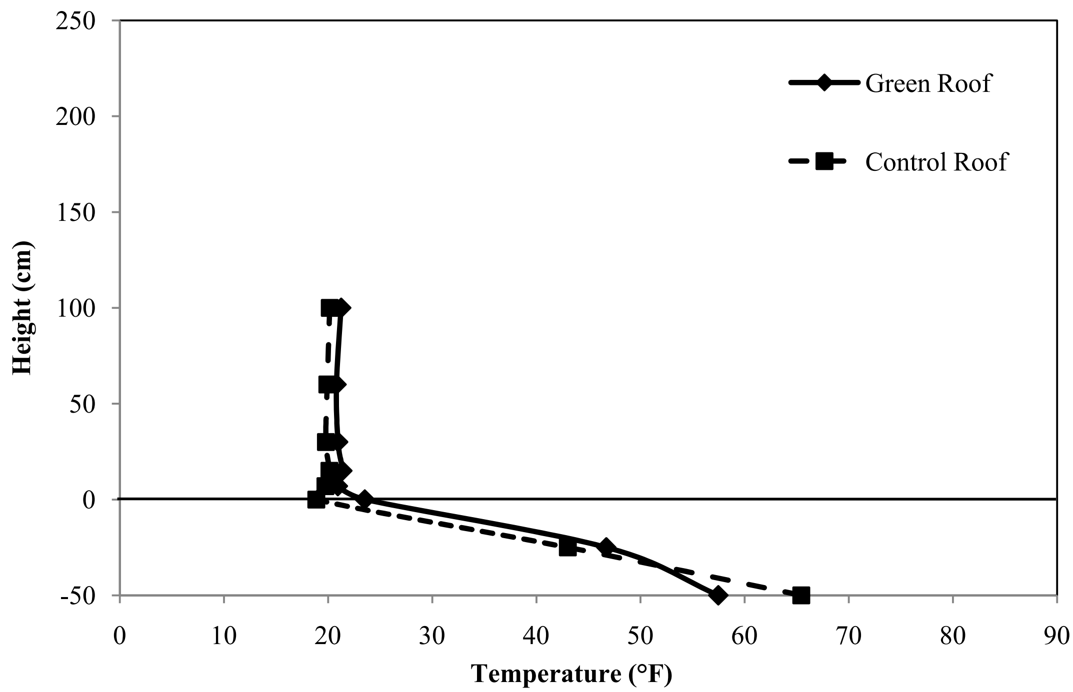
6.2.1 Winter thermal performance (cold weather conditions)

The temperature profile for the Giant Eagle roofs during January 2009 (shown in Figure 57a and Figure 57b), 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 B. 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 57a. 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 57b, 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



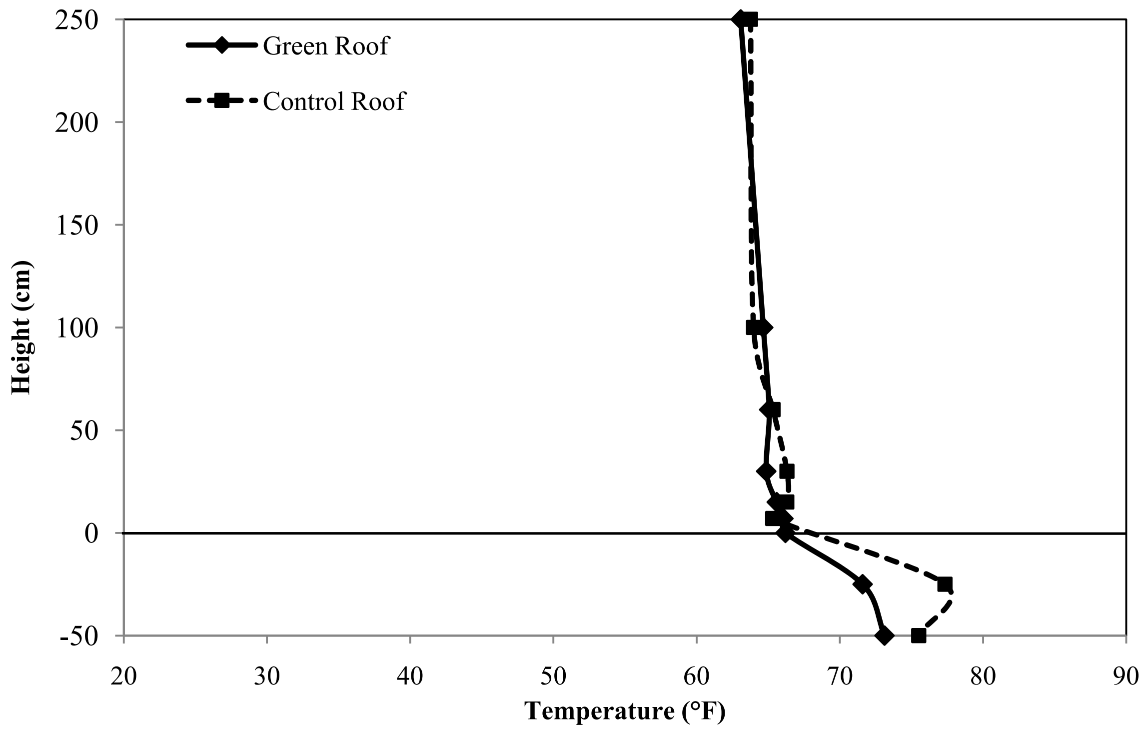
(b) Night-time temperature profile

Figure 57. January, 2009 temperature profile at Giant Eagle. Winter (cold) weather conditions

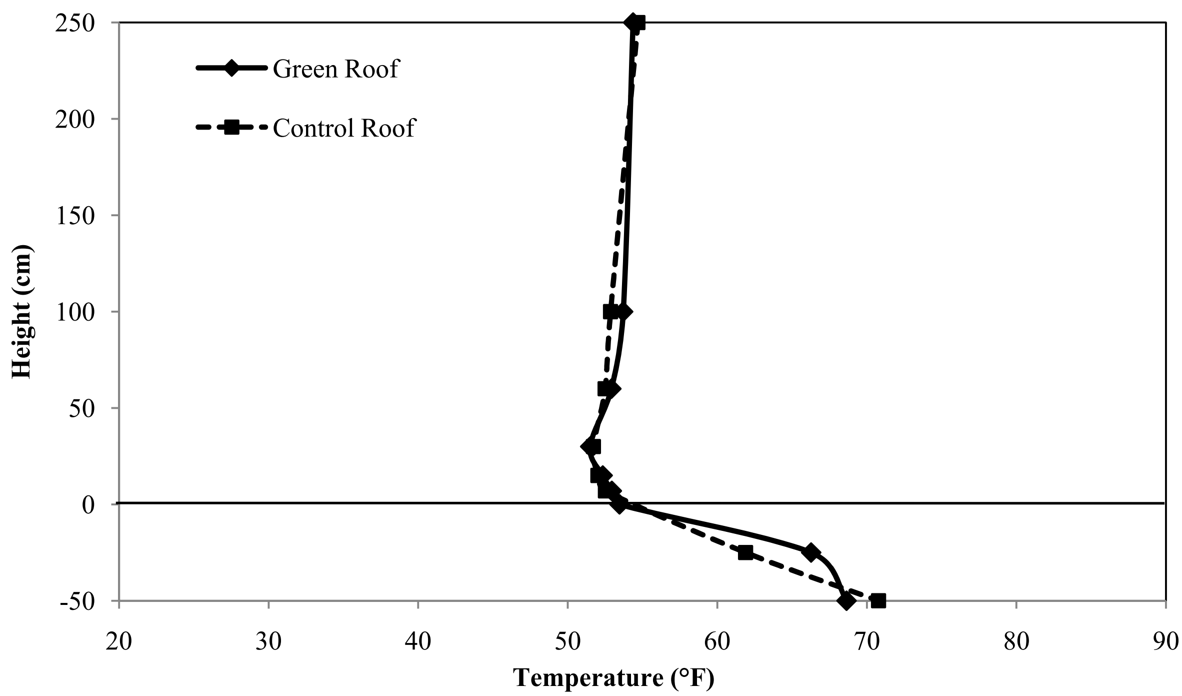
6.2.2 Spring and autumn thermal performance (moderate weather conditions)

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 B. The daytime and nighttime temperature profiles are presented in Figure 58(a) and Figure 58(b), respectively. As seen in Figure 58(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 58a, 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

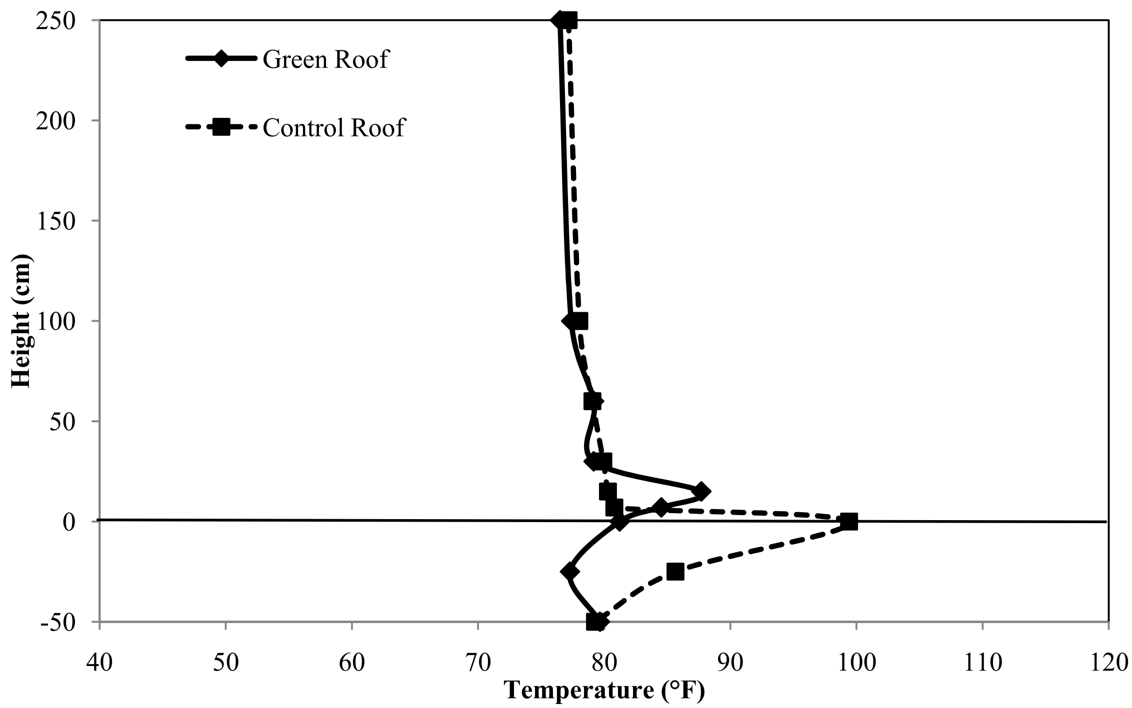
Figure 58. April 2008 temperature profile at Giant Eagle. Moderate weather conditions

6.2.3 Summer thermal performance (hot weather conditions)

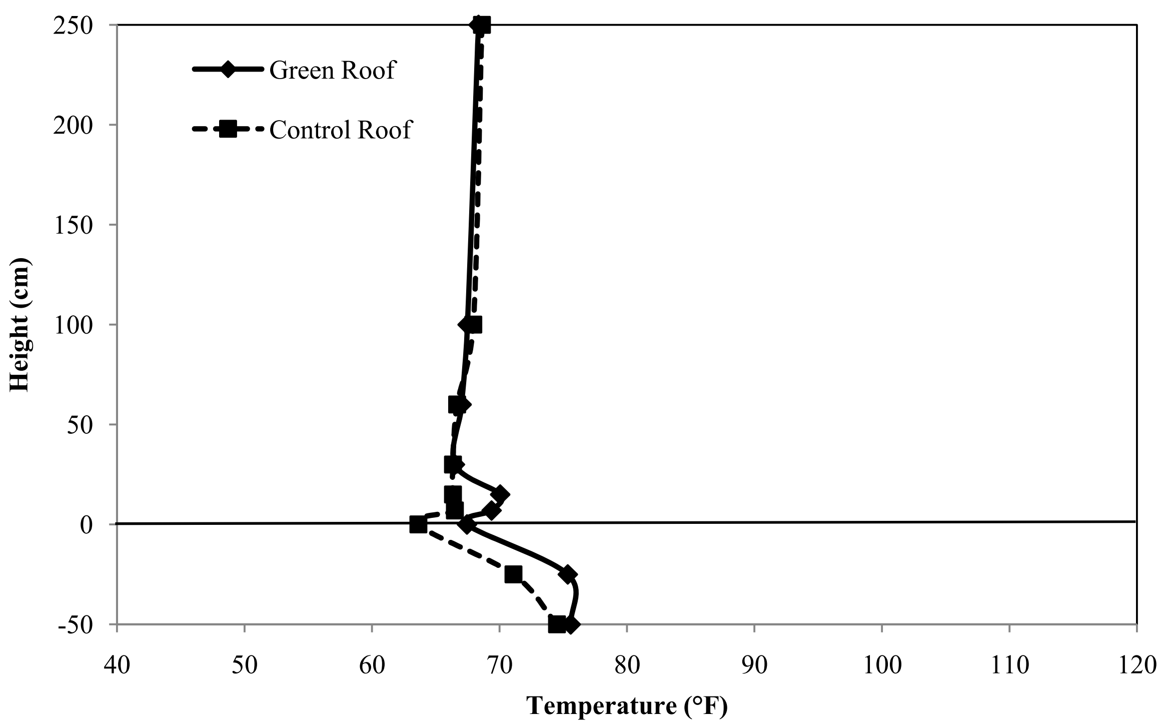
The temperature profile for Giant Eagle during June 2008 was chosen to be representative of the roofs thermal insulation properties during hot weather. Temperature profiles for other time periods during hot weather conditions for the Giant Eagle site are in Appendix B. The thermal profiles for daytime and nighttime are presented in Figure 59a and Figure 59b, respectively.

The ambient temperature above two roofs showed little differences. As seen in Figure 59(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 59b), 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 59a, 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 59b). 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 59. June, 2008 temperature profile at Giant Eagle

6.3 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.

6.3.1 Roof/soil surface temperature difference

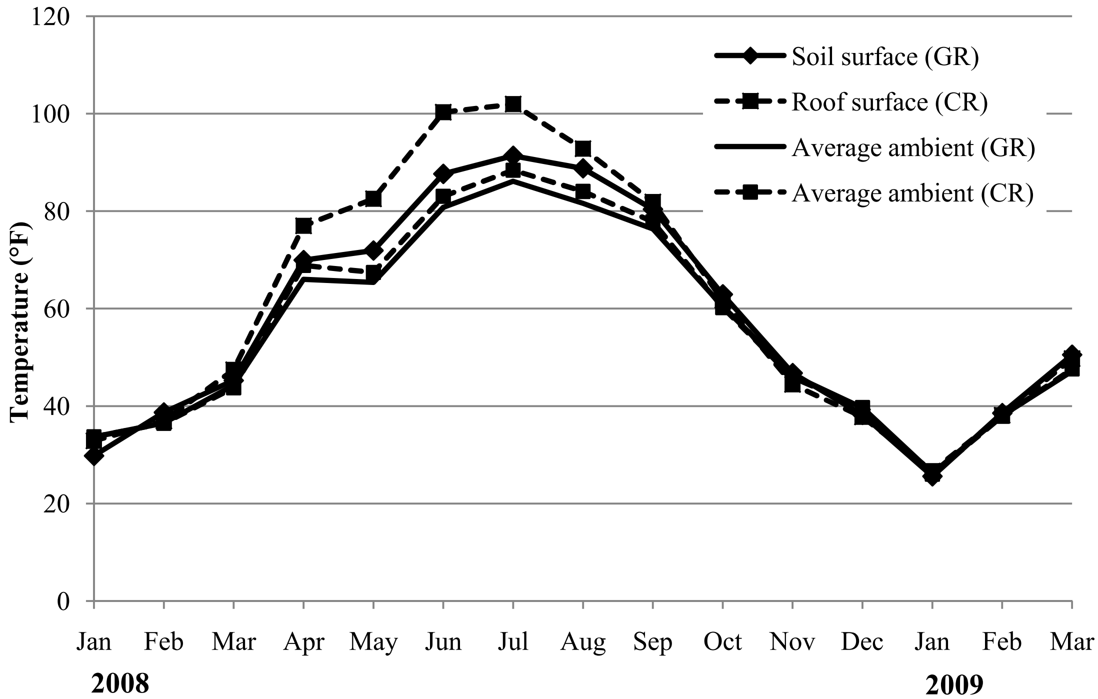
When looking at the entire 16-month time frame when comparative temperature profiles were collected, the average day time temperatures for the soil and roof surfaces were observed to be warmer than ambient for both the green and control roofs at both locations. Data for this section is listed on Table 10 and Table 11 of Appendix B.

During the warmer months, the thicker roof (Giant Eagle) was observed to maintain its temperature close or equal to ambient temperature (Figure 60b), whereas the thinner roof was observed to be generally warmer than the ambient temperature (Figure 60a). 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.

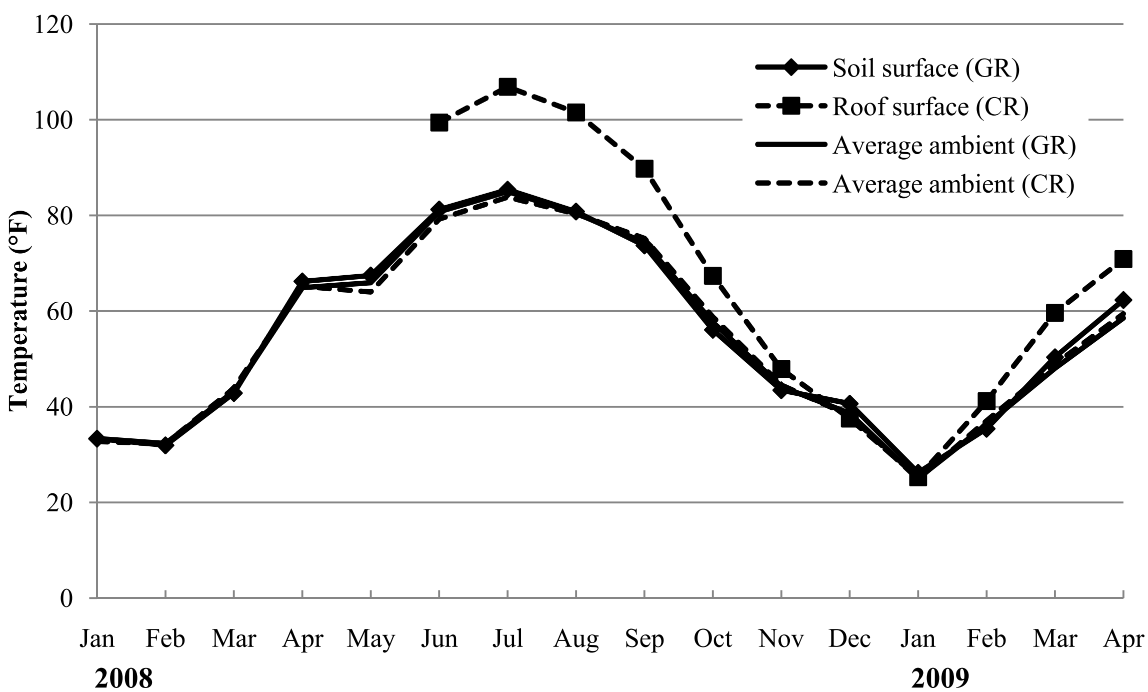
There was virtually no difference between the control roof and green roof surface at either location when the average temperature was below 45°F. As seen in day-time temperature profile at Homestead and Giant Eagle (Figure 60a & Figure 60b), the four temperature lines of ambient, soil surface and roof 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 61a+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 disappears.

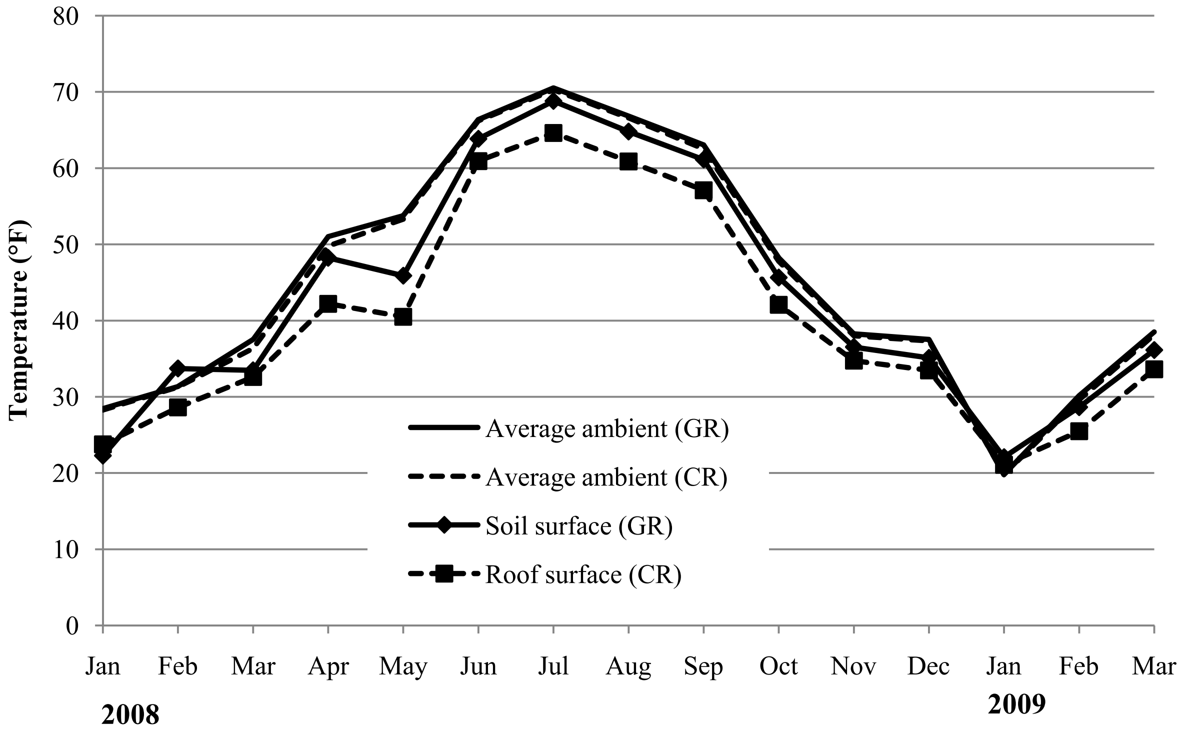


(a) Homestead

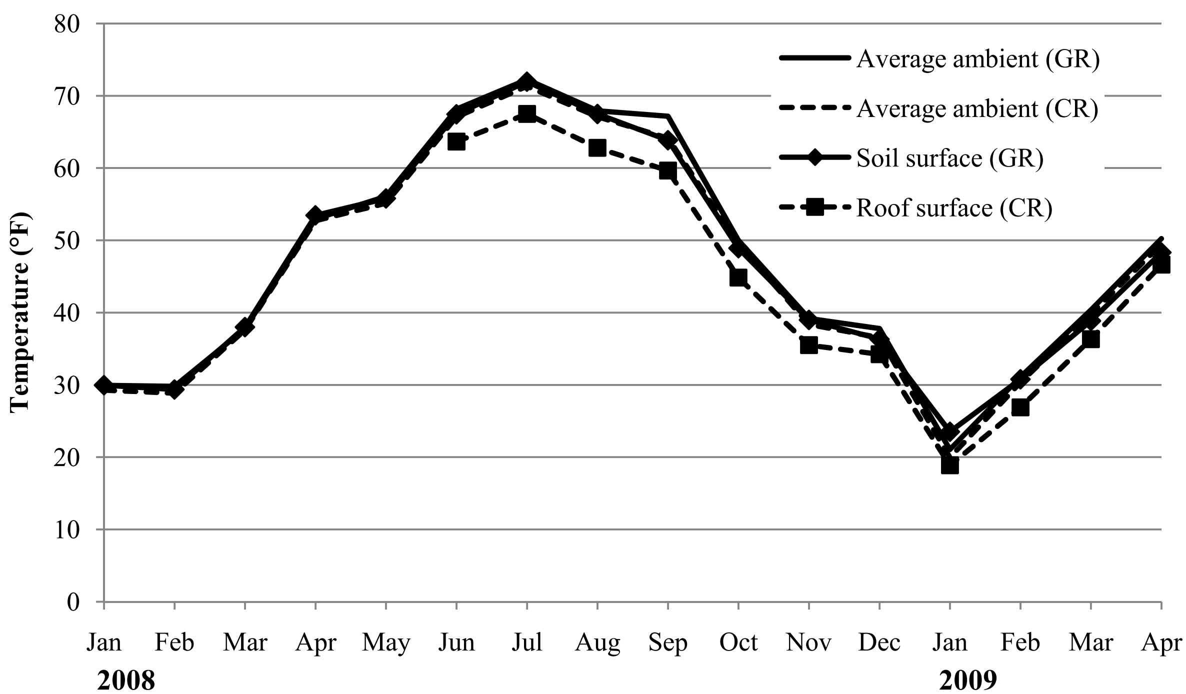


(b) Giant Eagle

Figure 60. Day-time monthly average temperature of ambient and soil/roof surface



(a) Homestead



(b) Giant Eagle

Figure 61. Night-time monthly average temperature of ambient and soil/roof surface

6.3.2 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 (Figure 62 and Figure 63) indicate that the largest seasonal and day to nighttime temperature 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 12 and Table 13 of Appendix B.

As shown on Figure 62, 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 63, 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.

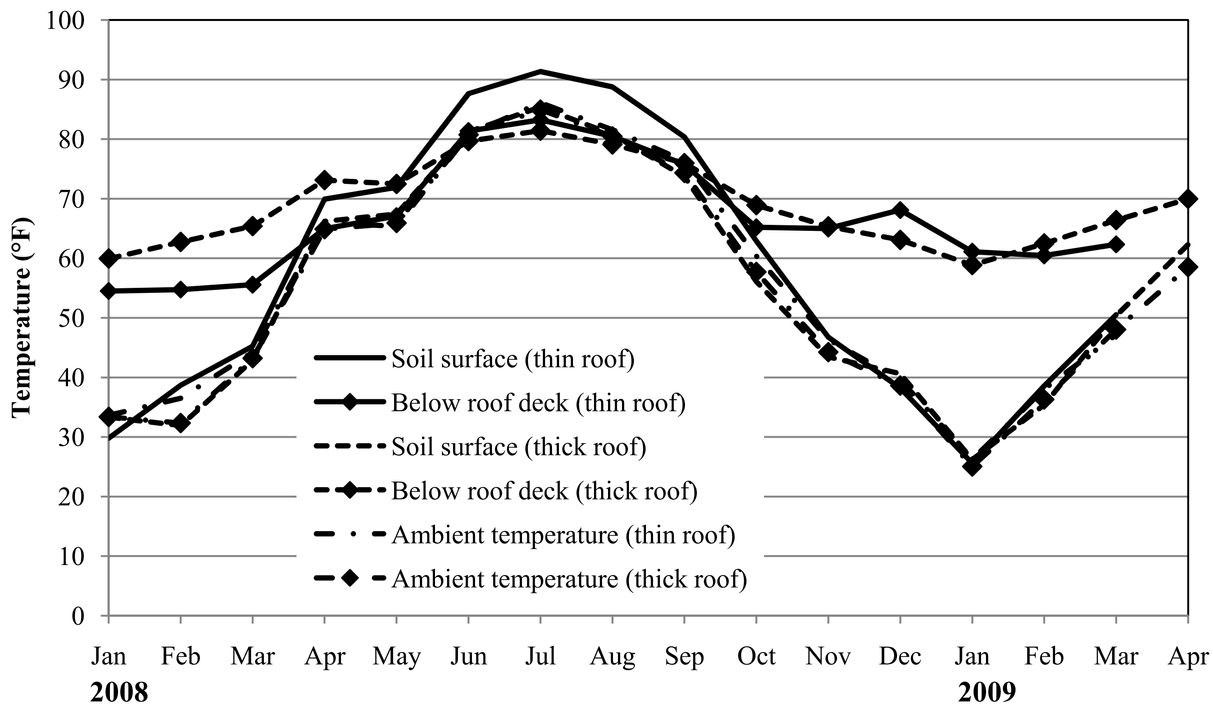


Figure 62. Day-time monthly average temperature of green roof soil surface and below roof deck

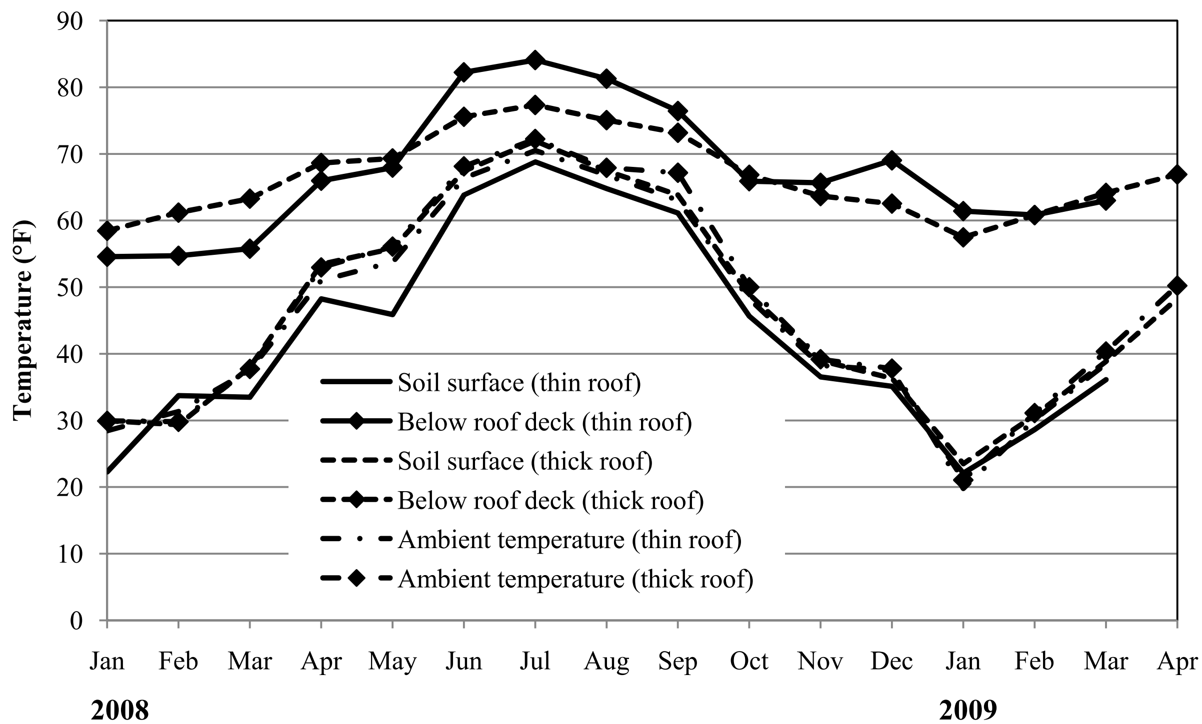


Figure 63. Night-time monthly average temperature of green roof soil surface and below roof deck

7.0 RUNOFF QUALITY ANALYSIS AND RESULTS

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). Since the valve system at Giant Eagle was no longer working at the end of 2007, the data of runoff quality will be referred to the article by Bliss (2007).

7.1 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 64) and green roof (Figure 65). Significant quantities of black solids (Figure 64) 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 solubilized within the green roof[5].

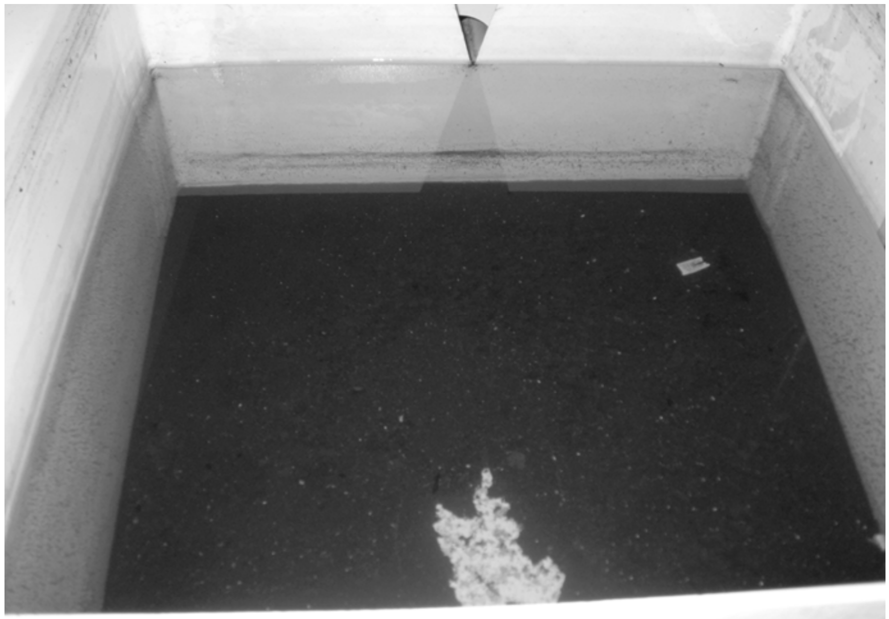


Figure 64. Runoff water from control roof stored in the weir box (Homestead)

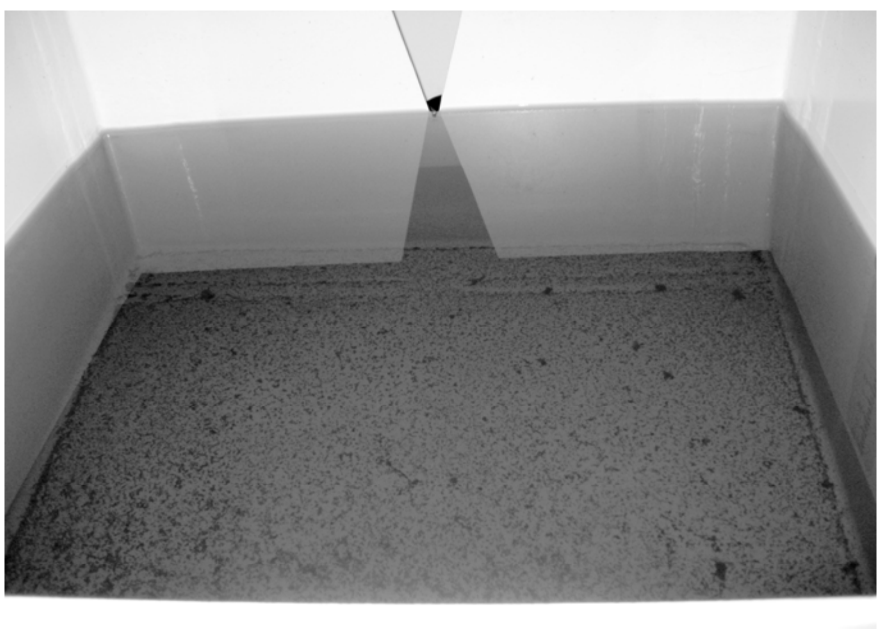


Figure 65. Runoff water from the green roof stored in the weir box (Homestead)

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

7.2 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 4**.

7.2.1 pH

The acid content in the runoff from the control roof at Homestead is higher than that from green roof. As seen in Figure 66, 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.

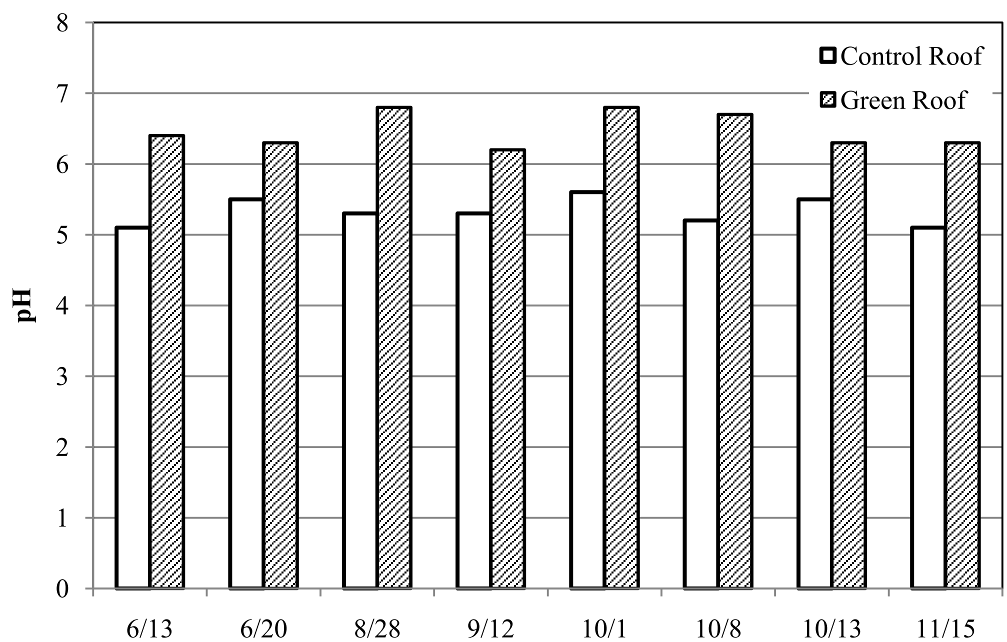


Figure 66. pH results (Homestead, 2008) (Samples were acquired on dates shown.)

7.2.2 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 67. 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.

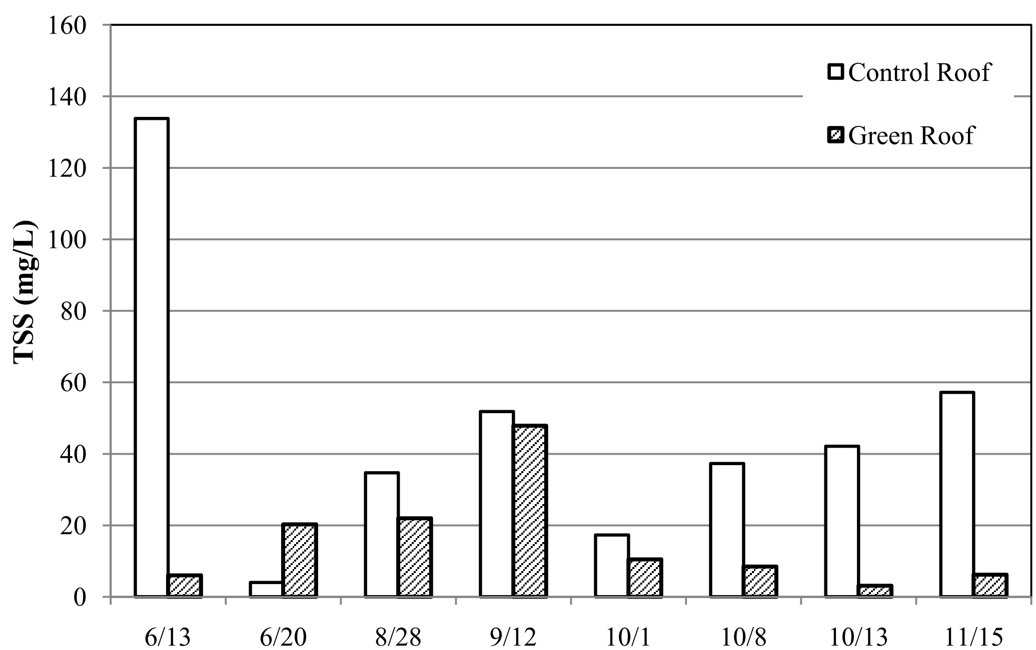


Figure 67. TSS results (Homestead, 2008) (Samples were acquired on dates shown)

7.2.3 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 68, 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.

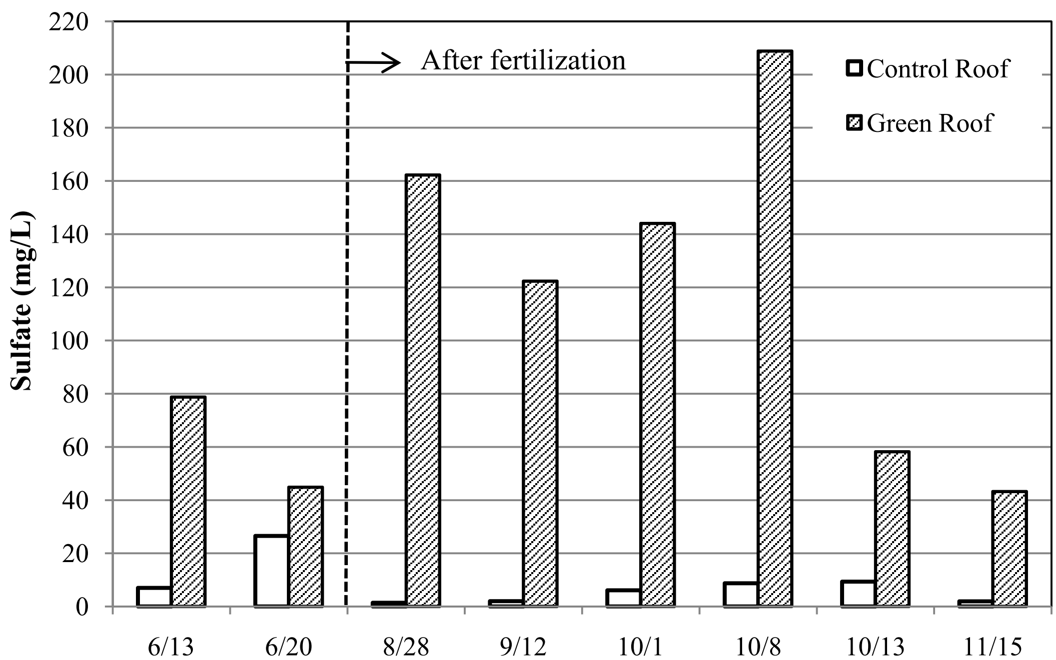


Figure 68. Sulfate results (Homestead, 2008)

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

7.2.4 Total Nitrogen

The nitrogen content of eight samples from Homestead during the 2008-growing season was measured. As shown in Figure 69, 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.

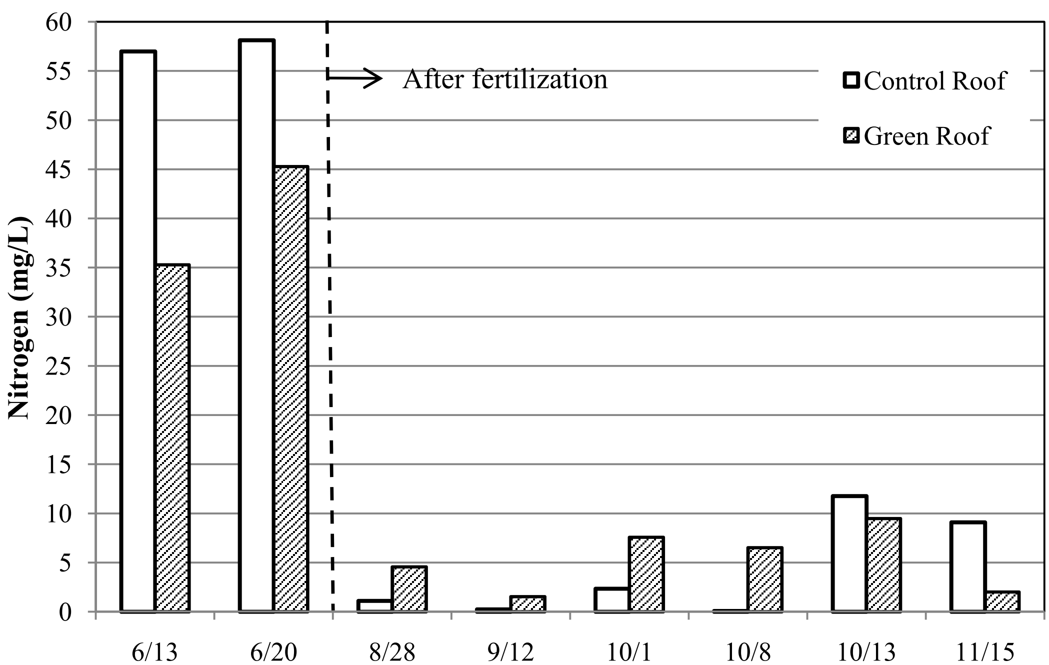


Figure 69. Nitrogen results (Homestead, 2008)

*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.

7.2.5 Total Phosphorous (Ortho and Polyphosphate)

The green roof consistently had higher phosphorous levels than the control roof in all runoff samples. Figure 70 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.

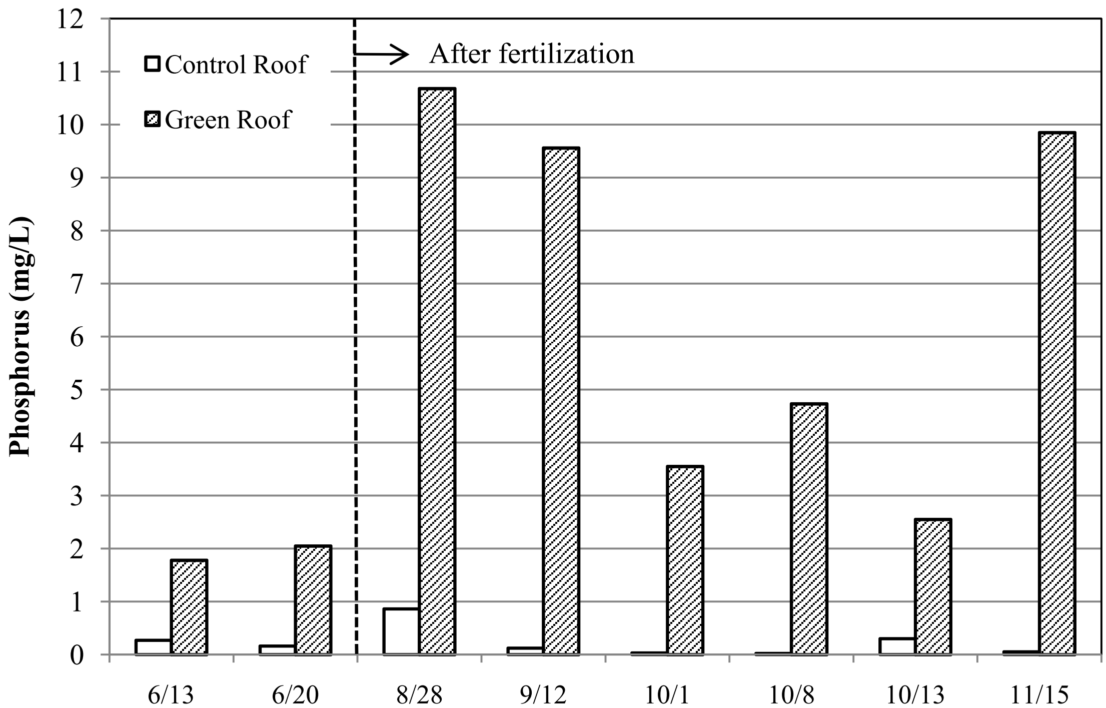


Figure 70. Phosphorus results (Homestead, 2008)

*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.

7.2.6 Chemical oxygen demand (COD)

The chemical oxygen demand for both green and control roof runoffs varied significantly. As seen in Figure 71, 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.

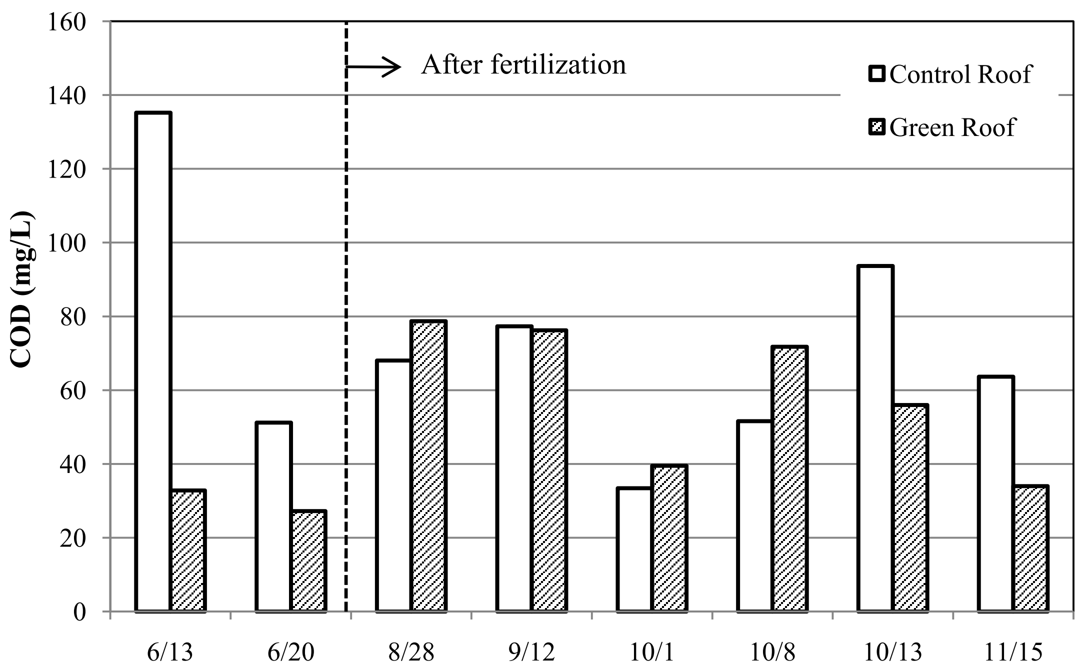


Figure 71. COD results (Homestead, 2008)

*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.

7.2.7 Metal ions

Metal ions include Cadmium, Lead and Zinc. However, the results came from the laboratory in **Table 4** does not show significant features among these metal ions.

7.3 SUMMARY: RUNOFF SAMPLES FROM GIANT EAGLE

The chemical parameters of runoff samples from Giant Eagle site are referred to Bliss (2007), which presented details of runoff water quality data 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 5 and shown on the figures below.

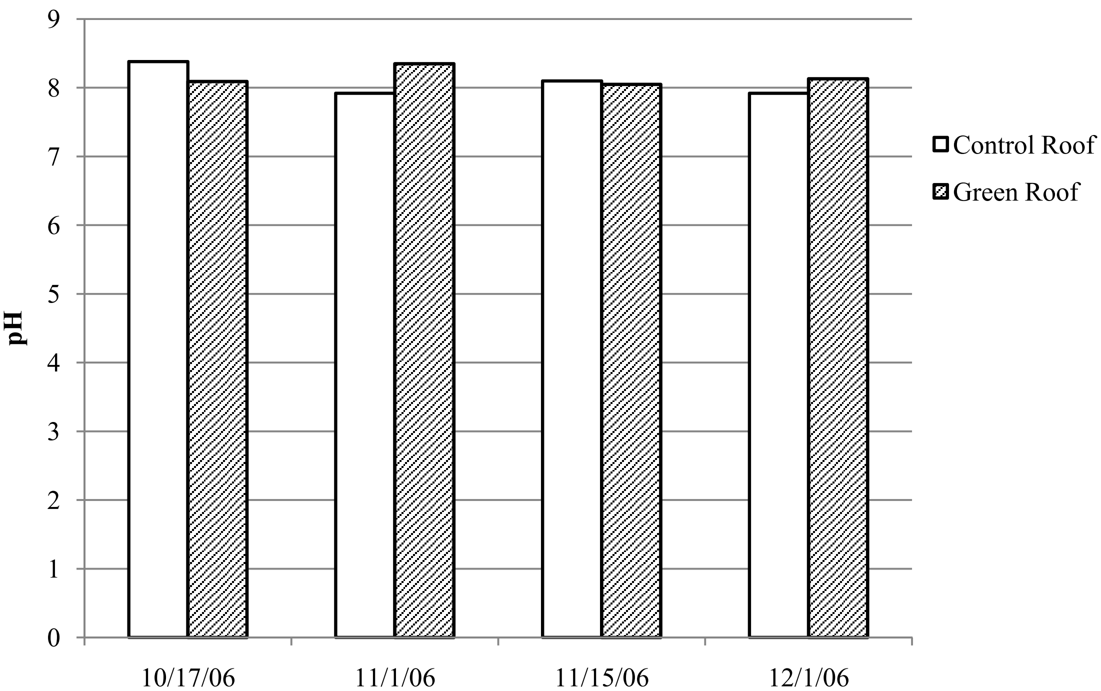


Figure 72. pH results (Giant Eagle, 2006)

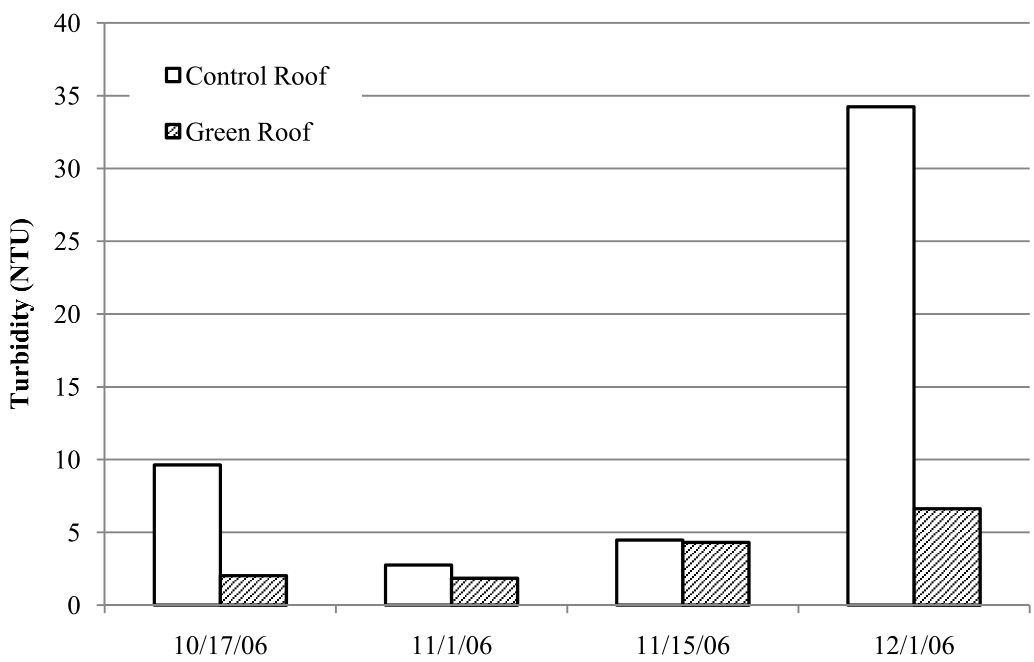


Figure 73. Sulfate results (Giant Eagle, 2006)

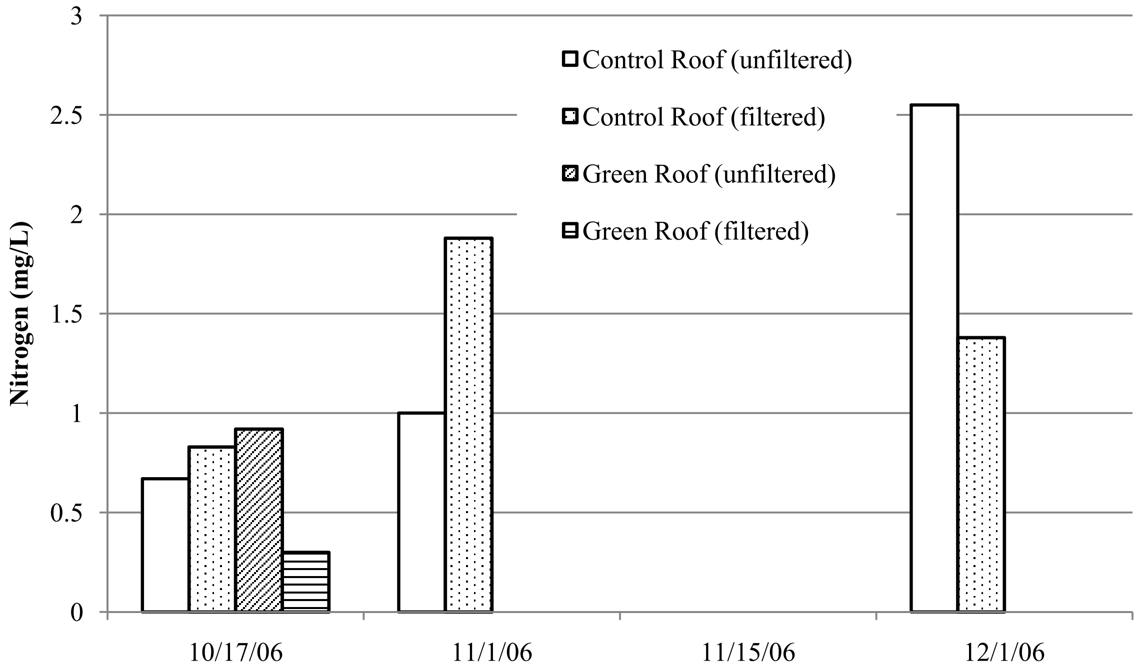


Figure 74. Nitrogen results (Giant Eagle, 2006)

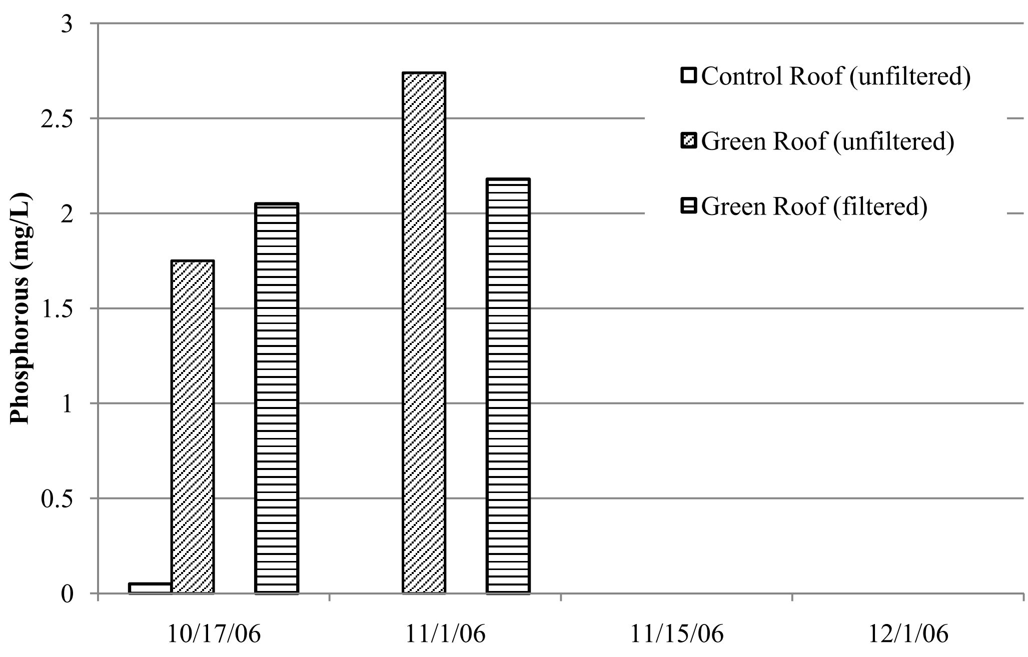


Figure 75. Phosphorus results (Giant Eagle, 2006)

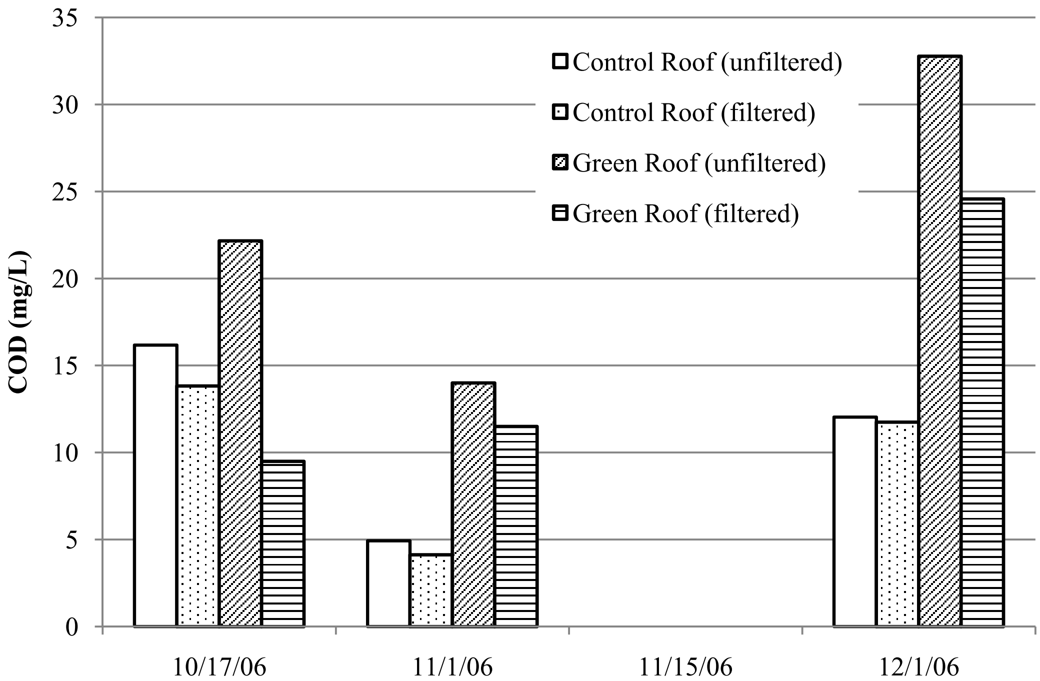


Figure 76. COD results (Giant Eagle, 2006)

7.4 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 for the Homestead thin roof on Table 4 for the Giant Eagle thick roof on Table 5 and a summary of conclusions showing significant differences is on Table 6.

The principle used to identify the statistical differences is the t-value (|t|) and t-critical, which are listed on Table 4 and Table 5. 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, 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 5, 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). The Homestead site exhibited high concentrations of TSS in the runoff sample of control roof (Table 4). 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 no significant differences between control and green roof at both sites for these metals.

Table 4. 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	Mean	S.D.[6]	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

[6] S.D. = Standard deviation

Table 5. 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.	t-value	t-critical
pH	Control		8.38	7.92	8.1	7.92	8.08	0.22	0.59	1.94
	Green		8.09	8.35	8.05	8.13	8.16	0.13		
Turbidity (NTU)	Control		9.63	2.75	4.47	34.23	12.77	14.60	1.23	1.94
	Green		2.02	1.85	4.31	6.62	3.70	2.25		
Sulfate (mg/L)	Unfiltered	Control	23.67	15.04		23.1	20.60	4.83	1.59	2.13
		Green	42	21.5		29.6	31.03	10.32		
	Filtered	Control	22.83	30.75		18.7	24.09	6.12	0.75	2.13
		Green	15.33	16		28.5	19.94	7.42		
Nitrogen (mg/L)	Unfiltered	Control	0.67	1		2.55	1.41	1.00	1.68	2.13
		Green	0.92	0		0	0.31	0.53		
	Filtered	Control	0.83	1.88		1.38	1.36	0.53	3.96	2.13
		Green	0.3	0		0	0.10	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	16.17	4.93		12.03	11.04	5.68	1.88	2.13
		Green	22.17	14		32.78	22.98	9.42		
	Filtered	Control	13.83	4.13		11.75	9.90	5.11	0.95	2.13
		Green	9.5	11.5		24.58	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		

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

<table>
<tr><th rowspan="2">Chemical parameters</th><th colspan="2">Homestead
(thin roof technology)</th><th colspan="3">Giant Eagle
(thick roof technology)</th></tr>
<tr><th>Roof type</th><th>Significant Difference?</th><th colspan="2">Roof Type</th><th>Significant Difference?</th></tr>
<tr><td rowspan="2">pH</td><td>Control</td><td rowspan="2">YES</td><td colspan="2">Control</td><td rowspan="2">NO</td></tr>
<tr><td>Green</td><td colspan="2">Green</td></tr>
<tr><td rowspan="2">TSS (mg/L) - Homestead; Turbidity(NTU) - Giant Eagle</td><td>Control</td><td rowspan="2">YES</td><td colspan="2">Control</td><td rowspan="2">NO</td></tr>
<tr><td>Green</td><td colspan="2">Green</td></tr>
<tr><td rowspan="4">Sulfate (mg/L)</td><td rowspan="2">Control</td><td rowspan="4">YES</td><td rowspan="2">Unfiltered</td><td>Control</td><td rowspan="2">NO</td></tr>
<tr><td>Green</td></tr>
<tr><td rowspan="2">Green</td><td rowspan="2">Filtered</td><td>Control</td><td rowspan="2">NO</td></tr>
<tr><td>Green</td></tr>
<tr><td rowspan="4">Nitrogen (mg/L)</td><td rowspan="2">Control</td><td rowspan="4">NO</td><td rowspan="2">Unfiltered</td><td>Control</td><td rowspan="2">NO</td></tr>
<tr><td>Green</td></tr>
<tr><td rowspan="2">Green</td><td rowspan="2">Filtered</td><td>Control</td><td rowspan="2">YES</td></tr>
<tr><td>Green</td></tr>
<tr><td rowspan="4">Phosphorus (mg/L)</td><td rowspan="2">Control</td><td rowspan="4">YES</td><td rowspan="2">Unfiltered</td><td>Control</td><td rowspan="2">YES</td></tr>
<tr><td>Green</td></tr>
<tr><td rowspan="2">Green</td><td rowspan="2">Filtered</td><td>Control</td><td rowspan="2">ND</td></tr>
<tr><td>Green</td></tr>
<tr><td rowspan="4">COD (mg/L)</td><td rowspan="2">Control</td><td rowspan="4">NO</td><td rowspan="2">Unfiltered</td><td>Control</td><td rowspan="2">NO</td></tr>
<tr><td>Green</td></tr>
<tr><td rowspan="2">Green</td><td rowspan="2">Filtered</td><td>Control</td><td rowspan="2">NO</td></tr>
<tr><td>Green</td></tr>
<tr><td rowspan="2">Cd (mg/L)</td><td>Control</td><td rowspan="2">ND</td><td colspan="2">Control</td><td rowspan="2">ND</td></tr>
<tr><td>Green</td><td colspan="2">Green</td></tr>
<tr><td rowspan="2">Pb (mg/L)</td><td>Control</td><td rowspan="2">ND</td><td colspan="2">Control</td><td rowspan="2">NO</td></tr>
<tr><td>Green</td><td colspan="2">Green</td></tr>
<tr><td rowspan="2">Zn (mg/L)</td><td>Control</td><td rowspan="2">NO</td><td colspan="2">Control</td><td rowspan="2">NO</td></tr>
<tr><td>Green</td><td colspan="2">Green</td></tr>
</table>

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.

8.0 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 also 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 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, and temperature probes 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. 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
Runoff quantity performances	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
Runoff quantity performances	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.
Runoff quantity performances	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
Thermal performances	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
Thermal performances	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	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.
Runoff quality performances	Fertilization during the summer of 2008 by the owner of the Homestead green roof influenced the runoff quality results.	

Table 8. 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 effect due to the 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 of N & P.	

9.0 CONCLUSION

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.

The peak flow rate reductions during the 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 77. 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).

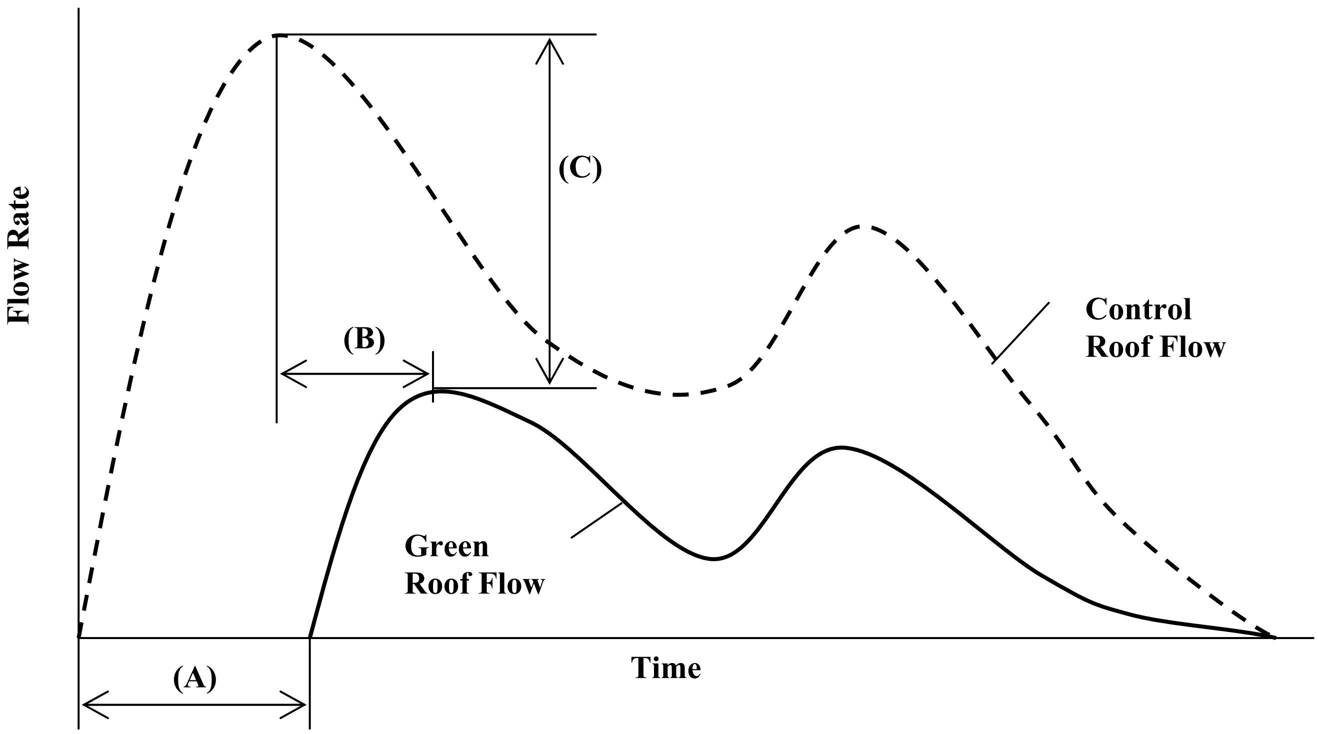


Figure 77. Runoff parameters of importance: control and green roof discharges

(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 the study

phase ranged from 100% for the light storm to 1% for the heavy. 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 3.4 hours behind the control roof runoff and only 1.2 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.

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. 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*).

2. 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.

3. 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.

4. 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 improving urban stormwater management, as well as mitigating urban island effect.

10.0 SUGGESTIONS FOR FURTHER STUDY

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.

APPENDIX A

RUNOFF QUANTITY DATA FOR INDIVIDUAL STORM

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 9. Flow Rate and runoff volumes for individual rainfall events

				Maximum Peak Flow Rate (cf/s)			Retardation (Δ_t) (hr)		Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		
	Location	Rainfall (in)	Soil Condition	Control	Green	% Reduc.	Dry	Wet	Control	Green	V_G/V_R	V_G/V_C	Water Retained (%)
4/20/2008	Homestead	0.57	Dry	0.0058	0.0035	40%	2.0		42.52	23.37	49%	55%	51%
	Giant Eagle		Dry	0.0116	0.0082	29%	4.0		62.28	26.79		43%	
4/28/2008	Homestead	1.04	Dry	0.0107	0.0084	21%	3.5		83.68	68.76	79%	82%	21%
5/7-5/8, 2008	Homestead	0.43	Dry	0.0091	0.0044	52%	8.7		32.65	6.23	17%	19%	83%
	Giant Eagle		Dry	0.0125	0.0022	82%	6.9		45.83	3.72		8%	
5/9-5/10, 2008	Homestead	1.25	Wet	0.0130	0.0117	10%		2.7	101.77	82.47	79%	81%	21%
	Giant Eagle		Wet	0.0251	0.0214	15%		1.3	92.21	83.18		90%	
5/11-5/12, 2008	Homestead	0.57	Wet	0.0135	0.0034	75%		3.1	44.79	19.76	42%	44%	58%
	Giant Eagle		Wet	0.0121	0.0096	21%		0	46.01	36.67		80%	
5/17/2008	Homestead	0.12	Dry	0.0234	0.0034	85%	3.0		10.00	1.71	11%	17%	89%
	Giant Eagle	0.2	Dry	0.0046	0.0024	48%	1.7		7.04	2.99	18%	42%	82%
5/18/2008	Homestead	0.18	Wet	0.0129	0.0057	56%		1	11.84	6.63	21%	56%	79%
	Giant Eagle	0.47	Wet	0.0096	0.0085	12%		0	32.85	27.87	71%	85%	29%
5/31/2008	Homestead	0.3	Dry	0.0075	0.0011	85%	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%	1.3		20.29	3.10		15%	
	Giant Eagle	0.98	Dry	0.0145	0.0029	80%	16.7		65.07	3.71	5%	6%	95%
6/5/2008	Homestead	0.15	Wet	0.0035	0.0022	38%		0.6	12.50	2.06	16%	16%	84%
	Giant Eagle	0.15	Wet	0.0084	0.0032	61%		0	11.27	4.21	34%	37%	66%
6/13-6/14, 2008	Homestead	2.25	Dry	0.0333	0.0174	48%	0		68.81	55.42	30%	81%	70%
	Giant Eagle	1.65	Dry	0.0208	0.0096	54%	10.3		91.92	36.11	26%	39%	74%
6/16/2008	Homestead	0.16	Wet	0.0077	0.0003	96%		0	13.33	0.18	1%	1%	99%
	Giant Eagle	0.16	Wet	0.0014	0	100%			1.83	0	0%	0%	100%

Table 9 (continued)

	Location	Rainfall (in)	Soil Condition	Maximum Peak Flow Rate (cf/s)			Retardation (Δ_t) (hr)		Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		Water Retained (%)
				Control	Green	% Reduc.	Dry	Wet	Control	Green	V_G/V_R	V_G/V_C	
6/20/2008	Homestead	0.25	Dry	0.0166	0.0023	86%	2.1		20.83	1.67	8%	8%	92%
	Giant Eagle	0	Dry	0	0				0	0			
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	0.0067	41%		0	46.67	12.87	28%	28%	72%
	Giant Eagle		wet	0.0260	0.0017	94%		0	33.77	2.55	4%	8%	96%
6/26-6/27, 2008	Homestead	1.39	Dry	0.0256	0.0091	64%	1.9		43.66	35.36	28%	81%	72%
	Giant Eagle		Dry	0.0258	0.0207	20%	1.8		122.46	92.73		76%	
6/28/2008	Homestead	0.37	Wet	0.0244	0.0077	69%		0	30.83	7.76	25%	25%	75%
	Giant Eagle		Wet	0.0156	0.0087	44%		0	23.69	14.11	35%	60%	65%
6/29/2008	Homestead	0.49	Wet	0.0257	0.0151	41%		0	40.83	22.06	54%	54%	46%
	Giant Eagle	0.4	Wet	0.0075	0.0061	19%		0	16.88	11.41	34%	68%	66%
6/30-7/1, 2008	Homestead	2.16	Wet	0.0407	0.0367	10%		0	106.00	136.8	76%	-29%	24%
	Giant Eagle	0.69	Wet	0.0132	0.0123	7%		0	35.90	29.79	52%	83%	48%
7/3/2008	Homestead		Wet	0.0042	0.0038	9%		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		32.71	20.91	36%	64%	64%
7/8-7/9, 2008	Giant Eagle	0.56	Wet	0.0207	0.0123	40%		0	28.58	20.06	43%	70%	57%
7/20/2008	Homestead	0.54	Dry	0.0402	0.0147	64%	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	15.31	5.75	31%	38%	69%
	Giant Eagle	0.22	Dry	0.0045	0	100%	0		5.35	0	0%	0%	100%

Table 9 (continued)

	Location	Rainfall (in)	Soil Condition	Maximum Peak Flow Rate (cf/s)			Retardation (Δ_t) (hr)		Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		Water Retained (%)
				Control	Green	% Reduc.	Dry	Wet	Control	Green	V_G/V_R	V_G/V_C	
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%		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%
	Giant Eagle	0	Dry	0	0				0	0			
7/30/2008	Homestead	0.47	Dry	0.0496	0.0054	89%	0		23.07	7.44	19%	32%	81%
	Giant Eagle	0.84	Dry	0.0720	0.0068	90%	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	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	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%	0.7		7.19	0.19	1%	3%	99%
	Giant Eagle		Dry	0.0236	0.0065	73%	0		48.44	19.61		40%	
8/25/2008	Homestead	0.04	Dry	0.0024	0	100%			0.67	0	0%	0%	100%
	Giant Eagle	0	Dry	0	0				0	0			
8/27-8/28, 2008	Homestead	0.88	Wet	0.0086	0.0084	1%		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%

Table 9 (continued)

				Maximum Peak Flow Rate (cf/s)			Retardation (Δ_t) (hr)		Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		
	Location	Rainfall (in)	Soil Condition	Control	Green	% Reduc	Dry	Wet	Control	Green	V_G/V_R	V_G/V_C	Water Retained (%)
9/12/2008	Homestead	1.83	Dry	0.0327	0.0219	33%	1.9		69.01	79.06	52%	-15%	48%
	Giant Eagle	2.42	Dry	0.0972	0.0350	64%	0		161.57	69.01	34%	43%	66%
9/13/2008	Homestead	0.29	Wet	0.0067	0.0019	72%		0	6.77	2.49	10%	37%	90%
	Giant Eagle	0.25	Wet	0.0033	0.0016	51%		10.3	15.31	2.44	12%	16%	88%
10/1/2008	Homestead	0.25	Dry	0.0109	0.0046	58%	2.6		9.41	4.66	22%	50%	78%
	Giant Eagle	0		0	0				0	0			
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%	6.6		33.53	36.41	33%	-9%	67%
	Giant Eagle	1.16	Dry	0.0196	0.0108	45%	4.7		95.56	61.00	63%	64%	37%
11/15/2008	Homestead	0.79	Dry	0.0035	0.0020	43%	0		9.70	10.03	15%	-3%	85%
	Giant Eagle	0.61	Dry	0.0104	0.0081	22%	1.1		46.15	34.35	91%	74%	9%
11/30/2008	Homestead	0.35	Dry	0.0029	0.0007	74%	7.2		2.10	0.56	2%	27%	98%
	Giant Eagle		Dry	0.0043	0.0033	24%	1.2		32.75	24.21		74%	
2/10/2009*	Homestead	0.07	Wet	0.0019	1.58E-05	99%		0	0.60	0.02	0.3%	3%	97%
	Giant Eagle	0.38	Wet	0.0110	0.0025	77%		0.7	24.85	20.49	65%	82%	18%
2/18-2/19, 2009*	Homestead	0.34	Wet	0.0035	0.0005	87%		5.7	5.37	0.98	3%	18%	82%
	Giant Eagle	0.32	Wet	0.0085	0.0047	45%		5.6	20.57	11.96	42%	58%	42%
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%	0.6		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%		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%

Table 9 (continued)

	Location	Rainfall (in)	Soil Condition	Maximum Peak Flow Rate (cf/s)			Retardation (Δ_t) (hr)		Cumulative Runoff Volume (cf/1000sf)		Cumulative Runoff Ratio (%)		Water Retained (%)
				Control	Green	% Reduc	Dry	Wet	Control	Green	V_G/V_R	V_G/V_C	
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%

GR: Green Roof, CR: Control Roof
Retardation (Δt)=Time of initial flowing of control roof - Time of initial flowing for green roof
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
As for rainfall events at 2/10/2009 and 2/18-2/19, 2009, due to the possibility of melted snow, the soil conditions prior to the storm were considered as wet.

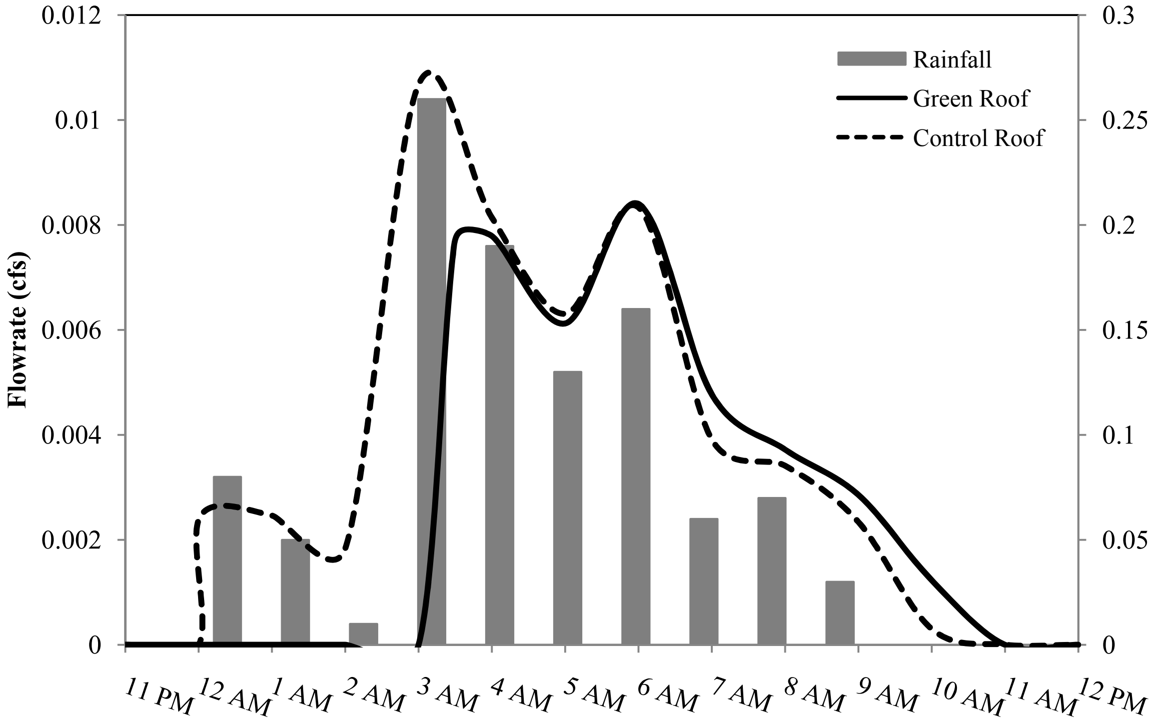


Figure 78. Runoff Flow Rates and Rainfall intensity – April 28, 2008 Storm (Homestead)

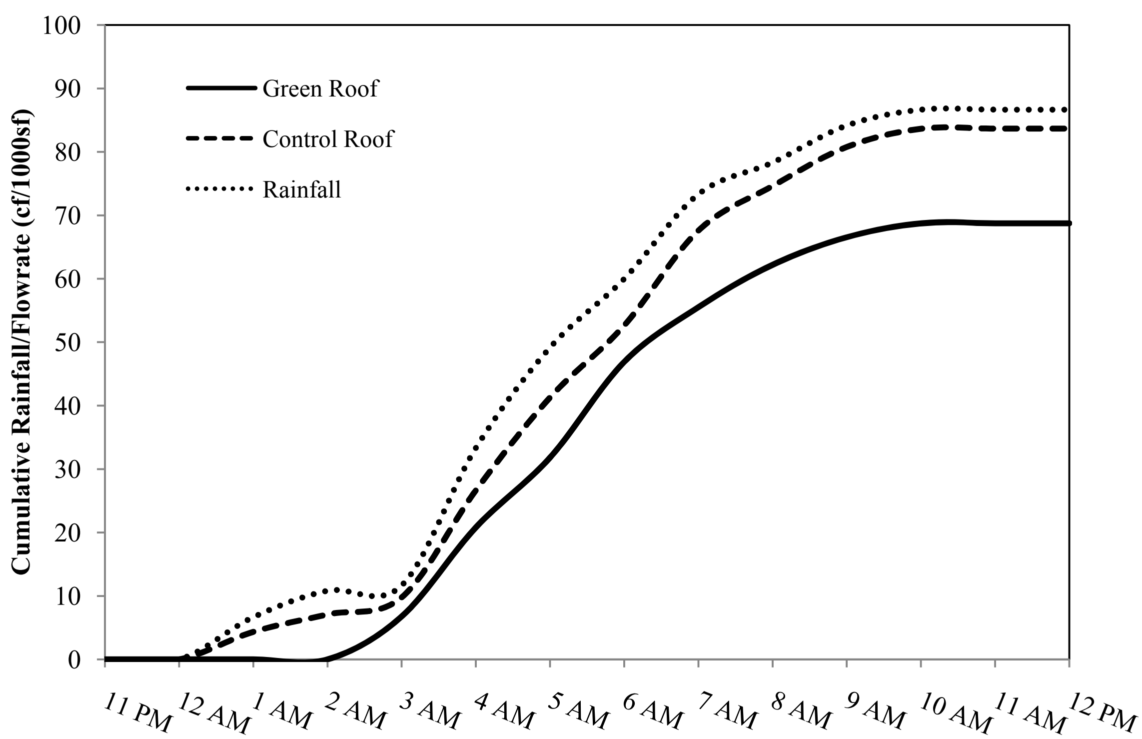


Figure 79. Runoff and rainfall volumes – April 28, 2008 Storm (Homestead)

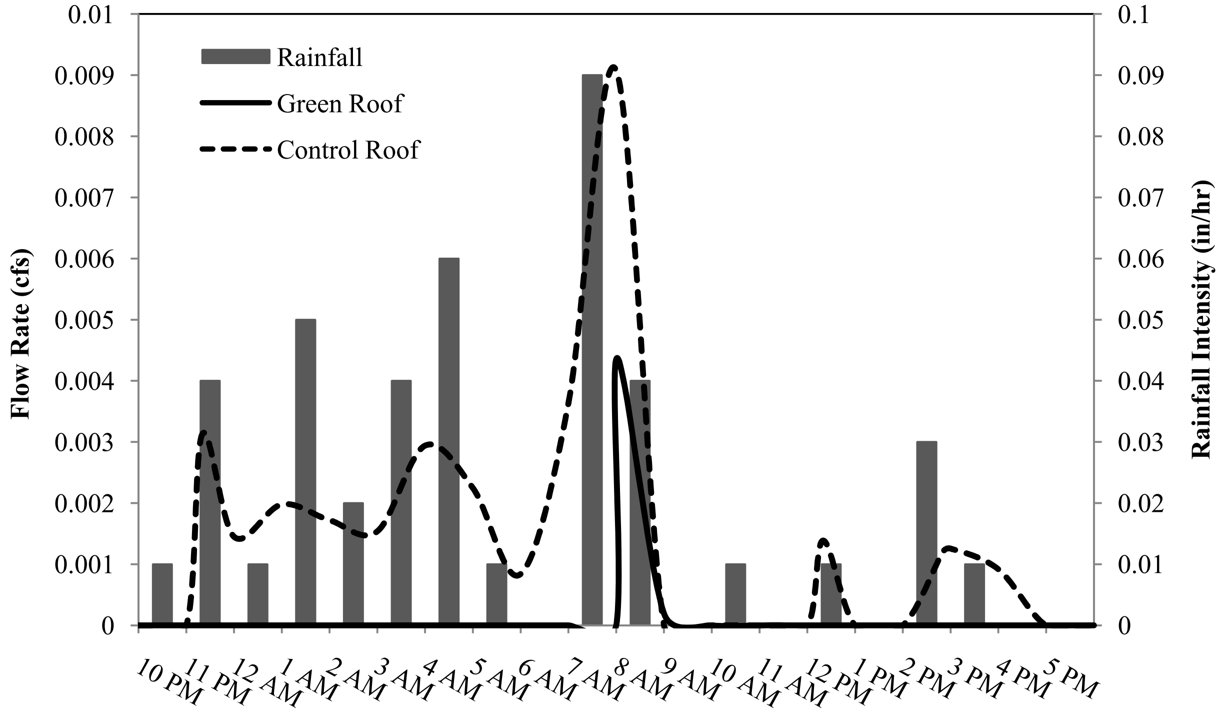


Figure 80. Runoff Flow Rates and Rainfall intensity – May 7-8, 2008 Storm (Homestead)

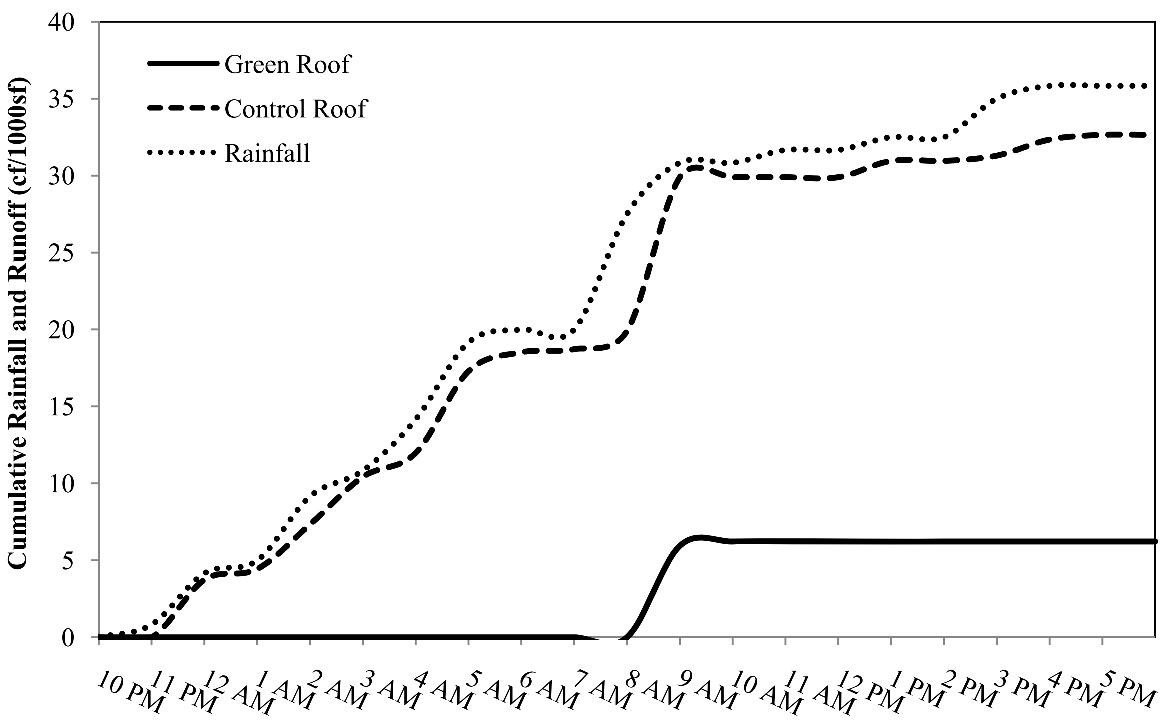


Figure 81. Runoff and rainfall volumes – May 7-8, 2008 Storm (Homestead)

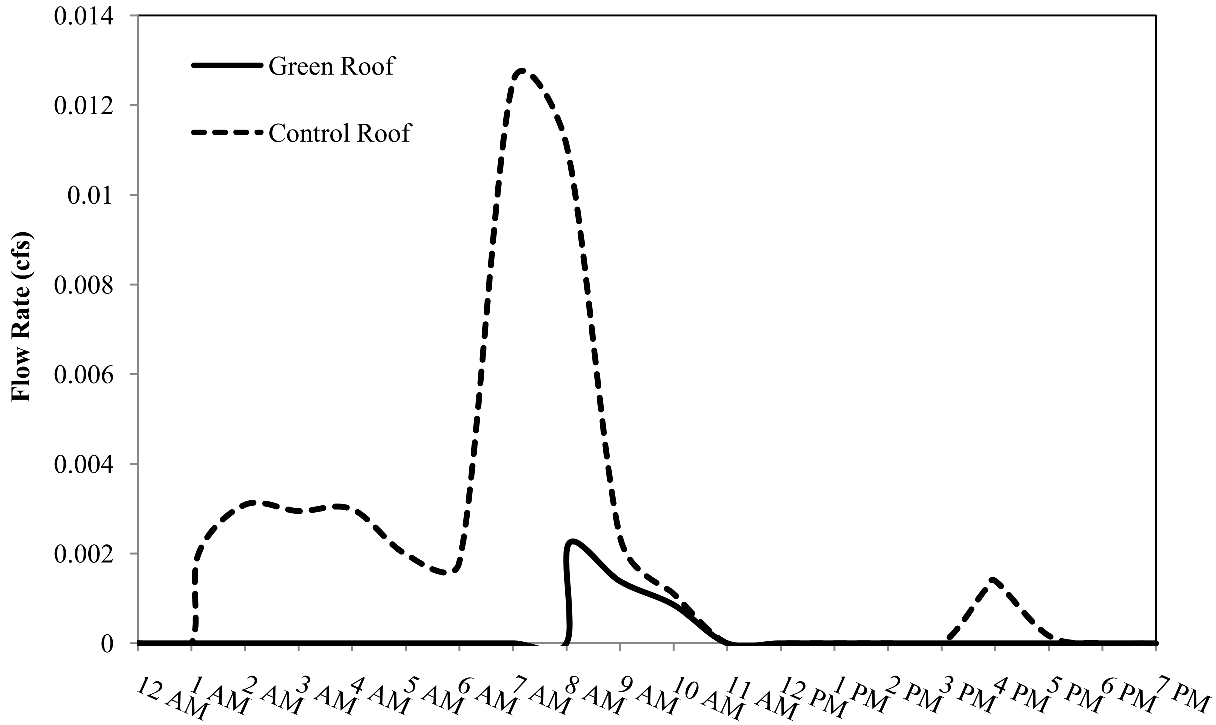


Figure 82. Runoff flow Rates – May 7-8, 2008 Storm (Giant Eagle)

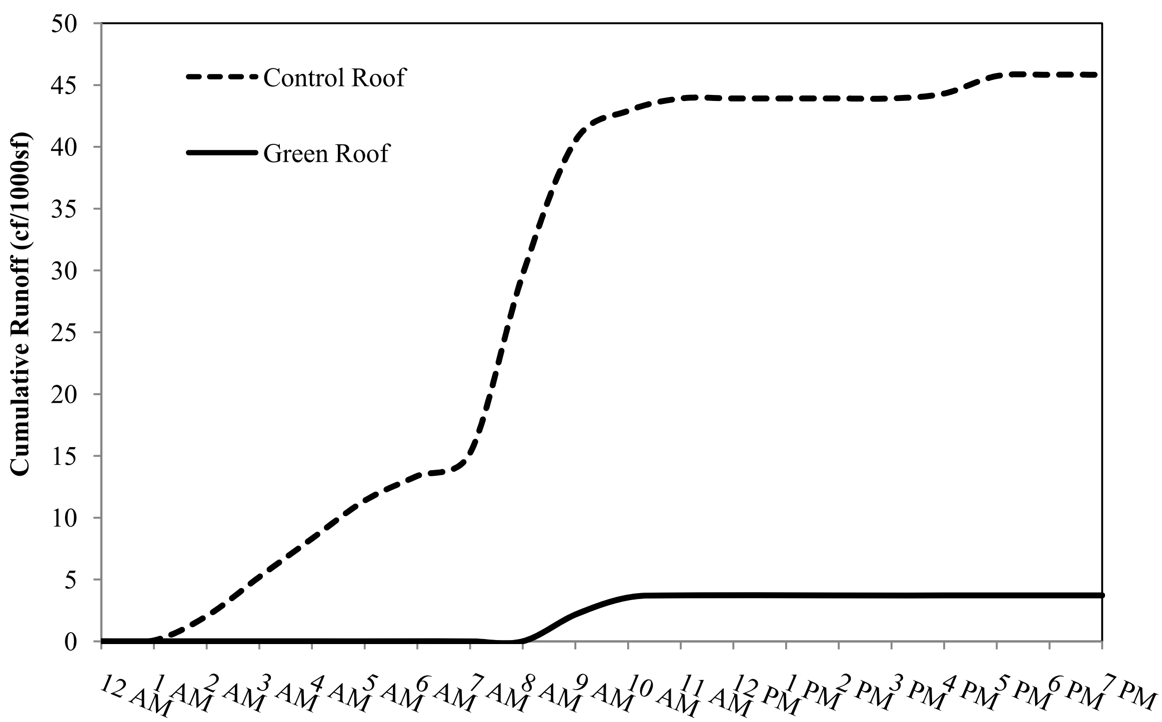


Figure 83. Runoff Volumes – May 7-8, 2008 Storm (Giant Eagle)

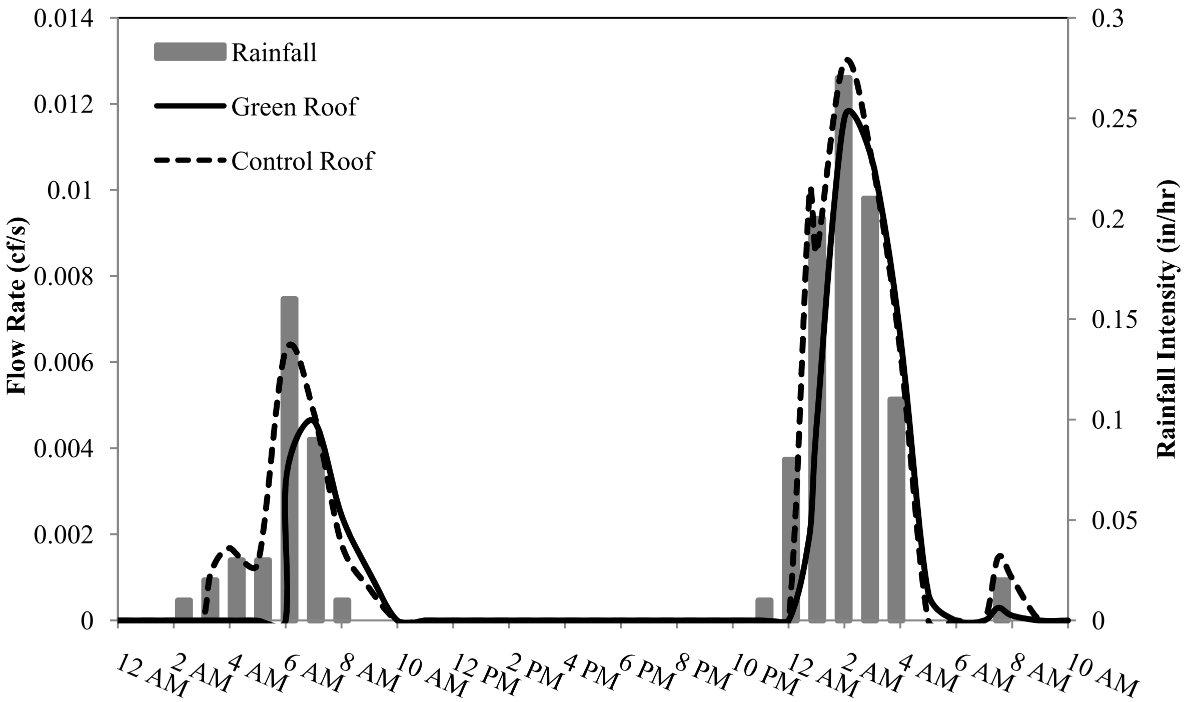


Figure 84. Runoff Flow Rates and Rainfall intensity – May 9-10, 2008 Storm (Homestead)

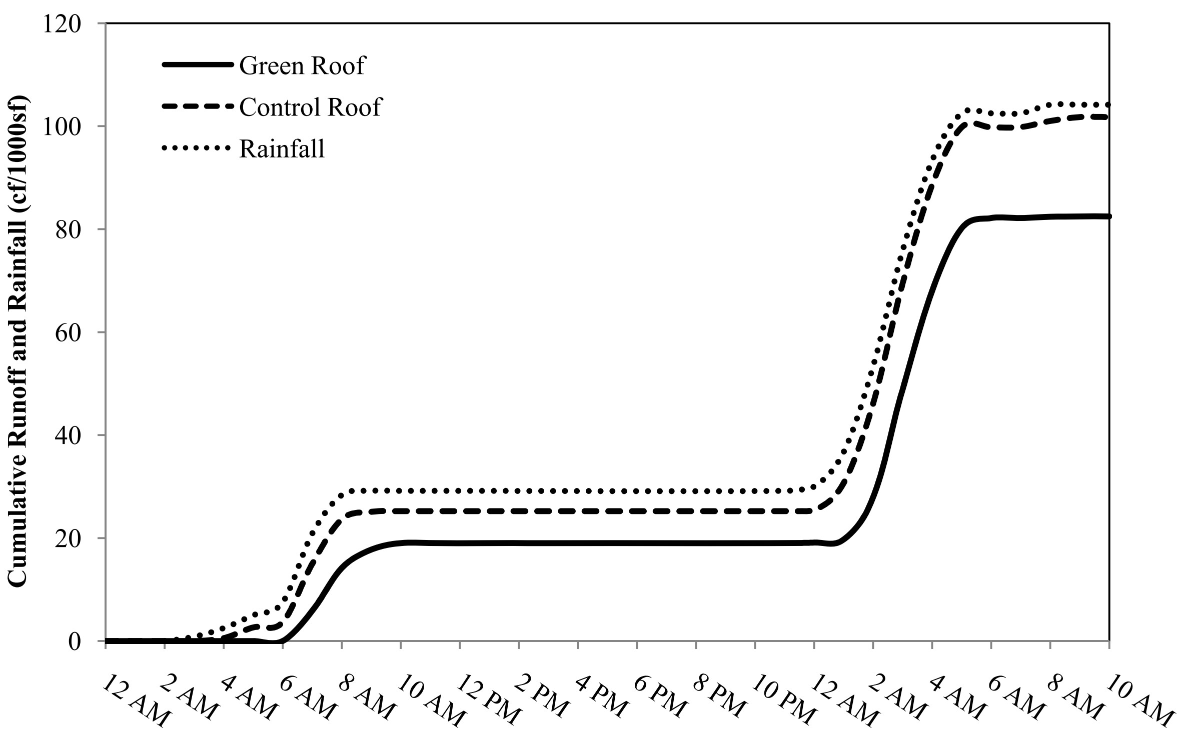


Figure 85. Runoff and rainfall volumes – May 9-10, 2008 Storm (Homestead)

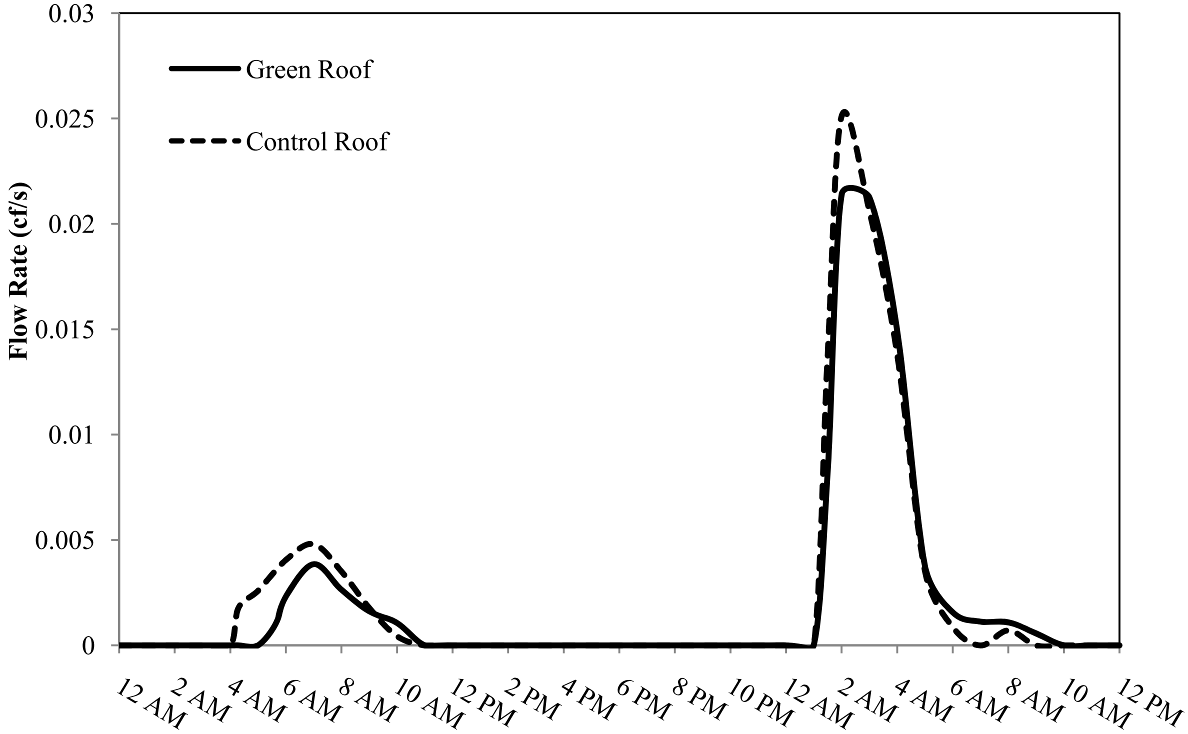


Figure 86. Runoff flow Rates – May 9-10, 2008 Storm (Giant Eagle)

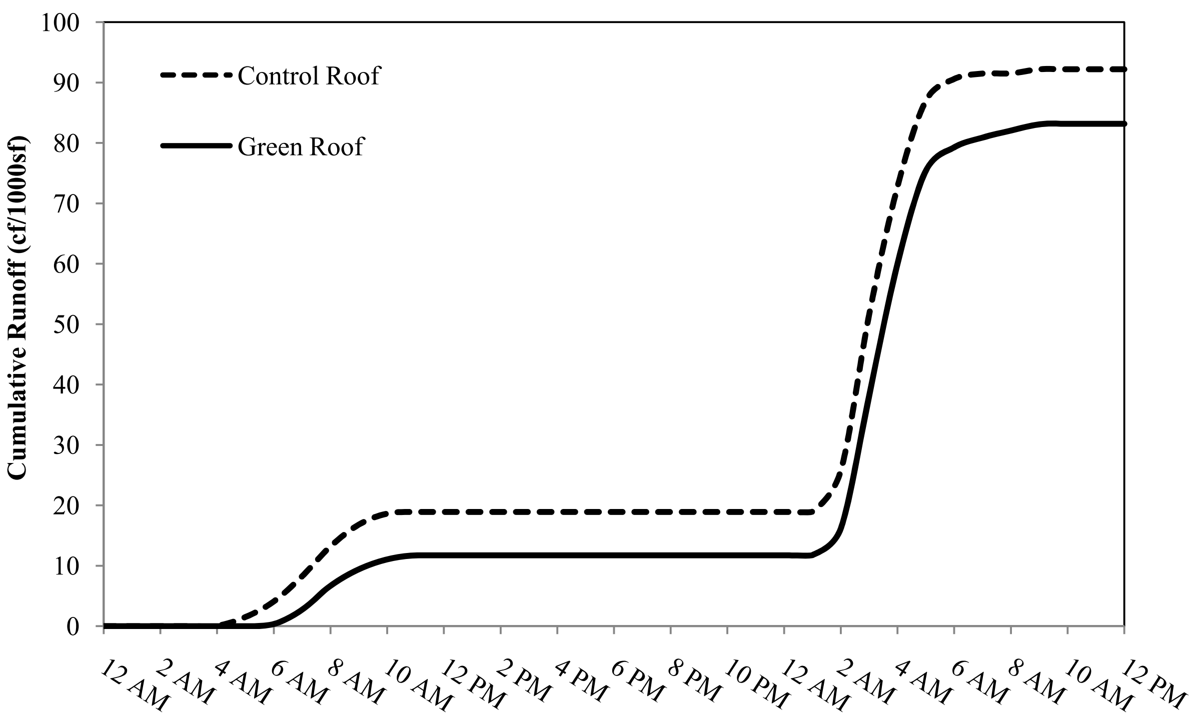


Figure 87. Runoff Volumes – May 9-10, 2008 Storm (Giant Eagle)

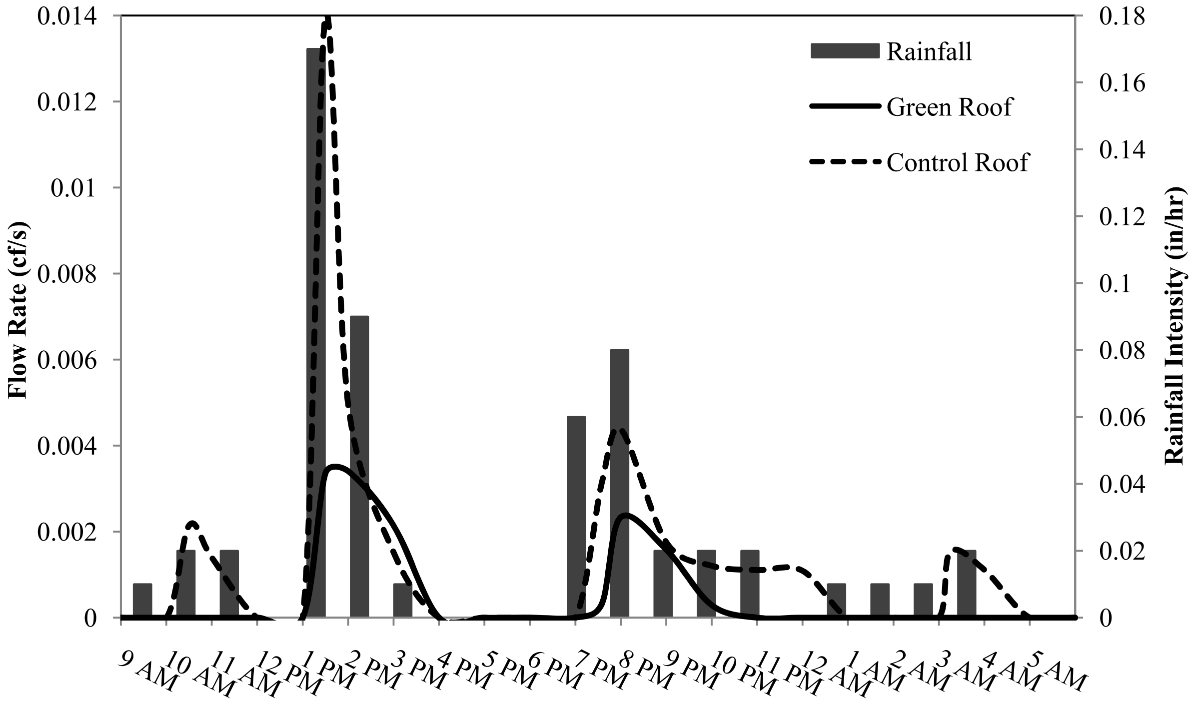


Figure 88. Runoff Flow Rates and Rainfall intensity – May 11-12, 2008 Storm (Homestead)

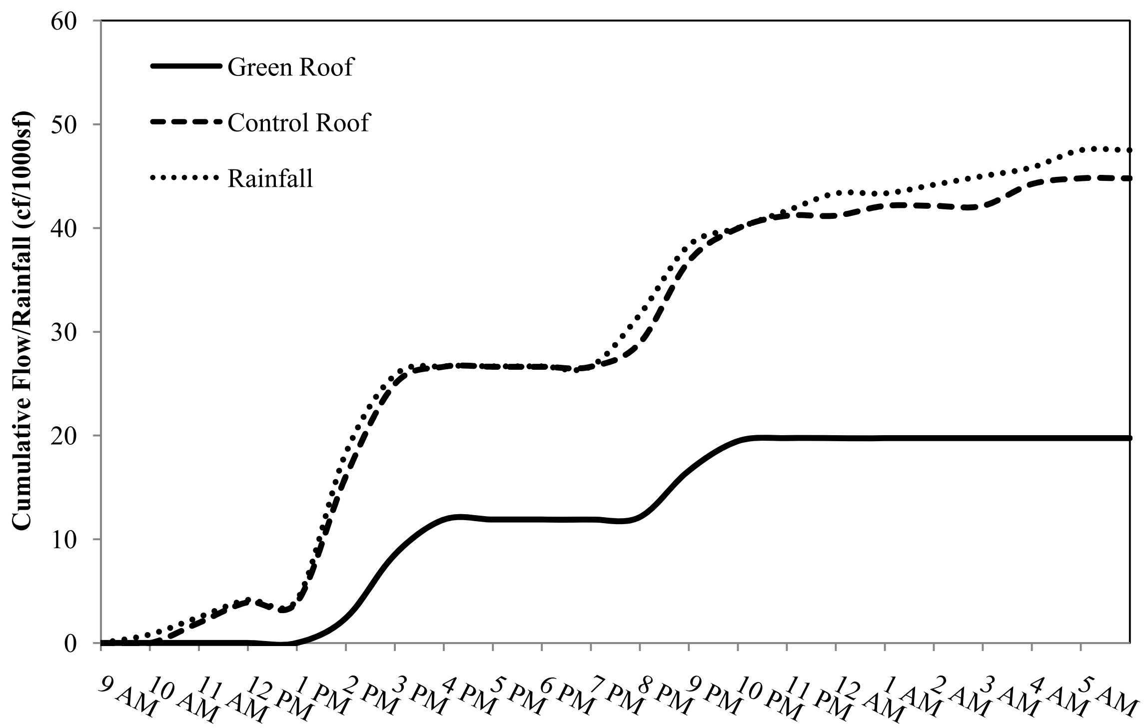


Figure 89. Runoff and rainfall volumes – May 11-12, 2008 Storm (Homestead)

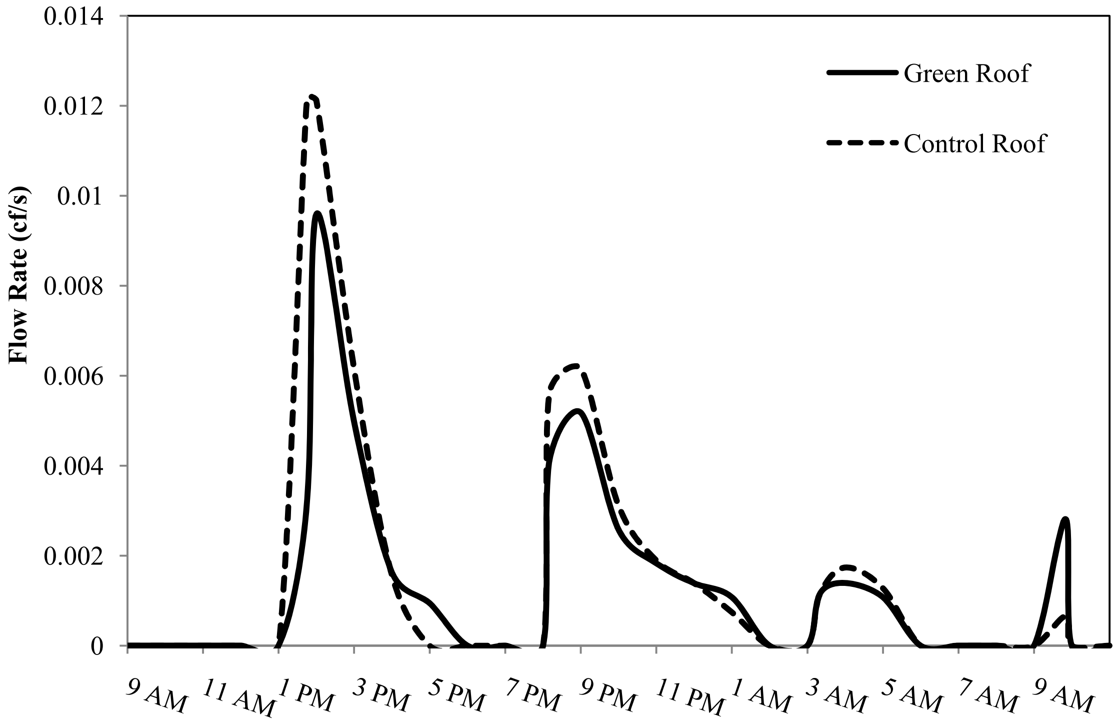


Figure 90. Runoff flow Rates – May 11-12, 2008 Storm (Giant Eagle)

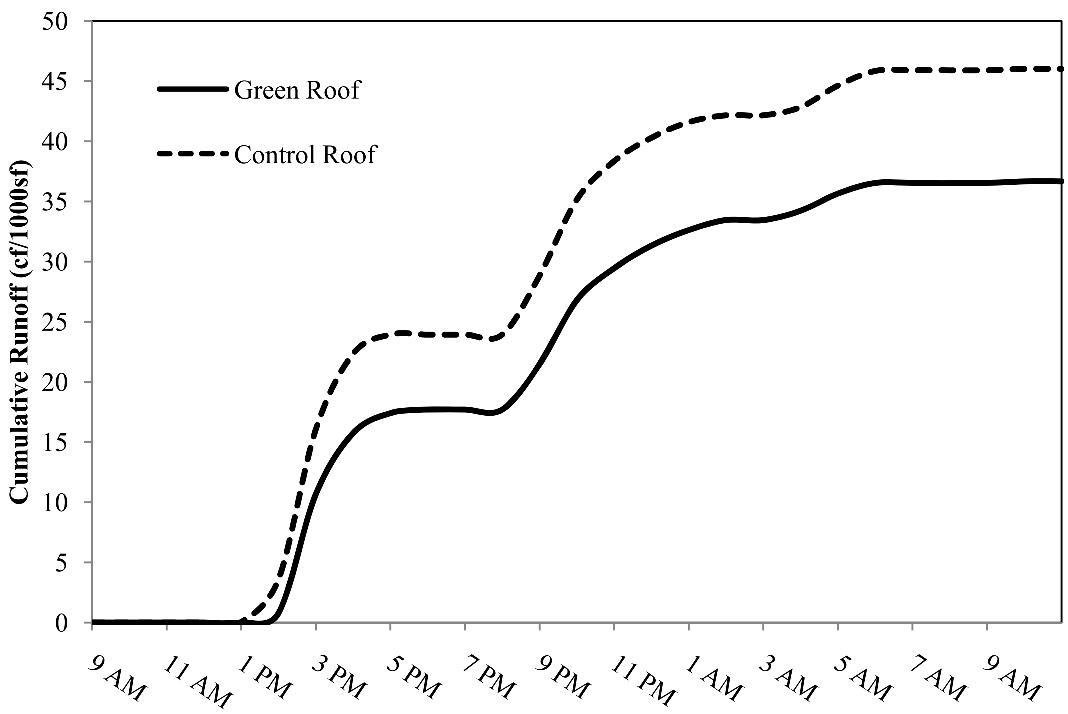


Figure 91. Runoff Volumes – May 11-12, 2008 Storm (Giant Eagle)

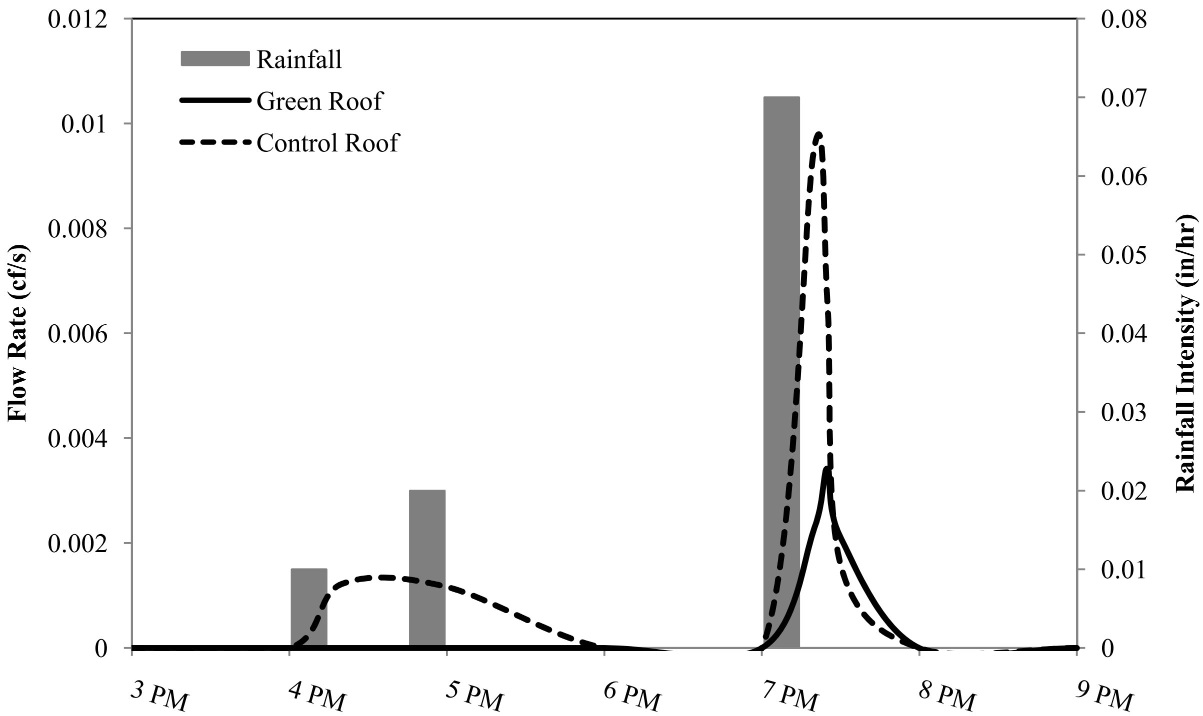


Figure 92. Runoff Flow Rates and Rainfall Intensity – May 17, 2008 Storm (Homestead)

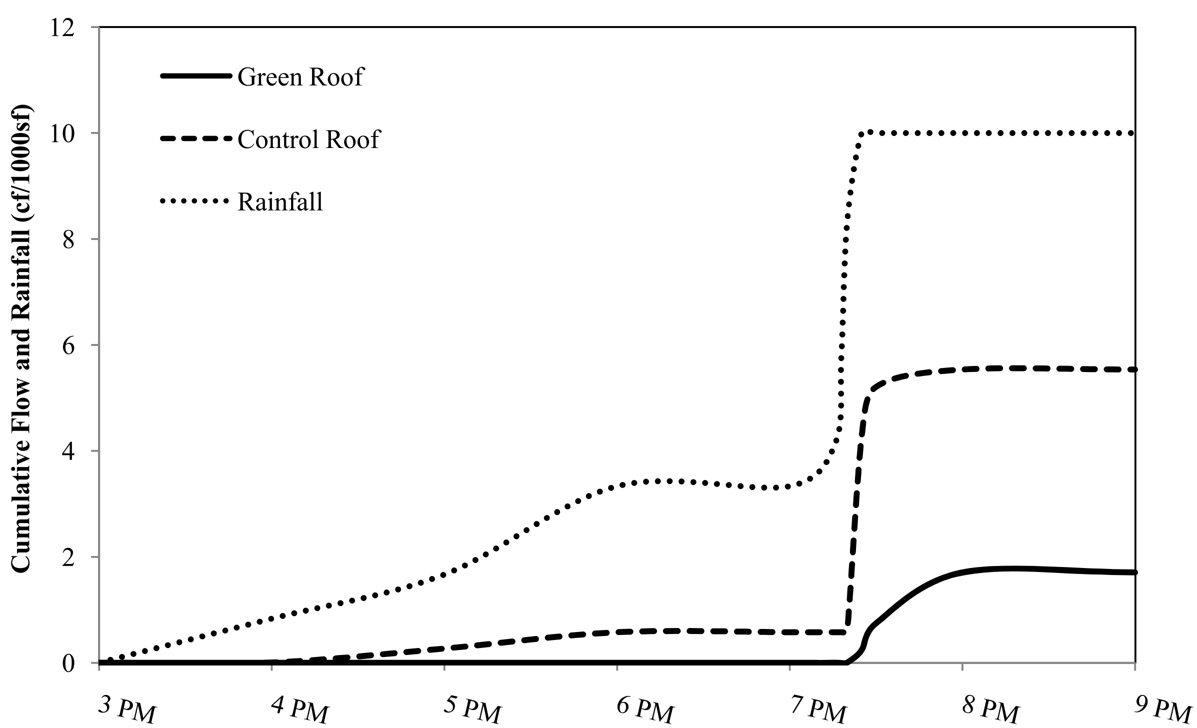


Figure 93. Runoff and Rainfall Volumes – May 17, 2008 Storm (Homestead)

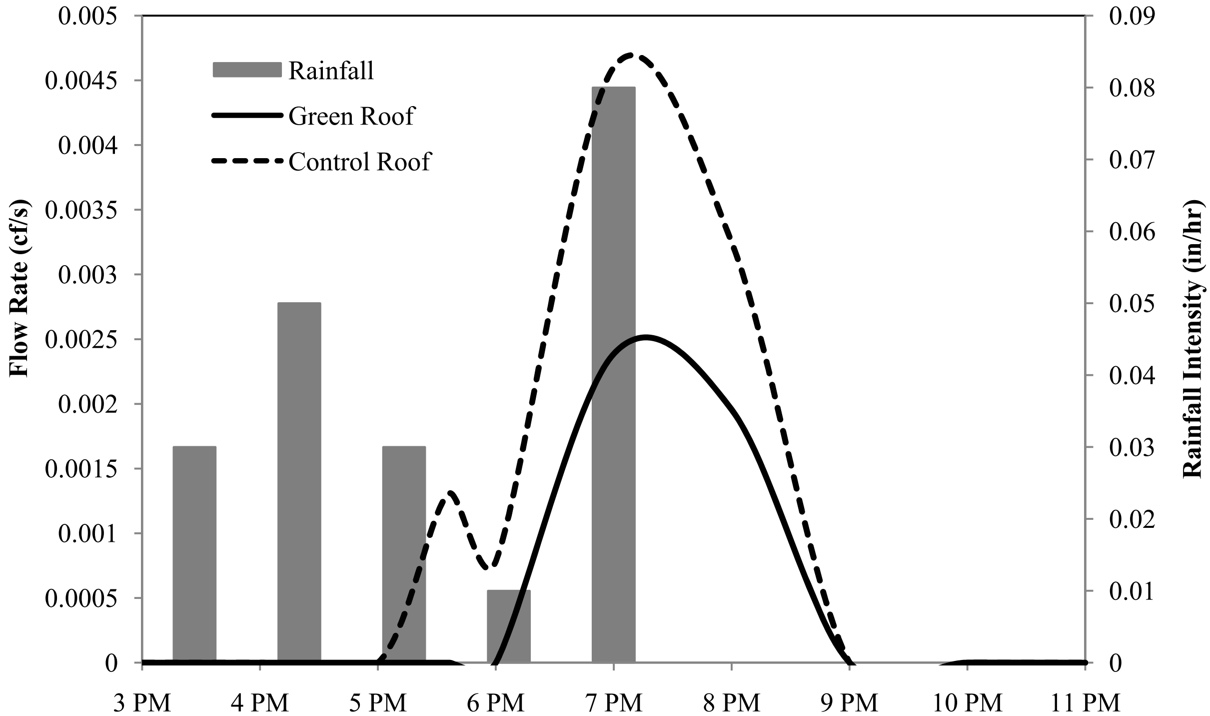


Figure 94. Runoff Flow Rates and Rainfall intensity – May 17, 2008 Storm (Giant Eagle)

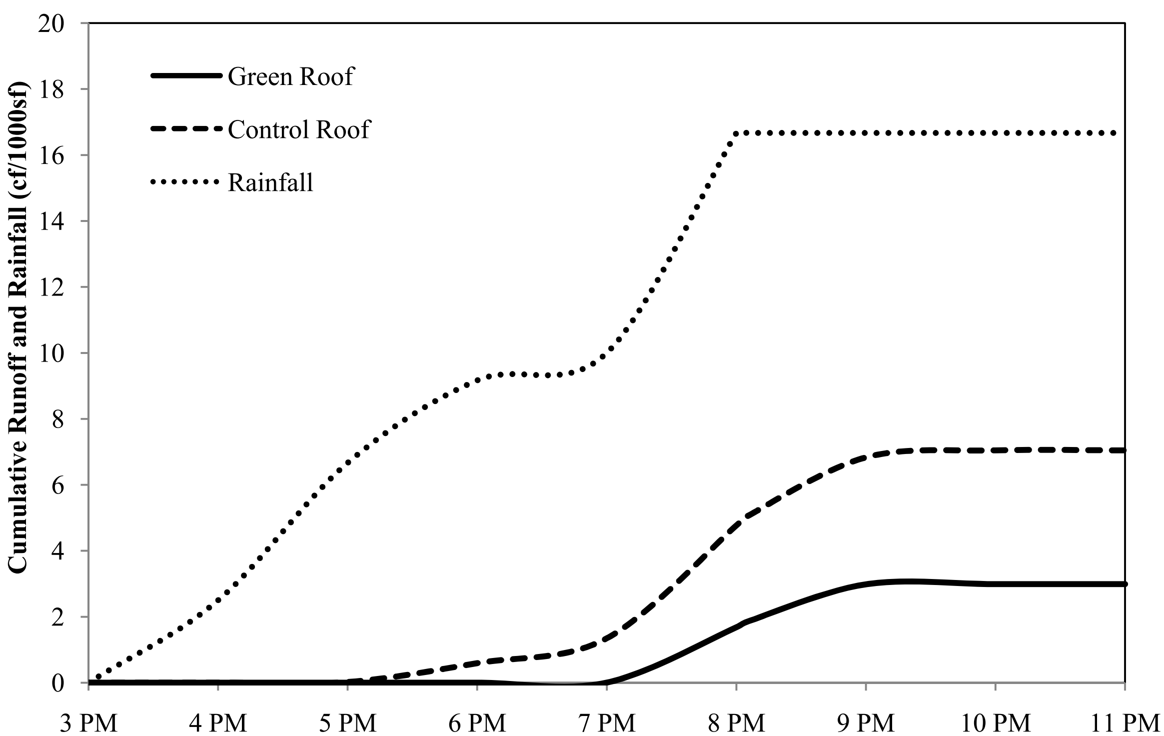


Figure 95. Runoff and Rainfall Volumes – May 17, 2008 Storm (Giant Eagle)

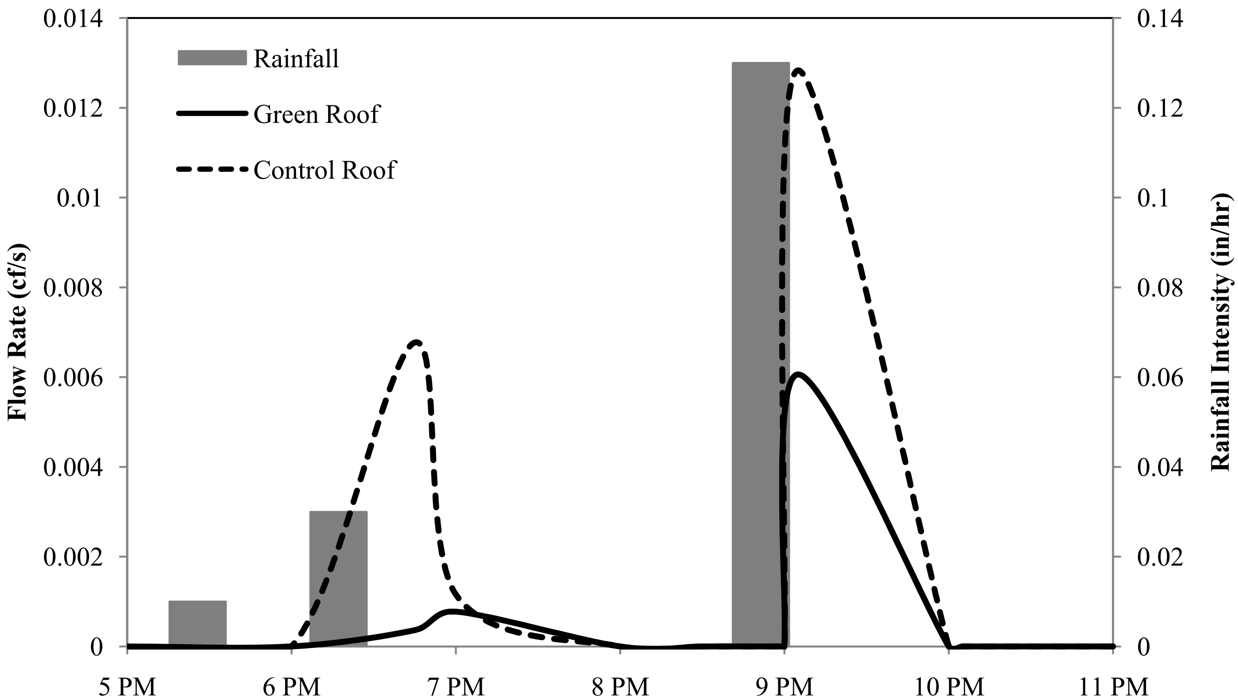


Figure 96. Runoff Flow Rates and Rainfall Intensity – May 18, 2008 Storm (Homestead)

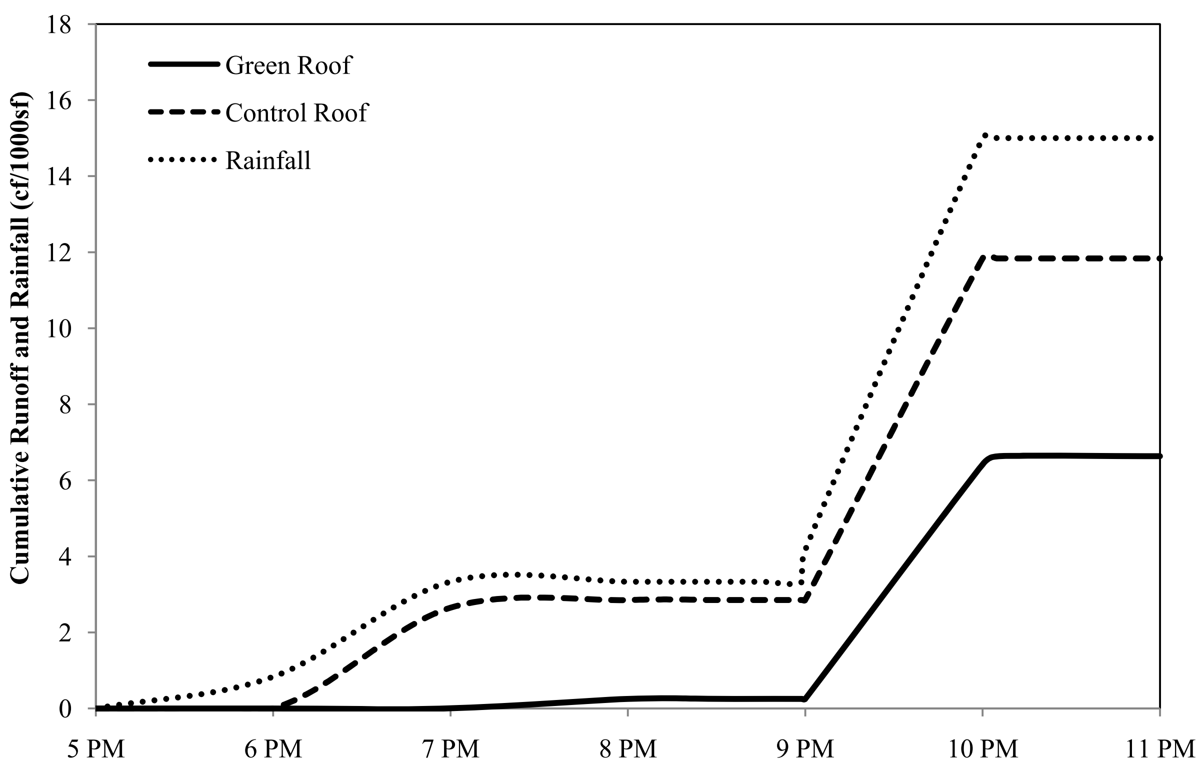


Figure 97. Runoff and Rainfall Volumes – May 18, 2008 Storm (Homestead)

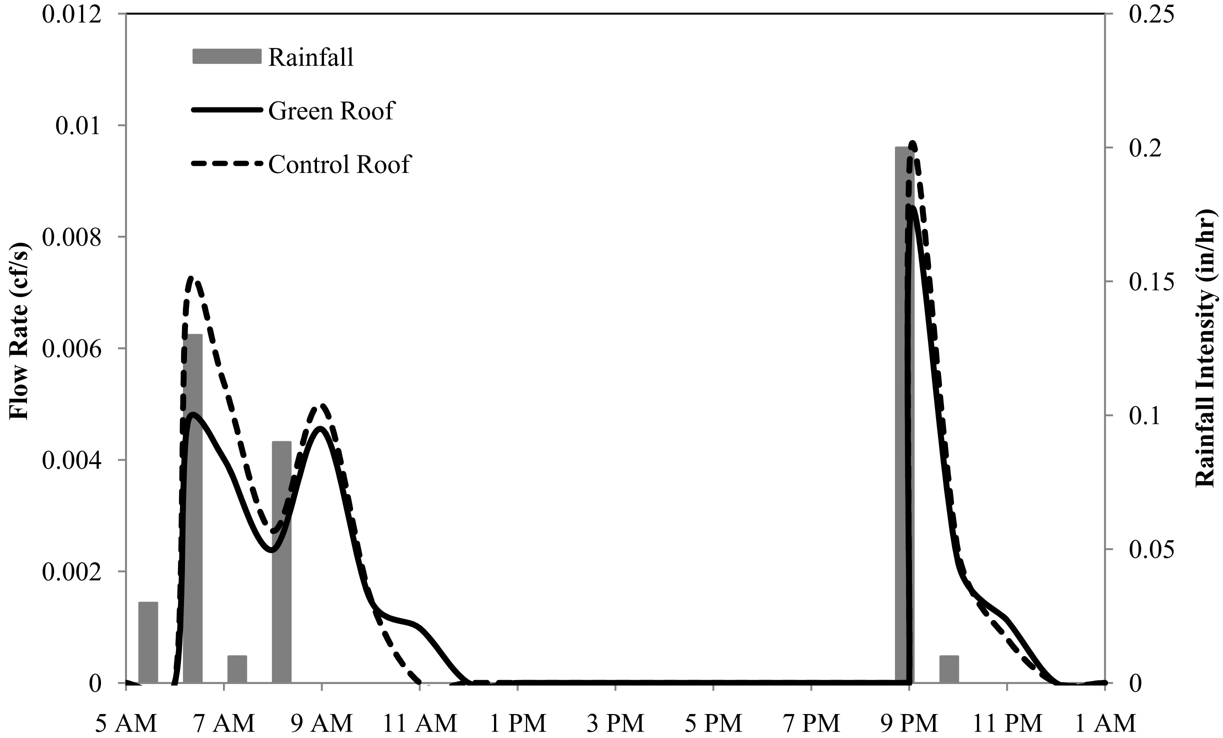


Figure 98. Runoff Flow Rates and Rainfall intensity – May 18, 2008 Storm (Giant Eagle)

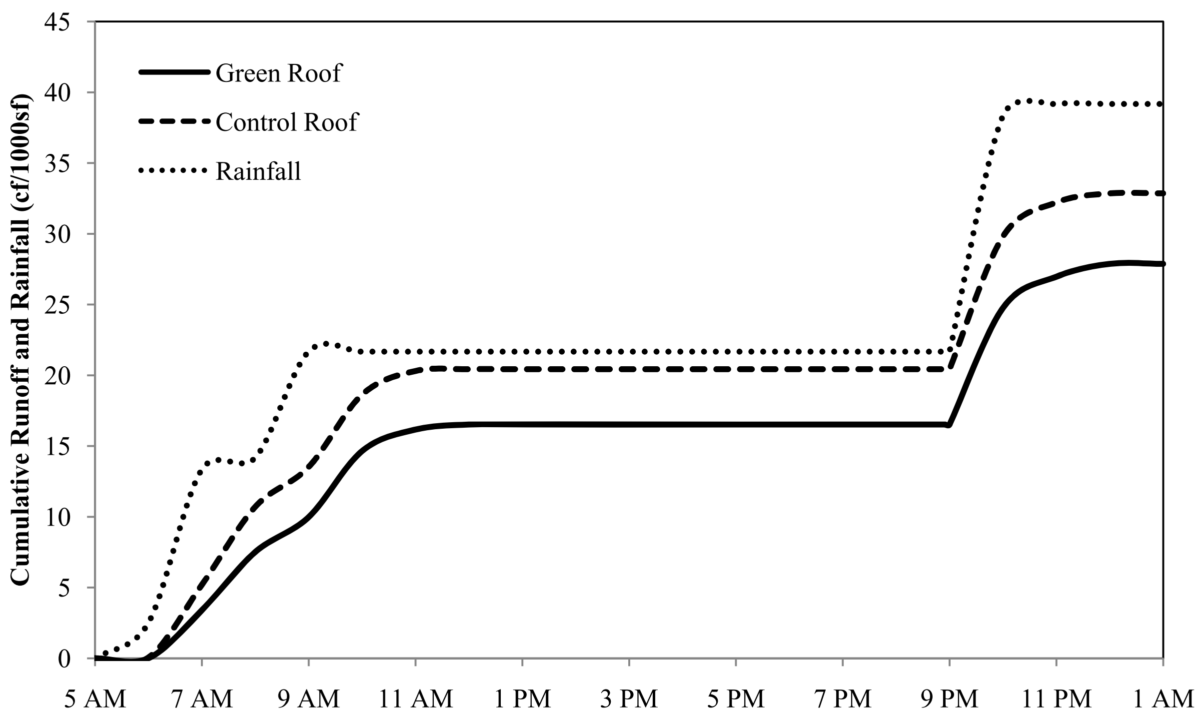


Figure 99. Runoff and Rainfall Volumes – May 18, 2008 Storm (Giant Eagle)

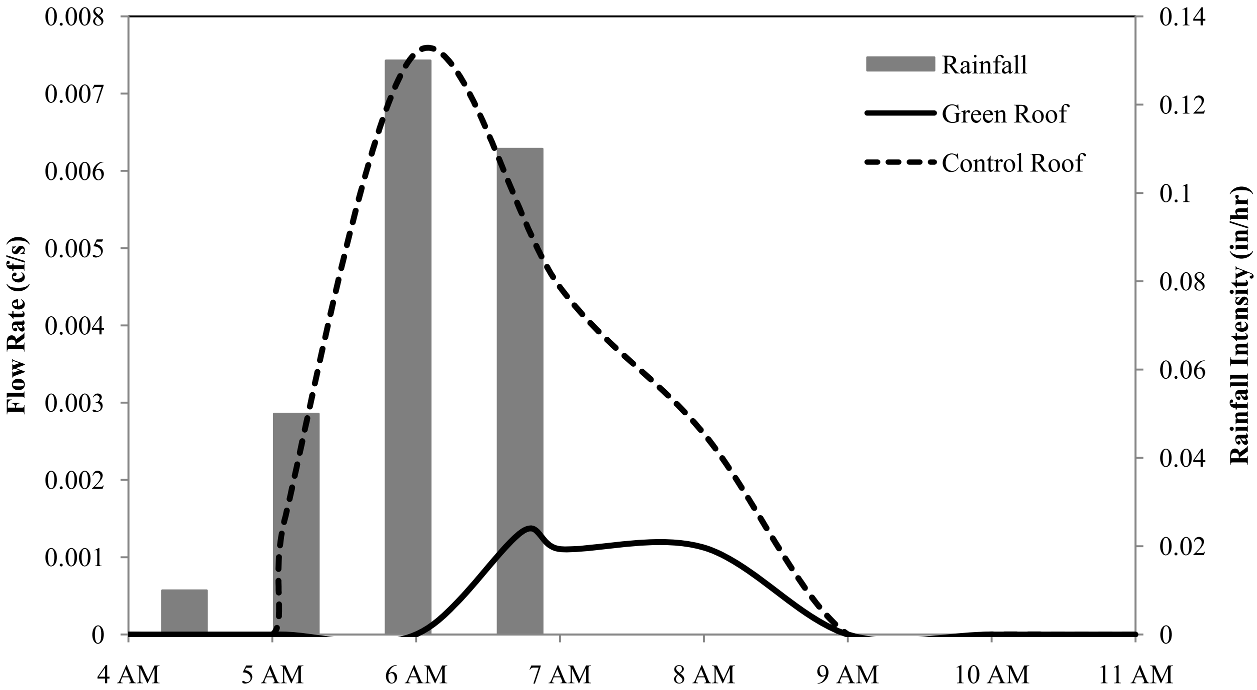


Figure 100. Runoff Flow Rates and Rainfall Intensity – May 31, 2008 Storm (Homestead)

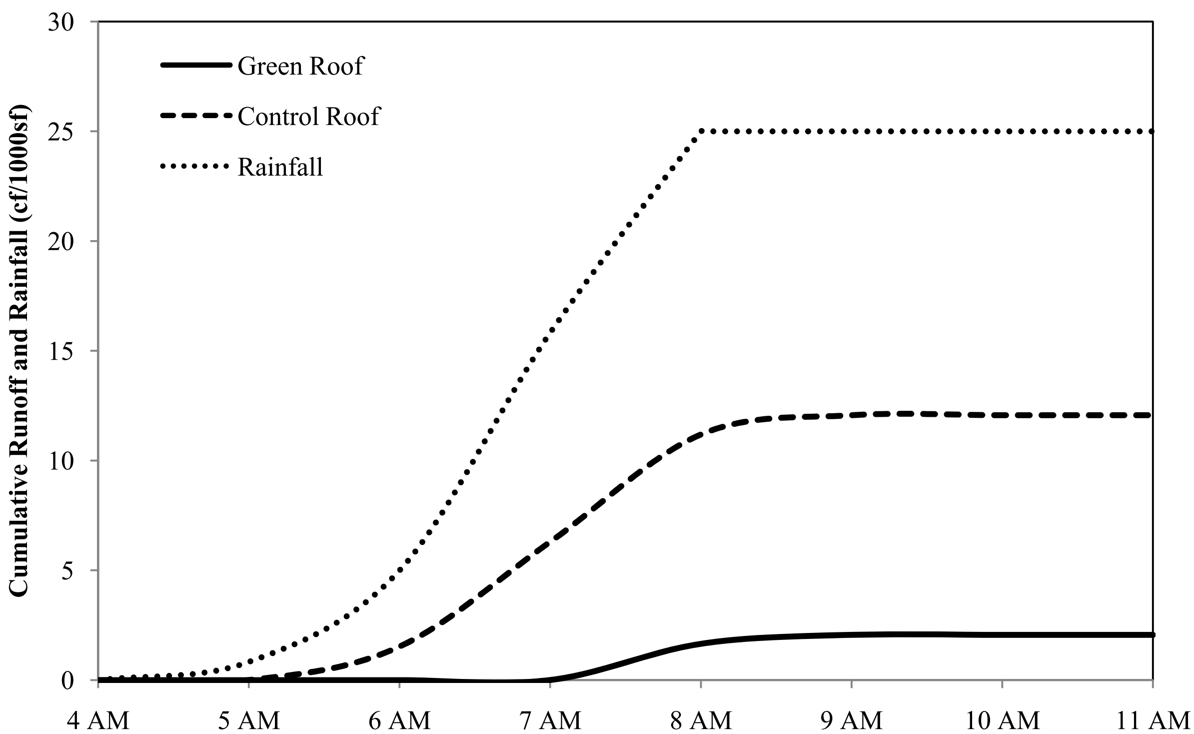


Figure 101. Runoff and Rainfall Volumes – May 31, 2008 Storm (Homestead)

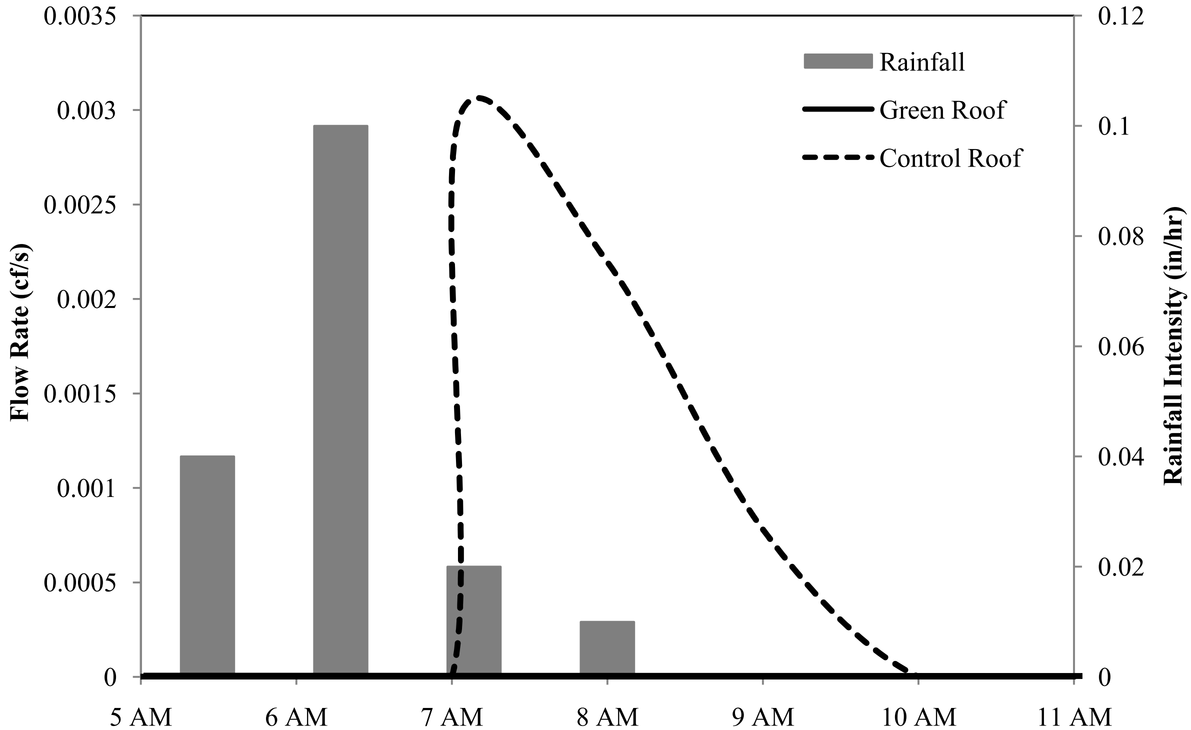


Figure 102. Runoff Flow Rates and Rainfall intensity – May 31, 2008 Storm (Giant Eagle)

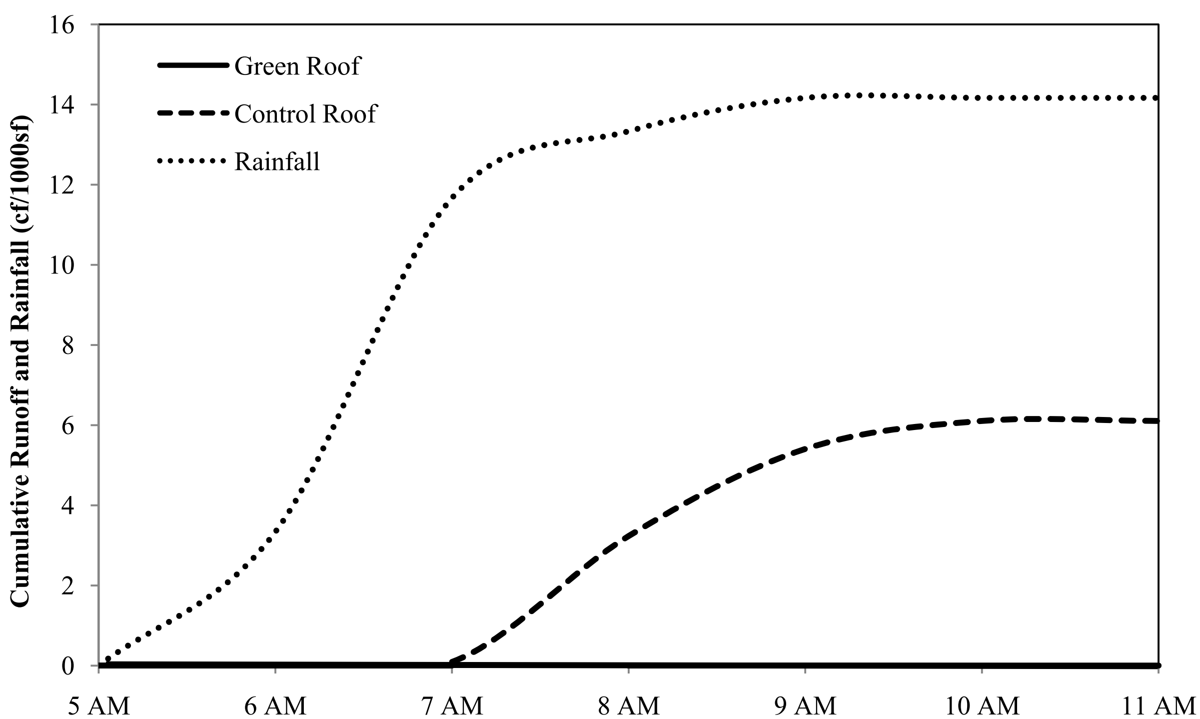


Figure 103. Runoff and Rainfall Volumes – May 31, 2008 Storm (Giant Eagle)

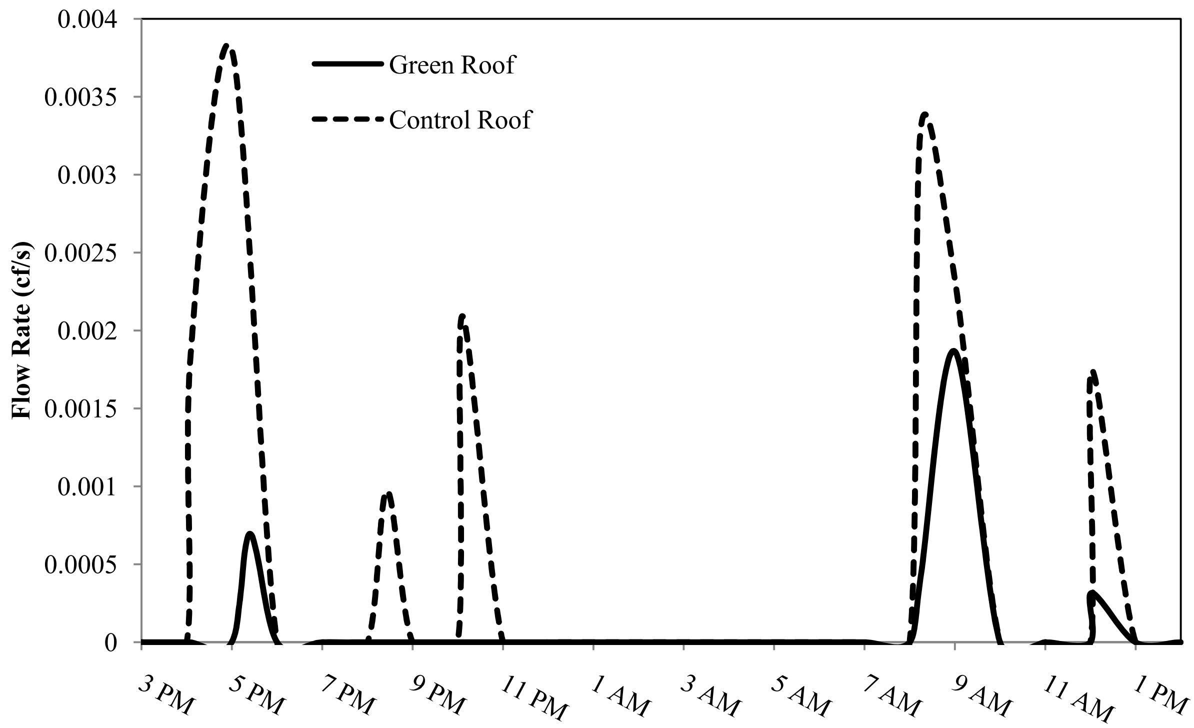


Figure 104. Runoff Flow Rates – June 3-4, 2008 Storm (Homestead)

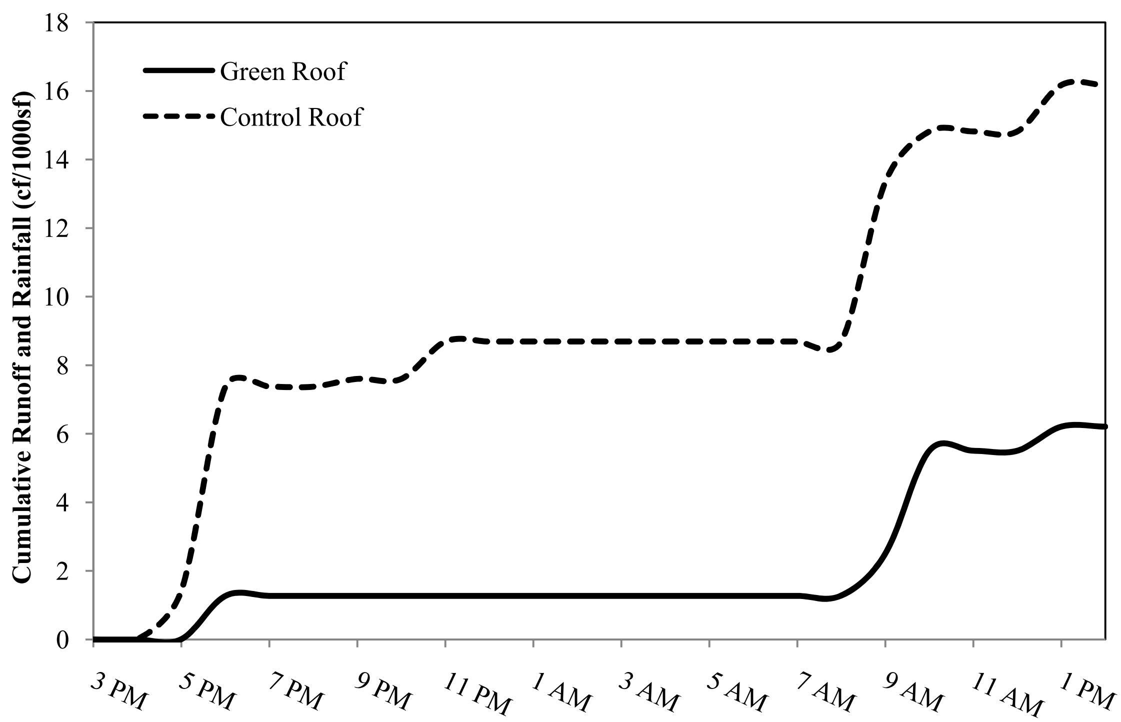


Figure 105. Runoff Volumes – June 3-4, 2008 Storm (Homestead)

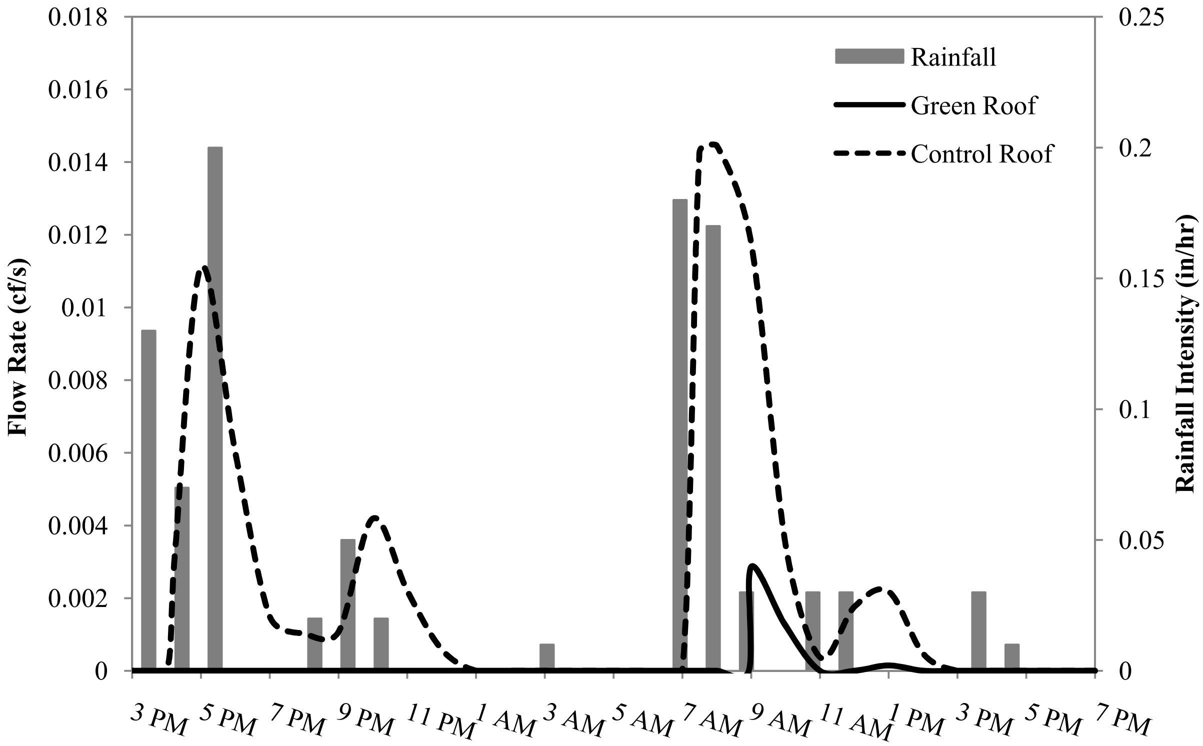


Figure 106. Runoff Flow Rates and Rainfall intensity – June 3-4, 2008 Storm (Giant Eagle)

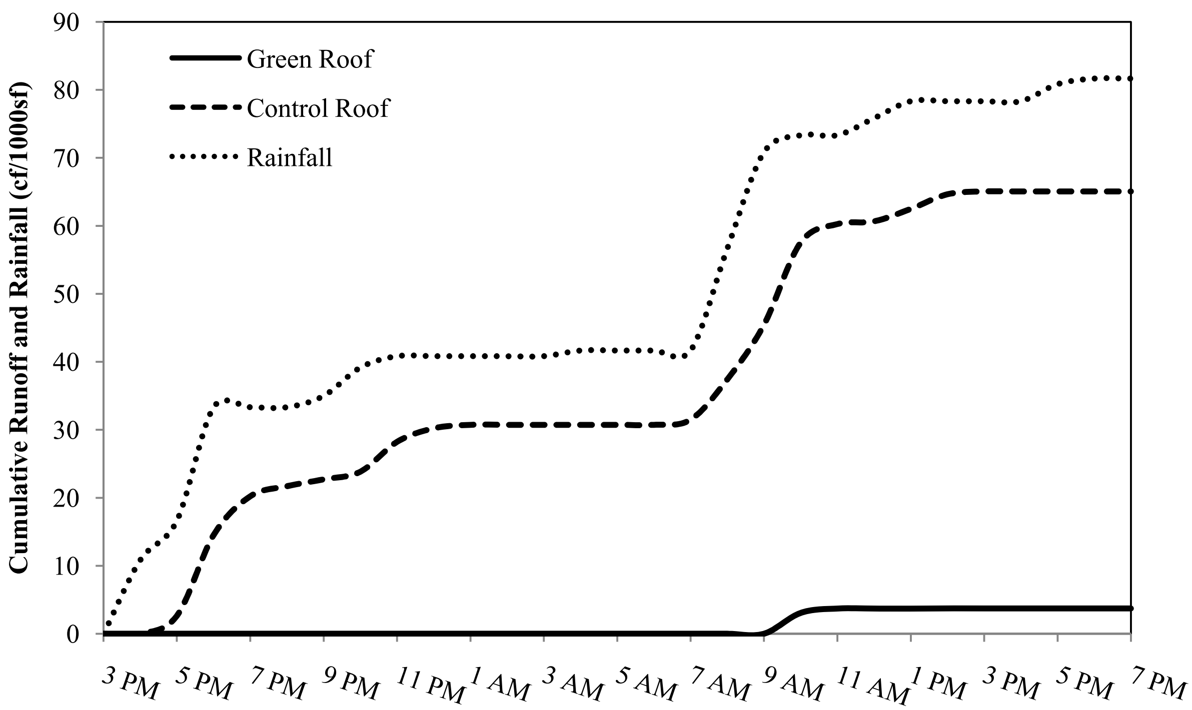


Figure 107. Runoff and Rainfall Volumes – June 3-4, 2008 Storm (Giant Eagle)

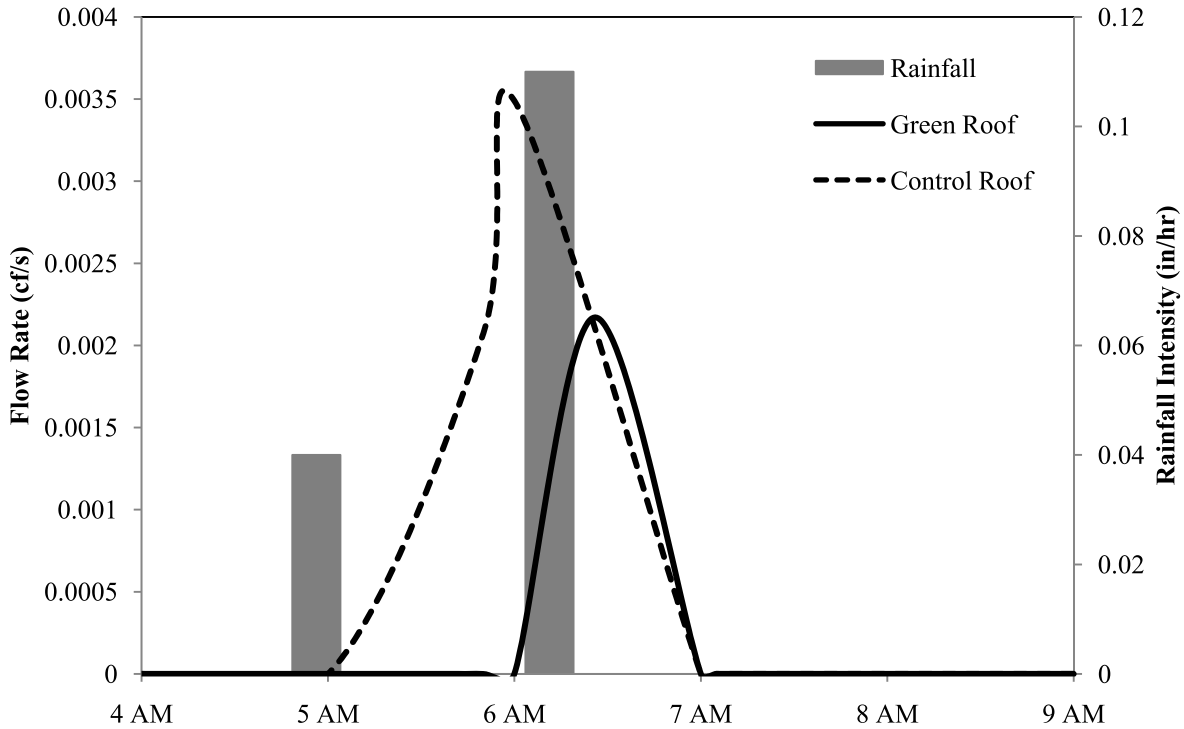


Figure 108. Runoff Flow Rates and Rainfall Intensity – June 5, 2008 Storm (Homestead)

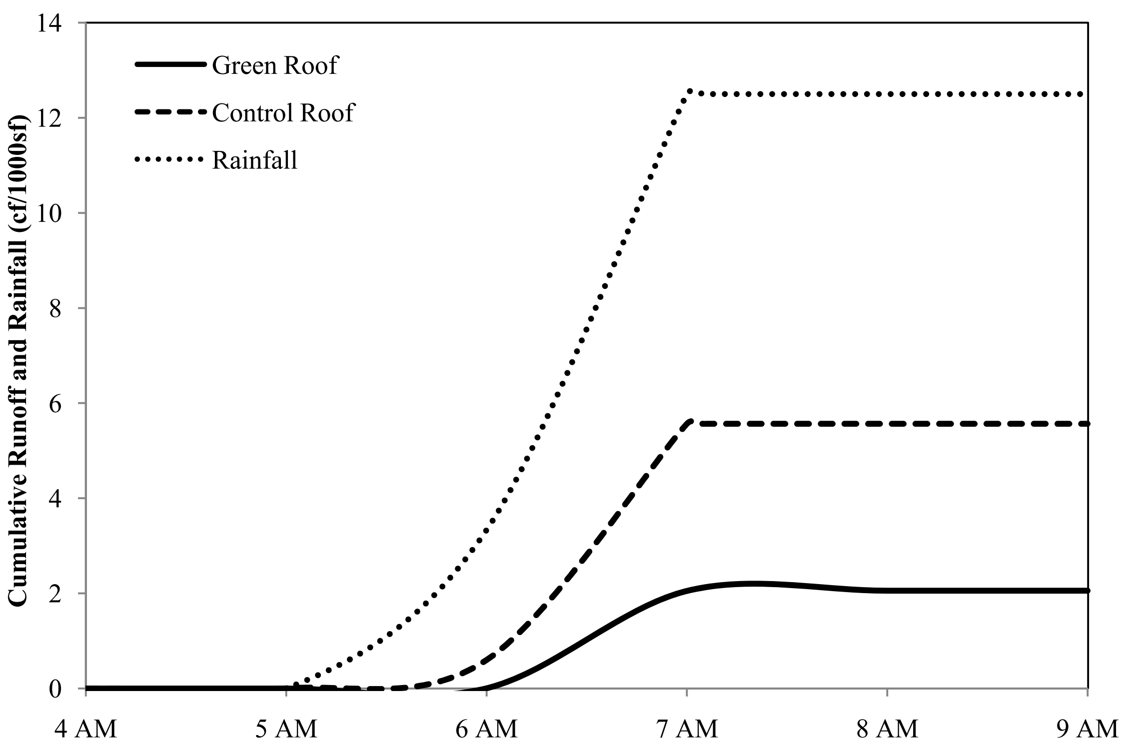


Figure 109. Runoff and Rainfall Volumes – June 5, 2008 Storm (Homestead)

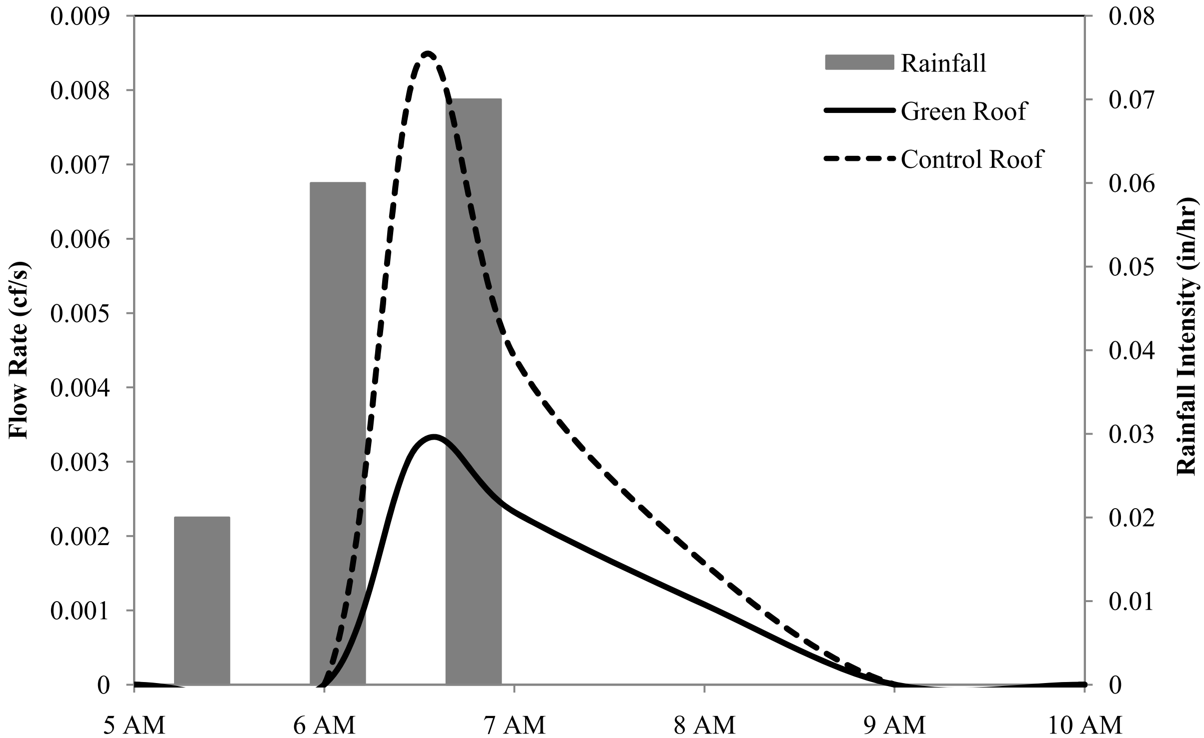


Figure 110. Runoff Flow Rates and Rainfall intensity – June 5, 2008 Storm (Giant Eagle)

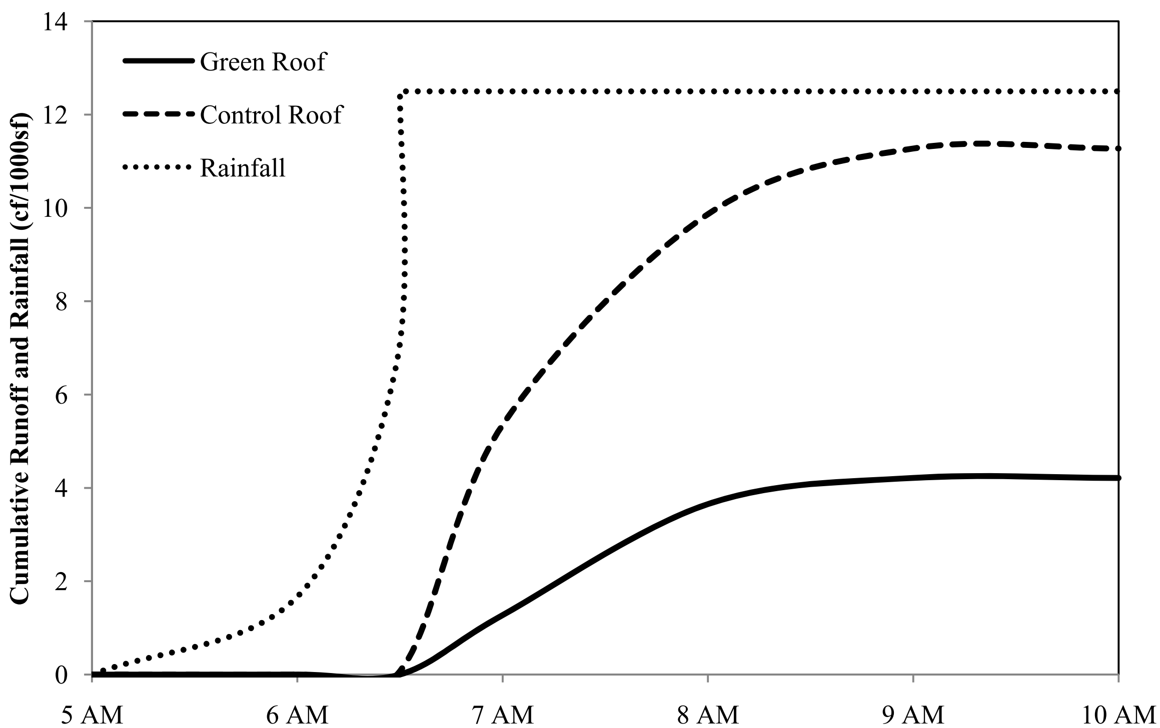


Figure 111. Runoff and Rainfall Volumes – June 5, 2008 Storm (Giant Eagle)

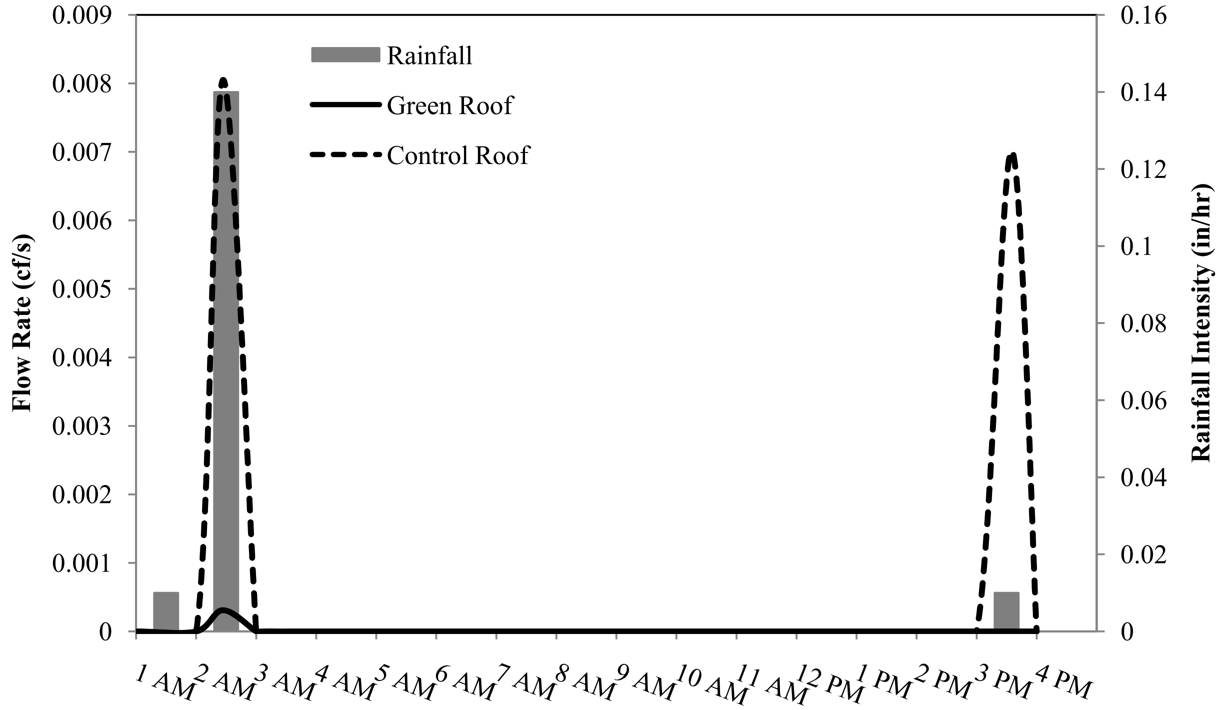


Figure 112. Runoff Flow Rates and Rainfall Intensity – June 16, 2008 Storm (Homestead)

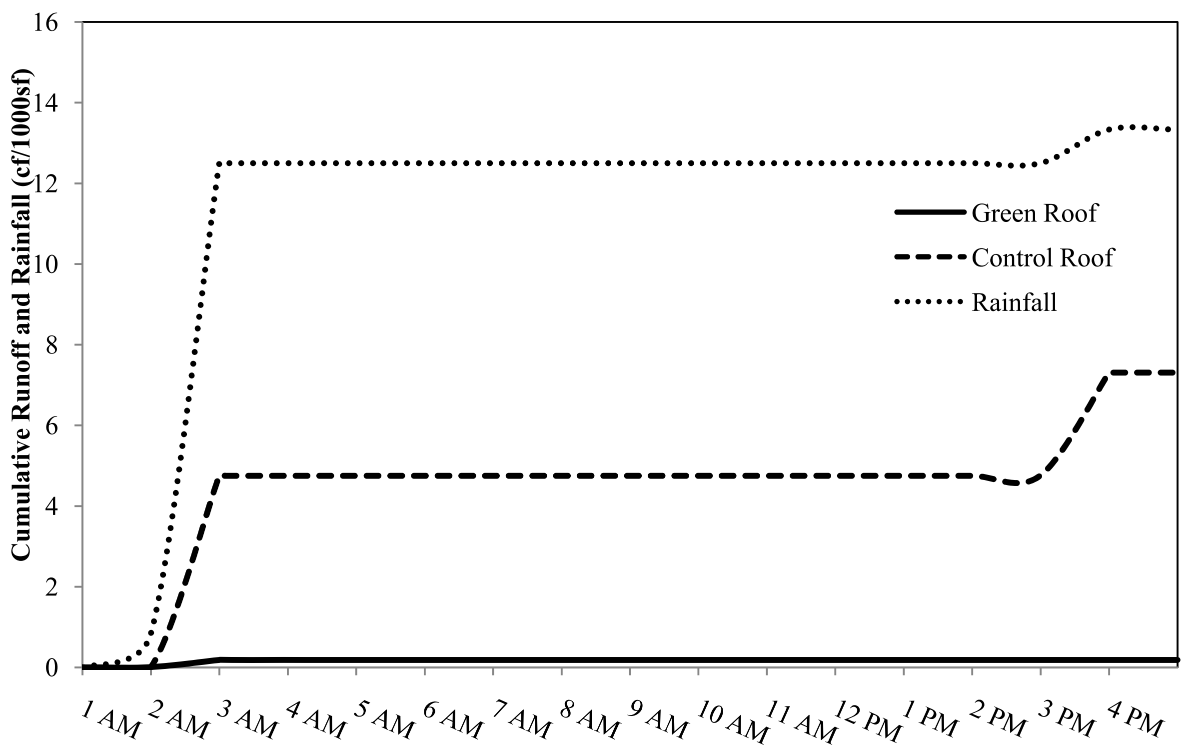


Figure 113. Runoff and Rainfall Volumes – June 16, 2008 Storm (Homestead)

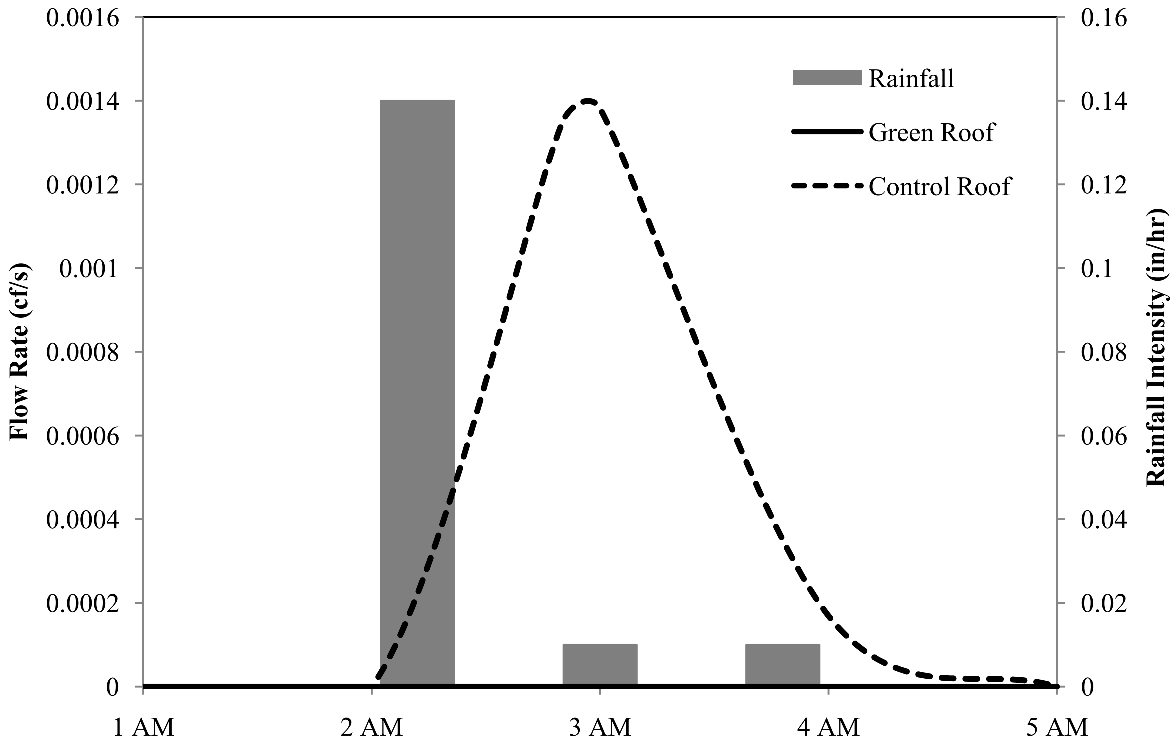


Figure 114. Runoff Flow Rates and Rainfall intensity – June 16, 2008 Storm (Giant Eagle)

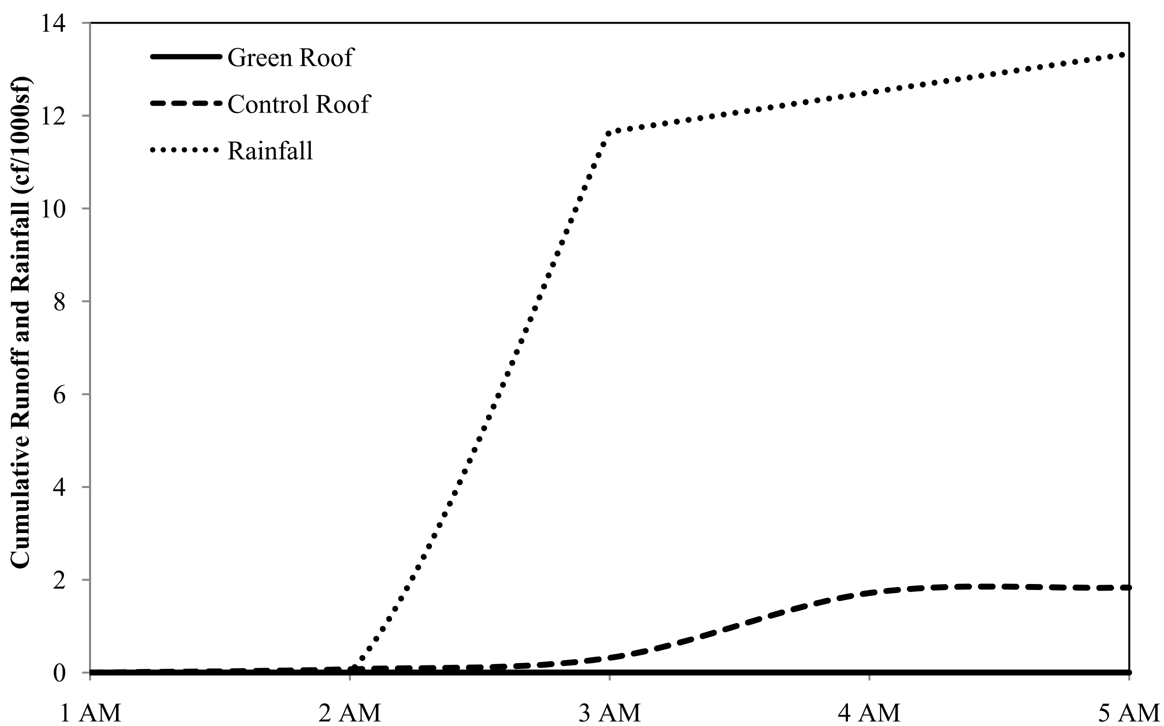


Figure 115. Runoff and Rainfall Volumes – June 16, 2008 Storm (Giant Eagle)

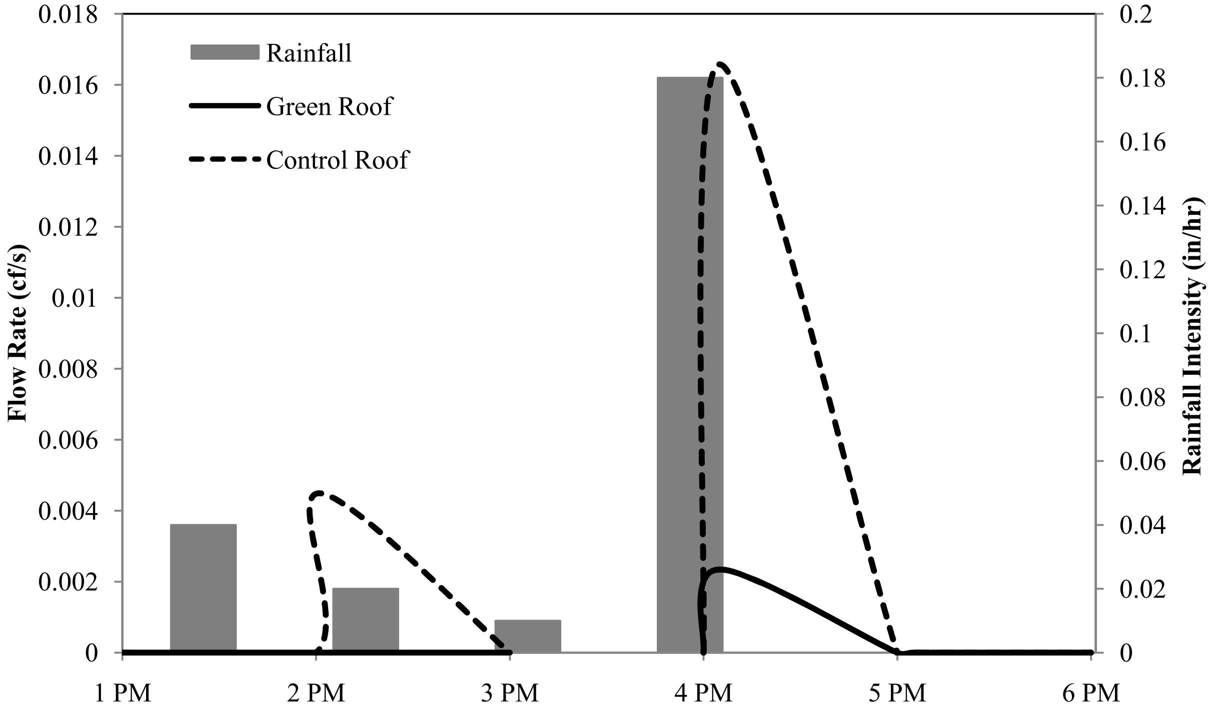


Figure 116. Runoff Flow Rates and Rainfall Intensity – June 20, 2008 Storm (Homestead)

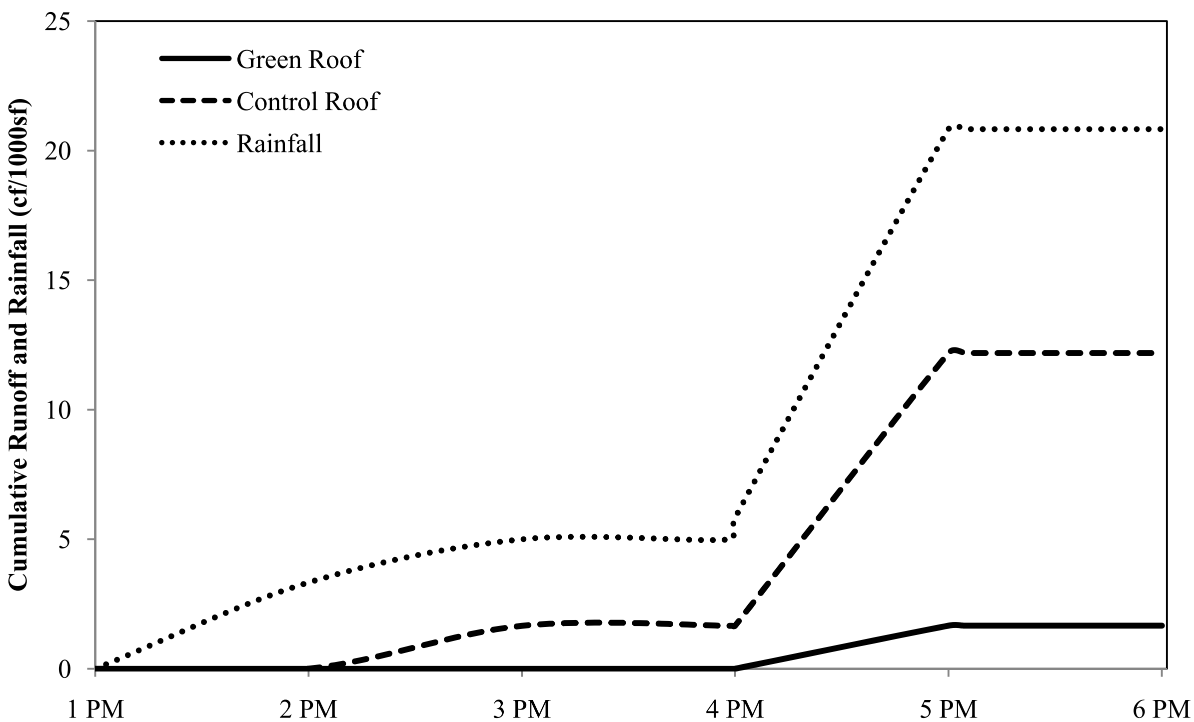


Figure 117. Runoff and Rainfall Volumes – June 20, 2008 Storm (Homestead)

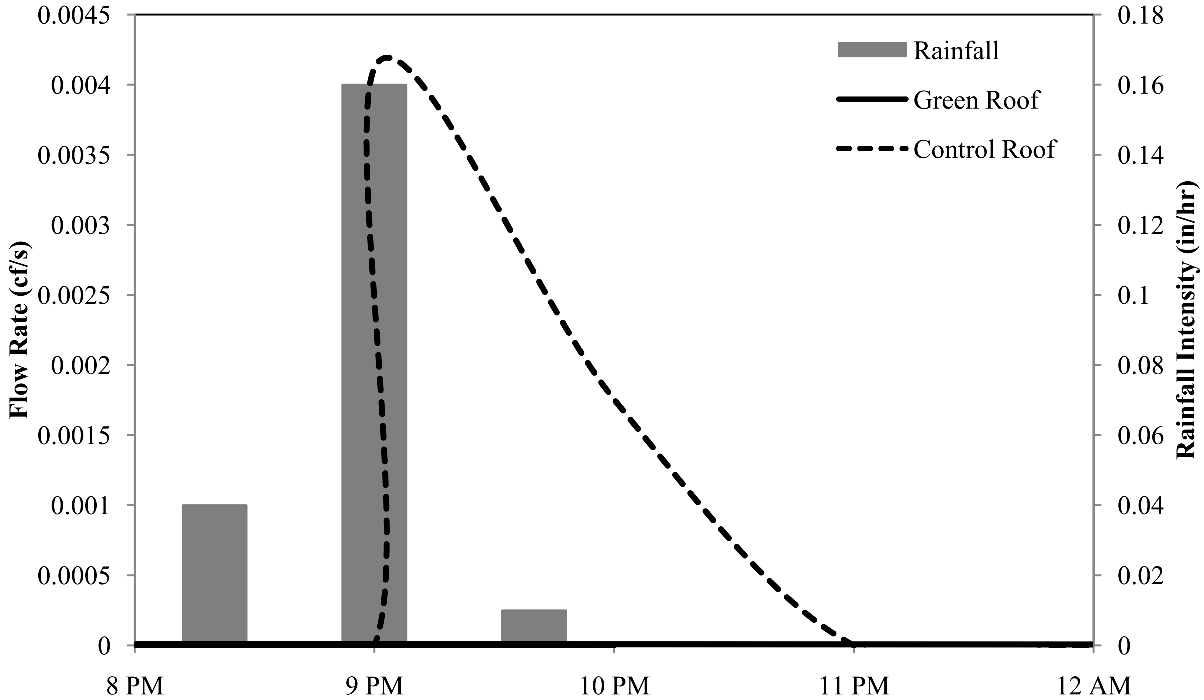


Figure 118. Runoff Flow Rates and Rainfall Intensity – June 21, 2008 Storm (Homestead)

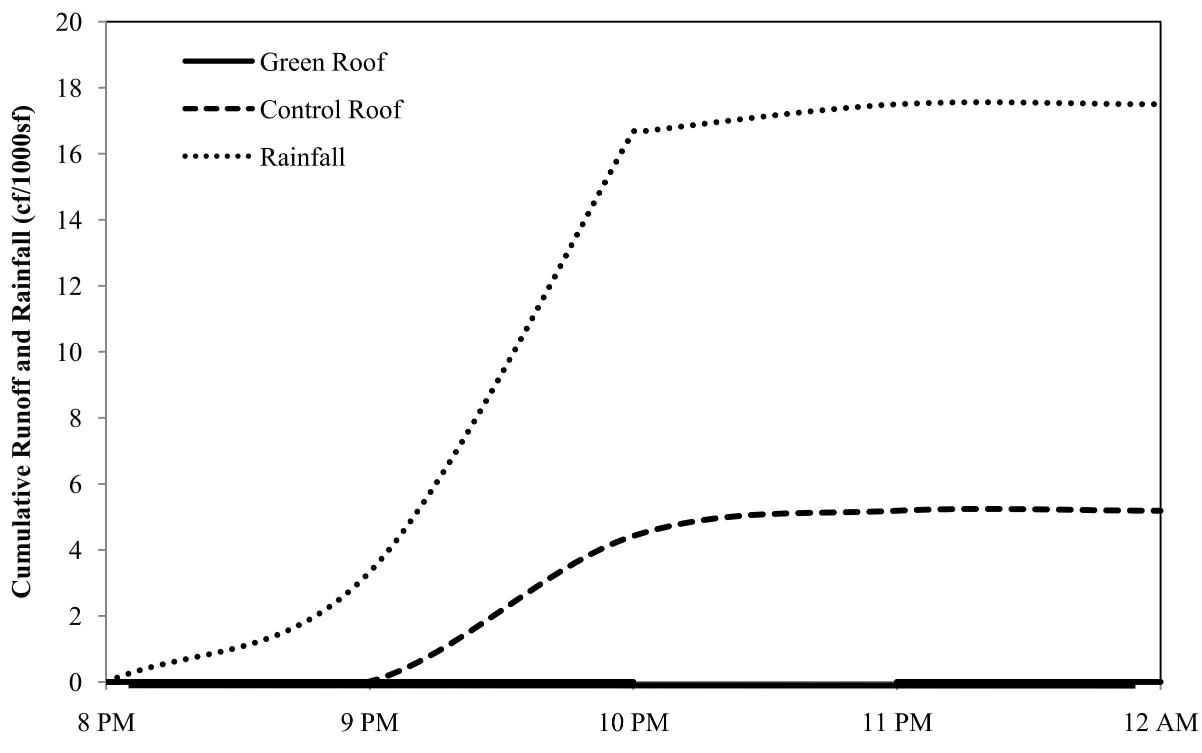


Figure 119. Runoff and Rainfall Volumes – June 21, 2008 Storm (Homestead)

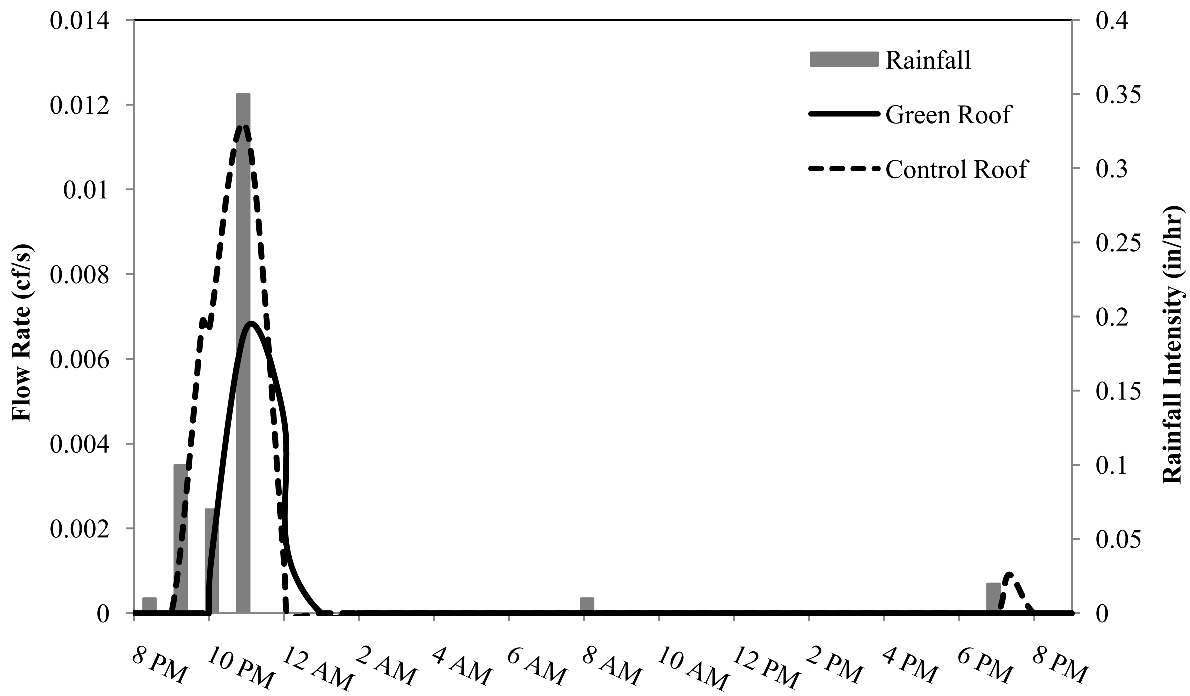


Figure 120. Runoff Flow Rates and Rainfall Intensity – June 22-23, 2008 Storm (Homestead)

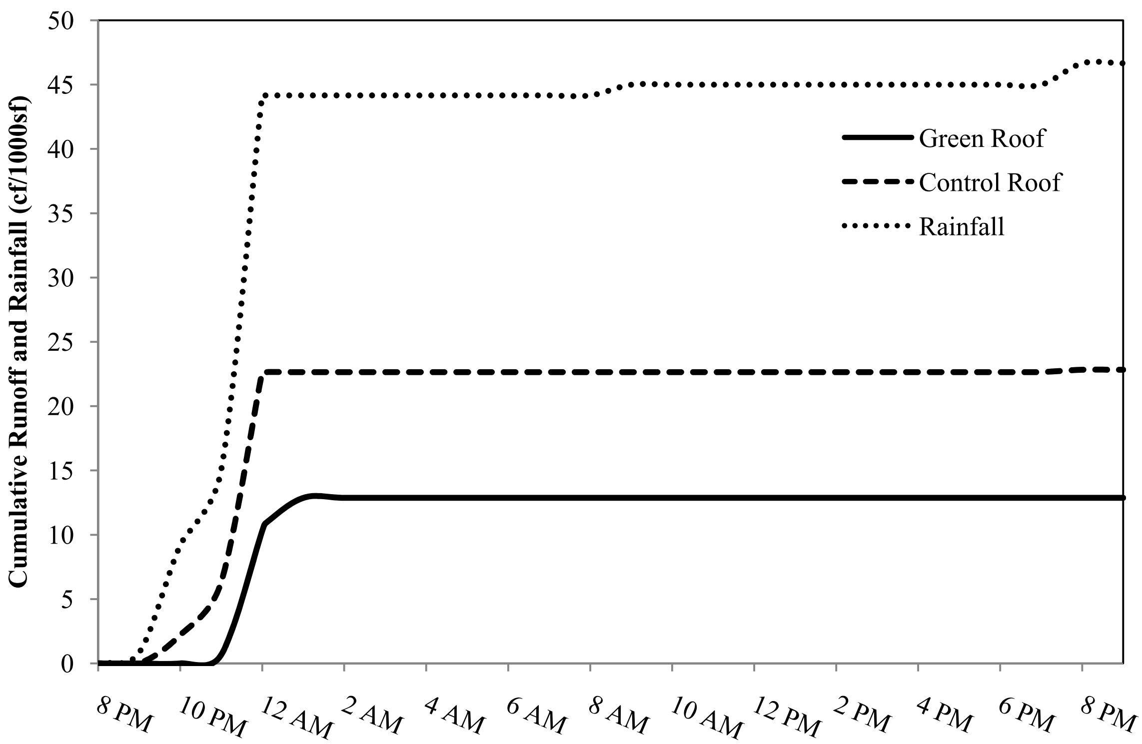


Figure 121. Runoff and Rainfall Volumes – June 22-23, 2008 Storm (Homestead)

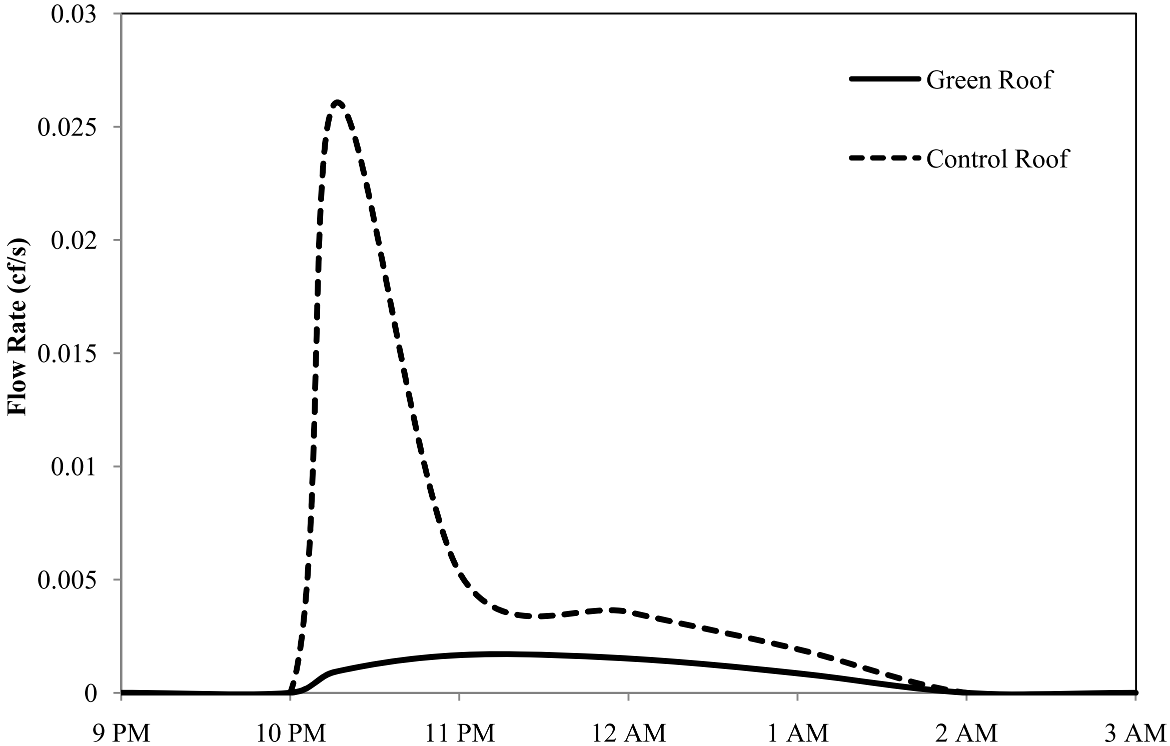


Figure 122. Runoff Flow Rates – June 22-23, 2008 Storm (Giant Eagle)

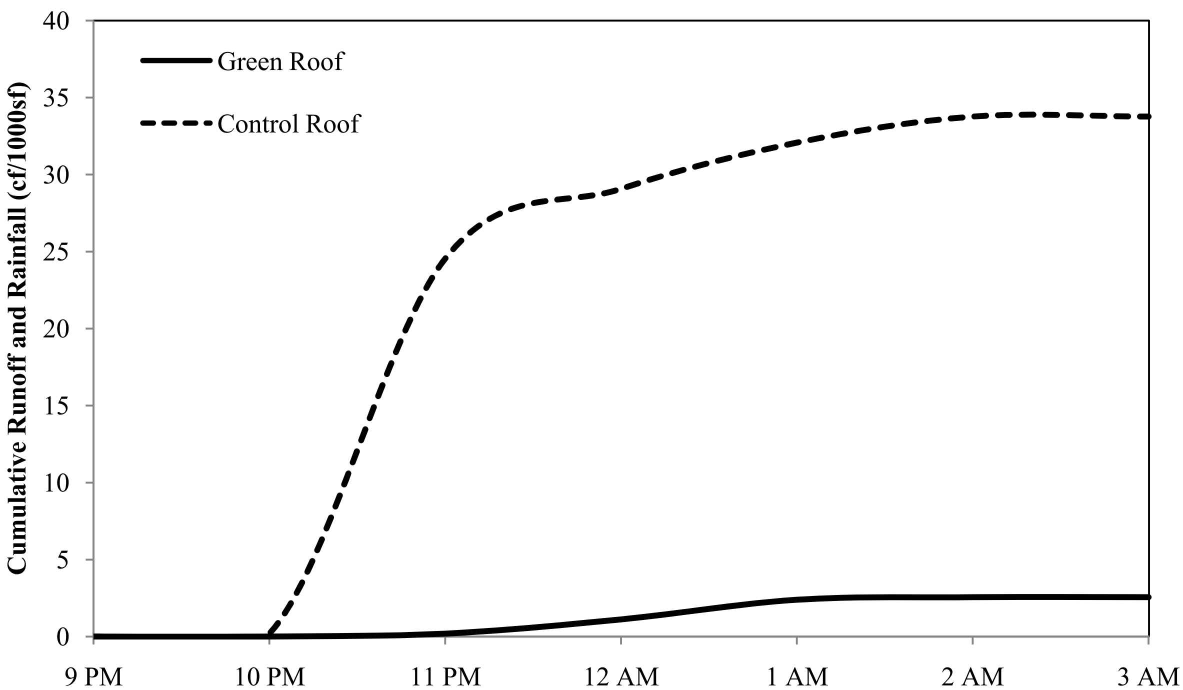


Figure 123. Runoff Volumes – June 22-23, 2008 Storm (Giant Eagle)

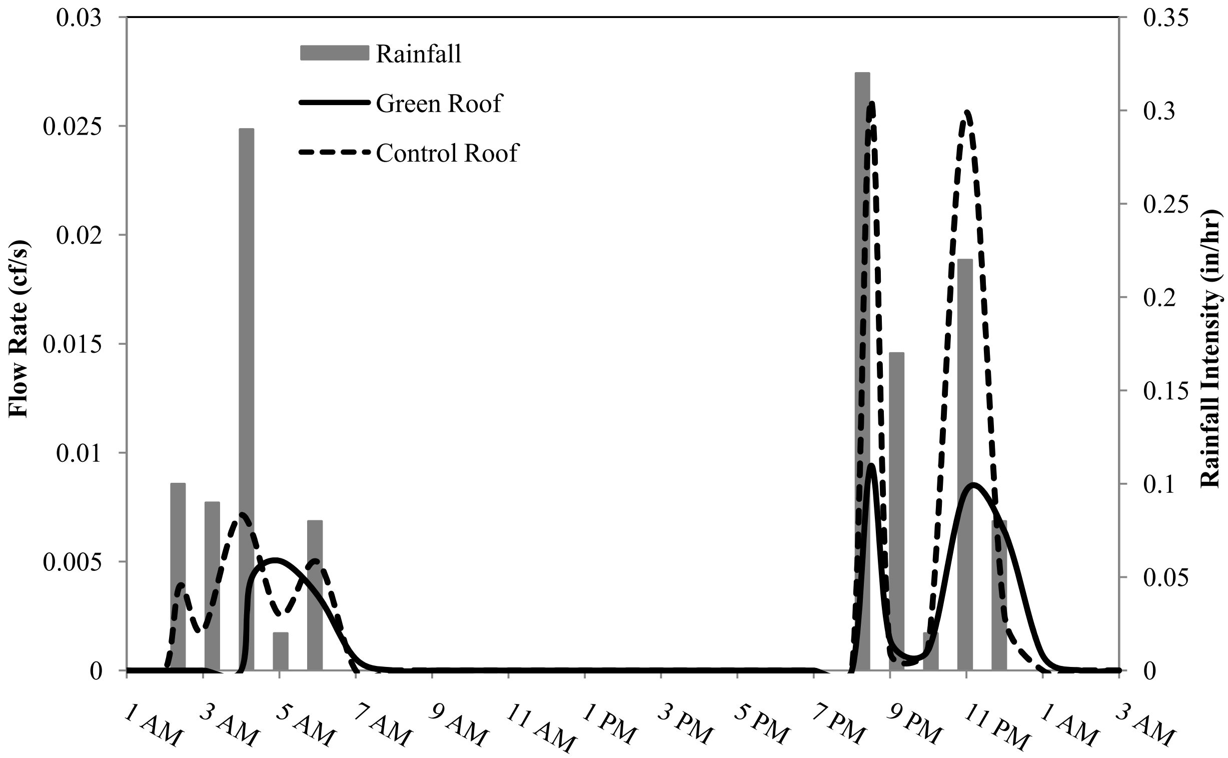


Figure 124. Runoff Flow Rates and Rainfall Intensity – June 26-27, 2008 Storm (Homestead)

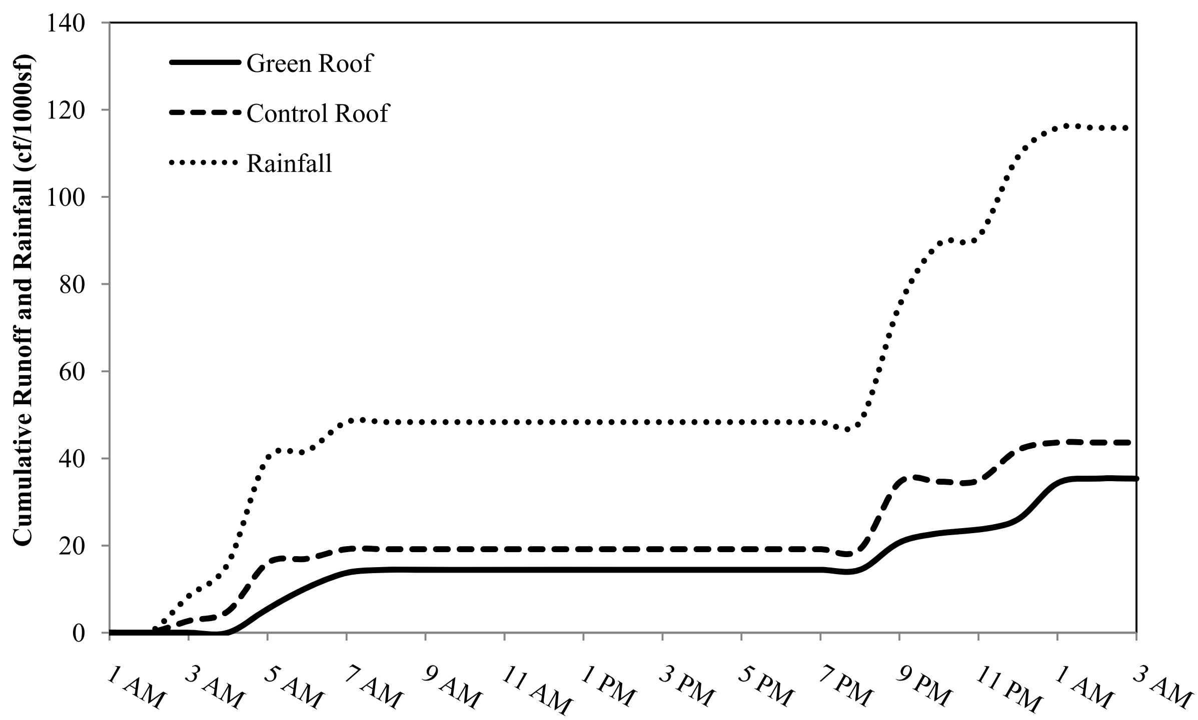


Figure 125. Runoff and Rainfall Volumes – June 26-27, 2008 Storm (Homestead)

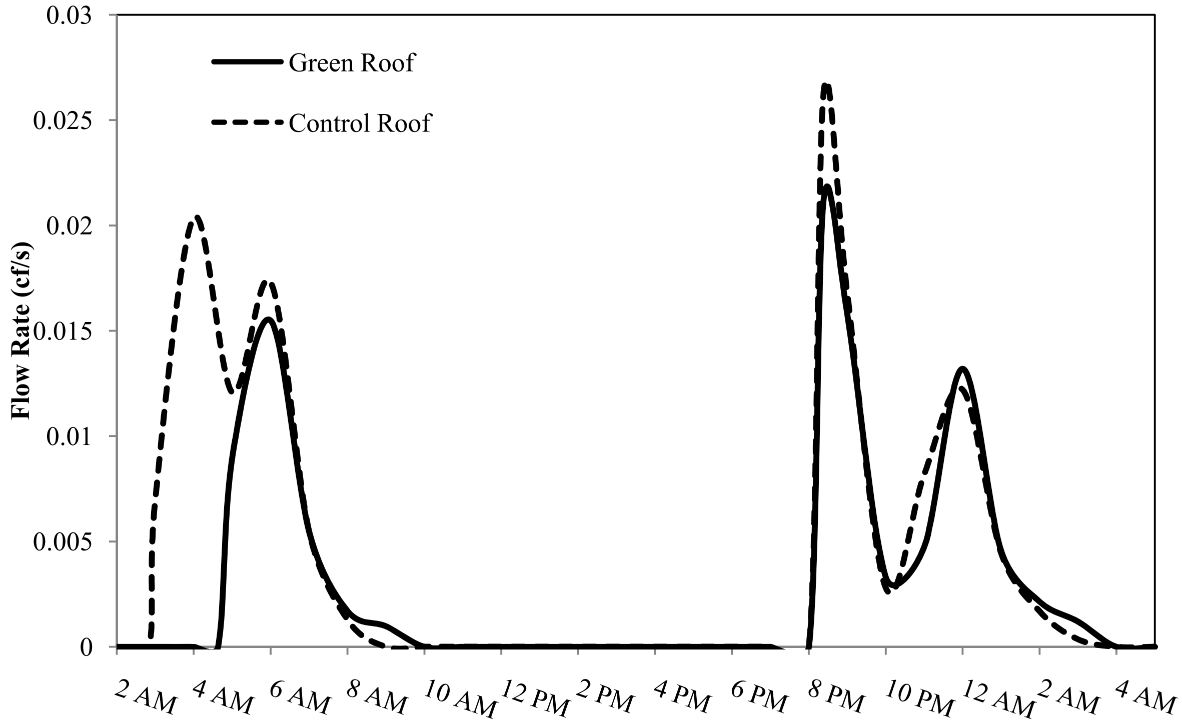


Figure 126. Runoff Flow Rates – June 26-27, 2008 Storm (Giant Eagle)

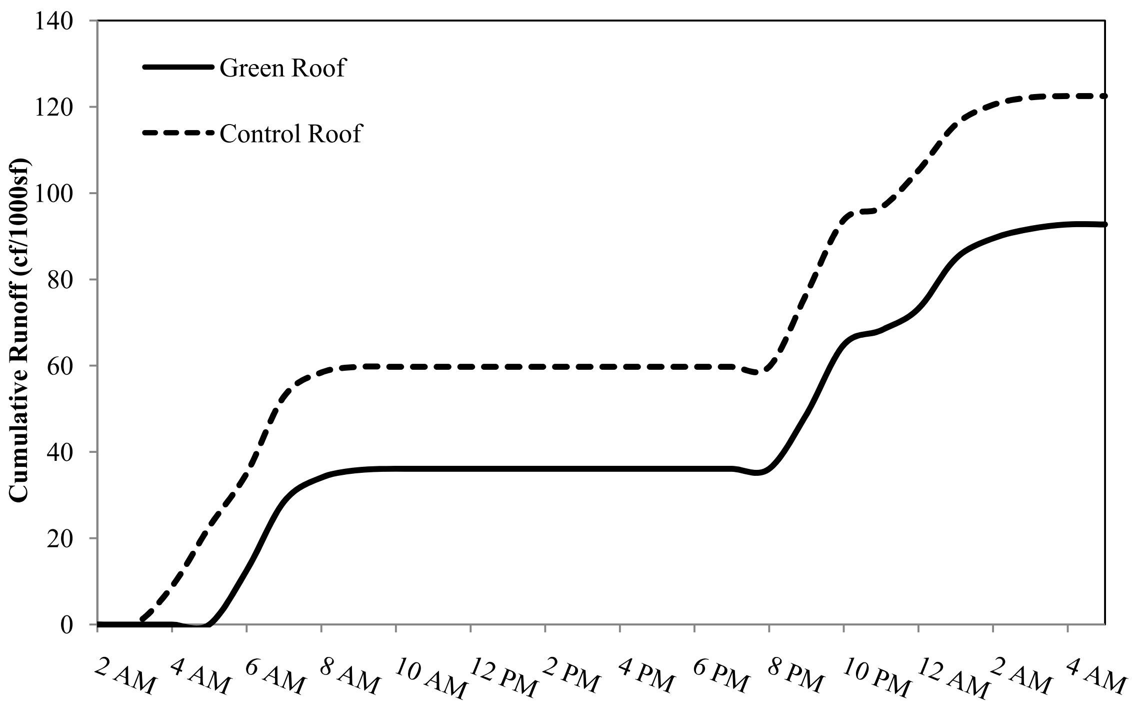


Figure 127. Runoff Volumes – June 26-27, 2008 Storm (Giant Eagle)

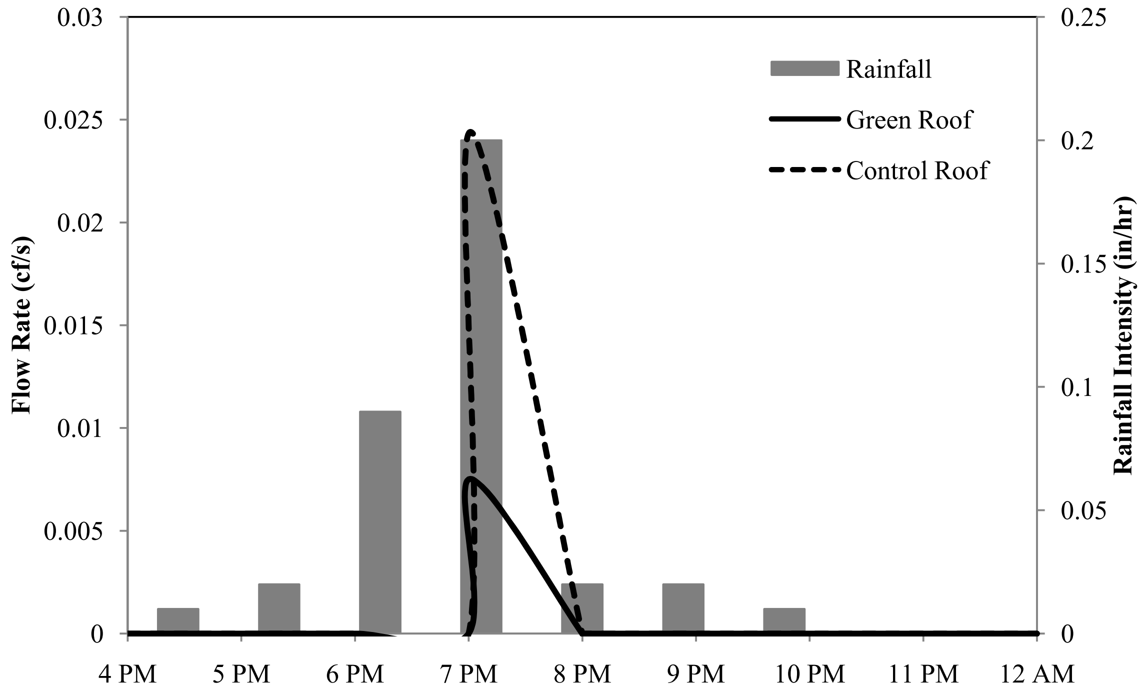


Figure 128. Runoff Flow Rates and Rainfall Intensity – June 28, 2008 Storm (Homestead)

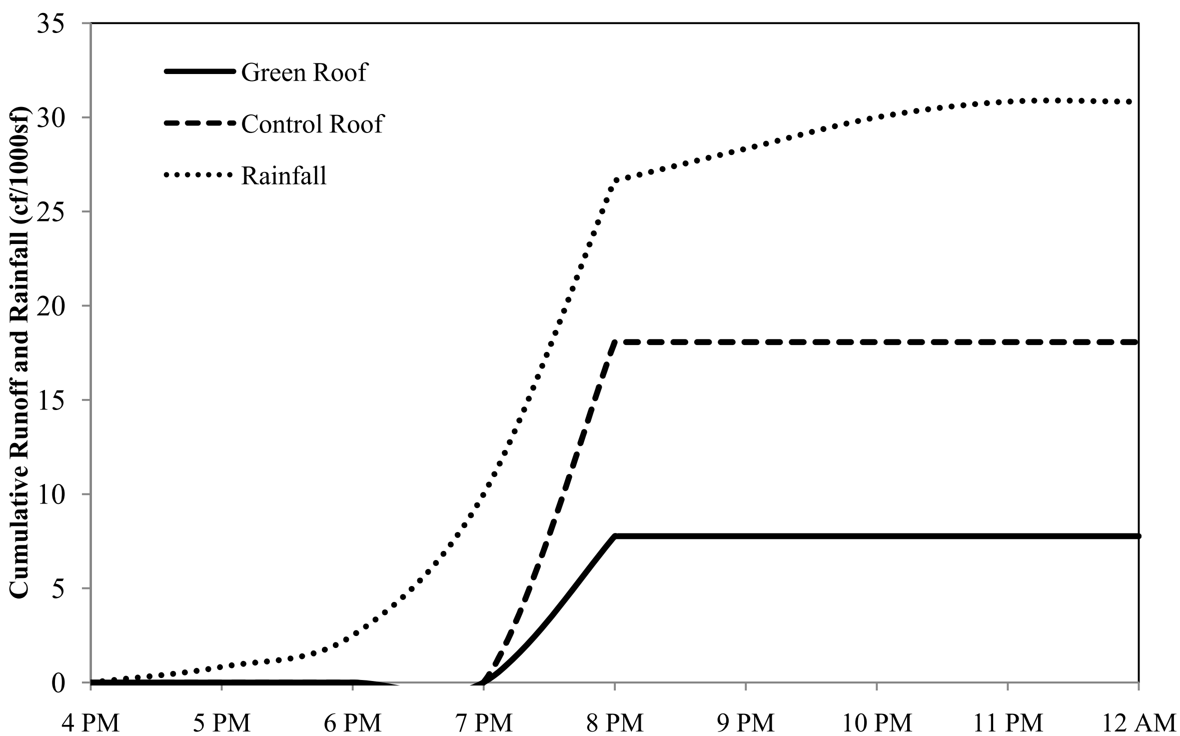


Figure 129. Runoff and Rainfall Volumes – June 28, 2008 Storm (Homestead)

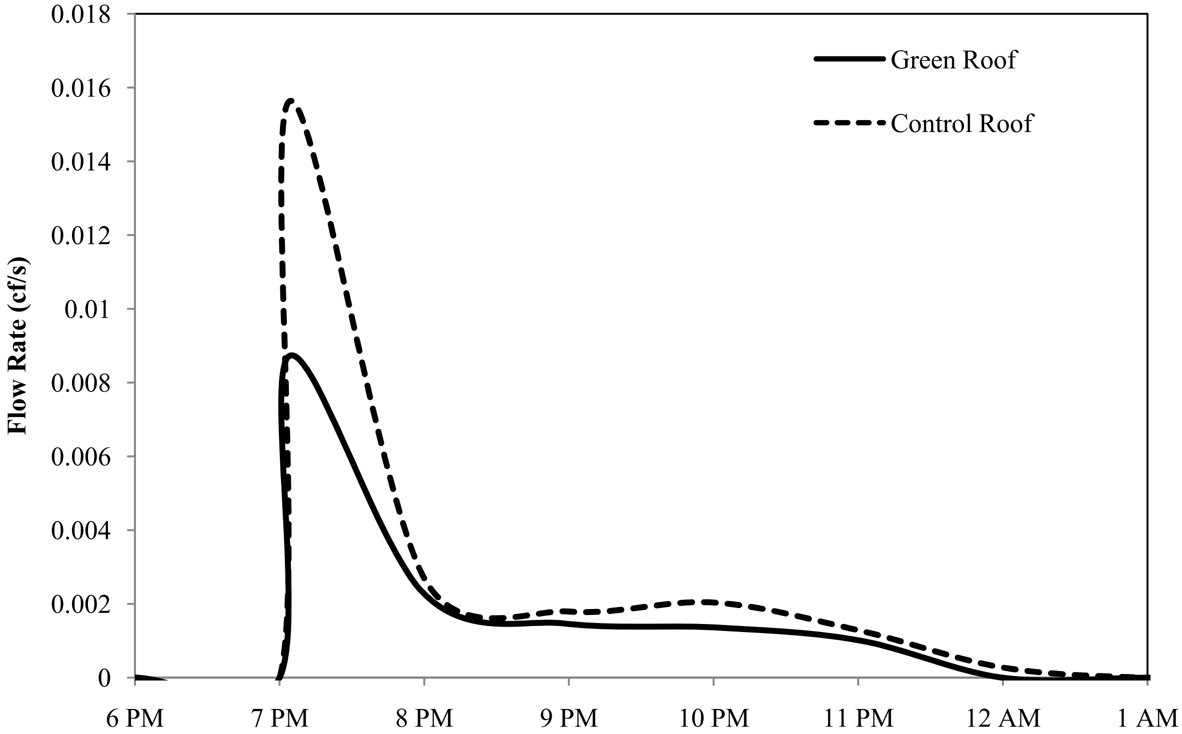


Figure 130. Runoff Flow Rates – June 28, 2008 Storm (Giant Eagle)

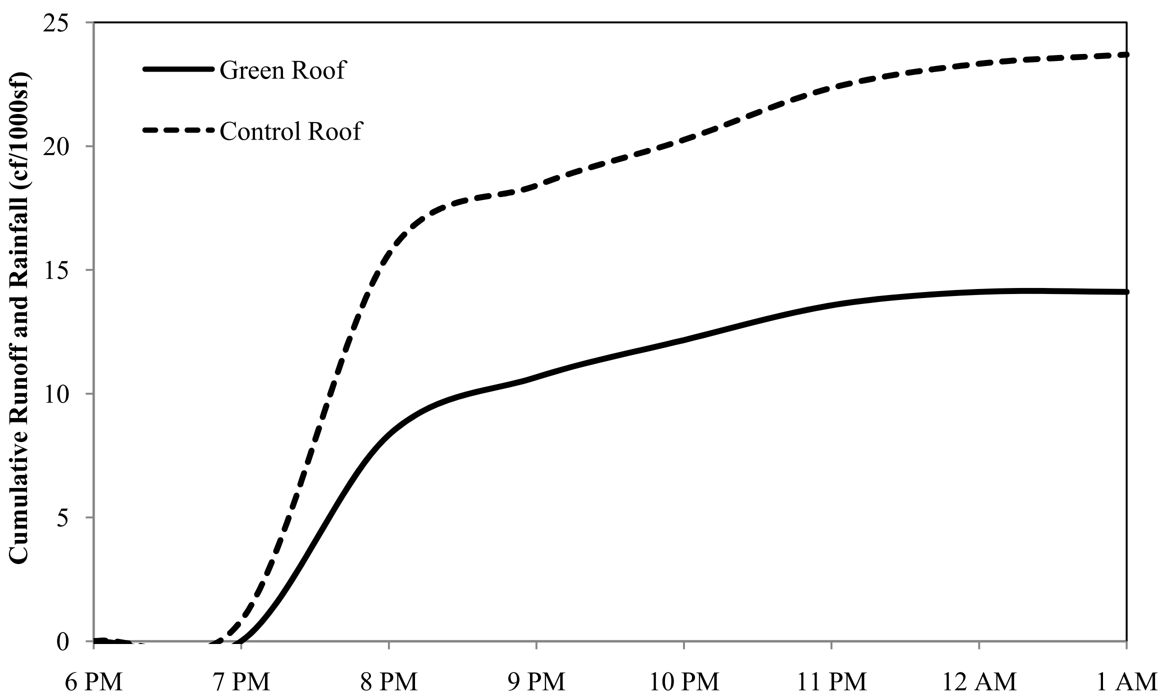


Figure 131. Runoff Volumes – June 28, 2008 Storm (Giant Eagle)

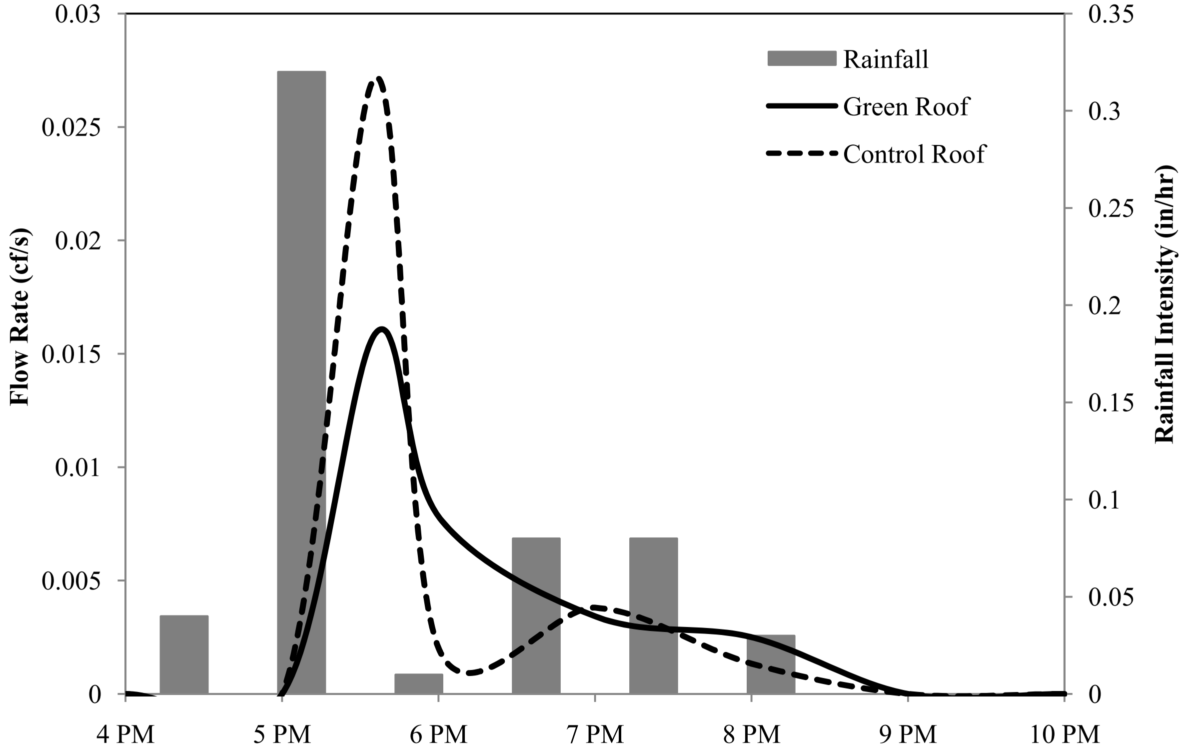


Figure 132. Runoff Flow Rates and Rainfall Intensity – June 29, 2008 Storm (Homestead)

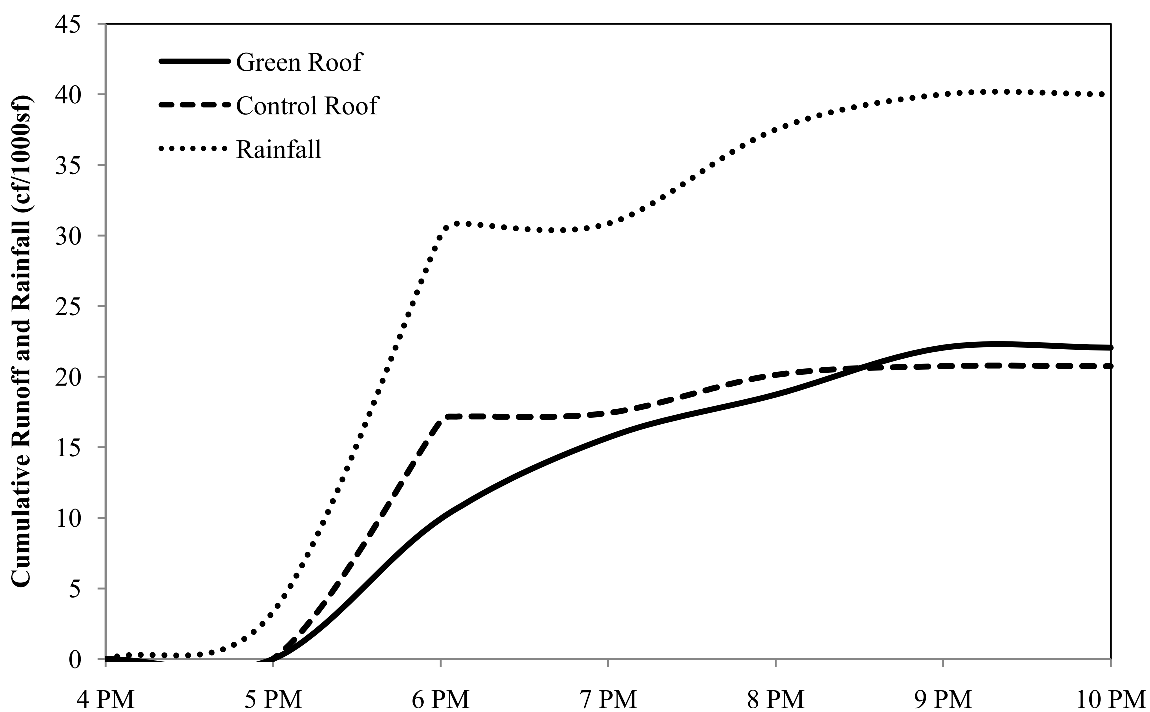


Figure 133. Runoff and Rainfall Volumes – June 29, 2008 Storm (Homestead)

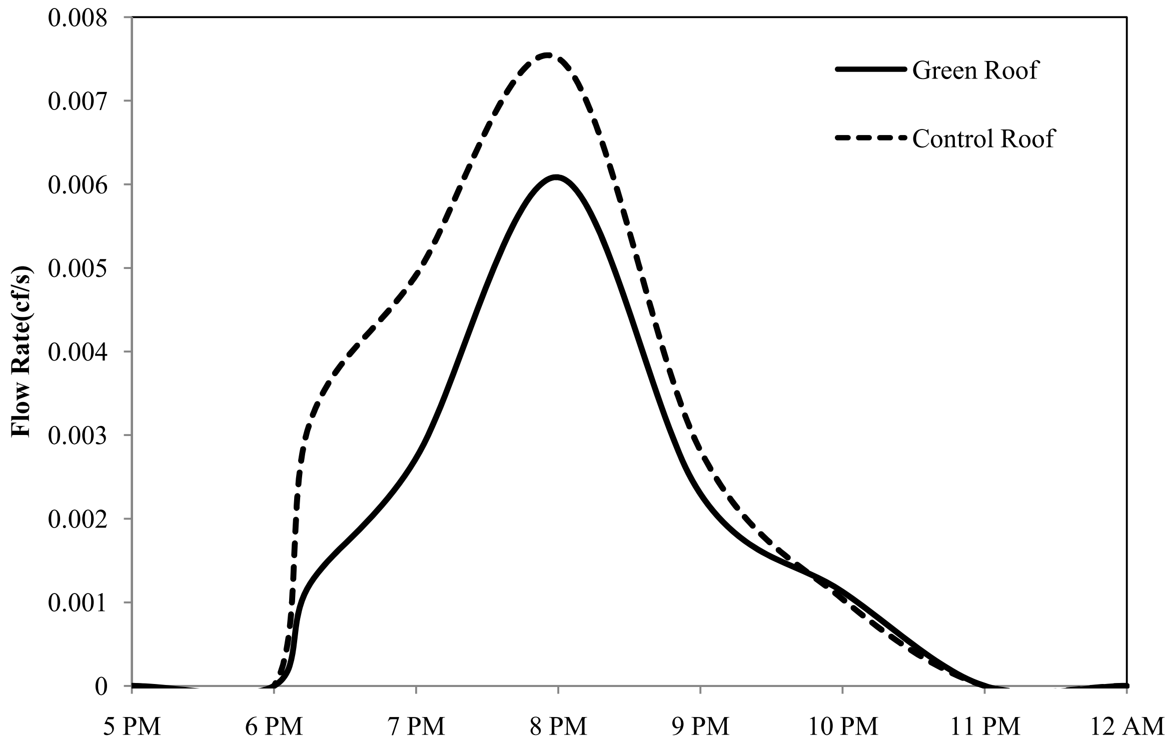


Figure 134. Runoff Flow Rates – June 29, 2008 Storm (Giant Eagle)

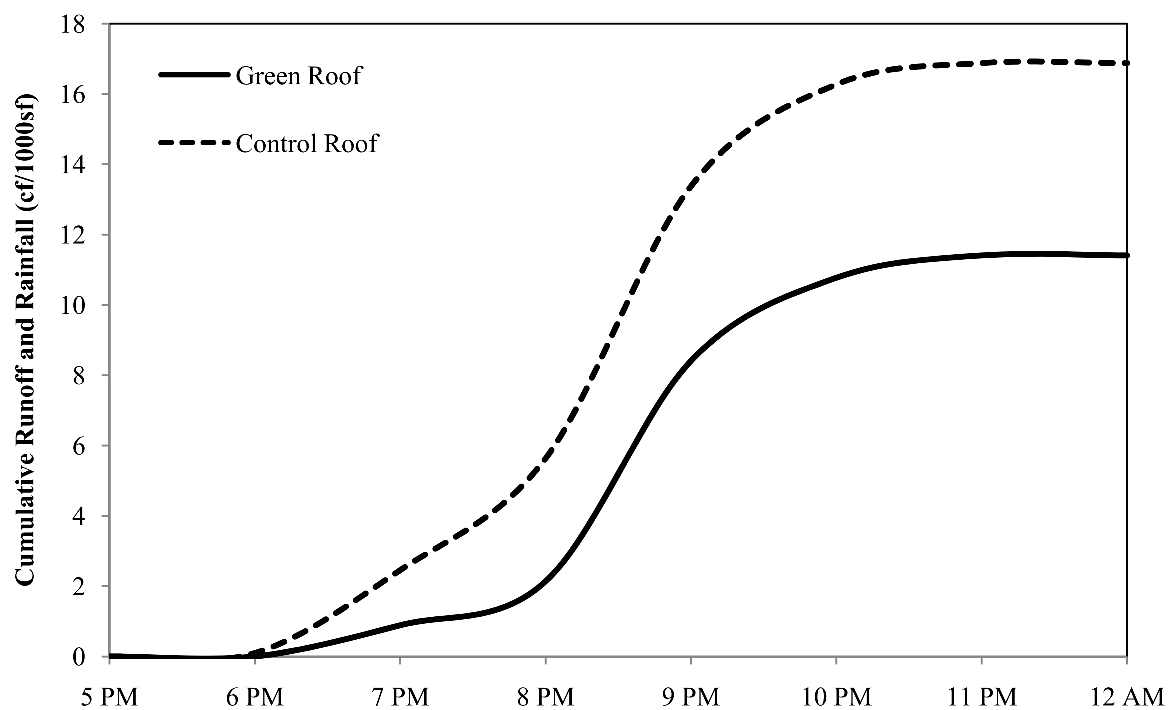


Figure 135. Runoff Volumes – June 29, 2008 Storm (Giant Eagle)

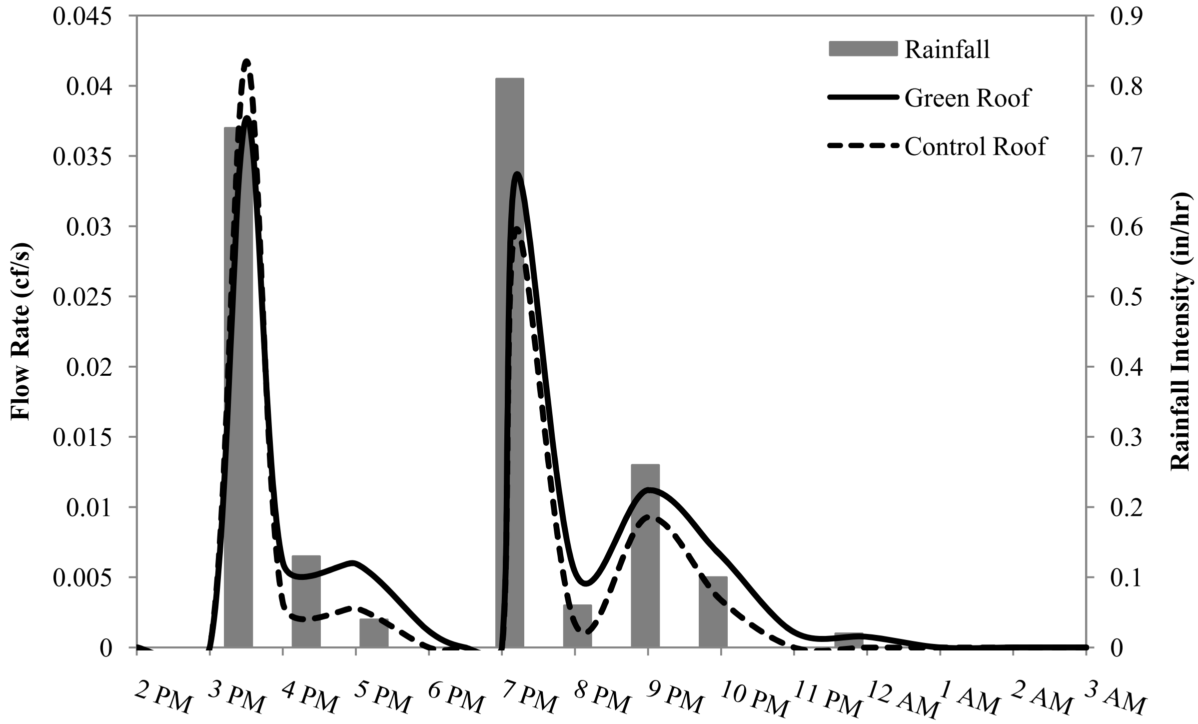


Figure 136. Runoff Flow Rates and Rainfall Intensity – June 30-July1, 2008 Storm (Homestead)

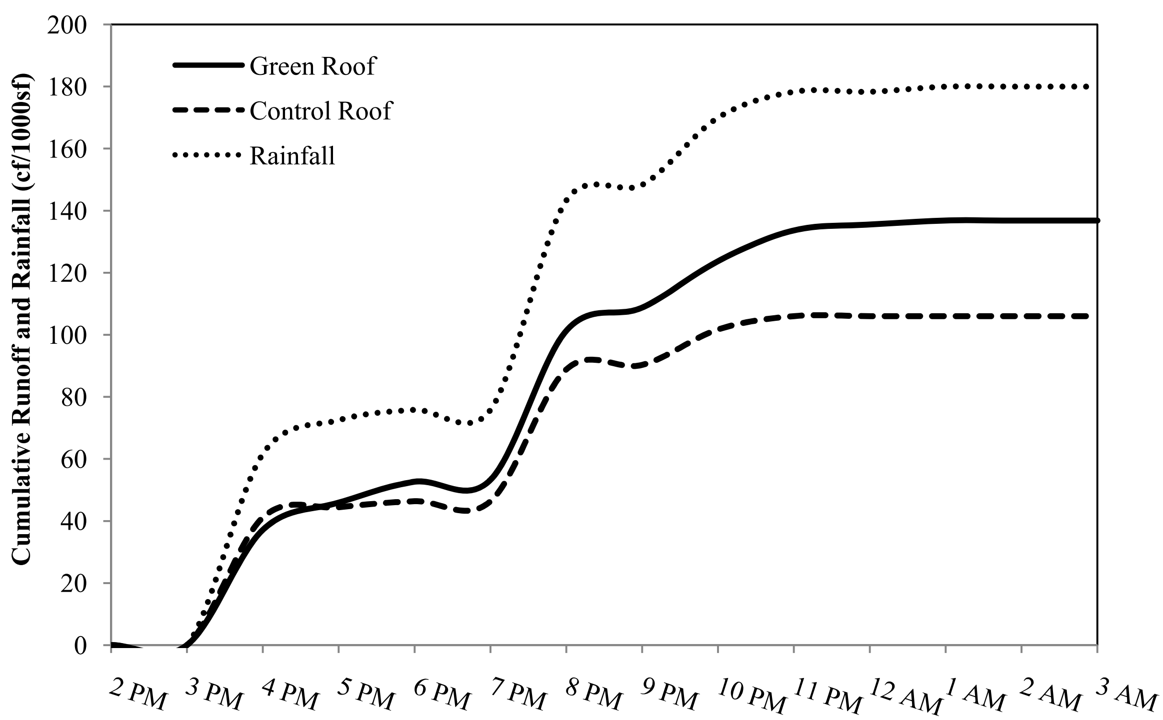


Figure 137. Runoff and Rainfall Volumes – June 30-July 1, 2008 Storm (Homestead)

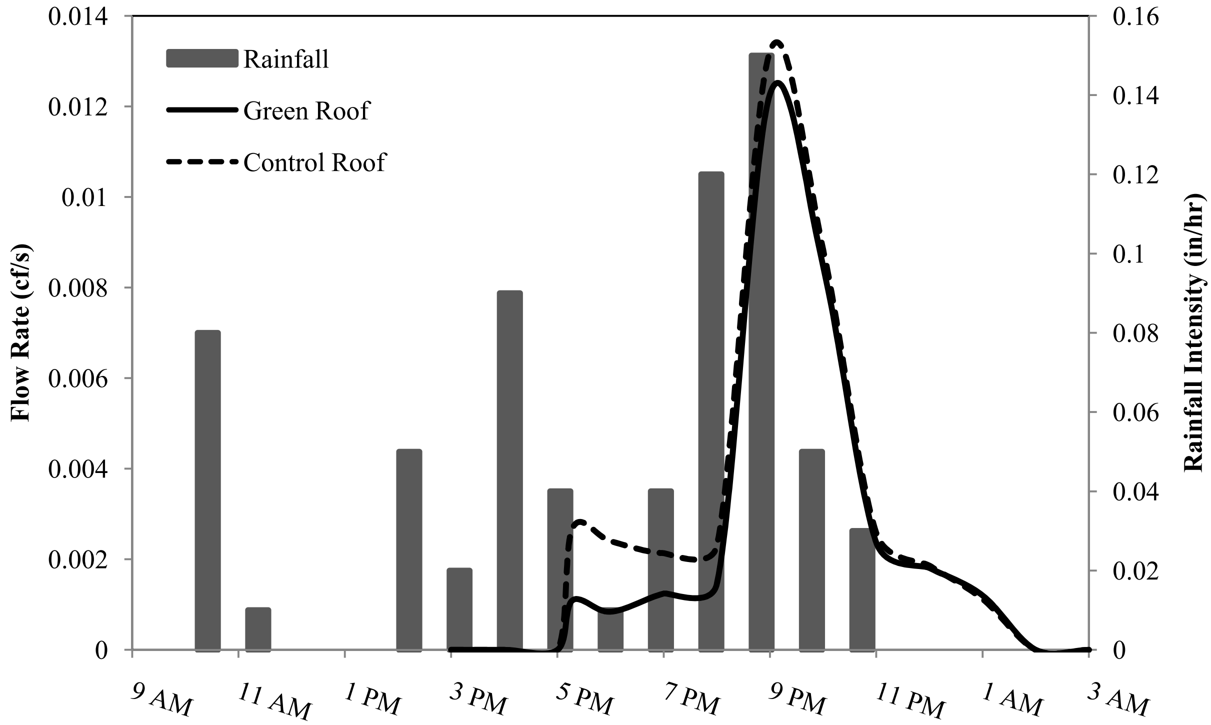


Figure 138. Runoff Flow Rates and Rainfall intensity – June 30-July 1, 2008 Storm (Giant Eagle)

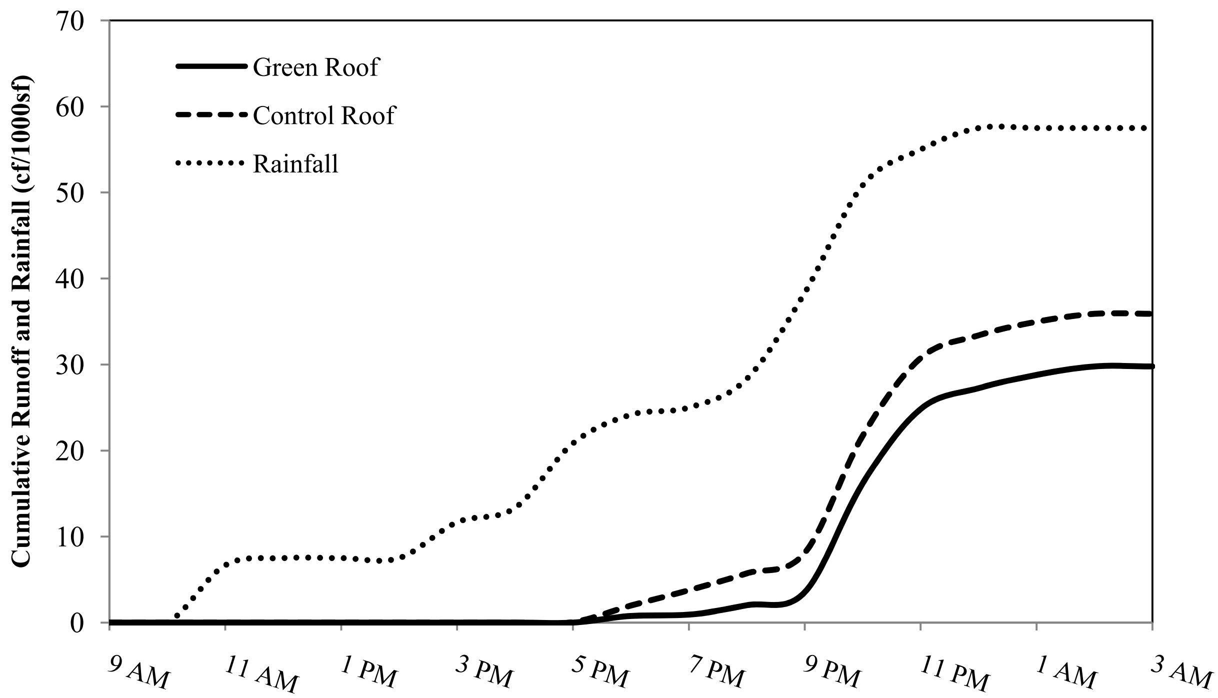


Figure 139. Runoff and Rainfall Volumes – June 30-July 1, 2008 Storm (Giant Eagle)

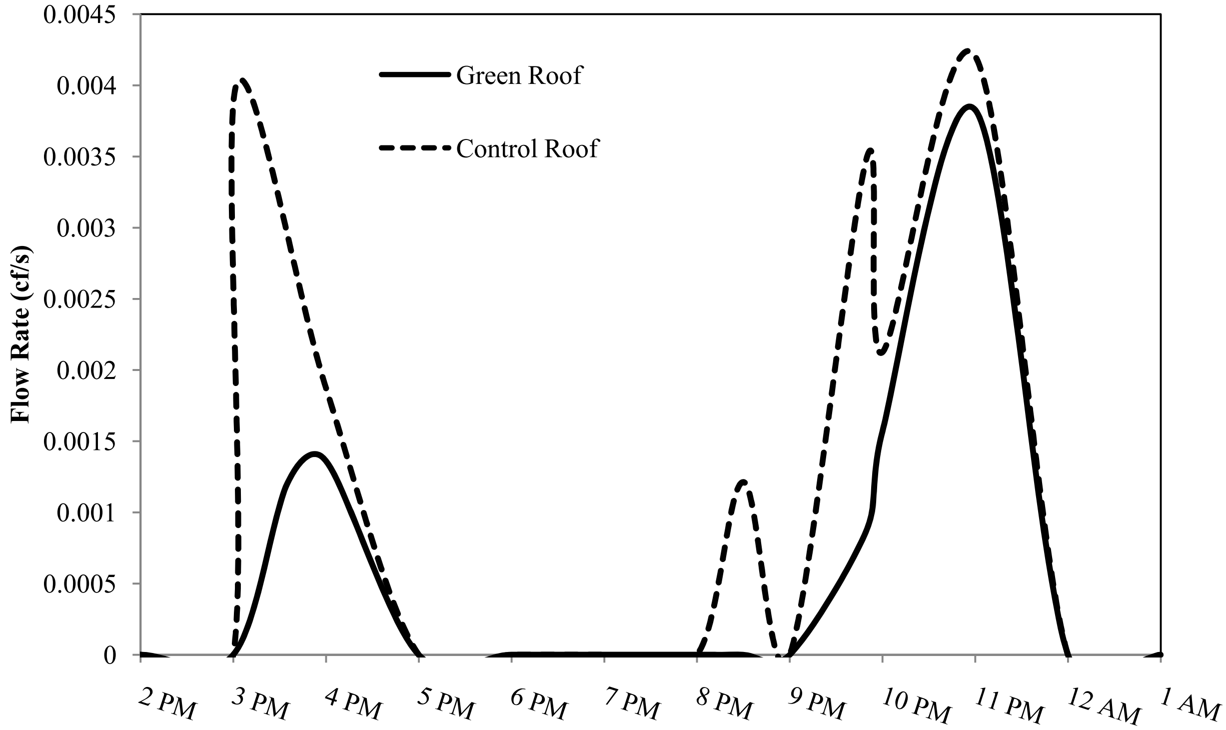


Figure 140. Runoff Flow Rates – July 3, 2008 Storm (Homestead)

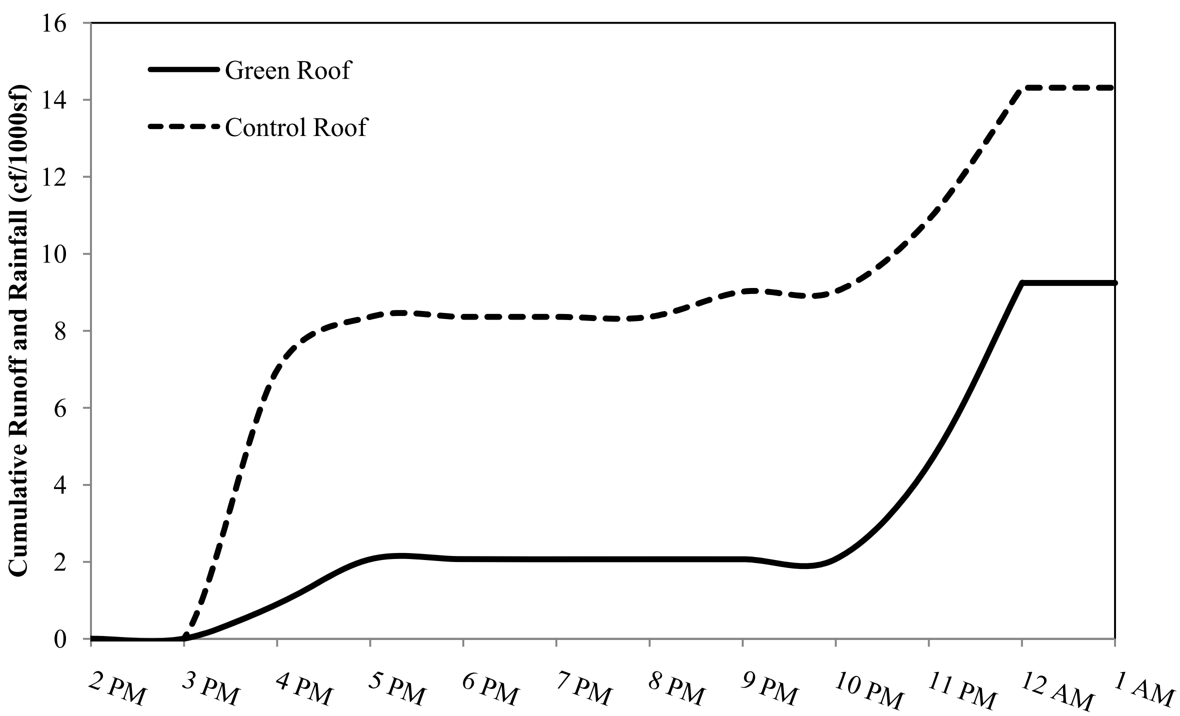


Figure 141. Runoff Volumes – July 3, 2008 Storm (Homestead)

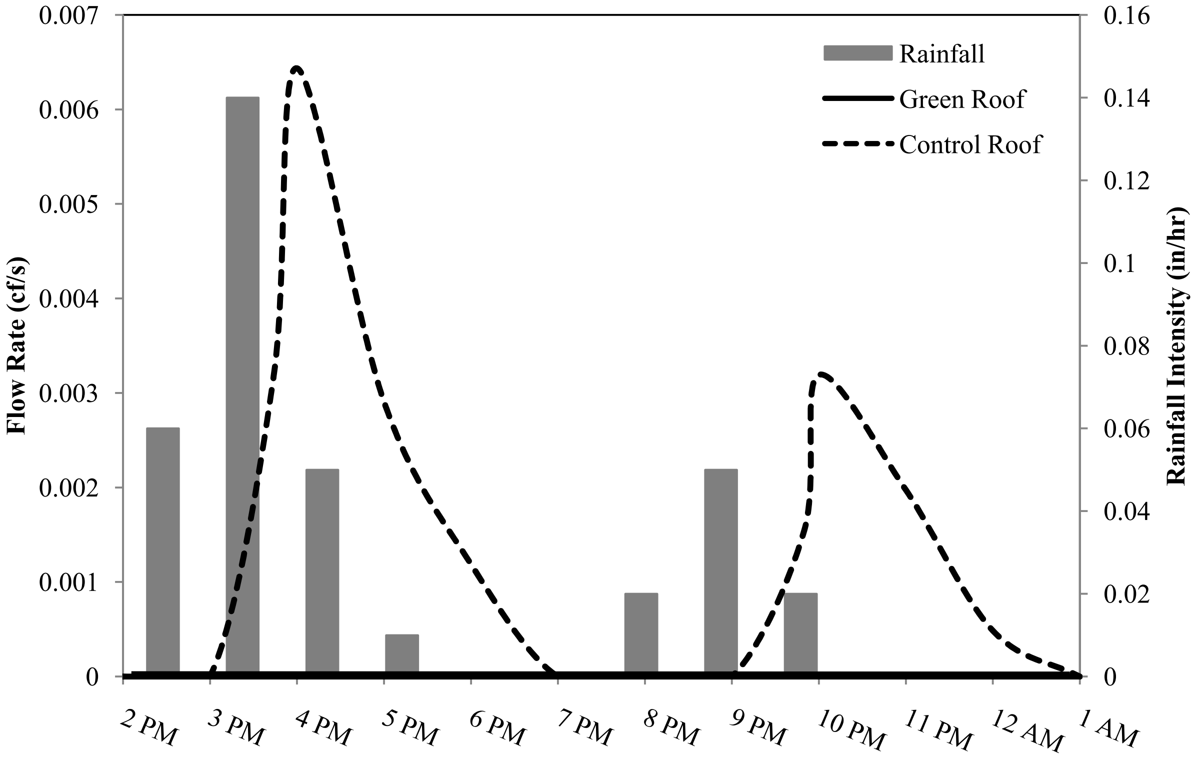


Figure 142. Runoff Flow Rates and Rainfall intensity – July 3, 2008 Storm (Giant Eagle)

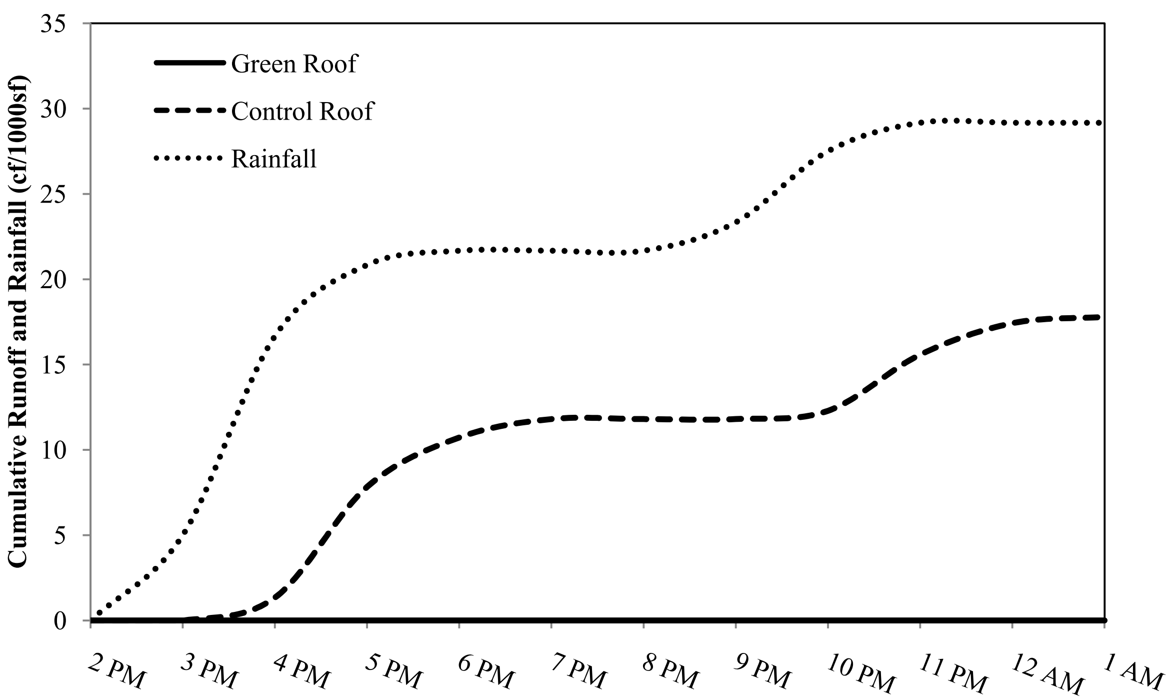


Figure 143. Runoff and Rainfall Volumes – July 3, 2008 Storm (Giant Eagle)

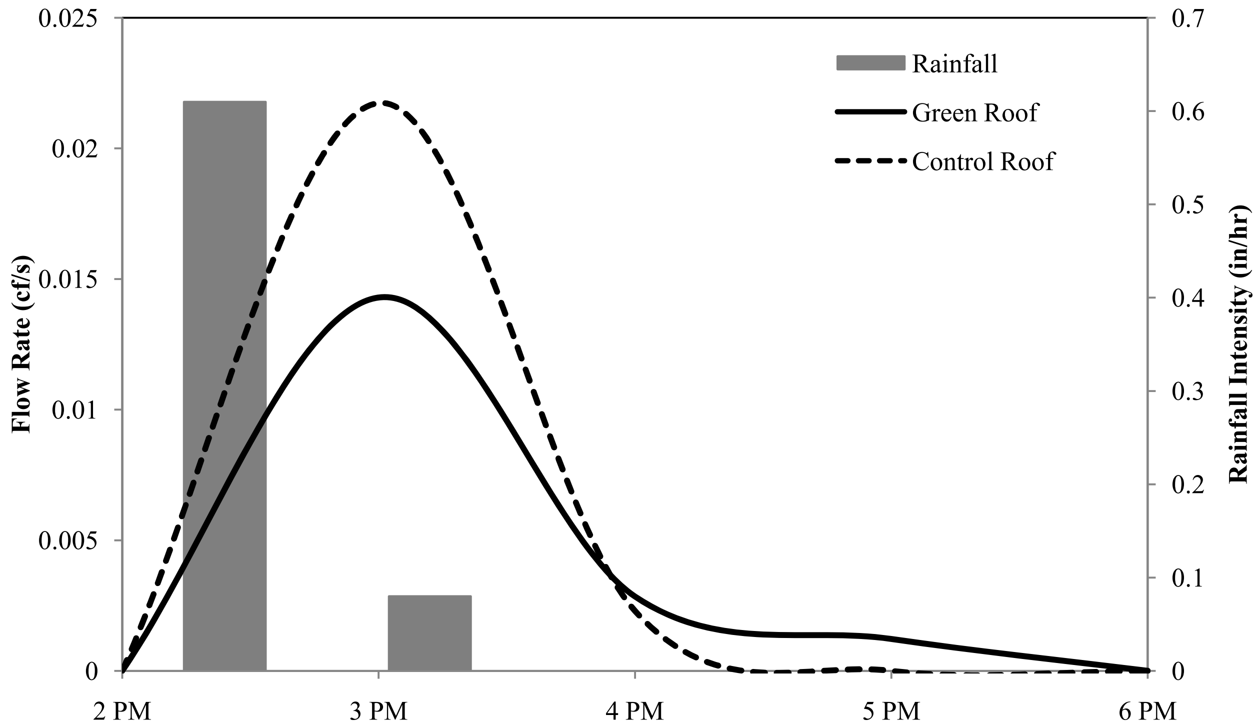


Figure 144. Runoff Flow Rates and Rainfall intensity – July 7, 2008 Storm (Giant Eagle)

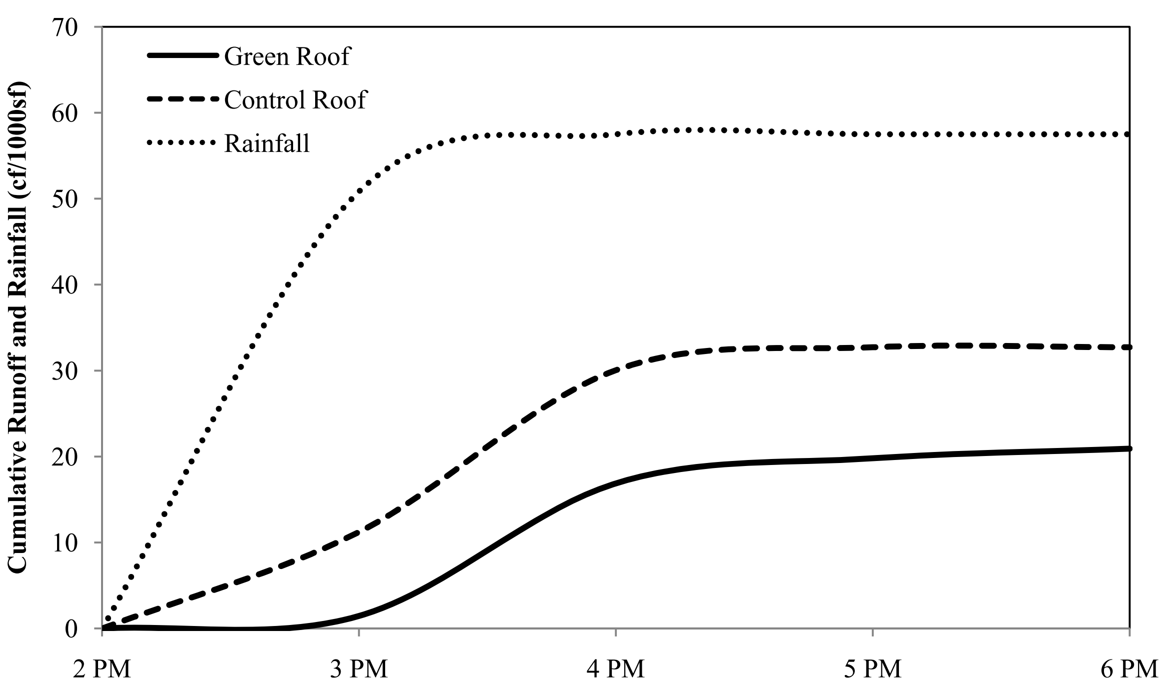


Figure 145. Runoff and Rainfall Volumes – July 7, 2008 Storm (Giant Eagle)

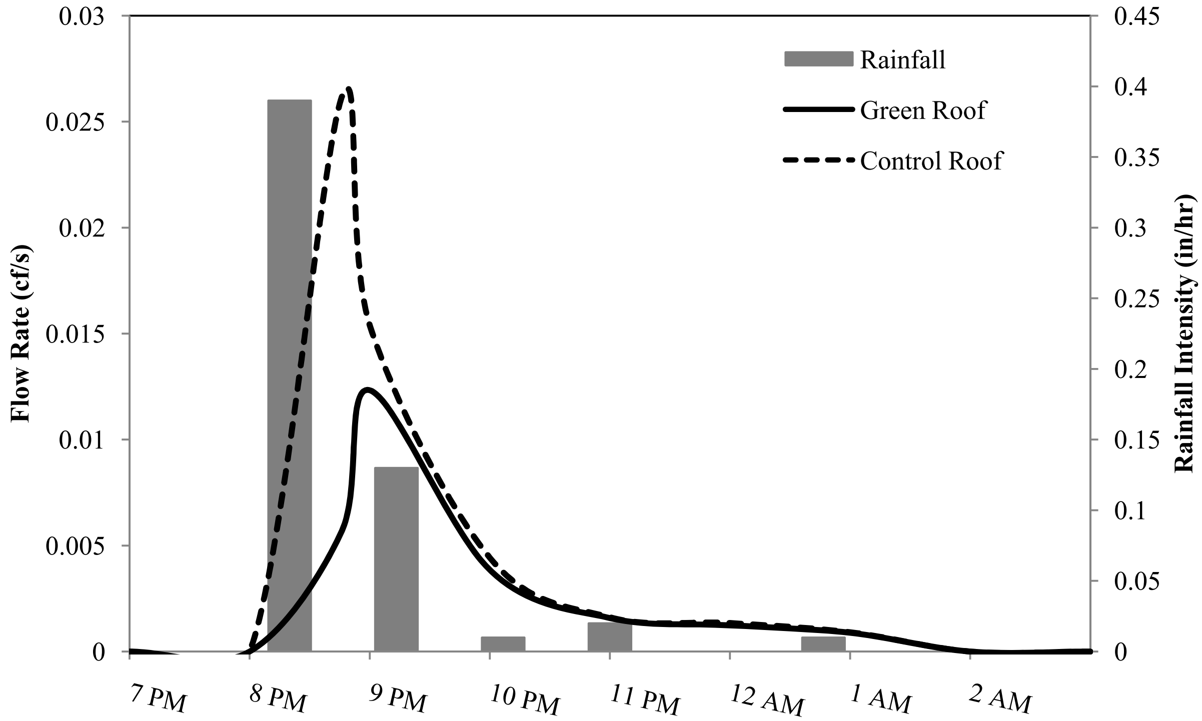


Figure 146. Runoff Flow Rates and Rainfall intensity – July 8-9, 2008 Storm (Giant Eagle)

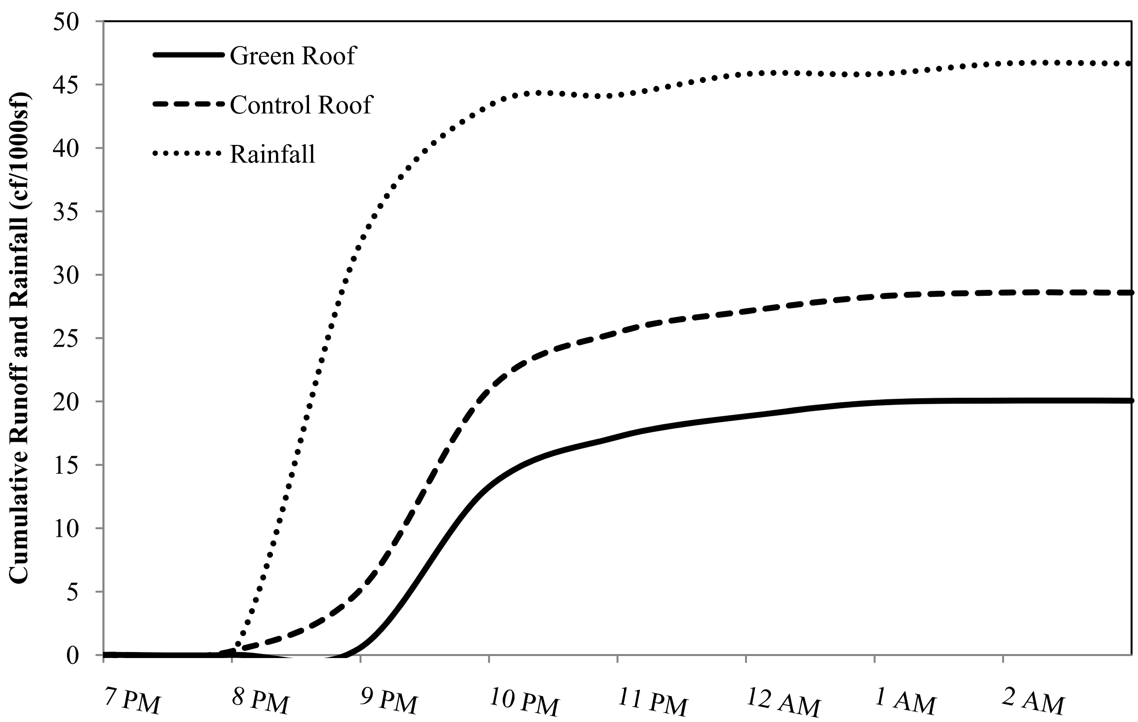


Figure 147. Runoff and Rainfall Volumes – July 8-9, 2008 Storm (Giant Eagle)

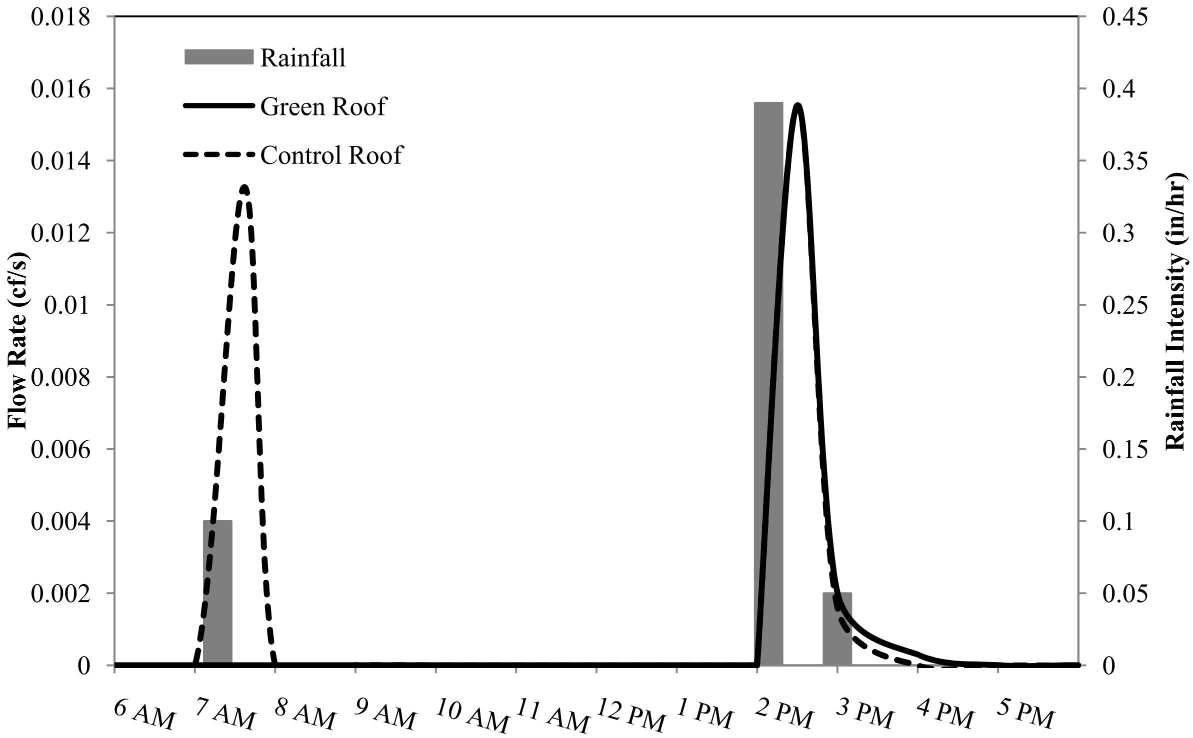


Figure 148. Runoff Flow Rates and Rainfall Intensity – July 20, 2008 Storm (Homestead)

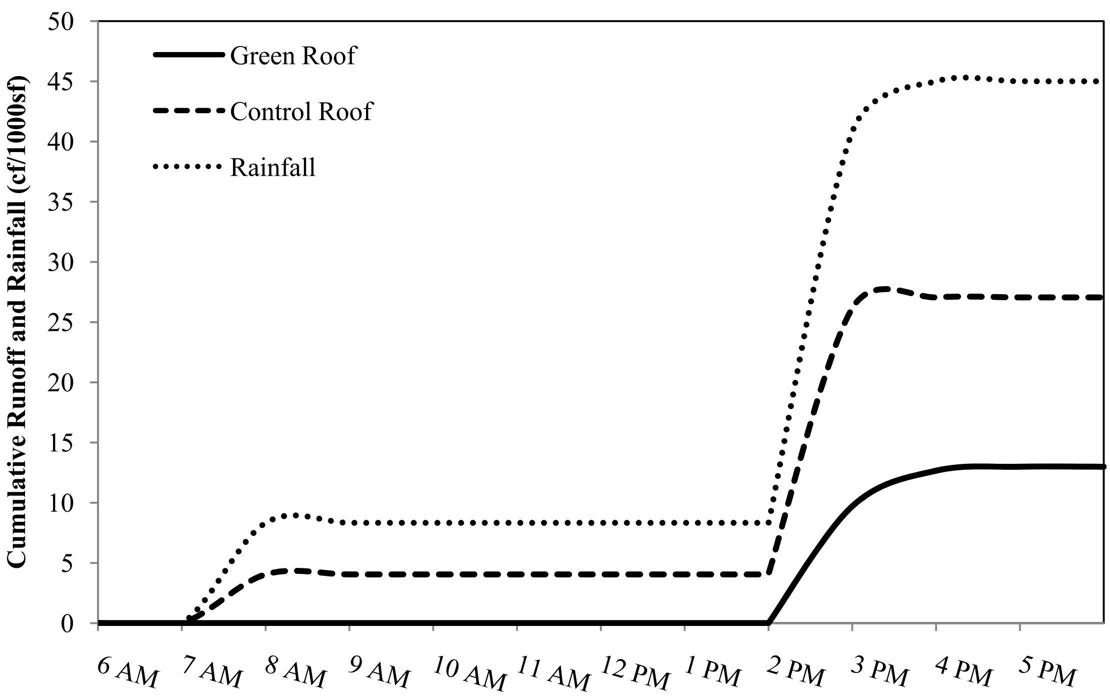


Figure 149. Runoff and Rainfall Volumes – July 20, 2008 Storm (Homestead)

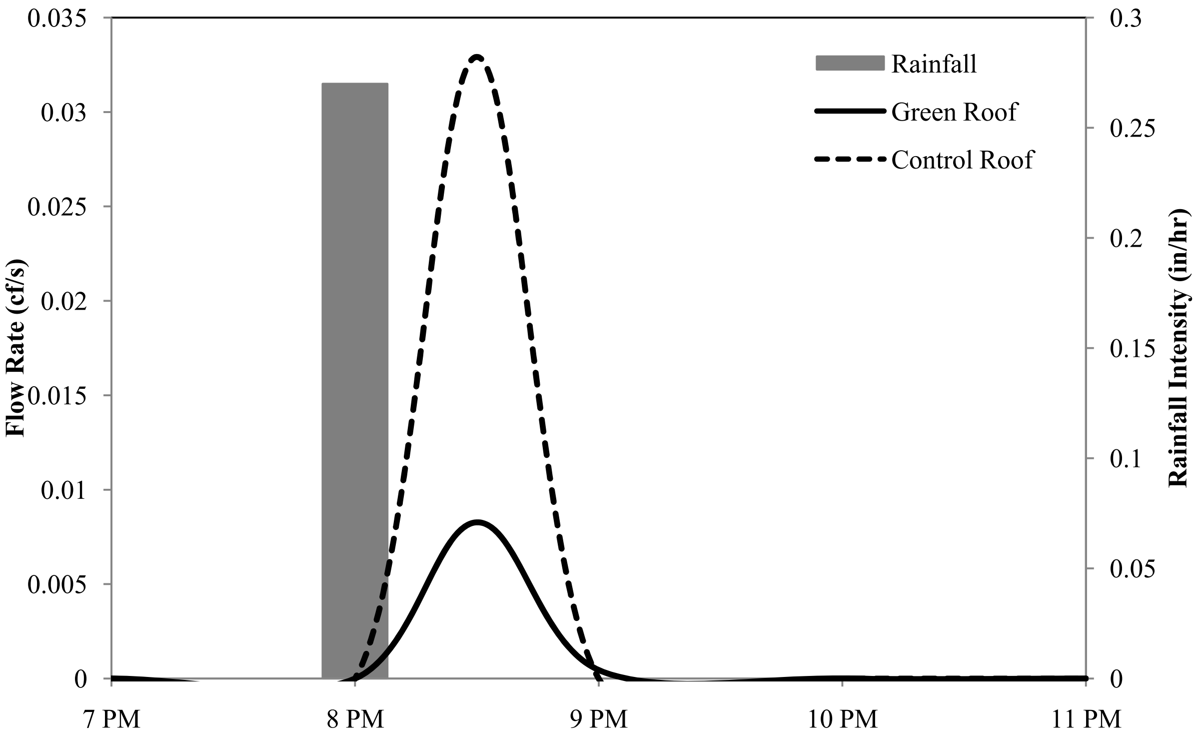


Figure 150. Runoff Flow Rates and Rainfall Intensity – July 21, 2008 Storm (Homestead)

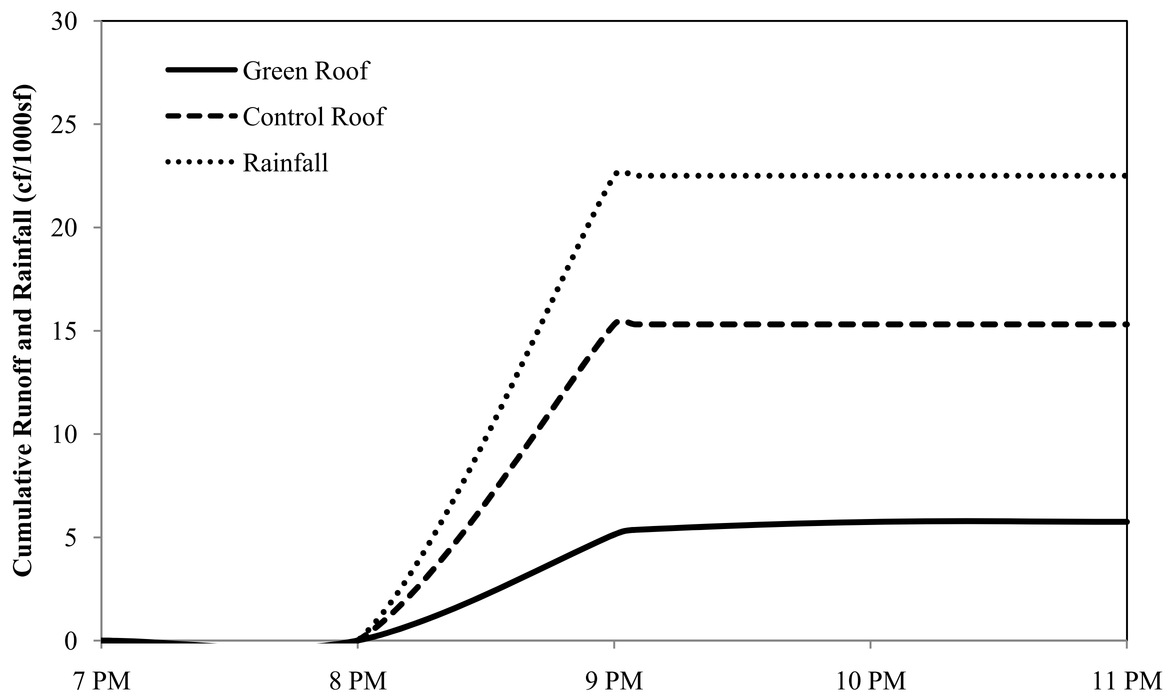


Figure 151. Runoff and Rainfall Volumes – July 21, 2008 Storm (Homestead)

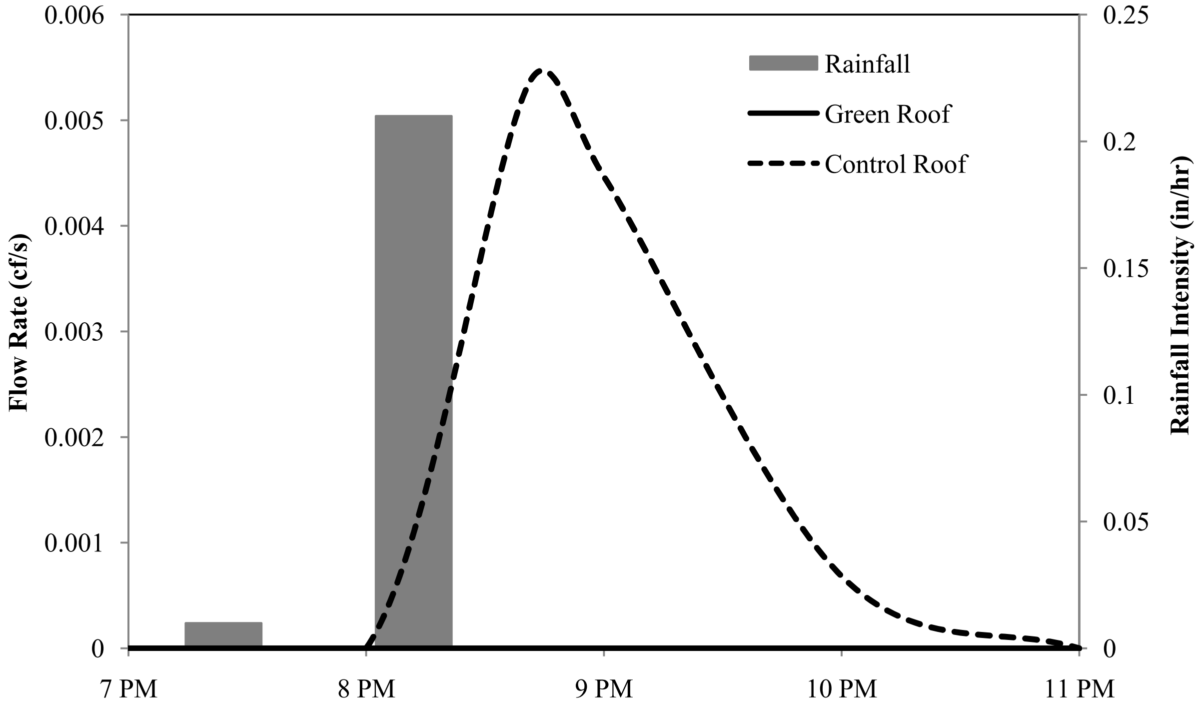


Figure 152. Runoff Flow Rates and Rainfall intensity – July 21, 2008 Storm (Giant Eagle)

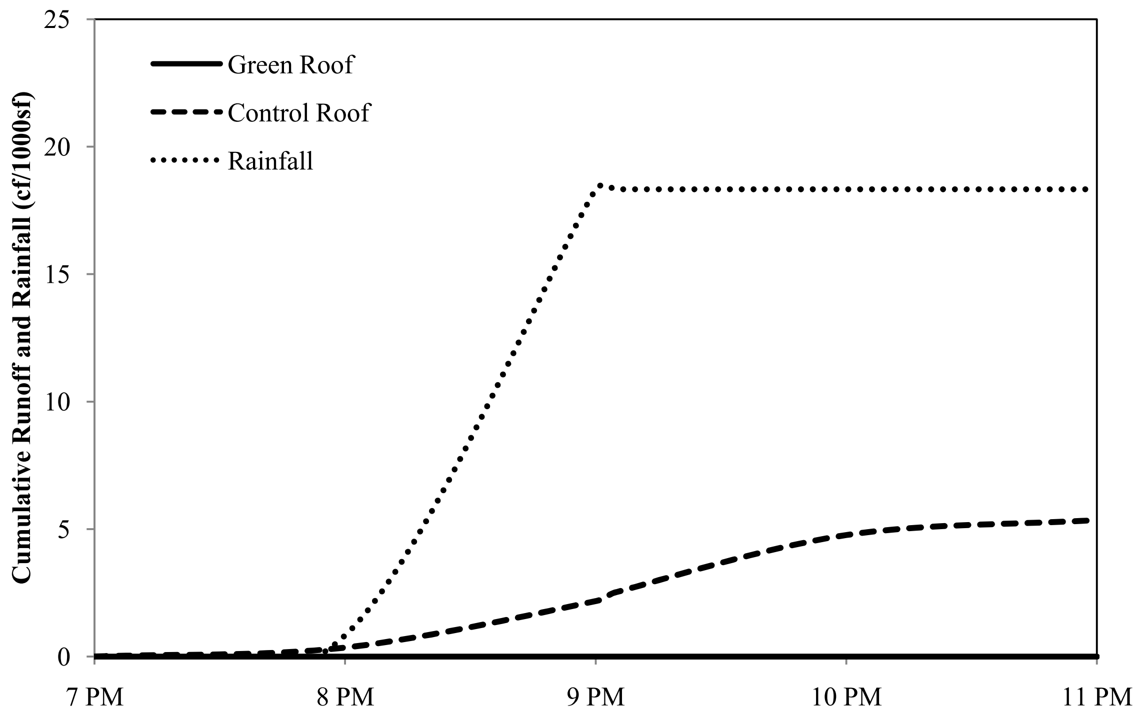


Figure 153. Runoff and Rainfall Volumes – July 21, 2008 Storm (Giant Eagle)

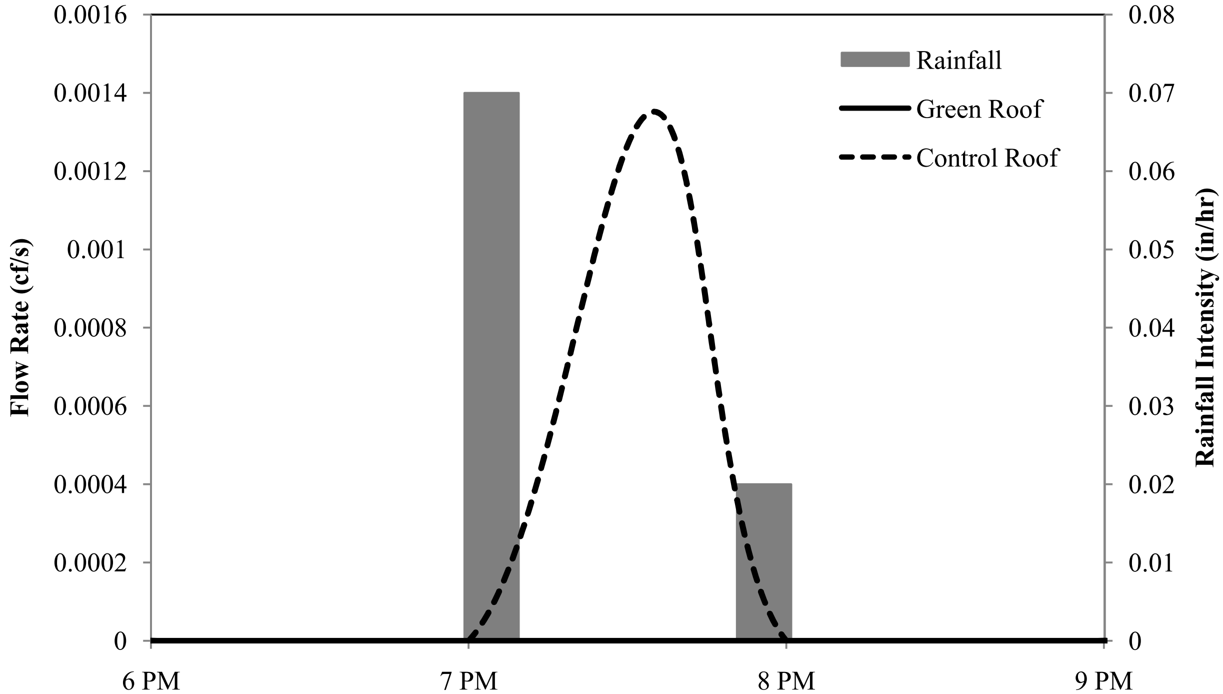


Figure 154. Runoff Flow Rates and Rainfall Intensity – July 22, 2008 Storm (Homestead)

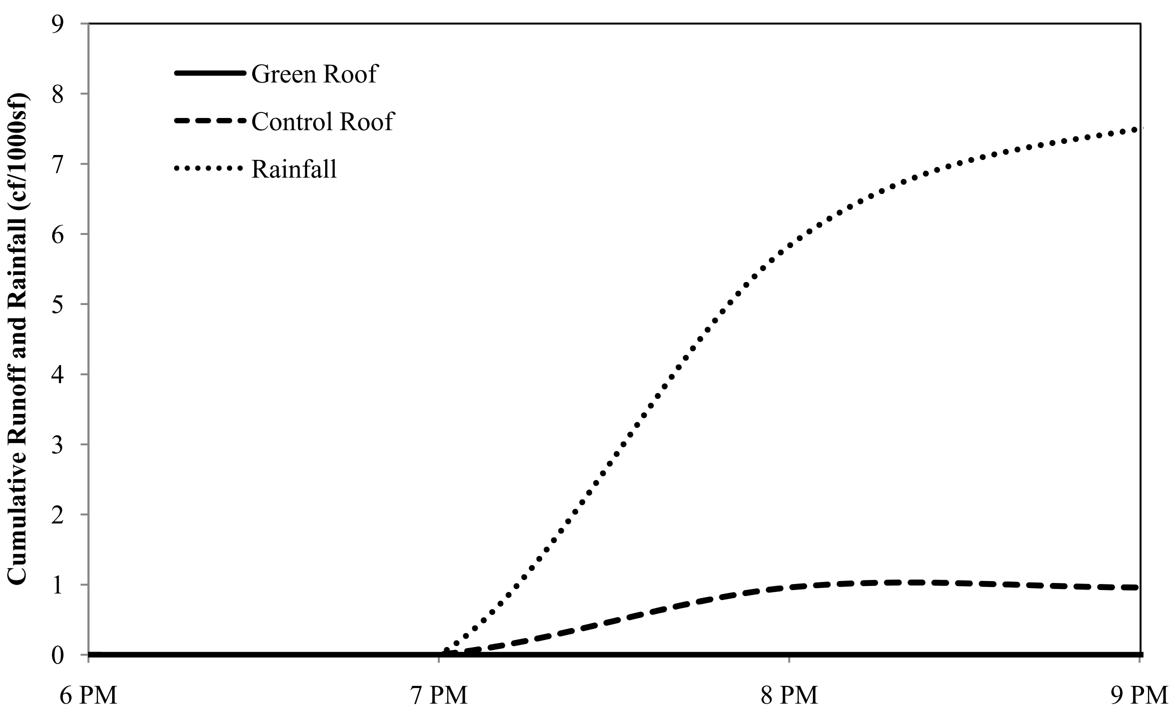


Figure 155. Runoff and Rainfall Volumes – July 22, 2008 Storm (Homestead)

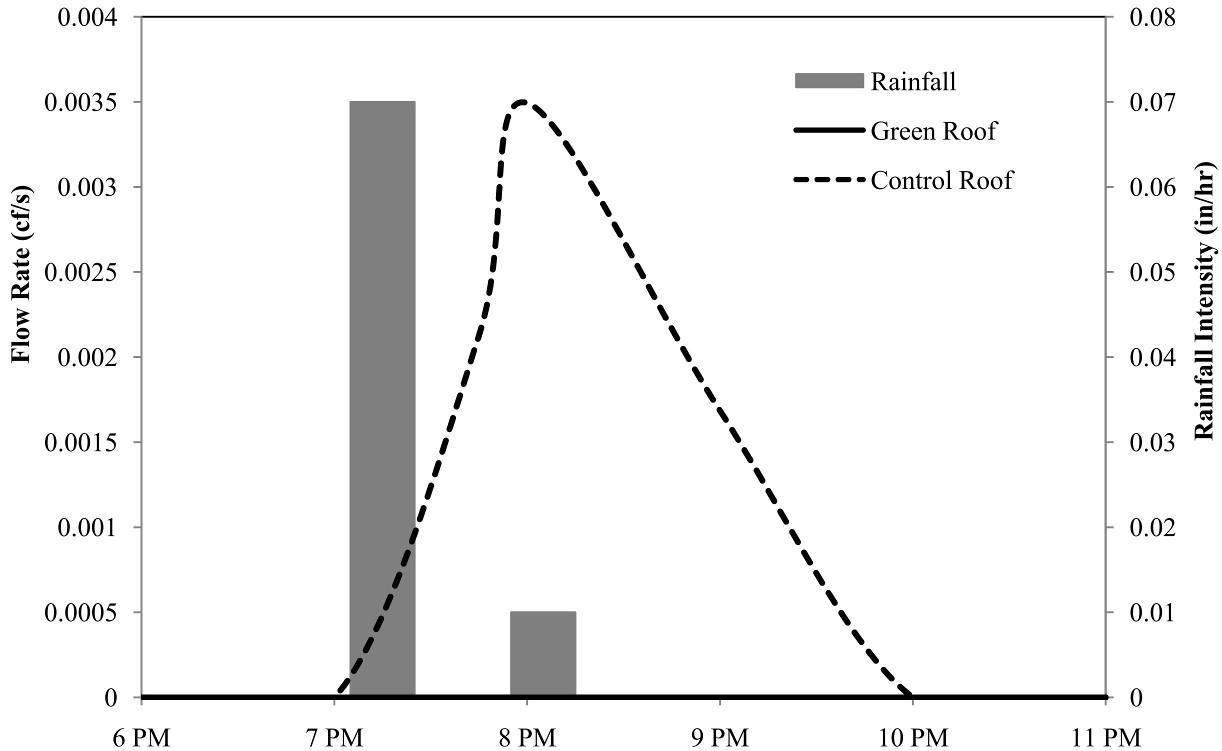


Figure 156. Runoff Flow Rates and Rainfall intensity – July 22, 2008 Storm (Giant Eagle)

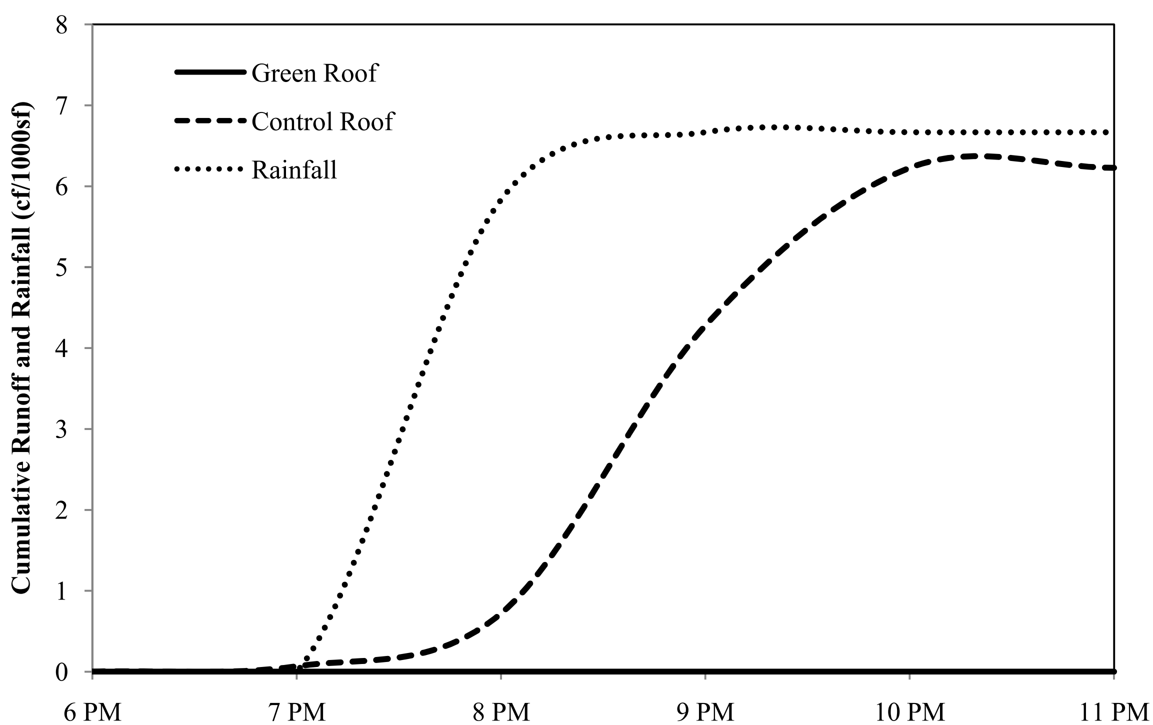


Figure 157. Runoff and Rainfall Volumes – July 22, 2008 Storm (Giant Eagle)

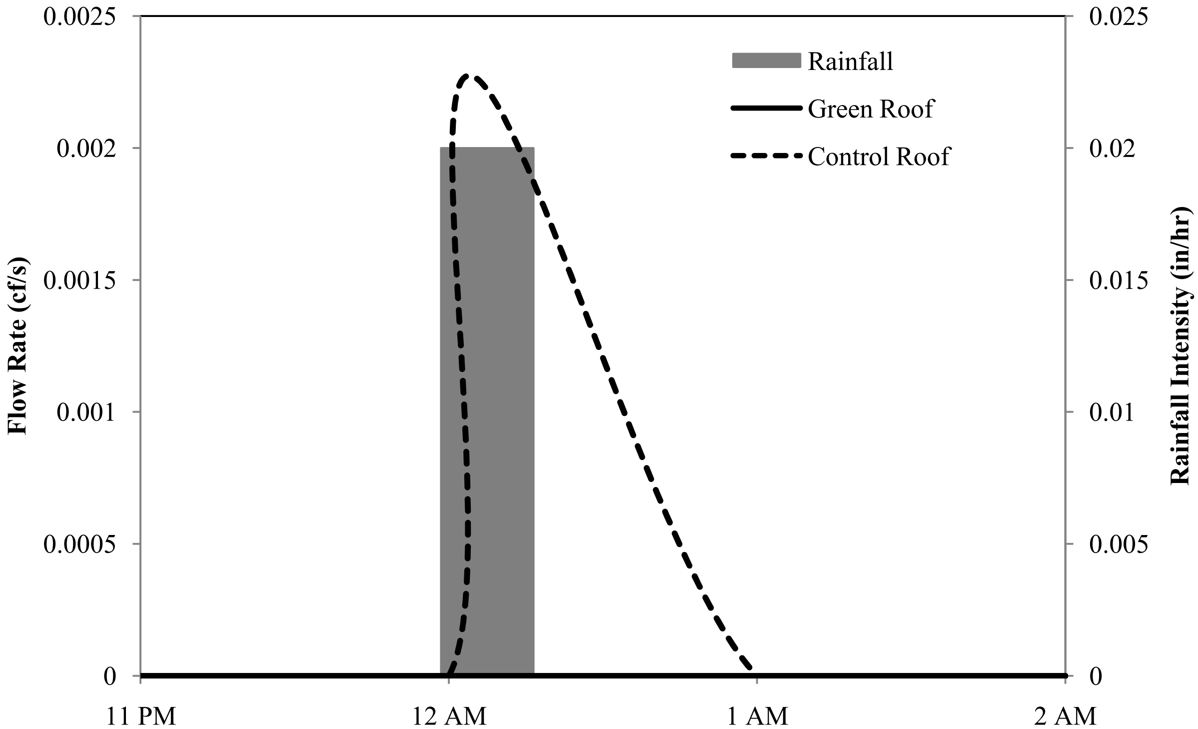


Figure 158. Runoff Flow Rates and Rainfall Intensity – July 27, 2008 Storm (Homestead)

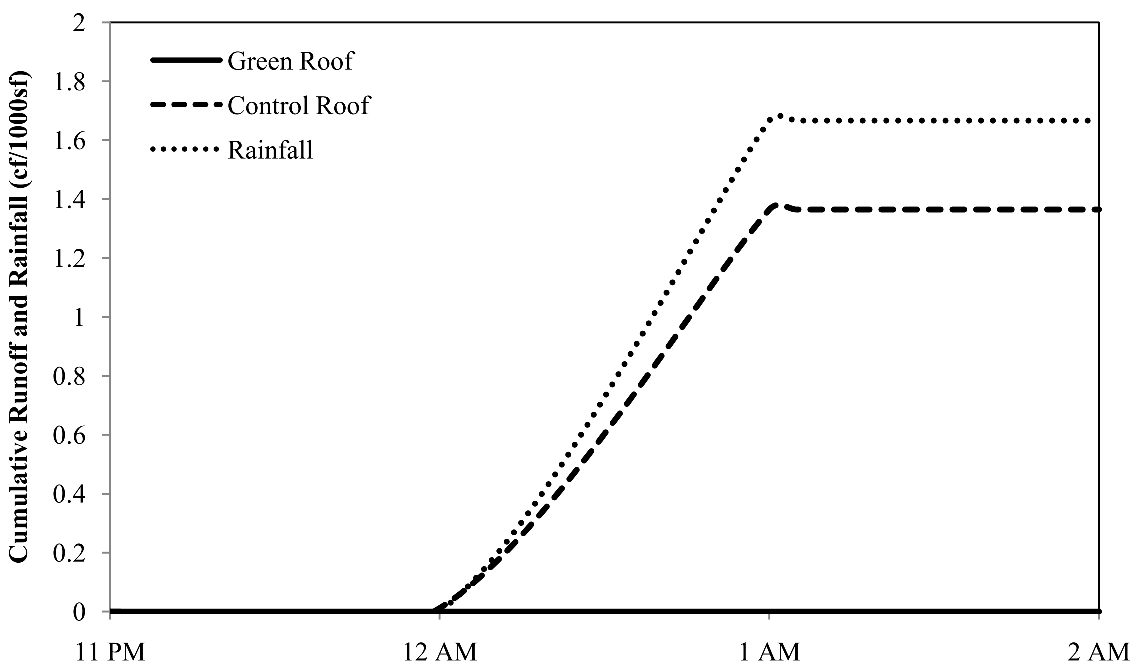


Figure 159. Runoff and Rainfall Volumes – July 27, 2008 Storm (Homestead)

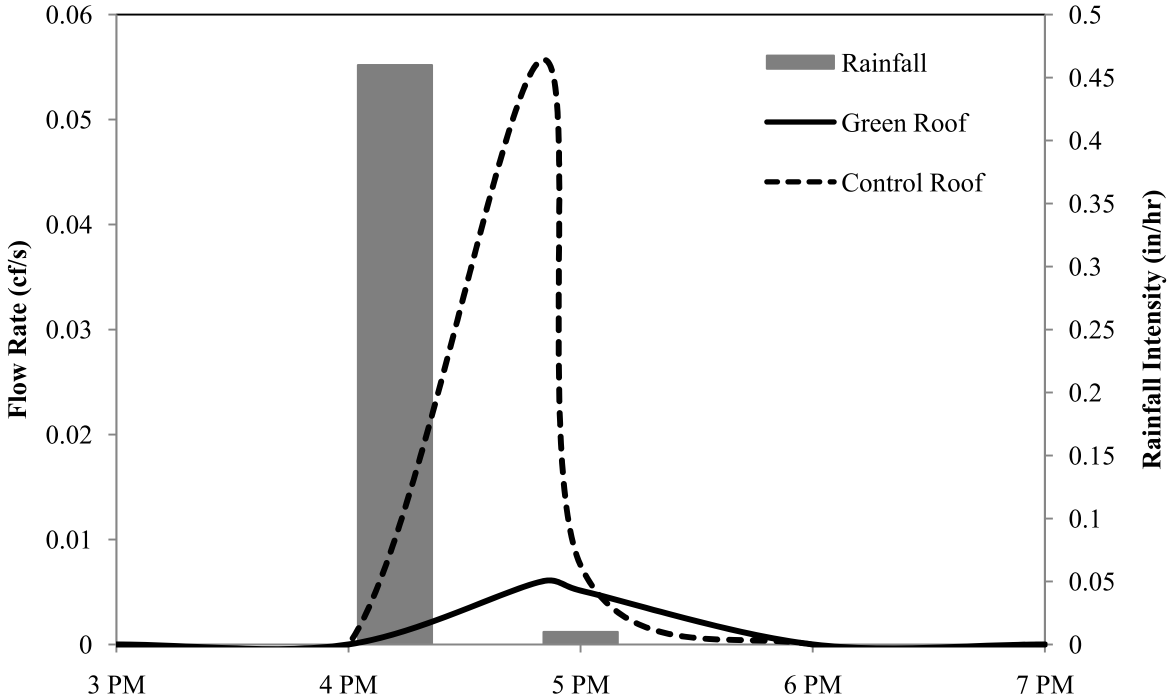


Figure 160. Runoff Flow Rates and Rainfall intensity – July 30, 2008 Storm (Homestead)

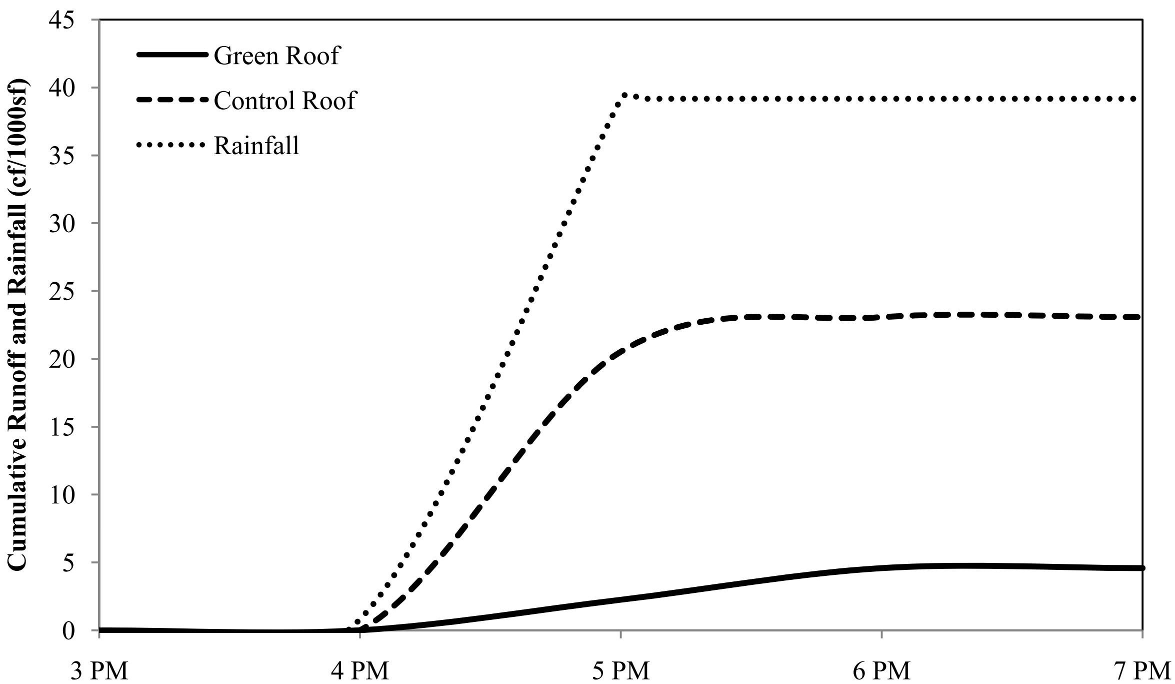


Figure 161. Runoff and Rainfall Volumes – July 30, 2008 Storm (Homestead)

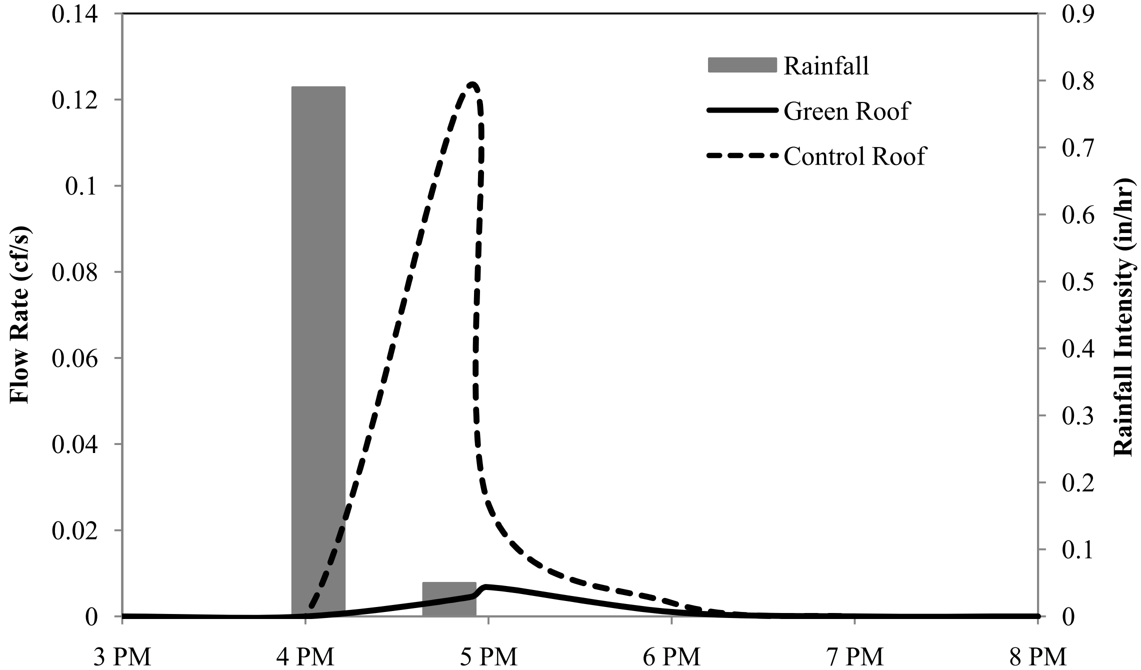


Figure 162. Runoff Flow Rates and Rainfall intensity – July 30, 2008 Storm (Giant Eagle)

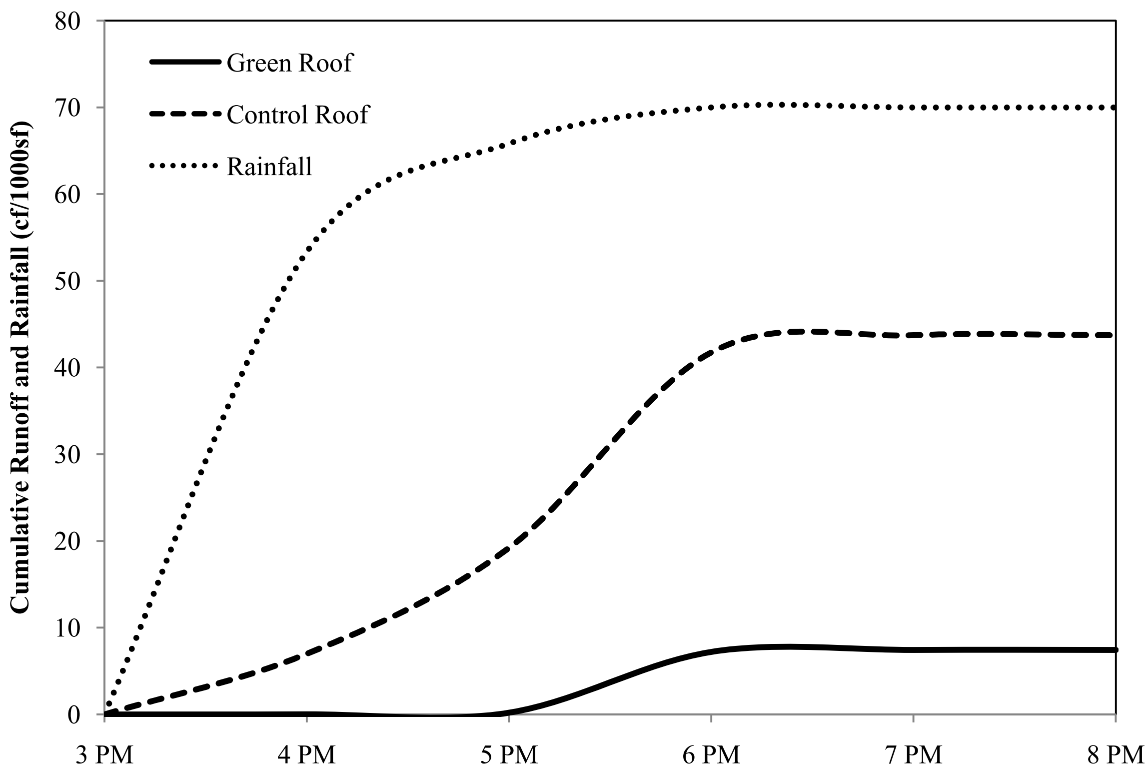


Figure 163. Runoff and Rainfall Volumes – July 30, 2008 Storm (Giant Eagle)

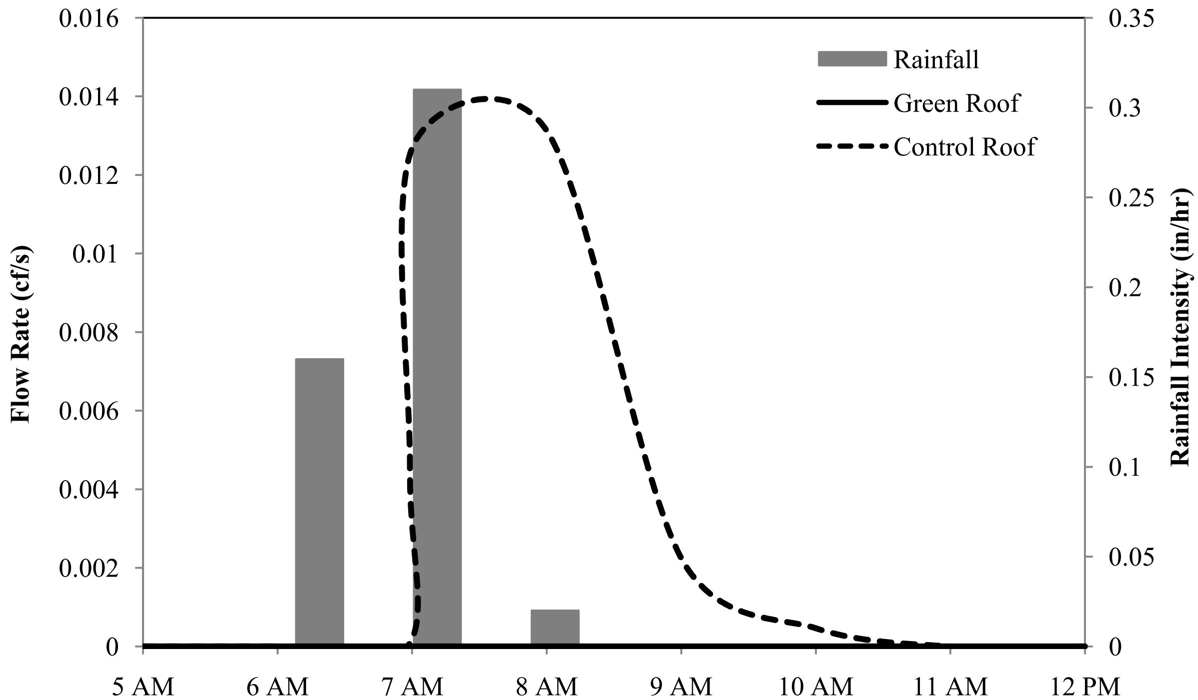


Figure 164. Runoff Flow Rates and Rainfall intensity – August 5, 2008 Storm (Giant Eagle)

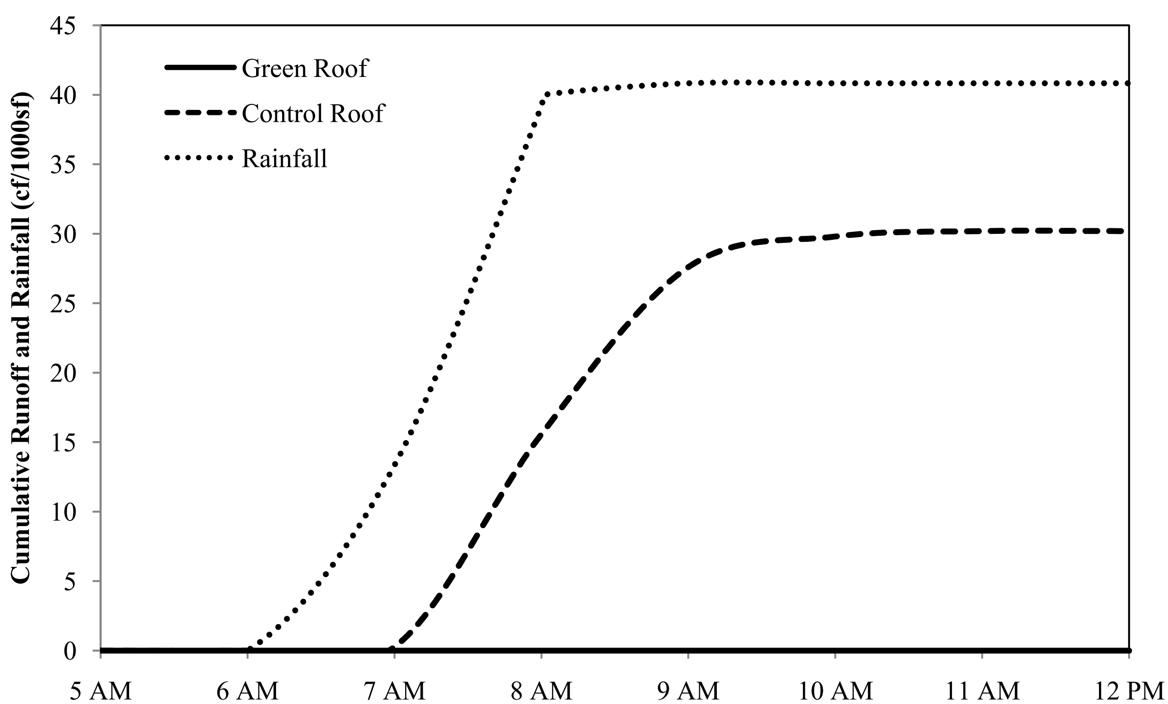


Figure 165. Runoff and Rainfall Volumes – August 5, 2008 Storm (Giant Eagle)

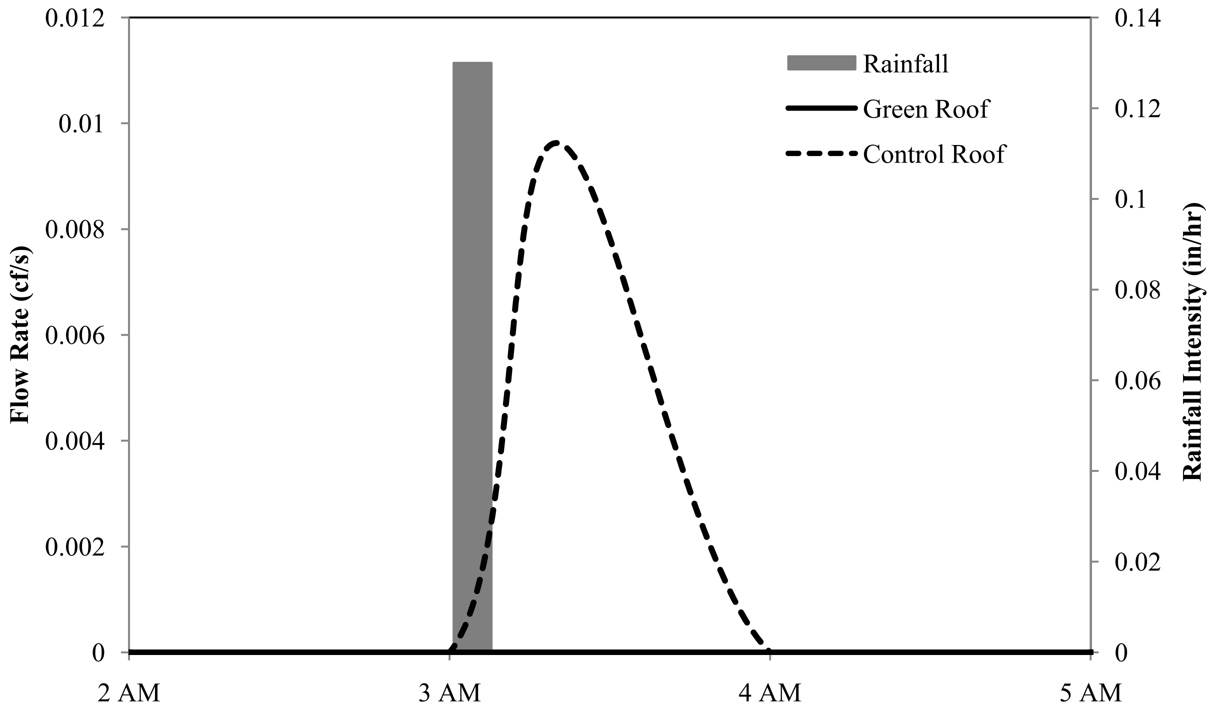


Figure 166. Runoff Flow Rates and Rainfall Intensity – August 6, 2008 Storm (Homestead)

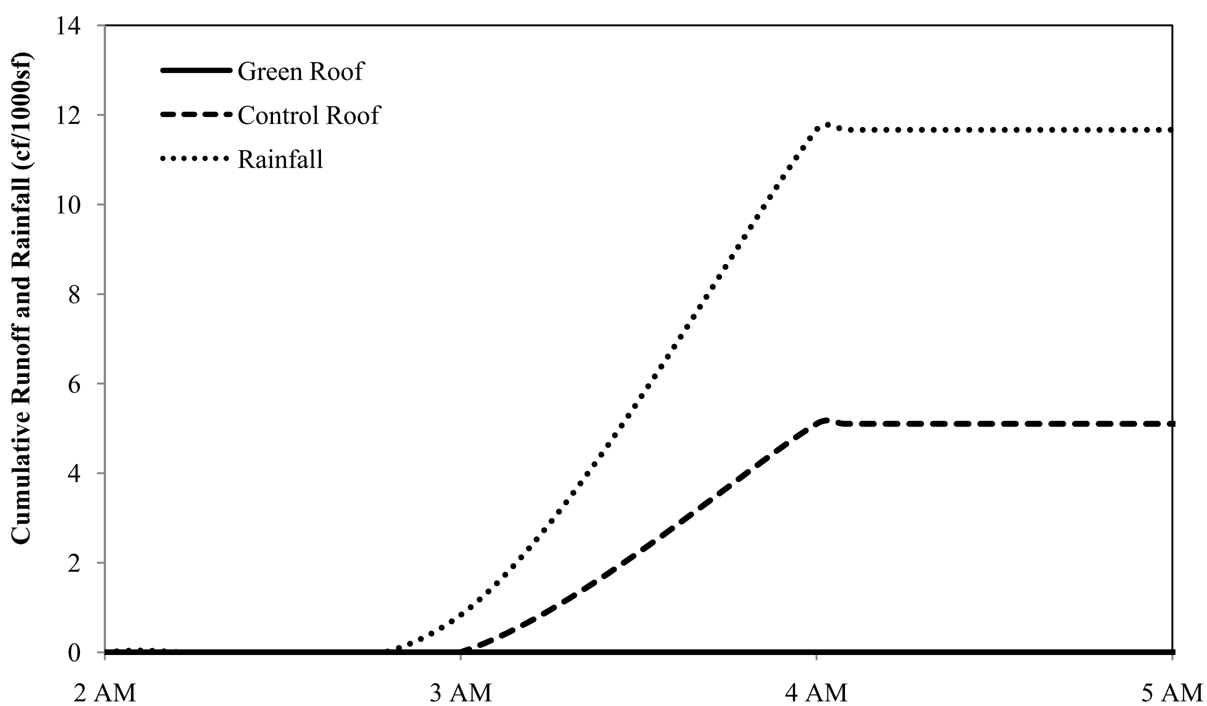


Figure 167. Runoff and Rainfall Volumes – August 6, 2008 Storm (Homestead)

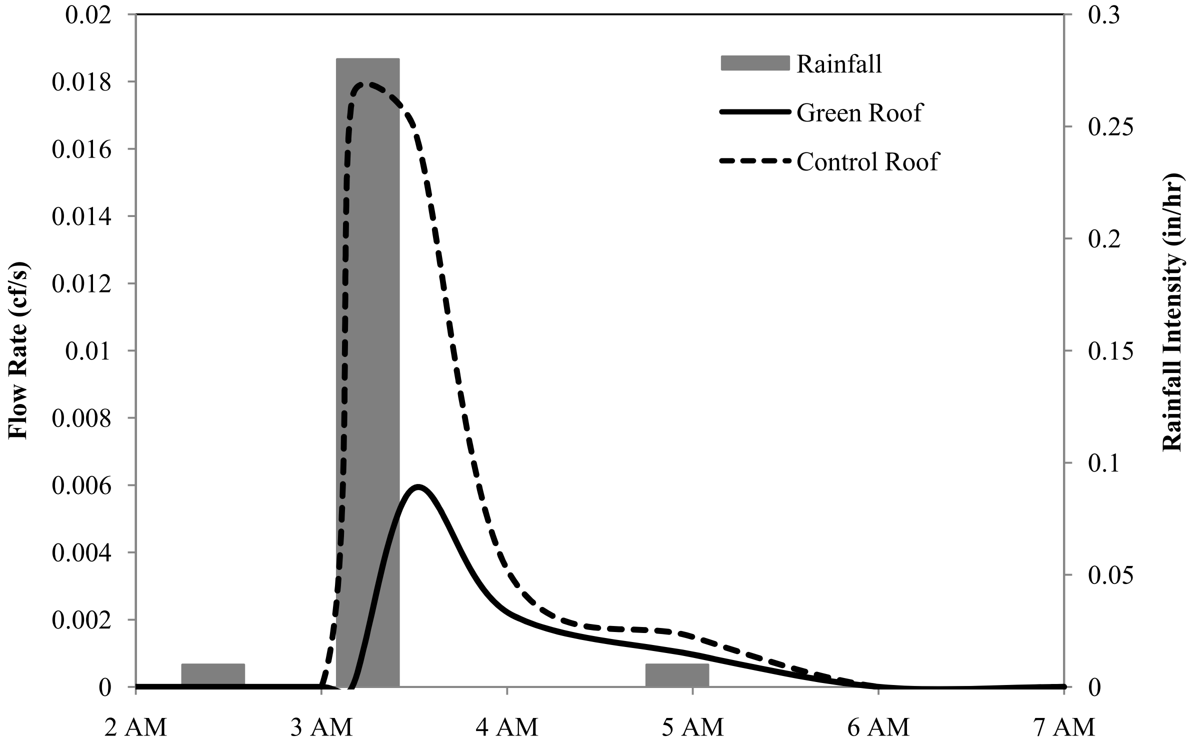


Figure 168. Runoff Flow Rates and Rainfall intensity – August 6, 2008 Storm (Giant Eagle)

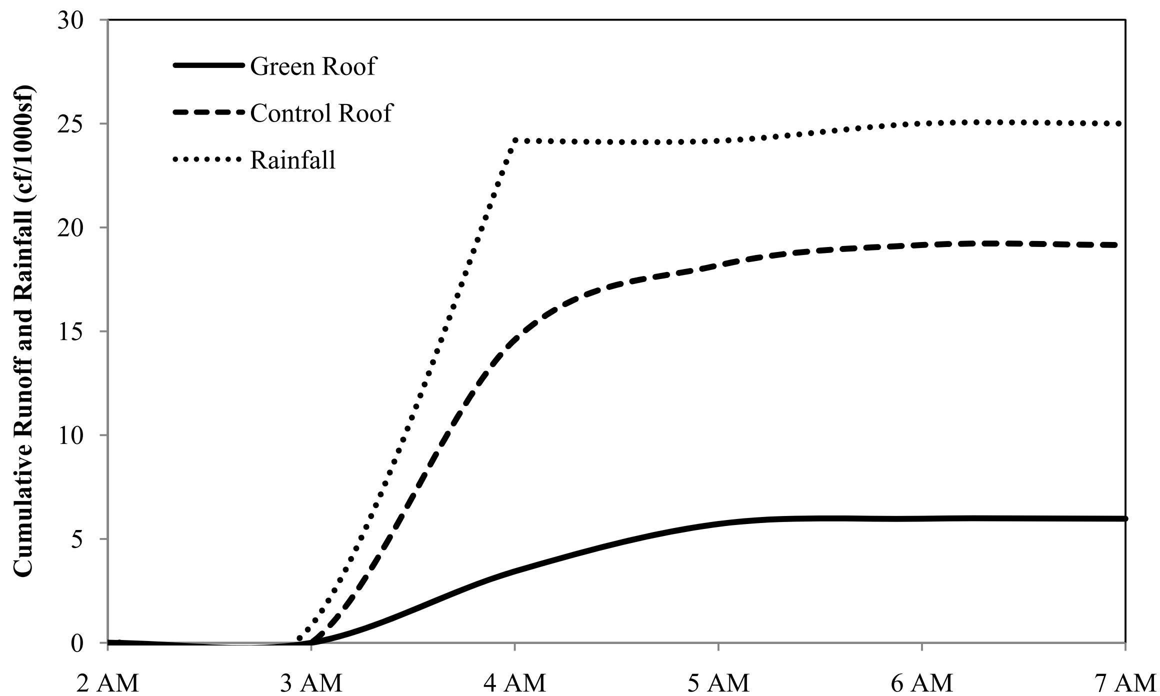


Figure 169. Runoff and Rainfall Volumes – August 6, 2008 Storm (Giant Eagle)

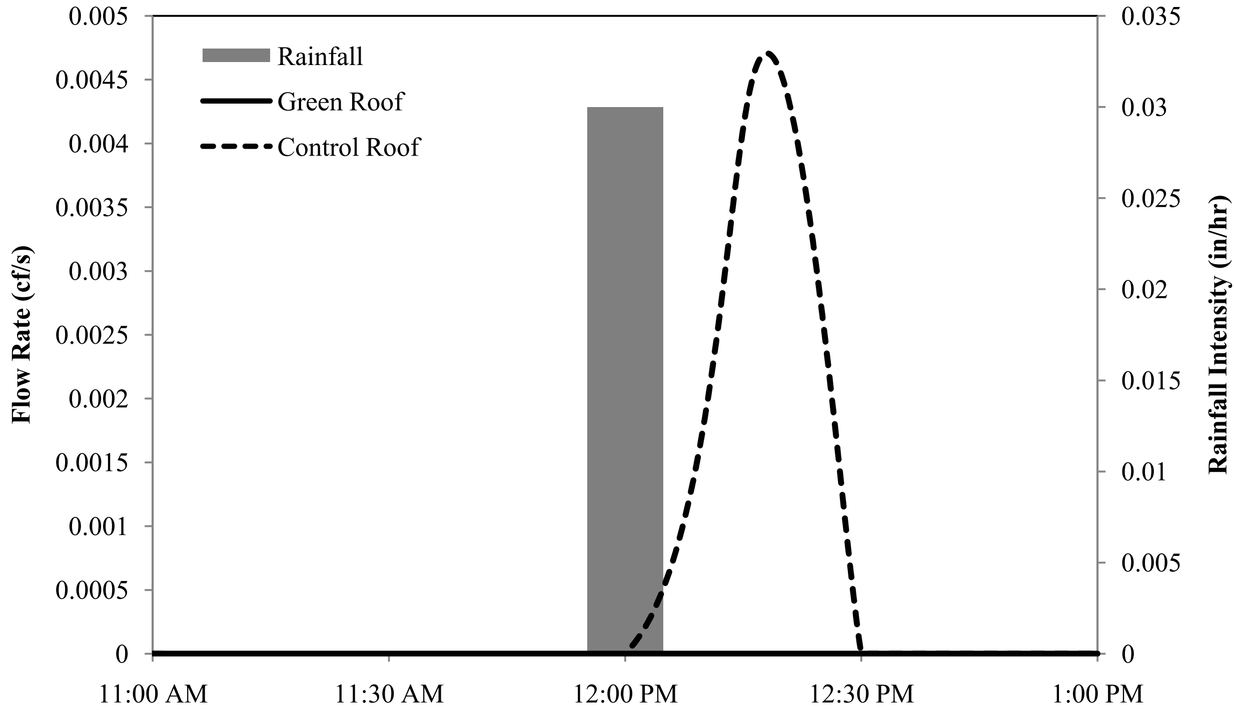


Figure 170. Runoff Flow Rates and Rainfall Intensity – August 8, 2008 Storm (Homestead)

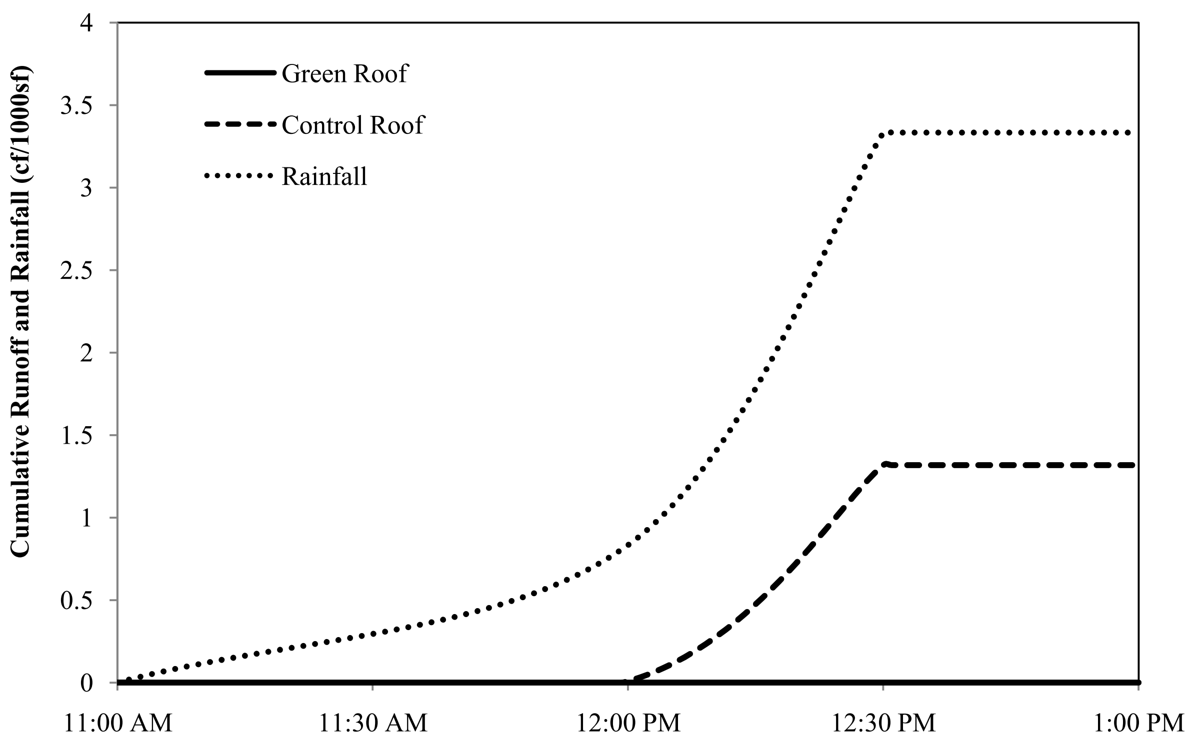


Figure 171. Runoff and Rainfall Volumes – August 8, 2008 Storm (Homestead)

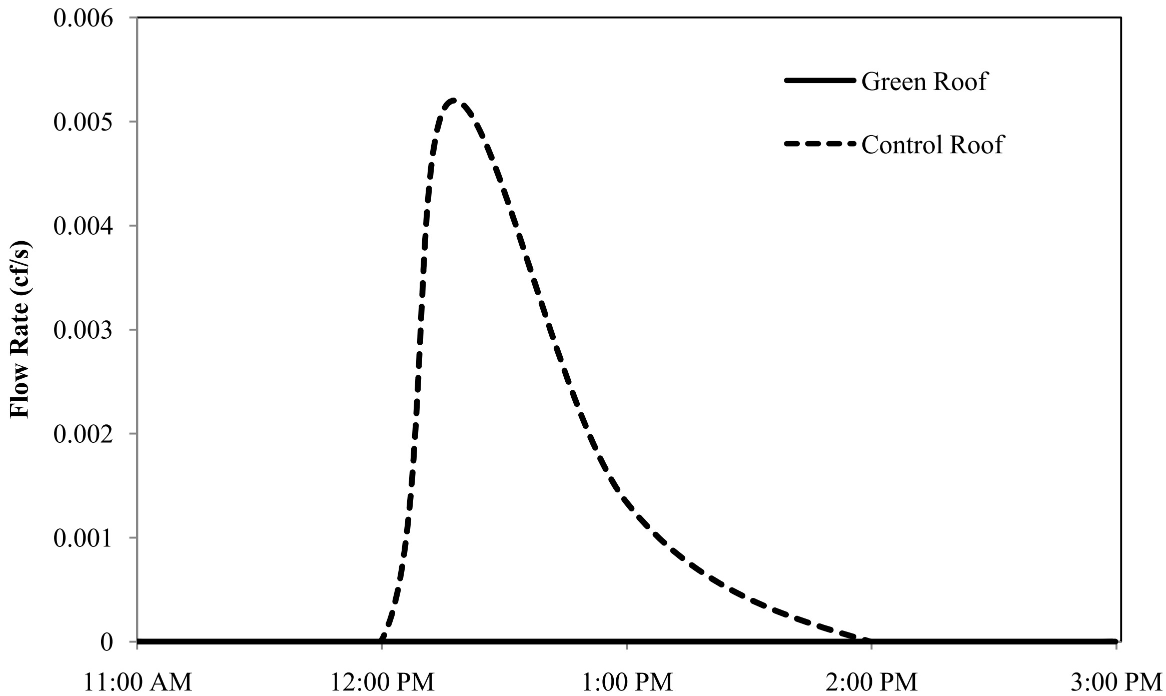


Figure 172. Runoff Flow Rates – August 8, 2008 Storm (Giant Eagle)

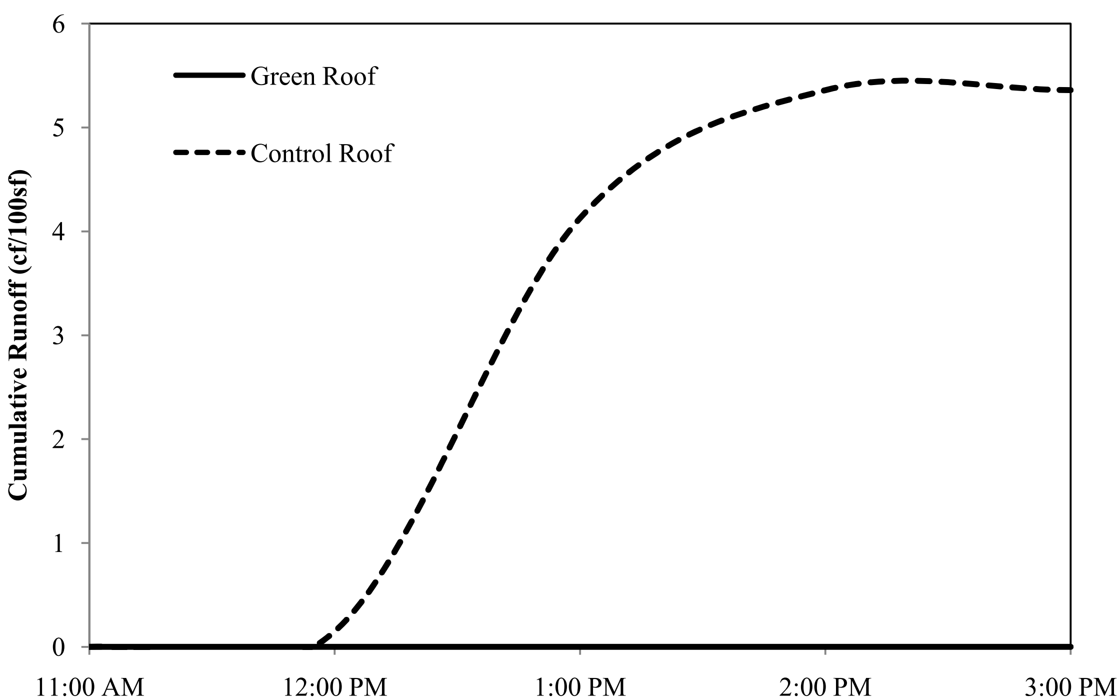


Figure 173. Runoff Volumes – August 8, 2008 Storm (Giant Eagle)

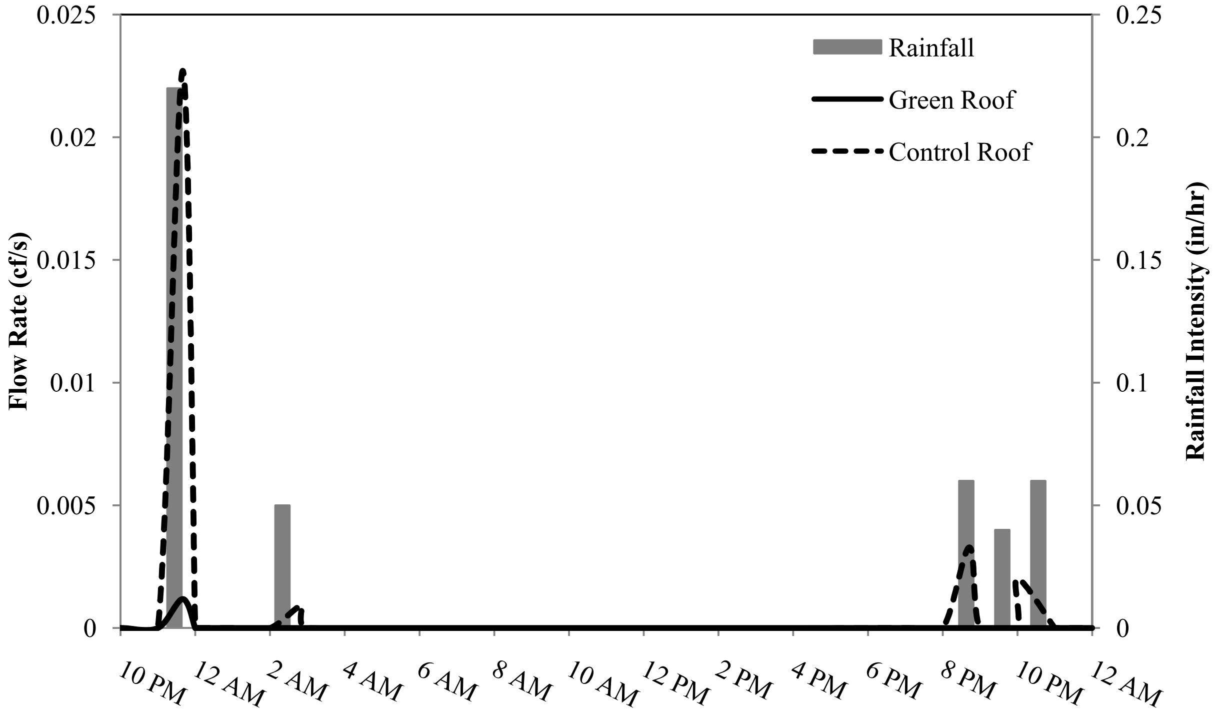


Figure 174. Runoff Flow Rates and Rainfall Intensity – August 9-10, 2008 Storm (Homestead)

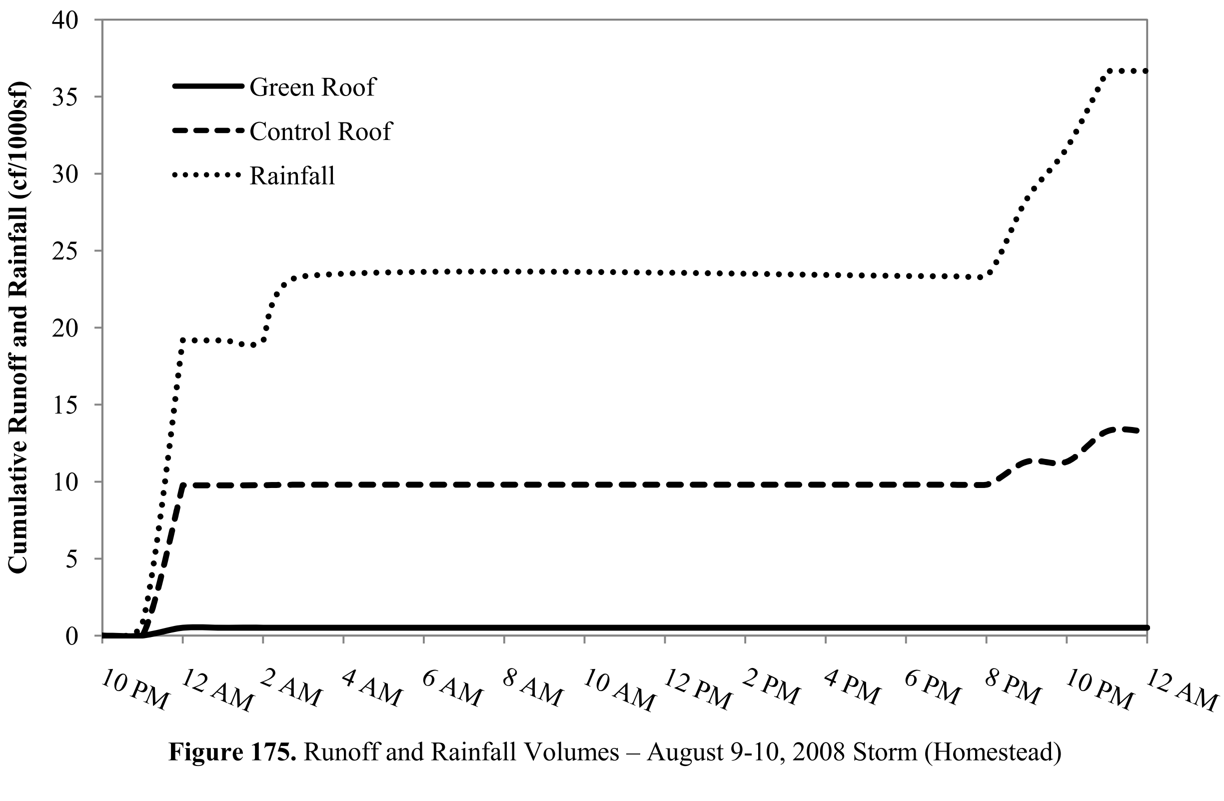


Figure 175. Runoff and Rainfall Volumes – August 9-10, 2008 Storm (Homestead)

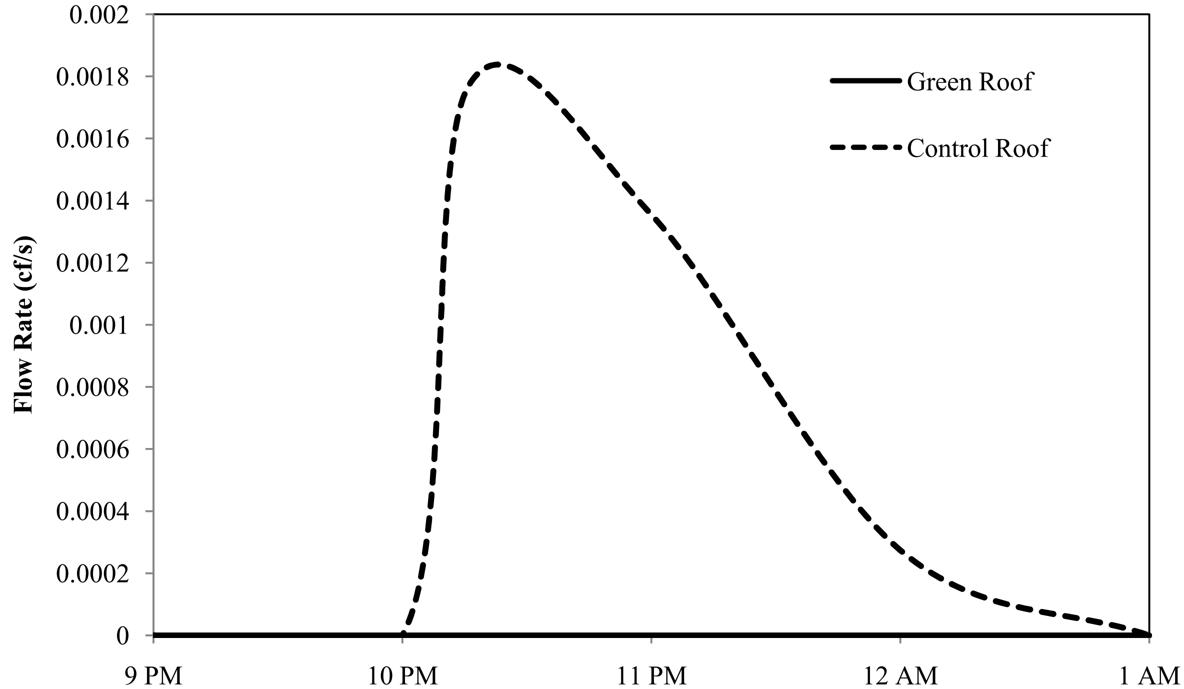


Figure 176. Runoff Flow Rates – August 10, 2008 Storm (Giant Eagle)

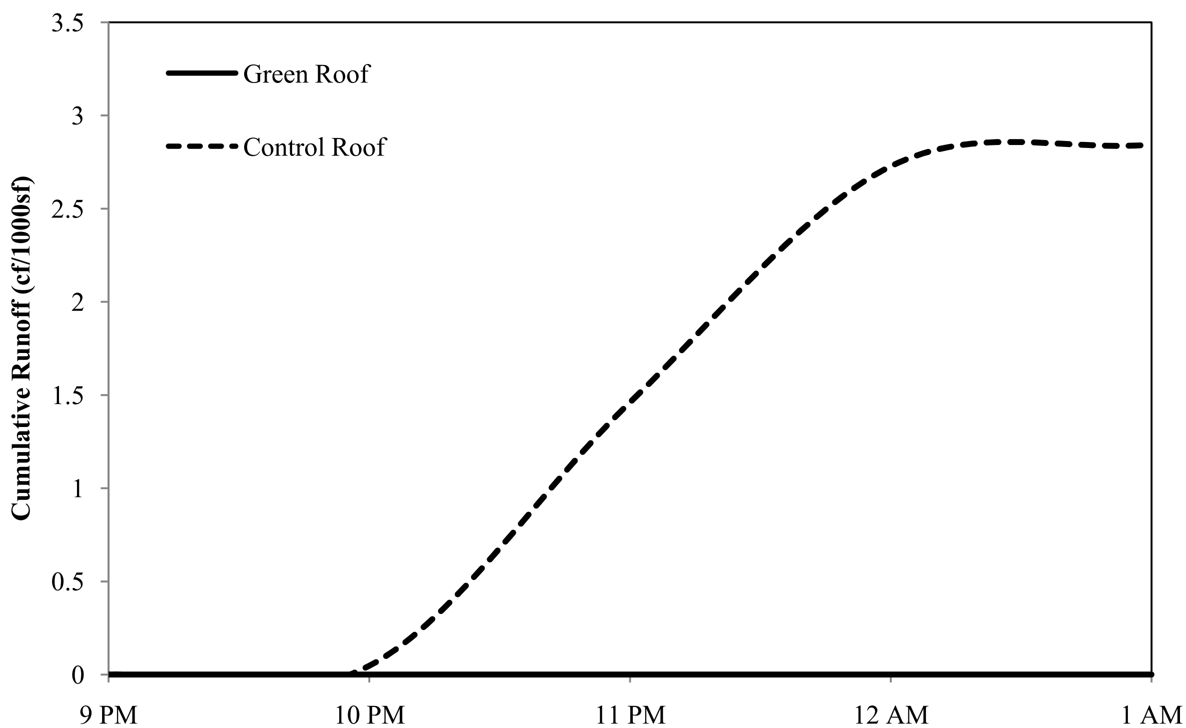


Figure 177. Runoff Volumes – August 10, 2008 Storm (Giant Eagle)

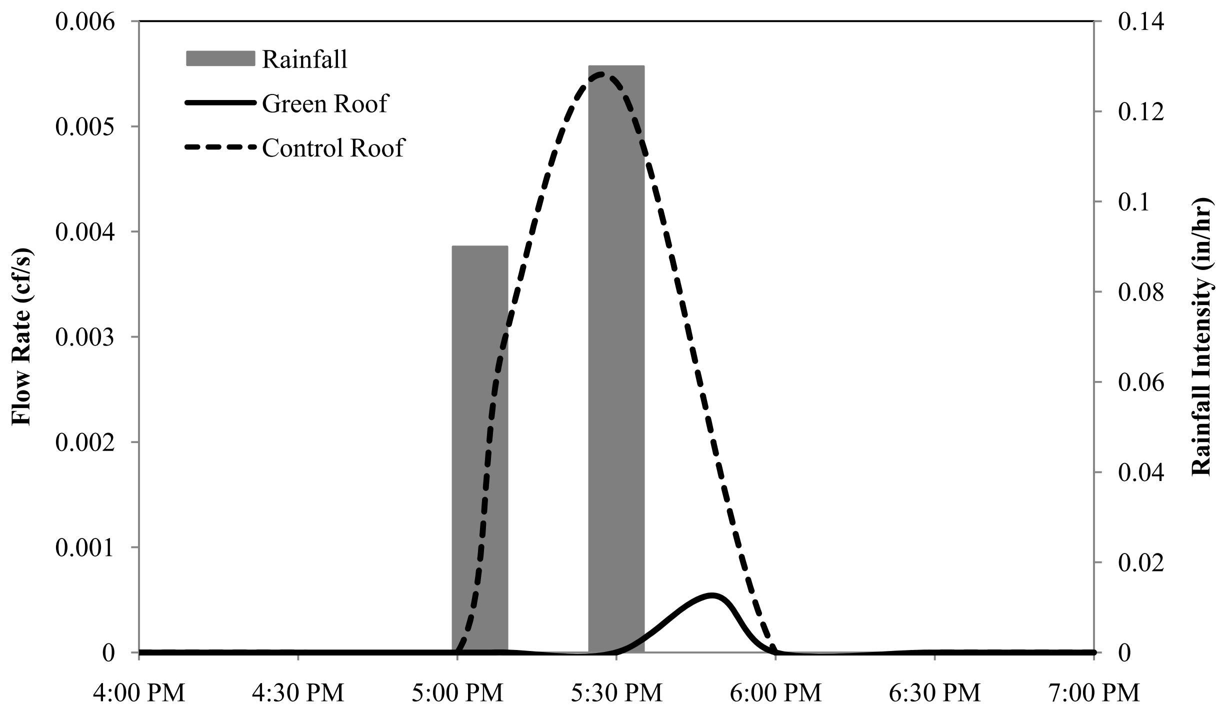


Figure 178. Runoff Flow Rates and Rainfall Intensity – August 14, 2008 Storm (Homestead)

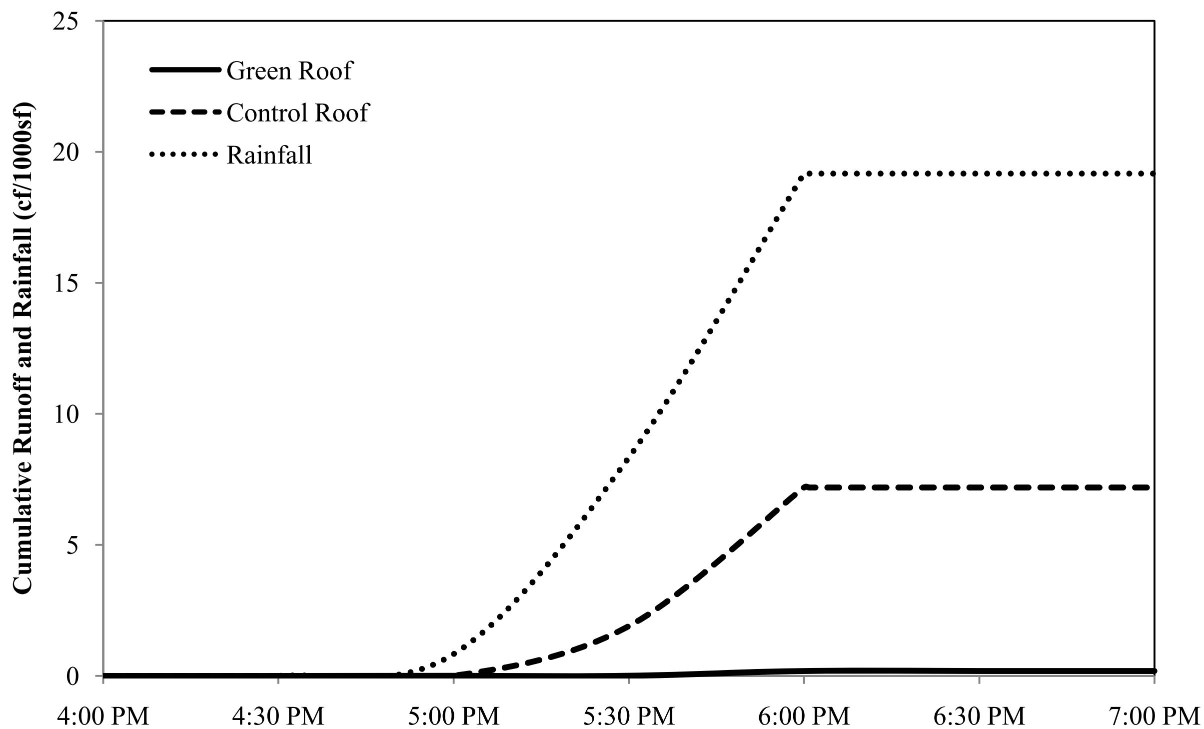


Figure 179. Runoff and Rainfall Volumes – August 14, 2008 Storm (Homestead)

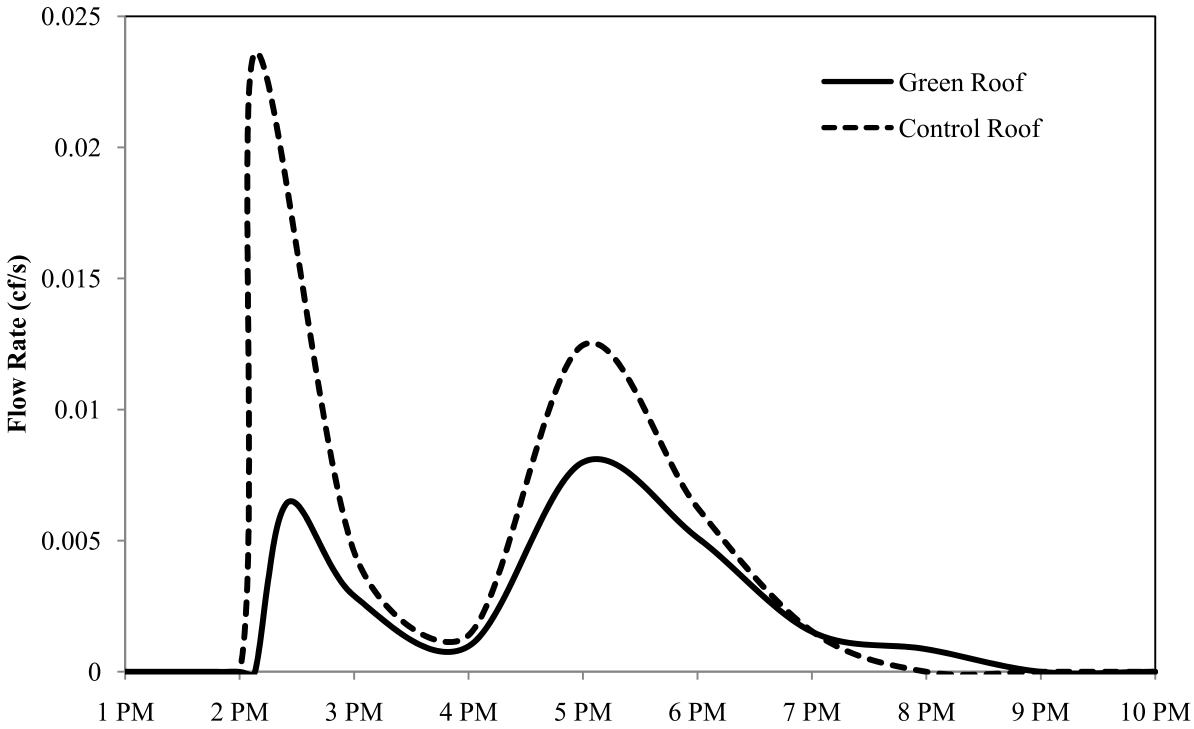


Figure 180. Runoff Flow Rates – August 14, 2008 Storm (Giant Eagle)

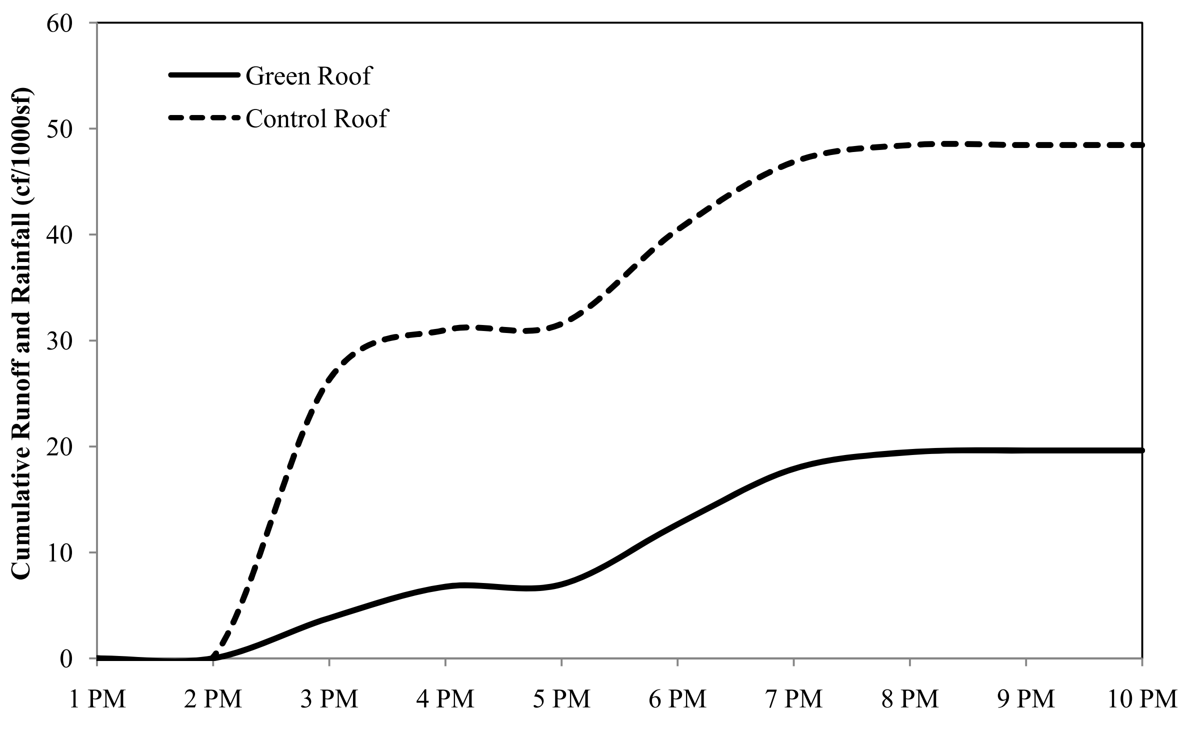


Figure 181. Runoff Volumes – August 14, 2008 Storm (Giant Eagle)

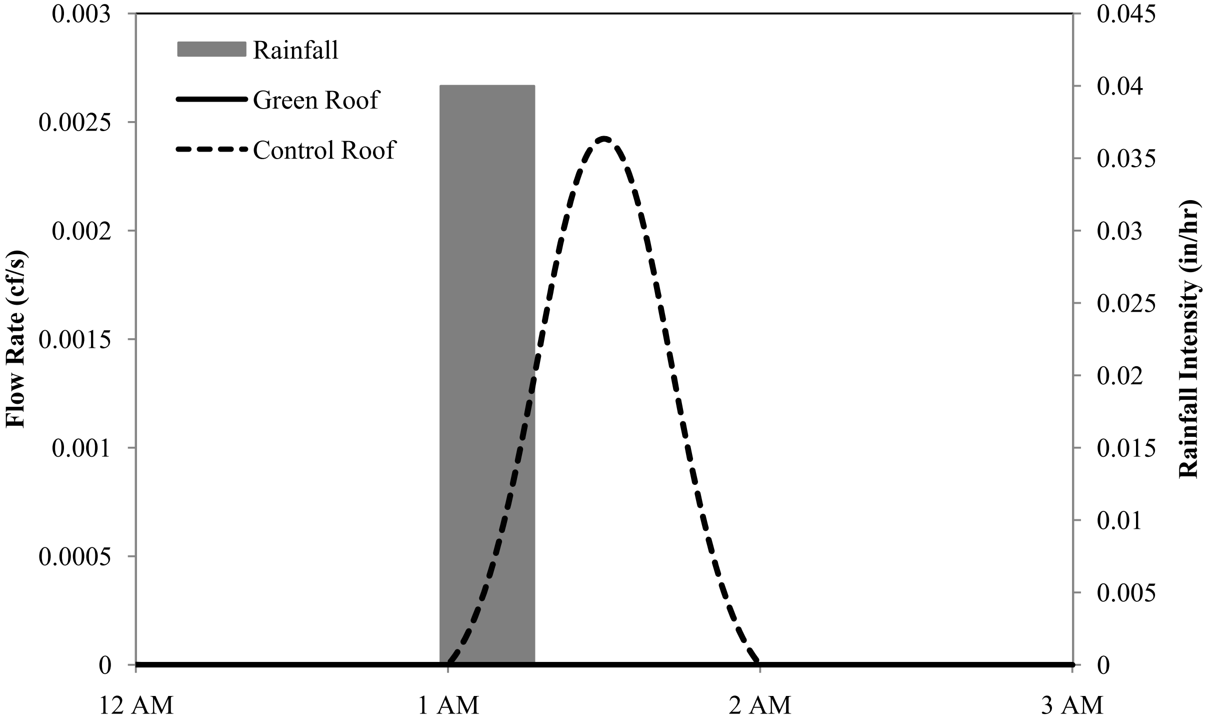


Figure 182. Runoff Flow Rates and Rainfall Intensity – August 25, 2008 Storm (Homestead)

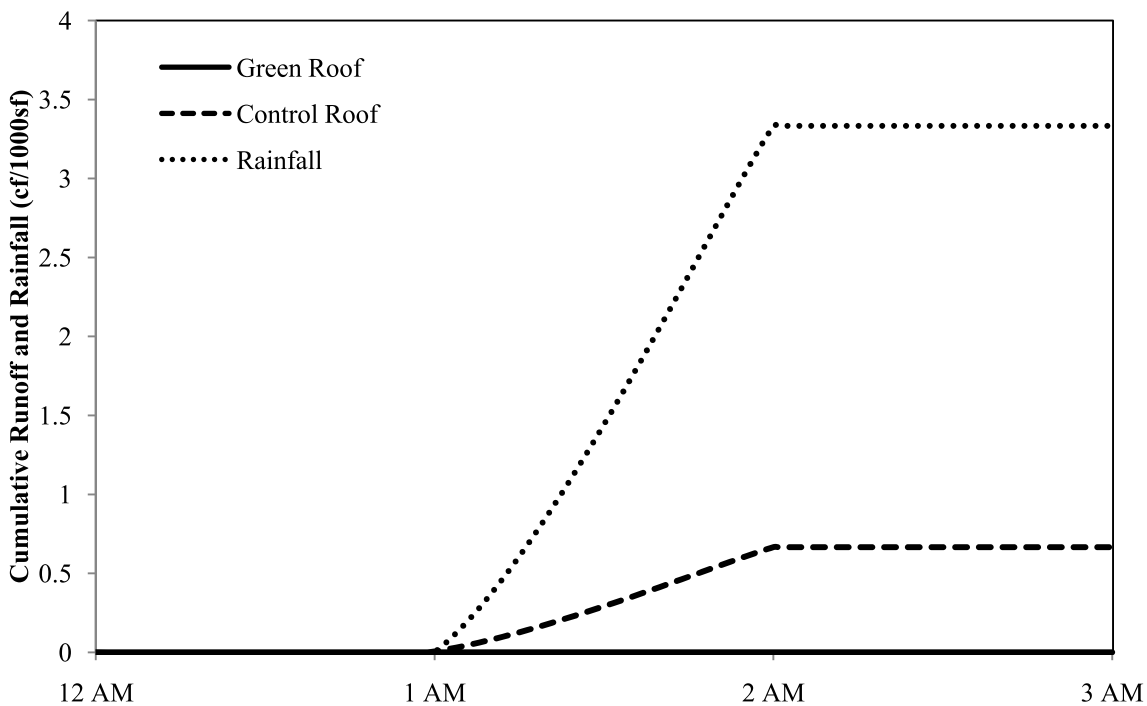


Figure 183. Runoff and Rainfall Volumes – August 25, 2008 Storm (Homestead)

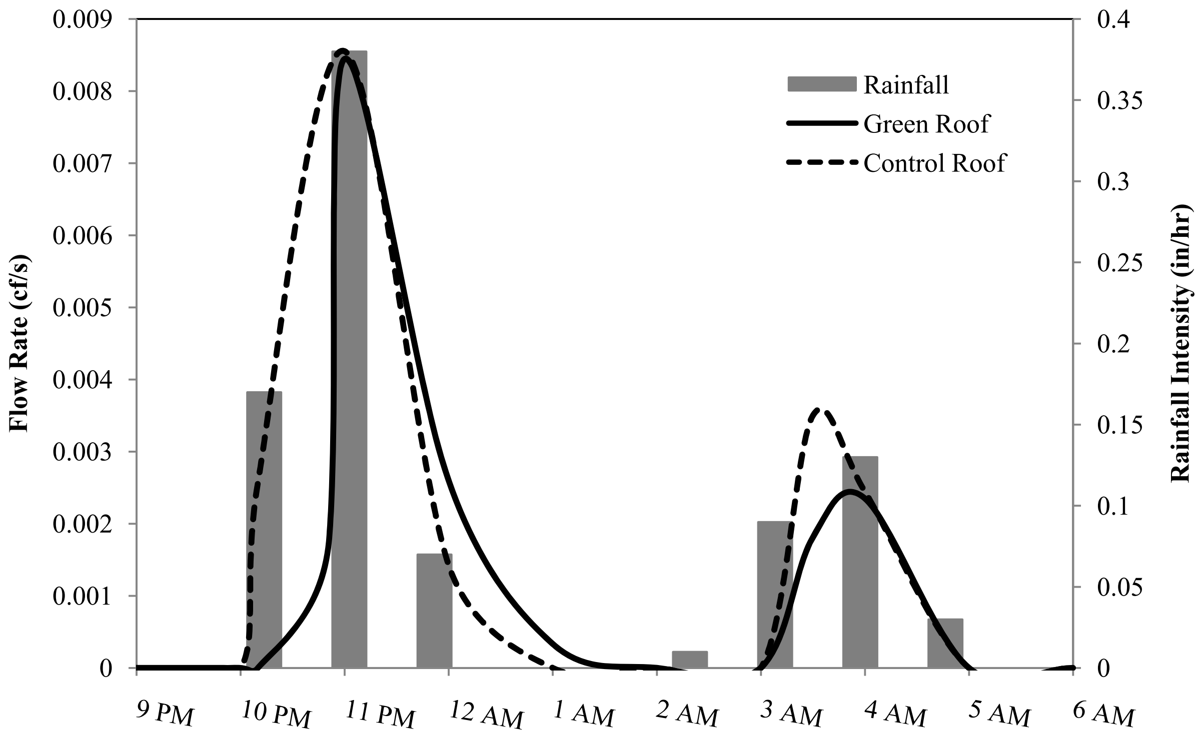


Figure 184. Runoff Flow Rates and Rainfall Intensity – August 27-28, 2008 Storm (Homestead)

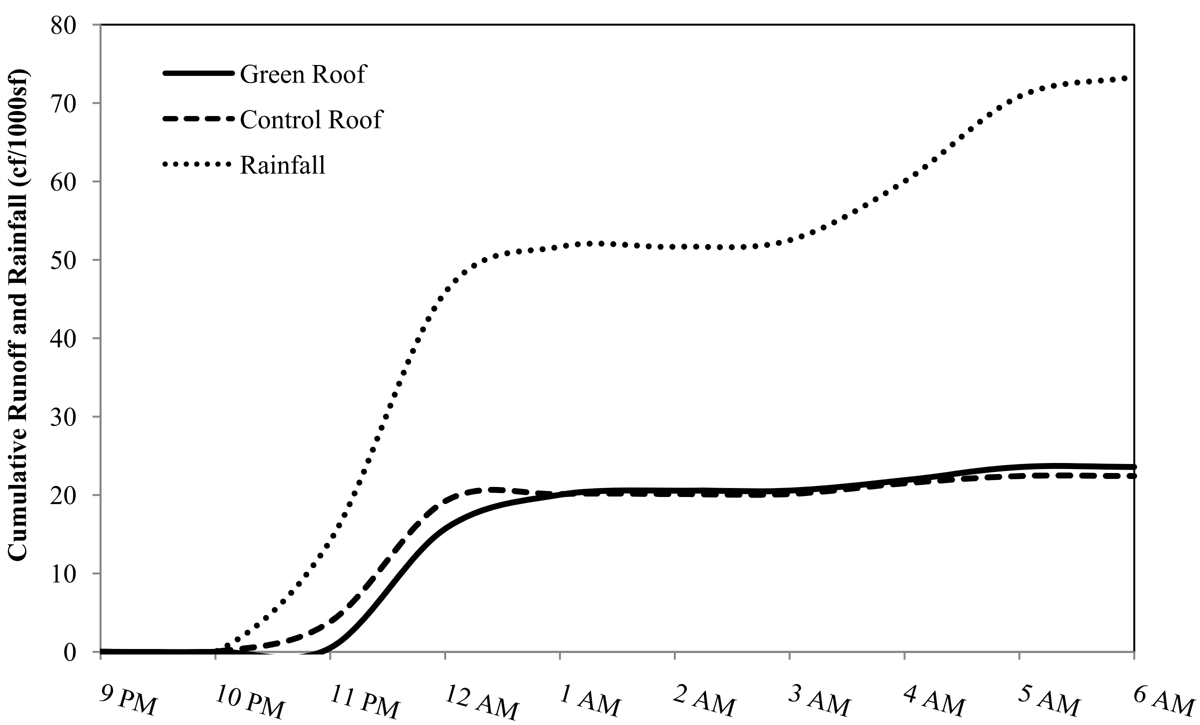


Figure 185. Runoff and Rainfall Volumes – August 27-28, 2008 Storm (Homestead)

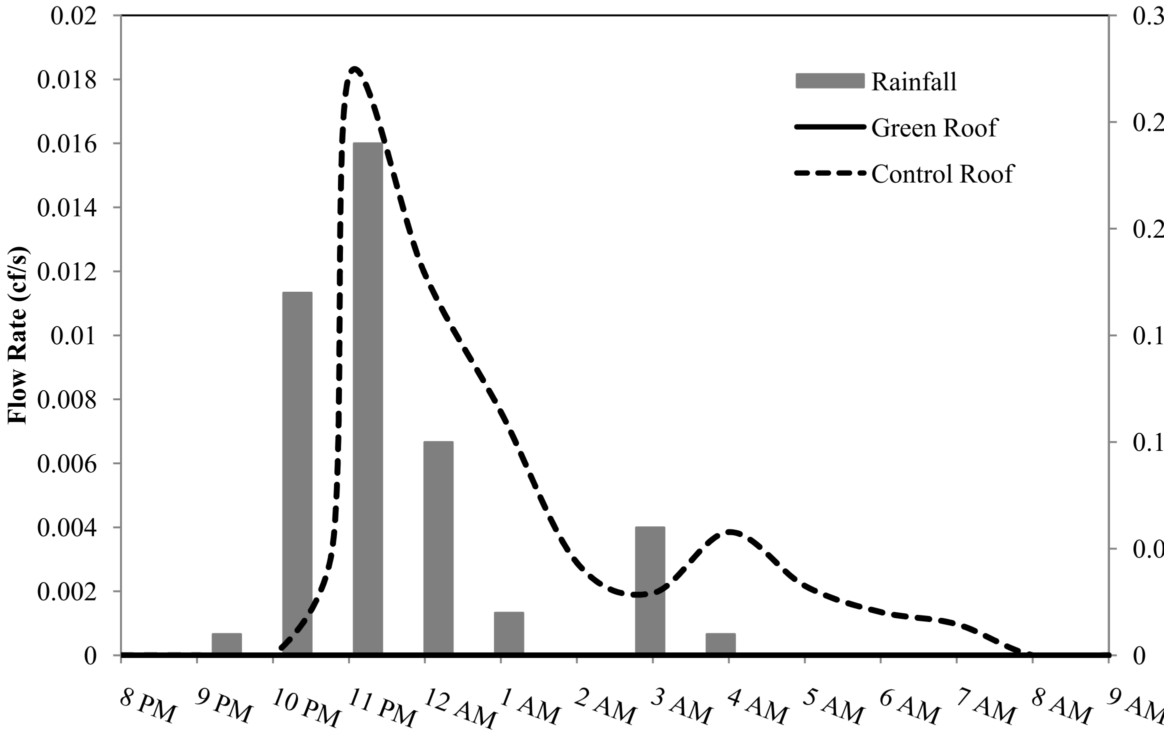


Figure 186. Runoff Flow Rates and Rainfall intensity – August 27-28, 2008 Storm (Giant Eagle)

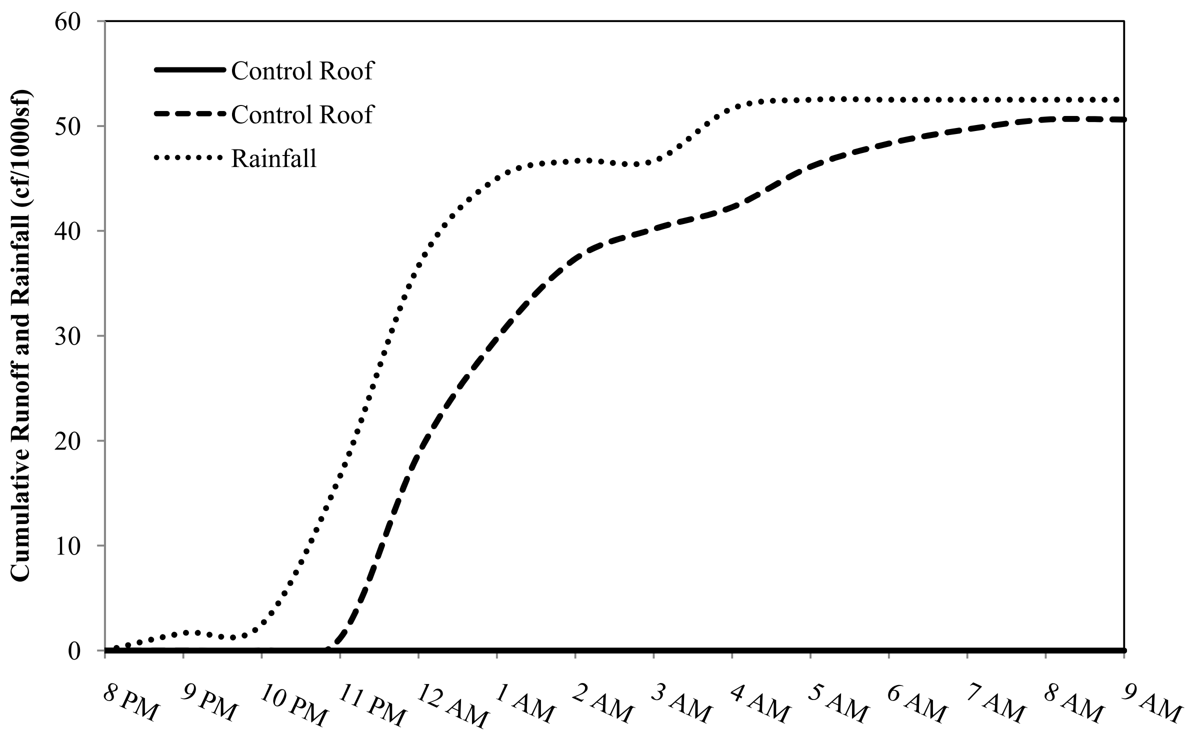


Figure 187. Runoff and Rainfall Volumes – August 27-28, 2008 Storm (Giant Eagle)

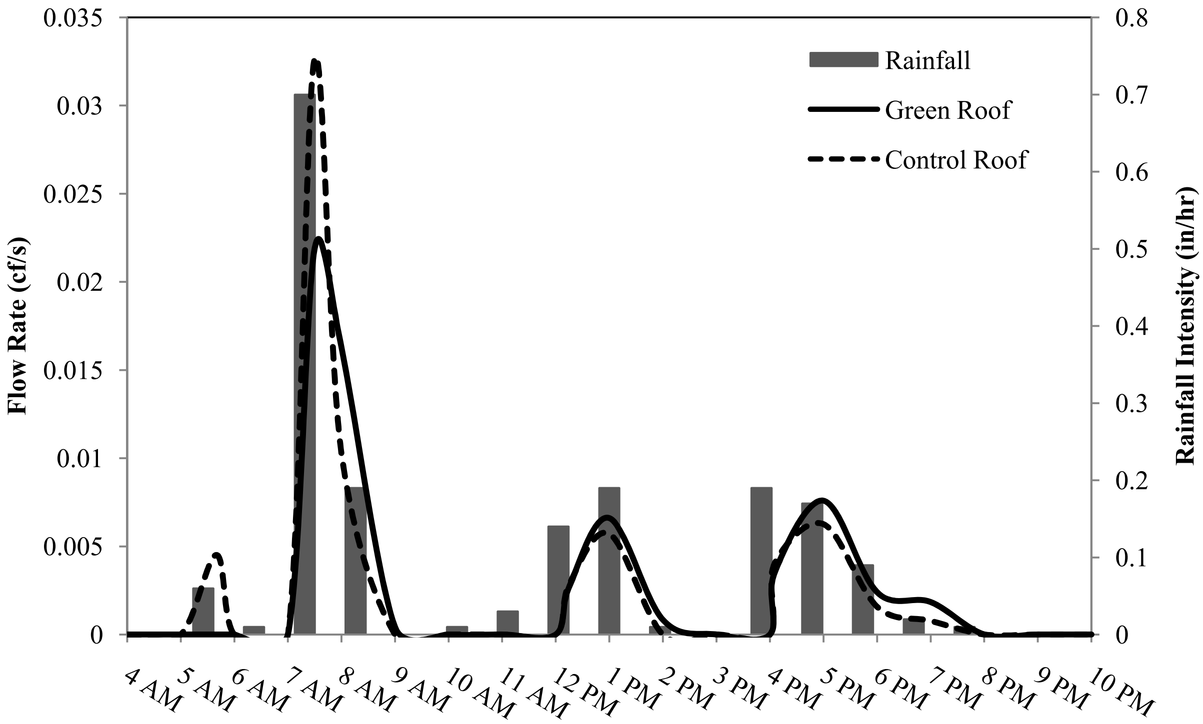


Figure 188. Runoff Flow Rates and Rainfall Intensity – September 12, 2008 Storm (Homestead)

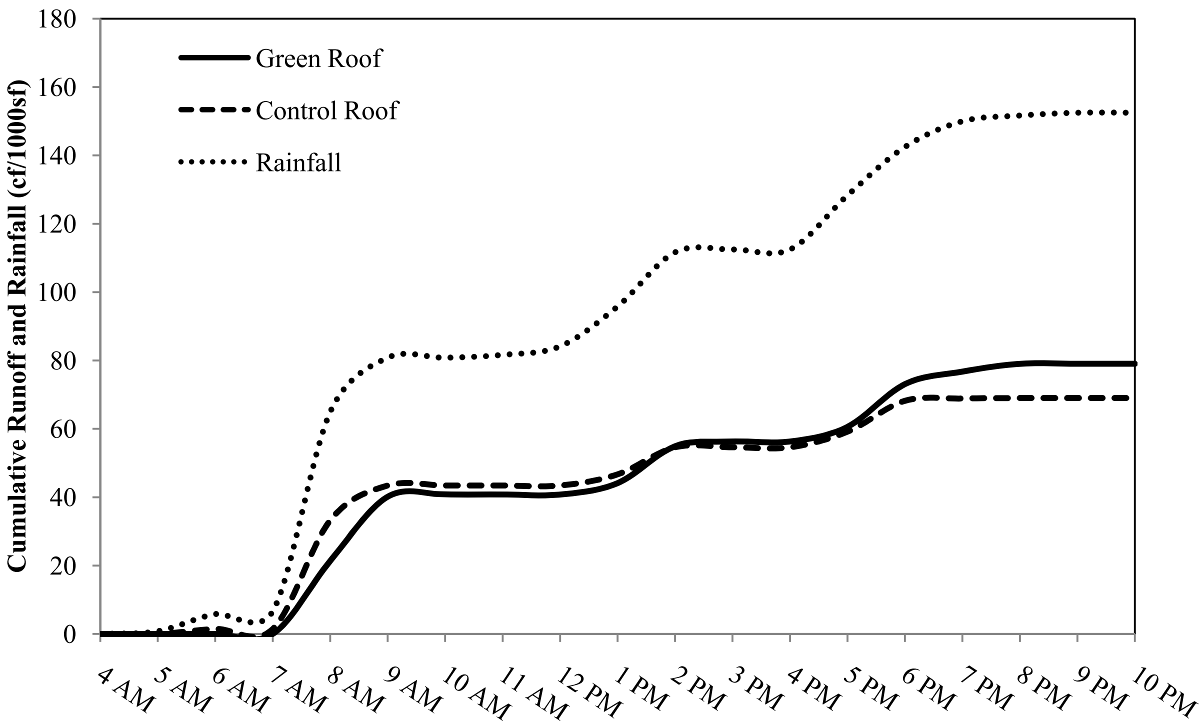


Figure 189. Runoff and Rainfall Volumes – September 12, 2008 Storm (Homestead)

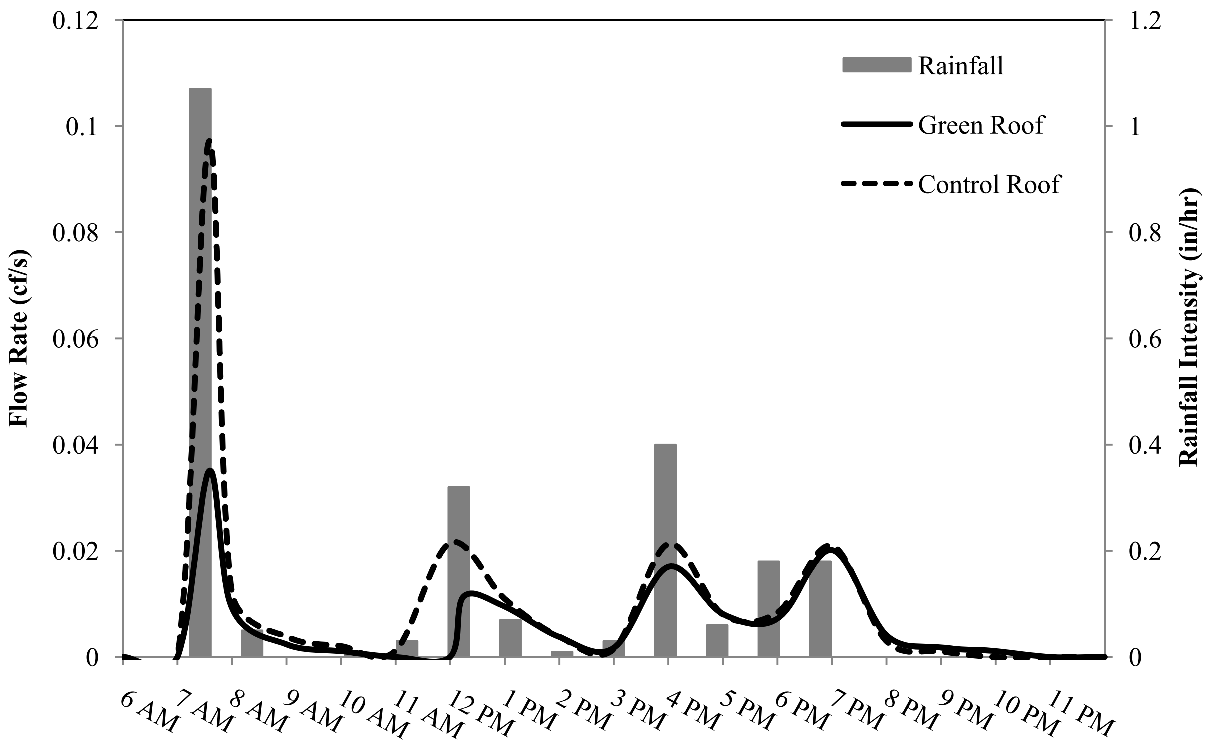


Figure 190. Runoff Flow Rates and Rainfall intensity – September 12, 2008 Storm (Giant Eagle)

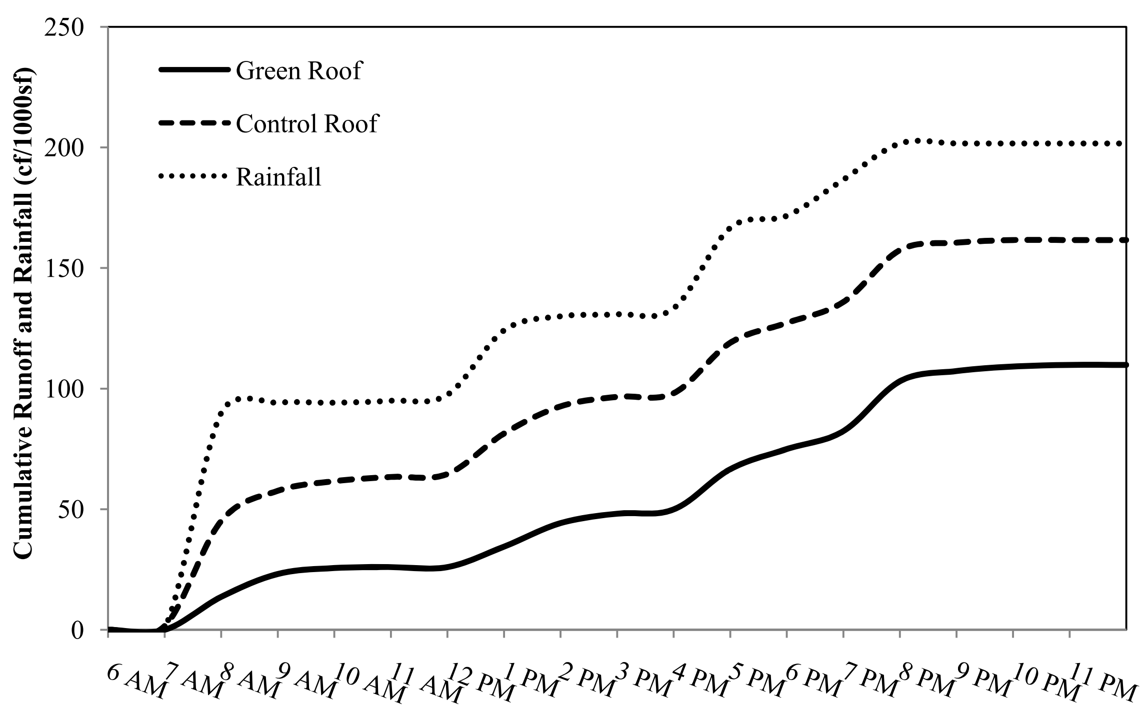


Figure 191. Runoff and Rainfall Volumes – September 12, 2008 Storm (Giant Eagle)

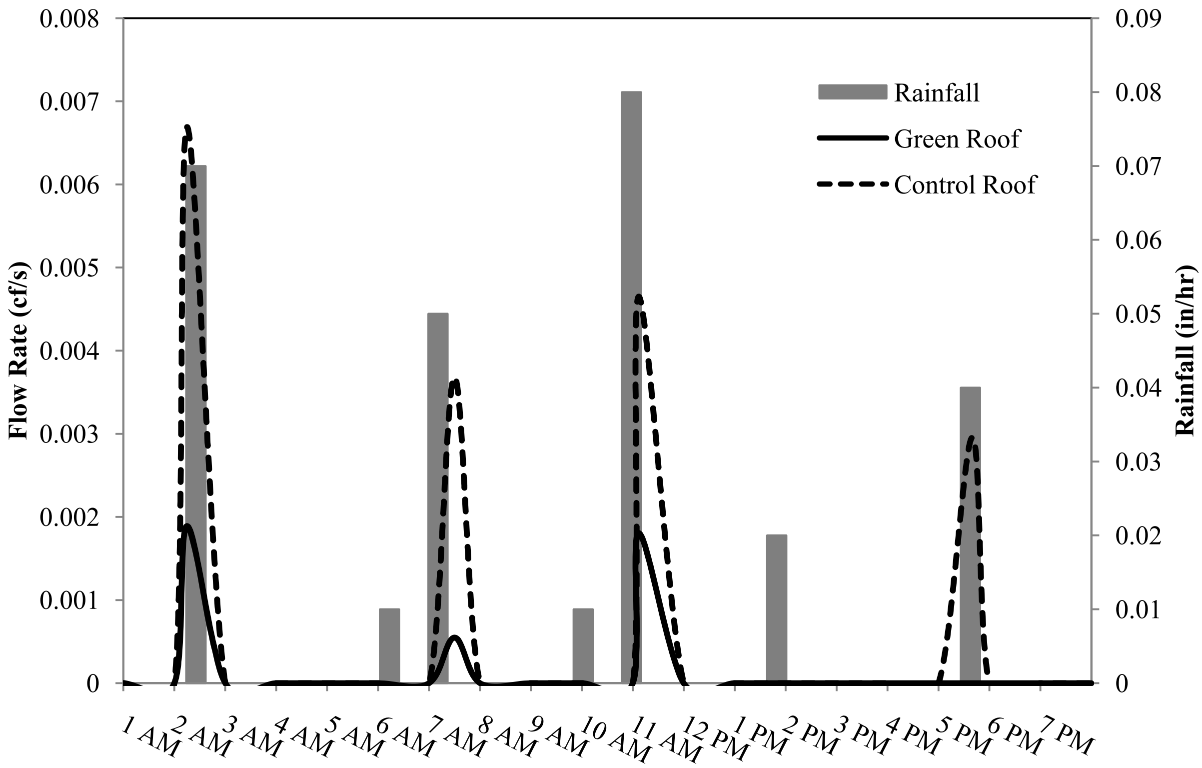


Figure 192. Runoff Flow Rates and Rainfall Intensity – September 13, 2008 Storm (Homestead)

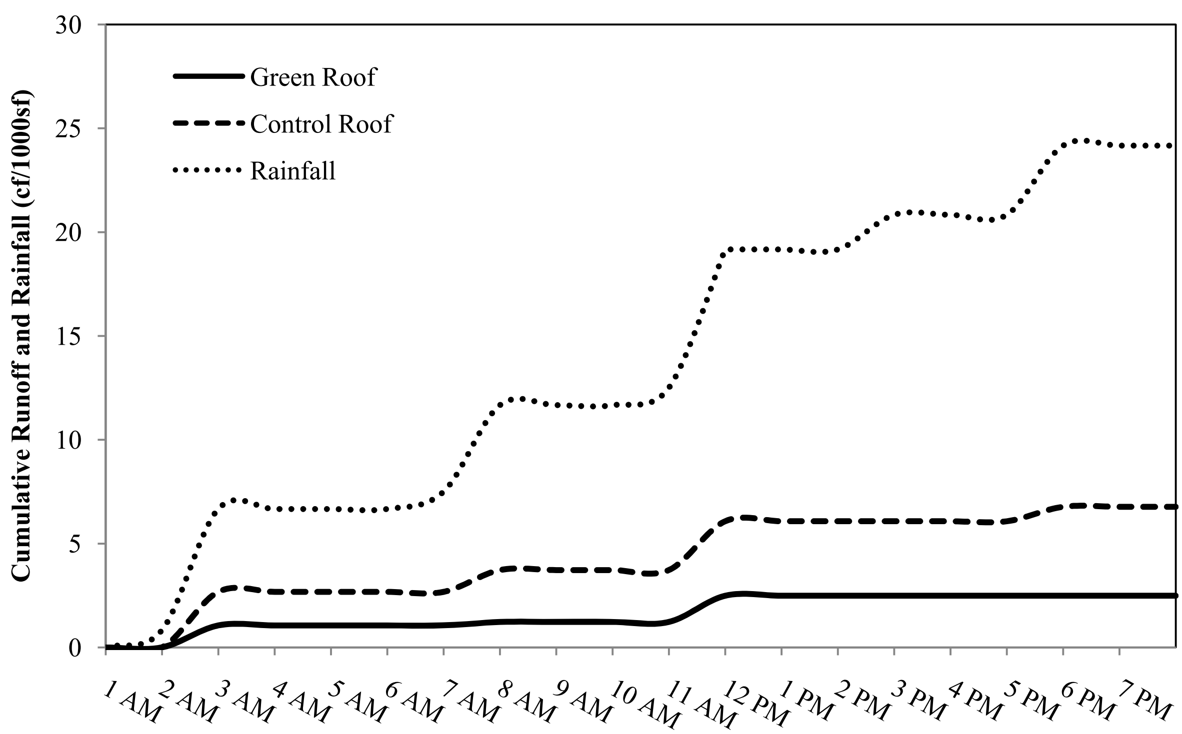


Figure 193. Runoff and Rainfall Volumes – September 13, 2008 Storm (Homestead)

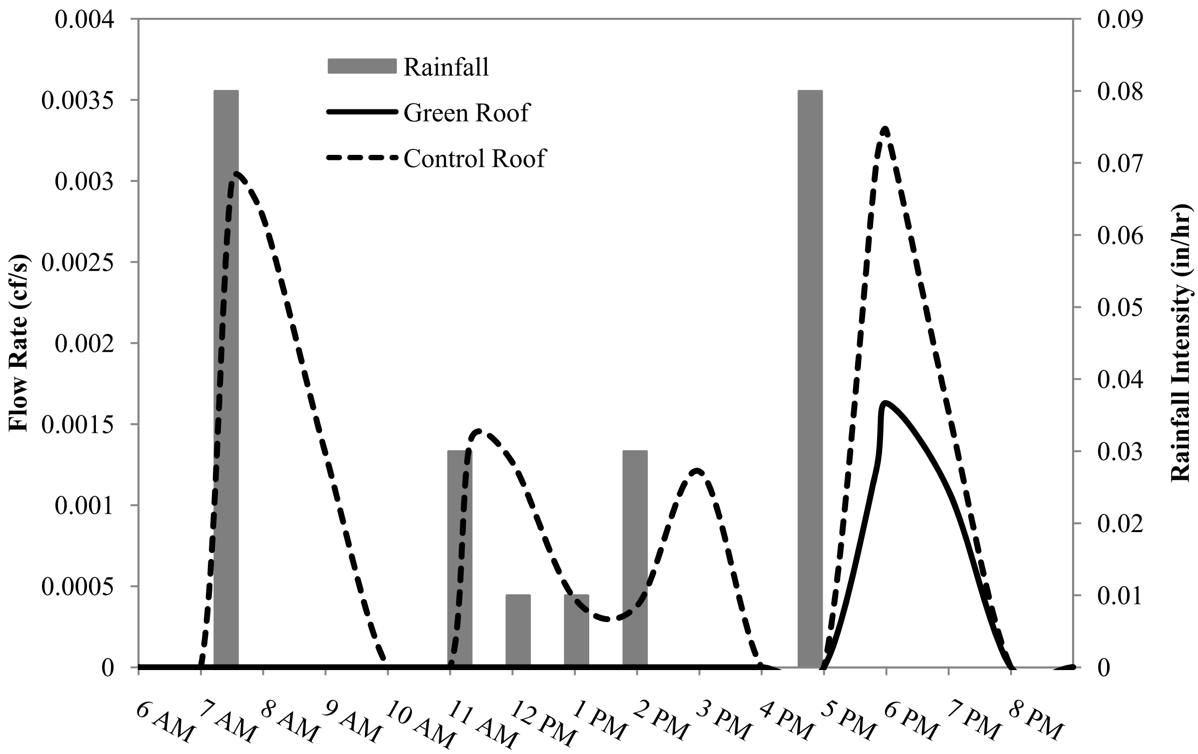


Figure 194. Runoff Flow Rates and Rainfall intensity – September 13, 2008 Storm (Giant Eagle)

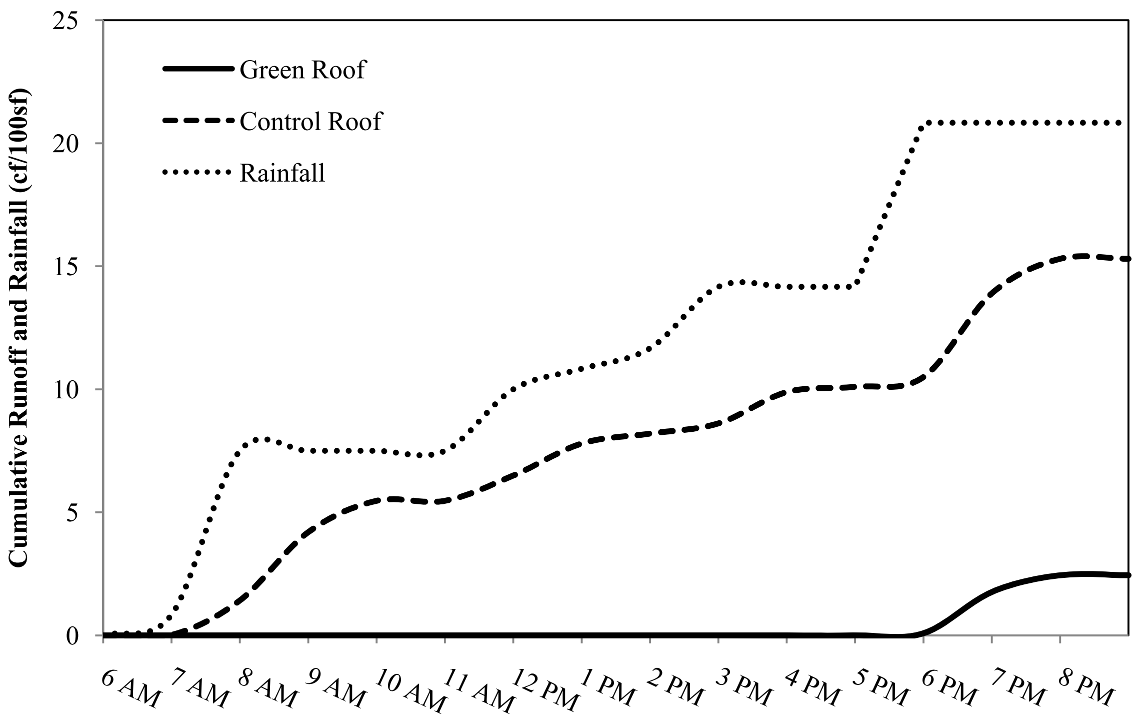


Figure 195. Runoff and Rainfall Volumes – September 13, 2008 Storm (Giant Eagle)

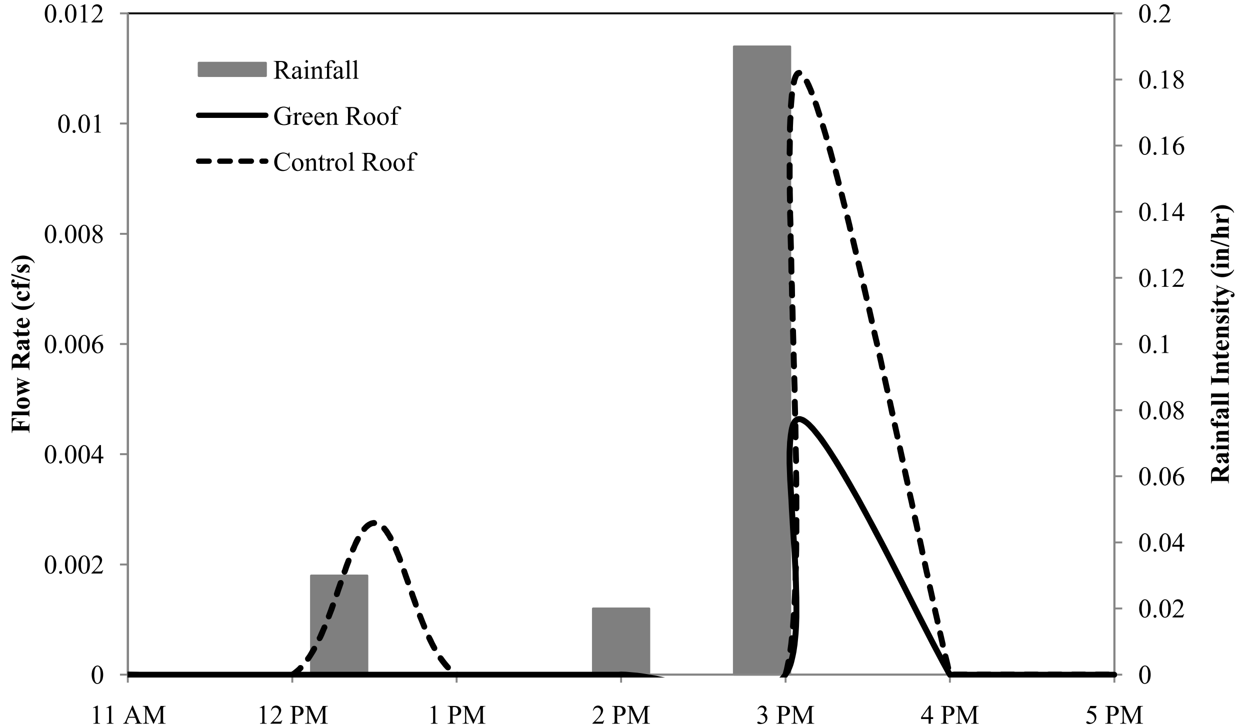


Figure 196. Runoff Flow Rates and Rainfall Intensity – October 1, 2008 Storm (Homestead)

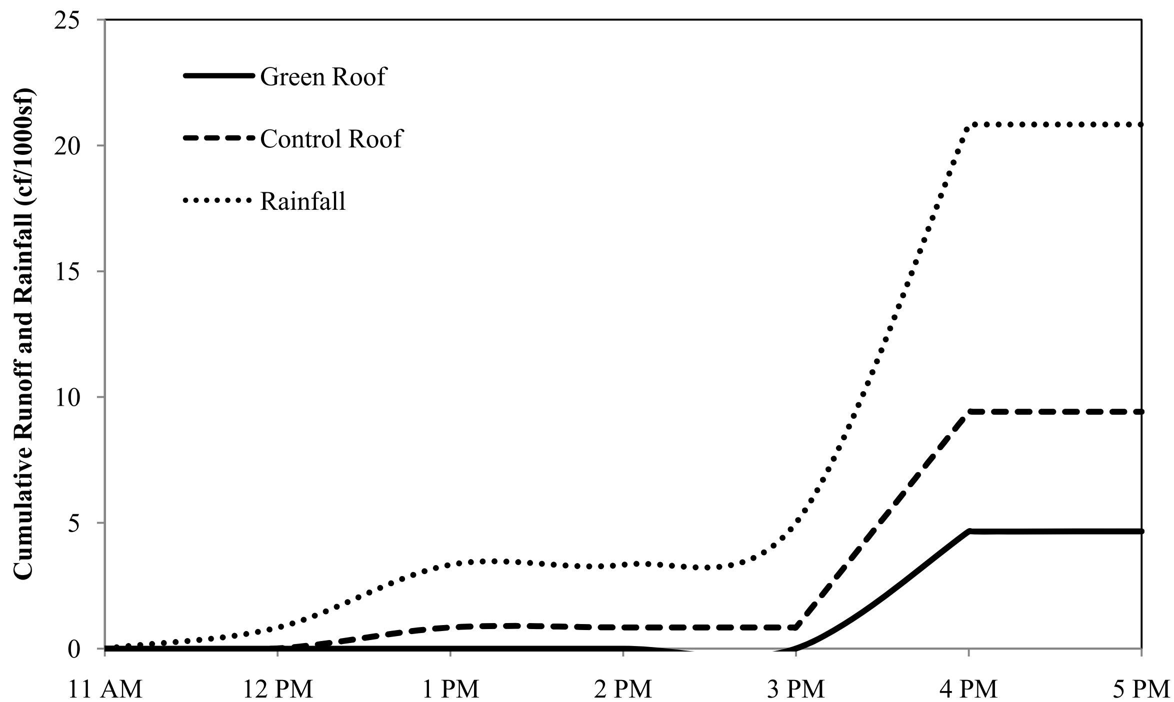


Figure 197. Runoff and Rainfall Volumes – October 1, 2008 Storm (Homestead)

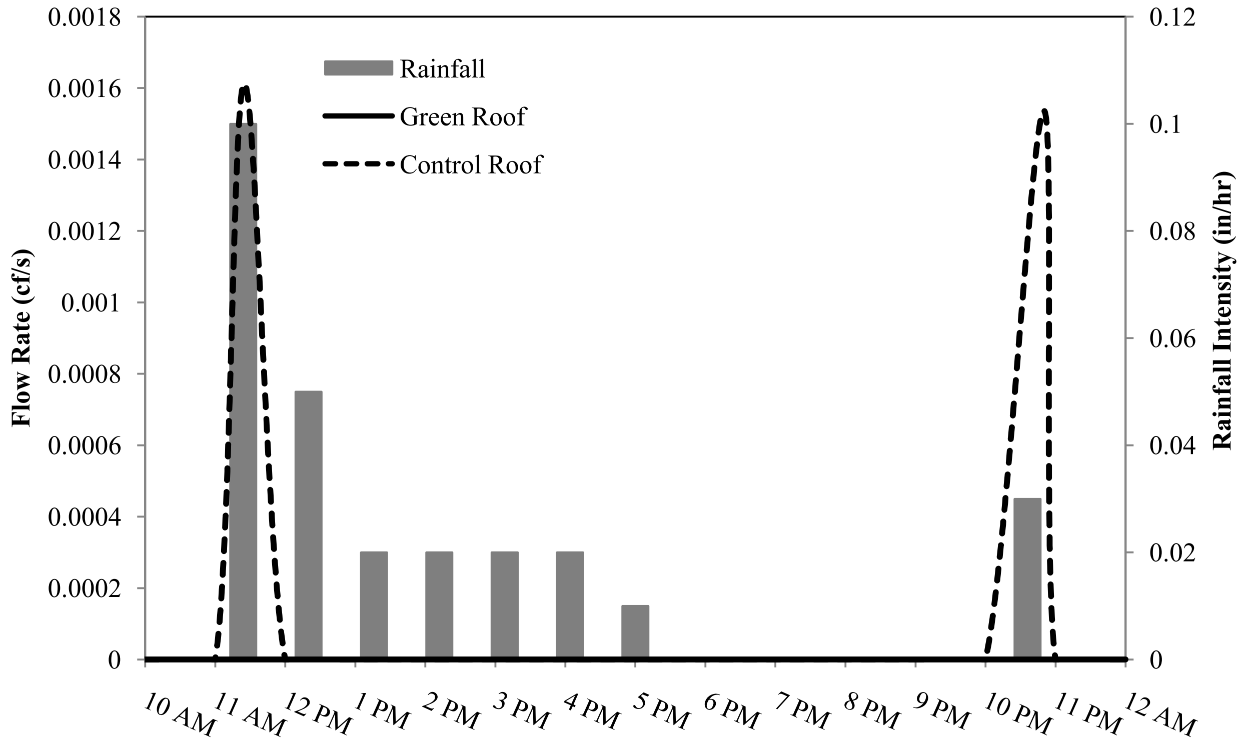


Figure 198. Runoff Flow Rates and Rainfall Intensity – October 8, 2008 Storm (Homestead)

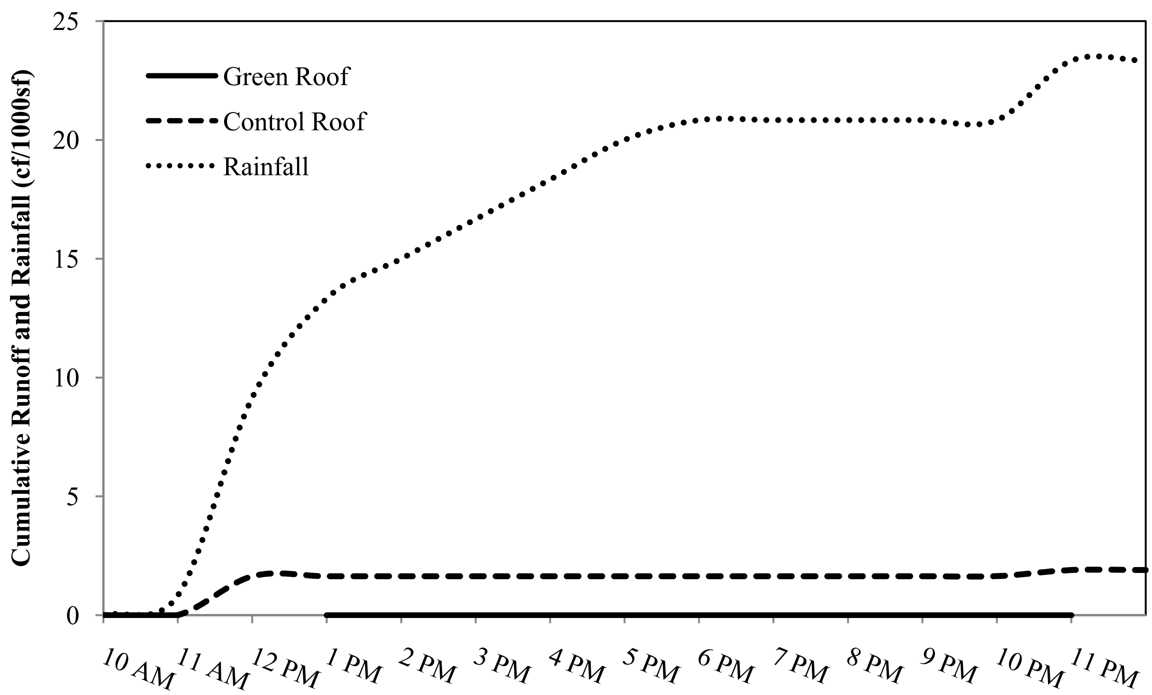


Figure 199. Runoff and Rainfall Volumes – October 8, 2008 Storm (Homestead)

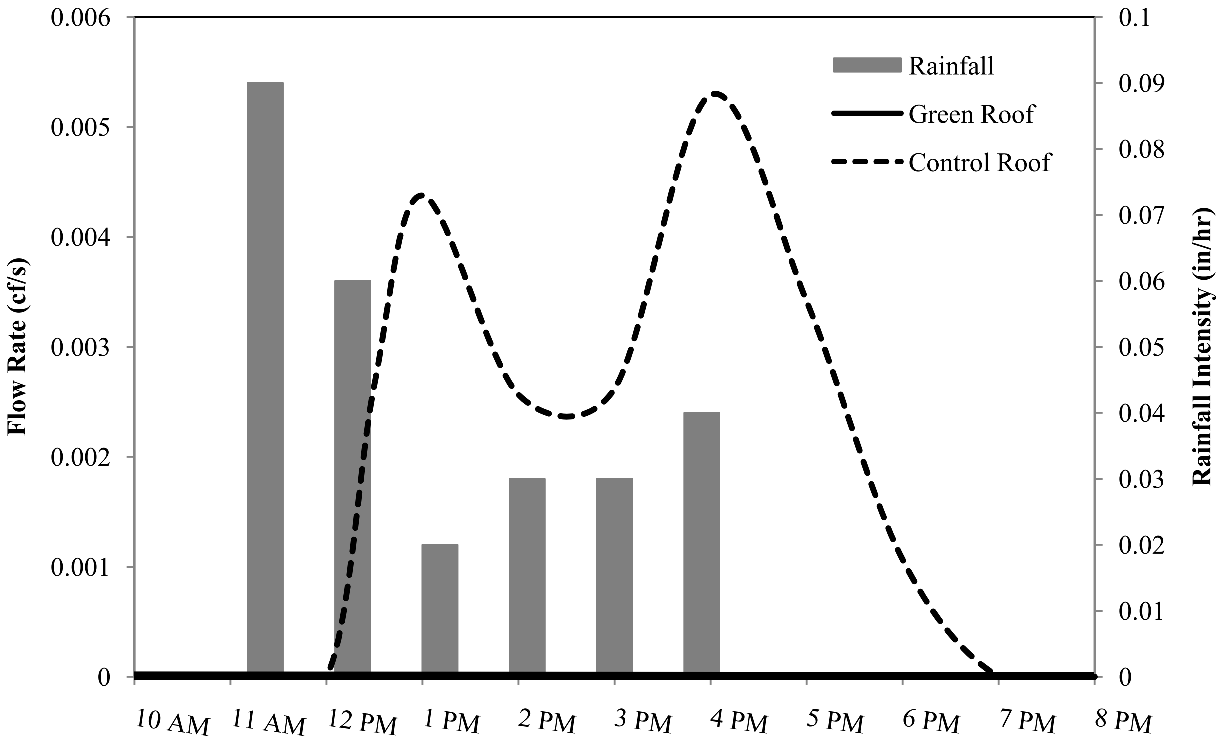


Figure 200. Runoff Flow Rates and Rainfall intensity – October 8, 2008 Storm (Giant Eagle)

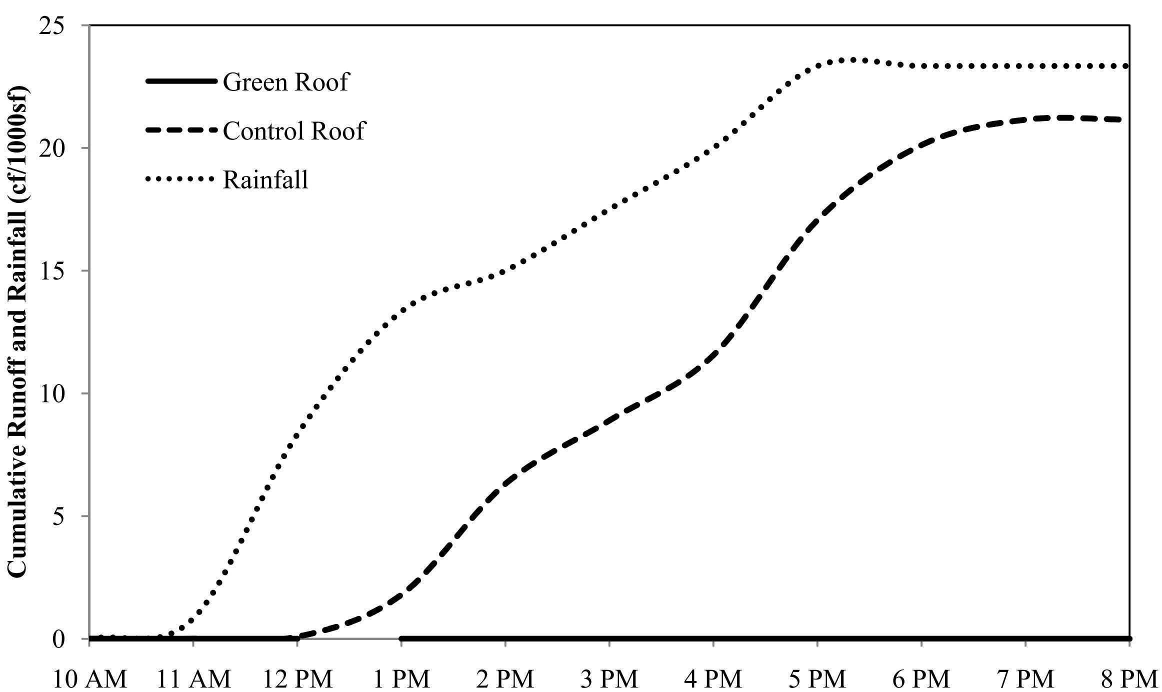


Figure 201. Runoff and Rainfall Volumes – October 8, 2008 Storm (Giant Eagle)

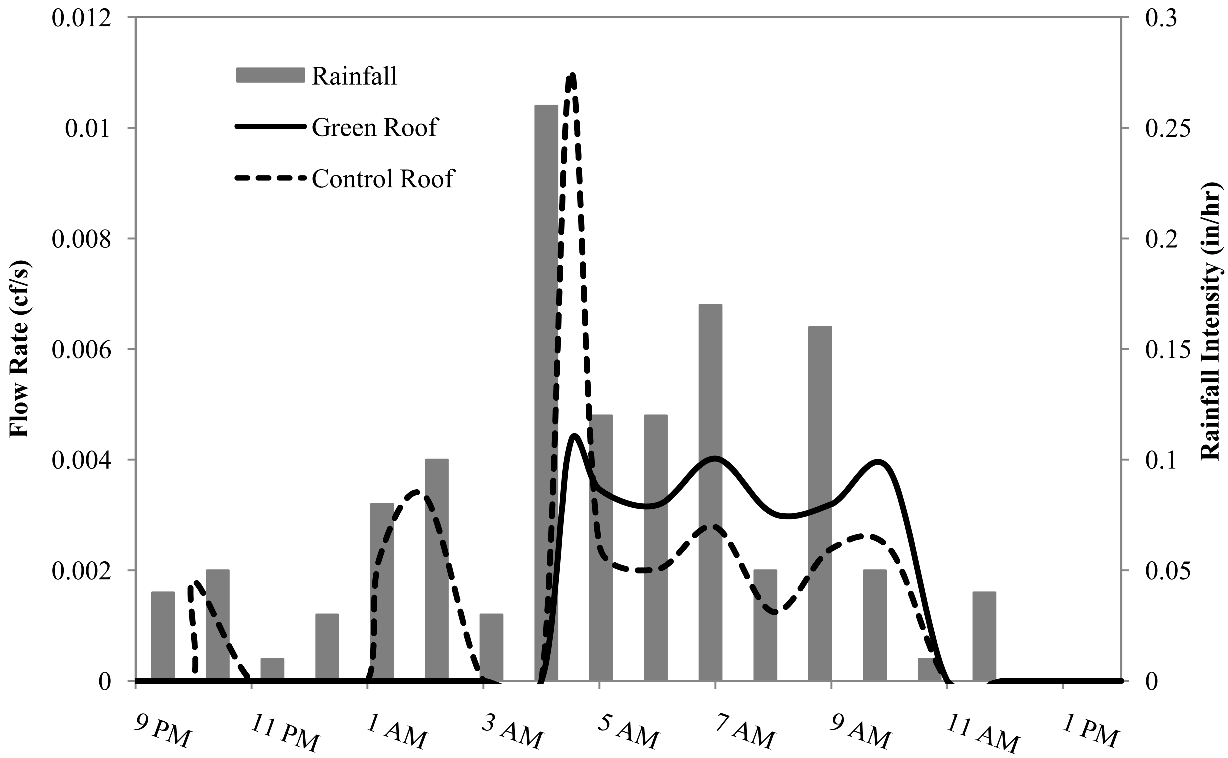


Figure 202. Runoff Flow Rates and Rainfall Intensity – October 24-25, 2008 Storm (Homestead)

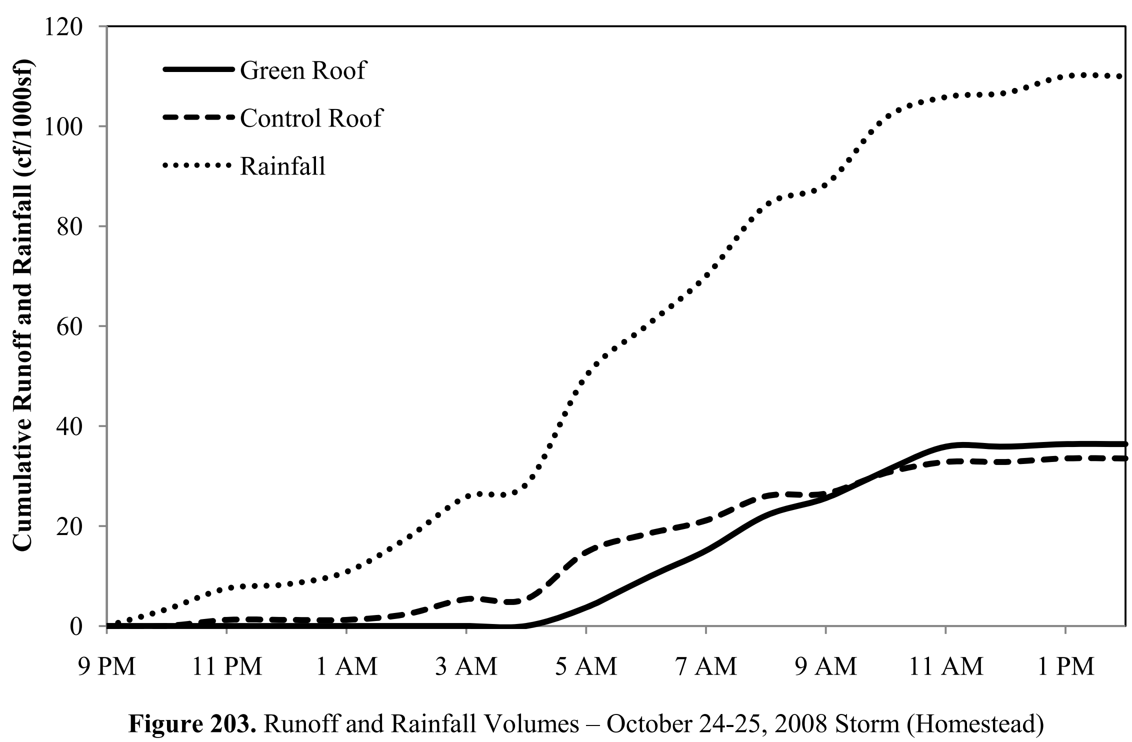


Figure 203. Runoff and Rainfall Volumes – October 24-25, 2008 Storm (Homestead)

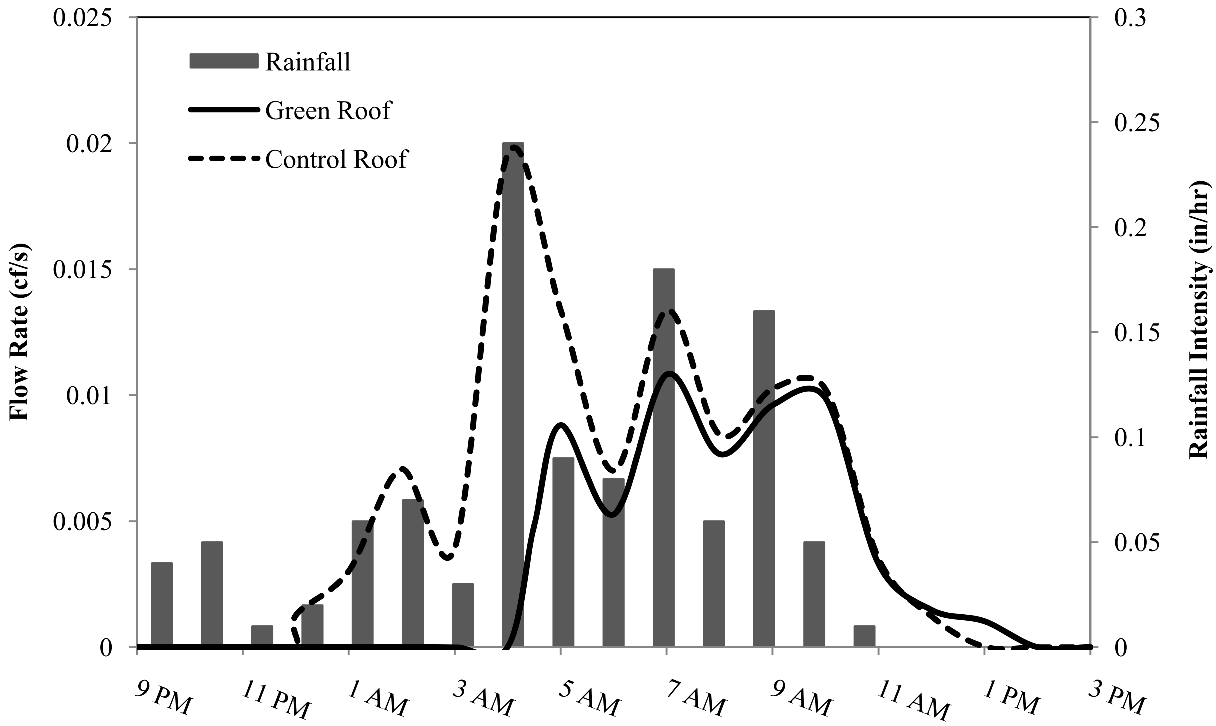


Figure 204. Runoff Flow Rates and Rainfall intensity – October 24-25, 2008 Storm (Giant Eagle)

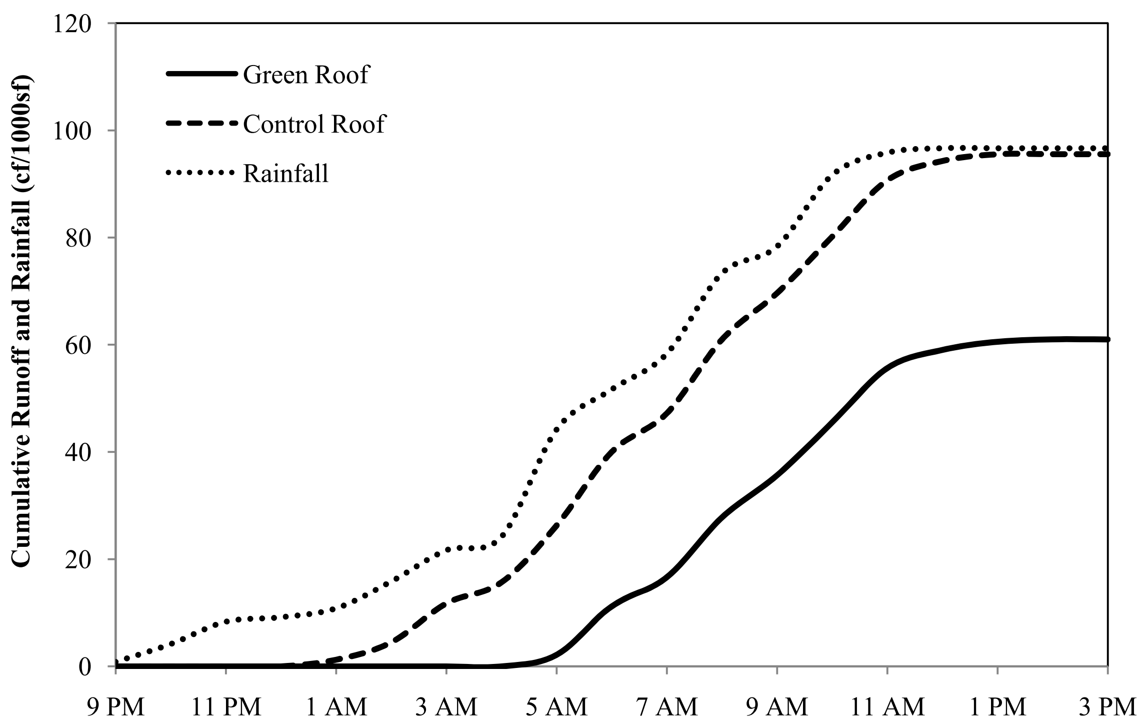


Figure 205. Runoff and Rainfall Volumes – October 24-25, 2008 Storm (Giant Eagle)

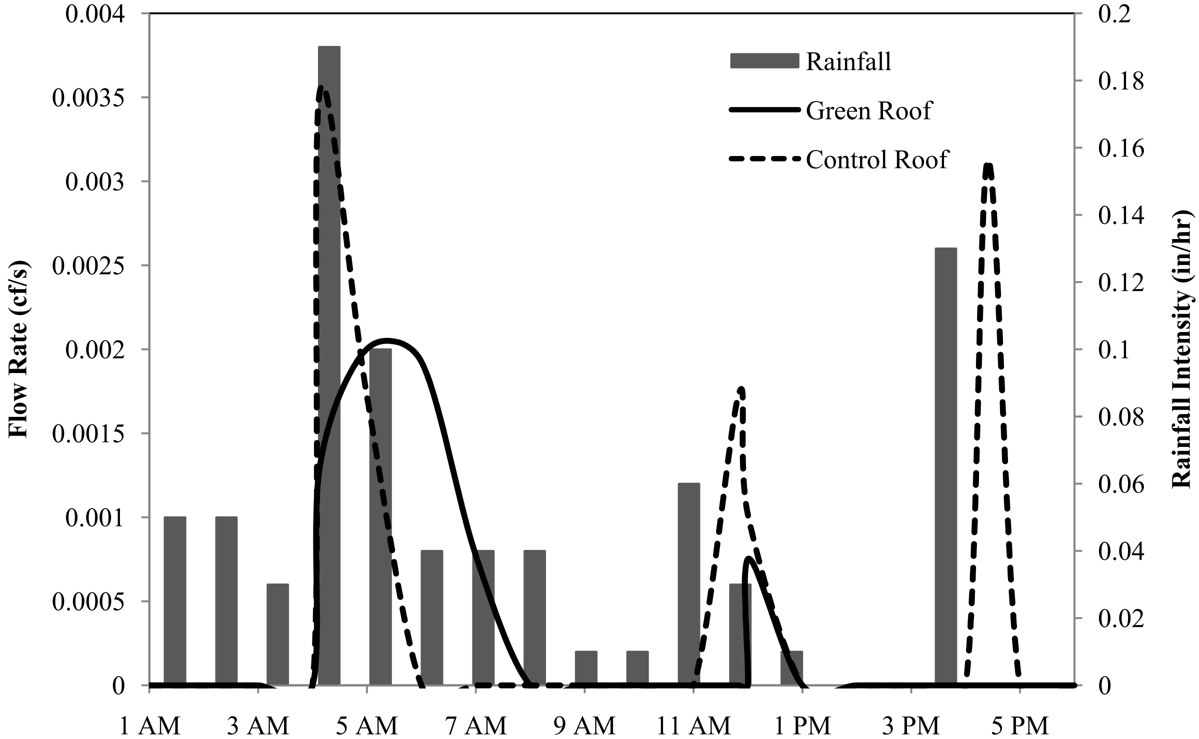


Figure 206. Runoff Flow Rates and Rainfall Intensity – November 15, 2008 Storm (Homestead)

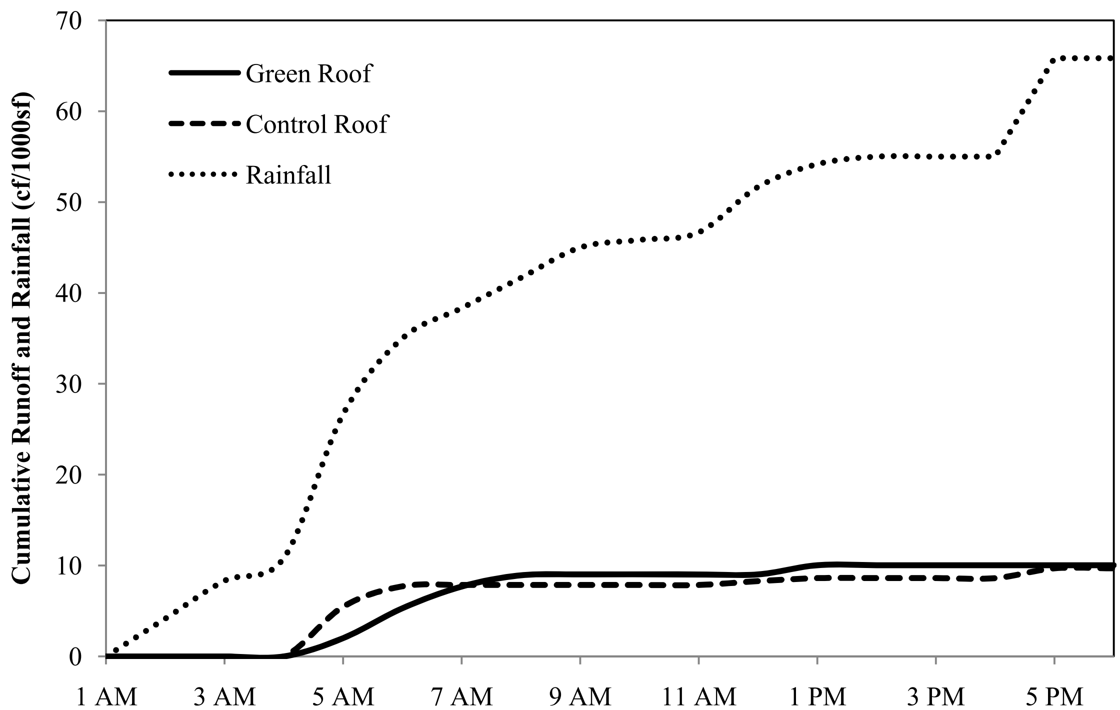


Figure 207. Runoff and Rainfall Volumes – November 15, 2008 Storm (Homestead)

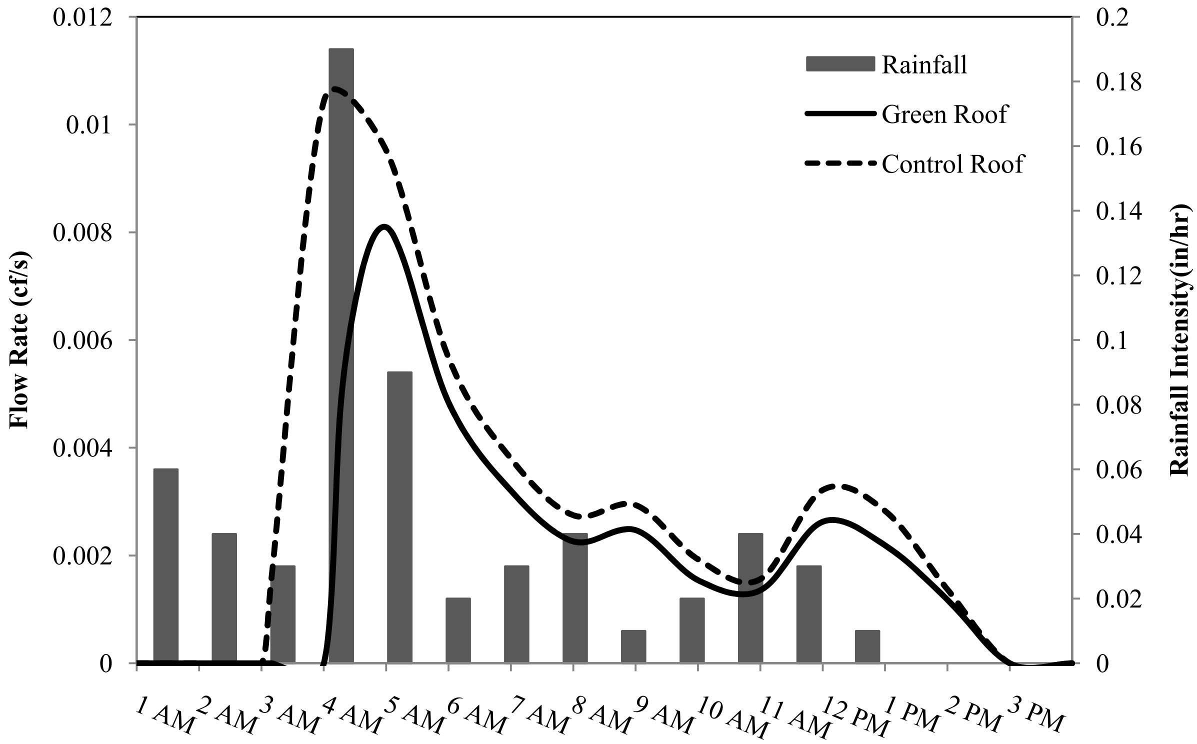


Figure 208. Runoff Flow Rates and Rainfall intensity – November 15, 2008 Storm (Giant Eagle)

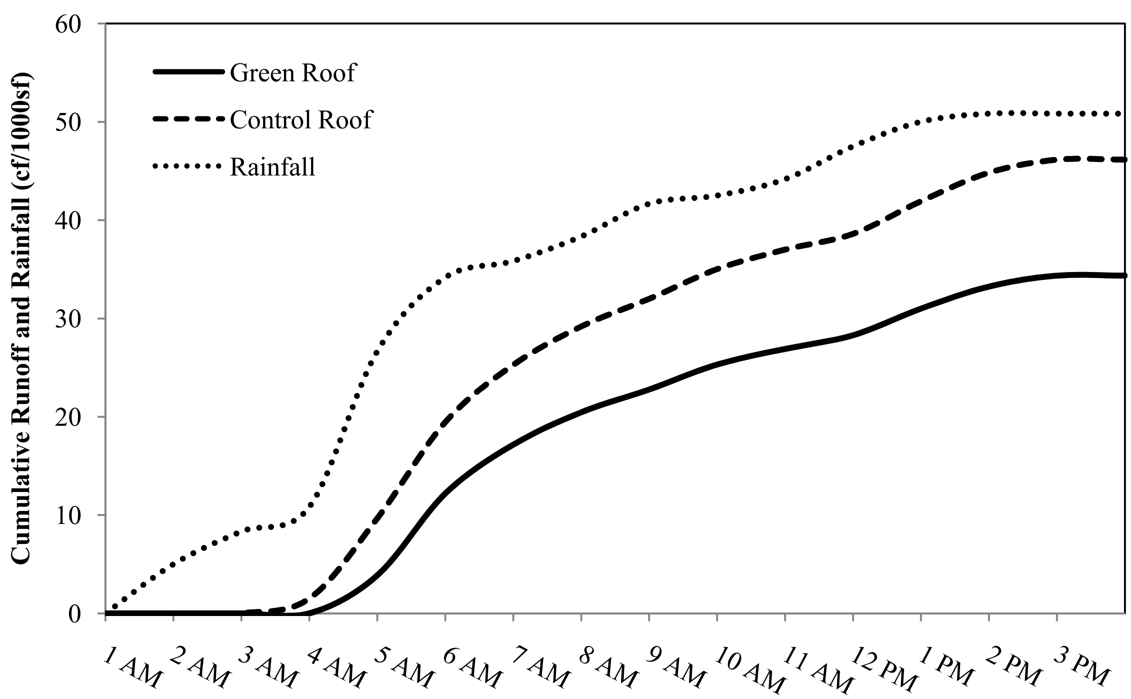


Figure 209. Runoff and Rainfall Volumes – November 15, 2008 Storm (Giant Eagle)

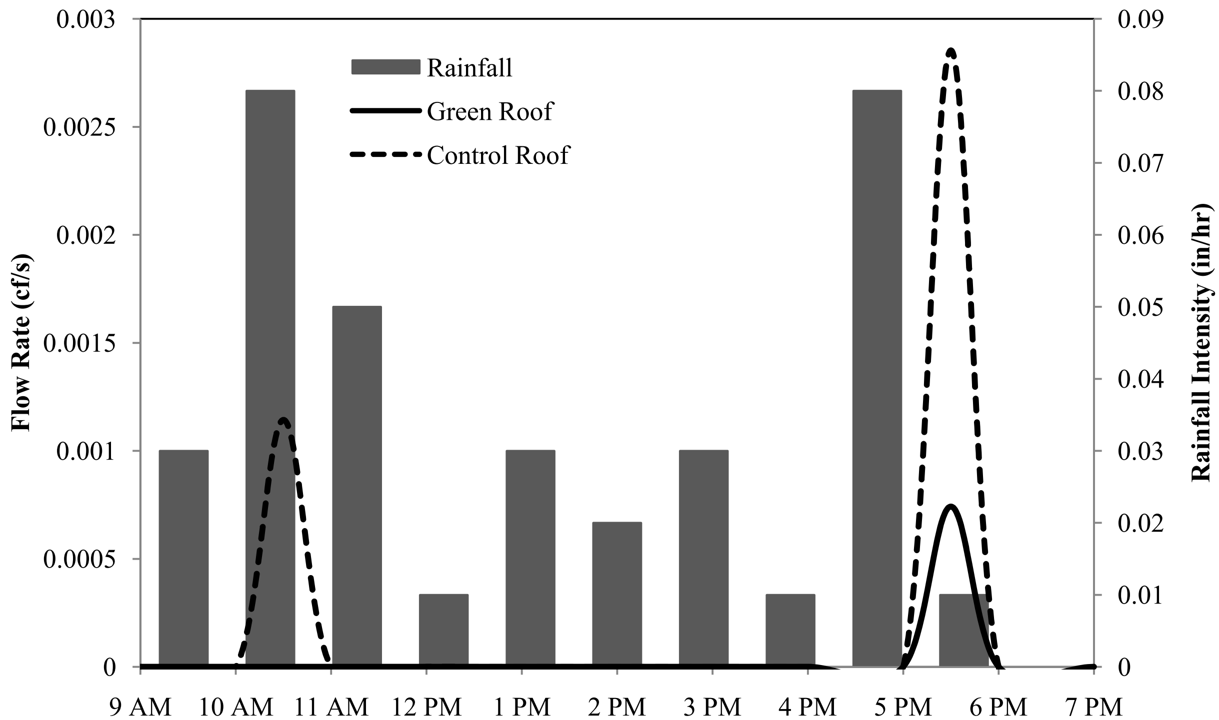


Figure 210. Runoff Flow Rates and Rainfall Intensity – November 30, 2008 Storm (Homestead)

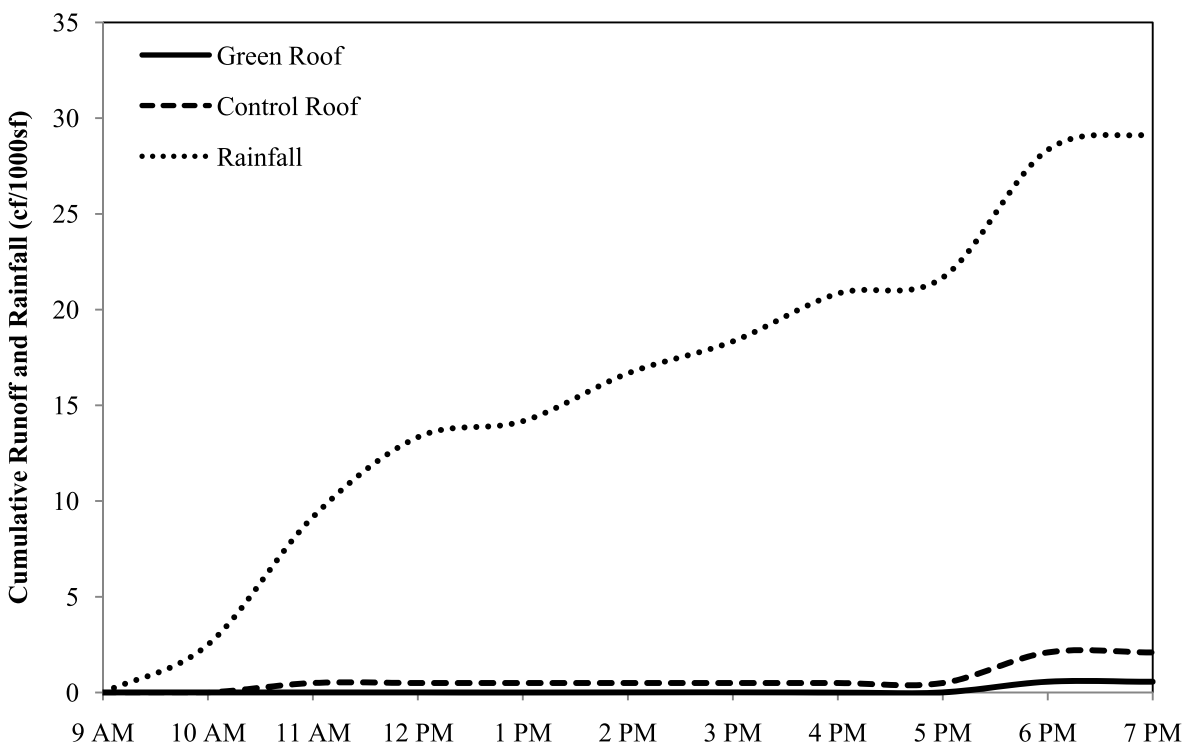


Figure 211. Runoff and Rainfall Volumes – November 30, 2008 Storm (Homestead)

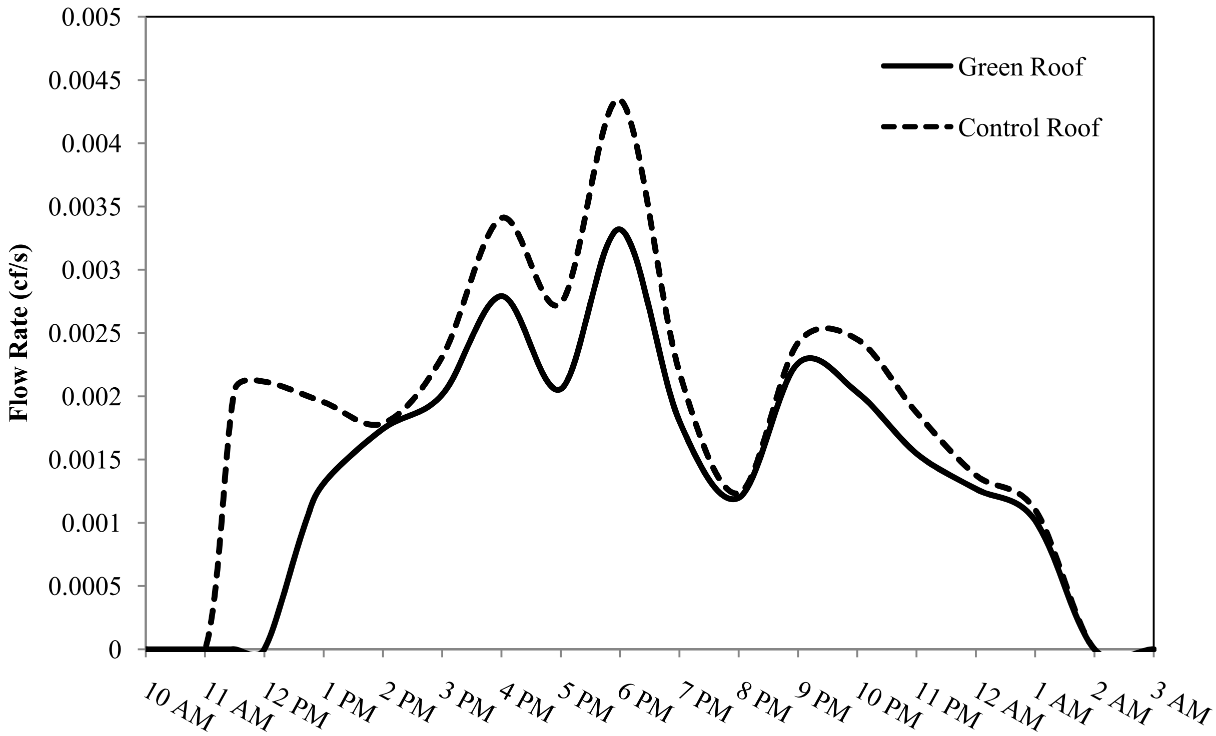


Figure 212. Runoff Flow Rates– November 30-December 1, 2008 Storm (Giant Eagle)

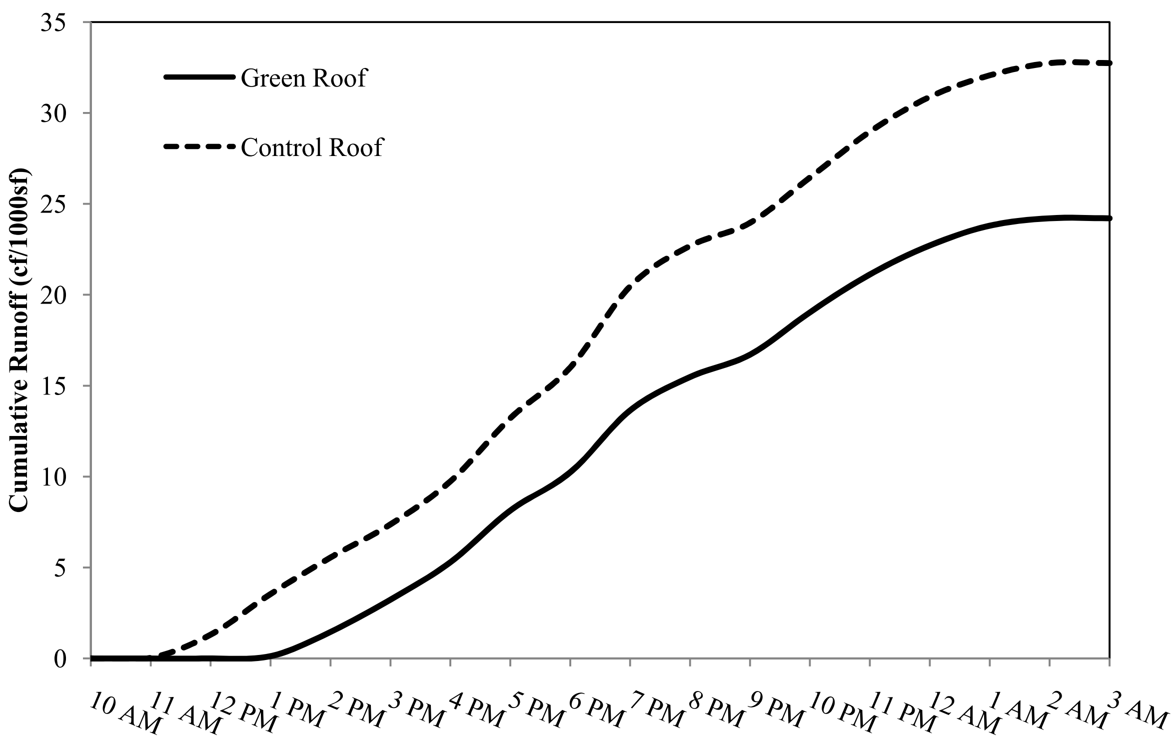


Figure 213. Runoff Volumes – November 30-December 1, 2008 Storm (Giant Eagle)

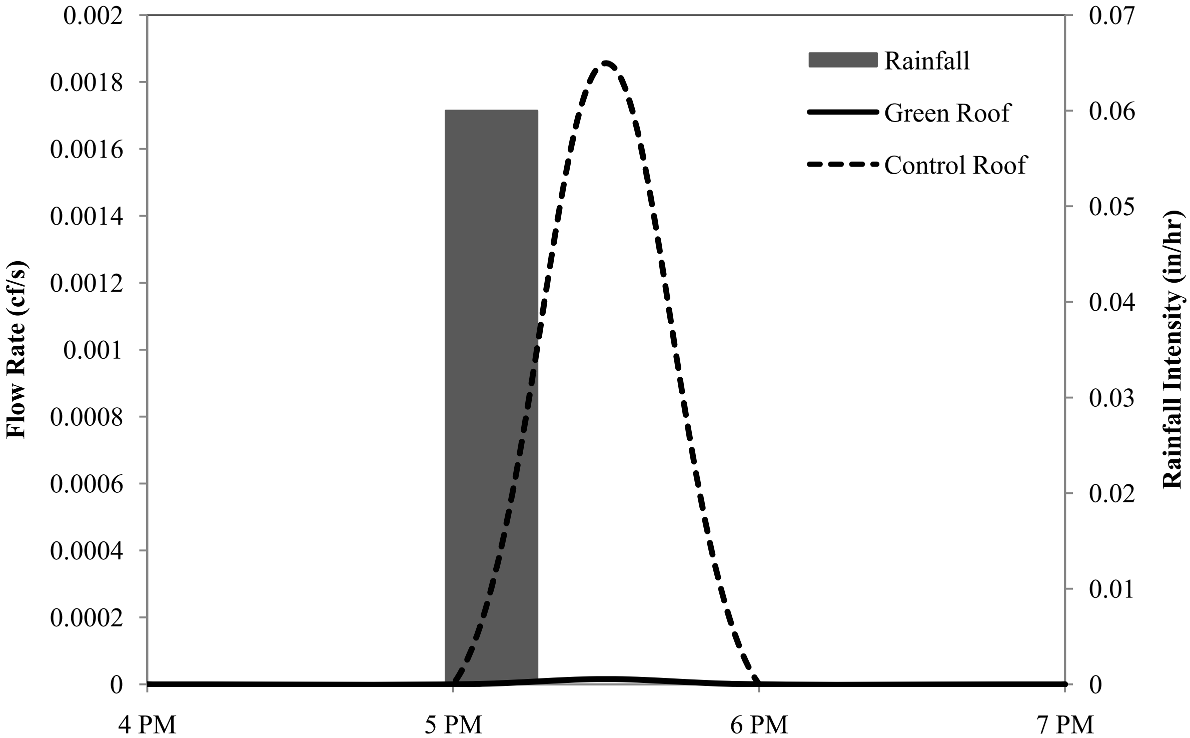


Figure 214. Runoff Flow Rates and Rainfall Intensity – February 10, 2009 Storm (Homestead)

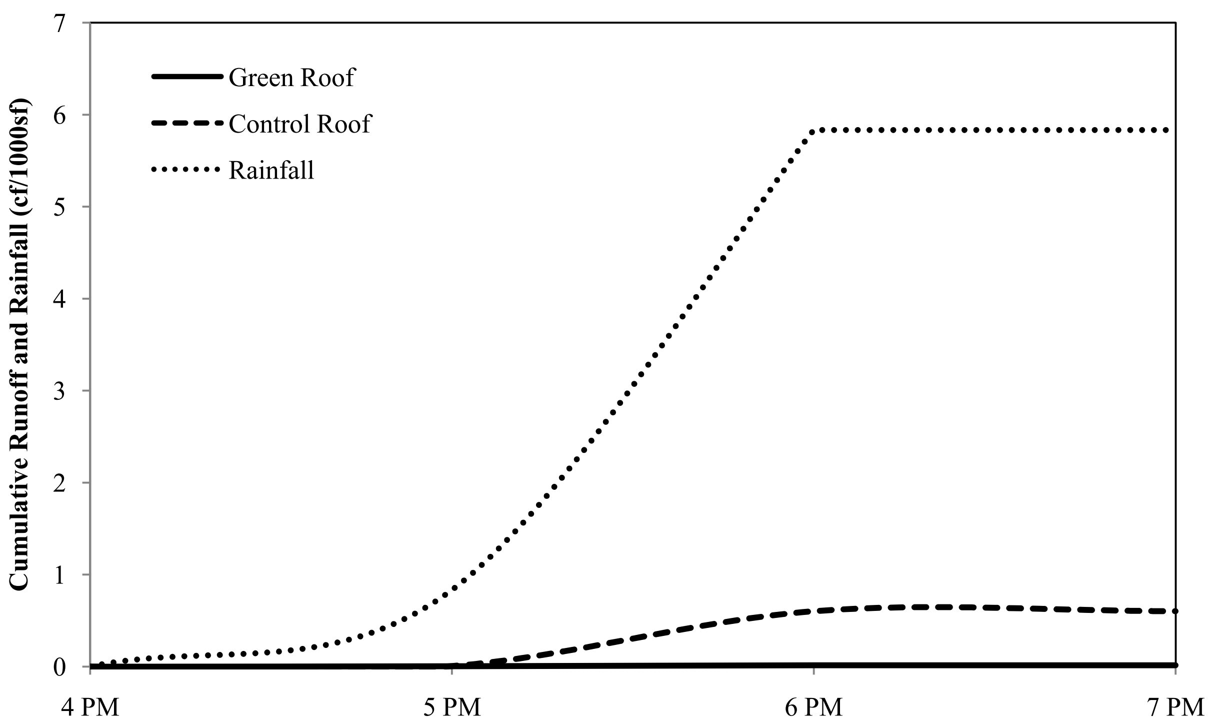


Figure 215. Runoff and Rainfall Volumes – February 10, 2009 Storm (Homestead)

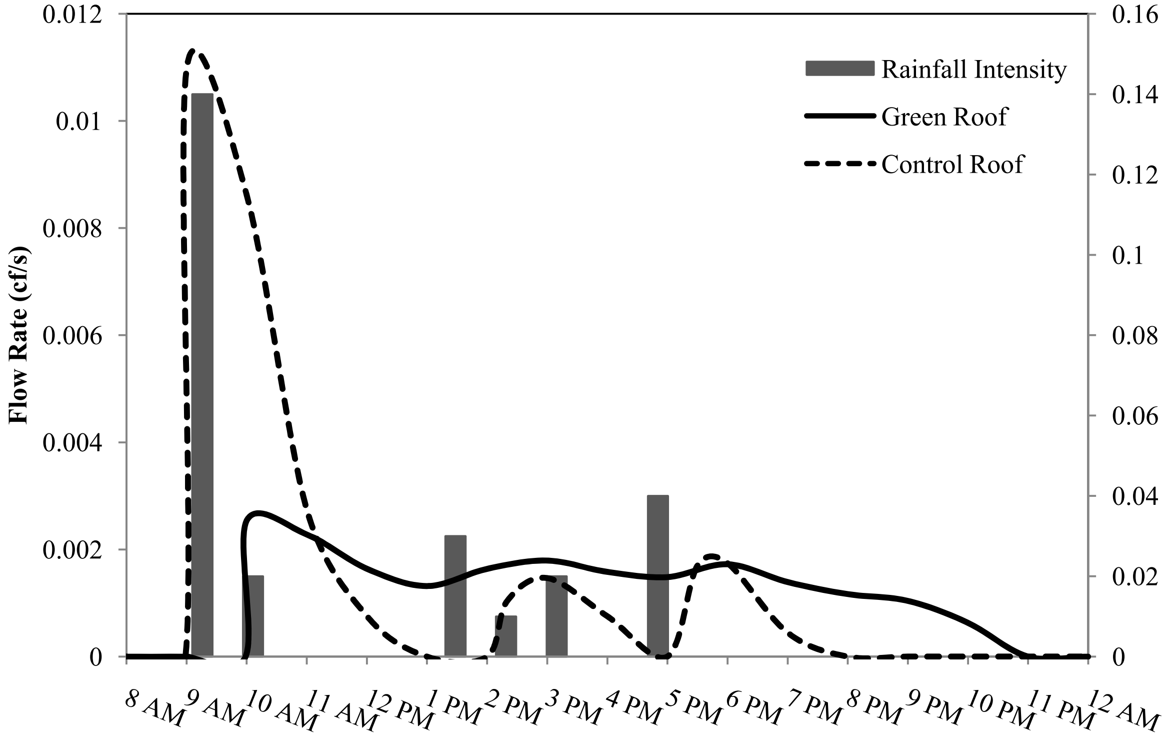


Figure 216. Runoff Flow Rates and Rainfall intensity – February 10, 2009 Storm (Giant Eagle)

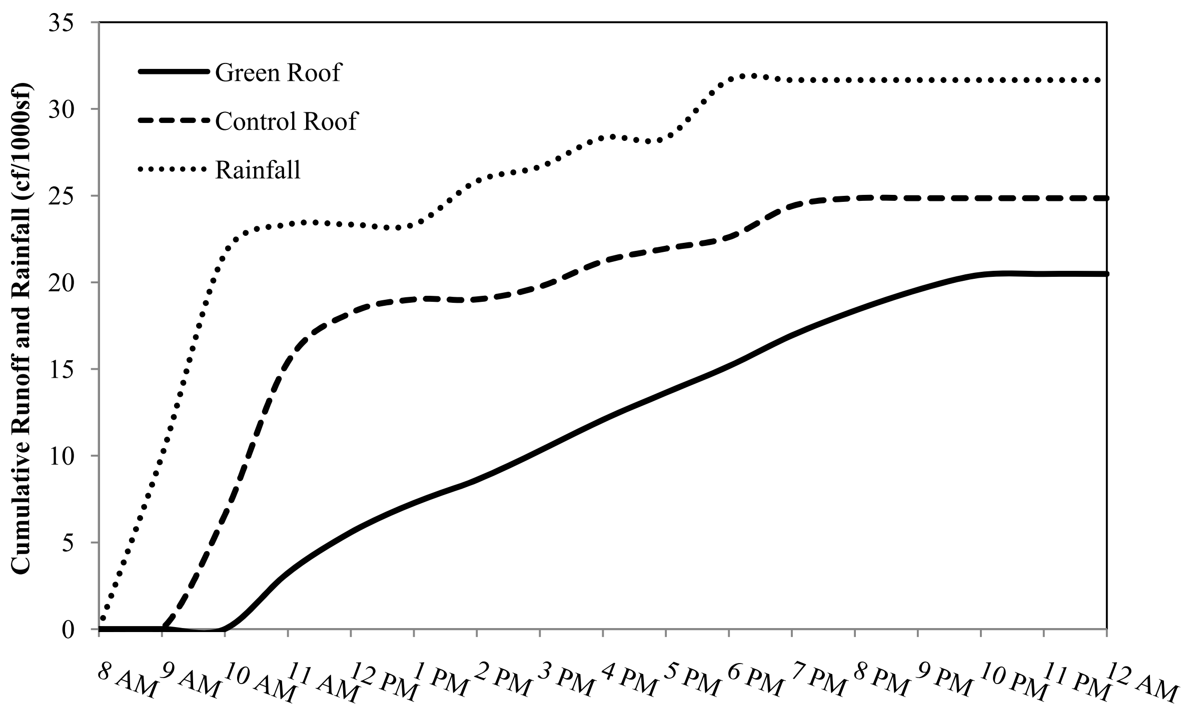


Figure 217. Runoff and Rainfall Volumes – February 10, 2009 Storm (Giant Eagle)

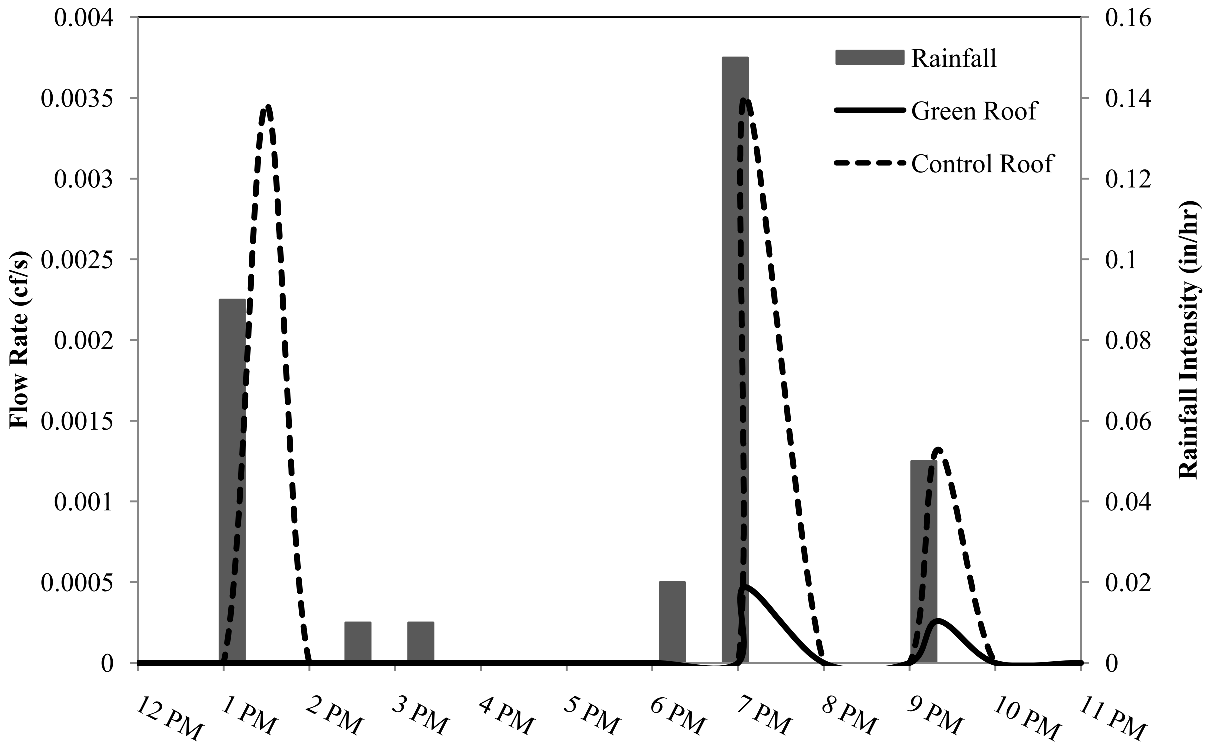


Figure 218. Runoff Flow Rates and Rainfall Intensity – February 18, 2009 Storm (Homestead)

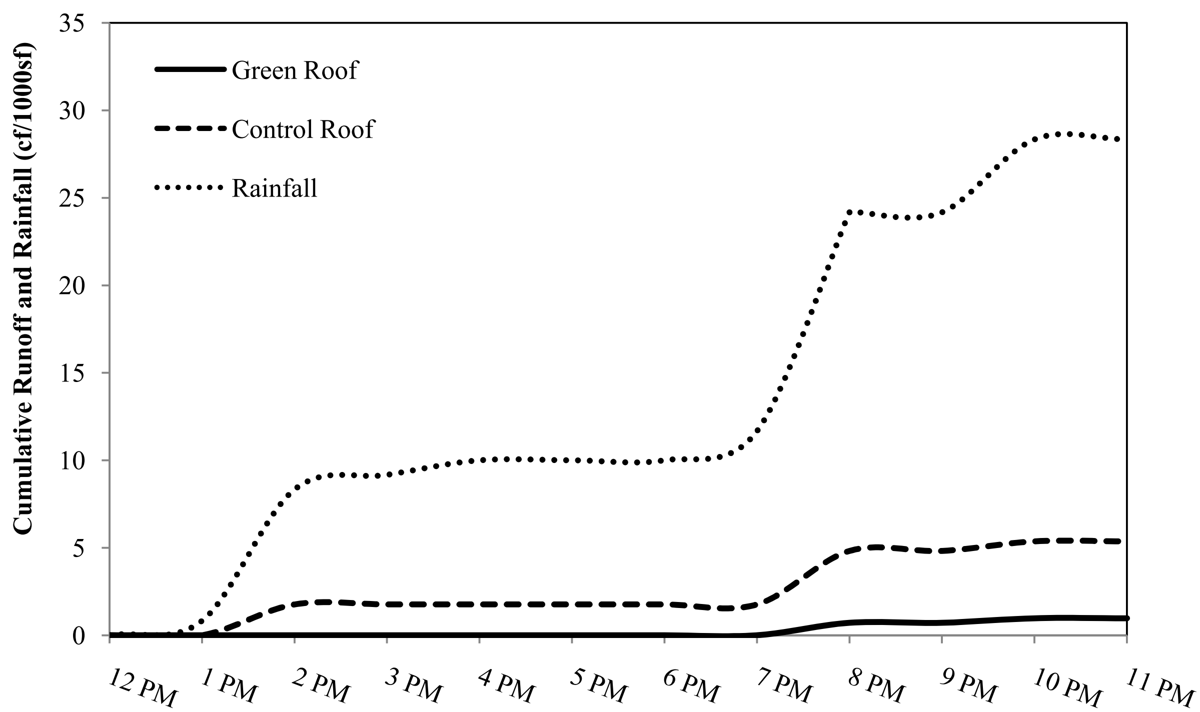


Figure 219. Runoff and Rainfall Volumes – February 18, 2009 Storm (Homestead)

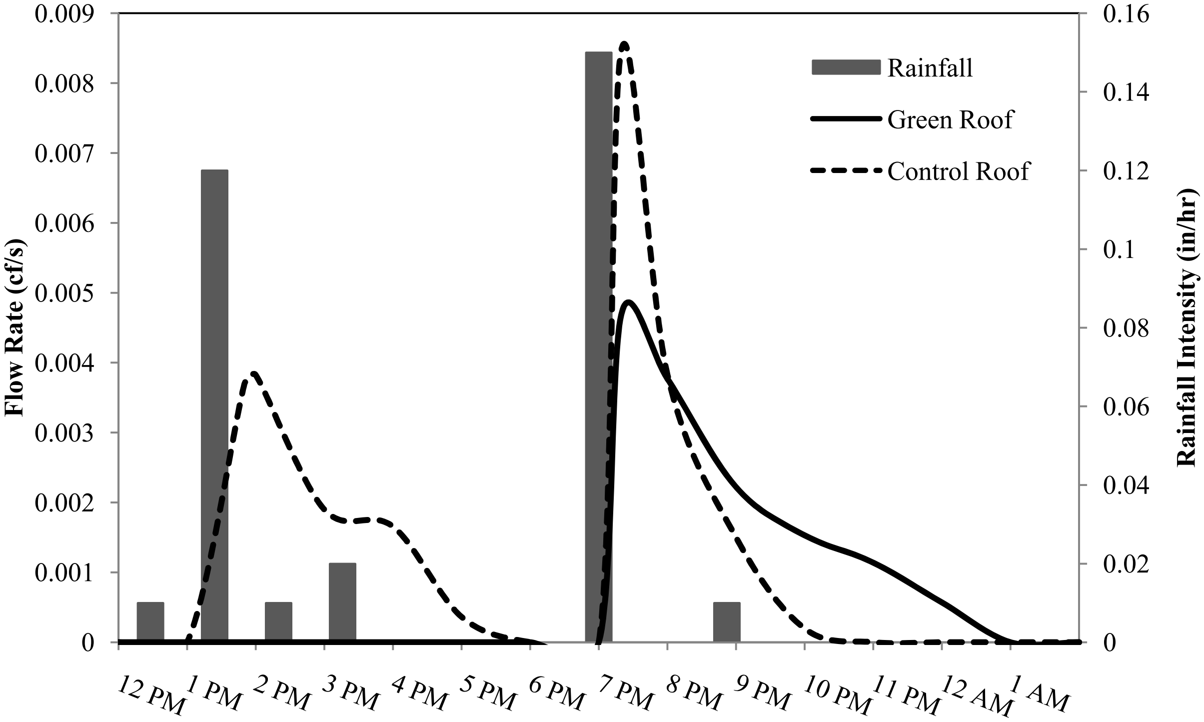


Figure 220. Runoff Flow Rates and Rainfall intensity – February 18-19, 2009 Storm (Giant Eagle)

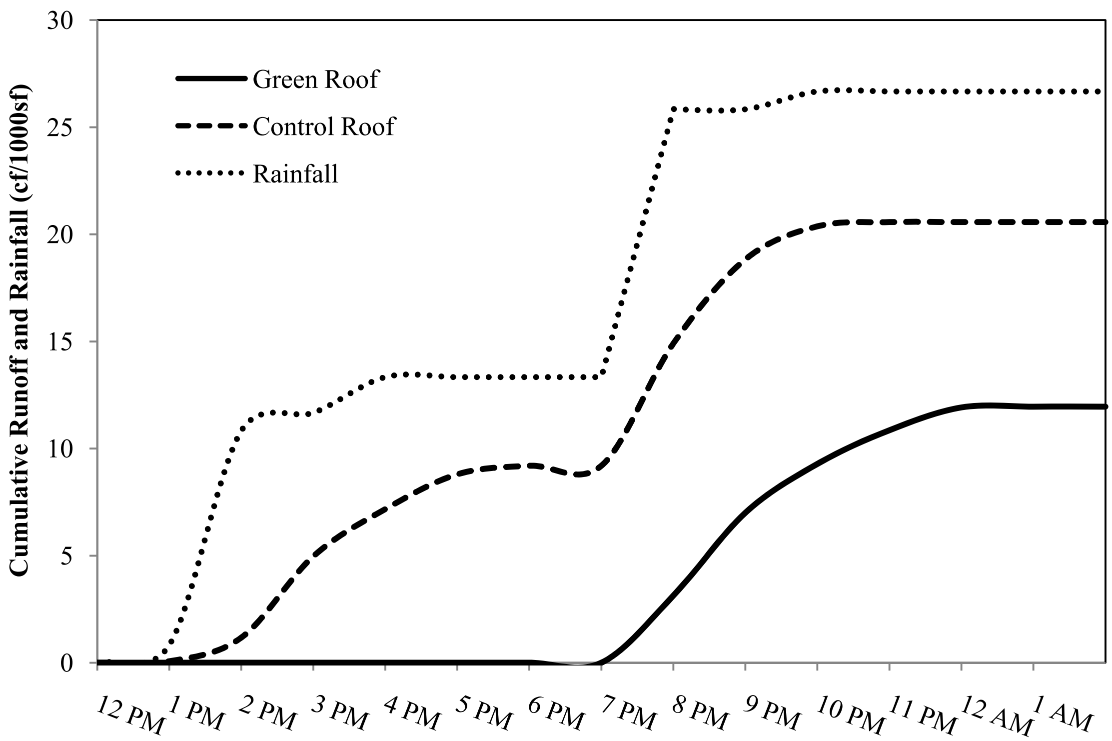


Figure 221. Runoff and Rainfall Volumes – February 18-19, 2009 Storm (Giant Eagle)

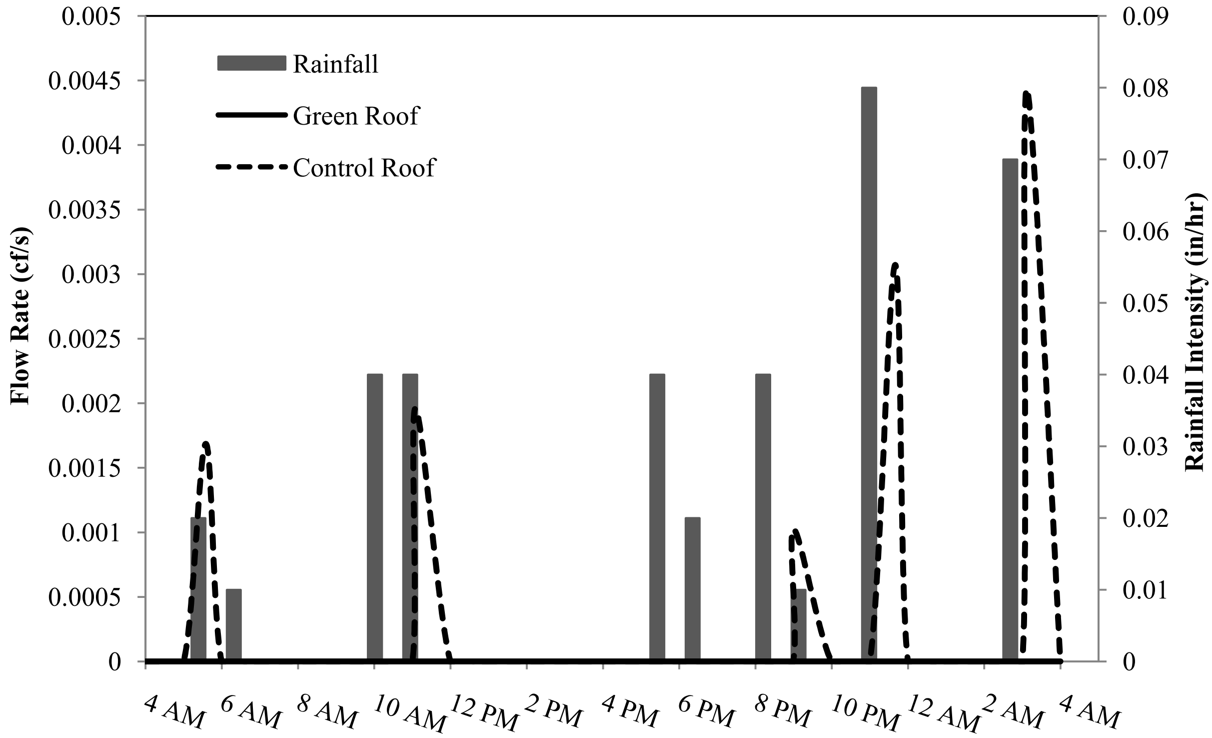


Figure 222. Runoff Flow Rates and Rainfall Intensity – March 8-9, 2009 Storm (Homestead)

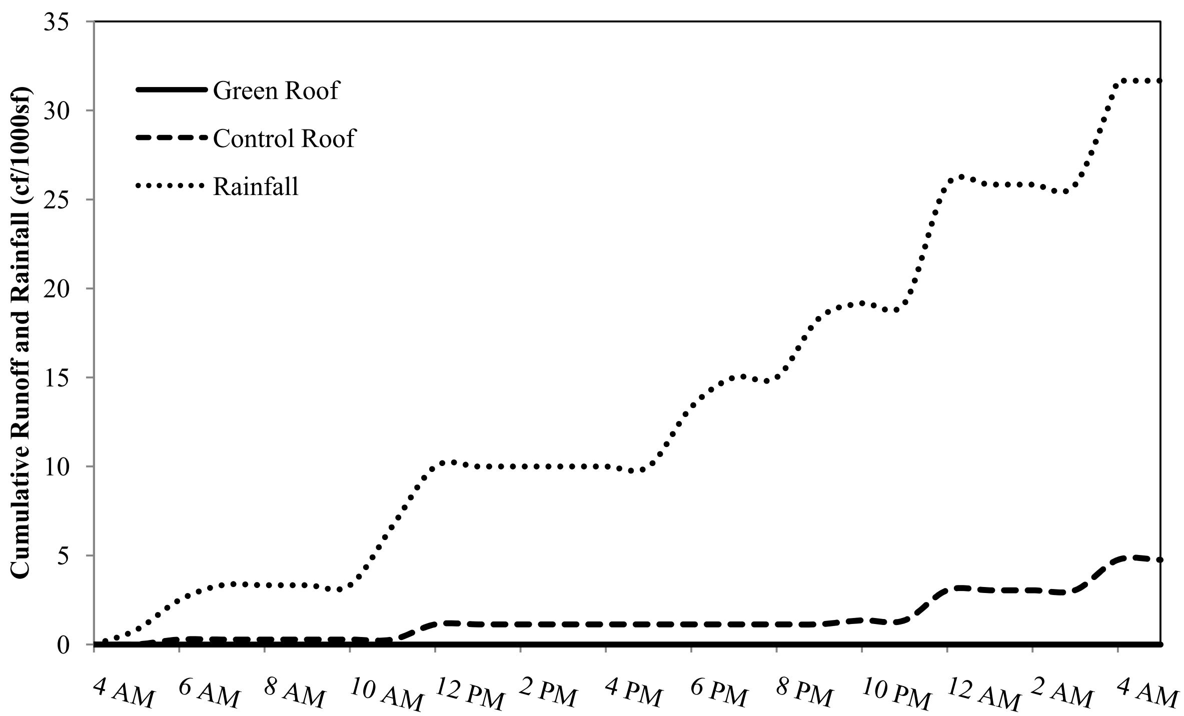


Figure 223. Runoff and Rainfall Volumes – March 8-9, 2009 Storm (Homestead)

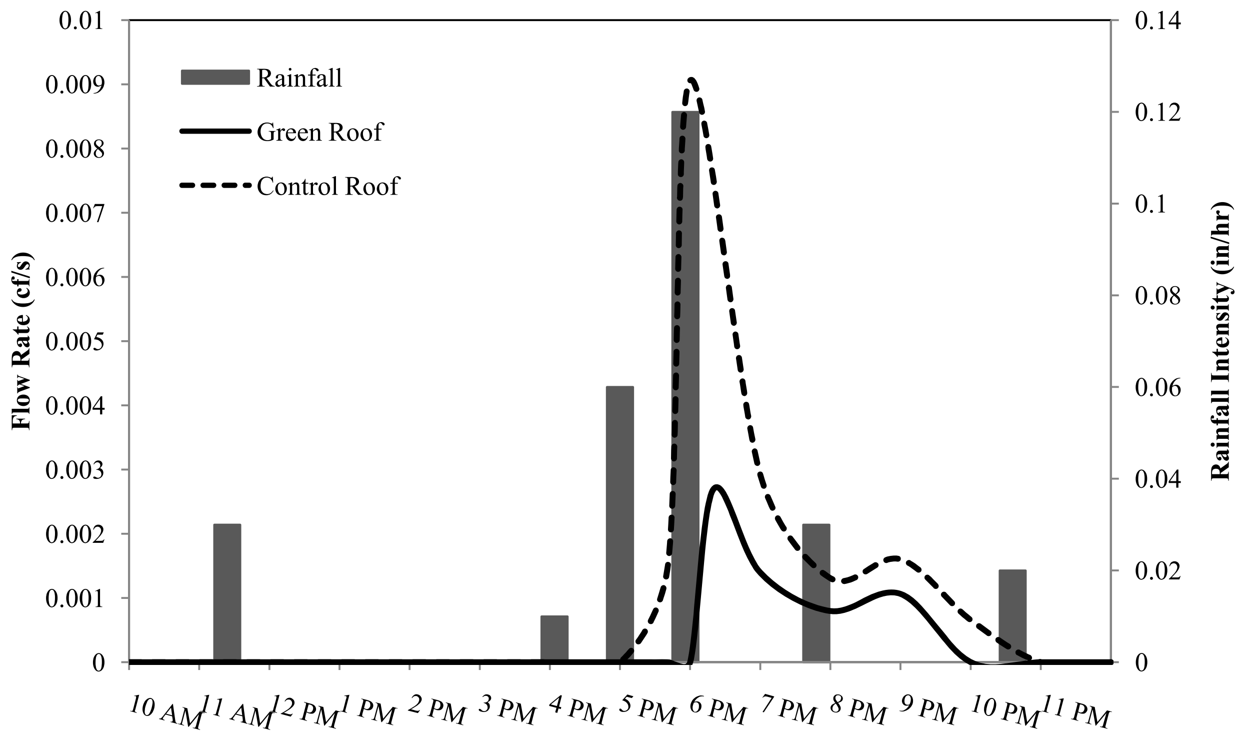


Figure 224. Runoff Flow Rates and Rainfall intensity – March 8, 2009 Storm (Giant Eagle)

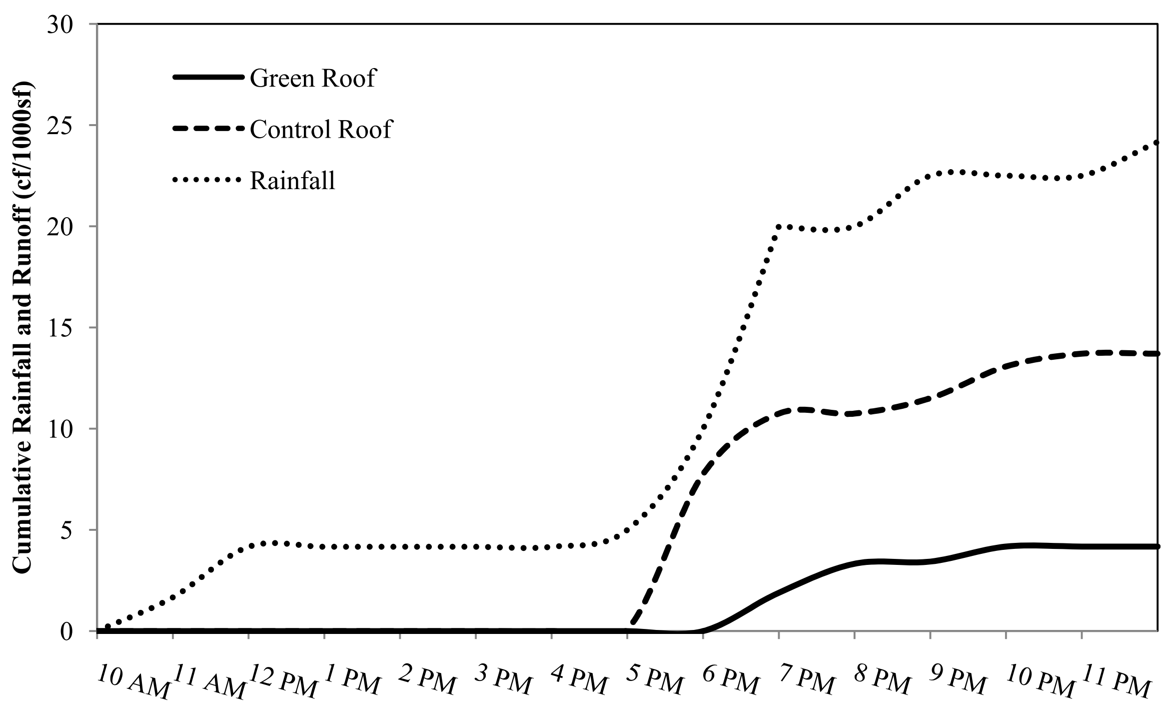


Figure 225. Runoff and Rainfall Volumes – March 8, 2009 Storm (Giant Eagle)

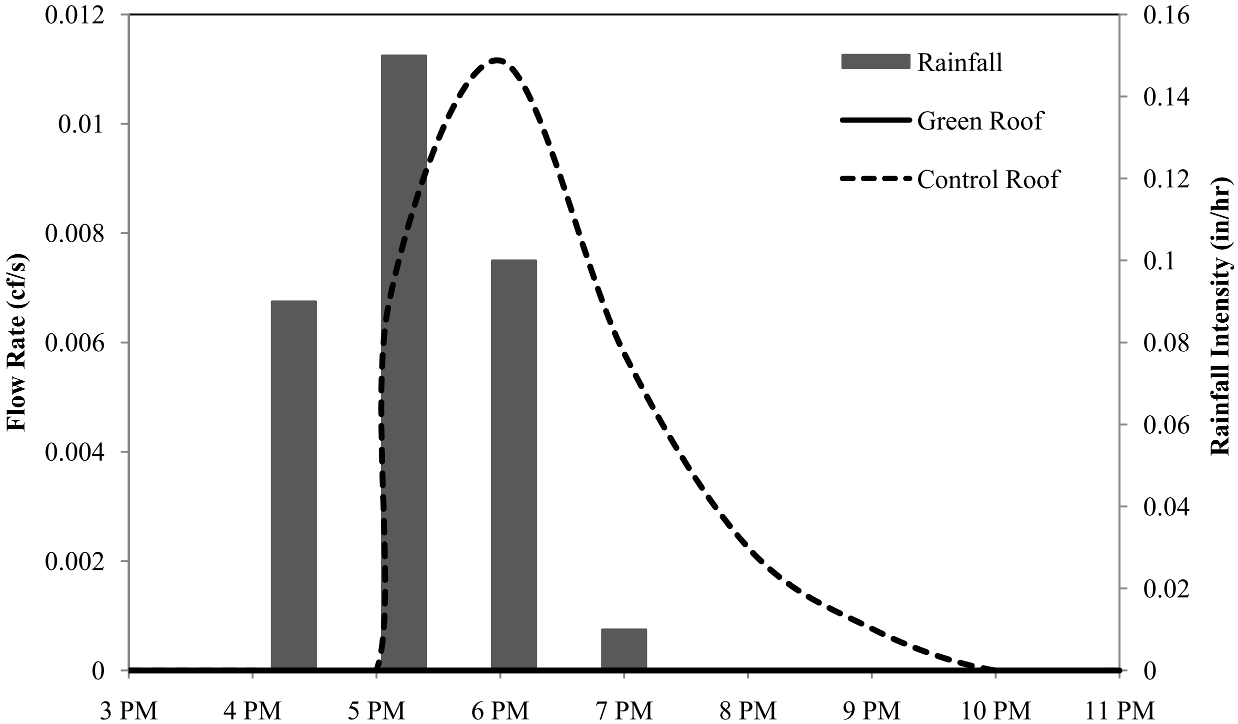


Figure 226. Runoff Flow Rates and Rainfall intensity – March 25, 2009 Storm (Giant Eagle)

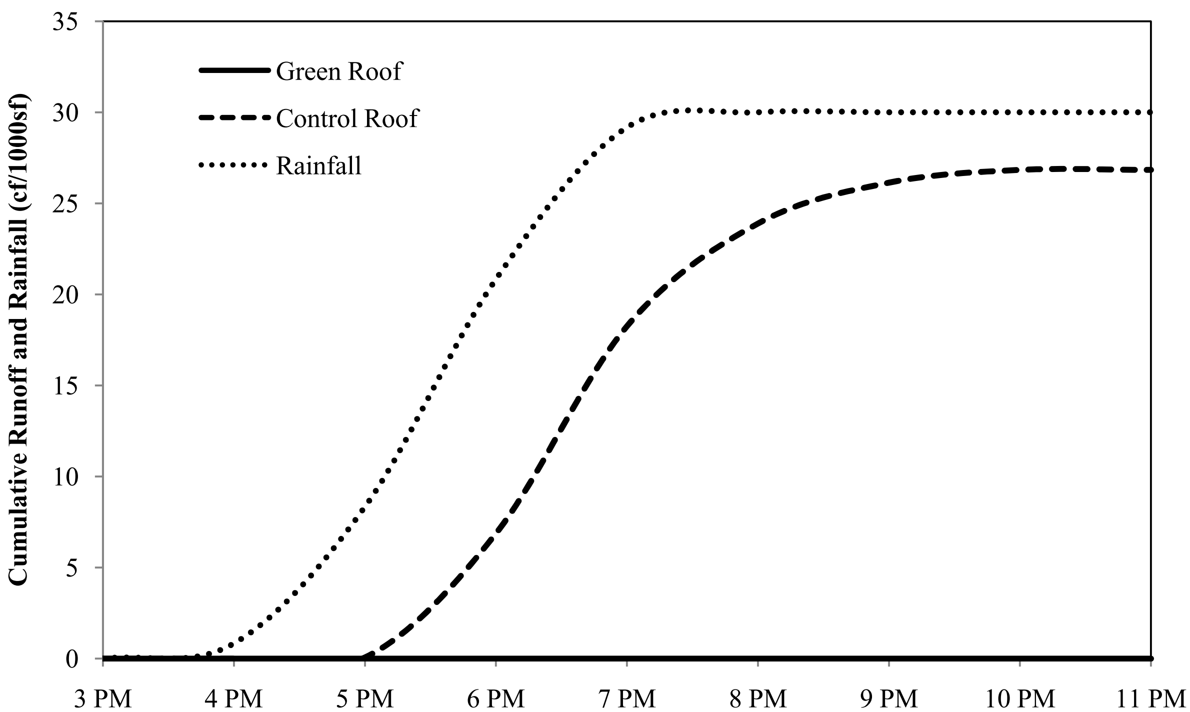


Figure 227. Runoff and Rainfall Volumes – March 25, 2009 Storm (Giant Eagle)

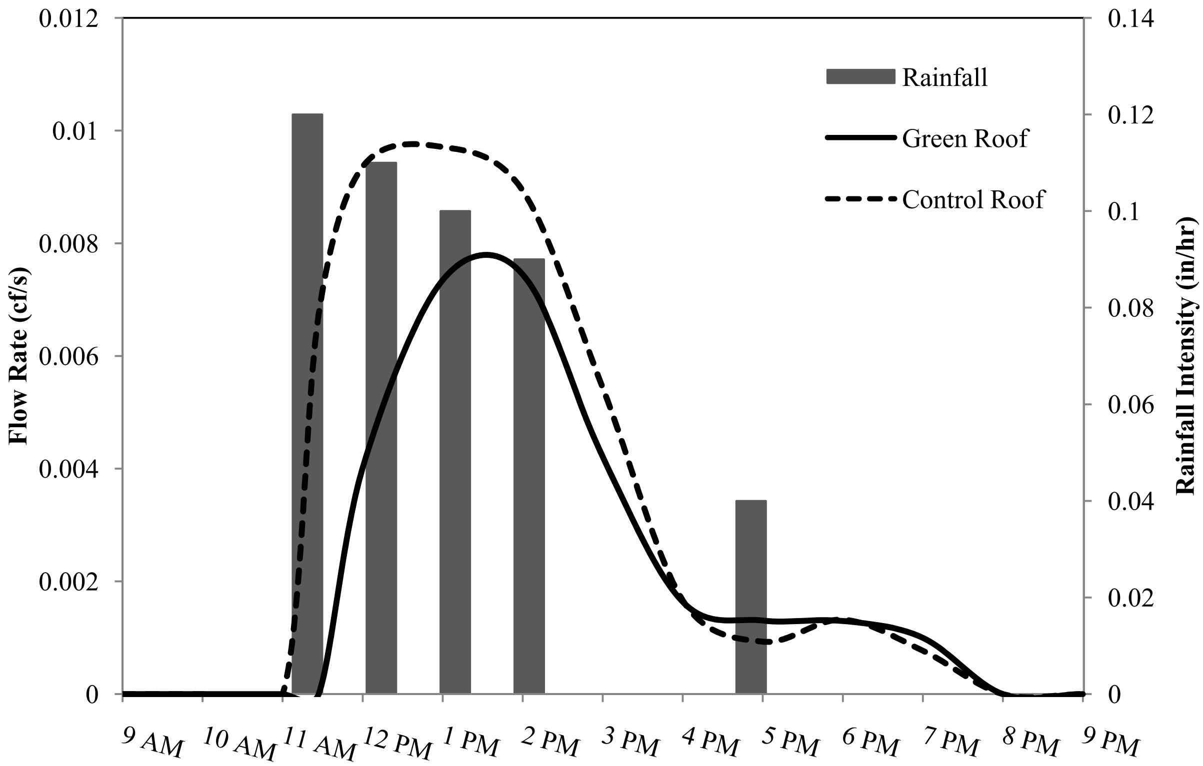


Figure 228. Runoff Flow Rates and Rainfall intensity – March 26, 2009 Storm (Giant Eagle)

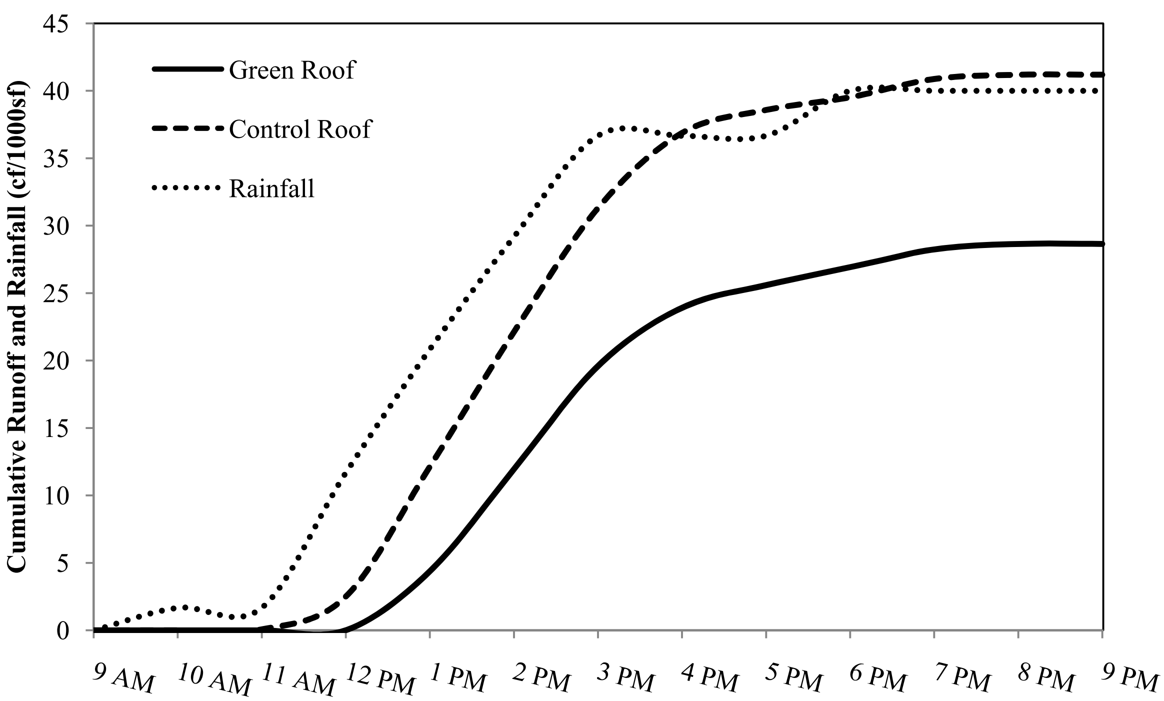


Figure 229. Runoff and Rainfall Volumes – March 26, 2009 Storm (Giant Eagle)

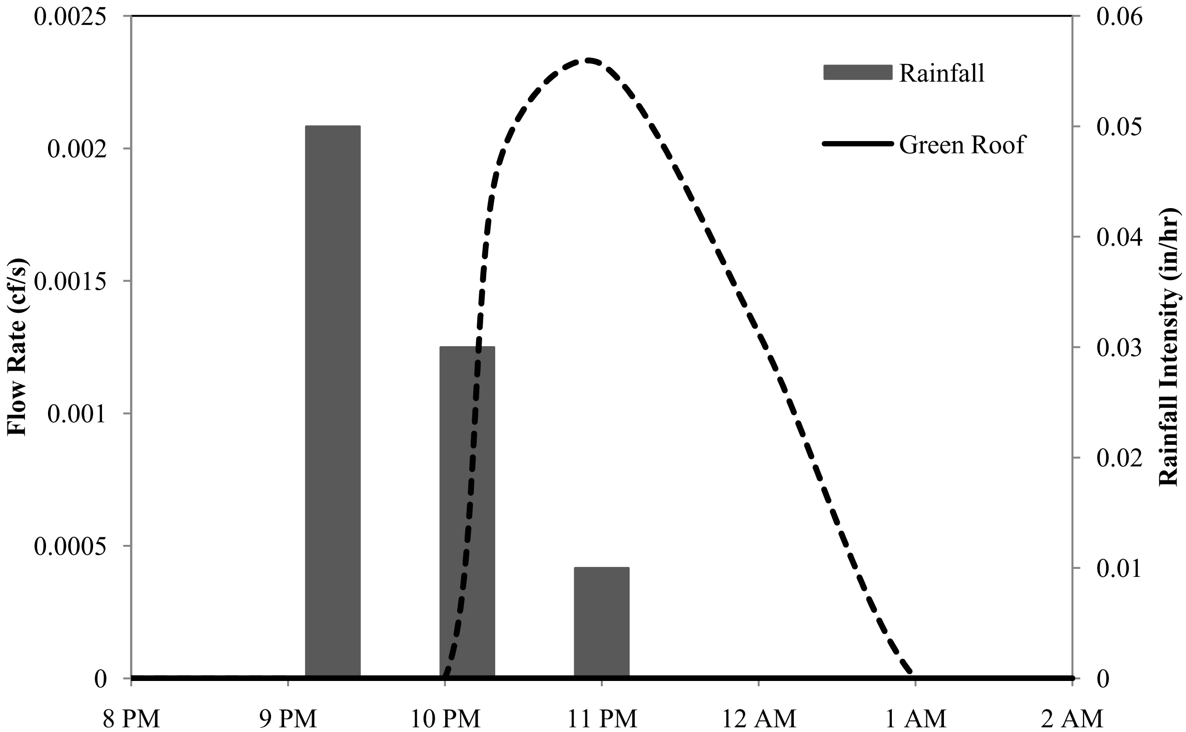


Figure 230. Runoff Flow Rates and Rainfall intensity – March 27-28, 2009 Storm (Giant Eagle)

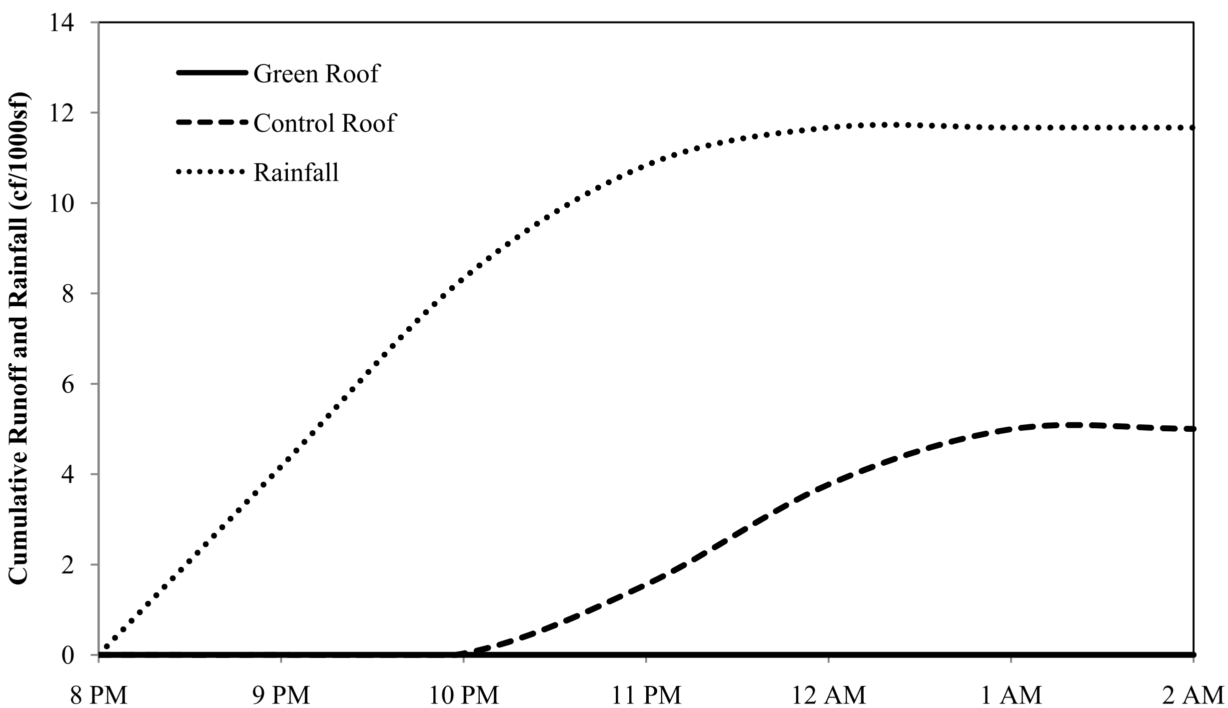


Figure 231. Runoff and Rainfall Volumes – March 27-28, 2009 Storm (Giant Eagle)

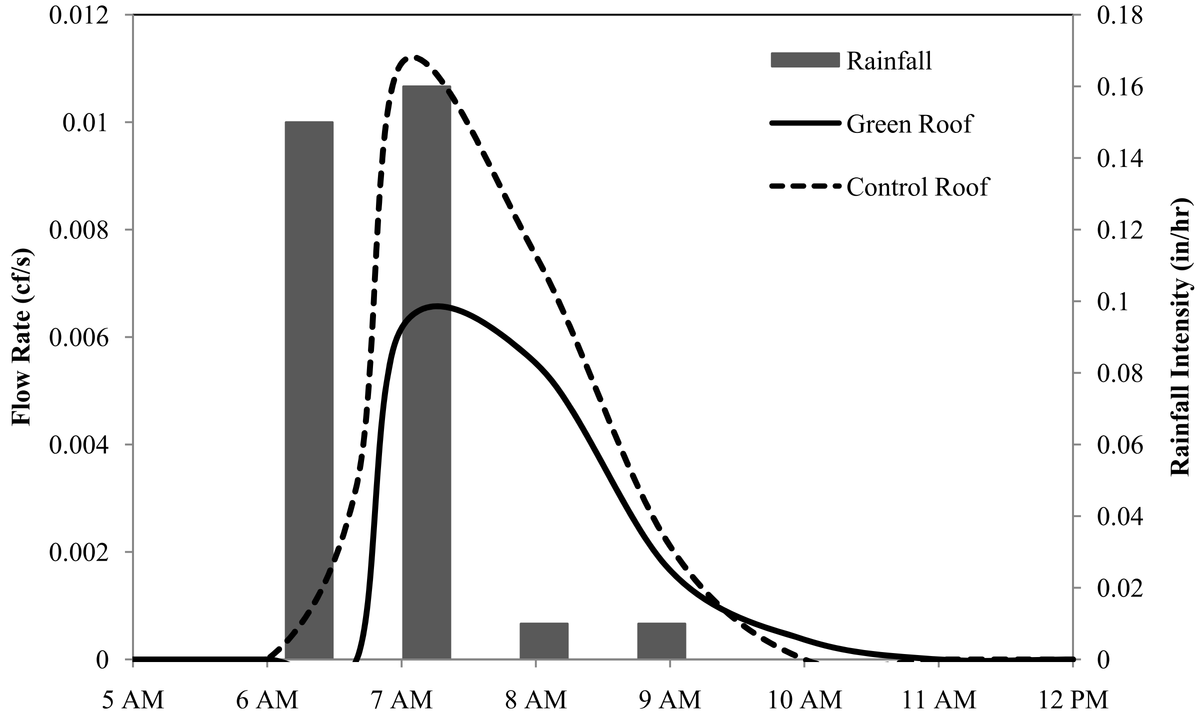


Figure 232. Runoff Flow Rates and Rainfall intensity – March 29, 2009 Storm (Giant Eagle)

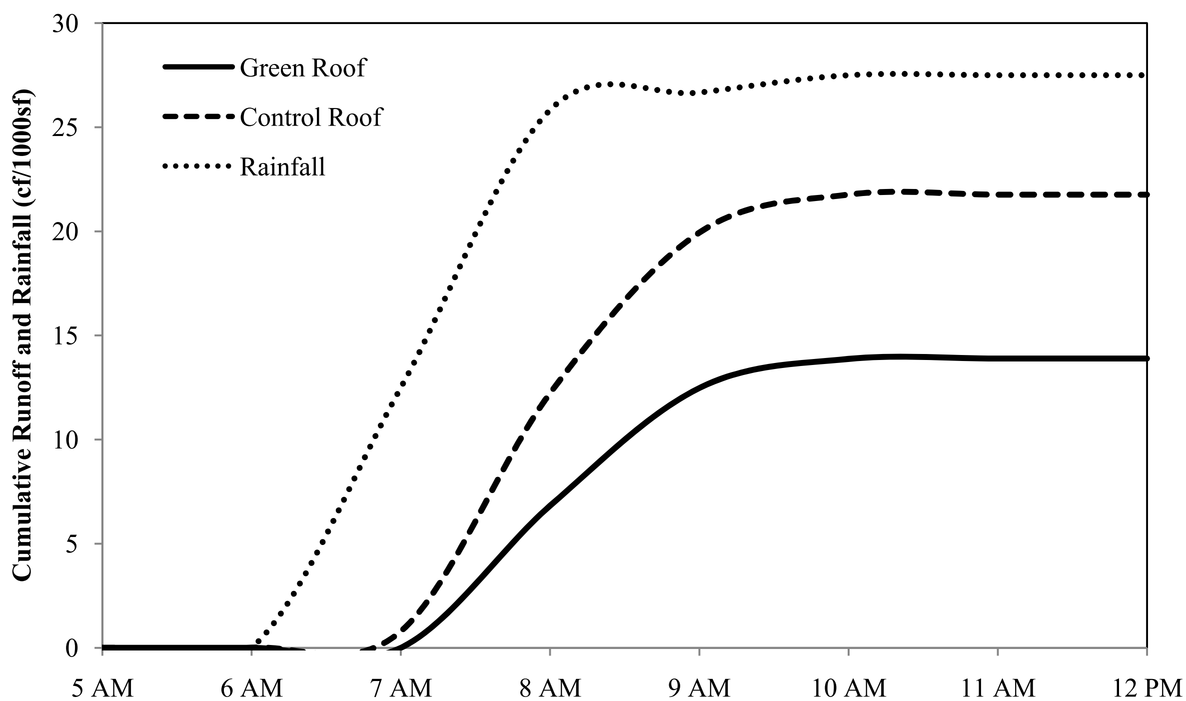


Figure 233. Runoff and Rainfall Volumes – March 29, 2009 Storm (Giant Eagle)

APPENDIX B

TEMPERATURE PROFILE

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 10. 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 10.

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 11. 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 **Error! Reference source not found.**.

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 12. 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 12.

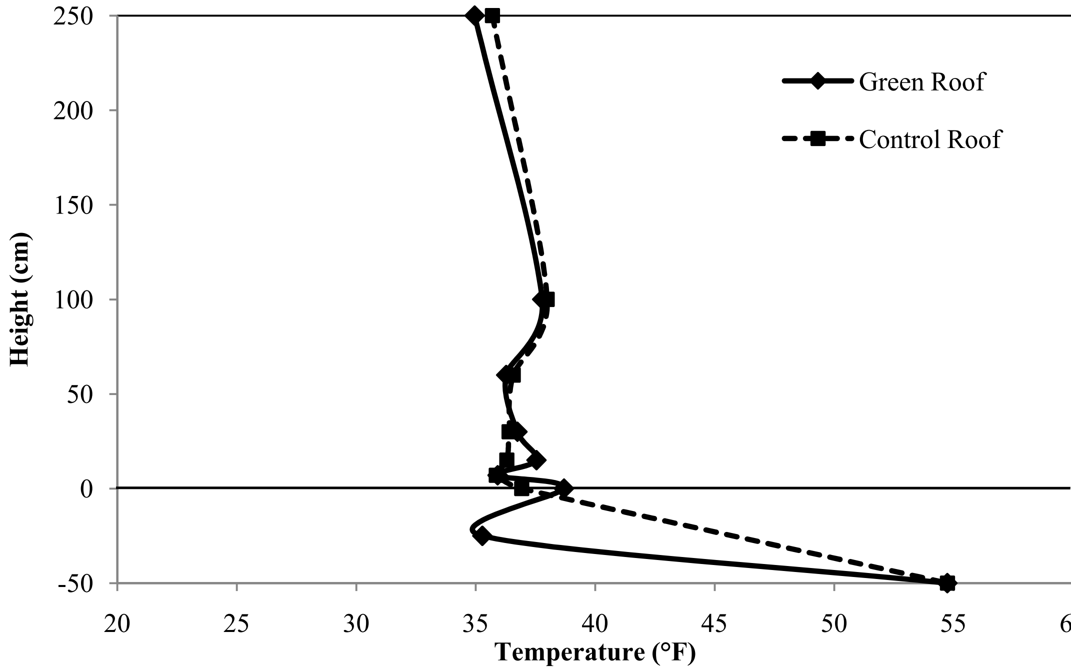
Δt = temperature at soil surface – temperature below (green) roof deck

Table 13. Night-time temperature data of soil surface and below roof deck

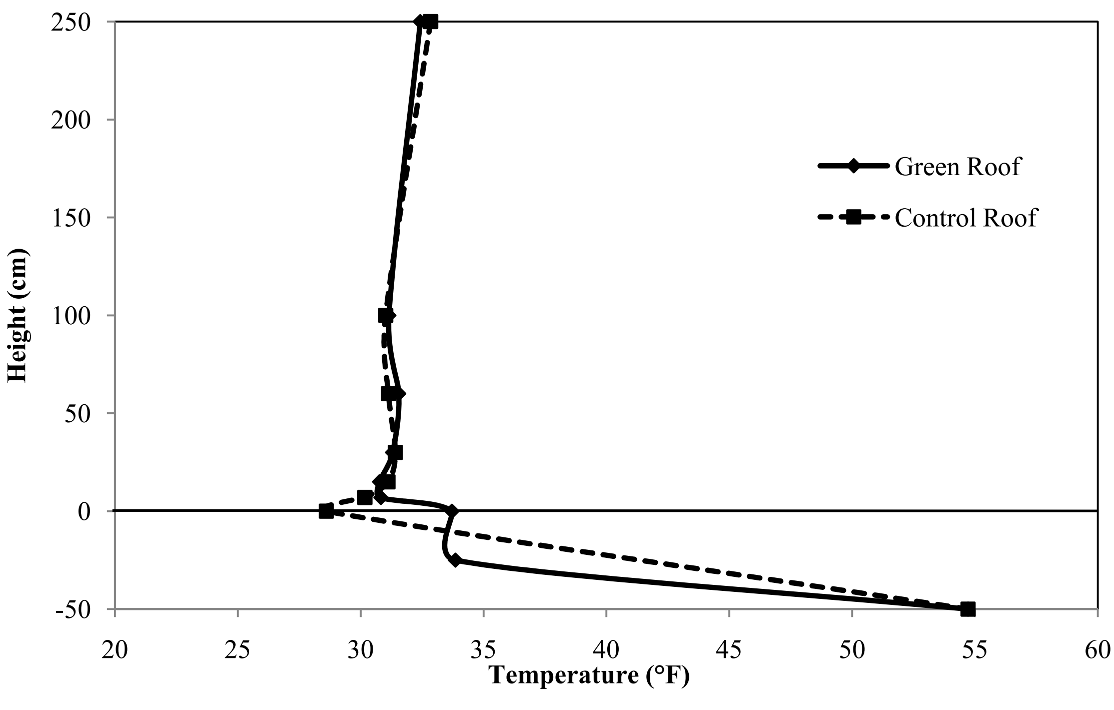
Month	Homestead *(thin roof)*			Giant Eagle (*thick roof)*		
	Temperature at soil surface	Temperature below (green) roof deck	Δt	Temperature at soil surface	Temperature below (green) roof deck	Δt
Jan	22.3	54.6	-32.3	30.0	58.5	-28.5
Feb	33.7	54.7	-21.0	29.4	61.2	-31.8
Mar	33.5	55.8	-22.3	38.0	63.3	-25.3
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 13.

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

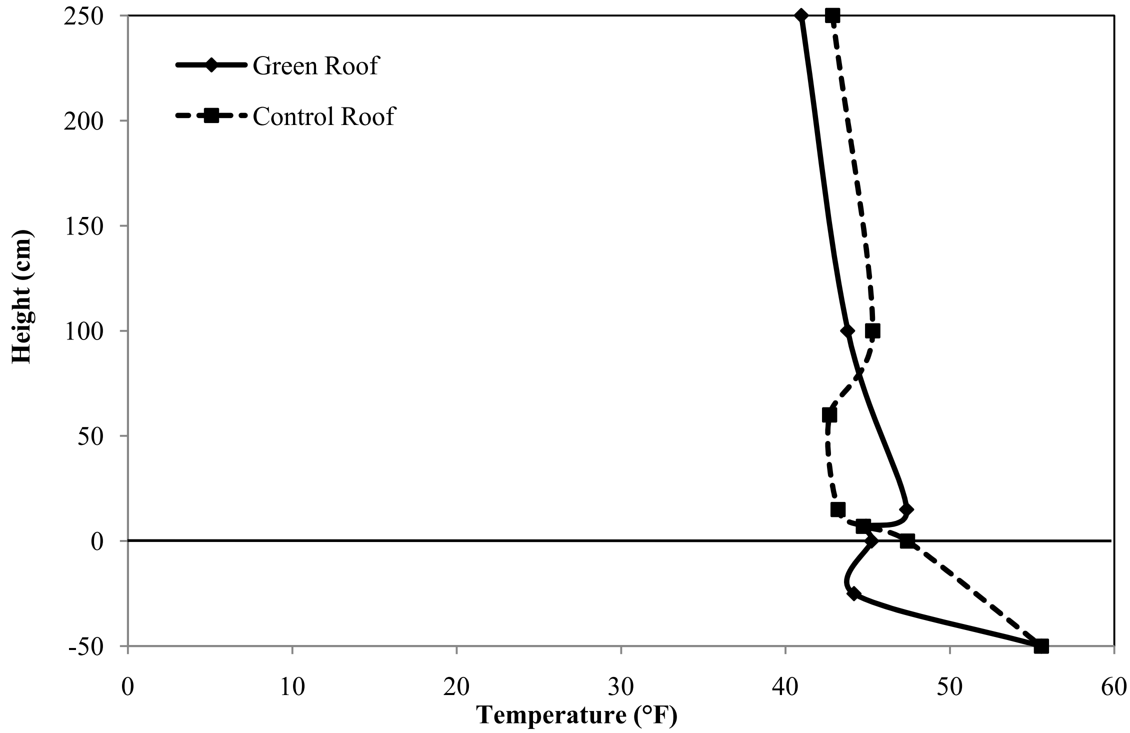


(a) Day-time temperature profile

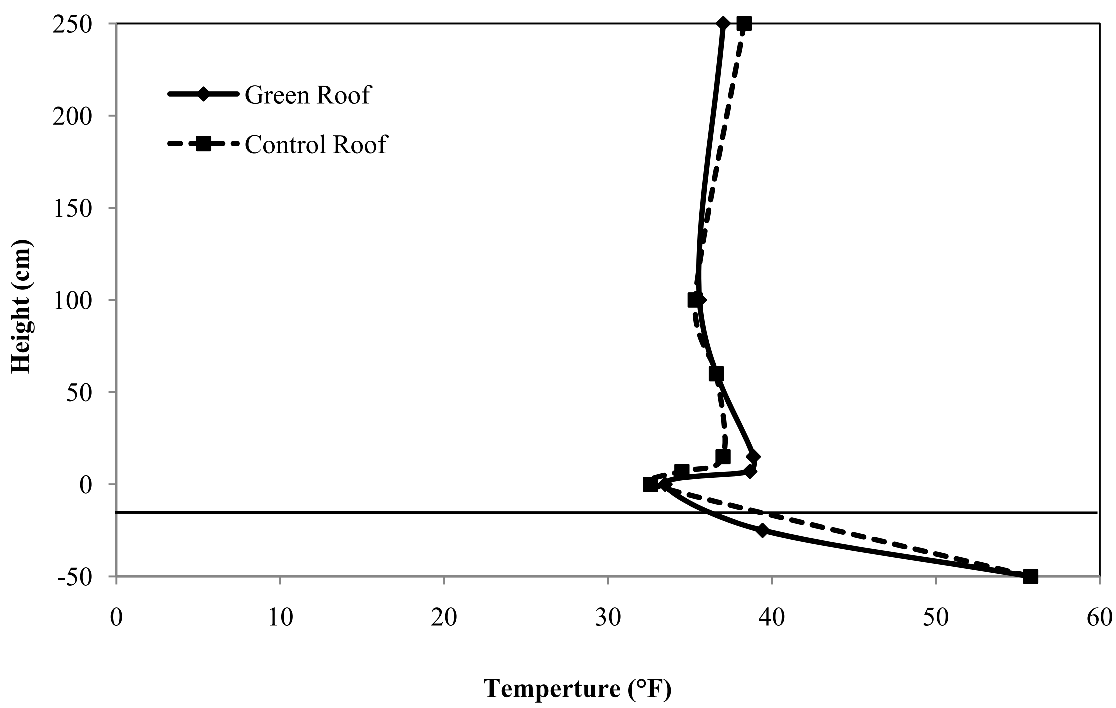


(b) Night-time temperature profile

Figure 234. February, 2008 temperature profile at Homestead

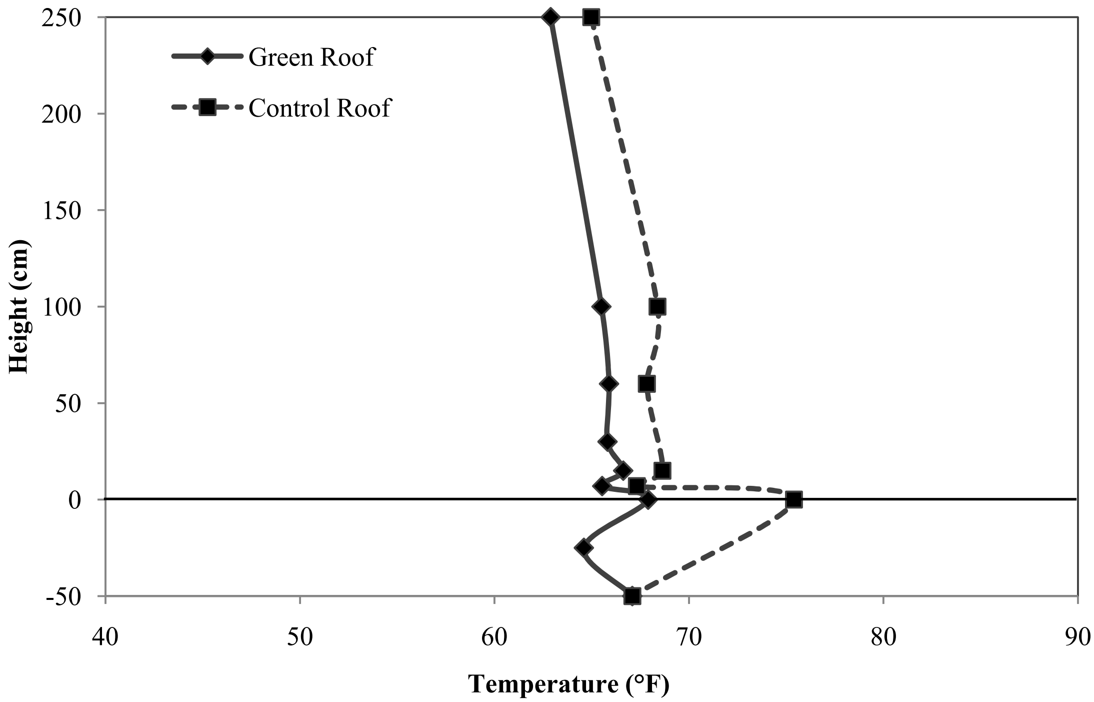


(a) Day-time temperature profile

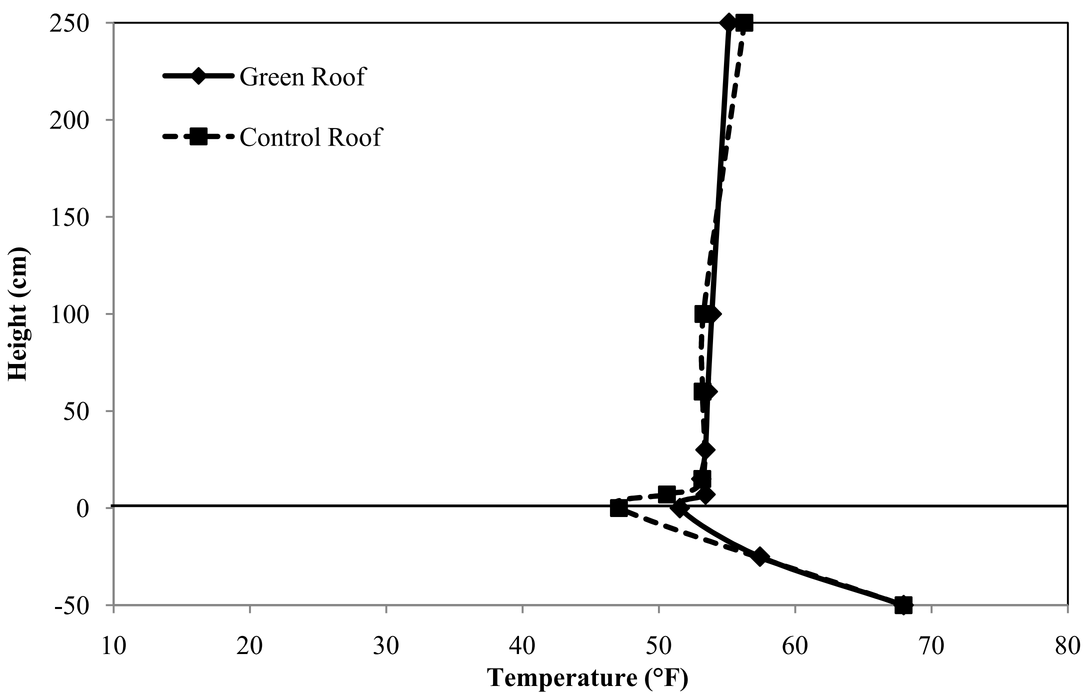


(b) Night-time temperature profile

Figure 235. March, 2008 temperature profile at Homestead

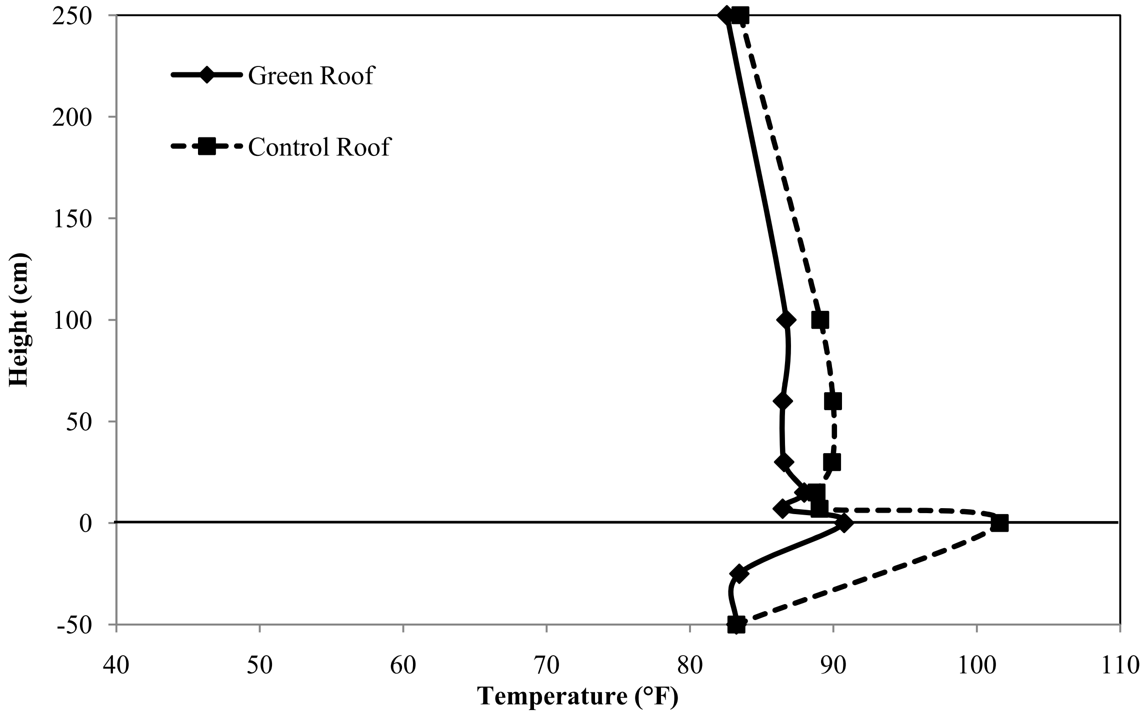


(a) Day-time temperature profile

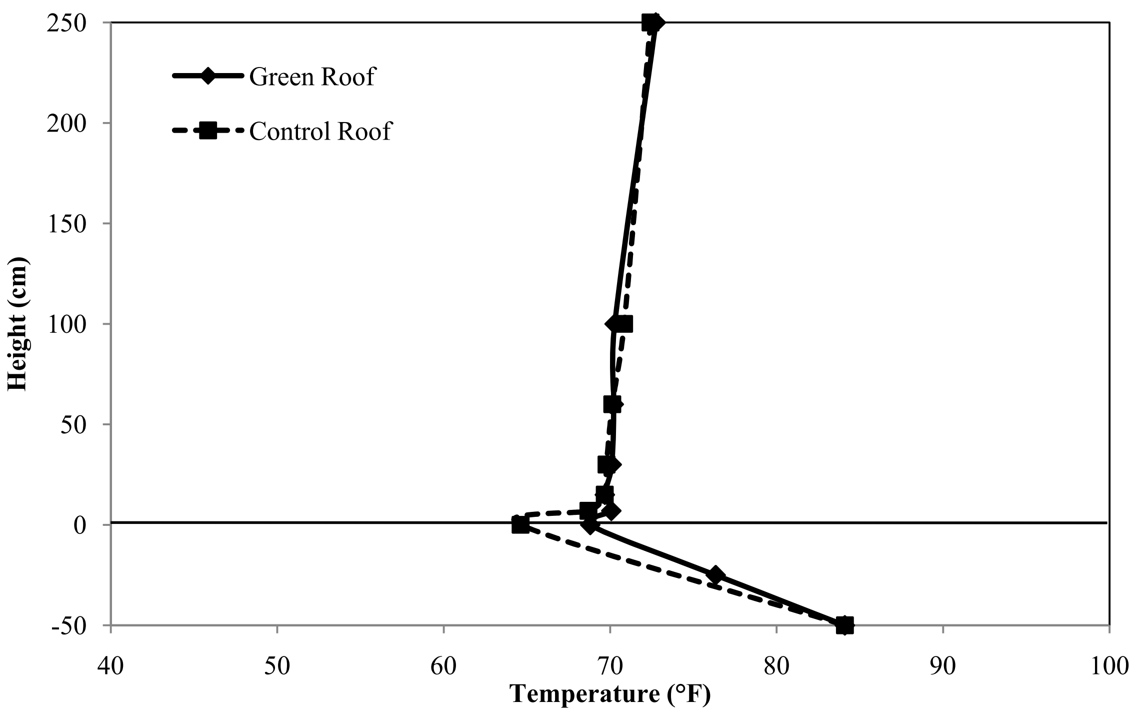


(b) Night-time temperature profile

Figure 236. May, 2008 temperature profile at Homestead

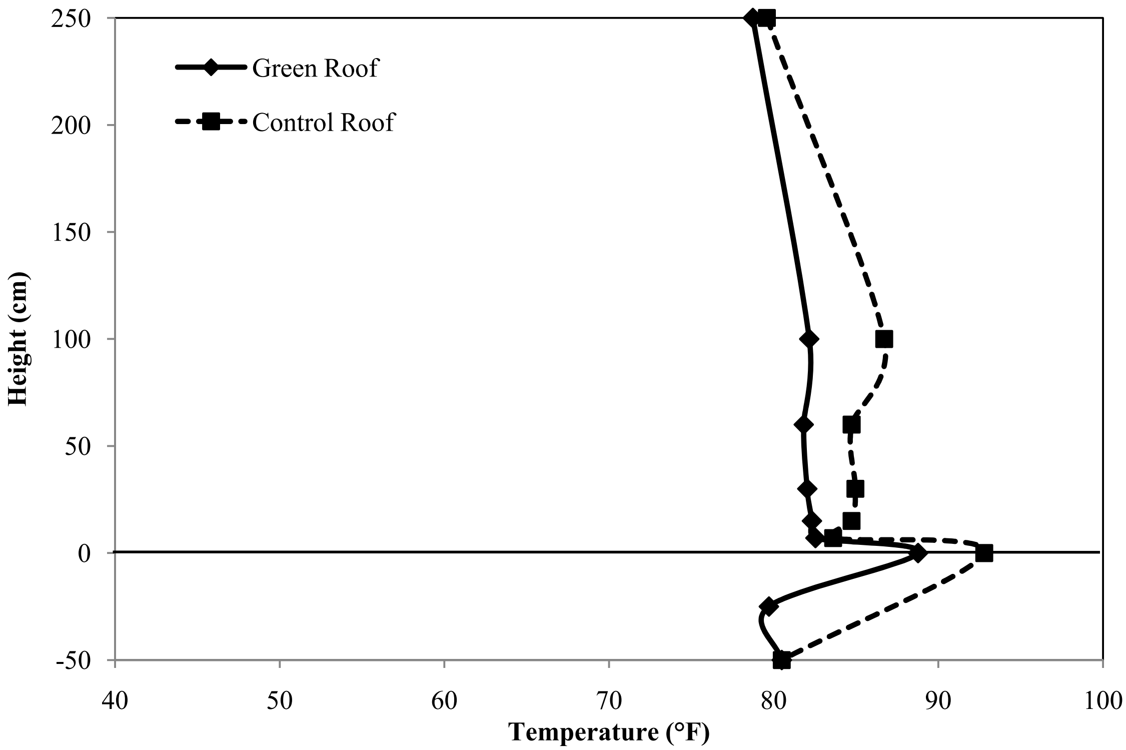


(a) Day-time temperature profile

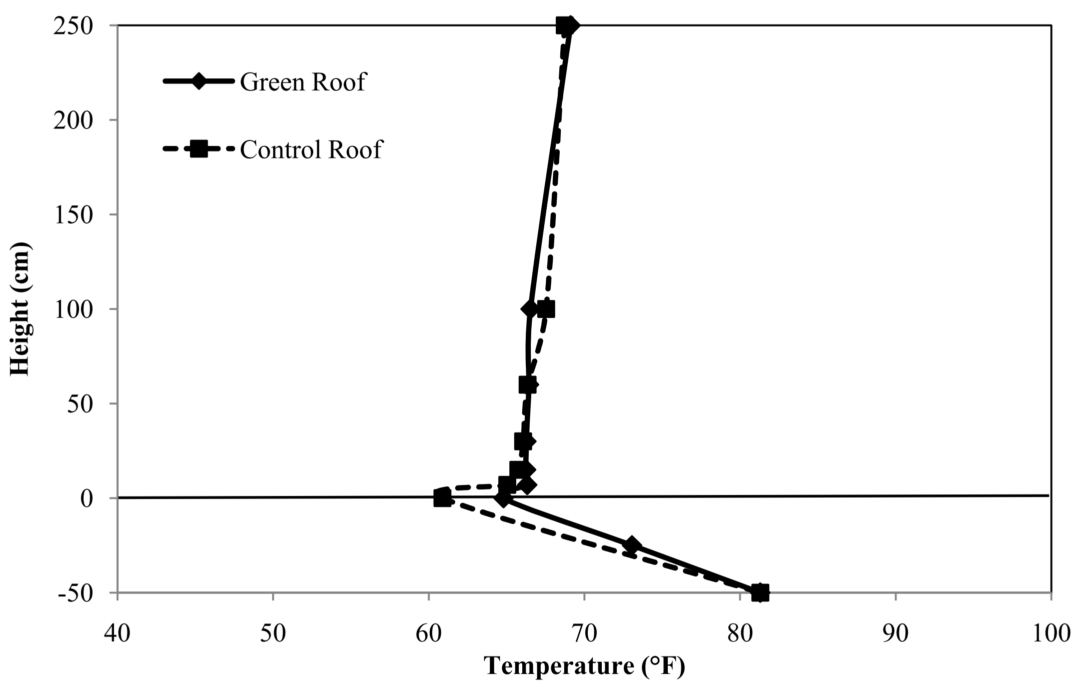


(b) Night-time temperature profile

Figure 237. July, 2008 temperature profile at Homestead

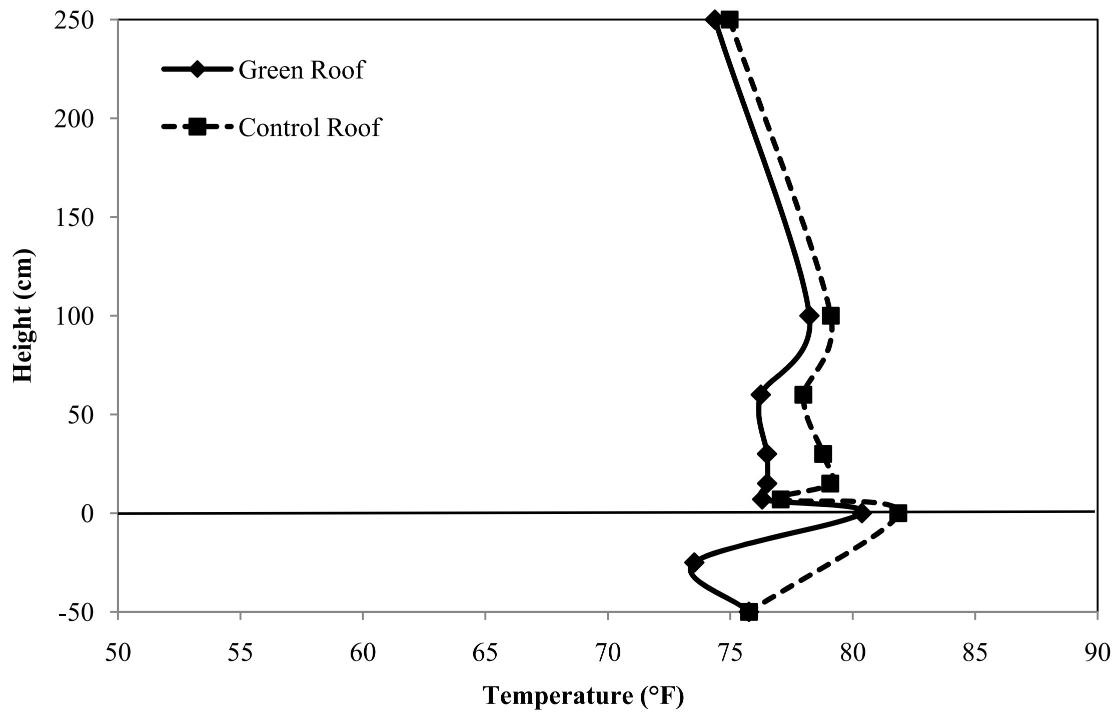


(a) Day-time temperature profile

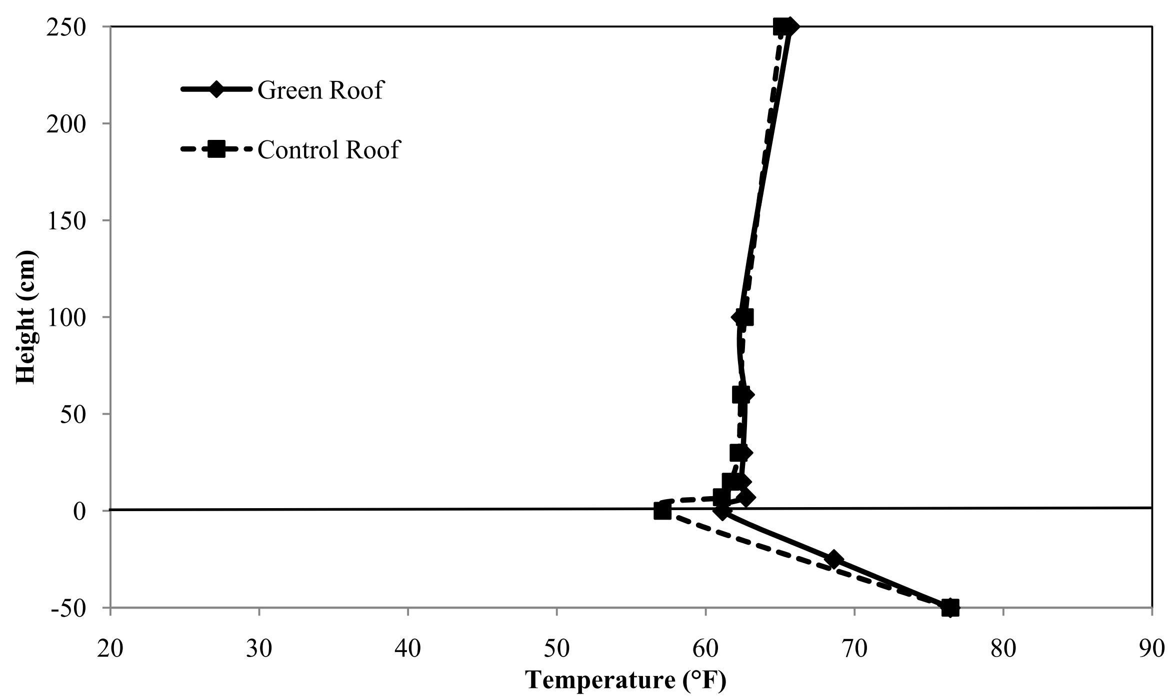


(b) Night-time temperature profile

Figure 238. August, 2008 temperature profile at Homestead

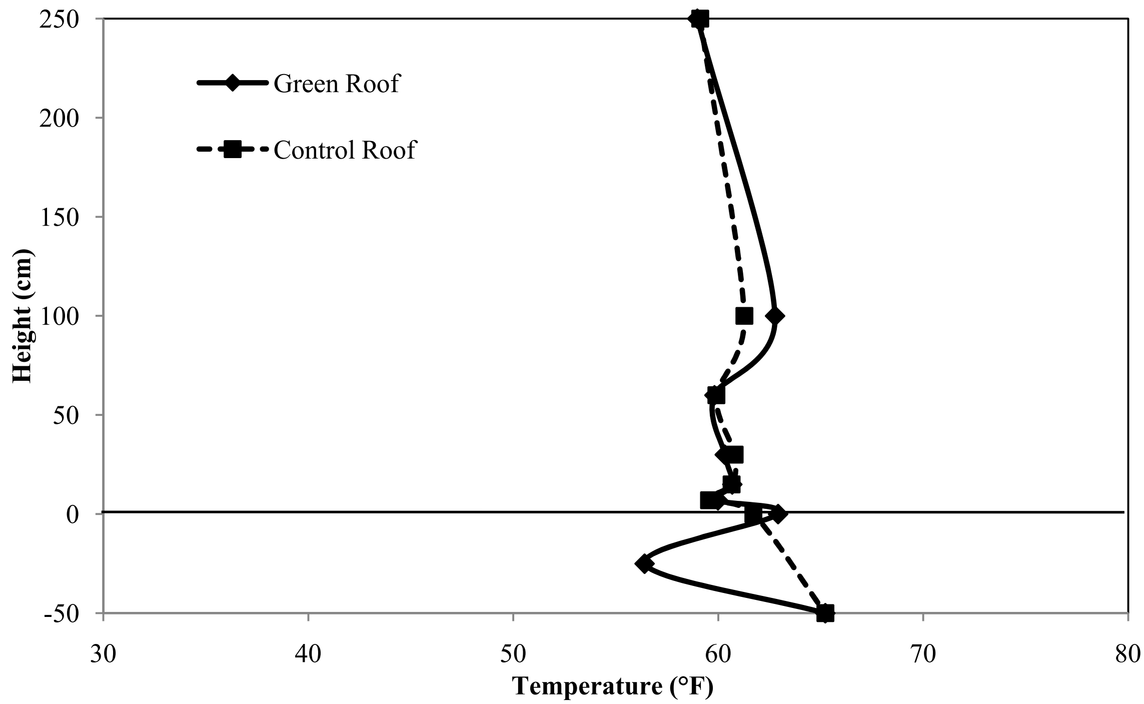


(a) Day-time temperature profile

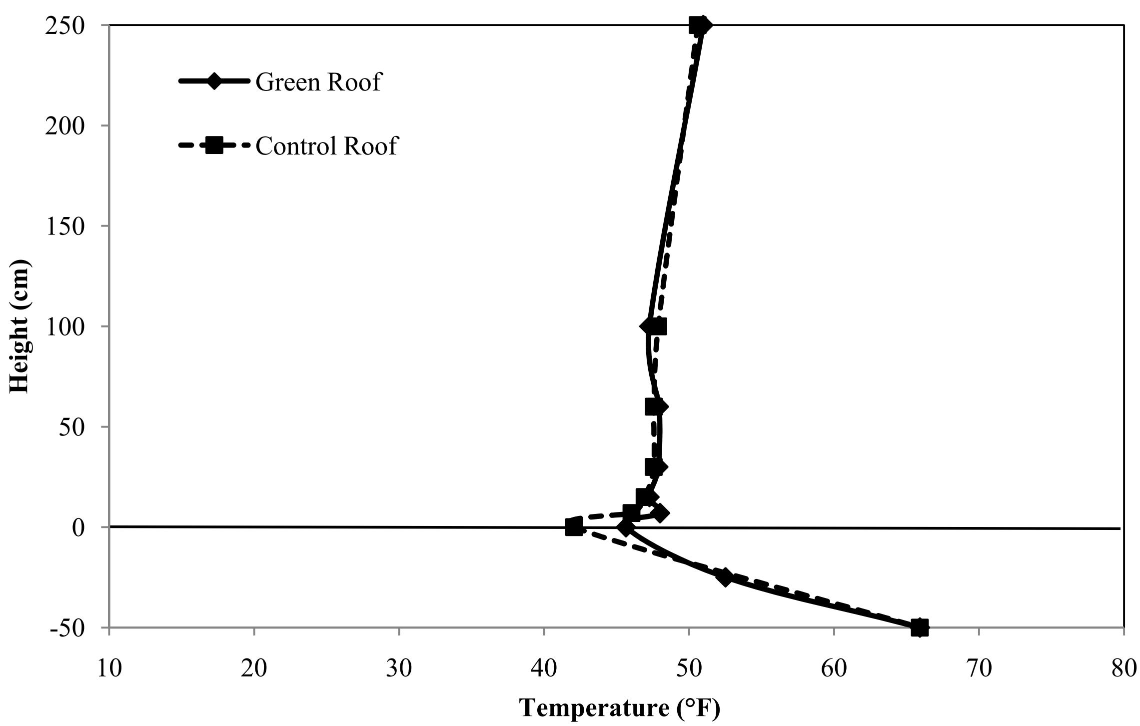


(b) Night-time temperature profile

Figure 239. September, 2008 temperature profile at Homestead

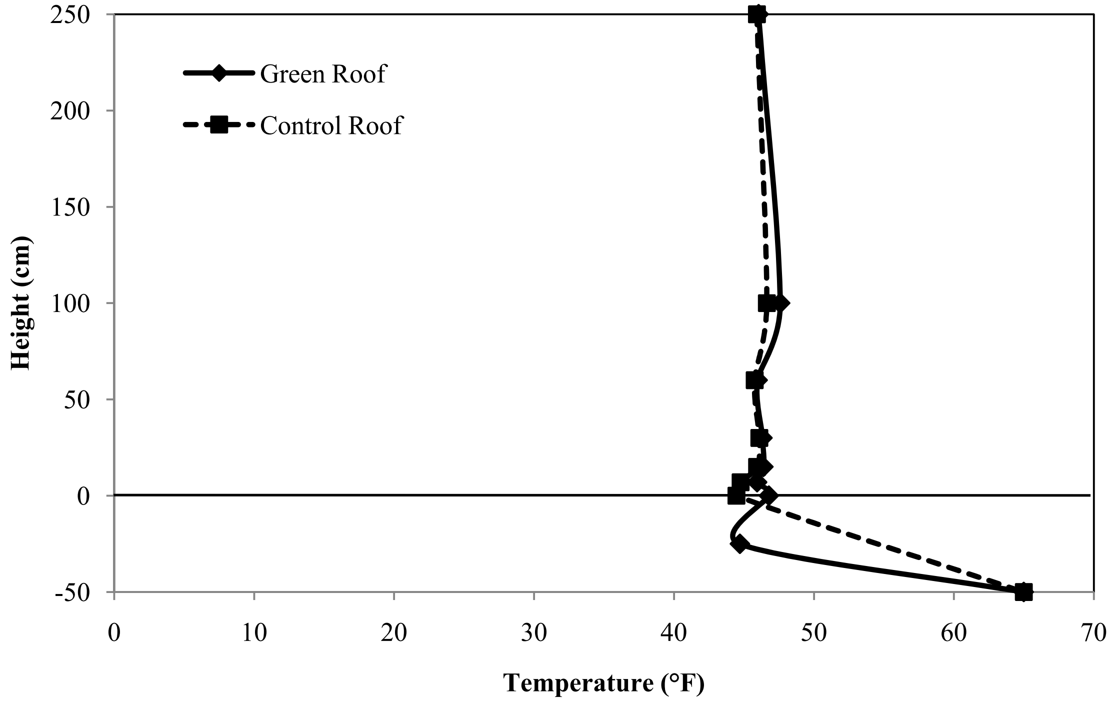


(a) Day-time temperature profile

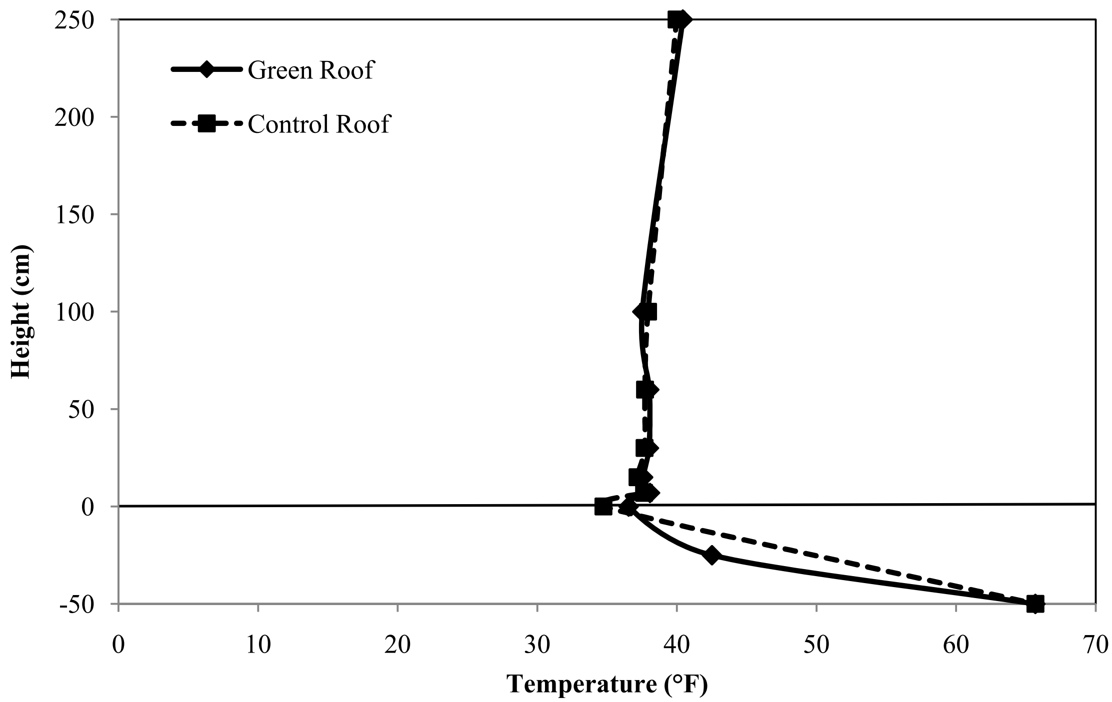


(b) Night-time temperature profile

Figure 240. October, 2008 temperature profile at Homestead

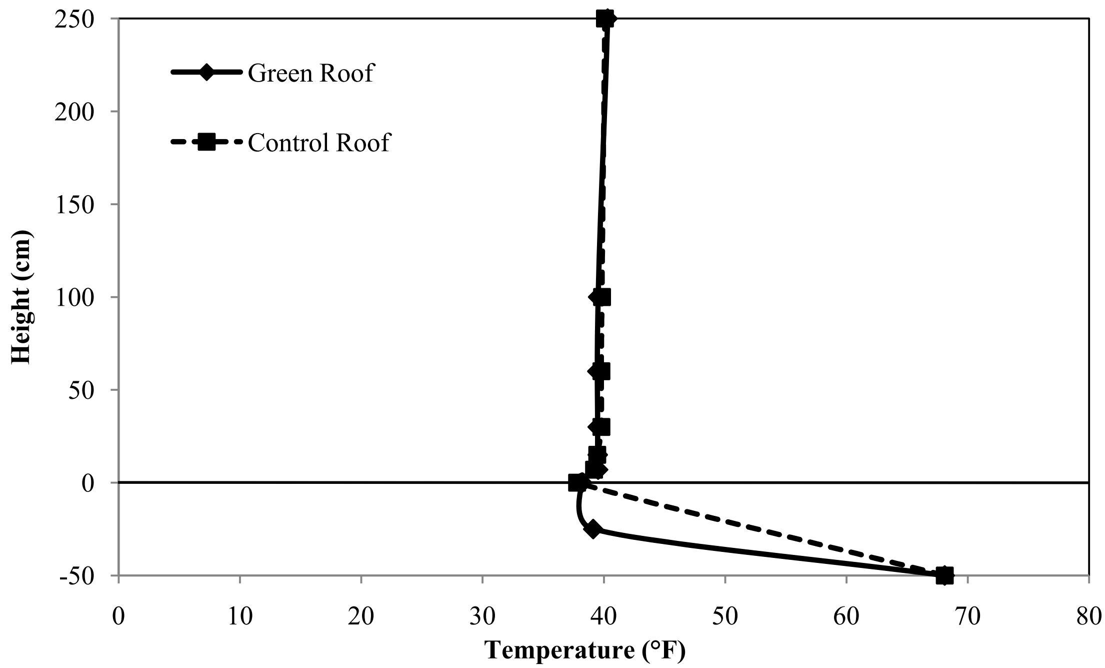


(a) Day-time temperature profile

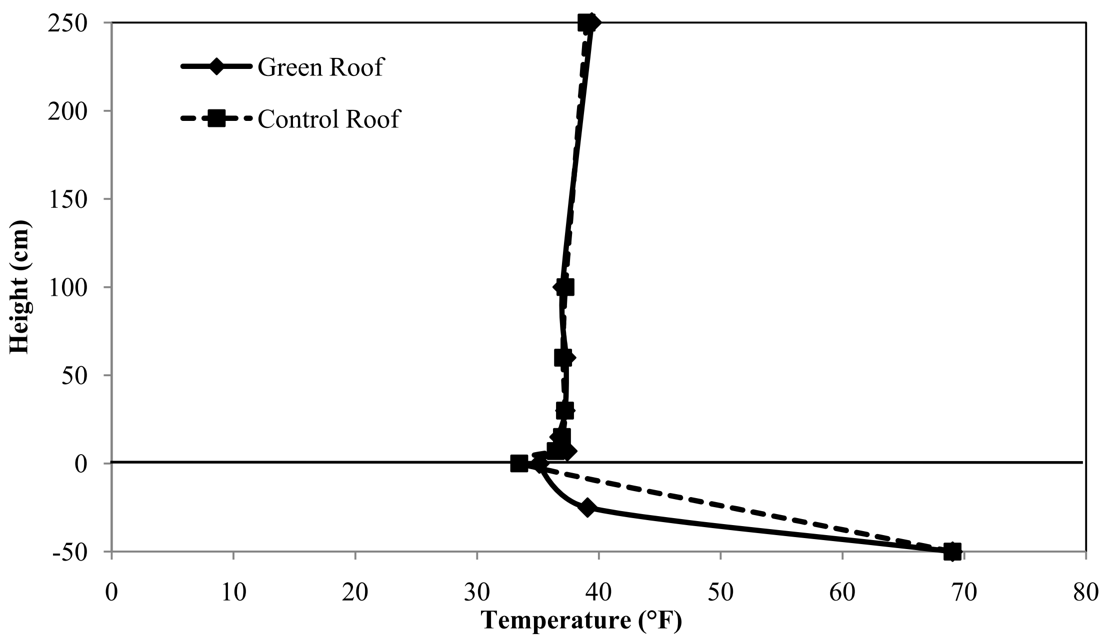


(b) Night-time temperature profile

Figure 241. November, 2008 temperature profile at Homestead



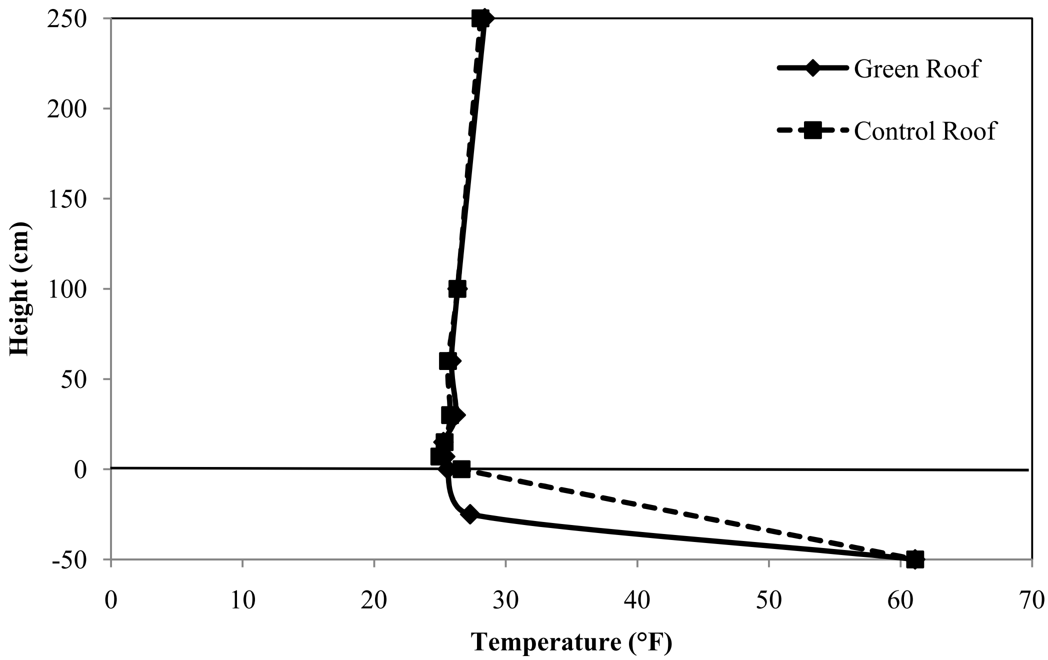
(a) Day-time temperature profile



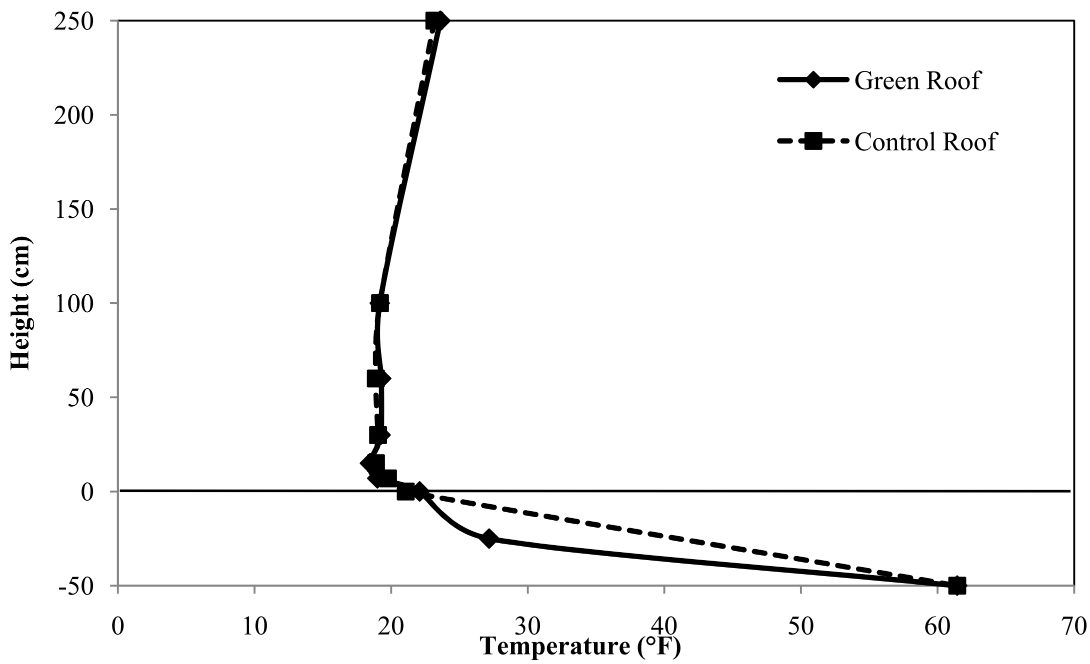
(b) Night-time temperature profile

Figure 242. 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.

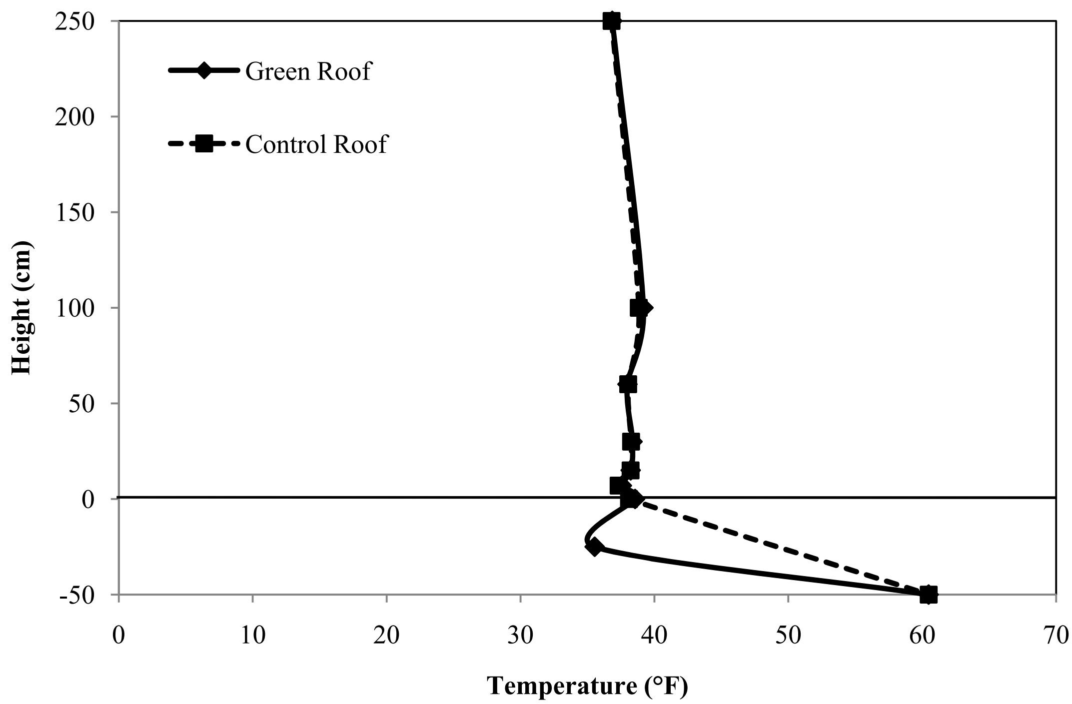


(a) Day-time temperature profile

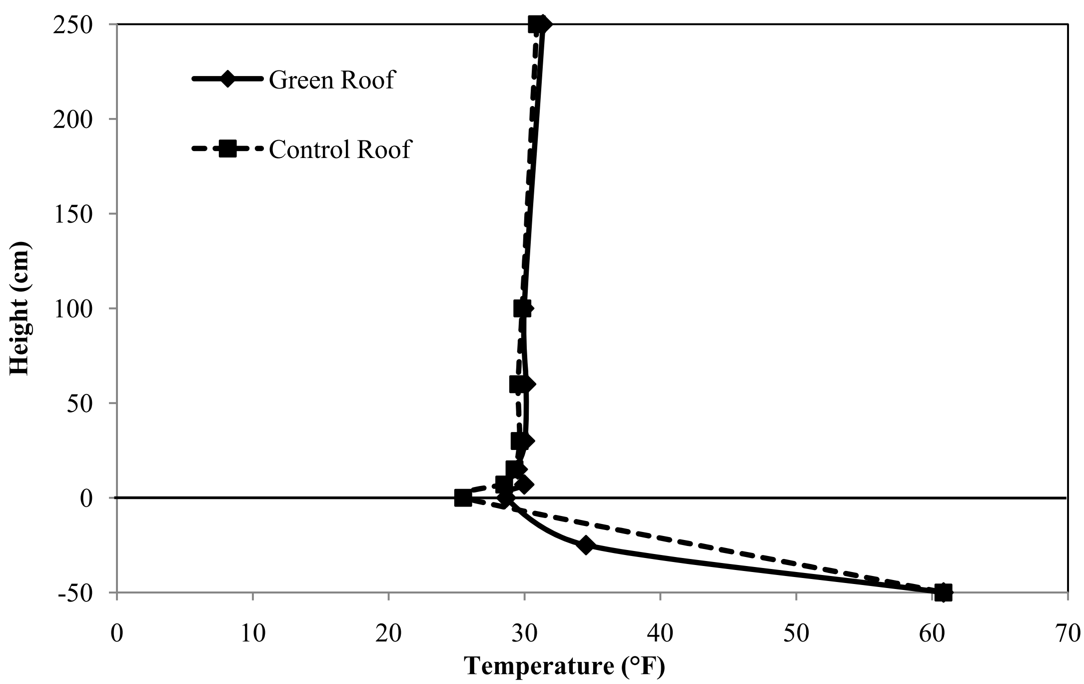


(b) Night-time temperature profile

Figure 243. January, 2009 temperature profile at Homestead

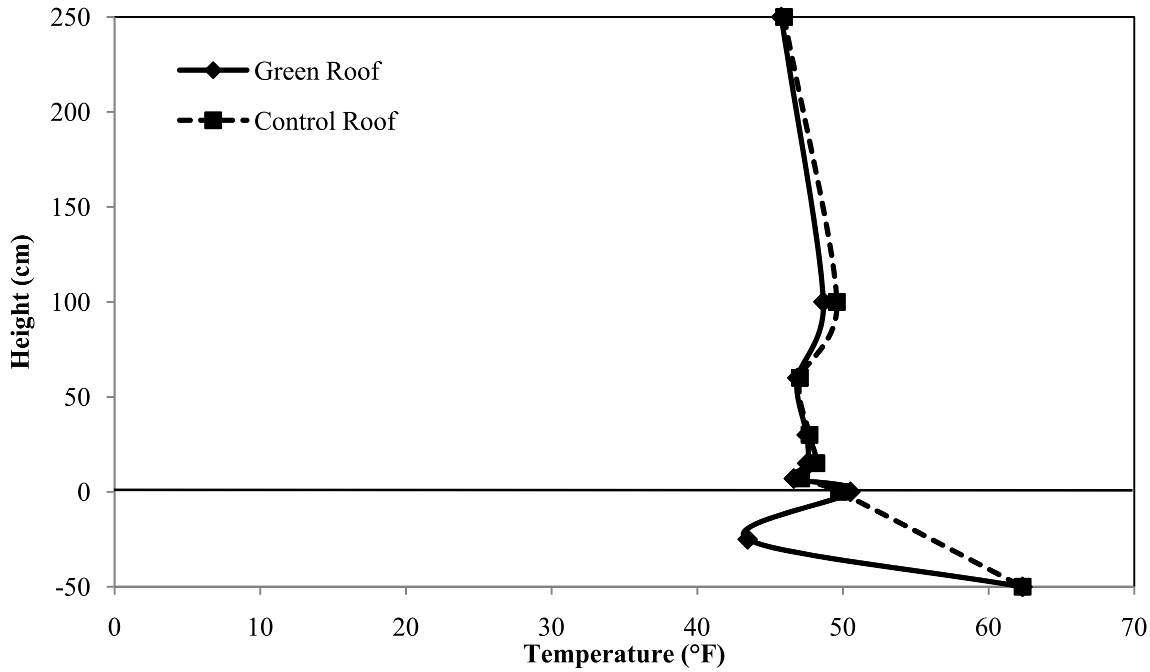


(a) Day-time temperature profile

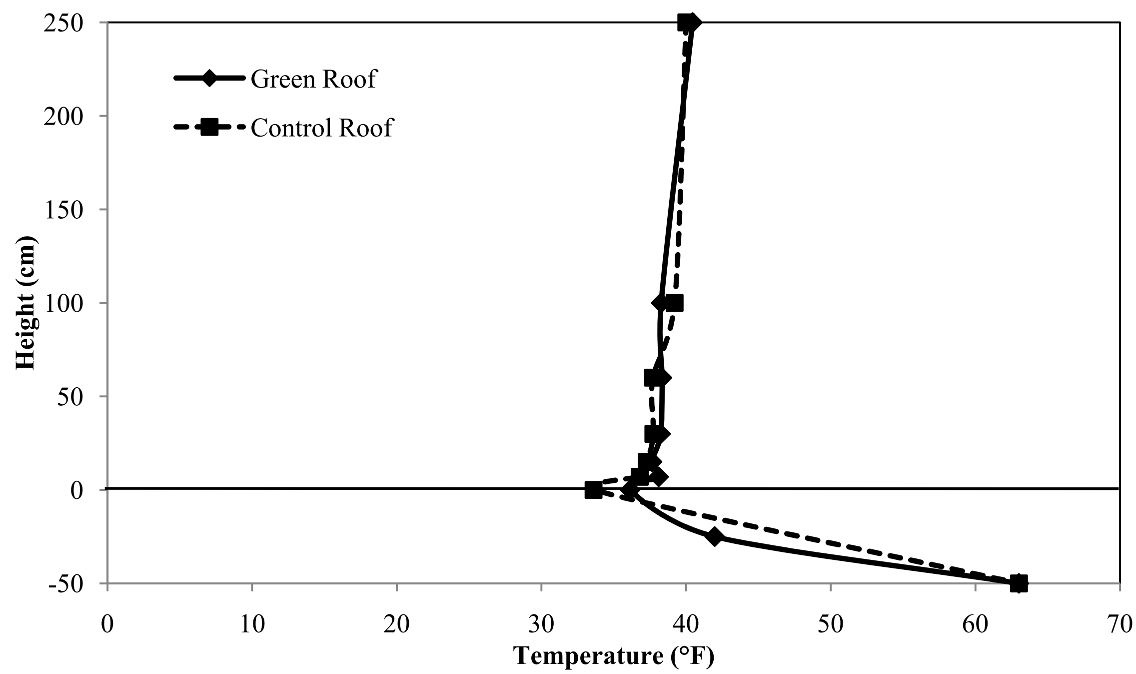


(b) Night-time temperature profile

Figure 244. February, 2009 temperature profile at Homestead



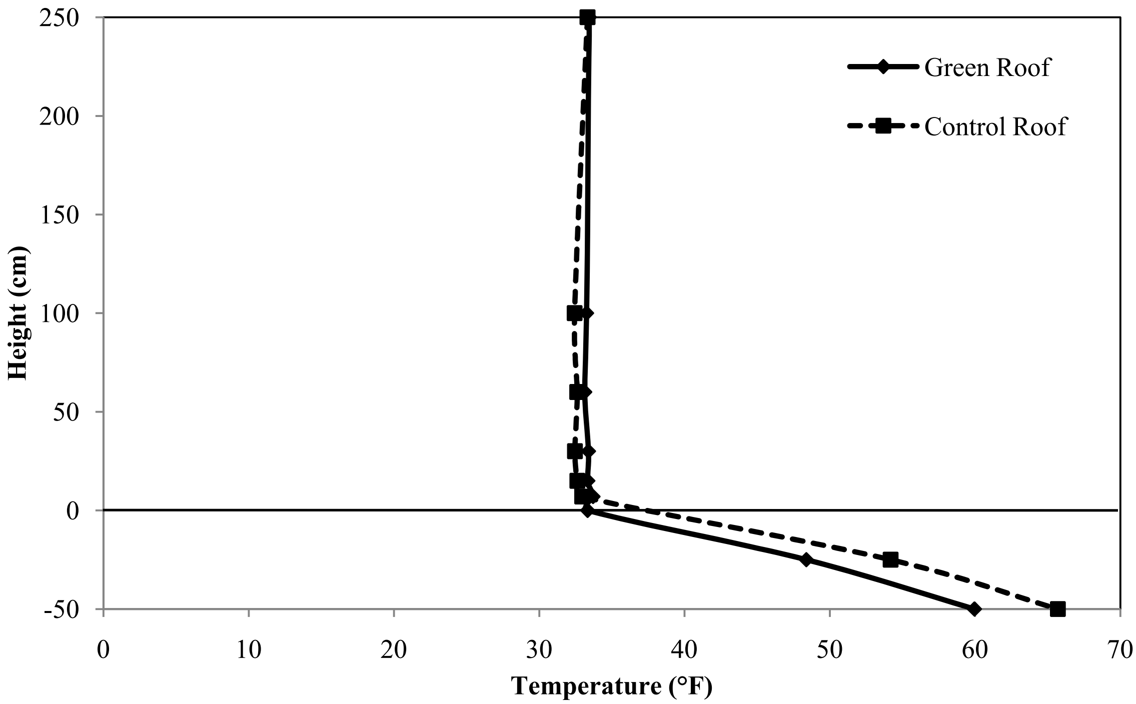
(a) Day-time temperature profile



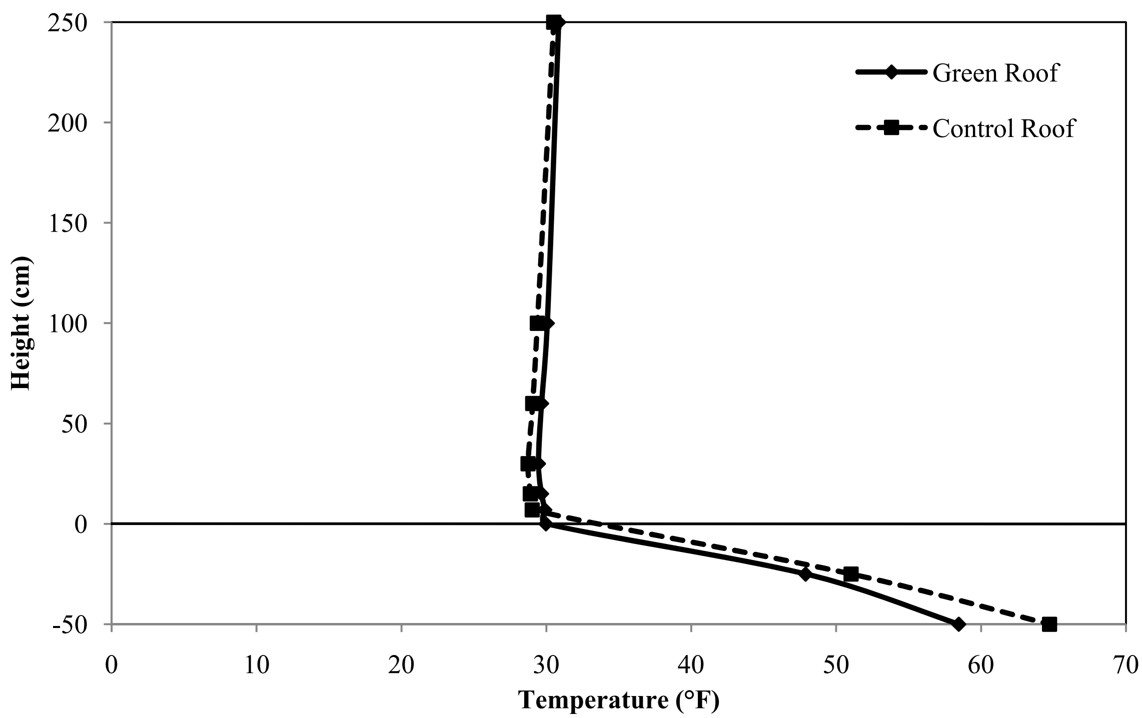
(b) Night-time temperature profile

Figure 245. 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.

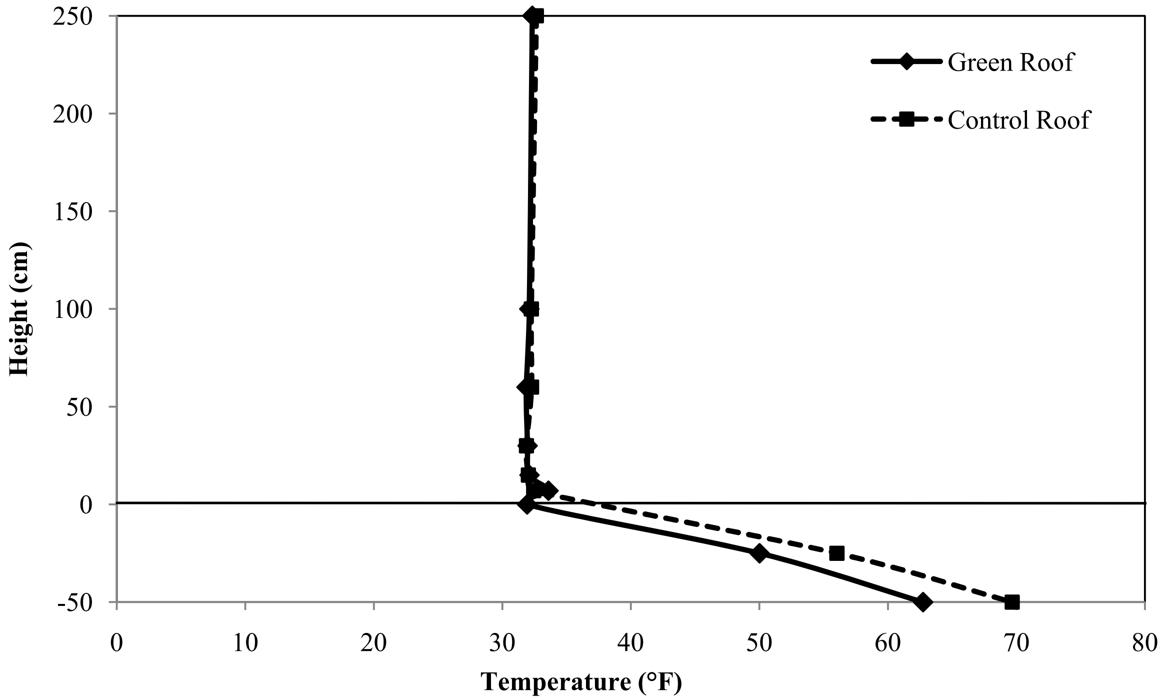


(a) Day-time temperature profile

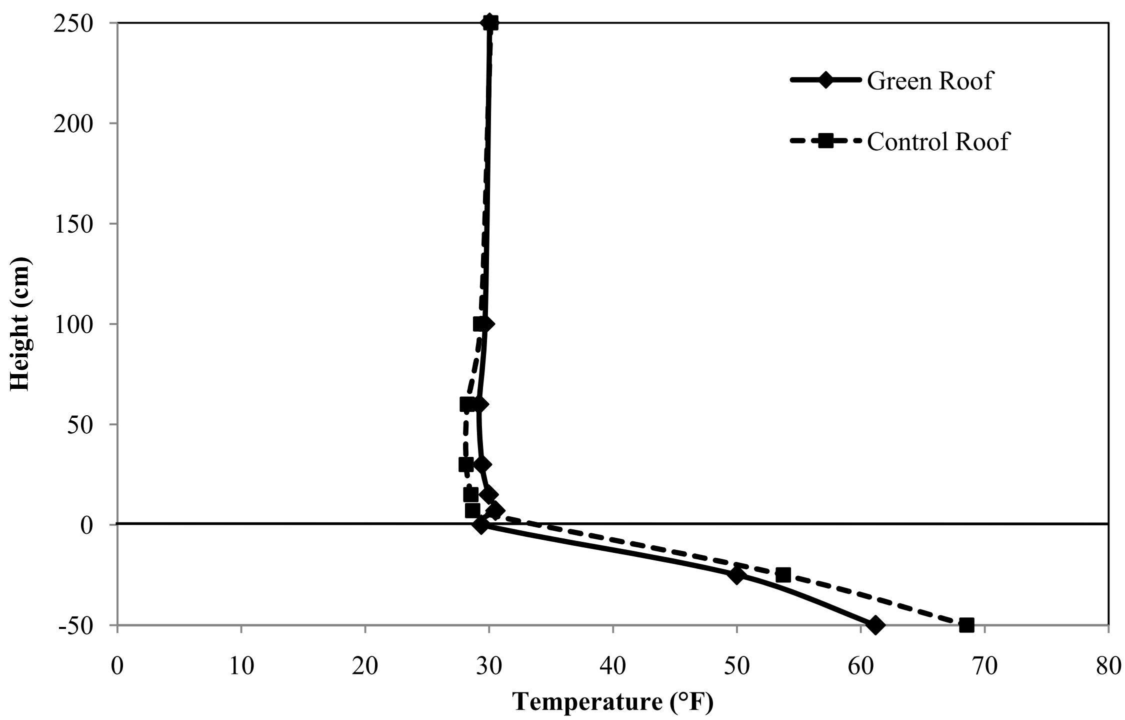


(b) Night-time temperature profile

Figure 246. January, 2008 temperature profile at Giant Eagle

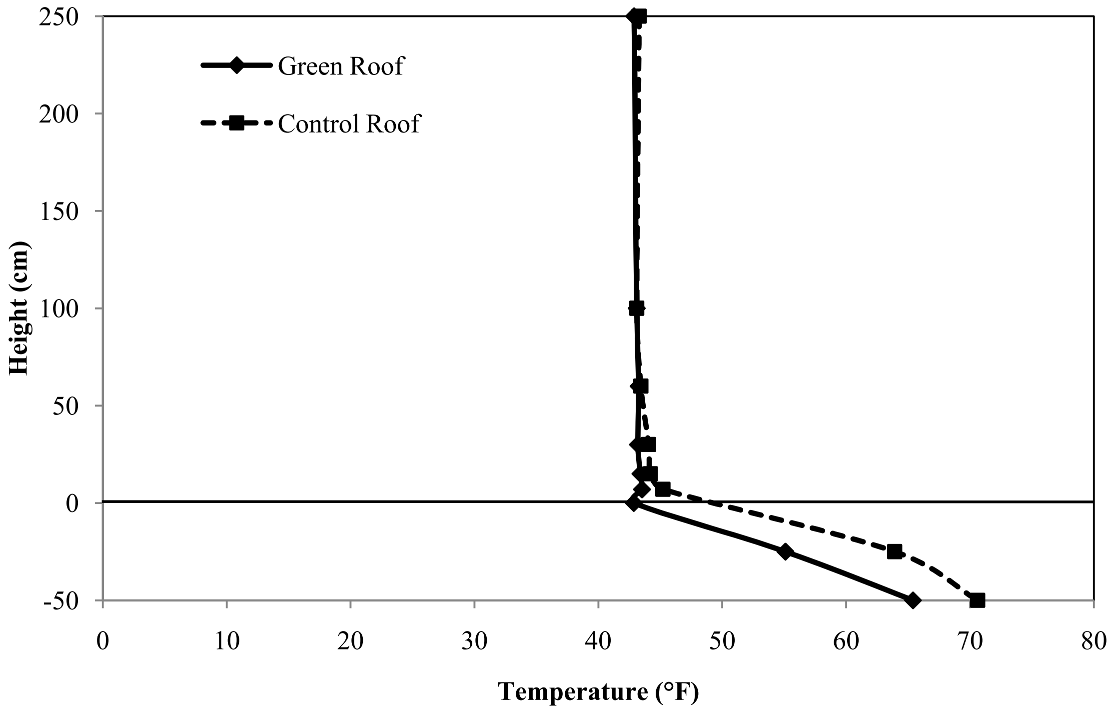


(a) Day-time temperature profile

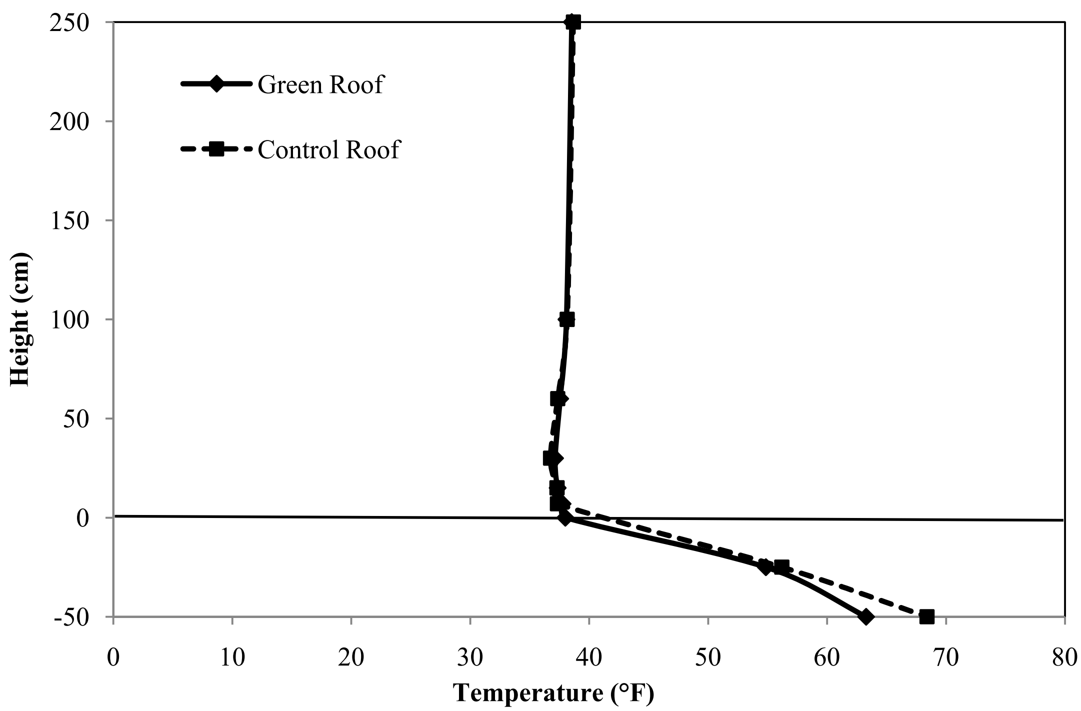


(b) Night-time temperature profile

Figure 247. February, 2008 temperature profile at Giant Eagle

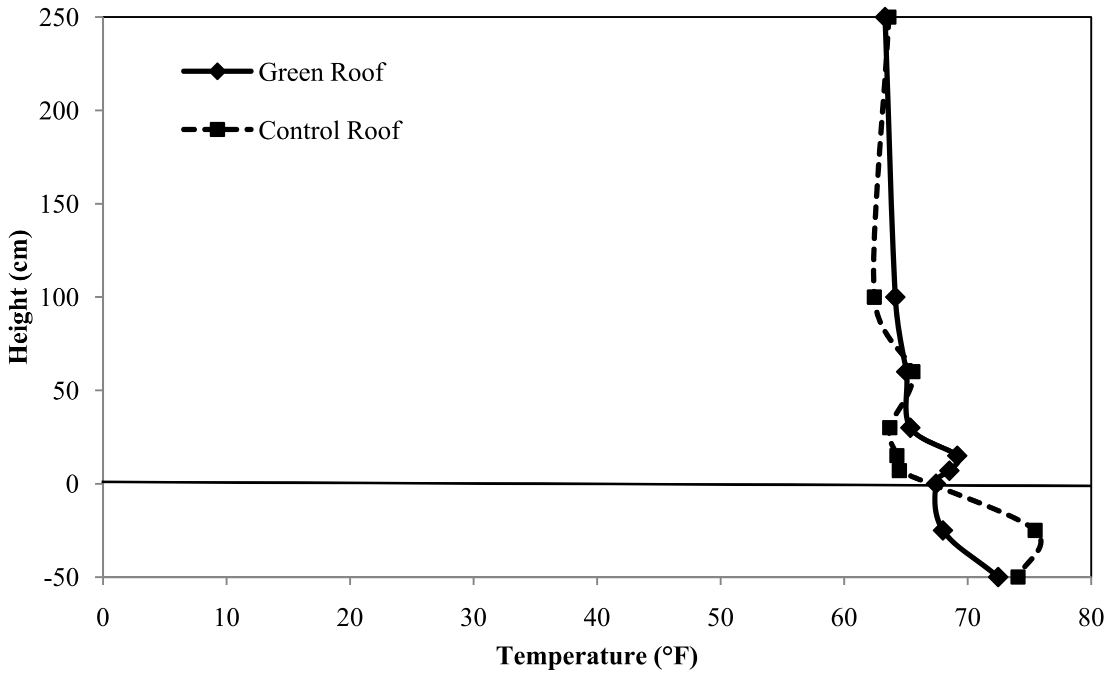


(a) Day-time temperature profile

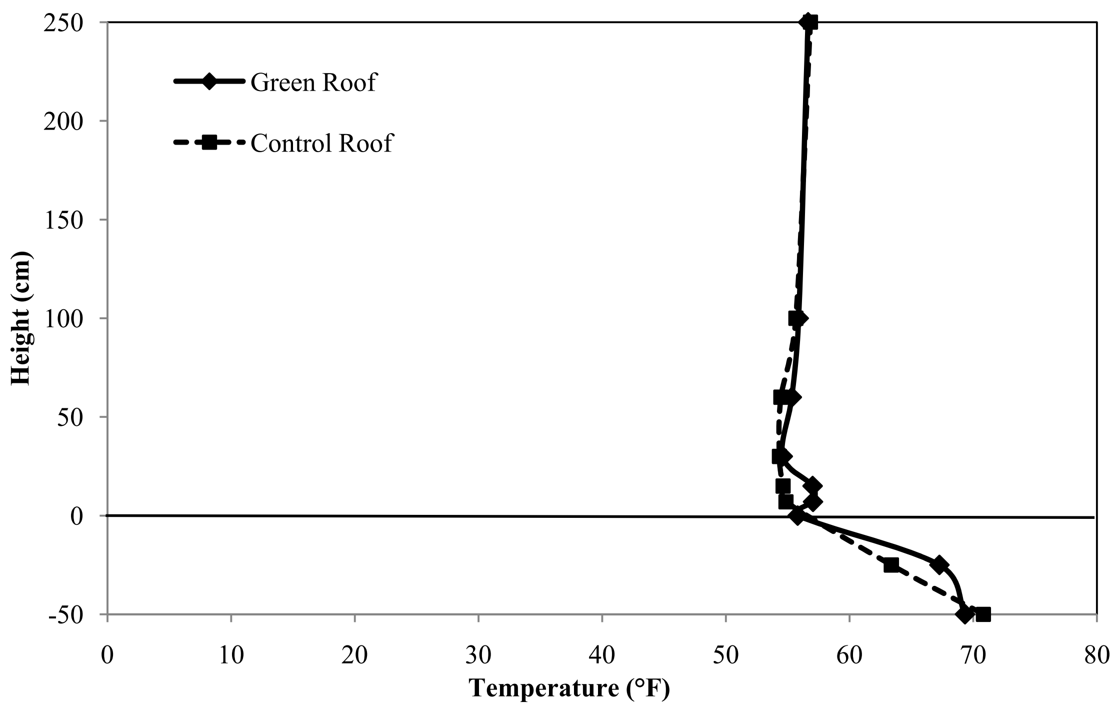


(b) Night-time temperature profile

Figure 248. March, 2008 temperature profile at Giant Eagle

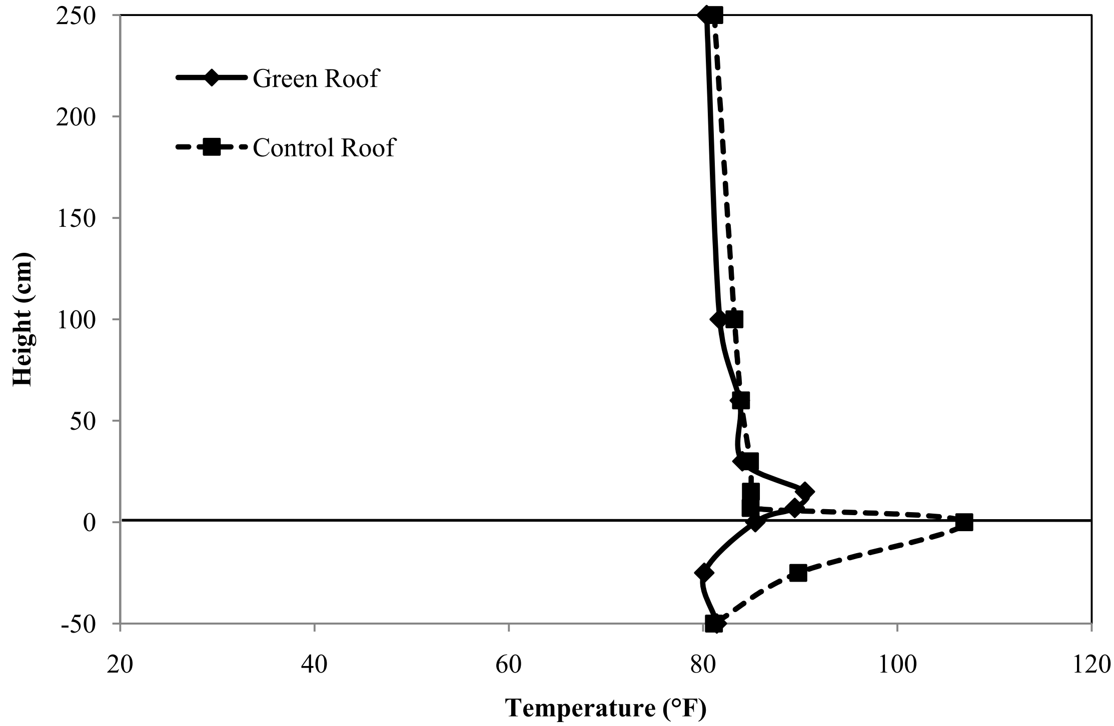


(a) Day-time temperature profile

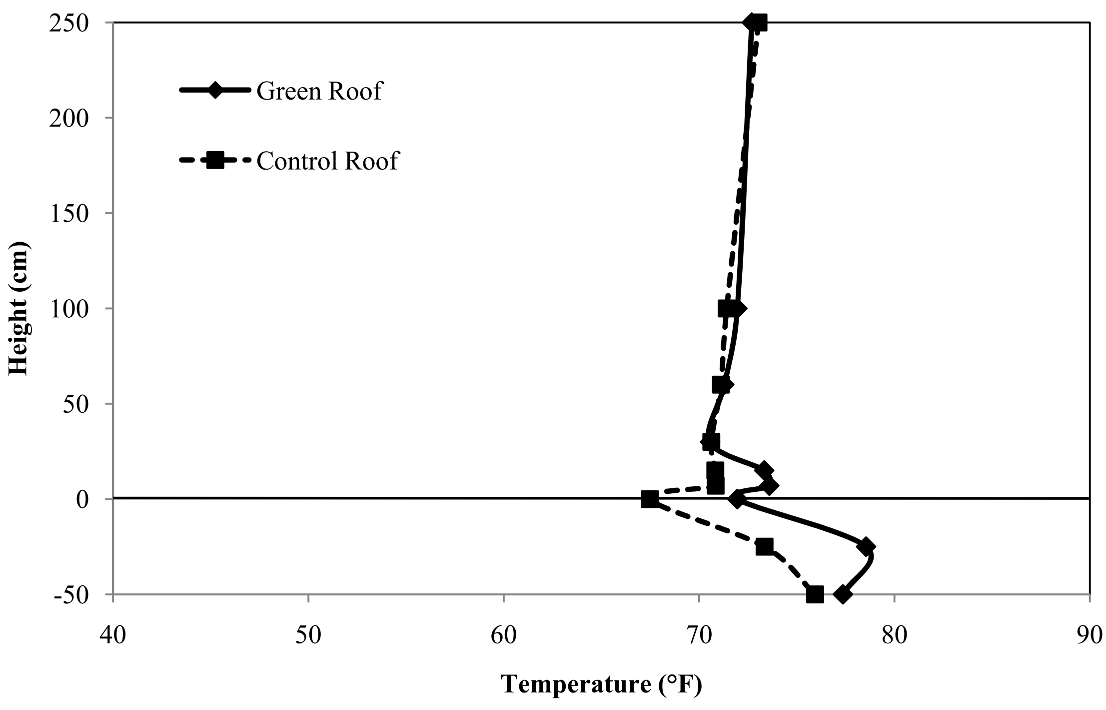


(b) Night-time temperature profile

Figure 249. May, 2008 temperature profile at Giant Eagle

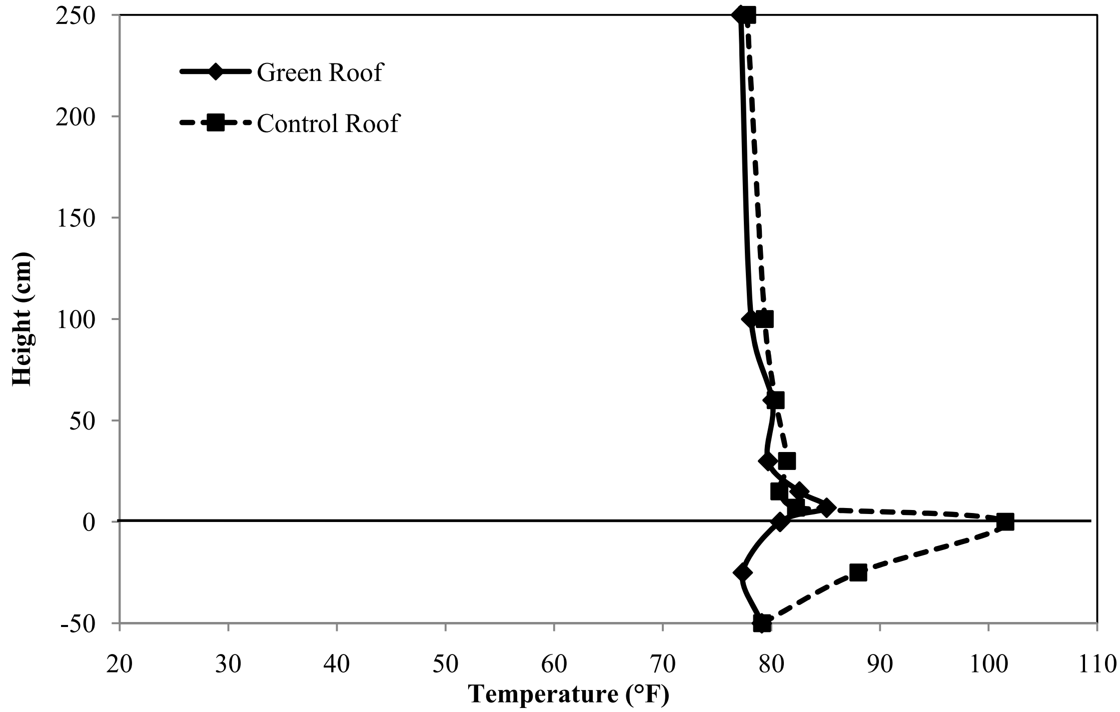


(a) Day-time temperature profile

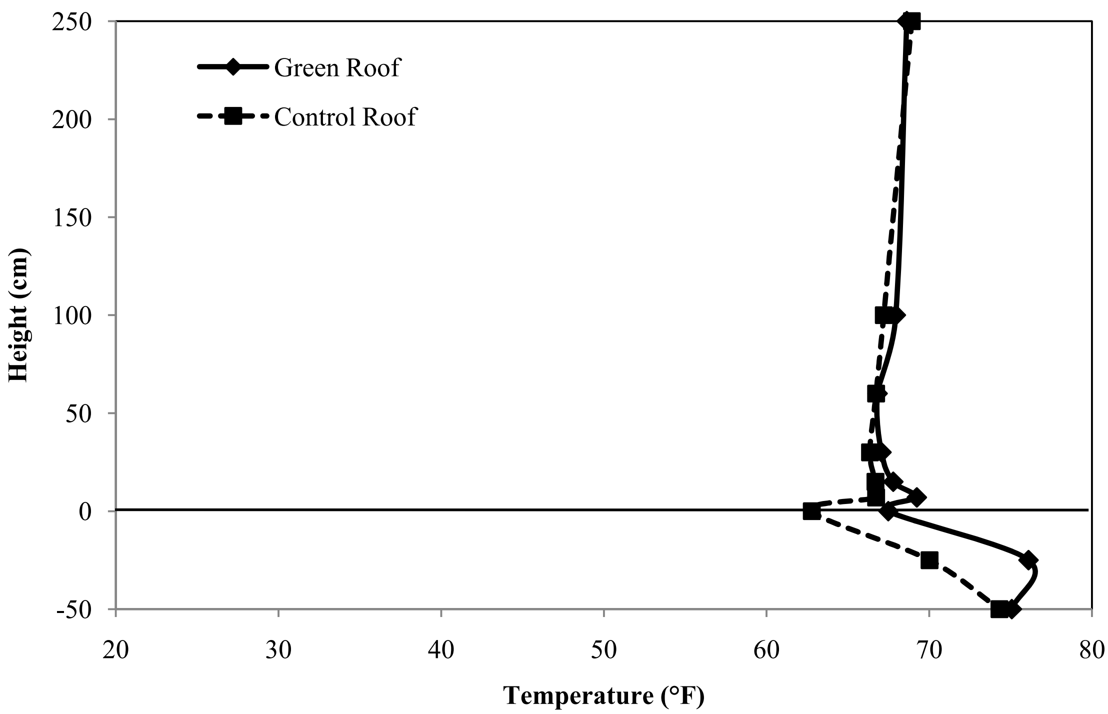


(b) Night-time temperature profile

Figure 250. July, 2008 temperature profile at Giant Eagle

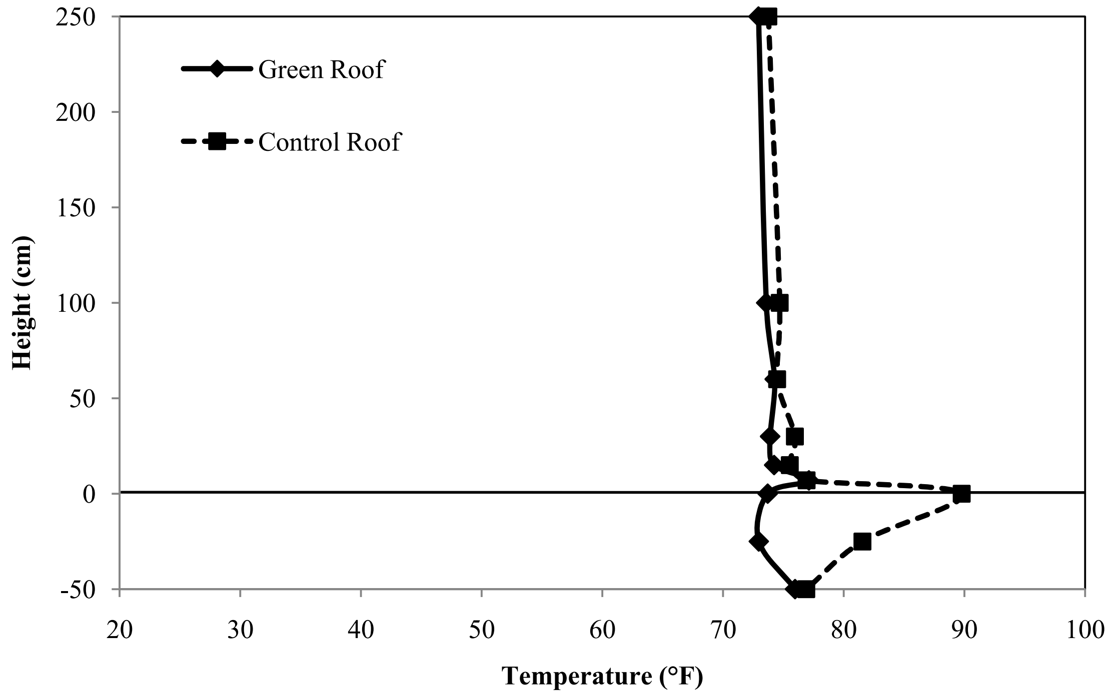


(a) Day-time temperature profile

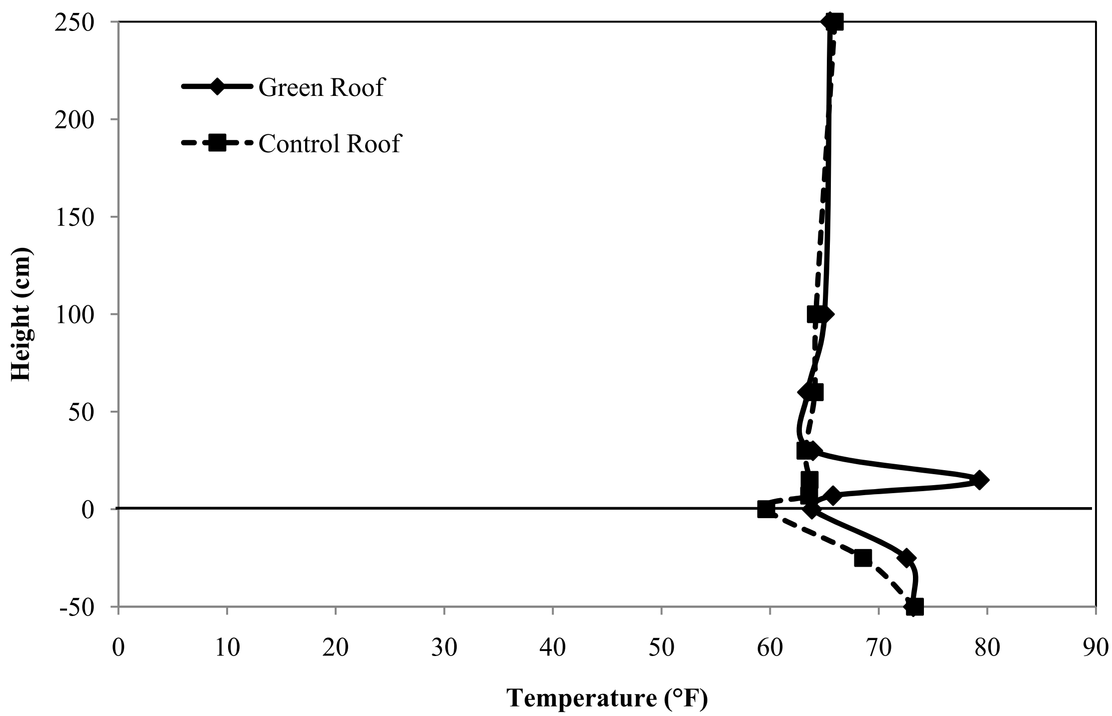


(b) Night-time temperature profile

Figure 251. August, 2008 temperature profile at Giant Eagle

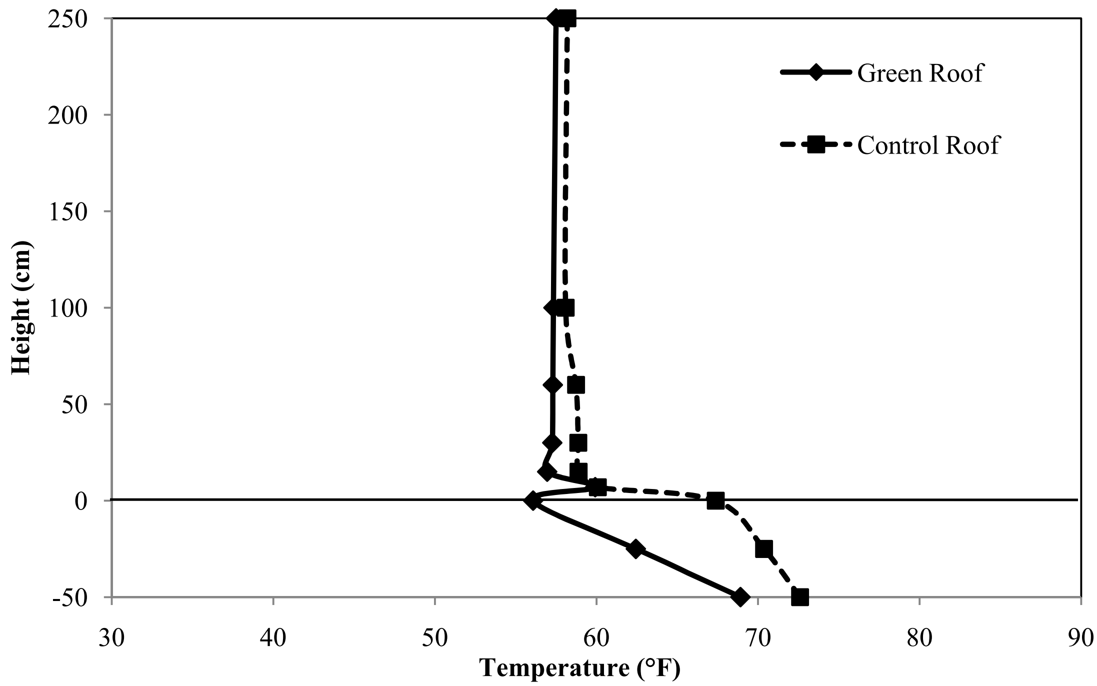


(a) Day-time temperature profile

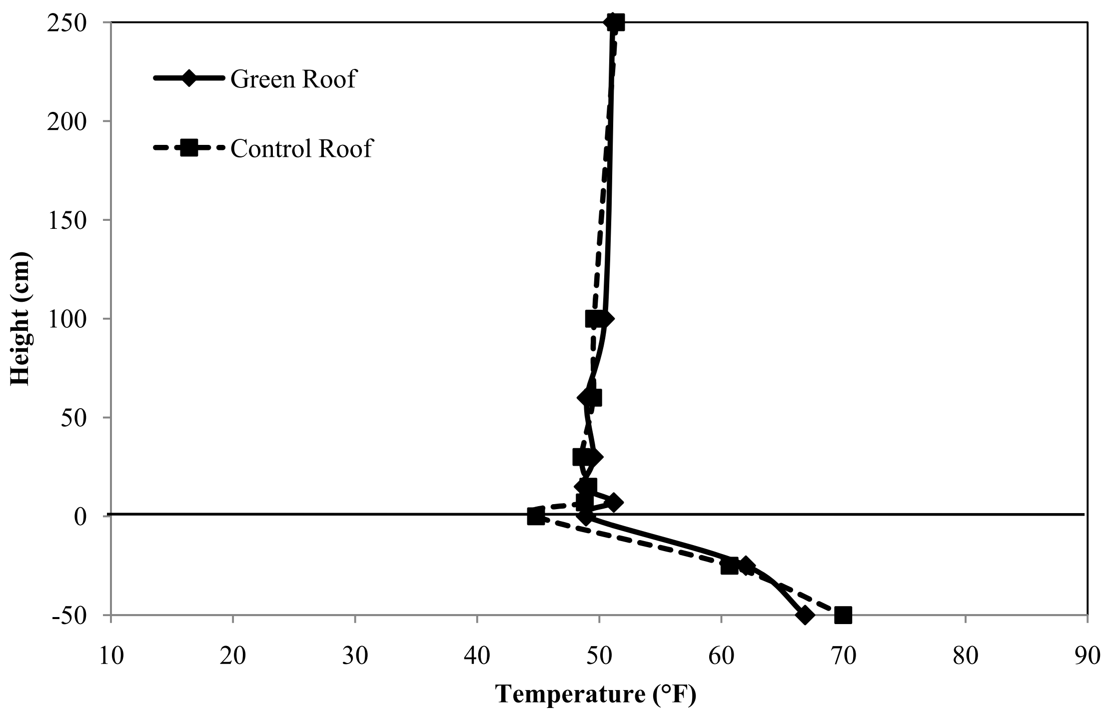


(b) Night-time temperature profile

Figure 252. September, 2008 temperature profile at Giant Eagle

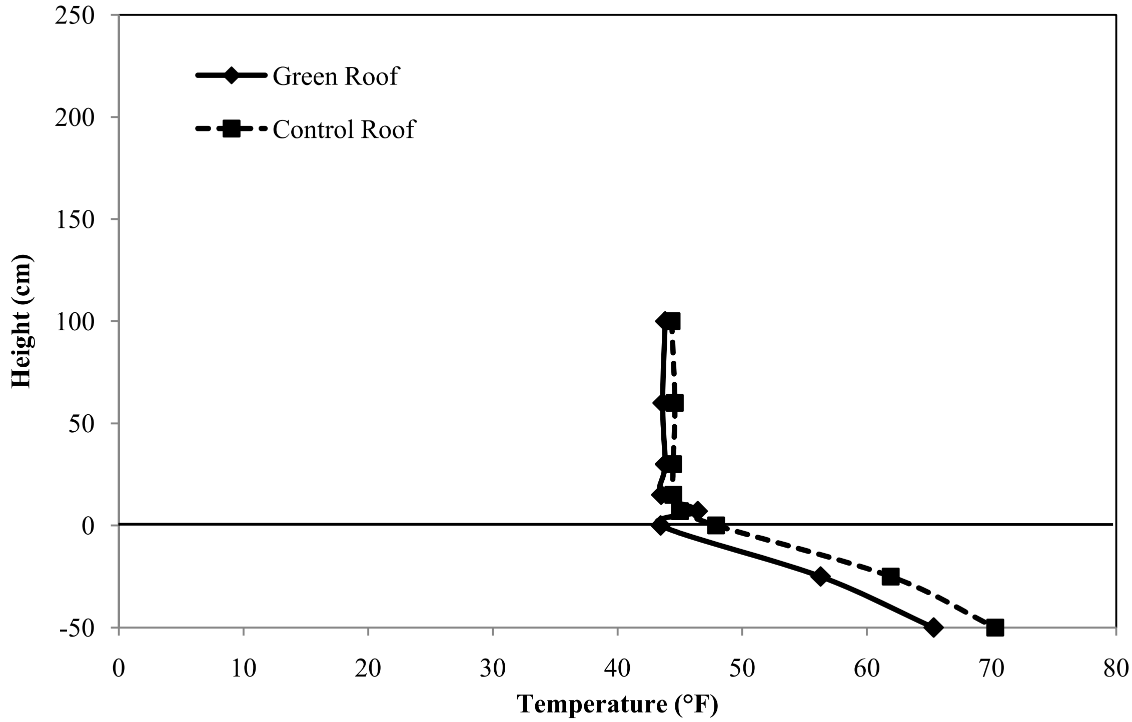


(a) Day-time temperature profile

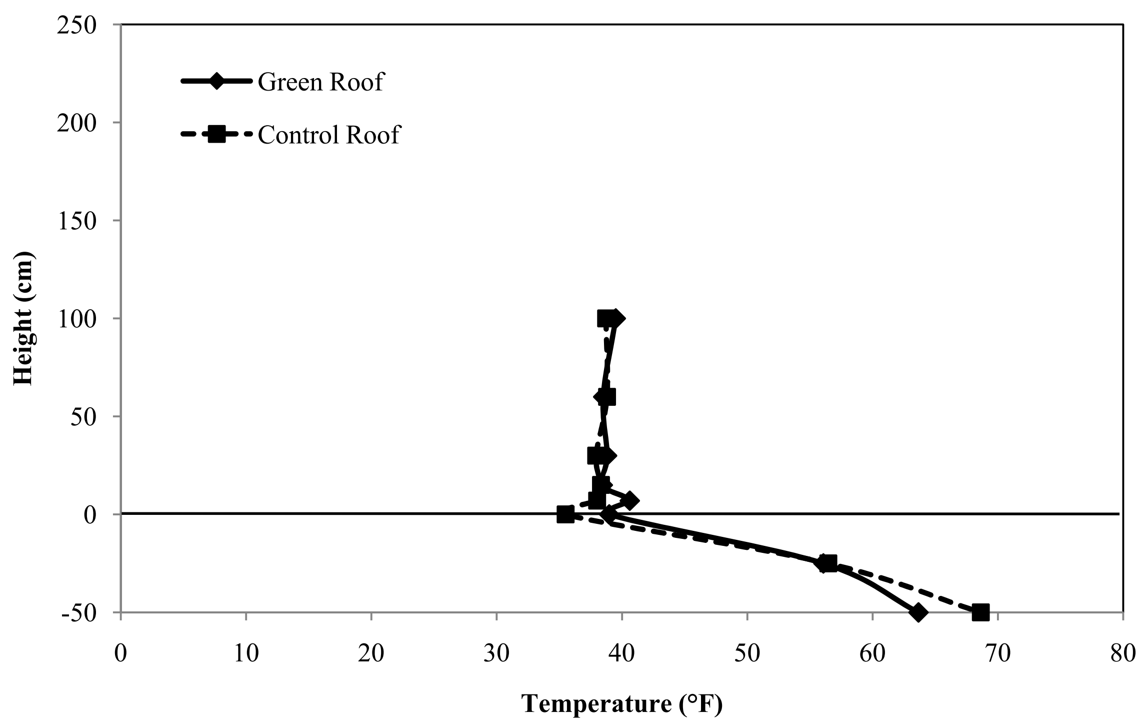


(b) Night-time temperature profile

Figure 253. October, 2008 temperature profile at Giant Eagle

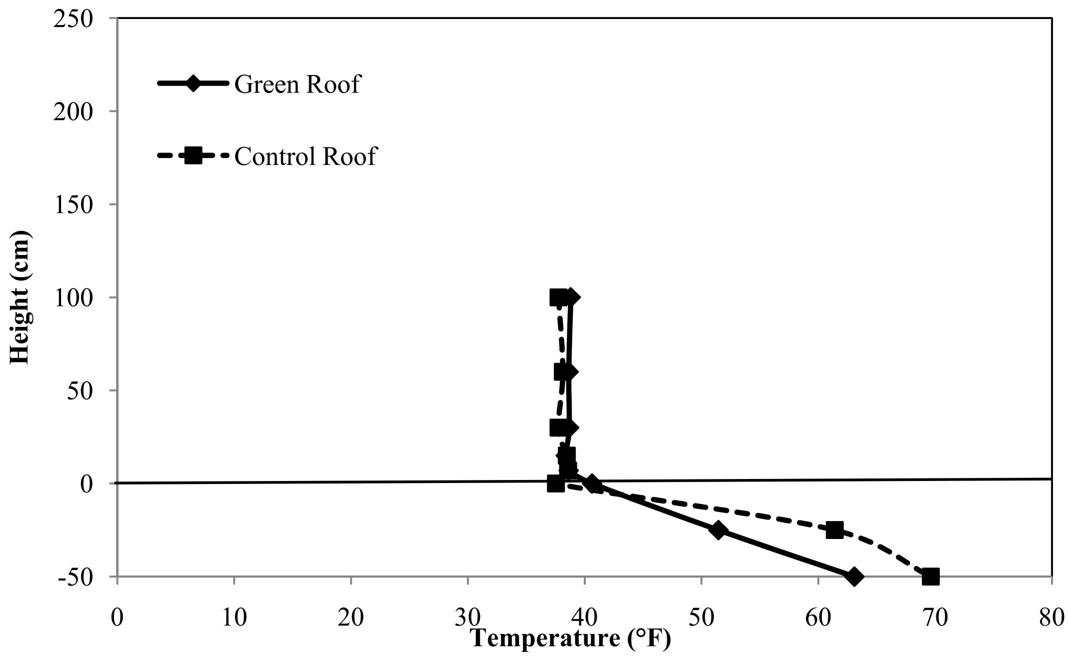


(a) Day-time temperature profile

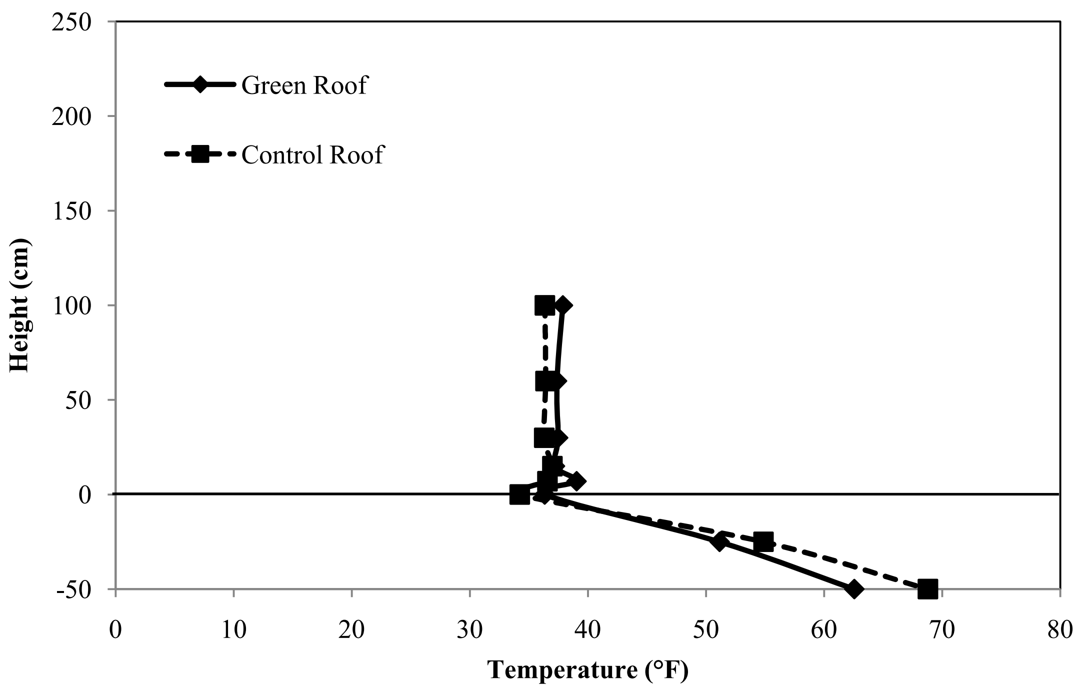


(b) Night-time temperature profile

Figure 254. November, 2008 temperature profile at Giant Eagle



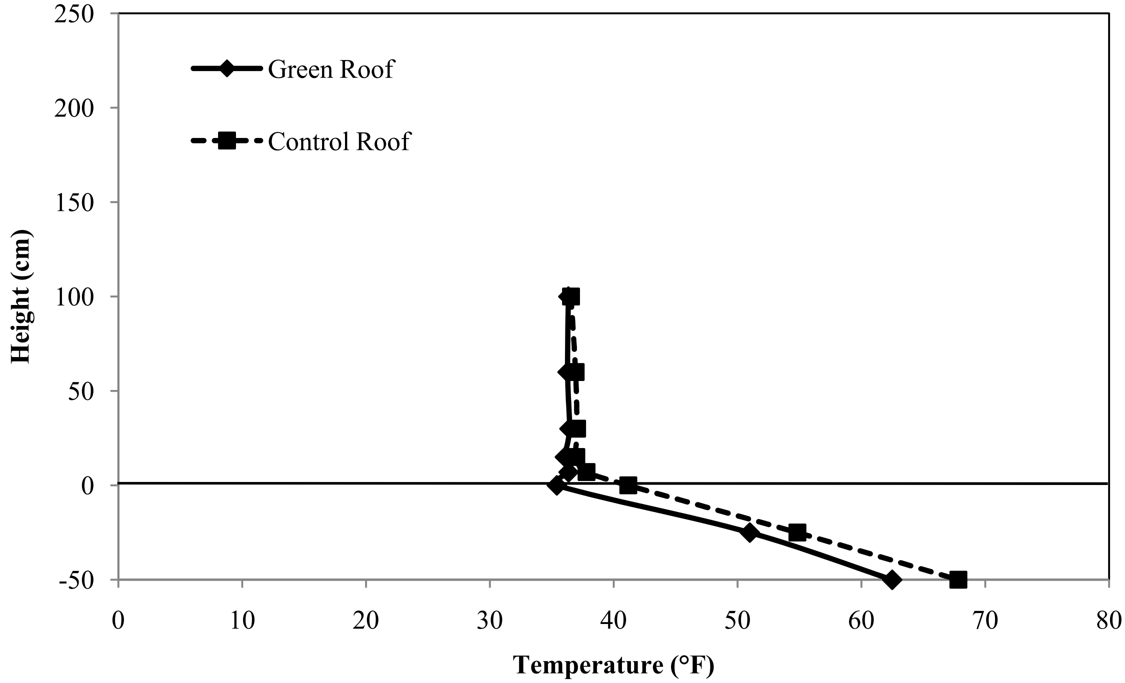
(a) Day-time temperature profile



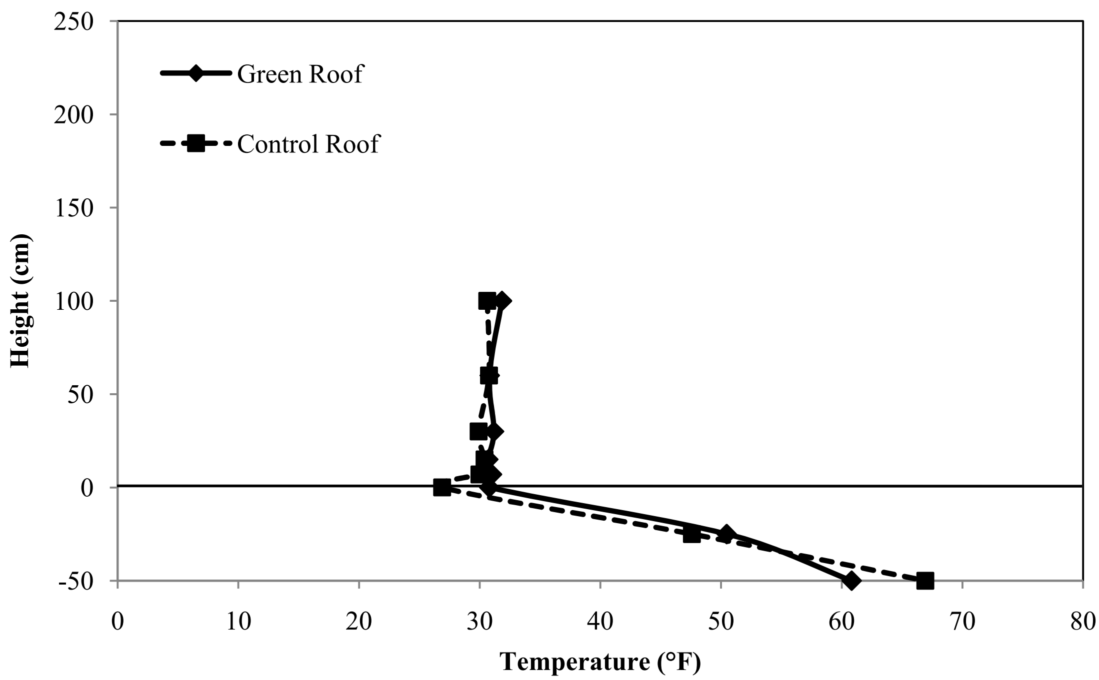
(b) Night-time temperature profile

Figure 255. 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.

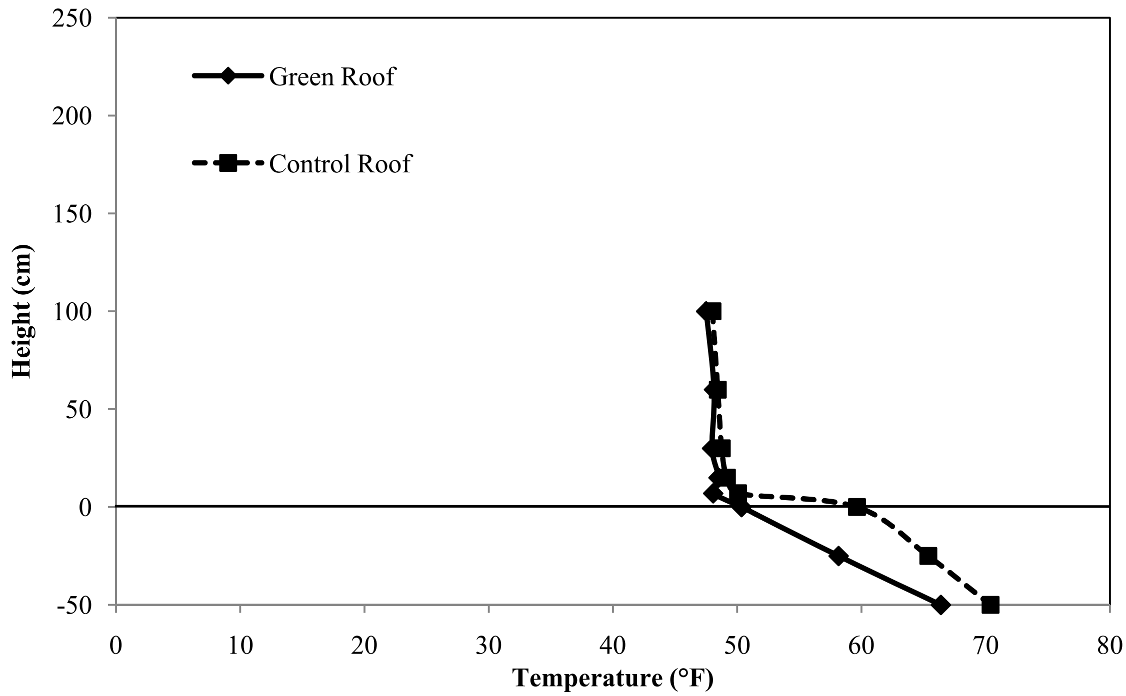


(a) Day-time temperature profile

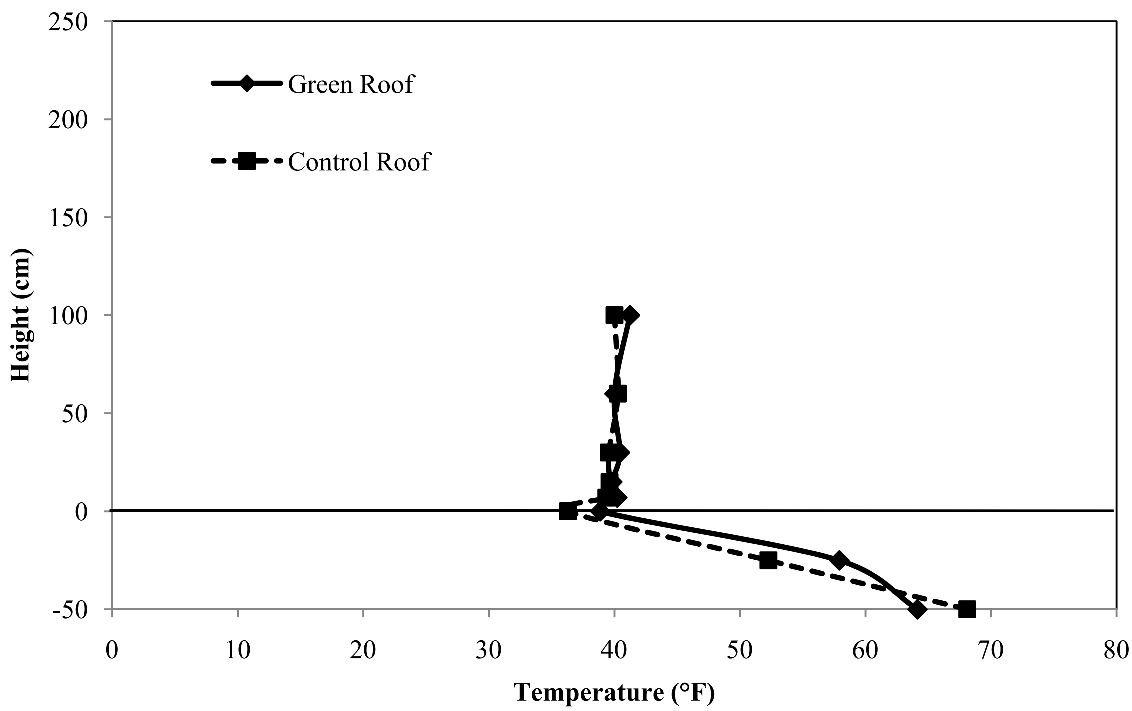


(b) Night-time temperature profile

Figure 256. February, 2009 temperature profile at Giant Eagle

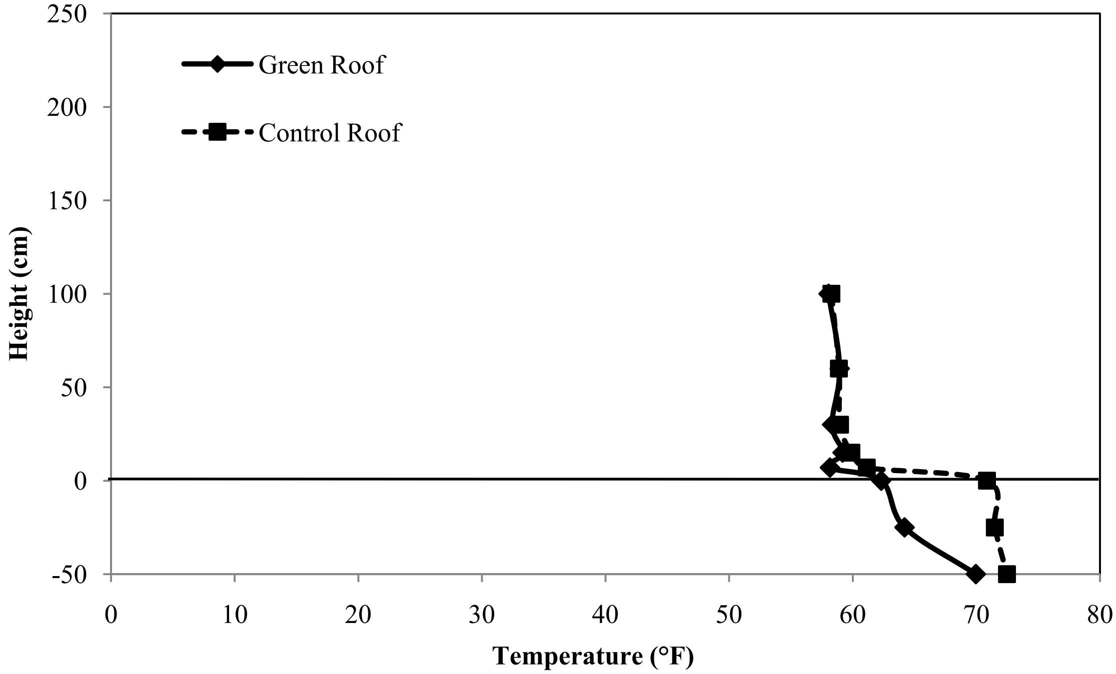


(a) Day-time temperature profile

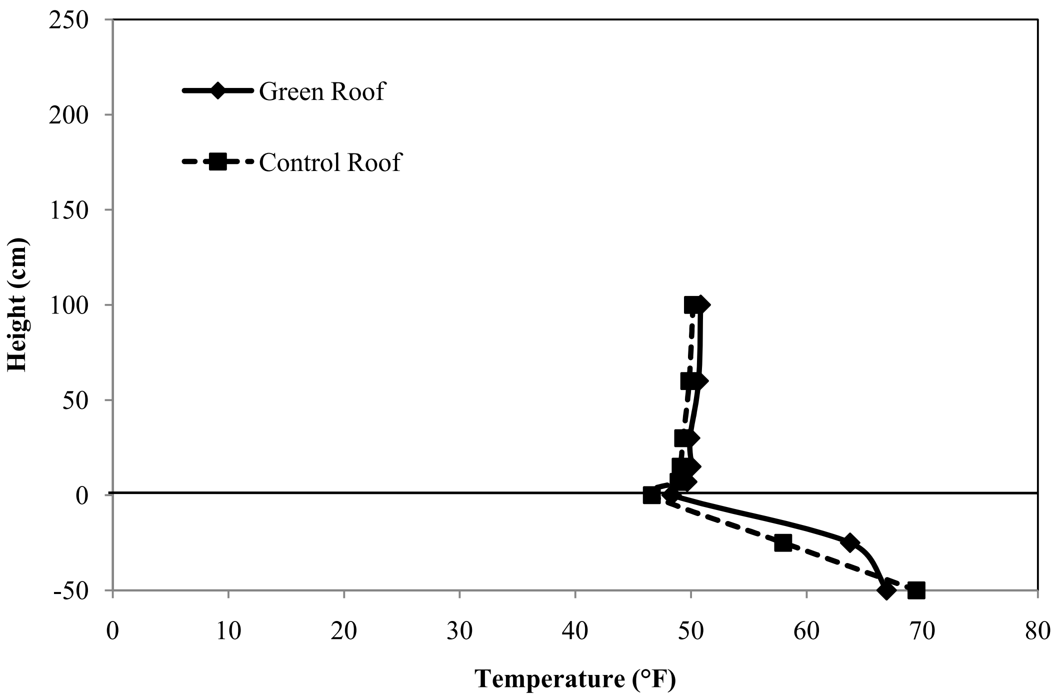


(b) Night-time temperature profile

Figure 257. March, 2009 temperature profile at Giant Eagle



(a) Day-time temperature profile



(a) Night-time temperature profile

Figure 258. April, 2009 temperature profile at Giant Eagle

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