Green Roofs for Stormwater Runoff Control

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Abstract

This project evaluated green roofs as a stormwater management tool. Specifically, runoff quantity and quality from green and flat asphalt roofs were compared. Evapotranspiration from planted green roofs and evaporation from unplanted media roofs were also compared. The influence of media type, media depth and drought during plant establishment on plant growth and long-term management of media pH were investigated. The goal of the project was to provide high-quality replicated data which could be used to develop and refine reliable anticipated runoff volumes and loadings from green roofs, respectively, as well as evaluate factors which impact plant growth and establishment.

Results indicate that the green roofs are capable of removing 50% of the annual rainfall volume from a roof through retention and evapotranspiration. Rainfall not retained by green roofs is detained, effectively increasing the time to peak, and slowing peak flows for a watershed. There are seasonal considerations as more runoff is generated during winter and for many summer storms there was no runoff. Green roof runoff does contain concentrations of some nutrients and other parameters, but values are in line with other planted systems. Due to the volume reduction, actual nutrient loadings from green roofs are less than asphalt roofing runoff or otherwise manageable at the downspout.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally C. Gutierrez, Director
National Risk Management Research Laboratory

Contents

Acronyms and Abbreviations

BMP = Best Management Practice
CAM = Crassulacean Acid Metabolism
CSO = Combined Sewer Overflow
CV = Coefficient of Variation
EC = Electrical Conductivity
ET = Evapotranspiration
EMC = Event Mean Concentration
EPA = U.S. Environmental Protection Agency
LID = Low Impact Development
NURP = National Urban Runoff Program
SM = Standard Methods
SWMP = Stormwater Management Plan
WWF = Wet-Weather Flow

Acknowledgements

A major undertaking of this type requires the dedication and cooperation of many individuals.

The Pennsylvania State University project team which performed the sampling and analysis was led by Dr. Robert D. Berghage, Dr. David Beattie and Dr. Albert. R. Jarrett of the Penn State Center for Green Roof Research. Funding from this project led to two master theses of Christine Thuring and Farzaneh Razaei.

EPA Region 3 identified this project for funding through the EPA's Regional Applied Research Effort (RARE). The technical direction and coordination for this Cooperative Agreement No. 83124401 was provided by the Office of Research Development (ORD) Project Officer, Thomas P. O'Connor.

Many others assisted in making this product available to the public. Special recognition is extended to Dr. Ronald Landy, ORD Regional Scientist, Region 3, for his help in coordinating and initiating the project. Dr. William Hunt, P.E., Dr. Bradley Rowe, and Dr. Scott Struck performed reviews of this report. Carolyn Esposito reviewed the quality assurance project plan and this report. Dr. Swarna Muthukrishnan, former Post Graduate Researcher, ORISE, provided technical assistance.

Dr. David Beattie passed away on February 11, 2008. Dr. Beattie pioneered green roof research while at Penn State University, and distinguished himself as a great supporter of the green roof industry.

Executive Summary

This report documents efforts to quantify and monitor the performance of green roofs. This project investigated green roofs as an approach to control stormwater discharge and pollutant content. The work was carried out by the Penn State Green Roof Center of The Pennsylvania State University at University Park, PA. Prior to this project, EPA had limited information available on the beneficial use of green roofs as a stormwater control due to the limited application of this technology in the United States.

The Urban Watershed Management Branch of Edison, New Jersey, as part of the EPA National Risk Management Research Laboratory seeks to develop new urban technologies and assist municipalities in selection of appropriate technologies to control urban wet-weather discharges. This report provides the data and background municipalities and private entities need to move forward with decisions to implement green roofs as a stormwater control technology, or best management practice (BMP). Green roofs fit into a subcategory of on-site BMP, termed low-impact development (LID) technology, that also includes, biofiltration, swales and rain gardens. Green roofs can be incorporated with other stormwater controls and included in a municipal stormwater management plan (SWMP).

Urban development has led to large areas of impervious surfaces such as parking lots and building roofs. Runoff from these areas is causing problems for many urban and suburban communities. Not only is total volume of WWF increased, but peak flow rates are also increased. Implementation of traditional stormwater BMPs in urban areas may not be practical in all circumstances due to limited available surface area and other concerns. Green roofs have been suggested as a means to reduce the stormwater impacts of development because they have been shown to both detain and retain stormwater. The purpose of this study was to quantify runoff reductions resulting from the use of extensive green roof systems.

This project investigated design specifications and materials of green roofs used as stormwater control devices. This was done through replicate experimental setups using small-scale buildings exposed to the elements and in controlled environment greenhouse test bed systems. The size of the buildings allowed the complete volume of runoff to be captured analyzed. Performance data derived from side-by-side field and laboratory tests provide clear performance criteria for stormwater volume control by green roofs. Key water quality parameters evaluated included: real-time, flow, turbidity, electrical conductivity (EC), pH and nitrate; and, grab sample pollution assessment, for nutrients, metals and hardness.

This report addresses the following:

1. Monitoring stormwater runoff from green roofs

Stormwater runoff was monitored and analyzed from January, 2005 through November, 2005. Replicated data were collected for 72 precipitation events from three green roofs and two flat asphalt roofs. Unreplicated data were collected from an unplanted, media-only roof section and a rooftop detention section. A range of events were monitored including a high-intensity short-duration [1 in. (25 mm) in 30 min] event and a high-total precipitation steady-rate [2.65 in. (67.3 mm) over 8 hr] event. Data were also collected from winter snow events.

These data confirm previous data from other studies' conclusions that a 3.5 - 4 in. (8 - 10 cm) deep green roof can retain 50% or more of the annual precipitation. The replicated data from this study provide estimates of expected differences in performance from similarly constructed green roofs. Green roof performance was quite consistent during the warm summer months (limited runoff) but was more variable during winter months. Flow rates were reduced in runoff from green roofs until the systems were saturated at which point runoff flow roughly equaled the rate of precipitation input. Even when rainfall led to saturated conditions, green roofs significantly increased the time to peak prior to producing runoff as compared to the flat control roofs. These data support the use of green roofs as a stormwater mitigation tool.

2. Monitoring runoff water quality from green roofs

Stormwater runoff samples were collected from green and flat asphalt roofs and analyzed for water quality parameters. Twenty three samples were evaluated for pH, EC, color, turbidity, and nitrate. A limited set of five samples was evaluated for additional nutrients, hardness, salts and metals. This small sampling of green roof runoff indicated the runoff was similar to what might be expected as leaching from any other planted system in the landscape.

Green roof runoff was colored yellow, had higher pH and EC, and generally had equal or higher concentrations of the nutrients and ions measured in solution. Loadings (in lb/acre) of various nutrients, with the exception of nitrate, and hardness from green roofs were greater than from flat asphalt roofs. However, other ion loadings in the green roof runoff were not statistically different from flat asphalt roofs. In summer, when green roofs retained nearly all precipitation, there was limited nitrate loading from the green roofs. Some of the water quality impacts of a green roof are thus seasonal, and depend on concentrations from a planted system, precipitation concentrations, and runoff rates. Established green roofs may discharge less nutrients than green roofs being established.

Green roofs can improve water quality with regard to pH and nitrate. The data suggest that green roof discharge from downspouts should be routed to another LID practice such as vegetated filter strips, rain gardens or stormwater collection systems with end-of-pipe BMPs for further treatment, when possible; however, green roofs are often used because there is limited space for other technologies. Green roof runoff should not be discharged directly to the receiving water without further treatment, if possible. Runoff discharged to stormwater collection systems that have water quality BMPs, is preferred; however, the time delay and volume reduction provided by green roofs still offer receiving water quality benefits for stormwater systems that discharge without treatment. For this reason, discharge from green roofs to a combined sewer system is appropriate and desirable, due to the significant reduction of volume discharge and extension of time to peak over flat asphalt roofs. Green roofs are an important stormwater technology for urban areas with limited space for retrofitting BMPs into the existing conveyance system.

3. Evaluating evaporation and evapotranspiration rates of green roofs

Eight 0.5 m^2 weighing lysimeters were planted with a mixture of *Delosperma nubigenum* and *Sedum album* or remained unplanted with green roof media and drainage geotextile. Weighing lysimeters have been used for many years to measure evaporation and evapotranspiration and these eight were monitored in a greenhouse during dry-down cycles during warm actively growing periods and cool dormant periods. Drying cycles lasted 21 days.

Green roof plants lose water rapidly following irrigation, after which they reduce water loss rates. This is a new finding. Evapotranspiration (ET) rates from green roofs were similar to other measured systems and could be described using normal ET prediction equations such as Pennman-Monteith. Unplanted media lost water at a similar rate initially but water loss declined below that of the green roof after a couple of days. Plants are thus essential to the system and move water from down in the media to the surface quickly, resulting in faster return of the retention potential for the green roofs. This is an important new finding.

These data demonstrate the superiority of a planted roof over an equivalent ballast roof for retention of stormwater during the summer months. Rapid initial loss of water from these plants followed by drought adaptation is a new finding that provides an important component of any model or design tool to predict the effectiveness of a green roof as a stormwater tool.

4. Factors affecting green roof establishment and maintenance

Media type, depth, and early drought were evaluated as factors affecting establishment and early management of a green roof. Early drought is very detrimental to survival and establishment of green roof plants particularly with shallow media depths. Sedum species may survive, but other green roof plants may not survive. The results suggest that 3 - 4 in. (8 - 10 cm) of media, with the potential for supplemental irrigation during establishment, will result in improved plant establishment for most species.

A test procedure for evaluating long-term pH buffering of the roof was developed and evaluated. Tests of pH buffering capacity of green roofs suggest that media can buffer acid precipitation for approximately 10 years, after which it may be necessary to amend the media with lime to maintain pH buffering capacity.

Chapter 1 Introduction

Significant water quality and quantity issues are caused by stormwater runoff from developed areas in North America. For the five years from 1997 to 2001, the rate of urban development averaged 890,000 ha/year (2,400 ha/day) (NRCS, 2003). Development results in water quality impairment and quantity management issues throughout the affected watersheds. For example, nutrient loading (a widespread result of agricultural runoff) may be replaced as the critical impairment issue for a watershed by increased peak flows, flooding, and urban pollutant loads as runoff is collected from impervious pavement and roof surfaces.

Wet weather flow (WWF) including combined sewer overflow (CSO), sanitary sewer overflow (SSO), and stormwater discharges is one of the leading causes of water quality impairment in the United States and improvement of controls is one of two priority water focus areas cited by the EPA's Office of Water in its National Agenda for the Future (Perciasepe, 1994). Pollution problems stemming from these WWFs are extensive throughout the country. Problem constituents in WWF include visible matter, pathogens, biochemical oxygen demand (BOD), suspended solids (SS), nutrients, and toxicants (e.g., heavy metals, pesticides, and petroleum hydrocarbons). National estimates have projected costs for WWF pollution abatement in the tens of billions of dollars (APWA, 1992). Therefore, municipalities need alternatives to control the high costs of WWF treatment prior to release. This report presents data showing that green roofs are effective best management practices (BMPs) for mitigation of the environmental impacts to receiving waters associated with urban runoff.

Greening of rooftops, by incorporating plants into the design of roofing systems, has been suggested as a method to reduce the impacts of stormwater runoff by reducing the impervious surface within a developed zone (Scholz-Barth, 2001). The benefits of green roofs (sometimes called Eco roofs) for stormwater control include direct retention of a portion of the rainfall, and delaying and decreasing the peak rate of runoff from the site (PACD, 1998). Most extensive green roofs currently being installed in North America consist of four distinct layers: an impermeable roof cover or roofing membrane; a “drainage net;” lightweight growth media, i.e. 3 in. (8 cm); and adapted vegetation (PACD, 1998).

Figure 1-1 is a cross-section of a typical extensive green roof system. The drainage layer is an open, highly permeable material that quickly channels gravitational water off the roof. Growth media, in addition to providing a suitable rooting zone for vegetation, is typically a low-density aggregate with high-water holding capability while also providing good drainage. A lightweight media from 3 - 6 in. (8 - 15 cm) deep allows for retrofit installation on existing buildings, and reduces the need for extra structural support in new buildings. Media depth and porosity play an important role in stormwater retention and plant growth. Plants provide shade to the surface below foliage, intercept rainfall, and slow direct runoff from sloped roofs (Miller, 1998). Plant size and selection depend on the depth of the roof overburden (growing media) and local climate, but almost always consists of winter-hardy, drought-tolerant, perennial plants, e.g., sedums which are a type of succulent, cactus-like plant.

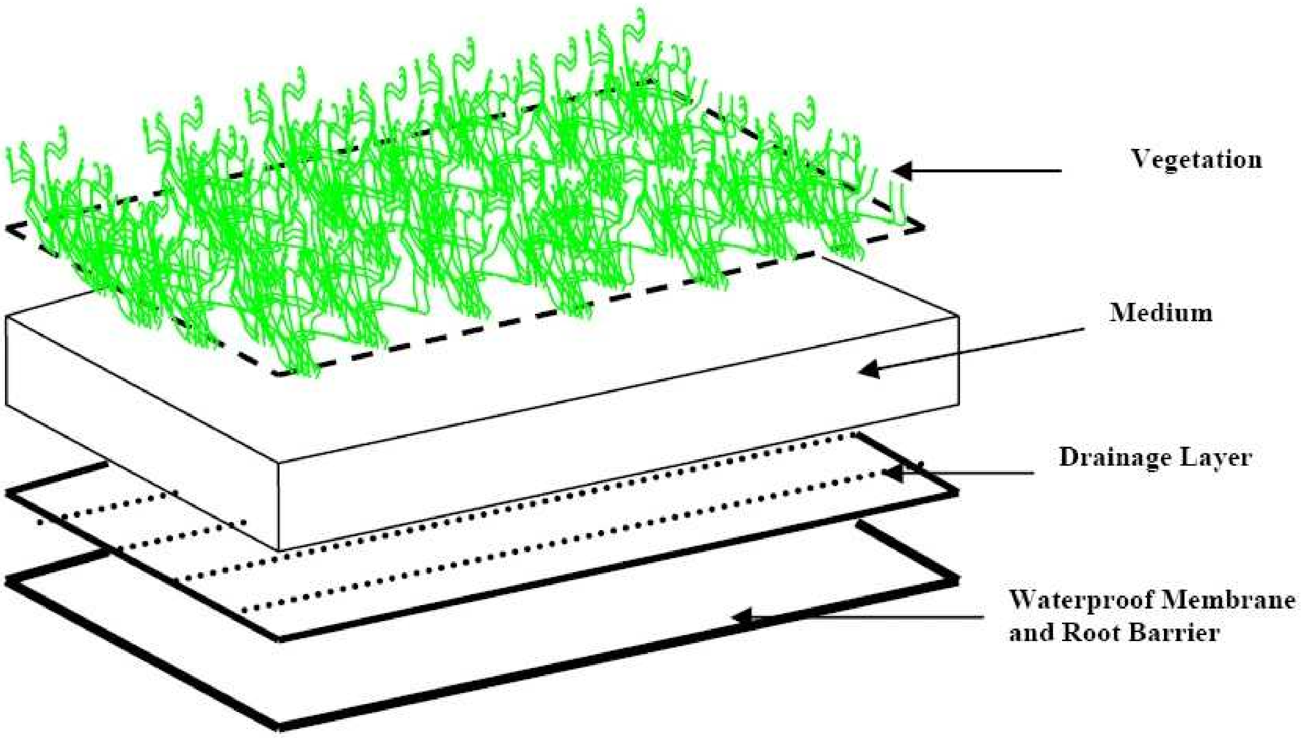


Figure 1-1 Typical cross-section of a green roof system (Berghage et al., 2007)

The use of green roofs in Germany is widespread and has been promoted in many cities through financial incentives (Pederson, 2001). Economies of scale, contractor experience, and specialized equipment have reduced the cost of installing a green roof in Germany and throughout Europe. In contrast, installing a green roof in the United States can be very expensive, adding from at least \$6/ft^2 (\$65/m^2), to more than \$30-\$40/ft^2 (\$320-\$430/m^2), to the cost of the roof. Other barriers also limit widespread use of green roofs in the US. Engineers, architects, developers, and policy makers are unsure of the actual quantifiable benefits of a green roof. In the U.S., Peck (2007) observed as recently as 2006, only 70 acres (28.5 ha or 285,000 m^2) of green roofs had been planted, as compared to Germany where in 1996 alone, 2,500 acres (1 Kha or 10,000,000 m^2) of green roofs were installed (Peck et al., 1999); however, the 2006 totals represent a 24% increase over the previous year, and only account for reported projects.

Annual reductions of runoff of 38 - 54% and 38 - 45% have been reported for 3 in. (8 cm) deep media (Miller, 1998). A media depth of 2.5 in. (6.5 cm) can retain 40% of the rain for an individual 2-in. (50-mm) storm (Scholz-Barth, 2001). The City of Portland, Oregon, has developed guidelines for green roofs that state that some jurisdictions may reduce water and sewer charges or may provide financial incentives to developers who retain stormwater on site, and that green roofs can help reduce the size of stormwater management ponds. Much of the existing published information on green roof performance in North America has been collected from pilot-scale or sometimes commercial-scale green roofs without replication. For example, recently Van Woert et al. (2005) performed studies of three simulated roof platforms with dimensions of 2.44 x 2.44 m (8 x 8 ft), divided into three sections, to quantify the effects of various treatments on stormwater retention. The mean precipitation retention ranged from 48.7% for gravel test beds to 82.8% for vegetated test beds. Roof slope and green roof media depth also impacted stormwater retention with the combination of reduced slope and deeper media reducing the runoff the most. They also observed moderation of peak flows. Little scientifically based replicated data have been collected in North America at the building scale.

EPA is emphasizing the use of BMPs to capture and treat runoff from small storms, especially the use of onsite BMPs, often termed low-impact development (LID), such as bioretention, swales, or rain gardens. Green roofs offer a practical alternative for new construction and for retrofitting existing structures. Implementation of green roofs in European countries like Germany is a regulatory driven technology in the municipalities that have adopted mandates for green roofs on new buildings. With more municipalities in the United States looking for flexible ways to control stormwater, including the use of stormwater credits or watershed-based trading, developing new stormwater controls such as green roofs is a vital initiative for the EPA. Green roofs appear to be a suitable technology for urban areas, as there is limited space to implement traditional stormwater controls. Land values are too high to devote much surface area to stormwater control devices. In addition, surface-based stormwater control devices can be vandalized and may pose public access and safety issues. Green roofs can slow the runoff from roofs during larger storms and during smaller storms are capable of absorbing a majority if not all of the rainfall. In essence, the impervious area is decreased when planted roofs are installed on, or retrofitted to, buildings. The plants also act as a bio-filter in reducing the pollutant content of the rainfall. This technology reduces the heat island effect of standard roofs by replacing the low albedo surface, as well as by increasing evapotranspiration, which helps cool the air by several degrees. Furthermore, because of reduced air temperature, less energy is needed for air conditioning (Osmundson, 1999).

Field Data

Six similar structures, three with, and three without green roofs, were used for this study so that statistically valid, replicated demonstrations could be performed. The six 6 x 8 ft (1.8 x 2.4 m) buildings were constructed in 2001, and have nearly flat (1:12 pitch facing south) plywood roofs. All structures were insulated, heated, and air conditioned. Each is covered with standard rolled, asphalt roofing. Three of the structures have green roof systems constructed on top of the standard roof layer. The three green roofs had a 1 x 4 wooden frame mounted to the top of the roof to contain the green roof system. Each green roof consisted of a drainage mat covered with 3.5 - 4 in. (9 - 10 cm) of green roof media. The media consisted primarily of expanded clay with some compost amendment. The green roofs were originally planted in the fall of 2001 and had 95% plant coverage (90% *Sedum spurium* and 5% *Sedum album*) at the beginning of this study.

The third roof without a green roof also had a 1 x 4 wooden frame mounted on the roof like the green roofs, but was modified to provide two experimental setups. One half of this rooftop provided detention with slow release, while the other was lined and filled with the same expanded clay-based green roof mixture that was used on other roofs. Media without compost, i.e., used strictly as a ballasted roofing system, was not tested, as previous studies have indicated green roofs work better than ballasted roofs. A “V” notch in the board of the detention rooftop allowed this section of the roof to retain the same volume of runoff as is retained by the media filled portion. This building was used for housing the computers for automated data collection, and did not provide a suitable replicate to the other flat asphalt roofs due to heat generated by the computer and data loggers. Modifications to this roof were completed in 2004.

A covered gutter and downspout was attached to the lower end of each roof to collect all runoff into a 55 gal (208 L) plastic barrel. Each barrel was connected to a pressure transducer which allowed continuous measurement of the water level in the barrel. Pressure transducers were connected to a Campbell data logger which recorded pressure every five minutes and downloaded to a computer hard drive every couple of days. Each barrel and associated pressure transducer was calibrated by adding water to the barrel in 1.3 gal (5.0 L) increments. Individual calibration curves (output from the transducers is linear) were used to process the raw pressure data. Barrels and associated gutter systems were initially wrapped with insulation and heat tape to prevent freezing; however, this was insufficient to collect winter data. In June, 2004, a lightening strike caused the failure of the weather station, several pressure transducers, and data loggers, requiring replacement. While the automated data collection system was not functional, several modifications to increase precision, accuracy, and reliability of stormwater collection were performed. New 60 gal (230 L) barrels with conical bottoms were installed and fitted so that complete drainage could be achieved, in addition to easier removal of water samples and elimination of standing water which caused subsequent algae growth that had been occurring in the old system. These barrels were also housed in wooden substructures with 1 in. (2.5 cm) thick insulation and a small heater to improve measurements during winter.

Rooftops were configured with thermisters to measure temperature in and over the green roof systems. A weather station including a tipping bucket rain gage, temperature, light, humidity, and wind speed and direction sensors was located on the corner of the roof of one of the buildings. Weather station data were recorded every 5 min. to correspond with data obtained from the pressure transducers. Data from the weather station was downloaded once each week. The measurement limit for the weather station was 0.01 in. (0.25 mm) of rainfall (one bucket tip). The pressure transducer systems also had a sensitivity which allowed determination of 0.02 in. (0.5 mm) of water runoff from the roofs. For the purpose of runoff data, a storm event was considered to be any event which resulted in measurable runoff (0.02 in.; 0.5 mm).

A sampling tube was installed in each gutter near the downspout to allow discrete grab sampling of runoff when needed. Routine grab samples of runoff water were obtained by sampling the water in the barrel following rain events. A simple field laboratory for water quality analysis was located at the site for field sample analysis. Field equipment included a Hanna Instruments of Woonsocket, RI, model HI9803 pH and electrical conductivity (EC) meter, Hach of Loveland, CO, model 52600-00 pocket turbidity meter, and a Hach model 890 portable colorimeter. Reagents for nitrate and ammonia analysis, standards, and deionized DI water were kept at the field site. Nitrate was measured using Standard Method (SM, 1998) 8039.

Additionally, discrete samples were collected using manual techniques and brought back to Penn State's analytical laboratory for further analysis. Five samples were evaluated for calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), phosphorous (P), and zinc (Zn). Two samples were evaluated for sulfur (S).

Experimental design of this project was based on preliminary data collected in the fall of 2002 and summer of 2003 where three building replicates of each type of roof allowed statistical analysis of runoff from green compared to flat asphalt roofs. Replicated buildings allowed estimation of variance of runoff volume from each roof type within each event so statistically significant differences can be described for any given rain event. Preliminary water quality data (Appendix C) also suggested that for measurements of pH, EC, color and nitrate, statistical significance for main effects of green versus flat asphalt roofs and individual rain events could be achieved.

Greenhouse and Laboratory Experiments

Controlled test bed systems located in the Penn State Horticultural Science greenhouses were used to obtain background information and to demonstrate differences in water storage, and retention and detention characteristics of the media, with and without the presence of plants. Rehydration, evapotranspiration (ET), and plant growth rates under controlled environmental conditions of temperature, light, and vapor pressure deficit were determined. Seasonality effects were observed by evaluating the characteristics of the plants year-round.

Test beds consisted of small modules (6.1 ft^2; 0.5 m^2) with a drainage layer and media identical to field-site buildings. Each of the eight planting beds was suspended from a load cell to provide continuous measurement of weight change (primarily water gain or loss). Load cells were connected to a datalogger and recorded individual weights. This method of testing is also termed weighing lysimeters. Lysimeters have been used for centuries, but measurement and instrumentation have been improved greatly during the past 50 years (Howell et al., 1991). As described above, lysimeters are simple containers or tanks filled with soil in which plants are growing. There are two different methods of using lysimeters to measure ET: weighing lysimeters and non-weighing lysimeters. The weighing lysimeters have been used for many years to measure the evaporation and ET from bare and cropped soils (Howell et al., 1991).

Each planting bed drained to a gutter system into a plastic bucket with a pressure transducer also connected to the datalogger. Weighing lysimeters were maintained with a 1:12 pitch to simulate the slope of the field rooftops. Four weighing lysimeters were planted with *Sedum album* and *Delosperma nubigenum*. Vegetation covered 80-100% of the surface of weighing lysimeters at the start of the study. The remaining four weighing lysimeters contained the drainage layer and media, but were not planted.

Simulated rainfall was applied using a low volume overhead irrigation system. The amount of simulated rain applied was controlled by timing the irrigation application. Irrigating at full volume for 1 hr resulted in approximately 6 in. of simulated rain. A known quantity of simulated rain of either 0.75 or 1.5 in. (1.9 or 3.8 cm) was applied over a 2 hr period based on observed rain events during the summer of 2003.

Weight change and runoff were measured. The weighing lysimeters were then allowed to dry for a series of fixed periods (1, 4, and 16 days). These times were selected based on preliminary data from both field and greenhouse projects. Weight change, light, temperature, humidity, wind speed, and flat pan evaporation were also recorded during this period. Plant conditions were monitored and changes in size, percent coverage, color or other visible changes were recorded. After drying periods, the weighing lysimeters were rehydrated with simulated rain and the process was repeated. This process was repeated four times for each hydration and simulated rain volume. Day length was maintained at a minimum of 16 hr with high-intensity discharge (HID) lights.

A drought and establishment study tested the responses of five plant species to three depths of two media under three drought regimes, in two replications. Two media were compared for their influences on plant performance in combination with treatments of depth and drought. Three watering regimes were used: no drought, early drought, and late drought.

In addition to these greenhouse studies, an accelerated aging study to determine the effects of acid rain on the length of roof life was conducted. In the course of this laboratory study, acid was delivered to different media, i.e., expanded slate or clay, to determine the buffering capacity of the media.

Chapter 2 Conclusions and Recommendations

Conclusions

Green roofs retained over 50% of total precipitation during the study period. During the summer months, nearly 95% of the precipitation was retained. During winter, retention was smaller (<20%) and not significant. Peak flows were delayed by green roofs and in many cases peak flow rates were also reduced. Green roofs were most effective at delaying and reducing peak flows when they were not fully saturated. Rapid peak flows, i.e. high-intensity, short-duration rainfalls were attenuated more than lower intensity, high-total volume longer period flows.

Monitoring Stormwater Runoff from Green Roofs

Stormwater runoff was monitored and analyzed from January, 2005 through November, 2005. Replicated data were collected for 72 precipitation events from three green roofs and two flat asphalt roofs. Unreplicated data were collected from an unplanted, media-only roof section and rooftop detention section. Events included high-intensity, short duration (1 in. (25 mm) in 30 min) events and high total precipitation steady rate (2.65 in. (67.3 mm) over 8 hr) events. Unique data were also collected from winter precipitation events, including snow and ice.

These data and data from other studies at this site confirm that under ambient conditions, a 3.5 - 4 in. (8 - 10 cm) deep green roof can retain 50% or more of the annual precipitation. The replicated data from this study provide the only available estimate of expected differences in performance from identical green roofs. Green roof runoff was quite consistent during the warm summer months (almost no runoff), but was more variable during winter months when runoff from buildings varied during some storm events from 80% for one building to 100% for others. Flow rates were reduced in runoff from green roofs until systems were saturated, at which point runoff flow roughly equaled the rate of precipitation input; however, peak flows were reduced and time-to-peak increased.

Monitoring Runoff Water Quality from Green Roofs

Stormwater runoff samples were collected from green and flat asphalt roofs and analyzed for water quality parameters. Twenty-one precipitation events were evaluated for pH, EC, color, turbidity, and nitrate. Additionally, discrete samples were collected using manual techniques and brought back to Penn State's analytical laboratory for further analysis. A limited data set of five sampling events was analyzed for nutrients, hardness, and other ions.

Analysis of the 21 precipitation events revealed that green roof runoff was colored yellow and had higher pH and EC. The increased pH was a benefit in an area of such acid precipitation. The smaller data set of five samples indicated that green roof runoff generally had equal or greater concentrations of nutrients (phosphorous and potassium) and hardness (calcium and magnesium) measured in solution than flat asphalt roof runoff. The concentration of green roof phosphorous release was comparable to that of known residential landscape values. Loadings of nutrients (to sustain plants) and hardness (a property of the clay based media) were significantly greater for the green roofs, approximately 300% for phosphorous and potassium, and as much as 1000% for magnesium. Analysis for other ions did not statistically discern whether the loadings were greater or lesser from green roofs. Partly, this is due to the small sampling size, but also indicates that beyond proper management of the planting media to reduce excess nutrient release, loadings from green roofs are not significant. Results based on this smaller, limited water quality monitoring data set (five samples) should be used cautiously.

Green roofs appeared to be beneficial for the removal of atmospheric nitrate. In the summer when green roofs retained nearly 100% of the precipitation almost no nitrate ran off the green roofs. Water quality impacts of a green roof are thus seasonal plant-related mechanisms and depend on both the input concentration and the precipitation and runoff rates.

The data collected suggest that the best use of a green roof is probably in conjunction with other stormwater BMPs such as bio-infiltration and rain gardens, where possible. Runoff discharged to stormwater collection systems that have water quality BMPs, is preferred; however, the time delay and volume reduction provided by green roofs still offer receiving water quality benefits for stormwater systems that discharge without treatment. For this reason, discharge of green roof runoff to a combined sewer system is appropriate and desirable, due to the significant reduction of volume discharge and extension of time to peak, regardless of discharge concentration. Green roofs are an important stormwater technology for urban areas with limited space for retrofitting BMPs into the existing conveyance system. Direct discharge of roof runoff to the receiving water is not recommended.

Evaluating Evaporation and Evapotranspiration Rates of Green Roofs

Eight 0.5 m^2 (6.1 ft^2) weighing lysimeters planted with a mixture of *Delosperma nubigenum* and *Sedum album* were compared to unplanted media. These lysimeters were monitored during 21-day dry-down cycles during warm actively growing periods and cool dormant periods. Drying cycles lasted 21 days.

Green roof plants rapidly lose water following irrigation after which water loss rates decline. This is a new finding. Initial ET from green roofs was similar to other measured systems and could be described using normal ET prediction equations such as Pennman-Monteith. Unplanted media lost water at a similar rate initially, but after several days, water loss rates declined below that of the green roofs. Thus plants are essential to the system, while the unplanted media are limited to evaporating water from the surface, the plants continue to remove water from down in the media, resulting in quick recharge of the stormwater runoff reduction potential.

These data demonstrate the superiority of a planted roof over an equivalent ballast roof for retention of stormwater during the summer months. Rapid initial loss of water from these plants followed by drought adaptation is a new finding that provides an important component of any model or design tool to predict the effectiveness of a green roof as a stormwater tool.

Factors Affecting Green Roof Establishment and Maintenance

Media type, depth, and early drought were evaluated as factors affecting establishment and early management of a green roof. A test procedure for evaluating long-term pH buffering of the roof was developed and evaluated.

Early drought is very detrimental to the survival and establishment of green roof plants particularly with shallow media depths. Sedum species may survive but other green roof plants may not survive. The results suggest that 3 - 4 in. (80 - 100 mm) of irrigation with the potential for supplemental irrigation during establishment will result in better plant survival rates.

Tests of the pH buffering capacity of the planting media suggest that the green roof media can buffer acid precipitation for approximately 10 years, after which it may be necessary to amend the media with lime to maintain the pH buffering capacity.

Implications

Green roofs can attain an annual 50% reduction in roof runoff. From a practical standpoint, this potentially translates into a reduction in area and volume control needed for the typical suite of water quality BMPs. In terms of practice, the stormwater volume and increased time to peak control offered by green roofs could result in more building space, additional parking spaces or additional and usable open space. However, this concept would need to be field tested at a larger scale and the actual percent reduction in stormwater BMPs would need to be evaluated, e.g., potential BMP reduction may be between 5 and 20%, not a full 50% annual capture, particularly in areas with dormant (winter) seasons.

Clay-based media may be better in areas affected by drought due to water retaining capacity of the media. Shale-based media may be better for areas subject to more frequent precipitation, particularly acid precipitation.

Recommendations

In this project, several constituents of concern from the green roof were studied. Results demonstrated that green roofs may reduce certain pollutants, e.g., acid precipitation and nitrate, but that it may increase loadings directly related to these planted systems, e.g., phosphorous, potassium, calcium, and magnesium. Due to the variability in results, continued sample collection and analysis to minimize the variability may be warranted. Further testing of materials used for green roof construction and planting should be conducted to determine loadings coming from roofs. Also, other constituents from atmospheric deposition and building materials for standard roofing should be tested under controlled systems. The nitrate results should not be viewed as a surrogate for all nitrogen and future studies should look at total nitrogen, and potentially ammonia and total Kjeldahl

Sampling for some of the water quality parameters was only represented by five storms; additional sampling is warranted due to the small size of this data set. In addition, only analyzing five paired events for green and flat asphalt roof runoff may have biased results toward lower loadings from the flat asphalt roofs as not as much rain was required to produce runoff, i.e., diluted flat asphalt runoff was compared to higher concentration, lower volume green roof runoff. If further comparison tests are performed to standard roofing materials and systems, paired analysis of loadings should include storm results from other roofing systems and should include a full range of precipitation events, from when green roofs are not producing runoff to events with large amounts of runoff. The greatest benefit green roofs can provide is the reduction in runoff, which is also a water quality benefit not adequately represented by the five paired data points.

The field site provided statistically valid results for runoff volumes and much of the concentration data; however, the calculated loadings are based on relatively small experimental rooftops, when compared to an urban watershed. Due to the variability observed in this study, modeling loadings for green roofs for watershed management may require additional monitoring with full-scale roofs or multiple roofs in an urban setting.

The size and time interval limited analysis of peak flows from the green roofs. Additional hydrology monitoring may be warranted on larger roofs to better determine potential peak flow values from green roofs.

The half-media and half-detention roofs, while providing insight to the experiment, were of limited value for individual storms because of the absence of replicates. Splitting the roof into two media sections or two detention sections would have provided additional replicates. Another rain gauge or triangulation of rain gauges around the buildings would have provided more insight to rainfall totals.

The laboratory studies indicate that ET can be modeled using standard equations; however, further testing should be conducted. Data suggest there may be a need to develop unique water loss model factors to account for water loss patterns in *Sedum* carpet roofs to accurately predict rate of recharge for water detention capacity.

The drought studies indicated some potential limitations without the use of irrigation. Green roofs need to be tested in other climates so that further design specifications on plant mixtures, media depth and amendments, and potential irrigation requirements can be determined. Other climatic conditions should also include year-to-year or long-term studies, as it seems very likely that in dry years the green roof runoff would be far less than in wet years.

The effects of green roof runoff discharge on receiving waters or the potential for additional treatment of green roof discharge were not addressed. For suburban or agricultural areas, green roof runoff treatment may be as simple as directing the downspouts to grassed areas (vegetated filter strips or swales) or collecting green roof runoff in rain barrels to be used for irrigation, but this may not be practical for urban areas where there is limited room for stormwater controls. For urban areas that have combined sewers, green roofs should be viewed as a benefit due to the volume reduction to the combined system and the delay in time to peak. The same can be said for stormwater conveyance systems that drain to stormwater BMPs. The effects of mixing and the delay in time to peak may be sufficient to allow discharge to stormwater conveyance systems that discharge to a receiving water even without treatment; however, further studies or modeling exercises may be warranted. Directly discharging green roof runoff to a receiving water is not recommended.

Additional lysimeter studies should be conducted to identify more plant species suitable for green roofs, especially varieties that are drought resistant and require minimal nutrient supplements.

Chapter 3 Green Roof Effects on Runoff Quantity

Introduction

Runoff samples were collected from six small buildings at the Center for Green Roof Research at Rock Springs, PA during the period from January 2005 through November 2005. Runoff from three green roofs, two flat-asphalt control roofs, and one roof divided between detention and a green-roof system without plants, was collected in rain barrels. Comparisons of runoff volumes are presented among roof types. Runoff water volume varied with both sample event and roof type. Analyses were performed on the study period, monthly and individual storm basis.

Methods

Six similar structures, three with green roofs, two with standard asphalt rolled roofing and one with half of the roof in a custom-built detention section, and the other half with an unplanted green roof media were used for this study. All green roofs were constructed to be identical replications of each other to allow statistical analysis and comparisons. The rooftop storage section was designed to provide approximately 1.0 in. (25 mm) of short-term water detention with slow release, and the unplanted media section containing lightweight expanded shale and compost amendment, was included as a control to evaluate the effects of plants on roofs in the field. Structures were insulated, heated, and air conditioned. Each structure was a 6 x 8 ft (1.8 x 2.4 m) building with a nearly flat roof (1:12 pitch). A covered gutter and downspout was attached to the lower end of each roof to collect all runoff from the roof. Each downspout drained into a 60 gal (230 L) plastic barrel. Total barrel capacity was approximately 2 in. (50 mm) of rain over the roof surface. Rain exceeding barrel capacity could overflow the top of the barrel to the ground, so in anticipation of overtopping during the largest storm monitored, the barrels were emptied to allow complete monitoring of the storm (as noted in comments Table 3-1). This size roof and barrel size combination allowed for complete capture for all but one event in the study. This was a unique approach to monitoring of green roofs.

Each barrel was connected to a pressure transducer to provide continuous measurement of the water level in the barrel. Pressure transducers were connected to a Campbell data logger which recorded the pressure every five minutes. The pressure transducer systems have a sensitivity which allows determination of approximately 0.02 in. (0.5 mm) of water runoff from the roof area. This sensitivity was more than adequate for assessing the total volume of the storms, but did introduce some uncertainty and variation in time series analysis or instantaneous results, as the transducer might toggle between values or experience drift. The data logger was downloaded to a PC hard drive every couple of days. Barrels were calibrated and standard curves developed to relate pressure to gallons of water in the barrel by adding water in increments until the barrel was full.

Barrels were periodically emptied, usually after each rain event, but during the winter for snow events and during periods where the end of a rain event was unclear, several defined events were combined. Barrels were enclosed in insulation and heat tape inside the barrels and gutters was used to prevent freezing of the barrel and associated gutter systems. Flat asphalt roofs were covered with standard asphalt roofing. Green roofs had a 1 x 4 wooden frame mounted to the top of the roof to contain the green roof system. The green roofs consisted of 3.25 in. (8.5 cm) of an expanded, clay-based mineral placed on top of a 0.75 in. (2.0 cm) drainage layer (Enkadrain 9615, Colbond, Enka, NC) for a total roof profile of 4 in. (10.5 cm) deep. The green roofs were first planted with *Sedum spurium* in the fall of 2001. *Sedum album* and *Delosperma nubigenum* were added at about 10% coverage per species in the spring of 2003. *Delosperma nubigenum* did not survive the winter. During the study the growth distribution on the three roofs was 90% *Sedum spurium* and 5% *Sedum album*. Approximately 5% of the roof surface, mostly near the edges, was not covered by plants and remained bare media throughout the study period. A weather station including a tipping bucket rain gage, temperature, light, humidity, and wind speed and direction sensors was located on the corner of the roof of the building with the split roof that housed the data storage. Weather station data were recorded every 5 minutes to correspond with data obtained from the pressure transducers. Data from the weather station were downloaded once each week. The measurement limit for the weather station was 0.01 in. (0.25 mm) (one bucket tip).

For the purpose of runoff data, a storm event was considered to be any event which resulted in more than 0.02 in. (0.5 mm) of rain preceded and followed by a minimum of 6 hr without measurable precipitation. Data used in the analysis included 1 hr before to 1 hr after the end of the precipitation event.

Measurements were terminated in November, 2005 when a cold spell froze and ruptured five of seven pressure transducers. Barrel connections to the pressure transducers also froze in January, 2005 and February, 2005, but the transducers were not damaged for these periods. A lightning strike in early July, 2005 damaged several transducers, the datalogger PC interface, and destroyed the PC. All transducers were replaced and calibrated, the datalogger interface was repaired and the PC was replaced. No runoff data were collected for the period from July 6, 2005 through July 23, 2005. There were several other events during the evaluation period where data were not complete either because of data-logging errors (Februrary 14, 2005 and March 28, 2005) or because the drain valves for the barrels were left open (November 9, 2005).

Precipitation Summary

A total of 111 events during the monitoring period resulted in 35.5 in. (902 mm) of precipitation measured by the weather station on the site (Table 3-1). Of the 111 total events 83 events resulted in precipitation greater than 0.02 in. (0.5 mm) for a total precipitation of 34.9 in. (902 mm). There were 54 events with greater than 0.10 in. (2.5 mm) of precipitation and seven events with more than 1 in. (26 mm) of precipitation. The largest single event occurred October 7, 2005 when 3.2 in. of precipitation was recorded. Roof runoff data were collected from 72 events with a total precipitation of 26.9 in. (683 mm). Winter (January - March) included snow, freezing rain and rain events.

Table 3-1 Precipitation Event Summary

Event number	**Event date start**	**Start time**	**Event date end**	**End time**	**Total Precipitation (in.)**	**(mm)**	**Comments**
1	01/02/05	10:05 PM	01/03/05	5:05 AM	0.03	0.8	Rain
2	01/03/05	11:15 AM	01/04/05	7:25 AM	0.81	20.6	Rain
3	01/05/05	1:35 AM	01/06/05	5:13 PM	2.02	51.3	Rain
4	01/08/05	4:48 AM	01/08/05	9:33 AM	0.43	10.9	Rain
5	01/11/05	4:28 PM	01/12/05	10:52 AM	0.64	16.3	Snow - precipitation total as measured by rainguage, not actual snow depth.
6	01/13/05	10:47 PM	01/14/05	5:52 AM	0.48	12.2	Snow/rain
7	01/30/05	11:15 AM	01/30/05	12:10 PM	0.05	1.3	Snow
8	02/04/05	9:55 AM	02/04/05	11:55 AM	0.07	1.8	Snow
9	02/08/05	2:51 AM	02/08/05	8:01 AM	0.21	5.3	Snow
10	02/09/05	1:41 PM	02/09/05	8:36 PM	0.74	18.8	Snow/rain
11	02/14/05	12:56 PM	02/14/05	7:46 PM	0.73	18.5	Incomplete data set - logging error. Data only available for first 0.3 in.
12	02/16/05	8:41 AM	02/16/05	10:16 AM	0.05	1.3	Snow/Rain

Event number	Event date start	Start time	Event date end	End time	Total Precipitation		Comments
					(in.)	(mm)	
13	02/21/05	11:56 AM	02/21/05	6:06 PM	0.25	6.4	Snow
14	02/25/05	12:55 PM	02/25/05	3:15 PM	0.08	2.0	Snow
15	03/01/05	1:00 PM	03/01/05	1:00 PM	0.01	0.3	Snow
16	03/03/05	10:45 AM	03/03/05	11:20 AM	0.02	0.5	Snow
17	03/04/05	9:55 AM	03/04/05	11:35 AM	0.07	1.8	Snow
18	03/07/05	11:02 PM	03/08/05	2:47 AM	0.11	2.8	Snow/rain
19	03/11/05	10:47 AM	03/11/05	5:42 PM	0.13	3.3	Snow/rain
20	03/12/05	1:07 PM	03/12/05	4:17 PM	0.02	0.5	Snow
21	03/20/05	7:38 AM	03/20/05	10:48 AM	0.07	1.8	Snow
22	03/23/05	3:57 AM	03/23/05	12:42 PM	0.42	10.7	Snow
23	03/23/05	7:52 PM	03/23/05	10:17 PM	0.02	0.5	Snow
24	03/24/05	8:22 AM	03/24/05	3:22 PM	0.5	12.7	Snow
25	03/25/05	11:22 AM	03/25/05	12:07 PM	0.03	0.8	Snow
26	03/26/05	9:17 AM	03/26/05	9:17 AM	0.01	0.3	Snow
27	03/27/05	5:17 PM	03/28/05	2:52 AM	0.58	14.7	Rain
28*	03/28/05	9:07 AM	03/29/05	3:27 AM	1.28	32.5	Incomplete data set - logging error. Data only available for first 063 in.
29	04/01/05	9:45 PM	04/03/05	12:45 AM	0.7	17.8	Snow/Rain
30	04/03/05	4:05 PM	04/03/05	10:15 PM	0.07	1.8	
31	04/20/05	9:09 PM	04/20/05	9:44 PM	0.08	2.0	
32	04/22/05	5:58 PM	04/23/05	7:58 AM	0.28	7.1	
33	04/23/05	3:23 PM	04/23/05	4:38 PM	0.22	5.6	
34	04/24/05	3:18 PM	04/24/05	6:38 PM	0.05	1.3	
35	04/27/05	12:00 AM	04/27/05	1:00 AM	0.02	0.5	
36	04/29/05	4:15 AM	04/29/05	10:40 AM	0.04	1.0	
37	04/30/05	2:25 AM	04/30/05	6:20 PM	0.18	4.6	
38	05/14/05	4:39 AM	05/14/05	4:44 AM	0.04	1.0	
39	05/14/05	6:54 PM	05/15/05	3:39 AM	0.26	6.6	
40	05/19/05	9:44 PM	05/20/05	11:04 AM	0.46	11.7	
41	05/21/05	4:44 AM	05/21/05	4:44 AM	0.01	0.3	
42	05/21/05	7:44 PM	05/21/05	8:14 PM	0.03	0.8	
43	05/22/05	2:44 AM	05/22/05	2:44 AM	0.01	0.3	
44	05/23/05	7:54 AM	05/23/05	3:13 PM	0.32	8.1	
45	05/24/05	12:03 PM	05/24/05	5:08 PM	0.12	3.0	
46	05/25/05	5:43 AM	05/25/05	5:43 AM	0.01	0.3	
47	05/28/05	10:51 AM	05/28/05	6:41 PM	0.37	9.4	
48	05/30/05	5:56 PM	05/30/05	10:36 PM	0.03	0.8	
49	06/03/05	2:32 AM	06/03/05	5:52 PM	0.28	7.1	
50	06/04/05	10:57 AM	06/04/05	10:57 AM	0.01	0.3	
51	06/06/05	11:45 AM	06/06/05	5:10 PM	0.67	17.0	
52	06/07/05	7:25 AM	06/07/05	7:25 AM	0.01	0.3	
53	06/09/05	3:50 PM	06/09/05	4:00 PM	0.15	3.8	
54	06/10/05	3:25 PM	06/11/05	4:15 AM	0.21	5.3	
55	06/13/05	2:35 PM	06/13/05	2:50 PM	0.05	1.3	
56	06/16/05	3:48 AM	06/16/05	3:48 AM	0.01	0.3	
57	06/17/05	1:18 PM	06/17/05	1:23 PM	0.06	1.5	No water in barrels
58	06/22/05	5:38 AM	06/22/05	5:38 AM	0.01	0.3	

Event number	Event date start	Start time	Event date end	End time	Total Precipitation (in.)	Total Precipitation (mm)	Comments
59	06/28/05	9:42 PM	06/28/05	10:17 PM	0.02	0.5	
60	06/29/05	6:32 AM	06/29/05	6:32 AM	0.01	0.3	
61	06/30/05	3:47 AM	06/30/05	3:47 AM	0.01	0.3	
62	07/05/05	6:18 PM	07/05/05	11:18 PM	0.75	19.1	Runoff estimated from barrel content
63	07/06/05	3:18 PM	07/06/05	3:18 PM	0.03	0.8	NDC - system down from lightning strike
64	07/07/05	8:53 PM	07/08/05	4:18 PM	1.13	28.7	
65	07/09/05	4:38 AM	07/09/05	4:38 AM	0.01	0.3	
66	07/14/05	5:14 PM	07/14/05	5:54 PM	0.03	0.8	
67	07/16/05	2:29 PM	07/16/05	2:49 PM	0.64	16.3	
68	07/16/05	9:34 PM	07/17/05	5:49 AM	1.31	33.3	
69	07/17/05	2:09 PM	07/17/05	3:29 PM	0.21	5.3	
70	07/21/05	2:49 PM	07/21/05	3:19 PM	0.08	2.0	
71	07/21/05	6:09 PM	07/21/05	6:09 PM	0.01	0.3	
72	07/22/05	8:44 PM	07/22/05	8:44 PM	0.02	0.5	
73	07/23/05	2:49 AM	07/23/05	2:49 AM	0.01	0.3	
74	07/25/05	1:19 AM	07/25/05	9:09 AM	0.68	17.3	Resumed data collection.
75	07/26/05	9:32 PM	07/26/05	9:52 PM	0.04	1.0	
76	07/27/05	2:07 PM	07/27/05	3:37 PM	0.03	0.8	
77	08/07/05	6:47 AM	08/07/05	7:57 AM	0.04	1.0	
78	08/08/05	6:52 AM	08/08/05	12:47 PM	0.29	7.4	
79	08/11/05	2:41 PM	08/11/05	3:06 PM	0.31	7.9	
80	08/16/05	6:56 AM	08/16/05	4:36 PM	0.98	24.9	
81	08/17/05	6:26 AM	08/17/05	6:26 AM	0.01	0.3	
82	08/19/05	3:11 AM	08/19/05	10:51 AM	0.27	6.9	
83	08/20/05	2:06 AM	08/20/05	2:06 AM	0.01	0.3	
84	08/20/05	9:26 PM	08/20/05	10:36 PM	0.03	0.8	
85	08/27/05	3:27 PM	08/28/05	4:02 AM	0.21	5.3	
86	08/29/05	7:32 PM	08/29/05	9:07 PM	0.05	1.3	
87	08/30/05	7:27 AM	08/30/05	10:37 AM	0.04	1.0	
88	08/30/05	11:42 PM	08/31/05	4:52 PM	1.43	36.3	
89	09/15/05	2:33 AM	09/15/05	2:38 AM	0.04	1.0	
90	09/16/05	2:43 PM	09/16/05	4:38 PM	0.14	3.6	
91	09/18/05	7:13 AM	09/18/05	7:33 AM	0.02	0.5	
92	09/24/05	5:21 PM	09/24/05	5:41 PM	0.02	0.5	
93	09/26/05	9:21 AM	09/26/05	6:33 PM	0.48	12.2	
94	09/29/05	7:18 AM	09/29/05	9:08 AM	0.25	6.4	
95	10/07/05	6:46 AM	10/08/05	11:21 AM	3.2	81.3	Barrels emptied to prevent overflowing.
96	10/08/05	5:36 PM	10/08/05	6:21 PM	0.02	0.5	
97	10/12/05	2:44 AM	10/12/05	9:34 AM	0.07	1.8	
98	10/13/05	8:19 PM	10/14/05	8:24 AM	0.04	1.0	
99	10/14/05	5:39 PM	10/14/05	5:59 PM	0.02	0.5	
100	10/20/05	10:21 AM	10/20/05	10:21 AM	0.01	0.3	
101	10/20/05	8:41 PM	10/21/05	6:01 AM	0.16	4.1	
102	10/21/05	10:31 PM	10/22/05	7:31 PM	0.6	15.2	
103	10/24/05	4:46 AM	10/24/05	1:21 PM	0.22	5.6	
104	10/24/05	7:56 PM	10/25/05	9:21 AM	0.48	12.2	
105	10/25/05	5:31 PM	10/26/05	3:26 PM	1.35	34.3	

Event number	Event date start	Start time	Event date end	End time	Total Precipitation (in.)	Total Precipitation (mm)	Comments
106	11/01/05	5:37 PM	11/01/05	8:02 PM	0.2	5.1	
107	11/02/05	9:12 AM	11/02/05	9:12 AM	0.01	0.3	
108	11/06/05	4:03 PM	11/06/05	4:18 PM	0.02	0.5	
109	11/09/05	7:38 AM	11/09/05	9:03 PM	0.23	5.8	NDC - barrel valves open.
110	11/14/05	11:42 PM	11/15/05	9:47 AM	0.69	17.5	
111	11/16/05	7:27 AM	11/16/05	4:57 PM	0.51	13.0	

NDC - No data collected

Analysis

Roof Runoff Volumes

For 26.9 in. (683 mm) of recorded precipitation, there was a corresponding mean value of 12.7 in. (323 mm) with a standard deviation of 2.8 in. (71 mm) of green roof runoff compared to a mean of 23.1 in. (587 mm) with a calculated standard deviation of 1.7 in. (43 mm) for the flat asphalt roofs. (Note: Standard deviation values were also calculated for two replicates of the flat asphalt roof, while recommendations are typically for a minimum of three). The green roofs retained 52.6% while flat asphalt roofs retained 14.1% of the precipitation. It is not surprising that some retention should occur with rolled asphalt roofing; all surfaces have “nooks and crannies” where initial abstractions (losses) of precipitation fill before runoff can occur. Additionally, some precipitation likely evaporated from roof surfaces, and some most likely was lost to splashing over the edges. The detention roof had 21.8 in. (554 mm) of runoff based on 26.1 in. (554 mm) of precipitation (excluding events from May 19, 2005 through May 24, 2005 when transducer not working properly), only retaining 16.3 %. The media-only roof had runoff of 15.8 in. (400 mm) based on 22.4 in.(569 mm) of precipitation (excluding February and events after October 25, 2005 when transducer not working properly) retaining 29.7%.

Rainfall retention by green roof buildings varied from month to month. Retention in cool weather months (January, through March, October and November) was less than in the warm weather months (April through September) (Figure 3-1). During the summer months almost no runoff from green roofs was observed; however, as might be expected, during wetter periods some runoff from the green roofs was observed. For example, runoff in August was 18% of the 3.65 in. (93 mm) of precipitation, as compared to September, which was only 4% of the 0.91 in. (23 mm) of precipitation. In the cool months, drier periods increased retention and produced less runoff, than during wetter periods. For example, only 44% of the 1.7 in. (43 mm) of precipitation in February generated runoff, while runoff of 71% and 82%, respectively was generated in the month of March with 2.54 in. (65 mm) of precipitation, and January with 4.46 in. (113 mm) of precipitation.

In the warm months, nearly all precipitation was retained by the green roofs. In contrast there was no real difference in retention by flat asphalt roofs between cool and warm season periods (Figure 3-2). Error bars represent the standard deviation for the three green roofs and two flat asphalt roofs for each month. These results are similar to results from monitoring of these roofs before the start of this study (Denardo et al., 2005) and other stormwater retention studies in the U.S. and Europe which also suggested that about 50% of the annual precipitation in certain climates can be retained by a green roof.

In addition to the green and flat asphalt roofs, the unplanted media roof section had similar runoff to the planted green roofs in cool months (within one standard of deviation green roof runoff), but much more runoff from April through September (exceeded standard of deviation of green roof runoff in Figure 3-2). Because the difference between the media section and green roofs is the plants, it is not surprising that the difference in runoff would be limited to periods when the plants are actively growing and transpiring. The media appear to play a role in some runoff retention when compared to flat roofs in six of nine directly comparable months, though this data is not as robust due to limited sample size.

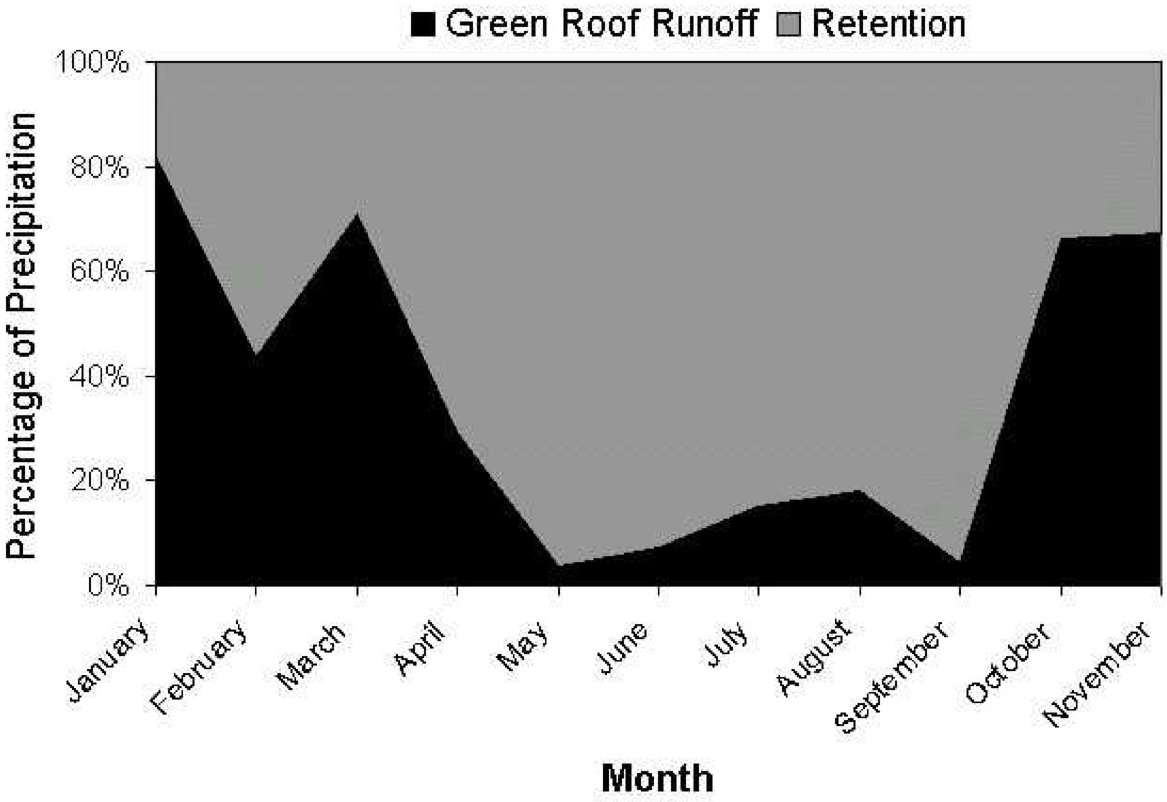


Figure 3-1 Retention and runoff from green roofs (percentage of average monthly precipitation)

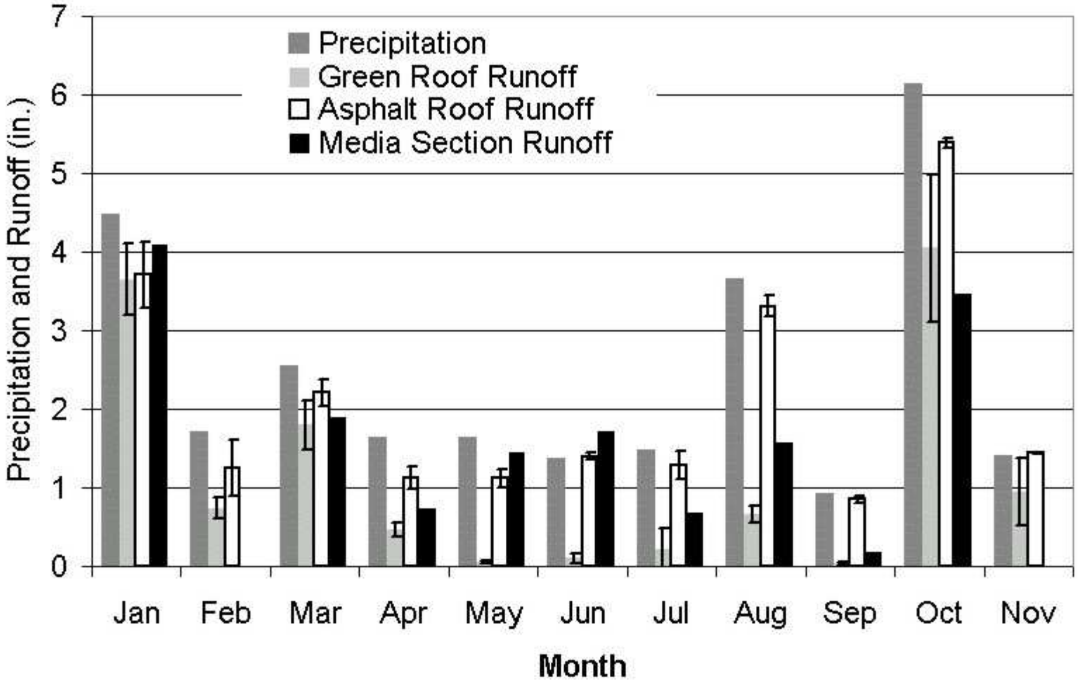


Figure 3-2 Monthly average precipitation and runoff for green and asphalt roofs including unplanted media roof section

This suggests that although some of the stormwater retention of a green roof can be obtained by simply putting an equivalent amount of media on the roof, the effectiveness will be less than if plants are used. Clearly, the plants serve more than an aesthetic purpose on the roof.

The runoff from the green roofs is much more variable with a cumulative monthly standard deviation (error bars in Figure 3-2) of 2.82 compared to the runoff from the flat asphalt roof with a standard deviation of 1.68. Even though the green roofs in the study were constructed to be identical, there were sometimes fairly large differences in retention for any given precipitation event. There were no obvious reasons for these differences. Plant cover and health was similar for all the green roof buildings, and the retention differences were not related to a specific building. Green roof design contributes to this variation, as it relies on non-uniform media and random survival rates of individual plantings.

Error bars may not capture all the potential variation in measurements of the precipitation and runoff monitoring system of the different roof types during the experiments. There was some drift in the pressure transducer values. One prominent example of drift is that of the flat-roof pressure transducers which appears to have decreased total accumulation on May 15, 2005 by at least -0.2 in. (5 mm) Another case of drift by the pressure transducer of the media roof for June 6, 2005, resulted in a 0.6 in.(15 mm) gain, as pictured below in Figure 3-3. This explains, at least in part, why the unplanted media roof total exceeded the flat roof totals for May and June in Figure 3-2. The results show that while drift may be a concern particularly for individual events, in terms of annual values, drift is only one source of error potentially contributing to the overall variability. Another factor is that some data were not duplicated for each storm event. There are no duplicates for the media and retention rooftop half-roof sections, this limits the degree of confidence for individual storm totals from these roofs. Precipitation measurements, typically a stand alone measurement, were also not duplicated, though this does not completely explain why, for some events, runoff totals unexpectedly exceeded precipitation totals. This was most likely due to antecedent or freezing precipitation conditions; the latter is discussed in more detail below. As noted earlier, however, there were precipitation events that were not monitored for runoff; therefore, discerning effects of antecedent conditions of several storms for all roofs was not always possible. For seasonal and annual assessments, individual storms are treated as replicates, while for comparison of individual events, only the asphalt and green roofs are compared with rainfall totals as a baseline.

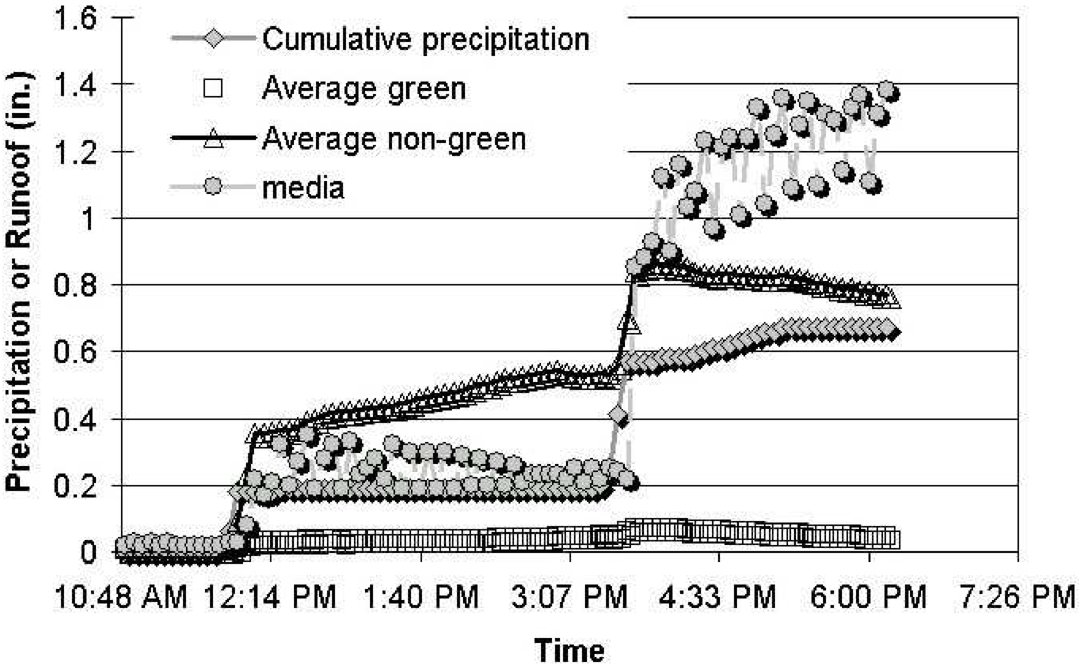


Figure 3-3 Measurements for June 6, 2005

The retention and runoff from green roofs also varied from one precipitation event to another. Figure 3-4 shows precipitation events for which runoff was generated. Trend line analysis fit using second order polynomial shows that the lines are parabolic in nature (Microsoft® Office Excel 2003). Green roof runoff data were not collected for events between July 5, and July 22, 200505, or after November 16, 2005 and error bars represent the standard deviation for three green roofs for each event measured. The green roof runoff trend line reinforces the observed seasonal effect demonstrating that there was little or no runoff from the green roof during the warm summer months. The regression coefficients were quite low ($r^2 \sim 0.1$), due to the randomness of the quantity and interval between storm events.

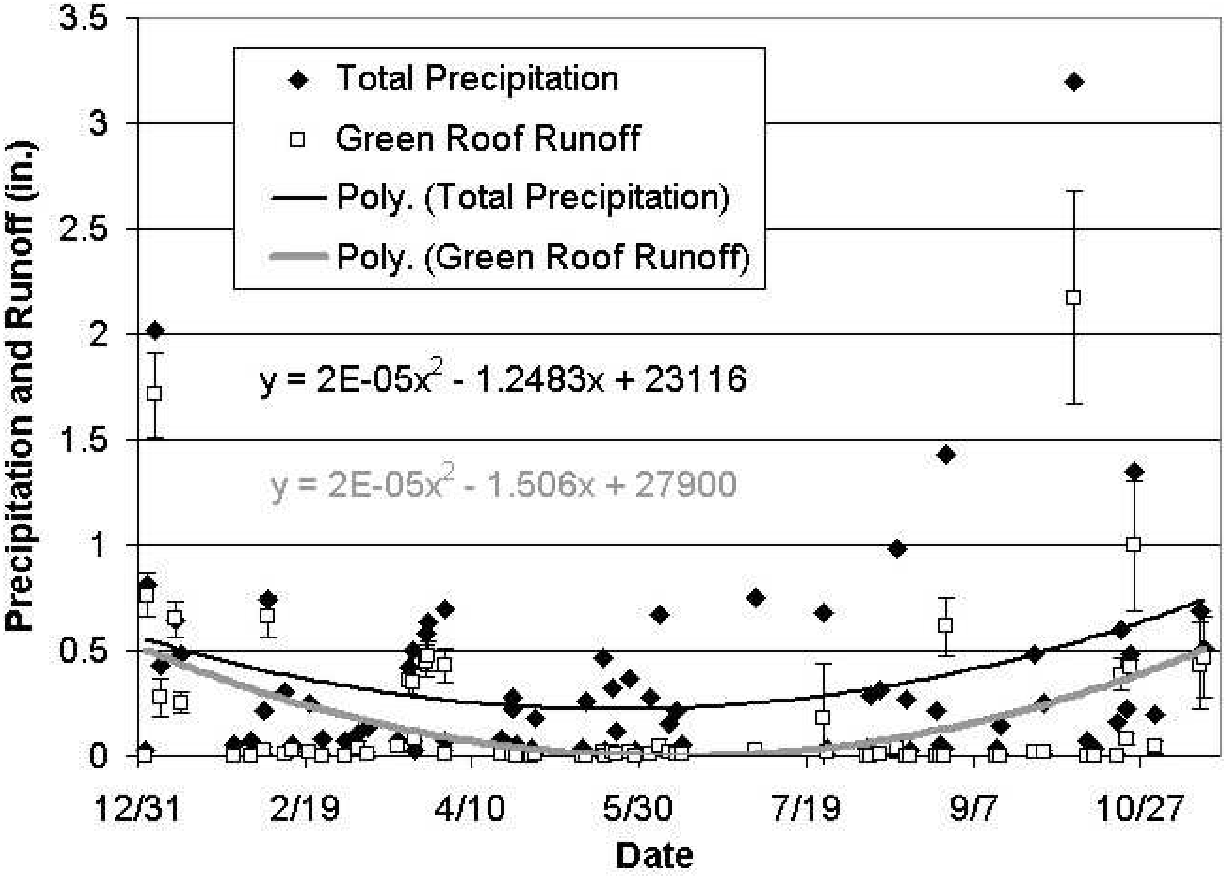


Figure 3-4 Plot of precipitation versus runoff from green roofs for paired events

An analysis of cumulative probability was performed, using 72 of the events and sorting based on the size of the precipitation events. The graph in Figure 3-5 is seasonally independent and used a rise-to-maximum function. A major conclusion from the graph is that green roofs have little or no runoff for 65% of the precipitation events up 0.4 in.(10 mm) of precipitation, regardless of season (with few exceptions, e.g., due to wet antecedent conditions on October 24, 2005 at the 0.51 percentile). A regression analysis for the precipitation event totals resulted in an r^2 value that is very high, 0.98, while the r^2 for the retained precipitation is 0.61. This regression value for retained precipitation is lower for two reasons. First, larger precipitation events have more runoff and greater variability in the green roof retention, and secondly, this sorting did not account for period between storms. This graph shows there will be more green roof runoff for larger storms; however, this is a volume assessment only, and does not quantify initial abstraction and time to peak that a green roof provides in delaying runoff. Two points of the retained precipitation were not used, as these values were negative, i.e., there was more runoff than precipitation. As both occurrences were in winter, January and March, they were most likely the result of the additional release of snow or ice melt from the roofs.

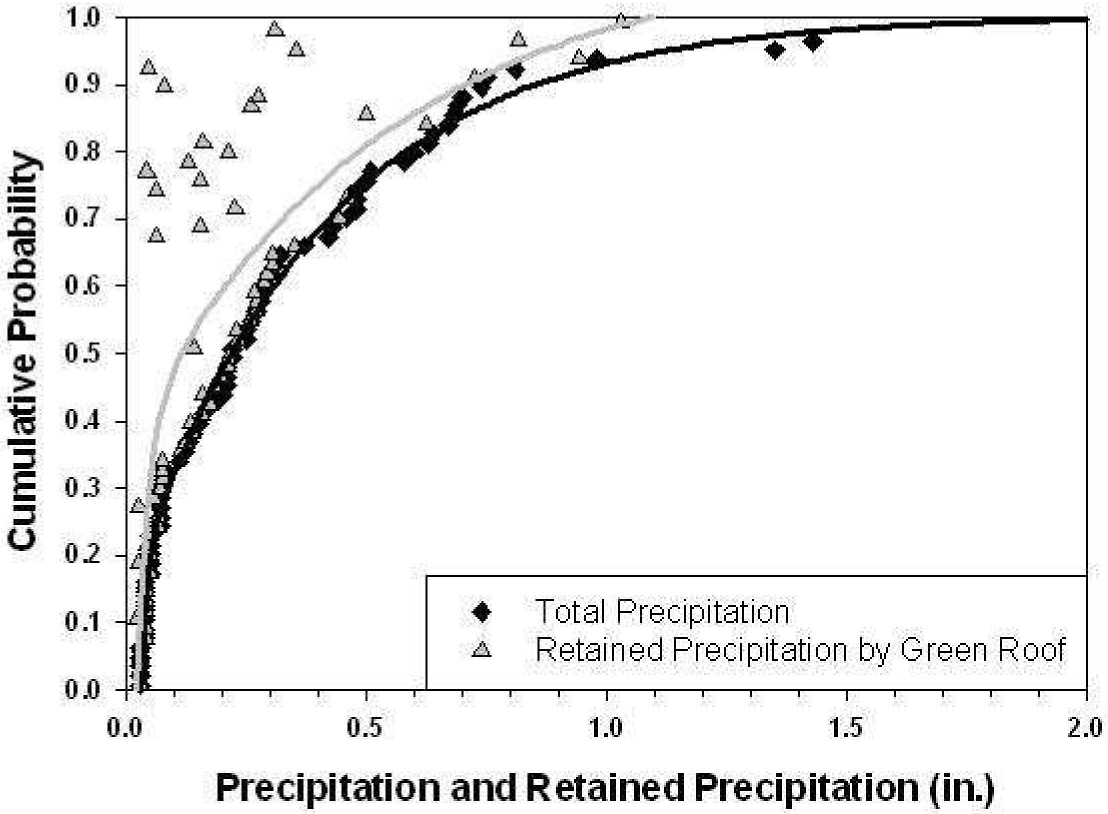


Figure 3-5 Probability plot of precipitation versus retained precipitation by green roofs

During winter storms the media in a green roof may freeze and slowly release moisture over an extended period. Snow may also accumulate and melt over an extended period. Figure 3-6 is a graph of several events during the period from March 23 through March 29, 2005, which included three storms consisting of snow (March 23 through March 25) and mixed precipitation (March 28). Precipitation and runoff (with out error bars, which would increase obscuration of the precipitation line) were plotted against each other on the same scale to show the retention and release as runoff of precipitation. Liquid precipitation (measured by the weather station tipping bucket) was about 1.6 in. during this period. Essentially, all the precipitation became runoff from the green roofs, but the runoff was clearly delayed as the snow melted. Interestingly, the runoff from the flat asphalt roofs followed very closely the runoff from the green roofs. All structures in this study were heated in winter and air-conditioned during the summer. The controlling mechanism for runoff in the time period of this graph was probably ambient temperature and sunlight as the predominant form of precipitation was snow and freezing rain. While these structures may not have had the most representative roof in terms of more sophisticated buildings, this tends to confirms anecdotal observations that snow on green roofs will generally melt with time.

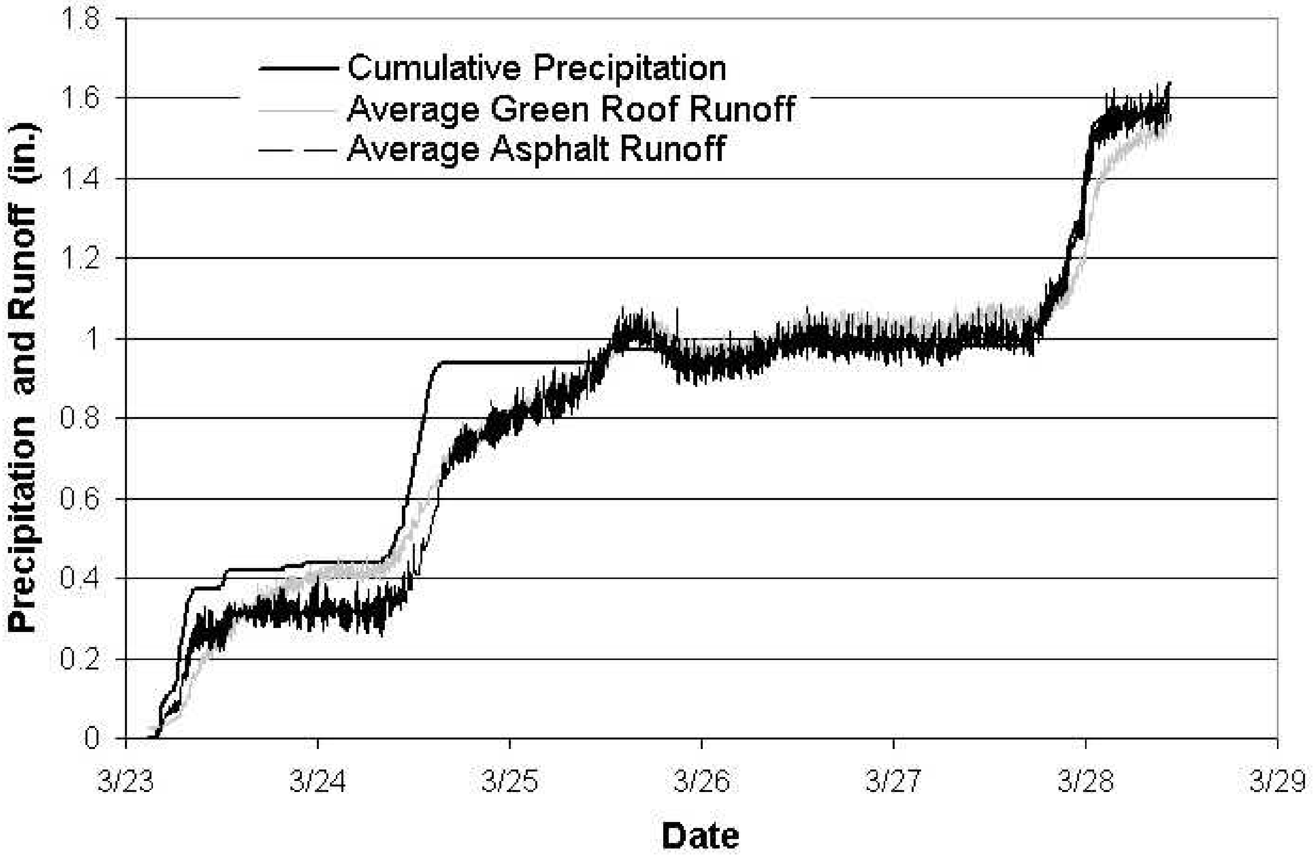


Figure 3-6 Precipitation and green and asphalt roof runoff from snow and mixed precipitation events in March, 2005

In addition to seasonal effects, runoff from green roofs was also greater for large storms or from precipitation events in close succession. The effect of the period between storms can be observed by looking at the results of select individual storms. For example (Figure 3-7), on August 16, 2005 there was 0.98 in. (25 mm) of precipitation and nearly all the precipitation was retained by the green roof (96%). In contrast (Figure 3-8), the August 30, 2005 precipitation was about 1.4 in. (36 mm) and the green roofs only retained 57% of the precipitation. Since the green roof media holds about 30% water by volume and the roofs were 3.5 - 4 in. (8 - 10 cm) deep the total water holding capacity of the roof should have been about 1.0 to 1.5 in. (25 to 38 mm), of which some is tightly bound and some is readily exchangeable, i.e., to be taken up by plants or evaporated. As media moisture is recharged through rain or lost to evaporation and taken up by plants, the potential to retain water for the next storm changes. The implications become clear in a closer examination of these two August precipitation events. Almost all the 0.98 in. (25 mm) rain was retained on August 16 due to no rain for five days. On August 30, with 1.4 in. (36 mm) of new precipitation and 0.3 in. (8 mm) from the preceding days, only about 1.0 in. (25 mm) was retained, while 0.6 in. (15 mm) of runoff was released from the green roofs. This is also the case for the large storm on October 7-8, where 2.2 in. (56 mm) of the 3.2 in. (81 mm) of precipitation were not retained by the green roofs (Figure 3-9).

Note, that there is a 0.2 in. (5 mm) gap between the rainfall total and asphalt roof discharge at 3:00 AM on Figure 3-7. Some of the rain falling on the flat roof at peak intensity must have either splashed off or potentially spilled over the size due in part to the flatness of the surface. Because of the more complex three-dimensional nature of the green roof, i.e. plants and media, it is assumed the green roof actually captured more rainfall than the asphalt roof. This is supported by data (not shown) from the split roof where the media and detention sections approached 1.2 in. (30 mm), of capture at 3:00 AM.

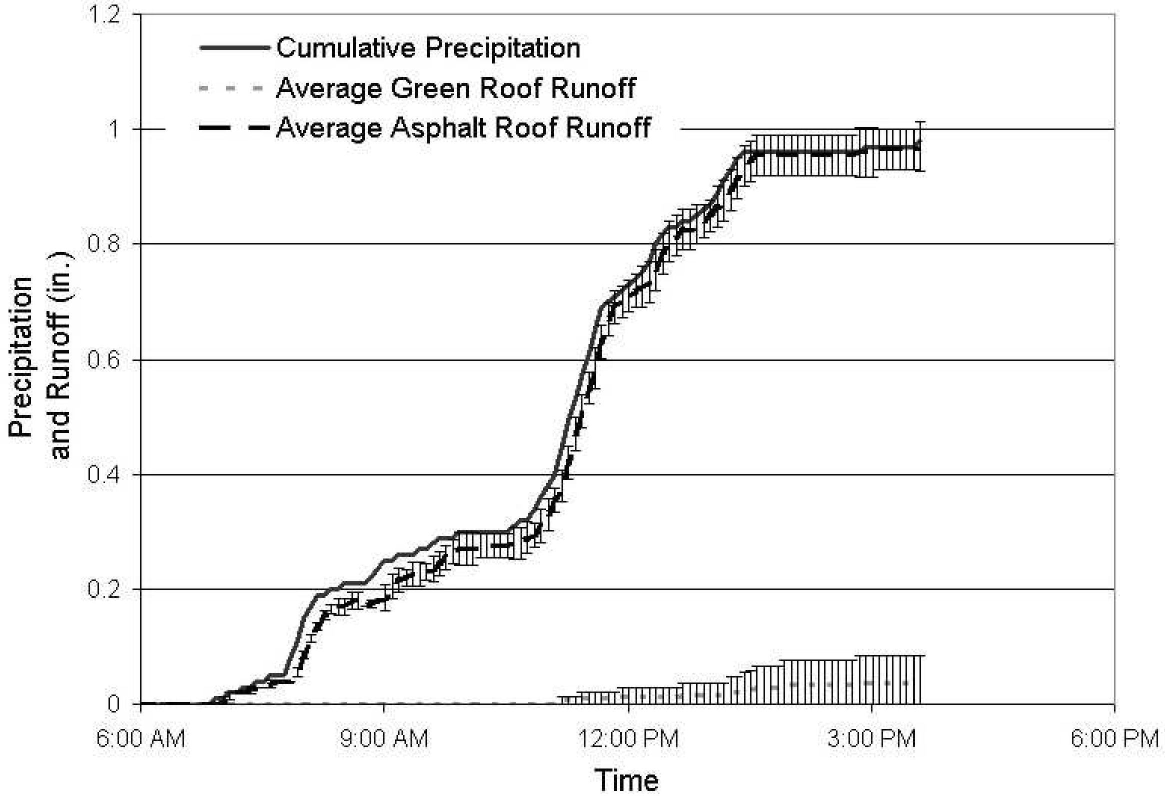


Figure 3-7 Precipitation and runoff from green and flat asphalt roofs on August 16, 2005

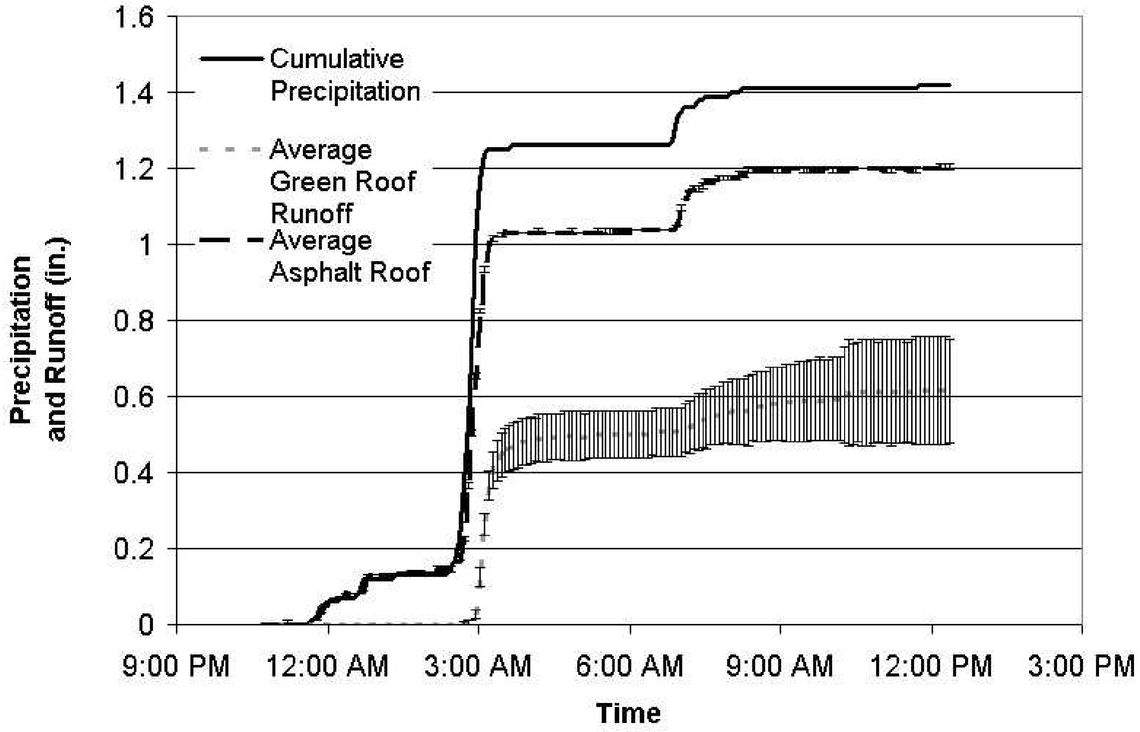


Figure 3-8 Precipitation and runoff from green and flat asphalt roofs on August 30, 2005

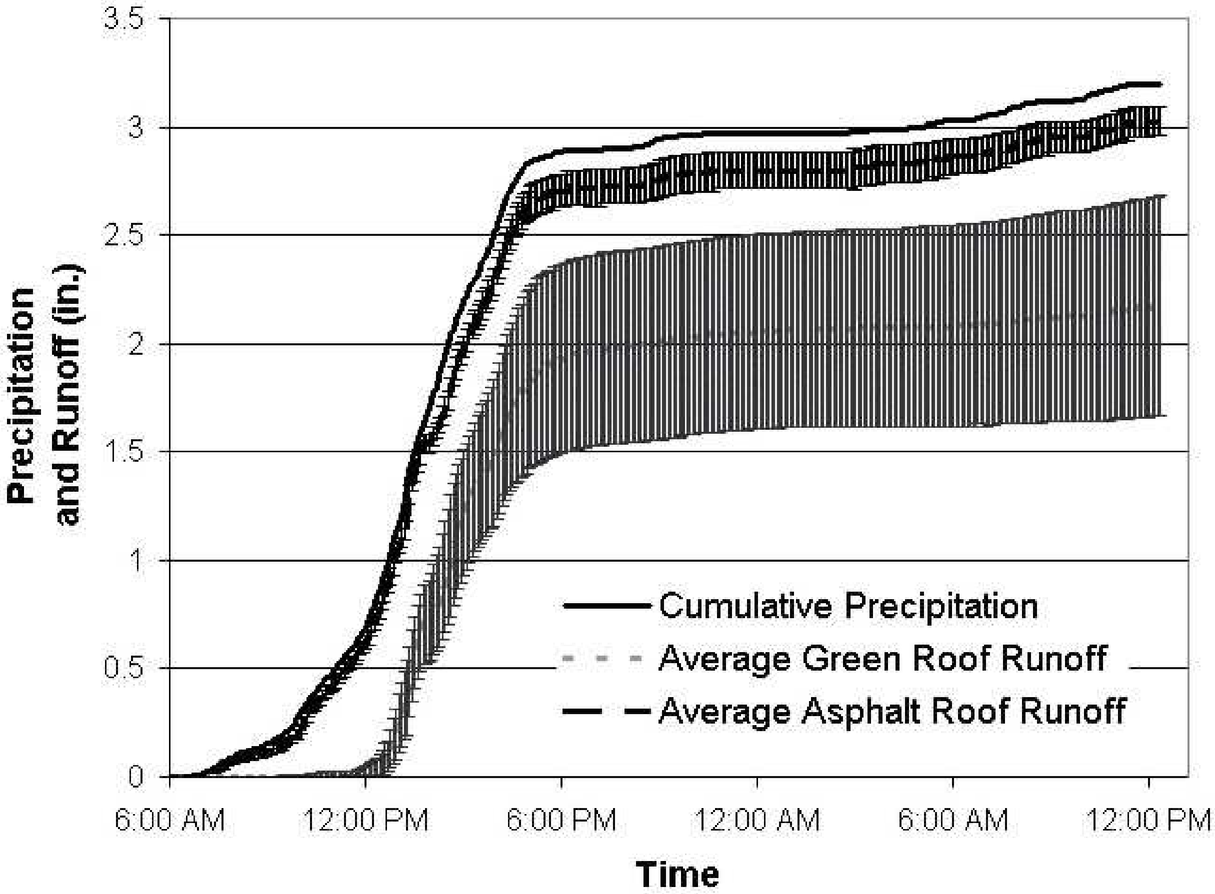


Figure 3-9 Precipitation and runoff from green and flat asphalt roofs on October 7-8, 2005

Peak Hydrograph Analysis

In a larger storm, the green roof typically will retain nearly all precipitation at the start of the event until storage capacity is exceeded. Once storage capacity, i.e., initial abstraction, is exceeded and runoff begins to occur, nearly all the additional precipitation is released as runoff as previously demonstrated in Figures 3-8 and 3-9. Runoff from green roof is thus delayed from the start of the storm by a period which corresponds to filling the media storage capacity. Runoff is also delayed because precipitation must pass through the vegetation canopy (interception and stem flow), root zone and the media before it reaches the drainage system. Delay for flow through the green roof system will be influenced by the size of the roof, vegetation cover, the path, hydraulic conductivity of the media, and the drainage layer. Once precipitation reaches the drainage layer, the water flows through the system to the gutter and downspouts. The vertical component is responsible for the initial abstraction and runoff delay, while the lateral component appears similar to other roofing systems.

During the second most intense rain of the study, the green roof runoff peak flow was not only delayed but generally was attenuated as well, reaching only about half of the peak rainfall as demonstrated in Figure 3-10 and 3-11 (these figures used runoff values that were corrected to increase monotonically). The peak intensity of this rainfall event approached 3 in/hr (~ 75 mm/hr) as can be seen in Figure 3-11, with peak asphalt roof coming at the next five-minute time interval and the green roof runoff peak coming at the next five-minute interval after that. The green roof also released runoff more gradually than the asphalt roof, which dropped off as rapidly as the precipitation intensity in this event.

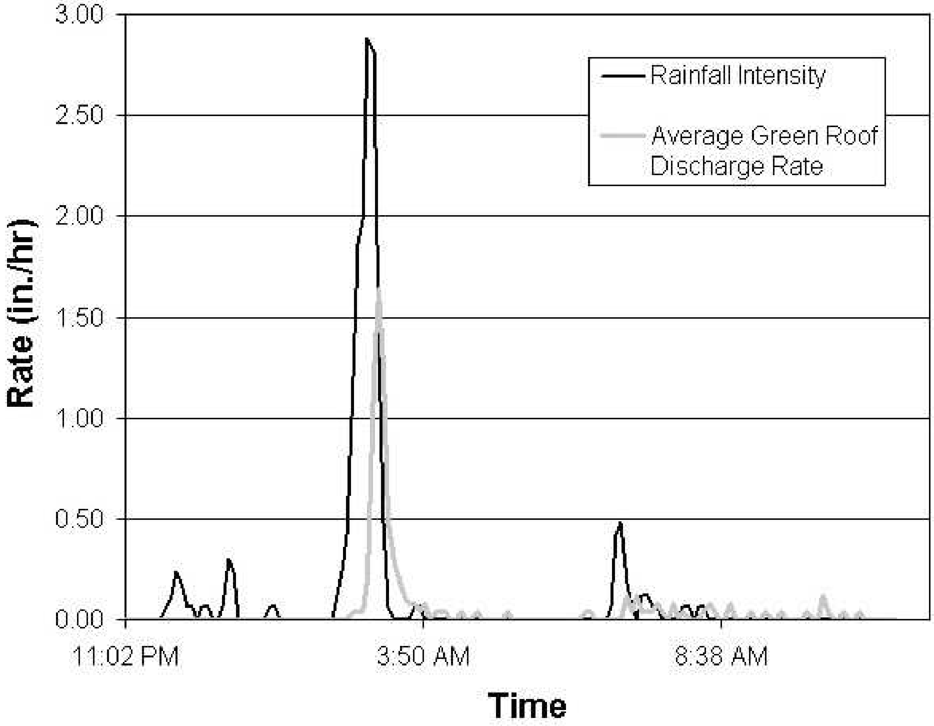


Figure 3-10 Hydrograph for August 30-31, 2005

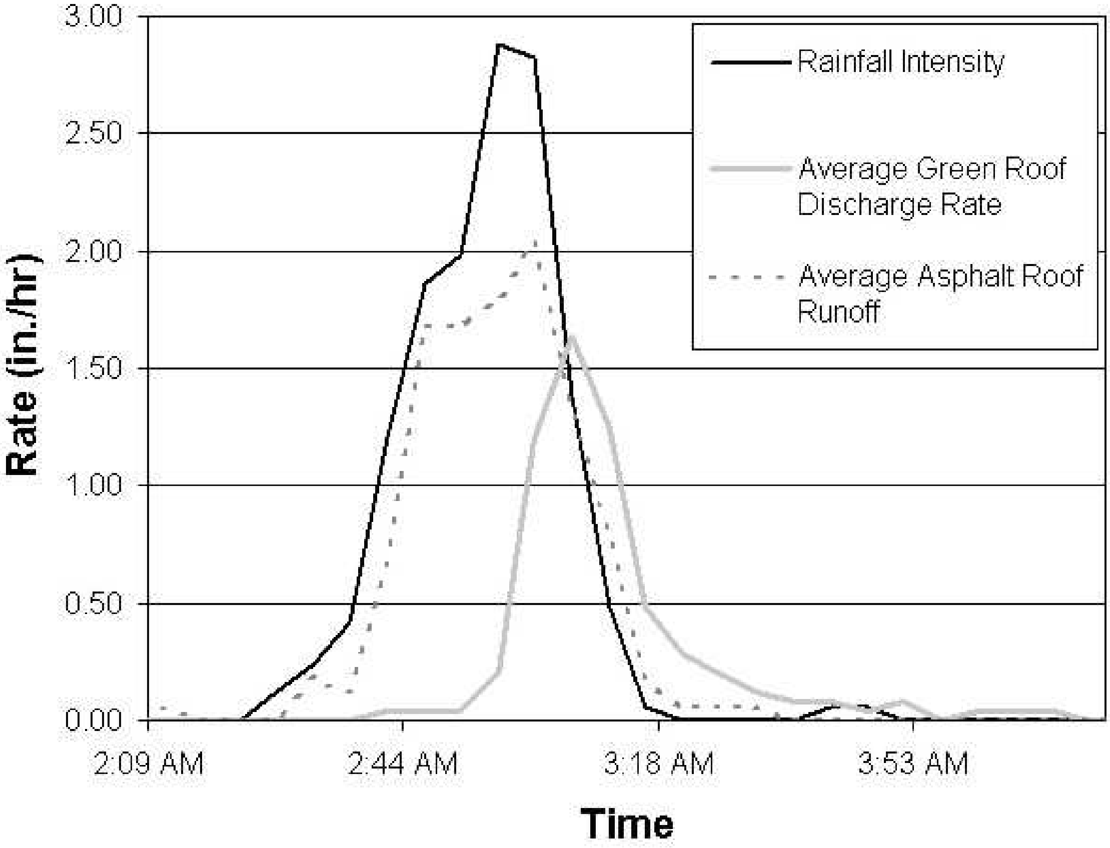


Figure 3-11 Hydrograph of most intense period of August 30-31, 2005 event

Table 3-2 lists events over 0.5 in. (13 mm) excluding storms where snowfall and freezing were an issue (storm number can be cross-referenced to Table 3-1). The clear implication is that in many ways the green roof will act to retain, detain and attenuate WWF; however, some events can exceed this capacity, reducing the performance of green roofs. Calculated time of concentration values for the asphalt roof ranged from 1.0 to 2.6 minutes for these storms, and were all less than the five-minute time interval used for the runoff measurements; therefore, only rudimentary peak flow analysis could be performed, as demonstrated in Figures 3-10 and 3-11. As stated in the "Recommendations", larger roofs should be monitored for hydrology routing. Also, decreasing the time interval may help, but it may also create more noise.

While green roof runoff performance is subject to the rainfall pattern, seasons and interval between storms, peak flow attenuation was demonstrated in most storms. Short, intense rainfall events, especially the events of July 15 and June 6, had short times to peak green roof runoff but still reduced runoff volume, while some of the longer events in the fall (October 25, 2005 and November 14 and 16, 2005) had slow times to peak but limited attenuation. In very large sustained events, exemplified by the August 30 and October 7 events, which demonstrated a typical S curve rainfall intensity pattern (highest rainfall intensity in the middle of the storm), a delay in peak rate was still evident, though muted, and there was still runoff reduction, though less than 50%.

Summary

Green roofs in the study retained over 50% of the total precipitation during the study period. During summer months nearly all the precipitation was retained. During the winter, retention was smaller (<20%). Seasonal effects appear to be a result of snow or freezing conditions, otherwise green roofs effectively retained up 0.4 in. (10 mm) regardless of season. For storms producing green roof runoff, peak flows rates were delayed by the green roofs and in many cases peak flow volumes were also attenuated. Green roofs were most effective at delaying time to peak and reducing peak flows when they when not fully saturated by rainfall events on previous day. The response of green roofs is subject to season, seasonal rainfall pattern, and interval between rains, but still offers benefits of attenuation and evapotranspiration even during non-growing seasons, and performed exceptionally well during the summer.

Table 3-2 Synopsis of Rain Events Greater Than Half an Inch

					Peak Runoff Intensity (in/hr)		**Time until Peak**			**Comments**
								Runoff After Rainfall (hr:min)		
Event Number	**Event date start**	**Rainfall Total (in.)**	**Green Roof Runoff Total (in.)**	**Peak Rainfall Intensity (in/hr)**	**Asphalt Roof**	**Green Roof**	**Rainfall (hr:min)**	**Asphalt Roof**	**Green Roof**	
95	10/7/2005	3.2	2.2	0.96	0.96	0.92	4:25	0:05	0:15	Barrels emptied to prevent overflows
88	8/30/2005	1.43	0.61	2.88	2.04	1.64	2:15	0:05	0:10	
105	10/25/2005	1.35	1.0	0.36	- -	0.16	10	- -	19:10	Steady rain, asphalt data not representative.
80	8/16/2005	0.98	>0.1	0.6	0.6	0.08	4:15	0:10	0:00	
110	11/14/2005	0.69	0.43	0.24	0.36	0.24	0:10	0:10	2:30	Steady rain
74	7/25/2005	0.68	0.18	2.76	1.38	0.32	0:10	0:05	0:05	0.33 in. in 10 min at start of storm
51	6/6/2005	0.67	>0.1	1.44	1.62	0.2	0:10	0:05	0:05	Double peak, 2nd peak 2.04 in/hr, 1.74 in./hr asphalt roof 0.12 in/hr green roof runoff.
102	10/21/2005	0.6	0.39	0.24	0.24	0.24	0:45	19:20	20:25	Rain on and off for 21 hrs.
111	11/16/2005	0.51	0.46	0.36	0.3	0.24	0:50	0:05	1:20	Rainfall previous day

Chapter 4 Green Roof Effects on Runoff Quality

Introduction

Runoff samples were collected from six small buildings at the Center for Green Roof Research at Rock Springs, PA during the period from January 2005 through May 2006. Runoff from three green roofs, two flat-asphalt control roofs, and one roof divided between detention and a green-roof system without plants, was collected in rain barrels and sampled for various water constituents following various precipitation events. Comparisons of runoff concentrations are presented among roof types. Runoff nutrient loadings in pounds per acre (lb/acre) were calculated from measured concentrations and measured runoff quantities of the flat asphalt and green roofs for comparison. Runoff water quality varied with both sample event and roof type.

Runoff Summary

Sampled precipitation events listed in Table 4-1 covered from February 14, 2005 to May 15, 2006, ranged from 0.07 in. (2 mm) to 1.31 (52.1 mm) for individual events (some multiple events are include din this analysis) and included rain, snow and freezing rain. Total precipitation from the sampled storms was 16.15 in. (410.2 mm), though, as noted in Table 1, lesser amounts are used for comparative volume analyses. Table 4-2 lists individual storm and total runoff values. Runoff volumes were not obtained for all events due to errors in collection systems, (e.g., a valve left open for detention runoff on May 23, problem with media runoff measurements in October and November) or data collection system problems (i.e., February 15, March 29 and July 16 through 17). Total runoff collected from sampled precipitation events was 202.9 gal (768.0 L) from green roofs, 400.3 gal (1515.1 L) from flat asphalt roofs, 175.9 gal (665.8 L) from the detention section (half roof), and 109.2 gal (413.3 L) from the media roof section (half roof). These runoff volumes correspond to 48% of the total precipitation for green roofs and 94% for flat roofs based on 425 gal (1610 L) of precipitation, 88% for the detention section based on 401 gal (1520 L) and 67% for the media roof section based on 328 gal (1240 L), respectively. These values are similar to the ratios cited for the full study runoff volume analysis presented in Chapter 3. Total runoff collected also varied seasonally as in the larger runoff study with a reduction in runoff from green roofs in April through September (4% of the precipitation). In contrast runoff from flat asphalt roofs was fairly consistent throughout the year, only dipping to 89% during this period.

Table 4-1 Precipitation Events Sampled for Water Quality Monitoring

Sample Number (Event Numbers)[1]	Precipitation Dates	Sample Date	Total Precipitation (in.)	Total Precipitation (mm)	Field Analysis	Laboratory Analysis	Comments
1 (11)	2/14/05	2/15/05	0.73	18.5	Yes		System failure (no volumes)
2 (17)	3/4/05	3/7/05	0.07	1.8	Yes		Snow - may include previous snow
3 (18 -20)	3/7 -12/05	3/15/05	0.26	6.6	Yes		Snow - may include previous snow, problem with volumes
4 (22-28)	3/23-28/05	3/28/05	1.75	44.5	Yes	Yes	Snow/rain -freezing rain

Sample Number (Event Numbers)[1]	**Precipitation Dates**	**Sample Date**	**Total Precipitation (in.)**	**(mm)**	**Field Analysis**	**Laboratory Analysis**	**Comments**
5 (28*)	3/28/05	3/29/05	0.85	21.6	Yes		System failure (no volumes)
6 (32-34)	4/22-24/05	4/26/05	0.55	14.0	Yes		
7 (40-43)	5/19-22/05	5/23/05	0.51	13.0	Yes		No data for detention roof
8 (44)	5/23/05	5/24/05	0.32	8.1	Yes		No data for detention roof
9 (51)	6/6/05	6/7/05	0.67	17.0	Yes		
10 (53)	6/9/05	6/10/05	0.15	3.8	Yes		
11 (62)	7/5/05	7/6/05	0.75	19.1	Yes		Runoff estimated by barrel content
12 (67)	7/16/05	7/16/05	0.64	16.3	Yes		Lightning strike (no volumes)
13 (68)	7/17/05	7/17/05	1.31	33.3	Yes		Lightning (system down)
14 (80)	8/16/05	8/17/05	0.98	24.9	Yes	Yes	
15 (82)	8/19/05	8/19/05	0.27	6.9	Yes		
16 (93)	9/26/05	9/27/05	0.48	12.2	Yes		
17 (94)	9/29/05	9/29/05	0.25	6.4	Yes		
18 (95)	10/7/05	10/8/05	3.2	81.3	Yes		
19 (103-105)	10/24-26/05	10/27/05	2.05	52.1	Yes		
20 (110-111)	11/14-16/05	11/16/05	1.2	30.5	Yes		
21 (NA)	4/24-25/06	4/25/06	0.14	3.6	Yes	Yes	
22 (NA)	5/11/06	5/13/06	0.61	15.5		Yes	No field measurements
23 (NA)	5/14-15/06	5/16/06	0.4	10.2		Yes	No field measurements
Totals Precipitation[2]			14.22	361.2			

1 - Event number from Table 3-1.

2 - Excludes flat and green roof samples for which no volume data were generated; 13.4 in. (340 mm) for detention roof and 11.0 in. (279 mm) for media roof.

NA - Events not listed in Table 3-1.

Table 4-2 Volumes for Water Quality Monitoring

Sample Number	**Sample Date**	**Green roof Runoff (Average of 3) (gallon) *(Stdev)***	**(liter)**	**Flat roof runoff) (Average of 2) *(Stdev)* (gallon)**	**(liter)**	**Detention runoff (gallon**	**(liter)**	**Media runoff (gallon)**	**(liter)**
		Roof dimensions (ft^2) (m^2)							
		48	**14.6**	**48**	**14.6**	**24**	**7.3**	**24**	**7.3**
1	2/15/05	N/A		N/A		N/A		N/A	
2	3/7/05	0.13 *(0.06)*	0.49	1.7 *(0.85)*	6.4	3.3	12.49	0	0.00
3	3/15/05	N/A		N/A		N/A		N/A	0.00
4	3/28/05	47.50 *(8.13)*	179.8	51.0 *(0.99)*	193.0	28.7	108.3	21.4	81.0
5	3/29/05	N/A		N/A		N/A		N/A	
6	4/26/05	0.37 *(0.12)*	1.4	10.45 *(0.35)*	39.6	8.8	33.31	0.6	2.27
7	5/23/05	0.43 *(0.15)*	1.6	11.4 *(1.27)*	43.2	N/A		1.2	4.54
8	5/24/05	0.43 *(0.12)*	1.6	6.50 *(1.41)*	24.6	N/A		1.9	7.19
9	6/7/05	1.43 *(0.87)*	5.4	23.0 *(0.42)*	88.2	9.5	35.96	19.5	73.81
10	6/10/05	0	0	4.2 *(1.56)*	15.9	1.9	7.19	1.5	5.68
11	7/6/05	0.5 *(0)*	1.9	13.5 *(2.12)*	51.1	2.0	7.57	3.0	11.36
12	7/16/05	N/A		N/A		N/A		N/A	
13	7/17/05	N/A		N/A		N/A		N/A	
14	8/17/05	1.17 *(1.36)*	4.43	28.9 *(1.13)*	109.4	12.8	48.45	0.4	1.51
15	8/19/05	0.37 *(0.31)*	1.40	7.8 *(0.71)*	29.5	2.5	9.46	0.4	1.51
16[3]	9/27/05	0.67 *(0.25)*	2.5	15.7 *(0.85)*	59.4	7.2	27.25	1.9	7.19
17	9/29/05	0.7 *(0.3)*	2.7	7.0 *(0.28)*	26.5	2.7	10.22	1.1	4.16
18	10/7/05	65.1 *(15.21)*	246.4	89.3 *(1.91)*	343.1	39.4	149.13	39.9	151.0
19	10/27/05	49.47 *(11.25)*	187.2	44.9 *(0.71)*	167.0	25.7	97.27	NA	
20[3]	11/16/05	29.07 *(11.74)*	110.0	36.25 *(0.78)*	137.2	15.8	59.80	NA	
21	4/25/06	0.77 *(0.12)*	2.9	3.65 *(0.49)*	13.82	1.0	3.79	1	3.79
22	5/13/06	3.4 *(1.83)*	13	31.4 *(0.85)*	118.9	11.7	44.28	12.7	48.07
23	5/16/06	1.4 *(0.46)*	5.3	12.0 *(0.85)*	45.4	2.9	10.98	2.7	10.22
Totals		202.9 *(52.3)*	768.0	400.3 *(17.5)*	1515.1	175.9	665.8	109.2	413.3

NA - not applicable.

Methods and Analyses

Samples were either analyzed in the field for pH, EC, turbidity, color, and nitrate or were sampled and tested for nutrients and other ions in the Penn State Agricultural Department Analytical Laboratory. An Orion electrode and meter measured pH, EC was measured using a Hach portable meter and probe, turbidity was measured with a Hach portable meter, color was measured using a Hach portable spectophotometer, and nitrate was measured with a Hach specific ion electrode and Orion meter.

Color and Turbidity

The most noticeable difference between runoff from green and asphalt roofs was the color of the water. The runoff appeared to be very similar to the leachate obtained from potted plants or other containerized planting systems. Color analysis was conducted because green roof runoff had a distinct yellow color. Green roof media contributed inorganic and humic substances to the runoff resulting in a yellow-to-brown coloration. Color is a function of the organic components (humic acids), primarily compost incorporated in the media to enhance plant growth and establishment, and will likely decrease with time as the media ages. Field analysis was conducted using a Hach DR 890 colorimeter which report in units of 0 to 500 Platinum-Cobalt (Pt-Co) color units (based on the 500 Pt-Co standard solution). Samples over the limit were diluted to within the limit, usually requiring a 50% to 75% dilution and were then calculated for full concentration. Expected standard accuracy is plus or minus 15 Pt-Co color units with a method detection limit of 25 Pt-Co color units. A yellow color was obvious in all runoff from the green roofs and the media roof section (Figure 4-1). Although the green roof runoff was colored and was detected by the colorimeter, it was quite clear. The intensity of the runoff color varied with the storm event. Figure 4-2 shows that events in the cooler seasons generally had less color while small events with little runoff, i.e., May 24, 2005, had the most color.

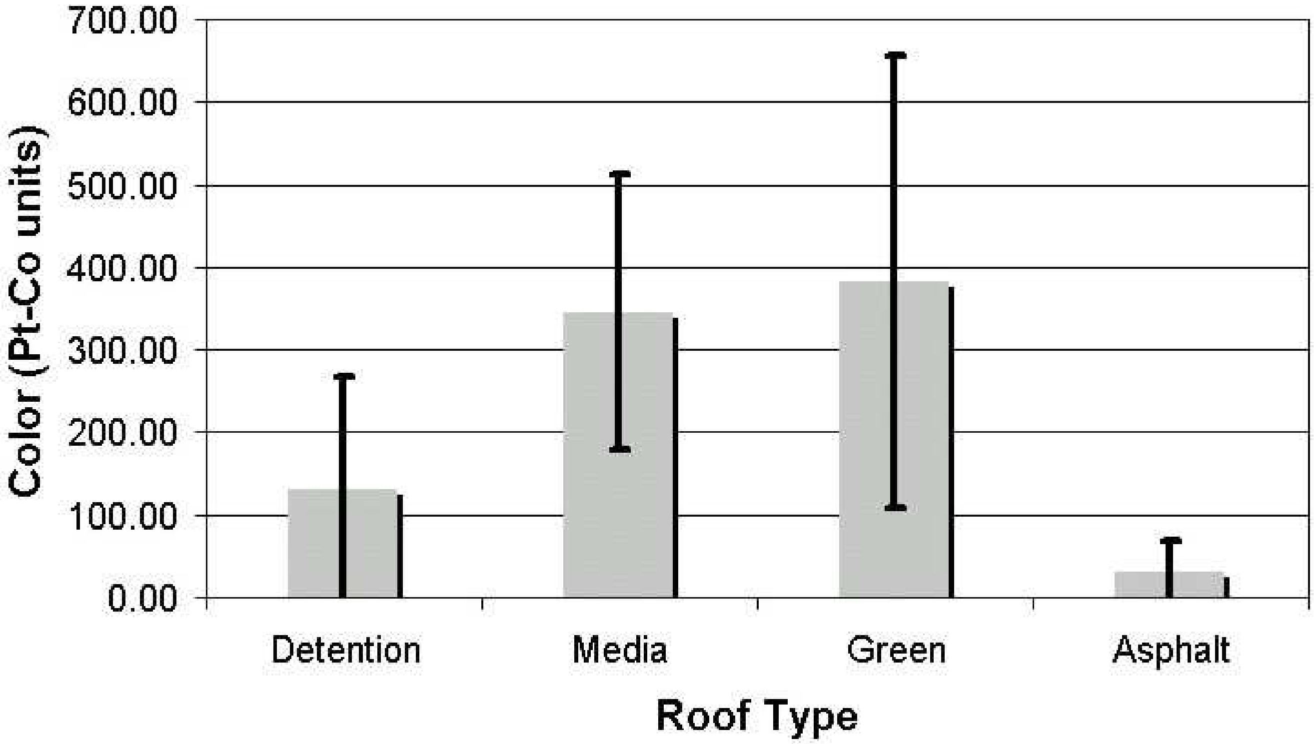


Figure 4-1 Average runoff color from all roof types

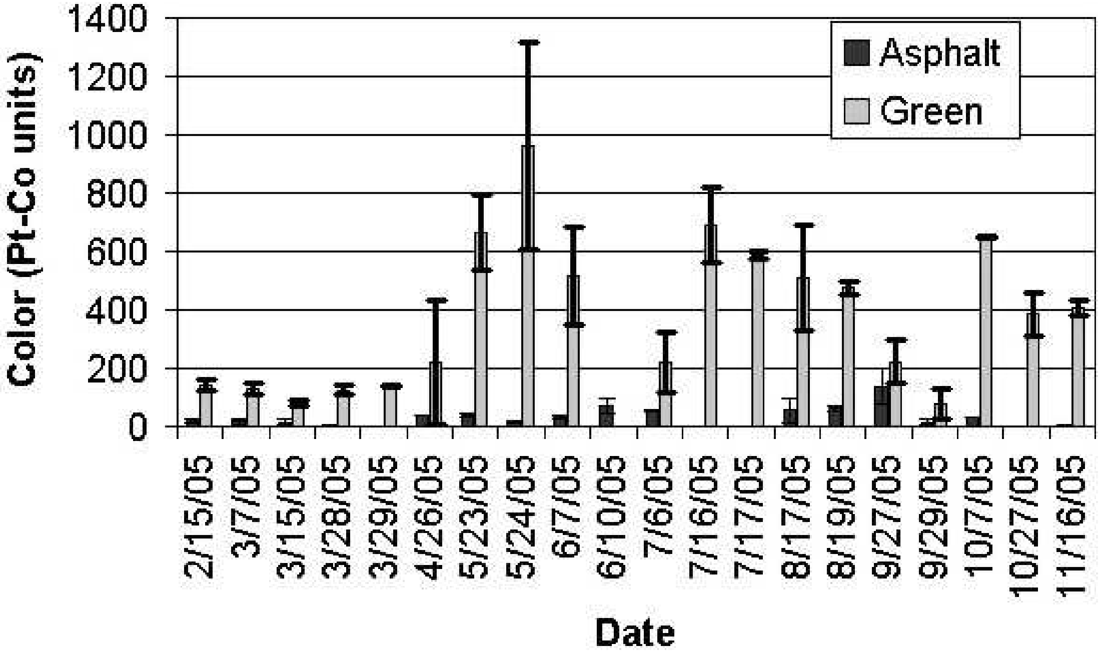


Figure 4-2 Runoff color comparison between green roofs and flat asphalt roofs

The turbidity of the runoff was more variable for green roofs and the media roof section compared with the flat asphalt roofs (Figure 4-3). Turbidity from green roofs, media roofs, and flat roofs was very similar ranging between 0.8 and 5.6, with the exception of two events May 23 and 24, 2005 when green roof values peaked at 24.4 and 18.1, respectively. This coincides with the May 24, 2005 peak in runoff color.

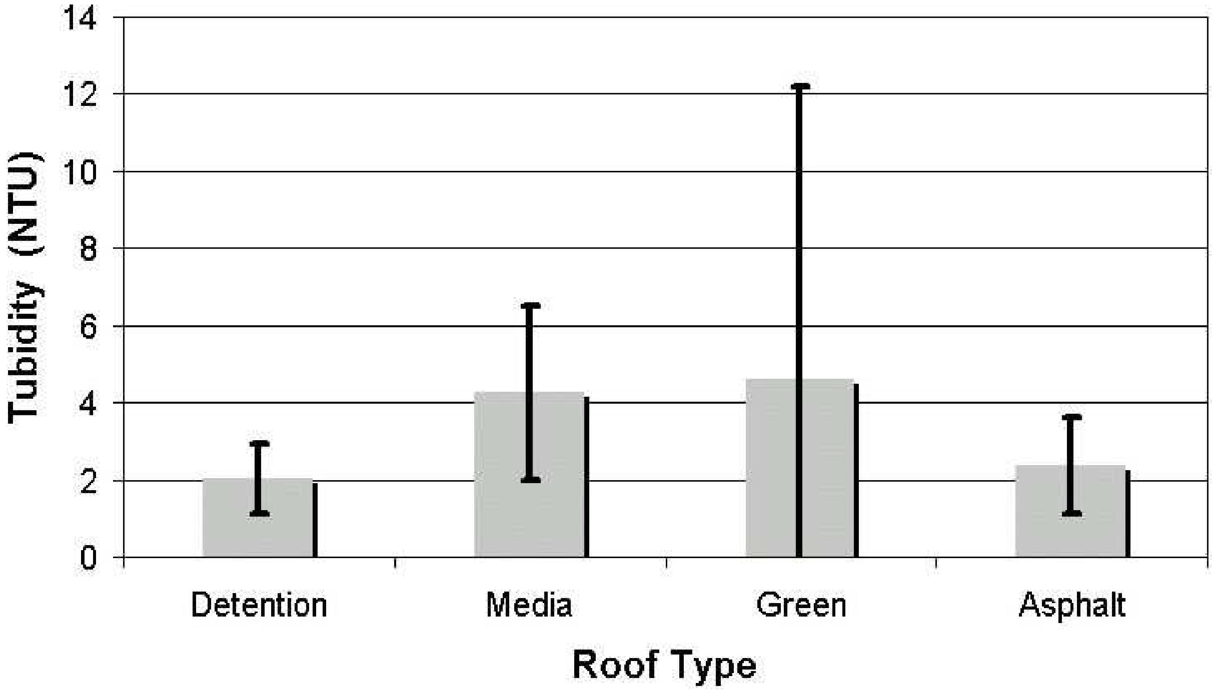


Figure 4-3 Average turbidity of runoff samples from all roof types

Events where green roof turbidity was elevated were events where very little runoff was collected, e.g., May 23 and 24, 2005 events. It seems likely that the elevated turbidity in these samples was related to the small amount of runoff. The color of green roof runoff is likely to limit the direct use of this water for anything other than landscape irrigation without some additional treatment or filtration. If the green roof runoff was planned to be the primary source of a grey water system for flushing toilets for example, the color might be aesthetically unpleasant to users.

pH

The average pH for three rain events was 4.7 (March 3, April 26 and May 24, 2005). Green roofs consistently raised the pH of runoff compared to flat asphalt roofs. The pH of runoff from the asphalt roofs ranged from 4 to 7, while runoff from the green roofs was consistently above 6.4 (Figure 4-4). This is clearly a function of the media. The media roof section had runoff sample pH values similar to those obtained from the planted green roof systems (Figure 4-5). Runoff from the rooftop detention was consistently lower than the other roofs. It is not clear why this runoff had a lower pH than runoff from the flat asphalt roofs. It is possible that the roofing tar used to waterproof the detention basin influenced runoff pH, and conversely, the asphalt roofing of the flat roofs may have raised the pH of the runoff due to the small granules of rock used. Note that the March 28, 2005 data point is several storms some of which had frozen precipitation, so when precipitation could not contact stones of asphalt roof due to sheet flow over frozen surfaces, buffering capacity was by-passed.

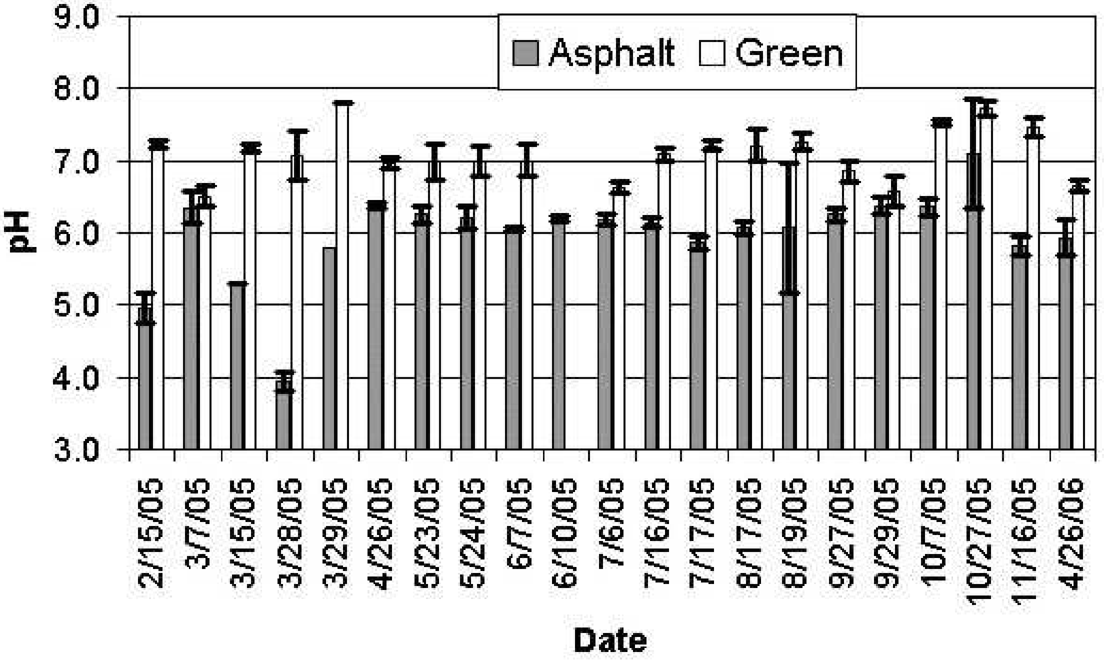


Figure 4-4 pH of runoff from green and flat asphalt roofs

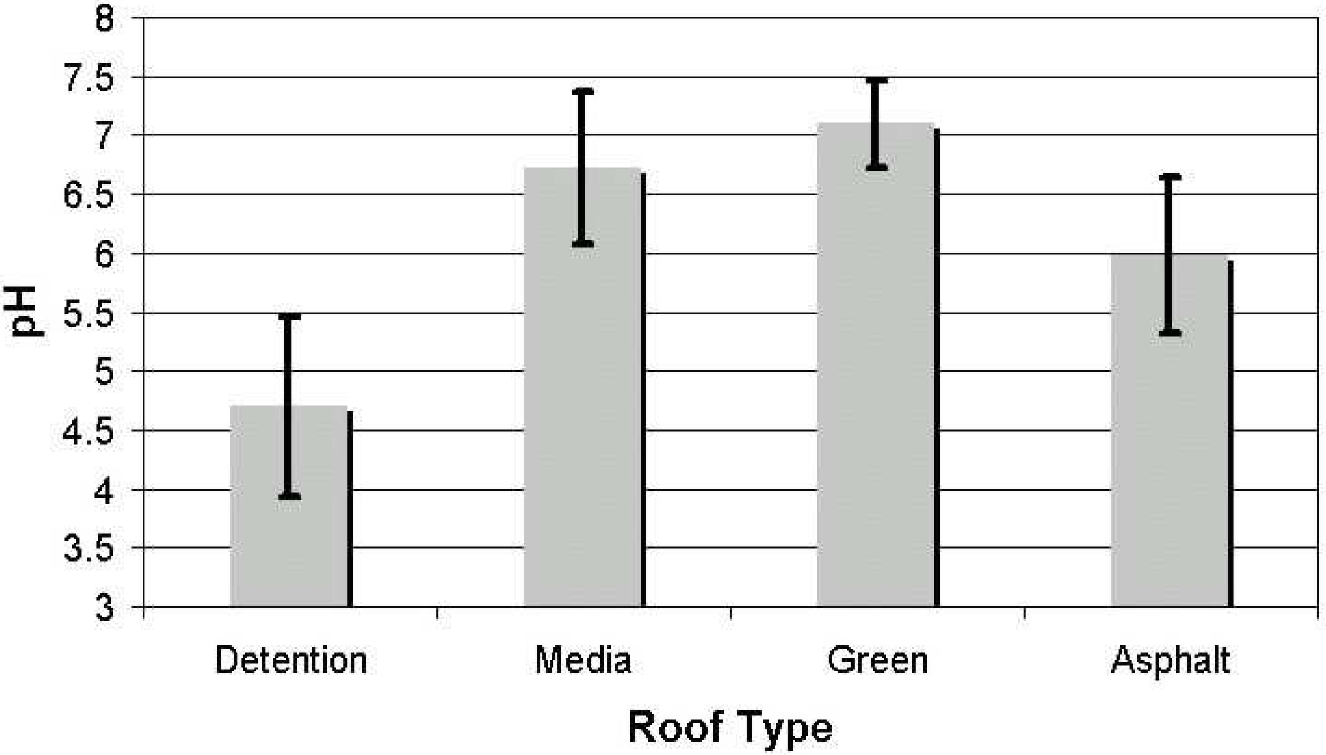


Figure 4-5 Average pH of runoff from all roof types

Buffering pH is one of the most significant and consistent effects of a green roof on water quality. The ability of a green roof to neutralize acid precipitation is a major potential benefit for using these roofing systems in areas like the Northeastern U.S. which are subject to acid rain, as can be seen in Figure 4-6. Acid rain has been demonstrated to have negative effects on surface waters and may contribute to metal concentrations in runoff. Acid in the rain comes in contact with metals in ventilation systems, roofs, drainage systems, and other building materials. Green roofs, if widely implemented in urban areas with acid precipitation, could potentially reduce these impacts. It should be noted that the limited soil depth of an extensive green roof would have a finite ability to maintain this buffering capacity. As acid precipitation is neutralized, the media buffering capacity will be expended and eventually the media will no longer be able to buffer the runoff. This will not only influence pH of the runoff, but will also affect plant growth on the roof. Many of the plants used on extensive green roofs do not grow well in acid soils, so replacing the buffer in the media through liming may be a necessary part of the long-term management or maintenance of a green roof. Roofs monitored in this study were established in 2000 though 2001. To date, there is no evidence that buffering capacity is running out; however, there is evidence from older, European green roofs that suggests that media acidification will eventually occur. Determining the limiting buffering capacity and other maintenance of the green roof is discussed later in Chapter 5.

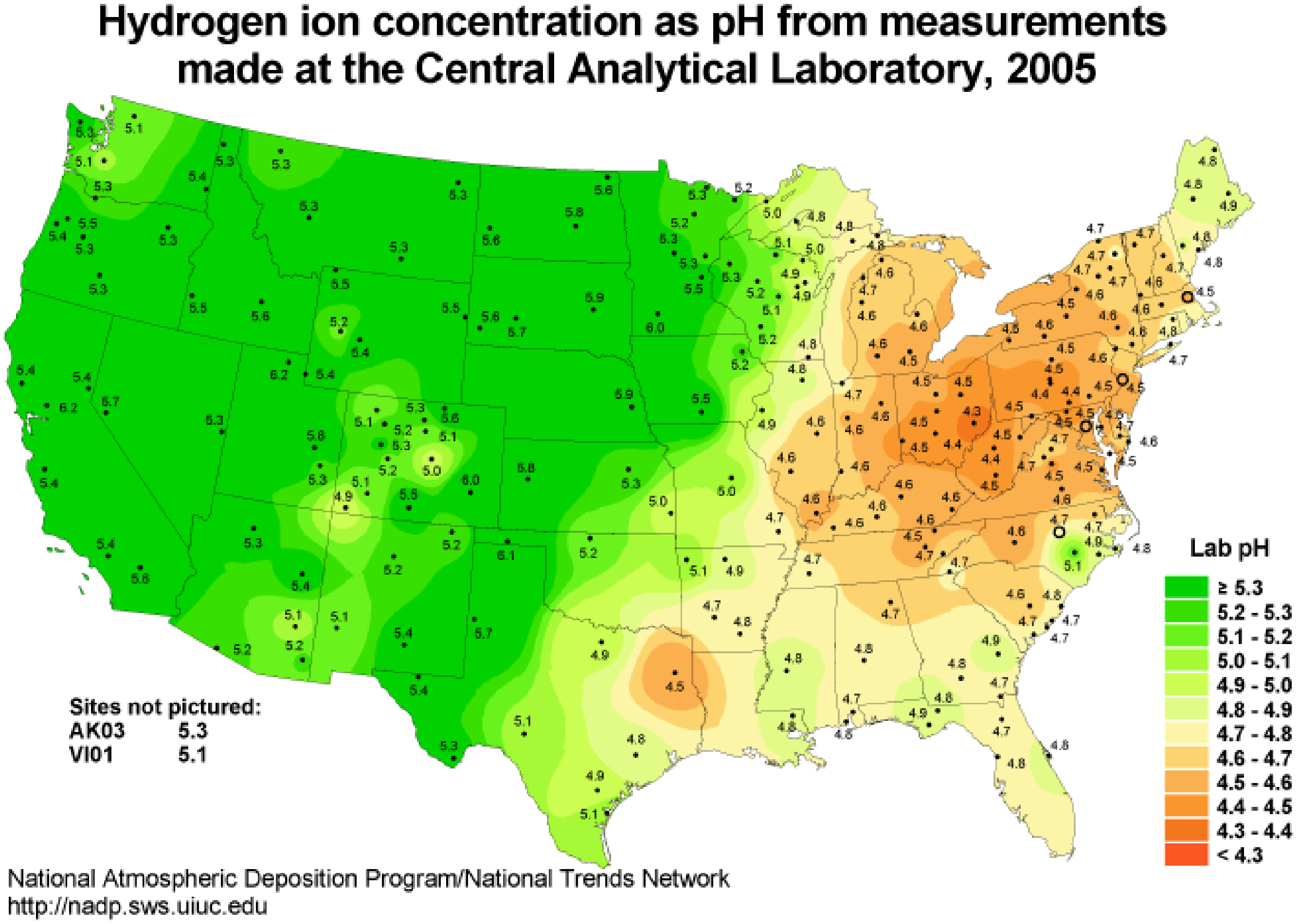


Figure 4-6 United States map of acid rain (National Atmospheric Deposition Program, 2006)

Electrical Conductivity

The EC of runoff from green roofs was significantly higher than conductivity of runoff from flat asphalt roofs (Figure 4-7). Electrical conductivity, reported in units of milliSiemens per centimeter (mS/cm), is a measure of the total salts or ions in solution. Since the green roof runoff was filtered through a media (soilless substrate) containing plant nutrients, roots, organic matter, and clay-based aggregate, it is not surprising that some salts are leached into the runoff.

Conductivity of the runoff also varied significantly with some precipitation events resulting in much higher EC than others (Figure 4-8). The highest EC in green roof runoff occurred in events where only a small amount of runoff was collected, i.e., May 23 and May 24. It is also interesting to note that there was a slight, general trend toward reduced EC in runoff from the media section of roof from the beginning of the evaluation period to the end (Figure 4-9). The average for first 10 media runoff events is 0.127 mS/cm versus 0.98 for remaining 10 events. Since this roof section was relatively new at the beginning of the evaluation period, less than a year old, compared with the green roofs which were five years old, it potentially suggests that new media of a new roof will leach more salts than the same roof once established. This has implications for future evaluations of new roofs, where water quality of the runoff in the first year may not be representative of the runoff of a mature established roof.

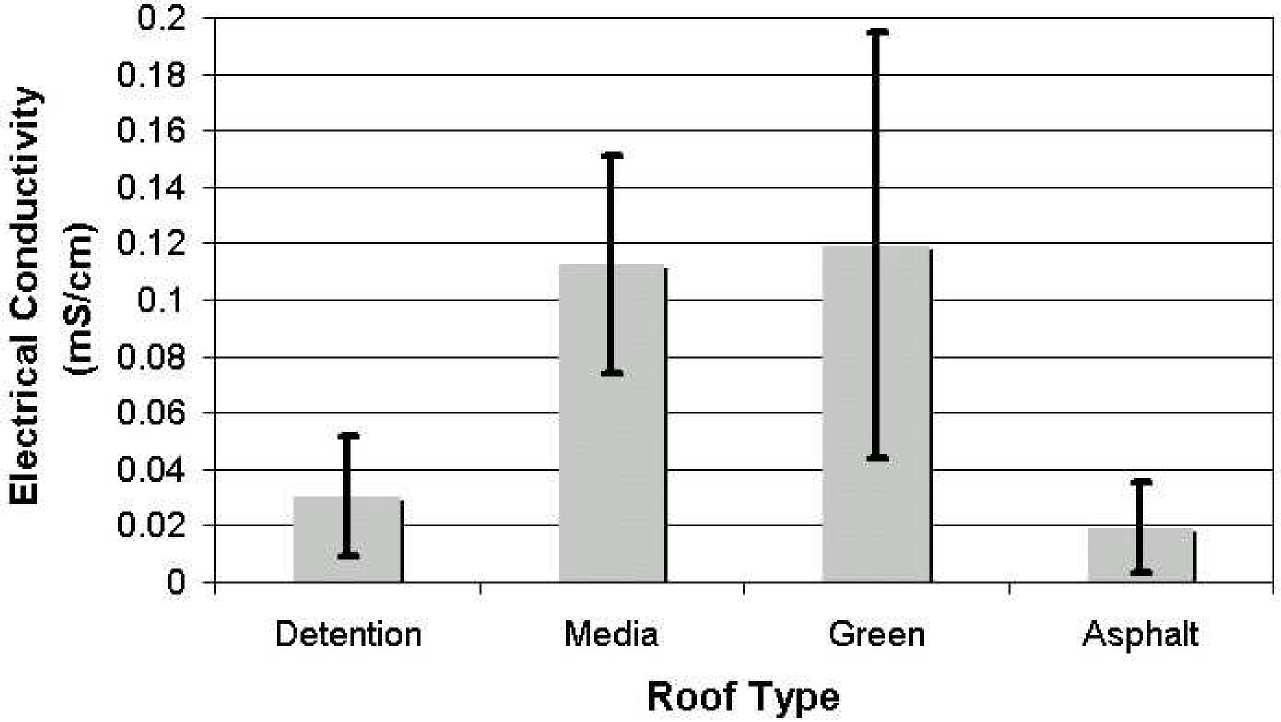


Figure 4-7 Electrical conductivity of runoff from all roof types

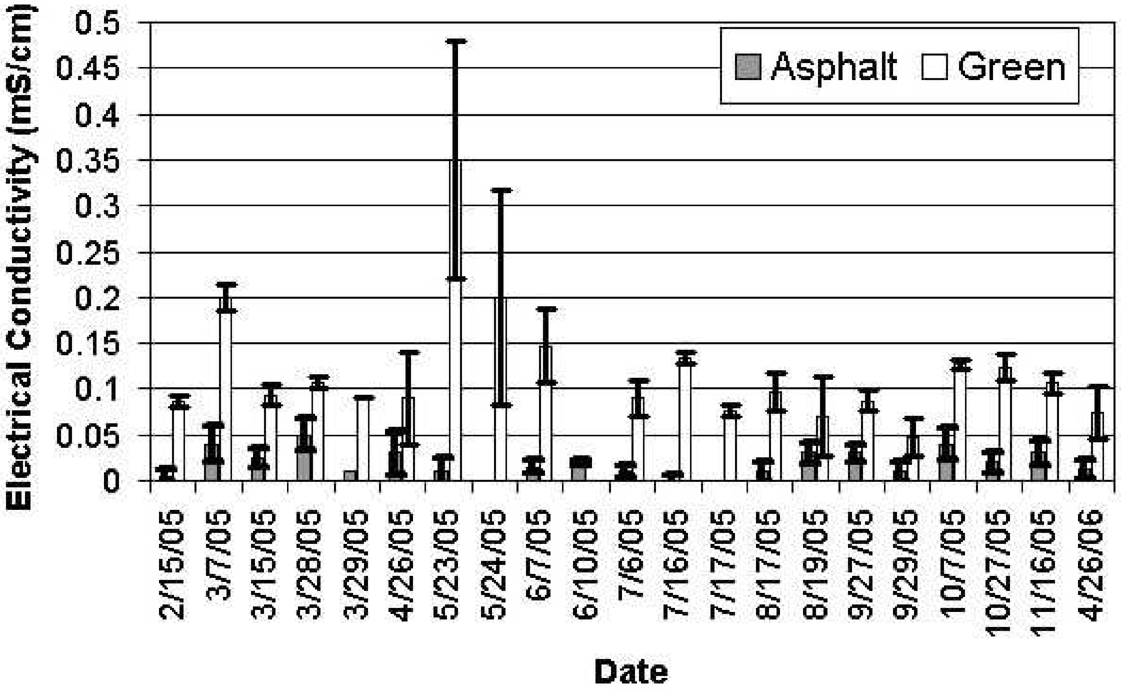


Figure 4-8 Electrical conductivity of runoff from green and asphalt roofs

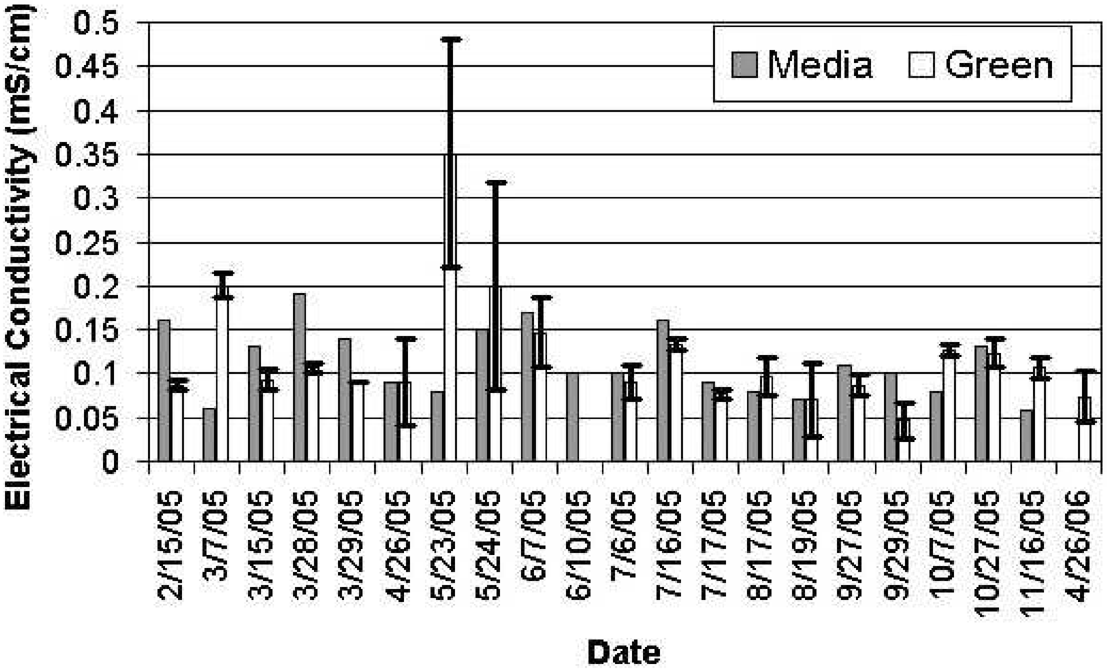


Figure 4-9 Electrical conductivity from green and media roofs

Nitrate

On average, over the entire period sampled there was no significant difference between green and asphalt roofs for runoff nitrate concentration (Figure 4-10). The media roof section runoff, in contrast was significantly higher than any other sampled roof. It is likely that the nitrate in runoff from the media roof section was derived from breakdown of the compost amendment to the media. In established green roofs, the organic content of the media is likely stable with breakdown matched by growth of the plants. In the planted roofs, nitrate is being used by both the plants and associated microbial communities, and is thus not as readily leached. The green roofs in this study had received only small amounts of supplemental fertilizer on an annual basis from 2001 to 2004, and thus, the systems were likely nitrogen starved and any available nitrogen would tend to be used by the biotic community. This suggests that new roofs without full plant cover may contribute nitrate to runoff, while established roofs, if managed correctly, may not.

Some sampled events resulted in higher nitrate concentrations in runoff from green roofs while runoff from flat asphalt roofs had higher nitrate concentrations for other events (Figure 4-11). Nitrate in the runoff from asphalt roofs was generally higher in winter months, while summer runoff had lower nitrate concentrations. This trend was not evident in runoff from green roofs. As a result, nitrate concentrations from green roofs were generally higher than runoff from flat asphalt roofs in the summer months, while in general the reverse was true in the winter.

Loading calculations were performed two different ways for comparison of runoff from the green and asphalt roofs; nitrate was the only constituent for which the detention and media roof was also compared, due to the limited data sets for other constituents. Average loading was calculated by multiplying the volume of runoff by the concentration per event and averaging events. For annual loading, the average concentration was multiplied by the annual runoff. Annual runoff was calculated from the average rainfall, 44 in. (1100 mm), multiplied by the fraction of runoff from the roofs derived from analysis presented in Chapter 3 (0.474 for green, 0.859 for asphalt, 0.837 for detention, and 0.703 for media). The roof area was scaled to acres (results in pounds per acre). In addition, ranges to these estimates are provided, based on standard deviations of the concentrations. Individual event loading values are presented in Figure 4-12 for green and asphalt roofs.

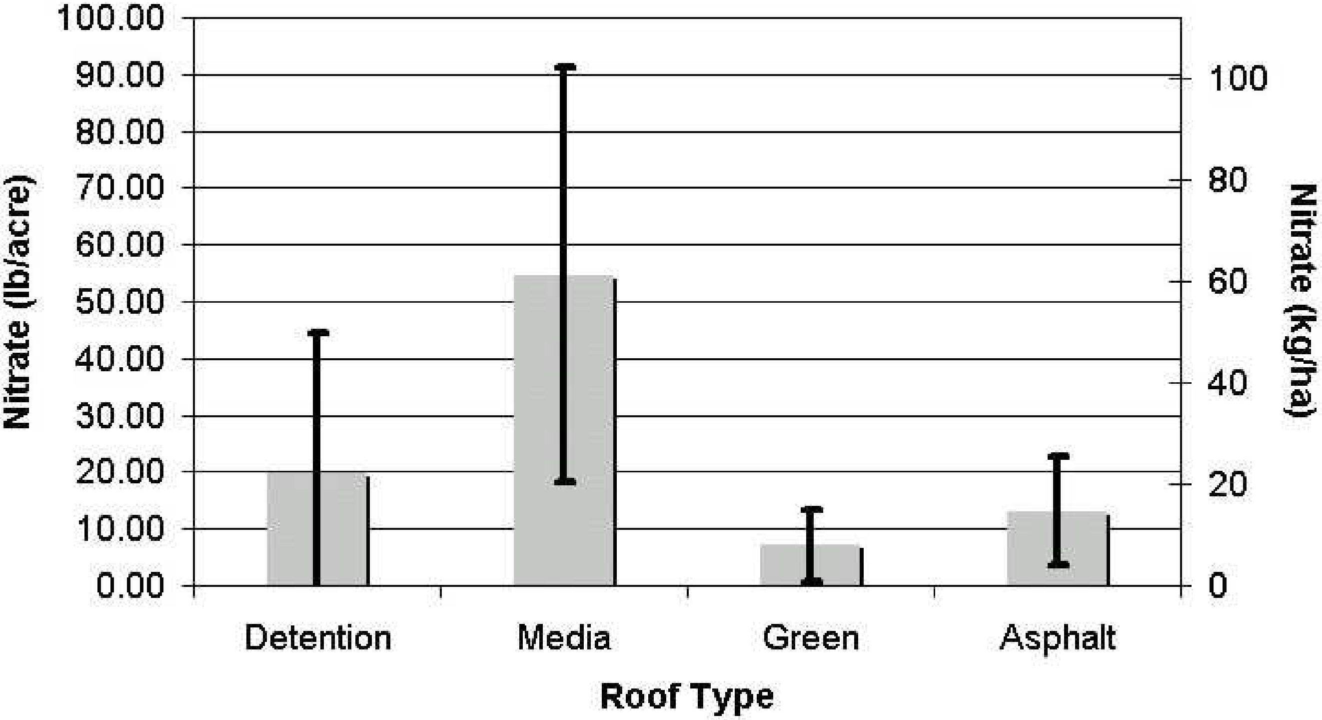


Figure 4-10 Average nitrate concentration in runoff from all roof types

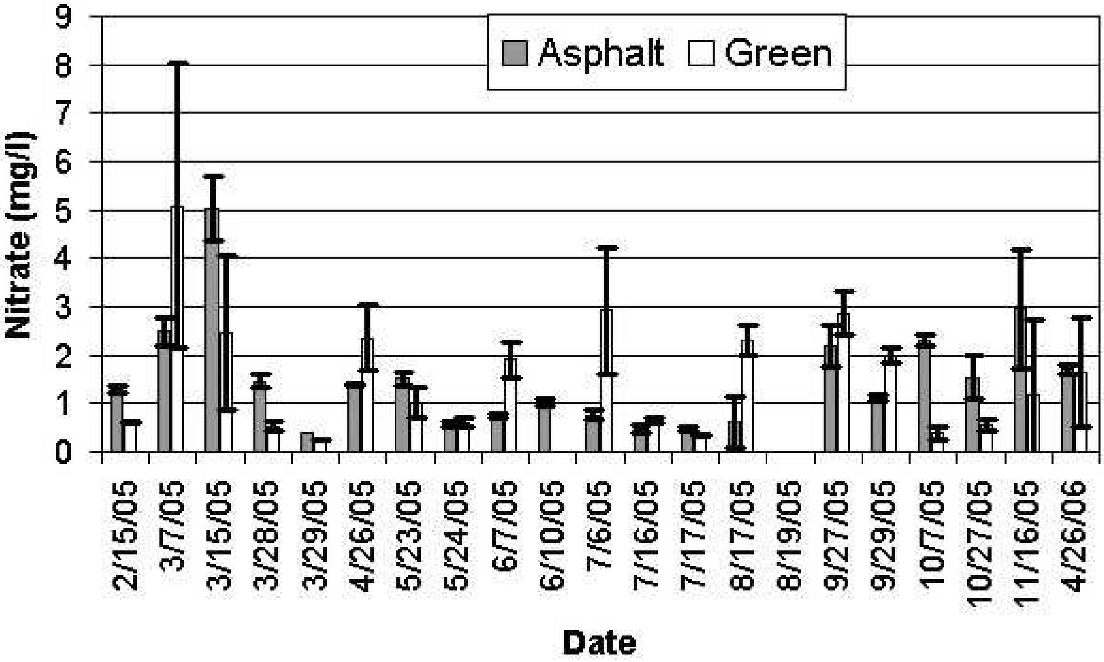


Figure 4-11 Nitrate concentration in runoff from green and flat asphalt roofs

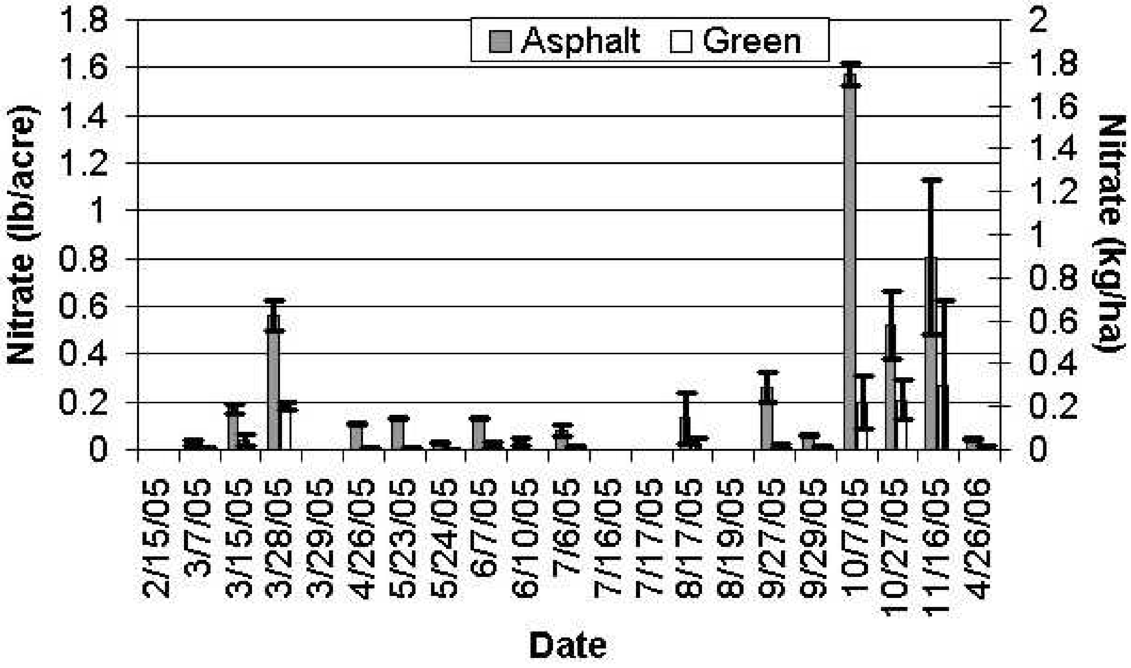


Figure 4-12 Nitrate (pounds per acre) in runoff from green and asphalt

Although runoff concentration was higher in the runoff from green roofs during summer when runoff was released, the total mass of nitrate in runoff was less because there was far less runoff from the green roofs than from the flat asphalt roofs during this period (Figure 4-12). Due to the decreased runoff, limited nitrate was released from green roofs during the summer, and even in winter when runoff resulted in release of nitrate to the environment, the total amount was less from green than asphalt roofs.

Over the study period for the sampled storms, the summation of nitrate in monitored events was 1.0 lb/acre of roof for green roofs, 3.9 lb/acre (4.4 kg/ha) for flat asphalt roofs, 2.8 lb/acre (3.1 kg/ha) for the rooftop detention and 9.8 lb/acre (11 kg/ha) for the media roof section. The media roof section not only had the highest concentration of nitrate in runoff but also resulted in the largest quantity of nitrate released, and this is with fewer monitored events. This is further demonstrated in Figure 4-13 which presents the calculated annual loadings. In addition, the average loadings per event were 0.06 lb/acre (0.07 kg/ha) of roof for green roofs, 0.24 lb/acre (0.27 kg/ha) for flat asphalt roofs, 0.16 lb/acre (0.18 kg/ha) for the rooftop detention and 0.51 lb/acre (0.57 kg/ha) for the media roof section.

The average background concentration of nitrate for the same three precipitation events as for pH was 0.87 mg/L. Figure 4-14 is a national map of atmospheric nitrate deposition, and indicates, as expected, that the test roofs were in an area of high nitrate deposition. Since nitrate is a major concern in surface runoff, green roofs offer the potential to significantly reduce total nitrate being discharged from urban environments in certain parts of the country, due to atmospherically deposited nitrate. In areas with lower nitrate concentrations in the precipitation, it is likely that the use of green roofs may be less effective in nitrate reduction, and green roofs may even require fertilization, which may contribute nitrogen to the runoff.

This study demonstrated that the green roof will remove and not leach nitrate with time, i.e., the media roof showed that initial fertilization may leach nutrients, less than one year old at time of study, while the more mature green roofs, about five years old, removed nitrate. However, further studies should be conducted on other nitrogen species.

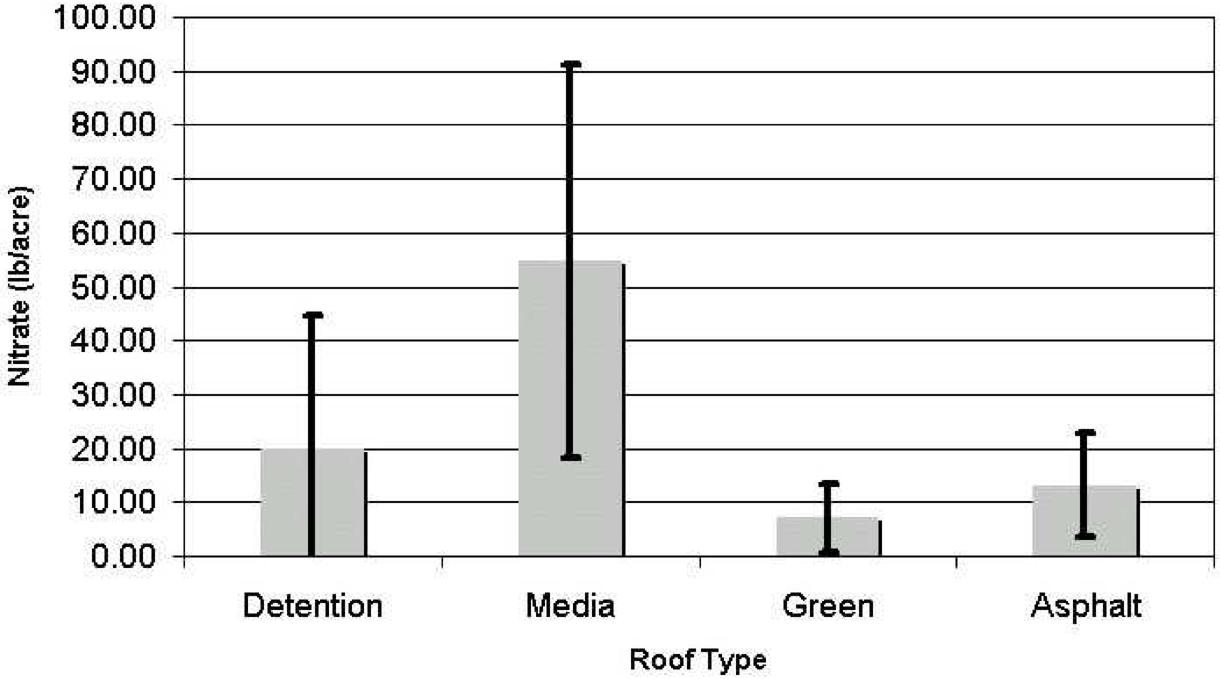
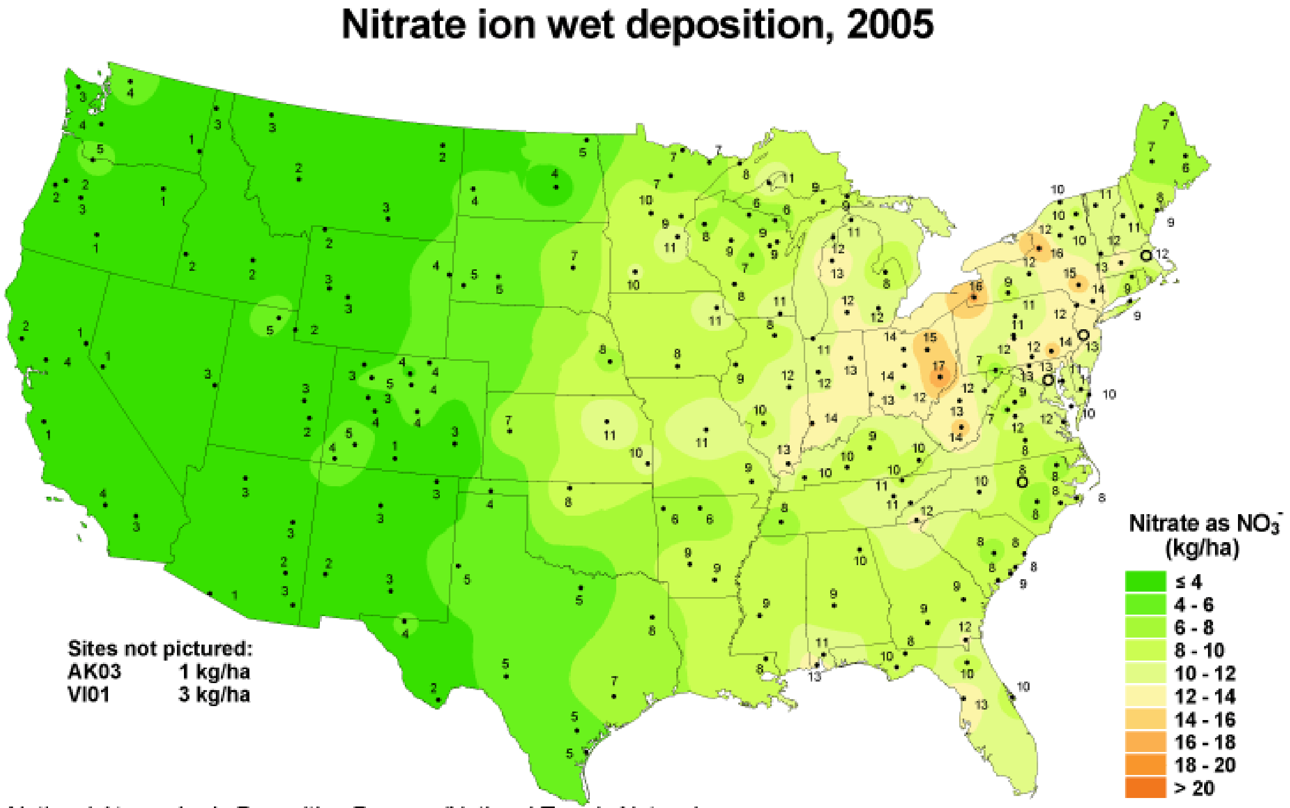


Figure 4-13 Calculated annual loading of nitrate from test roofs



National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

Figure 4-14 U. S. map of atmospheric nitrate wet deposition (National Atmospheric Deposition Program, 2006)

Other Water Quality Constituents

Water samples from storm-generated runoff were collected from the rain barrels and sent to the Penn State Agricultural Analytical Laboratory for qualitative and quantitative analysis for elemental composition. The five events ranged in individual rainfall totals from 0.14 in. (3.6 mm) to 0.98 in. (24.9 mm) with one sampling event being comprised of several precipitation events totaling 1.75 in. (44.5 mm). Ions analyzed for five events and their associated detection limits in mg/L were phosphorous (<0.06), potassium (<0.2), calcium, iron (<0.005), magnesium, manganese (<0.001), sodium, and zinc (<0.005). In addition samples from two events were analyzed for sulfur. Table 4-3 provides a summary of the analyses for five events. Not all samples provided concentration results as some were below associated detection limits; these values have been reported at half the detection limit. It was difficult to obtain green roof runoff samples in the growing season due to the limited runoff. Runoff from one of the green roofs for the August 17, 2005 event was less than a tenth of a gallon as reported in Table 4-3. In general concentrations from the green and media roofs were greater than the flat and detention roofs. The loadings were calculated in the same way as for nitrate and are presented in Table 4-4 with comparisons between green and the flat asphalt roofs. For values below detection limit values, one-half the value of the detection limit was used in the calculation of loadings for comparison purposes. A discussion of the individual nutrients and ions follows Table 4-4.

Nutrients

Phosphorous (P) concentration and loading in runoff from all five sampled precipitation events was higher from the green than the flat asphalt roofs. Phosphorous in runoff from flat asphalt roofs was low, with two events below detection limits. Concentration in runoff from green roofs was consistent. Runoff phosphorous concentration from the media roof section was higher than either green or flat asphalt roof runoff, mainly due to a very high concentration in the first event sampled (March 28, 2005; 2.53 mg/L). It is likely that this was due to the media being less than a year old. For the other measured events, phosphorous concentrations were similar for green and media roofs. For measured events where there was little runoff from the green roofs, phosphorous in the green roof runoff was very similar to the loading (April, 26, May, 13 and May 16, 2006) of phosphorous in flat asphalt roof runoff; however, in storms where there was more runoff from the green roofs (March 28, 2005), phosphorous in the green roof runoff was much higher, resulting in a higher overall average and higher sum for all the sampled storms and phosphorous from the flat roof was below detection limits for both roofs. Calculated average and annual loadings from the green roof clearly exceeded that of the flat asphalt roofs, by over 300%.

The average concentration of phosphorous 0.41 mg/L (CV = 0.45) in green roof runoff (Table 4-3) compares well to the total phosphorous event mean concentration (EMC) reported for landscaped residential areas by the National Urban Runoff Program (NURP) studies (EPA, 1983) 0.383 mg/L (CV = 0.69) and the National Stormwater Quality Database (Pitt et al., 2004), 0.30 mg/L (CV = 1.1).

Potassium (K) in runoff from green and flat asphalt roofs was similar to results for phosphorous. Potassium concentration was higher in runoff from green and media roof sections than flat asphalt roofs. Concentrations in earlier events (2005) were higher than later events (2006). It is possible that because the green roofs were not fertilized in 2005 and potassium is relatively mobile in the soil, that the available concentration decreased with time, resulting in less potassium in the runoff in 2006. This suggests that if a green roof is to be used as a stormwater management tool where water quality is an issue, care must be taken in the fertilizing rates of the roof. Enough fertility must be present to support plant growth but excess will result in higher concentrations in the runoff than might otherwise be necessary. As with phosphorous, the quantity of potassium in runoff was greatly influenced by the amount of runoff from the green roofs, and the calculated loading from green roofs greatly exceeded the calculated quantities from flat asphalt roofs.

Table 4-3 Summary of Concentrations and Volumes of Runoff for Five Sampled Events

Date	**Volume runoff**		**Concentrations (mg/L) (Detection limits)**								
	(gal)	**(L)**	P (<0.006)	K (<0.2)	Ca	Mg	Na (0.01)	Mn (<0.001)	Fe (<0.005)	Zn (<0.005)	S
Green roofs											
3/28/05	54.3	205.5	0.45	2.4	10.2	7.9	1.13	***0.001***	***0.0025***	***0.0025***	3.5
	49.7	188.1	0.44	2.6	9.7	7.3	1.26	***0.001***	***0.0025***	***0.0025***	3.6
	38.5	145.7	0.50	2.6	10.2	7.5	1.07	***0.001***	***0.0025***	***0.0025***	3.7
8/17/05	2.7	10.2	0.66	3.1	17.9	12.0	3.16	0.033	0.024	0.009	11.0
	0.7	2.7	0.62	1.9	13.7	8.2	2.76	0.027	0.018	0.035	8.3
	0.1	0.4	0.49	2.4	11.9	5.2	2.51	0.045	***0.0025***	0.026	5.4
4/26/06	0.7	2.7	0.18	0.8	13.0	9.2	0.91	0.008	0.094	0.010	
	0.9	3.4	0.14	0.7	12.1	8.5	1.16	0.010	0.079	0.009	
	0.7	2.7	0.75	2.6	25.6	12.1	1.89	0.004	0.079	0.006	
5/13/06	5.0	18.9	0.52	1.5	8.2	5.1	0.70	0.005	0.045	0.014	
	3.8	14.4	0.35	1.8	6.3	3.9	0.89	0.012	0.021	0.018	
	1.4	5.3	0.25	1.3	6.1	2.8	0.51	0.029	0.008	0.015	
5/16/06	1.3	4.9	0.16	1.0	12.4	7.8	0.91	0.005	0.074	0.022	
	1.9	7.2	0.26	1.0	12.3	8.6	1.03	0.006	0.069	0.014	
	1.0	3.8	0.43	1.3	18.8	11.7	1.67	0.001	0.087	0.014	
Average			0.41	1.8	12.6	7.8	1.44	0.012	0.041	0.013	5.9
Standard of Deviation			0.19	0.8	5.1	2.8	0.80	0.014	0.036	0.009	3.1
Coefficient of Variation			0.45	0.4	0.4	0.4	0.55	1.136	0.882	0.697	0.5
Flat asphalt roofs											
3/28/05	50.3	190.4	***0.03***	***0.1***	1.1	0.1	0.04	***0.001***	***0.0025***	0.007	0.9
	51.7	195.7	***0.03***	***0.1***	1.0	0.1	0.04	***0.001***	***0.0025***	***0.0025***	0.8
8/17/05	29.7	112.4	***0.03***	***0.1***	2.0	0.2	***0.01***	***0.001***	***0.0025***	***0.0025***	1.4
	28.1	106.4	***0.03***	***0.1***	7.3	0.7	0.06	0.004	***0.0025***	0.011	4.2
4/26/06	4.0	15.1	0.15	0.6	2.1	0.3	0.34	0.005	0.023	***0.0025***	
	3.3	12.5	***0.03***	***0.1***	2.4	0.3	0.09	0.001	0.013	***0.0025***	
5/13/06	32.0	121.1	0.09	1.2	3.5	0.3	0.15	0.017	***0.0025***	***0.0025***	
	30.8	116.6	***0.03***	0.5	3.2	0.3	0.05	0.013	***0.0025***	***0.0025***	
5/16/06	12.6	47.7	0.08	0.3	2.4	0.3	0.51	0.005	***0.0025***	***0.0025***	
	11.4	43.1	***0.03***	0.6	2.1	0.2	0.05	0.003	***0.0025***	***0.0025***	
Average			0.05	0.4	2.7	0.3	0.13	0.005	0.006	0.004	1.8
Standard of Deviation			0.04	0.3	1.8	0.2	0.16	0.006	0.007	0.003	1.6
Coefficient of Variation			0.77	1.0	0.7	0.5	1.21	1.120	1.239	0.782	0.9
Detention section											
3/28/05	28.7	108.6	***0.03***	***0.1***	0.5	0.2	0.06	***0.001***	***0.0025***	0.006	1.2
8/17/05	12.8	48.4	***0.03***	***0.1***	1.1	0.7	0.05	0.006	0.018	0.007	2.6
4/26/06	1.0	3.8	0.54	0.9	13.5	5.0	1.04	0.019	0.076	0.013	
5/13/06	11.7	44.3	0.42	0.8	1.4	0.4	0.10	0.025	0.021	0.005	
5/16/06	2.9	11.0	0.07	0.4	2.2	0.6	0.13	0.051	***0.0025***	0.010	
Average			0.22	0.46	3.73	1.36	0.28	0.02	0.02	0.01	1.89
Media section											
3/28/05	21.4	81.0	2.53	6.3	20.7	14.5	2.56	***0.001***	0.050	0.008	4.5
8/17/05	0.4	1.5	0.11	0.9	10.2	3.6	4.53	***0.001***	***0.0025***	0.022	4.8
4/26/06	1.0	3.8	0.54	1.0	13.3	4.9	1.03	0.018	0.073	0.014	
5/13/06	12.7	48.1	0.60	1.5	12.8	4.2	0.98	0.065	0.131	0.013	
5/16/06	2.7	10.2	0.15	0.5	4.8	1.6	0.39	0.027	***0.0025***	0.011	
Average			0.79	2.0	12.35	5.77	1.90	0.022	0.051	0.014	4.65
Mann-Whitney Rank Sum Test between green and flat/asphalt roofs											
P value*			<0.001	<0.001	<0.001	<0.001	<0.001	0.183	0.010	0.004	0.042**

Note - values in bold and italic represent one half the detection limit value.

*A P-value of 0.05 or less typically indicates the difference in median values between the two concentrations is greater than would be expected by chance and that there is a statistically significant difference between the results (Sigma Stat).

** The power of the t-test (0.484) was below the desired power of 0.800 (Sigma Stat).

Table 4-4 Estimated Loadings from Flat Asphalt and Green Roofs

Date	**Volume runoff (gal)**	**Loading (lb/acre) ***								
		P	K	Ca	Mg	Na	Mn	Fe	Zn	S
Green roofs										
3/28/05	54.3	0.185	1.001	4.2	3.3	0.47	***0.0002***	***0.0010***	***0.0010***	1.4
	49.7	0.167	0.974	3.6	2.7	0.48	***0.0002***	***0.0009***	***0.0009***	1.4
	38.5	0.147	0.754	3.0	2.2	0.31	***0.0001***	***0.0007***	***0.0007***	1.1
8/17/05	2.7	0.013	0.063	0.37	0.245	0.06	0.0007	0.0005	0.0002	0.23
	0.7	0.003	0.010	0.07	0.043	0.01	0.0001	0.0001	0.0002	0.044
	0.1	0.000	0.002	0.01	0.004	0.002	0.0000	***0.0000***	0.0000	0.004
4/26/06	0.7	0.001	0.004	0.07	0.049	0.005	0.0000	0.0005	0.0001	
	0.9	0.001	0.005	0.08	0.058	0.01	0.0001	0.0005	0.0001	
	0.7	0.004	0.014	0.14	0.064	0.01	0.0000	0.0004	0.0000	
5/13/06	5.0	0.020	0.058	0.31	0.192	0.03	0.0002	0.0017	0.0005	
	3.8	0.010	0.052	0.18	0.113	0.03	0.0003	0.0006	0.0005	
	1.4	0.003	0.014	0.06	0.030	0.01	0.0003	0.0001	0.0002	
5/16/06	1.3	0.002	0.010	0.12	0.077	0.01	0.0000	0.0007	0.0002	
	1.9	0.004	0.015	0.18	0.124	0.01	0.0001	0.0010	0.0002	
	1.0	0.003	0.010	0.14	0.088	0.01	0.0000	0.0007	0.0001	
Average loading (lb/acre)		0.038	0.20	0.84	0.62	0.097	0.0002	0.0006	0.0003	0.69
Standard of Deviation		0.067	0.37	1.5	1.1	0.170	0.0002	0.0004	0.0003	0.67
Coefficient of Variation		1.8	1.9	1.7	1.8	1.8	1.0	0.7	1.0	0.97
Annual loading (lb/acre)		2.0	8.5	59.4	37.1	6.8	0.058	0.19	0.062	28
Estimate of variation for annual loading		0.9	3.6	23.9	13.2	3.8	0.066	0.17	0.044	15
Average loading (kg/ha) *		0.042	0.22	0.94	0.69	0.11	0.0002	0.0007	0.0004	0.78
Annual loading (kg/ha) *		2.2	9.6	66.5	41.6	7.6	0.070	0.21	0.070	31
Flat asphalt roofs										
3/28/05	50.30	***0.011***	***0.04***	0.43	0.05	0.016	***0.0002***	***0.0010***	0.003	***0.011***
	51.70	***0.012***	***0.04***	0.41	0.06	0.015	***0.0002***	***0.0010***	***0.0010***	***0.012***
8/17/05	29.70	***0.007***	***0.02***	0.45	0.04	***0.001***	***0.0001***	***0.0006***	***0.0006***	***0.007***
	28.10	***0.006***	***0.02***	1.55	0.14	0.013	0.0008	***0.0005***	0.002	***0.006***
4/26/06	4.00	0.005	0.02	0.06	0.01	0.010	0.0001	0.001	***0.0001***	0.005
	3.30	***0.001***	***0.00***	0.06	0.01	0.002	0.00004	0.00034	***0.0001***	***0.001***
5/13/06	32.00	0.022	0.28	0.84	0.08	0.038	0.0041	***0.0006***	***0.0006***	0.022
	30.80	***0.007***	0.11	0.75	0.07	0.012	0.0031	***0.0006***	***0.0006***	***0.007***
5/16/06	12.60	0.008	0.03	0.23	0.03	0.049	0.0005	***0.0002***	***0.0002***	0.008
	11.40	***0.003***	0.05	0.18	0.02	0.004	0.0003	***0.0002***	***0.0002***	***0.003***
Average loading(lb/acre)		0.0081	0.061	0.50	0.050	0.016	0.0009	0.0006	0.0008	0.46
Standard of Deviation		0.0059	0.082	0.45	0.041	0.015	0.0014	0.0003	0.0009	0.28
Coefficient of Variation		0.73	1.4	0.92	0.81	0.96	1.5	0.46	1.1	0.60
Annual loading (lb/acre)		0.46	3.1	23.3	2.4	1.2	0.043	0.048	0.033	16
Estimate of variation for annual loading		0.35	3.0	15.2	1.3	1.4	0.048	0.060	0.026	14
Average loading (kg/ha) *		0.0091	0.068	0.56	0.056	0.018	0.0011	0.0006	0.0009	0.52
Annual loading (kg/ha) *		0.51	3.4	26.1	2.73	1.3	0.048	0.054	0.037	17
Percent difference between green and flat roofs										
Average loading		360	230	69	1100	500	-82	11	-61	49
Annual loading		330	180	160	1400	490	35	300	91	79

* Average and annual loading also presented in metric units of kilogram per hectare.
Note - values in bold and italic represent one half the detection limit value.

Hardness

Calcium (Ca) concentration in runoff from green roofs was greater than that from flat asphalt roofs. Calcium concentration in green roof runoff was similar to runoff from the unplanted media roof section. Although calcium concentrations were similar between planted green and unplanted media, total calcium in the runoff was much greater in unplanted media due to greater runoff than in the planted systems. It should not be surprising that there would be significant calcium in the runoff from green roofs since the primary parent material in the media used was expanded clay. Also, the ability of the media to buffer pH suggests that there must be significant quantities of calcium carbonates in the green roof media.

As might be expected, magnesium (Mg) concentration in runoff from the green roofs was similar, but slightly lower than calcium concentrations. In contrast, runoff from the flat asphalt roofs had much lower concentrations of magnesium. Total magnesium loading in the runoff was 10 times greater in green compared to flat asphalt roofs, although as with calcium, the total was largely a function of the first measured event.

Ions

With the exception of sodium, differences in concentrations and projected loadings of the remaining ions did not provide as clear cut statistical difference. Sodium (Na) concentrations were much greater in runoff from green roofs than flat asphalt roofs. Concentrations in runoff from green roofs and the unplanted media roof section were similar but total sodium in the runoff was higher in the unplanted media due to higher total runoff. While the calculated average and annual loading from the green roofs were significantly larger than that from the flat asphalt roofs.

Results of manganese (Mn), iron (Fe) and zinc (Z) are even less decisive, particularly when both roofs were often below detection limits. The calculated average loading and the annual loadings provided results that indicate green roofs can have either decreased or increased loadings. Most likely, more samples are necessary to provide a conclusive result, but indications are that green roofs will not be a significant source for these ions over other standard roofing systems.

Sulfur (S) concentration was analyzed for only two events. As with other ions tested, the concentration was higher in runoff from green than flat asphalt roofs and indicated a greater loading. However, total sulfur in the runoff was not statistically different in green versus flat asphalt roofs.

Summary

Runoff from green roofs had higher concentrations of most of the nutrients and ions evaluated. From the five precipitation events monitored, green roof runoff appears similar to what might be expected as leaching from any other planted system in the landscape. Concentration of phosphorous is comparable to that of the NURP and NSQD database residential values for total phosphorous. An important exception for nutrients was nitrate, where the average concentration in runoff from green and flat asphalt roofs was nearly the same.

Although the runoff concentrations were typically higher, the loading was not always higher. Since the total runoff from green roofs was about 50% less than the runoff from flat asphalt roofs over the study period, total loading of runoff was sometimes lower even when concentration was higher. Nitrate provides a good example of this loading reduction from green roofs over asphalt roofs and especially in this case, the media roof, demonstrating the added benefit of the plants. There were several ions which exhibited seasonal differences in either concentration or total runoff or both. Many of these differences were related to reduced runoff from green roofs during warmer months. Concentration of some ions, i.e., calcium and magnesium, in green roof runoff were very consistent, the concentration most likely controlled by buffers and/or exchange in the media. Clearly, total loading for hardness or ions evaluated depended greatly on the amount of precipitation retained and the amount of runoff from the different roof systems.

Relative effects of green roofs on total loadings and water quality of runoff will be a function of season and precipitation totals. In wet years, green roofs might contribute loadings of nutrients and hardness to total runoff during summer or winter, and in dry years, most of the green roof loading is likely to occur during winter months. Although runoff from the green roof for other ions was higher in concentration than runoff from flat asphalt roofs, it is not clear that the relatively low concentrations of ions found in green roof runoff should be a concern in most applications.

Sampling only compared paired events that produced runoff for both green and flat asphalt roofs. This may have biased results slightly, increasing the potential loadings from green roofs and decreasing the loadings from the asphalt roofs. It is expected that the washoff concentration of pollutants for flat asphalt roofs could be higher for smaller storms that may not produce any runoff from the green roofs. On the other hand, green roofs are biological systems, and increased rainfall volumes and intensity may lead to higher loadings, while, after the initial flush from a flat asphalt roof, loadings should diminish.

Runoff from the unplanted media roof section was considerably higher in both concentration and in total output than the planted green roofs. Since this roof was relatively new (less than 1 year old), and since there were no plants to utilize nutrients, it is not surprising that concentration in the runoff would be higher. This suggests that newly planted roofs are likely to have much higher runoff loading rates than established roofs. Any water quality data collected during the establishment phase of a green roof may not reflect steady state or long-term water quality. Also, during periods of plant establishment, green roofs in these circumstances should not be irrigated to the point of saturation to prevent leaching of nutrients.

Results indicate that a green roof will contribute more nutrients (except nitrate), hardness, salts, and other ions to the roof runoff, due mostly to the use of media and initial composting to provide nutrients for plants. Increased hardness appears to be related to pH of precipitation and neutralizing of runoff. Increased loadings of some water quality constituents does not necessarily indicate that green roofs would increase loadings to receiving waters; however, this would suggest that the green roof as a stormwater BMP should probably be integrated with other treatment techniques. Appropriate additional treatment, such as routing through a centralized BMP or more appropriately discharging from the downspout to LID type BMPs, (e.g., swale, bioretention system, rain gardens) could be recommended for green roof runoff as a part of an overall stormwater system. Green roof runoff could also be collected and used for ornamental landscape purposes. Due to the reduced volume, time lag from the green roof and the lower pollutant content of the green roof discharge in comparison to that of combined sewage, discharge to a combined sewer system in heavily urbanized areas would be a benefit. Directly connecting the green roof drainage to a separately sewered storm system without additional treatment or without benefit of the mixing and routing (time lag) may impact the receiving water. The extreme case of directly discharging to the receiving water without further treatment should be avoided.

Chapter 5 Green Roof Plant and Media Management Considerations

In addition to field studies, additional greenhouse and laboratory studies were performed to provide the user community with additional information to help implement and manage green roofs. Specifically, these studies evaluated evapotranspiration rates and related to existing models, determined both establishment criteria for plants and media depths required to resist drought and predicted the long-term buffering capacity of the green roofs though accelerated testing.

Evapotranspiration Rates from Green Roofs

One of the most likely and cost-effective reasons for a developer or zoning board to promote the use of green roofs is their ability to retain and detain stormwater, which could reduce or eliminate the need for increased stormwater management infrastructure by a municipality or watershed manager, or the need to set aside part of a development for onsite stormwater management basins. In either case, the costs and benefits are direct, easy to understand, and easy to assign to an individual entity. One of the major limitations to promoting this use of green roofs is the lack of accepted design tools or models to predict the stormwater reduction effects of the green roofs. A major limitation in current models is the lack of a good understanding of ET by the green roof systems. To address this need, controlled greenhouse studies attempted to develop accurate and dynamic estimates of ET for plantings with *Delosperma nubigenum* and *Sedum album*.

System Description

A weighing lysimeter system was used to conduct ET studies in a computer-controlled greenhouse section on the University Park Campus of the Pennsylvania State University. Eight test beds (3.5 ft long, 1.75 ft. wide and 4 in. deep; 105 cm long, 54 cm wide and 10 cm deep) were each suspended by cables from an Omega Mini-beam LCEB-150 lb (68 kg) load cell (Omega Mfg, Stanford, CT). Two Multiplexer 21X data loggers (Campbell Scientific, Inc., Logan, Utah), each with 16 input channels, were programmed to collect data from the aforementioned sensors, collected and recorded output from the load cells and other measurement systems. Each test bed box contained a multilayer green roof system consisting of a drainage mat (Enka-drain 9615, Cold Bond, Enka, NC) covered with approximately 3.5 in. (9.0 cm) of a clay-based, commercial green roof media (Big River Industries, Alpharetta, GA). Each weighing lysimeter was suspended at a pitch of 1:12 (approximately 8% slope) with a drainage slit in the box at the lower end. Drainage water was collected in a gutter and directed to a collection bucket. Four lysimeters were vegetated while the other four contained the green roof system without plants. The vegetated beds contained a mixture of *Sedum album* and *Delosperma nubigenum* which covered 80-95% of the surface of the bed throughout the project.

Air temperature and media surface temperature were measured with Omega Copper-Constantan HYPO-Series thermocouples. Two thermocouples measured surface temperature of vegetated lysimeters and two measured surface temperature of non-vegetated lysimeters. A wet and dry bulb thermocouple pair located in an aspirated sensor box was used to measure air temperature and calculate relative humidity. In addition, two infra-red thermocouple sensors

(IRTC Exergen, Watertown, MA) were installed, with one directed to measure surface temperature of a vegetated and the other directed to measure surface temperature of a non-vegetated lysimeter.

Light quantity was determined using a LiCor Pyranometer (Lincoln, NE) mounted two meters over the lysimeter systems. Wind speed was measured with an Omega hot wire anemometer. A pan system was used to estimate evaporation; it was composed of an open body of water in a 4.5 in. (11.5 cm) diameter and 0.2 in. (0.6 cm) depth cylindrical container with an Omega PX26-PSI pressure transducer placed on the bottom and connected to a data logger. The evaporation pan was calibrated by incrementally filling the cylinder and recording the data logger's response at the same time. Water was then incrementally removed from the cylinder and data logger readings were measured for each new level as before. This process was reported three times and averaged to increase the accuracy of the calibration. The calibration coefficient was 8.78 when pressure in mm of water was on y-axis and millivolts on x-axis.

Evapotranspiration Rates

Data collected suggest, as expected, that water use was greater in planted than in unplanted systems. The average water loss or measured ET rates before the plants responded to moisture stress was 0.41 in./d (10.5 mm/d), which was about 40% of the field capacity moisture. After the plants had used 40% of the soil's field capacity moisture, their water loss rates reduced to an average of 0.014 in./d (0.036 cm/d) for the remainder of the 21-day experiment. Example results of one dry-down period experiment are shown in Figure 5-1. In this 14-day dry-down period, 6 mm (0.25 in.) of water was lost through evaporation from unplanted systems, while 10 mm (0.39 in.) was lost from planted systems. In the beginning, water loss was similar for both systems, but after a few days water stored in the plants and the plants ability to extract water from deeper in the media via their roots resulted in greatly increased ET.

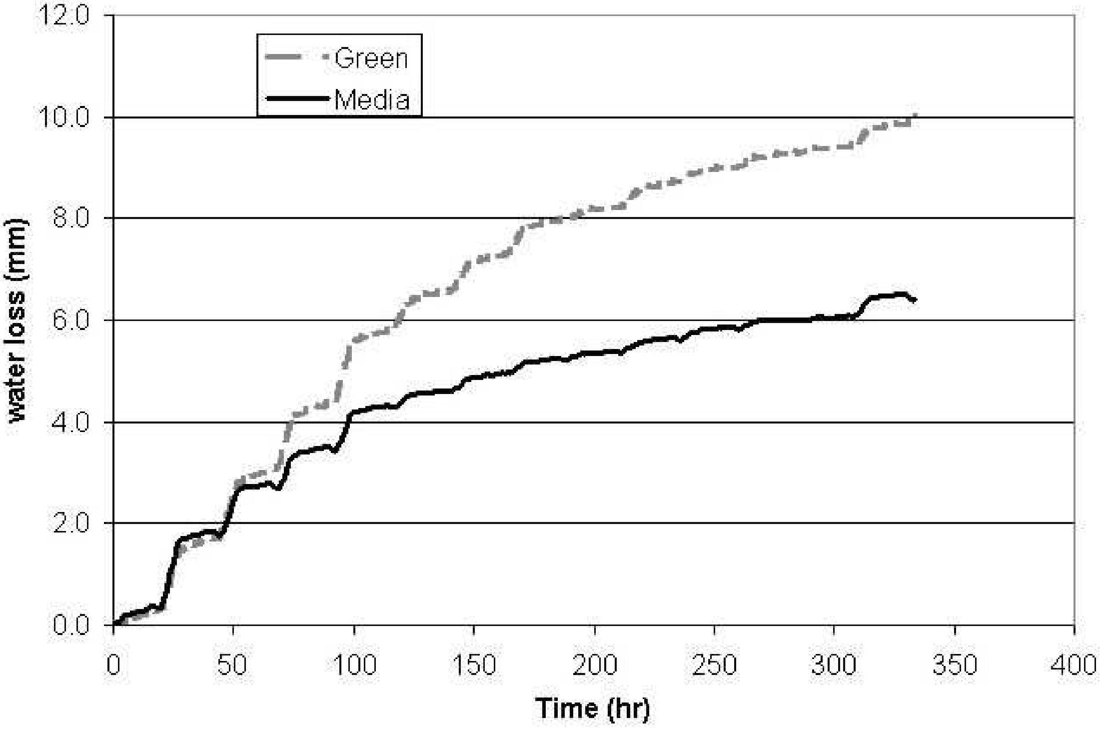


Figure 5-1 Average cumulative water loss from planted and non-planted green roof lysimeter test beds in the fall

Not only was the water loss of the planted systems greater, but some interesting patterns in water loss emerged when the data were examined more closely as demonstrated in Figure 5-2. In the beginning, water loss during the day greatly exceeded water loss at night. This was true for both planted and unplanted roof systems. The rate of water loss in the unplanted systems rapidly dropped over the first 4 to 5 days, presumably as the media surface dried. In contrast, planted systems continued rapid and fairly consistent water loss. Water loss during the night was lower and was roughly equal in green and flat asphalt systems during this period immediately following watering. After 3 to 4 days a change in the water loss patterns occurred in the planted systems. Water loss during the day dropped rapidly while water loss at night remained fairly consistent. The result was that the planted systems lost much more than unplanted systems at night during this phase, which lasted for about 4 to 5 days. This change may correspond to plants utilizing crassulacean acid metabolism (CAM), opening stomata at night. After 7 to 8 days the water loss rate difference between green and flat asphalt systems became increasingly small as plants became increasingly water stressed. Data from summer conditions suggested that water loss from planted systems at night was, in fact, less than from unplanted systems and that plants may in fact be extracting moisture from the air when the humidity was high.

Sedum album was chosen because it was anticipated to survive the stressful treatments of the experiment. This popular green roof plant is known to switch to CAM when water stressed. CAM plants open their stomata at night, taking up carbon dioxide and storing it as malic acid. During the day, they maintain closed stomata and photosynthesize the stored carbon dioxide (Ting, 1985). This results in CAM plants having very high water use efficiency because they open their stomata at night and close them during the day to minimize water loss through evapotranspiration.

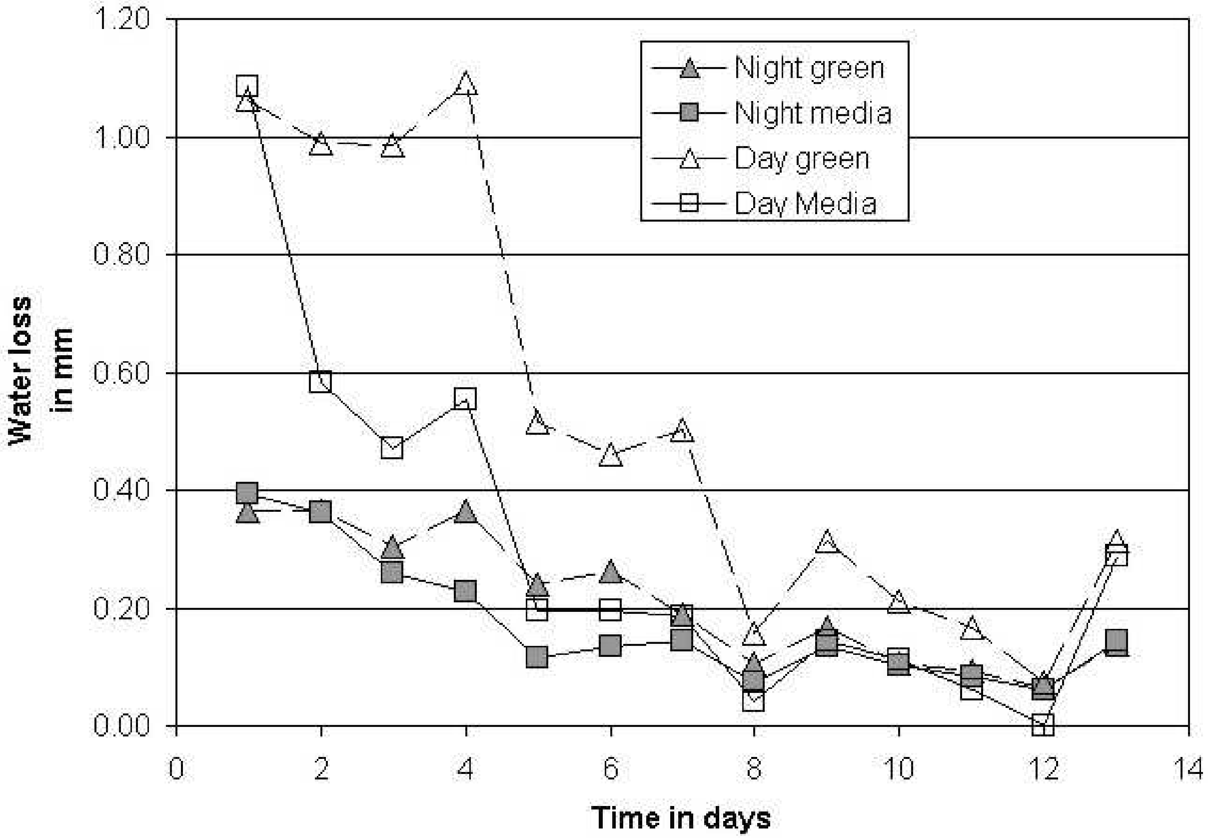


Figure 5-2 Average water loss during the daylight or night from planted and unplanted green roof lysimeter test beds in the fall

Figures 5-3 and 5-4 compare the average hourly water loss for the planted and unplanted test beds for a day when the water loss was not limited (second day, Figure 5-3) and a day when the water loss was limited (sixth day, Figure 5-4) for hot summer conditions. As can be seen from these figures, the planted test beds have less transpiration during nighttime, since the maximum ET rate occurred during the day in both figures.

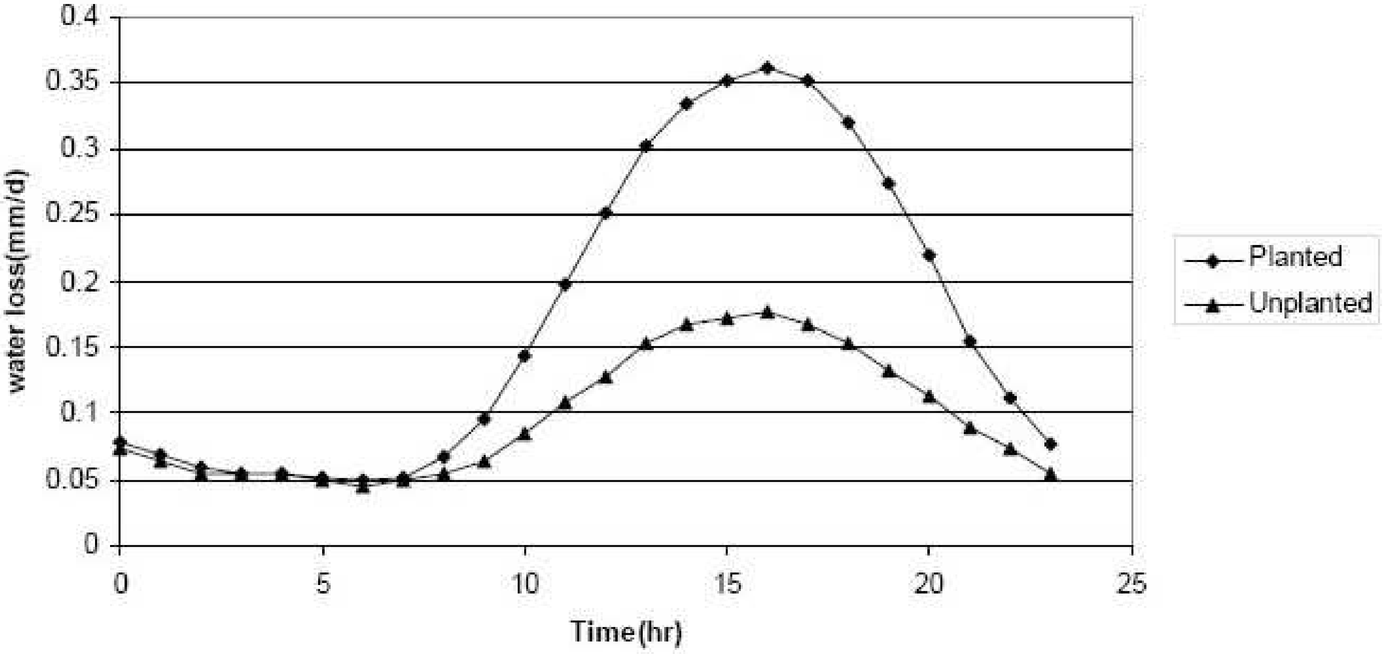


Figure 5-3 Average hourly water loss from planted and unplanted boxes for the 2nd day after watering during the hot summer condition (Rezaei 2005)

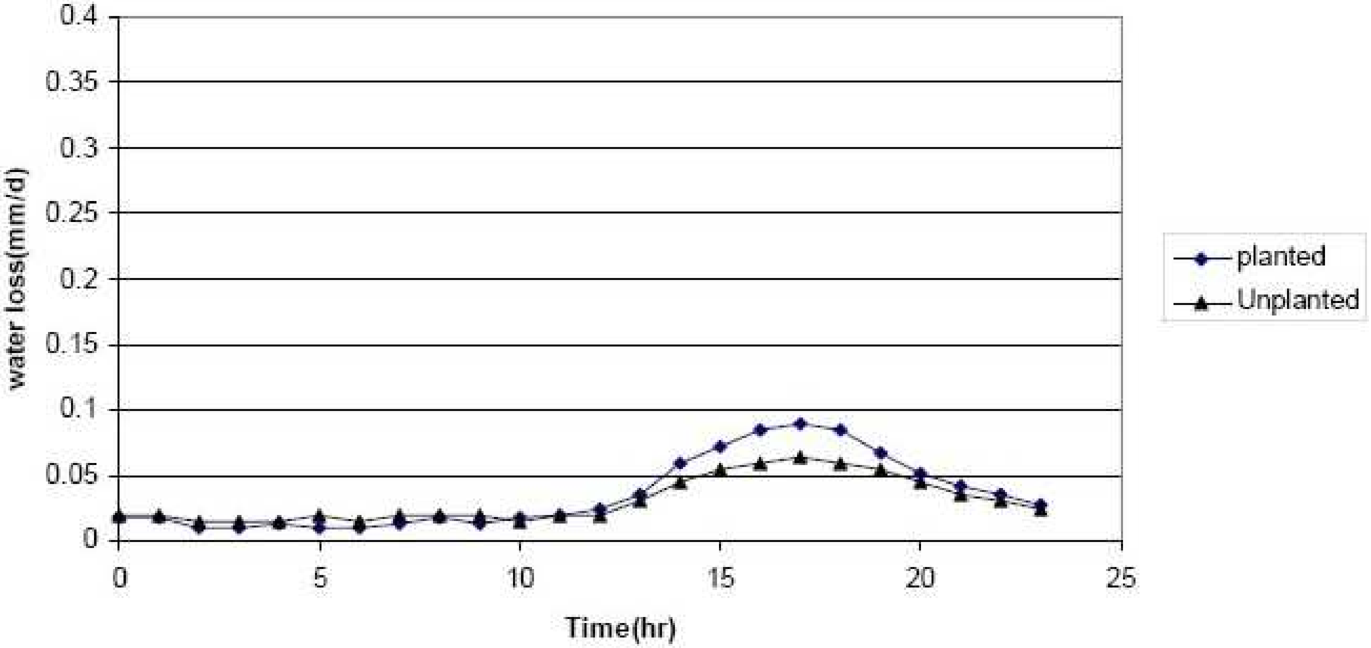


Figure 5-4 Average hourly water loss from planted and unplanted boxes for the 6th day after watering during the hot summer condition (Rezaei 2005)

Standard ET models, i.e., Penman Monteith, FAO Penman, Original Penman, and Blaney-Criddle, were applied to the data and regression analyses indicated ET was fairly well predicted with R^2 values of 0.815, 0.644, 0.796, and 0.697 respectively, for winter conditions, when the systems were not too water stressed. During warmer periods, the models adequately predicted water loss for the first seven days, with R^2 values of 0.855, 0.810, 0.794, and 0.646, respectively, but did a poor job of predicting water loss after that as the systems became dry.

The data suggest there may be a need to develop unique water loss model factors to account for the water loss patterns in these *Sedum* carpet roofs if there is a need to accurately predict the rate of recharge for water detention capacity of green roof. The runoff reduction potential by green roofs for storm events may need to be modeled with consideration to the ET rates. This may also require modeling of results in different areas of the country.

Effect of Media Depth, Type, and Drought during Establishment

Ideally, extensive green roofs do not require irrigation, and the growing media should be able to absorb and retain water, but also drain readily (Miller, 2003). In addition to limitations of water, green roof plants must tolerate direct solar radiation, high wind velocities, extreme temperatures and unpredictable precipitation (Durham et al., 2004). Preferred green roof plants are shallow-rooted perennials, with limited growth to prevent toppling and desiccation (White and Snodgrass, 2003). Well-designed 'soilless' media can provide comparable moisture holding properties to organic-rich mixes, depending on particle size and the substrate (Miller, 2003).

The responses of five plant species to three media depths under three drought regimes were tested. In addition, two different media, expanded clay and expanded shale, were compared for their influences on plant performance in combination with treatments of depth and drought. All tests were performed in two replications. The experiment ran for a period of 81 days, beginning June 16, 2004 and ending September 4, 2004. This period of time, after planting but prior to the first year dormancy, was considered the plant establishment period. In late April of 2004, cuttings from the three succulent taxa (*Sedum album*, *Sedum sexangulare*, *Delosperma nubigenum*) were taken from greenhouse stock and propagated in modular plug trays (2 cm^2, 0.5 in^2, 273 per tray) in a peat-based potting soil. The two herbaceous species (*Dianthus deltoides*, and *Petrorhagia saxifraga*) were provided, as plugs (8 x 4.5 cm, 3 x 1.75 in., 72 per tray), by Green Roof Plants (Emory Knoll Farms, Street, MD). On June 16, 2004, the plugs were transferred to the experimental study flats, which are described below, along with the media. Before planting, the flats were irrigated twice to saturation, or the point at which water drained freely from below. After planting, all flats received the same amount of water again.

The expanded clay was expected to support plants better than the expanded shale, as clay has a good capacity for holding water and exchanging cations (Nelson, 1998). The mineral aggregates were mixed with pelletized spent mushroom compost (Laurel Valley Soils, Avondale, PA) to obtain a ratio of 85% mineral to 15% organic matter by volume. The study flats, 1044 cm^2 (160 in^2) propagation flats (Anderson Dye and Manufacturing, Portland, OR), were filled and leveled to the desired depths of 3.0, 6.0, and 12.0 cm (1.2, 2.4 and 4.8 in.) to represent a range depth, from too shallow to exceeding design depth for extensive green roofs.. The bottom of each flat was fitted with a piece of Enkadrain (Colbond Geosynthetics, Enka, NC). Because the herbaceous plugs were longer than the depth of the shallower flats of 3.0 and 6.0 cm (1.2 and 2.4 in.), the root masses of these plugs were cut into four sections and the divided parts spread flat along the bottom of the flats, like octopus legs to completely bury the roots. The five plant taxa were planted at a density of five individuals per box for each treatment, for samples of n = 10.

The experiment was housed in a 12 x 100 ft (4 x 30 m) polyethylene greenhouse tunnel (located in Potter's Mills, PA) in order to control for drought. Three watering regimes were used: no drought, early drought and late drought. Control plants (no drought) received 1.4 in. (3.6 cm) of water twice weekly, or 2.8 in. (7.2 cm) per week, for the 11-week study period. Plants subjected to early drought received no water for the first two weeks after planting, while those subjected to late drought received no water in the last two weeks of the study period. When drought was not in effect, drought plants received the control amount of water. The experiment was designed in a split-block arrangement by randomized complete blocks, with drought conditions separated as blocks of irrigation treatments. The treatments of media type and depth were placed randomly within the blocks at factorial levels, and blocks were also placed randomly within the replications.

Data Analysis

To assess species performance under the various treatments at the close of the 11-week study period, the shoot biomass, defined as the above-ground plant material, including stems, foliage, flowers, was harvested and dried for 36 hr in an oven at 50ºC. Shoot dry weight for the means of two replications was analyzed with the SAS Mixed

Procedure and the General Linear Model (GLM) (Littell et al., 1996) at the 0.05 level of significance. The Mixed Procedure suited this study because the model contained both fixed and random effects, i.e., mixed effects parameters, and because the data set was unbalanced due to plant mortality. Dead plants were not used in the calculation of mean shoot dry weight.

Effects of Drought

Since the deepest media did not cause apparent stress, the responses of plants grown in the 12.0 cm (4.8 in.) deep media were attributed to drought and/ or media type, and were addressed first. As expected, the two herbaceous species were significantly affected by drought, while the succulents were not.

When grown in 12.0 cm (4.8 in.) and subjected to early drought, *Sedum sexangulare* had the fewest survivors and least shoot growth than control or late drought plants. Although mean shoot dry weight differed significantly between control and early drought plants (GLM), early drought plants did not match the shoot growth of plants subjected to late drought by the end of the study period. *Delosperma nubigenum*, *Dianthus deltoides* and *Petrorhagia saxifraga* also produced less shoot dry weight after early, rather than late drought, but only in the expanded shale, behaving oppositely in the expanded clay. In 12.0 cm (4.8 in.) expanded shale, these taxa produced less shoot biomass after early drought, and also suffered the most mortality.

The hardiest of the bunch after early drought, *Petrorhagia saxifraga* in 12.0 cm (4.8 in.) shale had 83% less mean shoot dry weight compared to control plants (or 17% of the biomass established by plants in control conditions), while plants grown in clay had only had 24% less mean shoot dry (76% of biomass of control plants) as demonstrated in Figures 5-5 and 5-6, respectively. Missing data points in these and following graphs signify that no plants survived that treatment combination, e.g. in Figure 5-5, no plants survived the 3 cm (1.2 in.) depth and only plants in clay survived the 6 cm (2.4 in.) depth. Under control conditions, this species established similar shoot growth in both media and, compared to *Sedum album*, performed the most consistently. Rapid establishment can be promoted by preventing transplant stress, i.e., providing water before the symptoms of water stress appear (Nelson, 1998). For non-CAM plants, irrigation in the first few weeks after planting is essential. Other studies suggest that irrigation in the first weeks of establishment promotes the longevity and robustness of a green roof plant community (Monterusso, 2003 and Dunnett and Nolan, 2004), and some recommend irrigation for the entire first growing season, unless weekly rainfall exceeds 25 mm (1 in.) (White and Snodgrass, 2003).

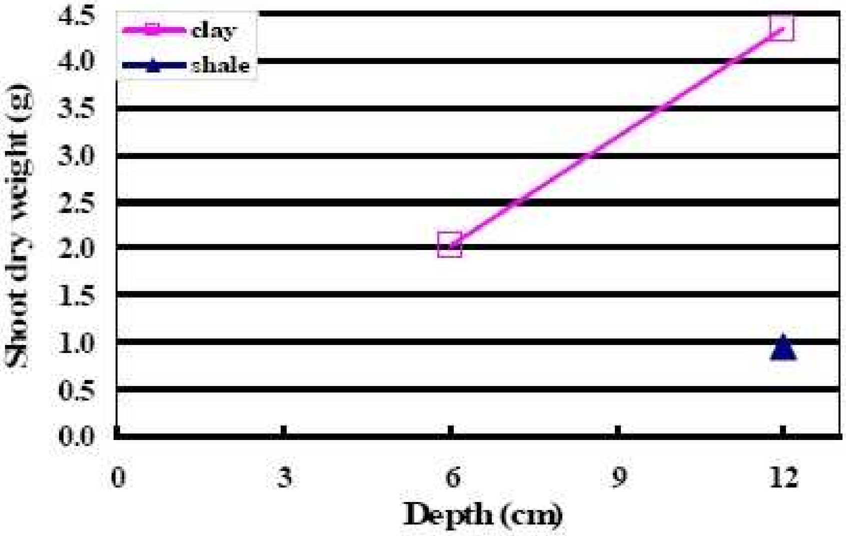


Figure 5-5 Mean shoot dry weight (g) (n=10) for *Petrorhagia saxifraga* in three depths of two media under early drought conditions (Thuring, 2005)

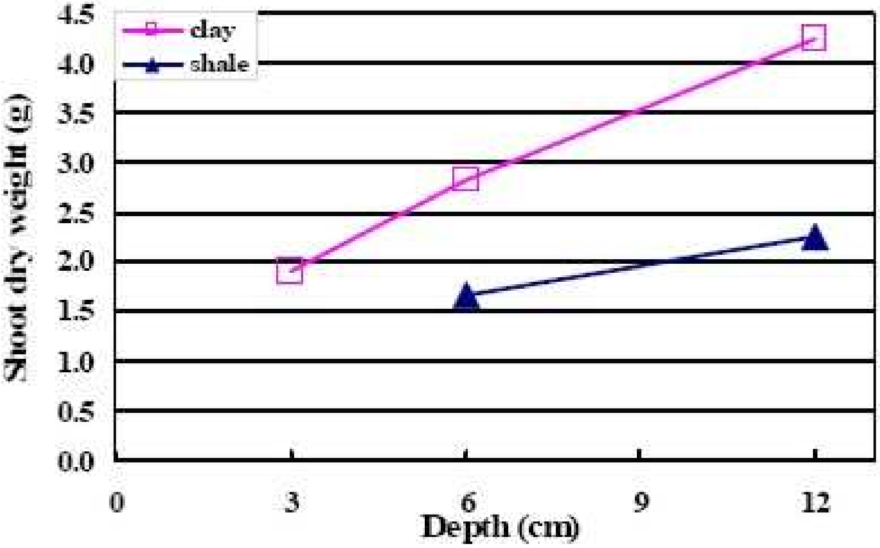


Figure 5-6 Mean shoot dry weight (g) (n=10) for *Petrorhagia saxifraga* in three depths of two media under late drought conditions (Thuring, 2005)

Sedum album was the only species that actually had more shoot biomass after early, rather than late, drought in 12.0 cm (4.8 in.) of both media**.** Compared with control plants in 12.0 cm (4.8 in.) shale, plants subjected to early drought had 47% less shoot dry weight, and in the expanded clay actually gained 5% shoot biomass. When subjected to late drought, this species had 49% (shale) and 70% (clay) less shoot dry weight than control plants (Figures 5-7 and 5-8). A similar study, testing media type, depth, and drought observed that *Sedum album* remained green after 100 days without water (38 of which had temperatures higher than 18°C), and did not exhibit the red coloration that indicates water stress (Lassalle, 1998).

Effects of Media Depth

Early drought conditions reduced survival or impacted biomass for most species, but especially so in combination with shallow media depths. Depth influenced shoot growth for the overall experiment significantly ($p<0.0001$), and all taxa studied, except for *Dianthus deltoides*, showed significant responses to depth. The results of *Dianthus deltoides*, are consistant with a study by Dunnett and Nolan (2004) that demonstrated *Dianthus deltoides* had good growth and survival when provided with regular and sufficient irrigation independent of media depth. Even when plants survived, plants in the shallowest depth of 3.0 cm (1.2 in.) always produced the least shoot biomass. Under early drought, *Delosperma nubigenum*, *Dianthus deltoides* and *Petrorhagia saxifraga* did not survive in 3.0 cm (1.2 in.) media, regardless whether it was clay- or shale-based. *Delosperma nubigenum* survived in 3.0 cm (1.2 in.) clay, but did not survive in the shale. The two herbaceous species did not survive in 6.0 cm (2.4 in.) shale media under early drought. Since the lifespan of perennials can be limited by media depth and other environmental factors, White and Snodgrass (2004) concluded these plants require at least 10 cm (4 in.) media.

When subjected to early and late drought, Figure 5-7 and Figure 5-8, respectively, *Sedum album* established similar mean shoot dry weight (g) across the three depths of expanded shale. In the deeper experimental depths of expanded clay, 6 cm (2.4 in.) and 12 cm (4.7 in.), respectively, this species produced remarkably more shoot biomass after early drought as compared to both late drought and control plants

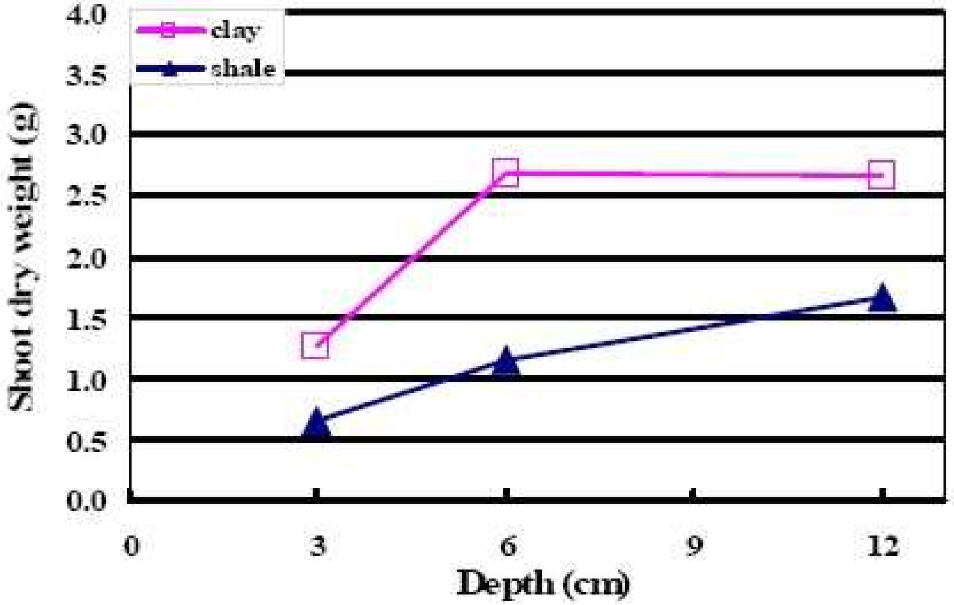


Figure 5-7 Mean shoot dry weight (g) (n=10) for *Sedum album* in three depths of two media under early drought conditions (Thuring, 2005)

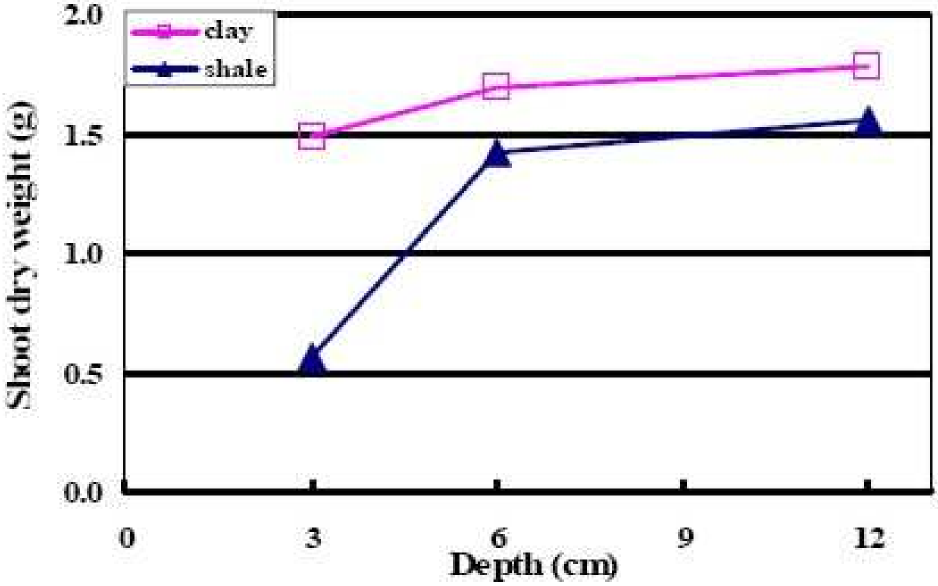


Figure 5-8 Mean shoot dry weight (g) (n=10) for *Sedum album* in three depths of two media under late drought conditions (Thuring, 2005)

The three hardiest taxa, *Petrorhagia saxifraga* and the two sedums, always produced more shoot biomass with increasing media depths, regardless of water availability. While the sedums performed well in all depths, plants grown in 6.0 and 12.0 cm (2.4 and 4.8 in.) media produced significantly more shoot biomass than those in 3.0 cm (1.2 in.) (GLM) as demonstrated in Table 1. If good performance by these hardy species indicates green roof success, then unirrigated extensive green roofs should never be less than 6 cm (2.5 in.) deep; this minimal depth corresponds to retaining 40% of the 2-yr storm (Scholz-Barth, 2001), as noted in Chapter 1. When it survived, *Petrorhagia saxifraga* flowered continuously. The benefit of *Petrorhagia saxifraga* for green roofs is its prolific seed production and ability to fill gaps in plant cover (Kolb et al. 1982). However, this species benefited from the deeper media depths.

Table 5-1 Mean Shoot Dry Weight for *Sedum album* under Early and Late Drought Conditions

Drought Conditions	**Depth (cm)**	**Expanded Shale Media**			**Expanded Clay Media**		
		mean dry weight (g)	**% reduction from control[1]**	**% survival (n=10)**	**mean dry weight (g)**	**% reduction from control**	**% survival (n=10)**
Early	3.0	0.65 (a)[z]	55	80	1.27 (a)[z]	29	90
	6.0	1.15 (a)	50	80	2.68 (a)	-56	90
	12.0	1.66 (a)	47	100	2.66 (b)	-5	100
Late	3.0	0.57 (a)[z]	39	100	1.49 (a)[z]	83	90
	6.0	1.42 (a)	62	100	1.69 (a)	98	100
	12.0	1.55 (b)	49	100	1.78 (b)	70	100

[1] The column "% reduction from control" shows how shoot growth was influenced by the drought conditions by contrast to control conditions.

Negative numbers indicate that more dry weight was produced.

z - Different letters indicate significant differences in shoot dry weight as influenced by medium depth z. Mean separation by Duncan's multiple range test at $P < 0.05$

Effects of Media Type

Species responses to media depth and drought were sometimes complicated by their responses to the two media. The capacity for the two media to support plants through drought was disparate. Since the herbaceous taxa performed similarly to *Sedum album* under early drought conditions when grown in the expanded clay, and plants grown in the shale either died or exhibited reduced biomass, it would appear that the clay is a better selection for green roofs that will not be irrigated. Similar studies which used media dominated by expanded slate also found that herbaceous perennials in green roof conditions required irrigation to thrive (Dunnett and Nolan, 2004; Durham et al. 2004; and Monterusso et al., 2005). Geologically, slate is produced by the compression of shale, so if these aggregates are considered similar, then those studies substantiate the poor plant growth observed in the expanded shale.

Discussion

Results from this study illustrate how factors such as type of media and depth and anticipated conditions such as drought can direct species selection and planning for the design of extensive green roofs. Fundamentally, these experiments revealed the variability in survival among drought tolerant species when subjected to other treatments. Shoot growth often varied per species depending on the timing of drought or the type of media. However, early drought apparently stunted the capacity for shoot growth, with the exception of *Sedum album*, since most species did not match their late drought counterparts in shoot dry weight. Initial irrigation in the beginning of an establishment period would benefit plant performance, especially for the long term.

Water stress has an enormous effect on plant cell development, and insufficient water during establishment can result in stunted roots and a permanent decrease in leaf size. This inhibits water and nutrient uptake and reduces surface area for photosynthesis, even after water is reinstated, further inhibiting a plant's capacity to grow (Boodley, 1998).

In planning for extensive green roofs, therefore, it is valuable to know the original habitats and morphologies of selected taxa. *Sedum* carpets will perform well in a minimum of 6.0 cm (2.4 in.) media without irrigation, while the inclusion of herbaceous perennials should be provided with no less than 10 cm (4 in.) media. *Sedum album* is an ideal green roof plant because it can avoid water stress by exhibiting CAM. For non-CAM plants, irrigation in the first few weeks after planting is essential. Additionally, if the roof is not ot be irrigated clay-based media may improve plant survivability.

Evaluating Long-Term Media Buffering Capacity

As presented in Chapter 4, the data suggested green roofs could effectively remediate acid precipitation. The green roof neutralized the acid rain and increased the pH of the runoff (see Figure 4-5). In particular, the commercial green roof media evaluated have tremendous potential to neutralize acid precipitation. Although the effects are clear and consistent, this potential benefit needs to be fully explored or quantified. Acid precipitation is known to cause a number of problems in urban runoff, including acid leaching of metal ions from rooftop flashings, downspouts, and other exposed metals on the roof. A green roof has the potential to all but eliminate the effects of acid precipitation. To manage a green roof for this purpose over the long term, both the inherent acid buffering capacity of the media, and the frequency of routine maintenance procedures (liming) needed to maintain this capacity over the life span of the green roof need to be better understood.

Results of this trial led to a more thorough investigation of the ability of green roofs to neutralize acid rain. Further information can be obtained in Berghage et al. (2007).

Media Buffering Capacity

To examine the long-term acid rain buffering characteristics of a green roof media an accelerated aging trial was conducted. Two media, one based on expanded clay and the other based on expanded slate were subjected to acid additions (5 ml of 0.02 M sulfuric acid) each day for 47 days. Each media was 9 cm (3.5 in.) deep. The pH was measured before and after the acid additions. Results are presented in Figures 5-9 and 5-10.

The buffering potential (pH) is presented in Figures 5-9 and 5-10 versus volume of simulated acid precipitation. Acid titrations were converted to potential cumulative acid rain (in cm) based on the acidity determined for rainwater collected from Rock Springs, PA, a pH of 4.5 (see Figure 4-6). When acid was added, the pH was reduced (lower line in each of the figures), but typically within 24 hr the buffering capacity had greatly recovered (upper line). Over time the ability of the buffering capacity to recover declined and there were significant differences in the recovery between slate- and clay-based media. The rate of pH recovery (acid rain buffering) appeared to be lower in clay-based media than the slate-based media. Further, the recovery seemed to be slower. Based on these accelerated aging (buffering potential) titrations it appears that while these media have high levels of pH buffering capacity, the capacity to neutralize acid precipitation becomes increasingly time-dependent as the materials age. It seems likely that this trend and the differences in media responses will dictate different long-term management approaches if neutralizing acid precipitation is a goal for the green roof. In either case, the buffering capacity appears to be adequate to neutralize acid rain for approximately 10 yr before liming would be necessary to keep the plantings functioning. This is based an annual rainfall of 110 cm/yr (44 in/yr.) and maintaining pH above 6 (about 1000 cm or 400 in. of simulated rain for each graph) resulting in a calculation of 8.9 yr.

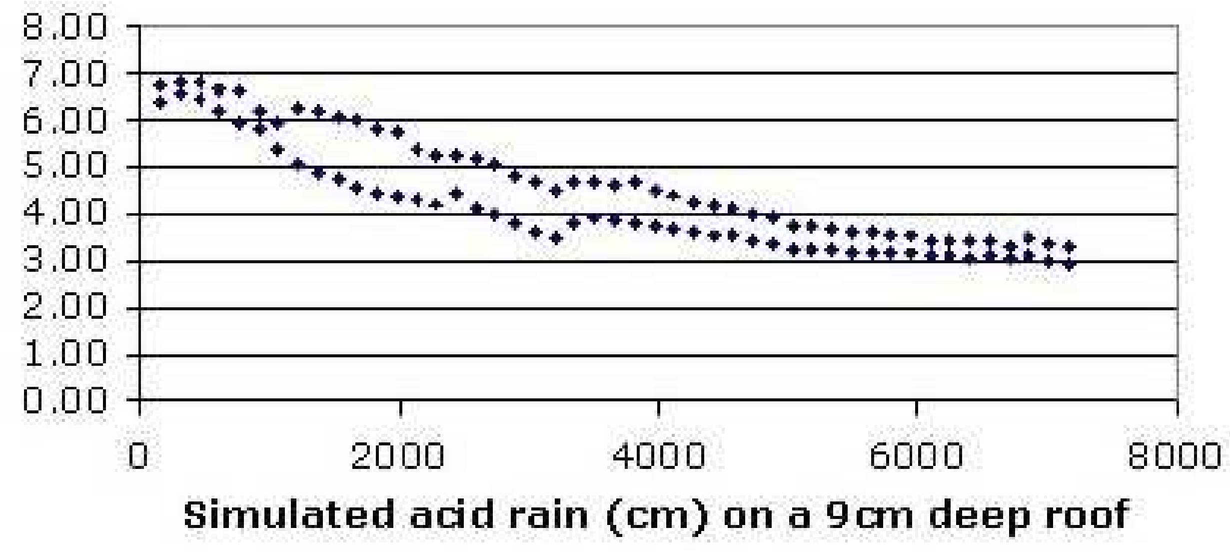


Figure 5-9 Accelerated acid aging trial for clay-based media

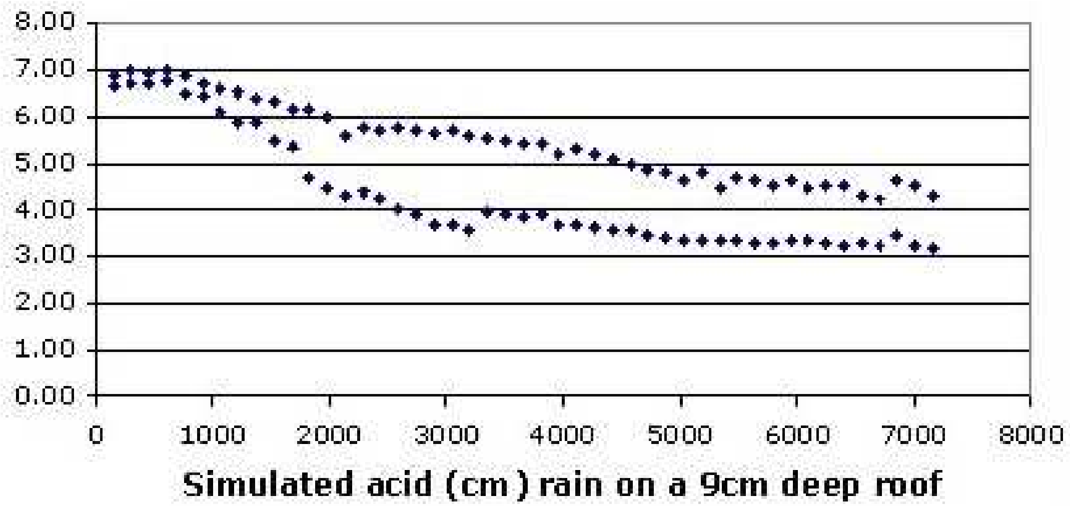


Figure 5-10 Accelerated acid aging trial for slate based media

Cation Exchange Capacity

In order to develop properly, plants require mineral nutrients. Nutrient uptake by plants is controlled by the cation exchange capacity (CEC) of the media in which they are grown (Boodley, 1998). CEC is normally associated with the clay colloids of a mineral soil, although organic matter (e.g., humus, peat, plants roots) also has good CEC, but less than that of clay (Bunt, 1988).

The negative surface charge of a clay colloid attracts positively charged ions (e.g., cations, like K^+, Ca^{++}). The combination of CO_2 (from root respiration) with hydrogen from soil water, causes the formation of carbonic acid (H_2CO_3), which releases hydrogen ions (H^+) from the clay surface. When these hydrogen ions exchange positions with other cations (between the soil solution and the surface of the clay colloid), those mineral nutrients become available for root absorption (Boodley, 1998). Another important key to plant nutrient uptake is the pH of the growing media. At the highest and lowest pH values, essential mineral nutrients may combine with other elements, limiting their availability for plants (Boodley, 1998). Also, CEC is dependent on pH, since an acidic media (less than pH 7) will contain more hydrogen ions than a neutral (pH 7) media, thereby inhibiting cation exchange and nutrient absorption (Bunt, 1988). A green roof media should maintain a stable pH over time, and should moderate the pH of rain to neutral, especially in areas like northeastern America where the pH of rain can be as low as pH 4.9 (Beattie and Berghage, 2004). During the course of this study, four sampled precipitation events yielded an average pH of 5.1. Roofs that become acidic lose the ability to neutralize acid precipitation, typically lose plantings and tend to favor moss. Roofs dominated by mosses will not have the same hydrology of green roofs as detailed here, and will not have the same aesthetic value.

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Microsoft® Office Excel 2003, Part of Microsoft Office Professional Edition 2003, Copyright © 1985-2003 Microsoft Corporation.
OMEGA. 2004. Omega engineering Inc. Stamford, CT.: Available at: http://www.omega.com.
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Appendix A Pictures of Experimental Setups

The following are pictures of the experimental setups in the greenhouse and the field.

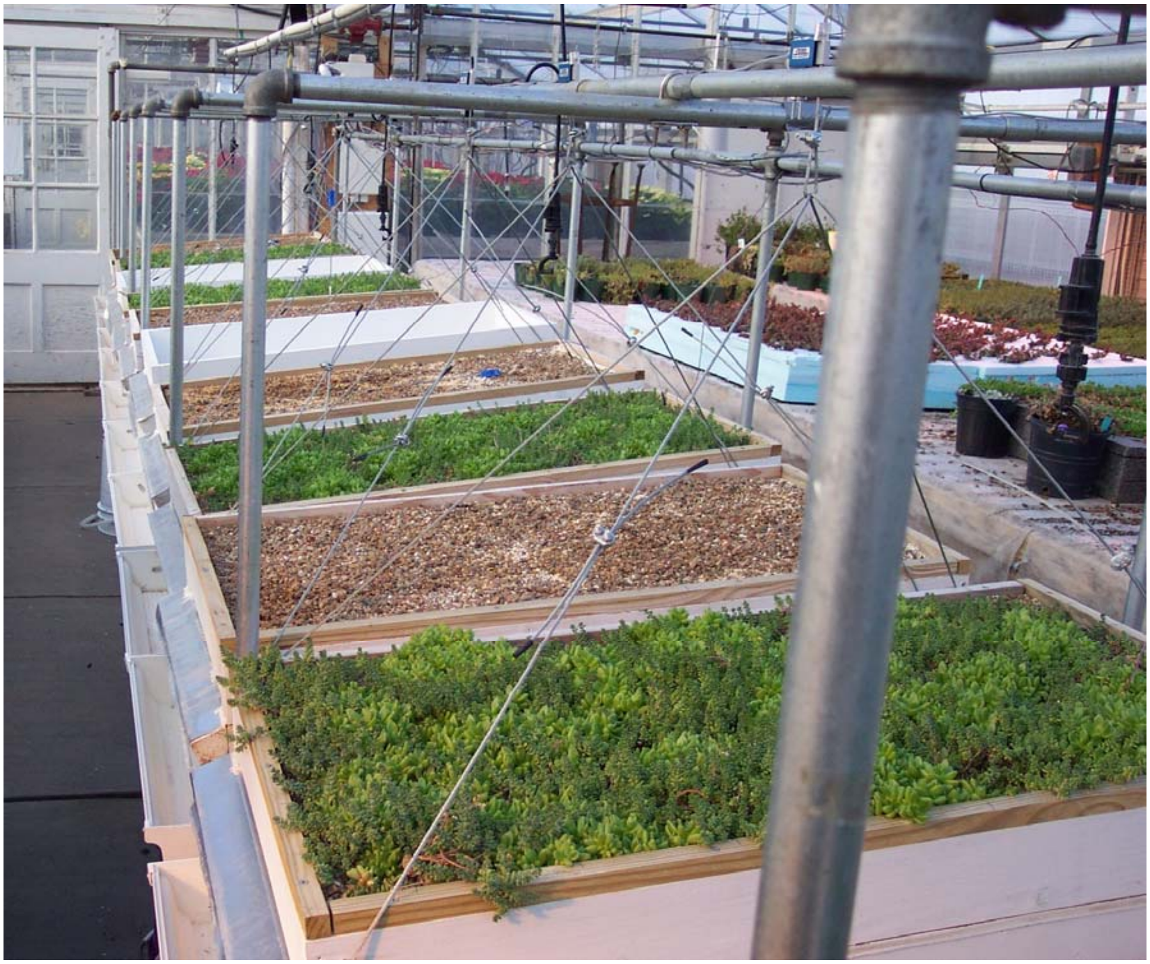

Figure A-1. Model green roof test beds suspended from load cells, lysimeters studies, in Penn State University greenhouse for evapotranspiration studies

Figure A-2. Four of the six structures used in the field evaluations

Figure A-3. Green roof with monitoring equipment, November 2003

Figure A-4. Same green roof with monitoring equipment, June 2005

Figure A-5. One flat asphalt roof divided in half with one half filled with media and the other half sealed to detain stormwater

Figure A-6. Barrel enclosure with 1 in. (2.5 cm) insulation with a small heater inside to prevent the barrels from freezing (closed view on left and open view on right)

Figure A-7. Close-up of green roof plantings with in bloom

Appendix B Cost and Implementation Information

Tables B-1 and B-2 show the cost of installing a green roof on an existing building with sufficient loading capacity. The larger the green roof, the cheaper the unit cost on an area basis (Peck and Kuhn, 2001).

Table B-1. Costs Associated with Installing an Extensive Green Roof on an Existing Building (Peck and Kuhn, 2001)

Component	**Cost**	**Notes & Variables**
Design & Specifications	5 - 10 % of total roofing project cost	The number and type of consultants required depends on the size and complexity of the project.
Project Administration & Site Review	2.5 - 5% of total roofing project cost.	The number and type of consultants required depends on the size and complexity of the project.
Re-roofing with root-repelling membrane	\$100.00 - \$160.00 per m^2 (\$10.00 - \$15.00 per ft^2)	Cost factors include type of existing roofing to be removed, type of new roofing system to be installed, ease of roof access, and nature of flashing required.
Green Roof System (curbing, drainage layer, filter cloth, and growing medium).	\$55.00 - \$110.00 per m^2 (\$5.00 - \$10.00 per ft^2)	Cost factors include type and depth of growing medium, type of curbing, and size of project.
Plants	\$11.00 - \$32.00 per m^2 (\$1.00 - \$3.00 per ft^2)	Cost factors include time of year, type of plant, and size of plant-seed, plug, or pot
Installation/Labor	\$32.00 - \$86.00 per m^2 (\$3.00 - \$8.00 per ft^2)	Cost factors include equipment rental to move materials to and on the roof (rental of crane could cost as much as \$4,000.00 per day), size of project, complexity of design, and planting techniques used.
Maintenance	\$13.00 - \$21.00 per sm^2 (\$1.25 - \$2.00 per sf^2) for the first 2 years only.	Cost factors include size of project, timing of installation, irrigation system, and size and type of plants used.
Irrigation System *	\$21.00 - \$43.00 per sm^2 (\$2.00 - \$4.00 per sf^2)	Optional, since the roof could be watered by hand. Cost factors include type of system used.

*Usually there is no need to have an irrigation system for extensive green roofs.

Table B-2. Costs Associated with Installing an Intensive Green Roof on an Existing Building (Peck and Kuhn, 2001)

Component	**Cost**	**Notes & Variables**
Design & Specifications	5 - 10% of total roofing project cost.	The number and type of consultants required depends on the size and complexity of the project.
Project Administration & Site Review	2.5 - 5% of total roofing project cost.	The number and type of consultants required depends on the size and complexity of the project.
Re-roofing with root-repelling membrane	\$100.00 - \$160.00 per m^2 (\$10.00 - \$15.00 per ft^2)	Cost factors include type of existing roofing to be removed, type of new roofing system to be installed, ease of roof access, and nature of flashing required.
Green Roof System (curbing, drainage layer, filter cloth, growing medium, decking and walkways)	\$160.00 - \$320.00 per m^2 (\$15.00 - \$30.00 per ft^2)	Cost factors include type and depth of growing medium, type and height of curbing, type of decking, and size of project. (cost does not include freestanding planter boxes.)
Plants	\$54.00 - \$2,150.00 per m^2 (\$5.00 - \$200.00 per ft^2)	Cost is completely dependent on the type and size of plant chosen, since virtually any type of plant suitable to the local climate can be accommodated (one tree may cost between \$200 to \$500).
Irrigation System	\$21.00 - \$43.00 per m^2 (\$2.00 0 \$4.00 per ft^2)	Cost factors include type of system used and size of project.
Guardrail/Fencing	\$65.00 - \$130.00 per m (\$20.00 - \$40.00 per ft)	Cost factors include type of fencing, attachment to roof and size of project/length required.
Installation/Labor	\$85.00 - \$195.00 per m^2 (\$8.00 - \$18.00 per ft^2)	Cost factors include equipment rental to move materials to and on roof, size of project, complexity of design, and planting techniques used.
Annual Maintenance	\$13.50 - \$21.50 per m^2 (\$1.25 - \$2.00 per ft^2)	Cost factors include size of project, irrigation system, and size and type of plants used.

Note: It is not necessary to use an irrigation system and guardrail/fencing in all the green roof structures. Therefore, these costs can be deducted from the intensive green roof cost

There are several approaches to establishing vegetation on green roofs, and the speed of plant establishment is closely related to cost. The most rapid cover, to the degree of "instant green", is the most expensive, and the more economical methods take longer to achieve full cover. Green roofs can also be planted with nursery-grown plugs. The most economical planting method for extensive green roofs is sowing seeds and/or cuttings.

For the most rapid and the most expensive green roof, plants can be prepared in advance in modular containers, and installed as complete systems over a protective roof membrane. If any problems on the roof arise, these modules can simply be moved around as contained systems. Including labor and installation, the 2.5 - 4 in. (6.35 - 10.16 cm) deep modules offered by Weston Solutions cost between \$9 - \$15/ft^2 (\$96 - \$160/ m^2) (Herris, 2005).

The second most expensive method involves growing plants in advance on mats and then transporting and unrolling onto a prepared roof. Vegetation mats are made from a geotextile base (spun-bonded fabric), onto which a thin layer of media and plant seeds or cuttings are placed. After roots have anchored into the mat they can be cut to size and must be immediately installed on the media of the new green roof. Mats are especially valuable for preventing erosion on pitched roofs. The mats cost \$6/ft^2 (\$65/m^2), not including labor (Snodgrass, 2004).

Plants can also be propagated and prepared in plug trays in nurseries, taking care that the root ball will not be greater than the depth of media. Plugs were used for the drought test in Chapter 5, and the difficulty of excess depth for the study was described. Because plug plants already have an established root system and shoots, these plants can start growing immediately after being transplanted. To establish a dense plant cover, initial plant coverage should be a minimum of 1 plug/ft^2 (11 plugs/m^2) (Dunnett and Kingsbury, 2004). The material cost of plugs is \$0.50/ft^2 (\$5.50/m^2) (Snodgrass, 2004) with an additional cost of planting individual plugs (Scholz-Barth, 2001).

The most economical planting method for extensive green roofs is through seeding and/ or cuttings. This method does not create instant green effects as the more expensive options described above. However, Liesecke (1985) found that cuttings of *Sedum album* scattered at 4-6 pieces/ft^2 (40-60 pieces/m^2) established 60 - 85% plant cover within one growing season, which included some extreme weather conditions. The material cost of cuttings in is \$0.10/ft^2 (\$2.69/m^2) (Snodgrass, 2004).

There are long-term economical benefits to installing green roof systems due to extension of the impervious roof membrane functionality. Ballast is commonly used over single-ply flat roofs to prevent wind uplift of a membrane. Green roofs also prevent wind uplift, but the vegetation protects the roof membrane better than ballast systems, due to moderation of temperature extremes and reduction of ultraviolet light (Scholz-Barth, 2001), thereby increasing the life of the roof membrane. As additional suppliers and installers of green roof systems become available, costs are expected to decrease due to competition and increased availability. Scholz-Barth, (2001) projected that extensive green roof installation costs, which were ranging from \$15-\$20/ft^2 (\$160-\$220 m^2) should drop to \$8-\$15/ft^2 (\$90-\$160 m^2) as installations increased, and soil substrate and plants became more available.

Preliminary Data for Experimental Design

Sample data collected in 2003 are presented in Table C-1. The pH and electrical conductivity were measured using a combined meter/probe (Hanna Instruments model HI9803), nitrate (Method 8039) and color (Method 8025) measured using HACH DR890 series colorimeter, and turbidity measured with HACH pocket turbidity meter Model 52600-00. This preliminary data was used for the experimental design of the EPA Cooperative Agreement.

Table C-1 Summary Water Quality Data of Runoff from Green and Flat Asphalt (NG) Roofs at the Center for Green Roof Research in Rock Springs, PA

Event	pH		Electrical Conductivity		Ntitrate		Turbidity		Color	
	Asphalt	Green	Asphalt	Green	Asphalt	Green	Asphalt	Green	Asphalt	Green
10/11/02	5.5	6.9	0.09	0.09	2.32	1.0				
10/16/02	6.3	7.3	0	0.11	0	0.18				
10/24/02	6.1	7.0	0.05	0.11	1.5	0.47				
10/29/02	5.9	7.3	0.02	0.10						
5/21/03	6.3	7.5	0.02	0.33	2.1	1.1	7.2	3.7		
6/7/03	5.7	7.4	0.04	0.16	3.8	0.38	4.6	2.7	27	550
6/8/03	5.7	7.5	0	0.13	1.0	0.3	9.9	4.4	29	546
6/17/03			0.03	0.16	4.4	0.8	7.1	4.8	30	550
6/20/03					1.42	0.3	10.4	3.1	69	550
Average	5.9	7.3	0.03	0.15	2.03	0.57	7.8	4.4	39	549