ABSTRACT

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Green roofs are increasingly being used as part of primary urban strategies to improve stormwater management and reduce energy costs. Different methods for green roof design are based on different assumptions and parameters. However, the input parameters are uncertain, which influences design accuracy. A mathematical model was developed to simulate the water movement across and through a green roof. This model was used to assess the sensitivity of the hydrological response of a green roof to roof and rainfall characteristics. Peak discharge rates and depths of runoff mainly depend on the rainfall characteristics. Green roofs can significantly reduce both the peak discharge rates and runoff depths for small storms but they have little effect on large storms. Furthermore, roof characteristics mainly the roof slope is an important design criteria. The model benefits from using the NRCS infiltration equation and curve number, as well as the specific yield of the soil.

THE HYDROLOGIC DESIGN OF GREEN ROOFS

By

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Dedication

This work is dedicated to my parents for their faithful support and constant encouragement.

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Most of all, I want to express my deep and loving gratitude to my parents, Mohsen Ahmadian and Yasamin Memari, who have always supported me in every possible way. They have always encouraged me throughout my eighteen years of education, thus enabling me to reach a level of success that I could not have imagined. I also want to thank my brothers for their advice. Without my family, completing this degree away from home would not have been possible.

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List of Abbreviations

ASTM: American Society for Testing of Materials

BMP: Best Management Practices

CN: Curve Number

EPA: Environmental Protection Agency

GIN: Green Infrastructure

IDF Curve: Intensity Duration Frequency Curve

LEED: Leadership in Energy and Environmental Design

NRCS: National Resources Conservation Services

USGS: United States Geological Survey

Chapter 1: Introduction

1.1 Background and Problem Statement

Due to climate change and population growth, green roofs have become a popular best management practice (BMP) because of the large areas devoted to rooftops. Moreover, according to EPA (Environmental Protection Agency), one of the primary sources of pollution in the United States is the stormwater that is caused by urbanization and land development (EPA 841-F-07-006 2007). Endreny (2007) mentioned that the urban development rate in the United States has been twice the population growth rate over the last two decades. It is also predicted that the U.S. population growth will increase by 22 percent from year 2000 to year 2025. This growth phenomenon is accompanied by the development of 68 million acres of land; hence, stormwater management will be essential (Beach, 2002). These changes have created the need for BMPs, such as green roofs.

The design characteristics of green roofs that have been proposed in the past were established by rough estimations often using subjective assessments. This study focused on the design specifications of green roofs, as well as the study on the optimum green roof design. Previous green roof specifications have the following limitations:

1. The National Recourses Conservation Services (NRCS) rainfall-runoff equation is valid only for moderate rainfall depths (38mm) or larger. To use it with smaller depths, a CN modification would be needed.

2. Green infrastructure, which is effective primarily for small volume storms, does not provide sufficient storage to significantly affect runoff from the larger storm events; to effectively use green infrastructure will require modification of the CN method, so that the effect of including Green Infrastructure (GIN) can be accounted for in small watershed design.
3. When GINs are included as part of microwatershed planning and development, the overall timing of runoff may be affected. Any potential effect of the time of concentration needs to be assessed.

1.2 Motivation and Objectives

The goal of this research was to model the functioning of the green roof so hydrological and environmental impacts of the roof could be assessed. The objectives of this research were:

- To modify the NRCS curve number concept for shallow soils that are applicable to green roof design criteria.
- To develop a mathematical model that can simulate the green roof hydrological and stormwater response using infiltration and surface runoff concepts based on the NRCS curve number.
- To analyze and identify the effects of simulated green roof response to different rainfall and different green roof characteristics.
- To compare the functioning of green and bare roofs and assess the effectiveness of green roofs and the influence of each design variable.
- To study the hydrologic sensitivity of green roofs to important design variables.

Generating new and modified curve numbers was necessary to take both the shallow soils and the different land conditions into consideration. As the proposed model was designed based on the NRCS infiltration equation, the curve number values play important roles in the peak discharge rate and depth of runoff calculations. The major improvement of this model is using the modified curve number values in the green roof design. The hydrologic characteristics of both green roofs and bare roofs were studied for different rainfall and roof characteristics. These analyses were made to study the sensitivity of the green roof design variables and their hydrologic responses to different rainfall characteristics. By determining the important design parameters and by achieving these objectives, effective green roofs designs can be completed.

Chapter 2: Literature Review

2.1 Introduction

The increase in the urbanization in the United States caused different consequences; hence, Leadership in Energy and Environmental Design (LEED) administrated by the U.S. Green Building Council (USGBC). LEED promotes the design and construction of buildings that are environmentally responsible, profitable, and healthy places to live and work (USGBC, 2005). LEED creates standards for green buildings, which include the water efficiency, energy, materials, resources, and indoor environmental quality, as well as the sustainability of the site (USGBC, 2009). The goal of LEED is to decrease detrimental environmental impacts of built environments (Watson, 2009). To be able to design an effective green roof, the variables that increase the environmental quality and efficiency of the design were studied. Literature on green roofs was reviewed to be able to meet the objectives of this research. The types, benefits, and costs of green roofs and the important factors in the design of green roofs that influenced the efficiency of them were studied. Moreover, the background in the curve number definition and spatio-temporal modelling was researched.

2.2 Green Roofs: Definition and Benefits

A green roof is a roof overlain with vegetation. Other terms such as ecoroof, living roof, brown roof, and roof garden are somehow used instead of green roof (Peck and Kuhn, 2001; Scholz-Barth, 2001). The term green roof may sound new, but in fact, this practice is thousands of years old. Roof vegetation was used by Greeks, Romans, and Persians to cool their landscapes (Snodgrass, 2006). These simple designs were also used in Northern Europe (Cantor, 2008), but nowadays they have been improved and in some areas, like New York City, turned into modern gardens for high-rise buildings. After World War II, Northern Europe started using green roofs for practical, environmental, and aesthetic reasons. Currently, in many European cities, for example Linz, Zürich, and cities in Germany, green roofs are a requirement for all newly constructed buildings and are based on environmental regulations (Cantor, 2008). Rockefeller Center in New York has one of the earliest green roofs in the United States (Osmundson, 1999). This green roof was built in 1936 with an area of about 0.7 hectares (Greenroofs.com, 2010). Other famous sites with green roofs exist, such as the Museum of African and Asian Art at the Smithsonian Institution in Washington, D.C., and Union Square in San Francisco (Osmundson, 1999). Currently, there are more than 97 hectares of green roofs in the United States (Greenroofs.com, 2010).

Green roofs are recommended because the soil layer stores rainwater that contributes to reduced direct runoff. The roughness of the vegetation and soil also increase travel times. The duration and magnitude of a rainfall event, as well as soil and vegetation characteristics, affect the infiltration rate (Potter et al., 2003), thus, delaying flow from the roof. After a rain event, detained water can drain for hours until the level of water reduces to the maximum storage capacity of the green roof (Hutchinson et al., 2003). This spreading out of runoff over time reduces peak discharge rates.

The characteristics of green roofs are similar. The drainage layer lets the excess water flow away from the roof. Another construction component is a filter fabric that is located above the drainage layer and protects the drainage layer by preventing silt from entering the media and causing clogging. A water retention fabric can be placed on top of the filter fabric to retain more water. The water retention fabric stores additional water, which is beneficial to the vegetation. It should be noted that these components may vary due to the purpose of the green building and design criteria (Getter and Rowe, 2006).

2.3 Advantages of Green Roofs

Green roofs have many advantages including numerous economic and environmental benefits; they can extend the life of waterproofing membranes, reduce summer cooling costs, and aid in decreasing Urban Heat Islands (UHI), all due to the thermal regulation and UV radiation diffusion effect they offer.

One of the most important environmental benefits of green roofs is their ability to control the quantity and quality of stormwater runoff. Graham and Kim (2003) suggested that over the next 50 years the climate change effects and land use changes can be nullified by retrofitting existing buildings with green roofs. Some local governments recognize the benefits of green roof as a stormwater management method and pass regulations that require them. Some Swiss and German municipalities have passed laws promoting green roof construction, with many offering incentives (Beattie and Berhage, 2001; Osmundson, 1999; Peck et al., 1999). Additionally, based on the type of vegetation used on green roofs, green roofs may reduce the volume of runoff by 60% to 100%. They also delay stormwater runoff.

When the soil layer in a green roof is saturated, runoff occurs. The delay in runoff avoids overflowing or flooding in the area, with delays ranging from 95 minutes to 4 hours (Getter and Rowe, 2006). This delay can also mitigate the erosion that happens due to runoff through direct runoff or storm sewers (Getter and Rowe, 2006).

Jennings et al. (2003) and Rowe et al. (2003) stated that the time to the peak increased by installing a green roof when compared to traditional bare roofs. The increase in the time to peak is about 2 to 4.5 hours. Furthermore, Mentens et al. (2006) found that rainfall retention capability may range from 75 percent for intensive green roofs to 45 percent for extensive green roofs on a yearly basis. In addition, Bliss et al. (2009) reported that using the green roof prototype the time to peak increased due to the time the soil needed to get saturated; this caused delayed in the surface runoff. Their prototype demonstrated that the water did not leave the green roof because it was absorbed by the growing medium and roof materials. Another study by Carpenter and Kaluvakolanu (2011) concluded that the centroid of runoff in green roof is delayed by more than 2 hour.

Another important benefit of green roofs is the aesthetic benefit. This offers many advantages to humans, such as stress reduction, lowered blood pressure, reduced muscle tension, and an increased feeling of well-being (Ulrich and Simons, 1986). As an instance, Kaplan et al. (1988) stated that employees who have a view of a natural landscape feel less stress and have higher job satisfaction. Moreover, the aesthetic factors can bring value to the real estate or any services, e.g., hotels, restaurants, condominiums, etc. (Dunnett and Kingsbury, 2004).

Green roofs can help in mitigating air pollution. A German study revealed that vegetation on green roofs can reduce the air pollution caused by diesel engine exhaust (Liesecke and Borgwardt, 1997). They stated that plants filter the air pollution and the particles will either be absorbed in the plant tissue or will be washed away by precipitation into the soil. Another study demonstrated that green roofs can remove 0.2 kg of dust particles per year per square meter (Peck and Kuhn, 2001). This reduction in air pollution can reduce lung, respiratory, and cardiovascular diseases (Pope et al., 1995).

Green roofs can also reduce noise through the reflection of sound. Hard roof surfaces reflect noise while vegetation absorbs noise. Green roofs absorb sound waves. Dunnett and Kingsbury (2004) stated that a 10-cm thick green roof reduced noise levels by 5 decibels.

2.4 Types of Green Roof Systems

Today, modern vegetated roofs are categorized into different types, depending on their construction and purpose (Beattie and Berghage, 2001). Three different types of green roofs are available: extensive green roofs, intensive green roofs, and semi-intensive green roofs. The main difference between the first two types is the depth of the growing medium and their level of maintenance (Weiler and Scholz-Barth, 2009).

2.4.1 Extensive Green Roofs

The growing medium on an extensive green roof is thin, about 2.5 cm to 15 cm; as a result, this type of roof has minimal added weight. Extensive green roofs are mostly used for insulation purposes rather than to provide open space. They need very low maintenance, which is important to building owners. The plants used in this type of green roof are selected based on the specific climate conditions, their ability to grow in thin soil layers, and low required maintenance (Weiler and Scholz-Barth, 2009). Extensive green roofs are often referred to as “layered systems” due to having several layers in their components (Boivin et al., 2001). These layered components mainly contain inorganic materials that do not decompose over time and do not need replacement (Cantor, 2008).

2.4.2 Intensive Green Roofs

The soil depth in this type of green roof is thicker (greater than 15 cm). Due to their greater thickness, they need stronger structures to sustain the weight (Weiler and Scholz-Barth, 2009). Since intensive green roofs are like conventional gardens or parks, more plant variation is used in their design (Cantor, 2008). Intensive roofs are much more expensive to build and maintain when compared to extensive green roofs (Panayiotis et al., 2003). Figure 2-1 displays the structure of both extensive and intensive green roofs. The difference in their thickness and the plant varieties used in the two different roofs can be seen.

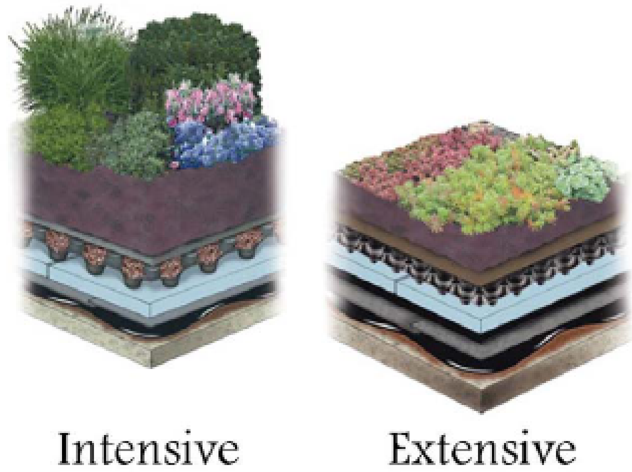

Figure 2-1. Intensive and Extensice Green Roof (American Hydrotech Inc., 2010)

2.4.3 Semi-Intensive Green Roofs

A semi-intensive green roof is a combination of the two stated green roofs. In this type, 25 percent of the roof has a growing medium of 15 cm or more (Cantor, 2008). There is a New American phrase that refers to the semi-intensive green roof as the landscape over structure (Weiler and Scholz-Barth, 2009). This term is used when the growing medium in the roof is deeper than 20 cm and when it can be designated as available open space. In addition, this term applies to a green roof when it is not easy to recognize the exact type of its system and to determine whether it is in the extensive or intensive category due to its thickness, growing mediums, or other factors (Weiler and Scholz-Barth, 2009).

2.4.4 Cost of Green Roofs

The cost of each type of green roof differs. Extensive green roofs need less maintenance and as a result their cost is low. In contrast, intensive green roofs are costly due to high maintenance requirements. The price of installing the semi-intensive green roofs varies, but this type is always more expensive than extensive green roof (Green Roofs for Healthy Cities, 2008).

Table 2-1. General Characteristics of Different Green Roof Categories (Green Roofs for Healthy Cities, 2008)

Characteristic	Extensive	Semi-Intensive	Intensive
Substrate depth	6 inches (15 cm) or less	25% above or below 6 inches (15 cm)	More than 6 inches (15 cm)
Accessibility	Often inaccessible	May be partially accessible	Usually accessible
Fully saturated weight	Low 10 - 35 lb/ft^2 (48.8 – 170.9 kg/m^2)	Varies 35 - 50 lb/ft^2 (170.9 – 244.1 kg/m^2)	Varies 35 - 300 lb/ft^2 (170.9 – 1,464.7 kg/m^2)
Plant diversity	Low	Greater	Greatest
Cost	Low	Varies	High
Maintenance	Minimal	Varies	Varies, but is is generally high

2.5 Definition of a Curve Number

The runoff curve number (CN) is an index that reflects the combination of a hydrologic soil group and a land use and treatment class. Studies have shown that the CN is a function of the following factors: soil group, the cover complex, and antecedent moisture conditions (Davis and McCuen, 2005).

Table 2-2. NRCS Soil Hydrologic Groups (Davis and McCuen, 2005)

Group A	Deep sand; loess; aggregated silts
Group B	Shallow loess, sandy loam
Group C	Clay loams; shallow sandy loam
Group D	Heavy plastic clays; soil that swell when wet

The U.S. Natural Resources Conservation Service (NRCS) divided over 8,500 soil series into four hydrologic groups (A, B, C, and D) based on the soil characteristics, county soil surveys, and minimum infiltration rate (see Table 2-2). Group A includes soils that have low runoff potential and high infiltration rates even when they are saturated. Group B contains soils with moderate infiltration rates. Group C includes soils with slow infiltration rates. Soils with high potential for runoff are in Group D (Davis and McCuen, 2005). The infiltration capacity depends on the ground cover quality and the vegetation. Hence, the cover quality is separated into the following three categories that in the ultimate-planned open spaces, the "good" cover condition is used (Davis and McCuen, 2005):

1. Poor: Heavily grazed or regularly burned areas. Less than 50% of the ground surface is protected by plant or brush and tree canopy.
2. Fair: Moderate cover with 50 to 75% of the ground surface protected by vegetation.
3. Good: Heavy or dense cover with more than 75% of the ground surface protected by vegetation.

2.6 Spatio-Temporal Modeling

Spatio-temporal models are used when data are collected and analyses are made across both space and time (Cressie and Haung, 1999). In the past, there were not many theories that accounted for spatio-temporal processes separate from the already well established theories of spatial statistics and time series analysis; as an example, Cressie (1993) included only four pages in his 900-page book about spatial modeling. However, there has been a very rapid growth of research in spatio-temporal data over the last decade. Bissett et al. (2008), Pauly (2007), and Lan et al. (2010) stated that today spatio-temporal modeling has effectively been used in a wide range of phenomena, e.g., to model contaminant, sulfate depositions, acid rains, human impacts on the environment, and rockfall analysis. Lan et al. (2010) mentioned that environmental and geographical analyses are in three spatial dimensions and time. On the other hand, two-dimensional analyses are used for population and demographic analyses. Spatial analysis usually considers particular parameters or characteristics of different phenomenon in multiple dimensions. Temporal modeling includes using time steps in the program; time steps may change based on the parameters of interest and their rate of happening.

Spatio-temporal modeling includes both spatial analysis and accounting for temporal variation. Such methods model a process in space over a given period of time. Spatio-temporal modeling was used before for green roof design. One of the programs used for this design is called HYDRUS-ID; this program simulated the detention time, peak flow, and retention for a specific green roof that is subjected to variable design storms (Hilten et al., 2008). In addition, Lazzarin et al. (2005) evaluated the time variation of thermal and energy performance of green roofs under variable meterological conditions using simulation software.

Chapter 3: Model Development

3.1 Introduction

While green roofs potentially offer many benefits, extensive monitoring of such facilities would be costly and would likely not be economically justified. Therefore, the assessment of the effectiveness of such facilities, as well as their efficiency, will likely need to be done initially using computer models. Such a model can include all of the important design variables and then be used to perform analyses to show the functioning of a green roof. To be an effective tool for making such assessments, the model needs to adequately reflect both the physical characteristics of a green roof and the hydrologic processes relevant to the real system. The development of such a model is discussed in this chapter.

All of the hydrologic variables that are encountered in green roof design are identified and used as inputs to the model. The rainfall characteristics and the passage of water through the soil are important. The model is based on the following variables: the total rainfall depth for the storm (mm), the number of rainfall ordinates, the number of downgradient cells, the length (m) and width (m) of the cells, the downgradient slope (m/m), the number of soil layers, the thickness of each soil layer (m), and the porosity of the soil. Moreover, the program requires the curve number for the cover type, the time increment (sec), the initial water content of soil storage (m^3) per cell, the roughness coefficient of the rooftop, the gutter slope (m/m), the gutter width (m), the gutter roughness coefficient, the maximum hold storage (m^3) per cell, and the initial water content of hold storage (m^3) per cell. The model separated into cells (longitudinally) and several soil layers (vertically). Figure 3-1 displays the different layers in a green roof design. This schematic drawing shows the water storage beneath the vegetation and growing medium that is modeled like an egg-carton, with overflow when the maximum volume is exceeded. In the model, all of the hydrologic components are evaluating simultaneously. When performing sensitivity tests, all of the input variables were kept constant, with one variable changed in each trial.

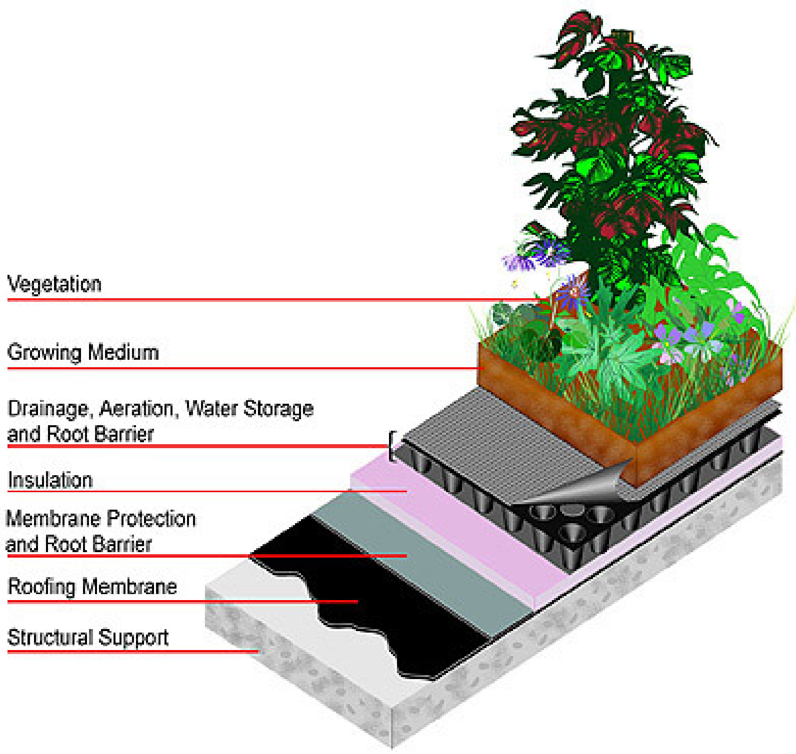

Figure 3-1. A Schematic Drawing of a Green Roof Layers (http://www.glwi.uwm.edu/research/genomics/ecoli/greenroof/benefits.php, Retrieved on March 18. 2011)

3.2 Developing a Modified Curve Number

Given the wide use of curve numbers in hydrologic analyses, a decision was made to incorporate CNs into the model. Traditional curve numbers were not applicable because of the shallowness of the soil mass of a green roof. Therefore, new CNs had to be developed for use with green roofs.

A curve number is a function of land cover (e.g., grass), treatment and hydrologic condition (e.g., good, fair, poor), and soil type (i.e., A, B, C, D). Curve numbers are used primarily to model losses into the soil cover. Moreover, these values reflect the infiltration rates and are used to separate losses and direct runoff. The objective of the following analyses is to develop curve numbers based on the land use description, treatment condition, and soil depth under conditions of very shallow soil depths that are typical of green roofs.

To be able to define the numerical effect of good, fair, and poor hydrologic conditions, factors were needed for each soil group to show the percentage change in the curve number when a lawn condition was changed from good to fair and from fair to poor. These factors were calculated as follows: the difference between any two CN values of different land use descriptions (listed in Table 3-1) for each soil group is calculated. This value is divided into the average value of that two curve numbers that were used in the calculation. The sample calculations are shown below. For instance, the CN value of lawns with soil type A and fair condition versus good condition are 49 and 39, respectively. To find the factor, k, which describes the impact of the land use condition 39 was subtracted from 49. Then this value was divided by the average of the two CNs 39 and 49, which is 0.227. This fraction (k=0.227) represents the relative reduction in the CN for soil type A from fair condition to good condition, i.e., the curve number value should be decreased by 22.7%. The calculations below show the factor k for different soil types. As stated, the factor k is calculated to define the numerical effects of good, fair, and poor lawn covers for different soil groups.

Group A:

Fair to Good Condition= (49-39)/ ((49+39)/2) = 0.227 (22.7%)

Poor to Fair Condition= (68-49)/ ((68+49)/2) = 0.325 (32.5%)

Group B:

Fair to Good Condition= (69-61)/ ((69+61)/2) = 0.123 (12.3%)

Poor to Fair Condition= (79-69)/ ((79+69)/2) = 0.135 (13.5%)

Group C:

Fair to Good Condition= (79-74)/ ((79+74)/2) = 0.065 (6.50%)

Poor to Fair Condition= (86-79)/ ((86+79)/2) = 0.085 (8.50%)

Group D:

Fair to Good Condition= (84-80)/ ((84+80)/2) = 0.049 (4.90%)

Poor to Fair Condition= (89-84)/ ((89+84)/2) = 0.058 (5.80%)

Table 3-1. CNs for Different Land Use Conditions

Land Use Description	**Curve Numbers for Hydrologic Soil Group**			
Lawns, open spaces, parks, golf courses, cemeteries, etc	**A**	**B**	**C**	**D**
Good Condition: grass cover on 75% or more of the area	39	61	74	80
Fair Condition: grass cover on 50% to 75% of the area	49	69	79	84
Poor Condition: grass cover on 50% or less of the area	68	79	86	89

Specific yield is the ratio of the water drained from the soil under the influence of gravity to the total volume of soil voids or pore space in the soil (USGS, 1993). The value of the specific yield is less than the porosity due to molecular forces that cause some water to remain in the soil even after drainage. The specific yield describes the amount of water that a unit volume of saturated permeable soil will yield when drained by gravity (Fetter, 1994). Determining appropriate specific yield values for each soil type results in a new CN based on the depth of the soil and the specific yield. The specific yield values are shown in Table 3-2 for different soil groups (U.S. Geological Survey, 1993).

Table 3-2. Specific Yield (Sy) (Robson, 1993)

A	B	C	D
0.16	0.12	0.07	0.04

Green roofs are generally designed to have shallow depths in order to avoid high dead loads. Total soil depths of to 4, 8, 12, 16, and 20 inches were tested. A new variable denoted as S_m, was calculated by multiplying the soil depth in inches and the specific yield for each soil type. Table 3-3 shows the values of S_m using the following equation:

$$S_m = DS_y \tag{3-1}$$

In Eq. 3-1, S_m and D are in inches. As an example for soil type A and a depth of 4 in., the value of S_m is $0.16 \times 4 = 0.64$ inches.

Table 3-3. Modified S Values, Sm (in.)

D (in.)	A	B	C	D
4	0.64	0.48	0.28	0.16
8	1.28	0.96	0.56	0.32
12	1.92	1.44	0.84	0.48
16	2.56	1.92	1.12	0.64
20	3.20	2.40	1.40	0.80

Once the S_m values were computed, the modified CN values can be calculated as follows:

$$CN_m = \frac{1000}{S_m + 10} \tag{3-2}$$

In Eq. 3-2, S_m is in inches. The modified curve numbers (CN_m) are listed in Table 3-4. These values are rational since they do not exceed 98, which is the curve number value for a bare roof.

Table 3-4. Modified Curve Number Values (CN_m) Based on Different Soil Depths

Soil depth		Soil types			
inch	**meter**	**A**	**B**	**C**	**D**
4	0.1	94	95	97	98
8	0.2	89	91	95	97
12	0.3	84	87	92	95
16	0.4	80	84	90	94
20	0.5	76	81	88	93

The CN_m values in Table 3-4 are assumed to be the curve number for poor condition. Since lawn condition is another factor that changes the curve number, the CN_m values were modified for different treatment conditions regarding the numerical factors (k) that describe the effect of lawn conditions that were calculated previously based on Table 3-1 using Eq. 3-3.

$$CN_c = CN_m - (CN_m \times k) \tag{3-3}$$

In Eq. 3-3, CN_c is the curve number for different lawn covers (good, fair, and poor) and CN_m stands for the curve numbers that were calculated using Eq. 3-2 based on the modified S values. For instance, the curve number of the poor condition for soil type A with the depth of 0.1 m was calculated to be 94 (see Table 3-4). The k value of 0.325 was found when the lawn condition was changed from poor to fair, and the k value of 0.227 was calculated when the lawn condition was varied from fair to good. Thus, to get the values for a fair condition, the calculated factor (0.325) should be multiplied by the poor condition curve number and subtracted from the poor condition curve number. Hence, for fair condition, CN_c was calculated to be 63 $[94-(94\times0.325)=63]$ using Eq. 3-3 and for good condition, the CN_c was computed to be 49 $[63-(63\times0.227)=49]$. The same equation (Eq. 3-3) was used for the other soil types and soil depths combinations. As a result, Table 3-5 shows the final curve numbers that contain the effects of the specific yield, green roof soil depths, and hydrologic condition.

Table 3-5. Modified CN Values (CN_c) for Different Hydrologic Condition, Soil Type, and Soil Depth for Green Roofs

CN_c															
Lawn condition	**Poor**					**Fair**					**Good**				
Soil depth (m)	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Soil type A	94	89	84	80	76	63	60	57	54	51	49	46	44	42	40
B	95	91	87	84	81	82	79	75	73	70	72	69	66	64	61
C	97	95	92	90	88	89	87	84	82	81	83	81	79	77	75
D	98	97	95	94	93	92	91	89	89	88	88	87	85	84	83

It is crucial to understand the trend of the modified curve numbers (CN_c) as the soil depth increases. The CN_c values can be compared to the traditional CN values of Table 3-1. Based on Table 3-5, it is realized that as the soil gets deeper (reaching 0.5 m) the CN_c decreases, which makes physical sense. Furthermore, it can be observed that the CN_c for soil type A in good condition and a depth of 0.5 m is 40. This value is still higher than the traditional curve number of 39 for a very deep soil.

3.3 Rainfall Characteristics

Every rainfall event is characterized by its duration and intensity. In this study, the USDA/NRCS Type II Storm distribution, storm type in Maryland area, (McCuen, 2005) was used. The shape of the dimensionless rainfall distribution was used as input to the computer model. The following rainfall depths, which reflect the storm characteristics of Middle Atlantic region, were assumed for storm durations of 1 hour, 2 hours, 3 hours, 6 hours, 12 hours, and 24 hours: 1.270 mm, 4.567 mm, 9.652 mm, 19.05 mm, and 38.10 mm, respectively.

The way that rainfall is modeled is described in the following sections. When rain falls onto the green roof, some of the water infiltrates through the soil layers. The rainfall that does not infiltrate enters surface storage and subsequently drains across the soil surface to the gutter. The rainfall that infiltrates into the soil moves through the drainage layers and into the hold storage containers. Once the hold storage is completely filled, water overflows onto the roof surface through orifices. The overflow runs off as sheet flow to the gutter and then into the downspout. A schematic of the process is presented in Figure 3-2.

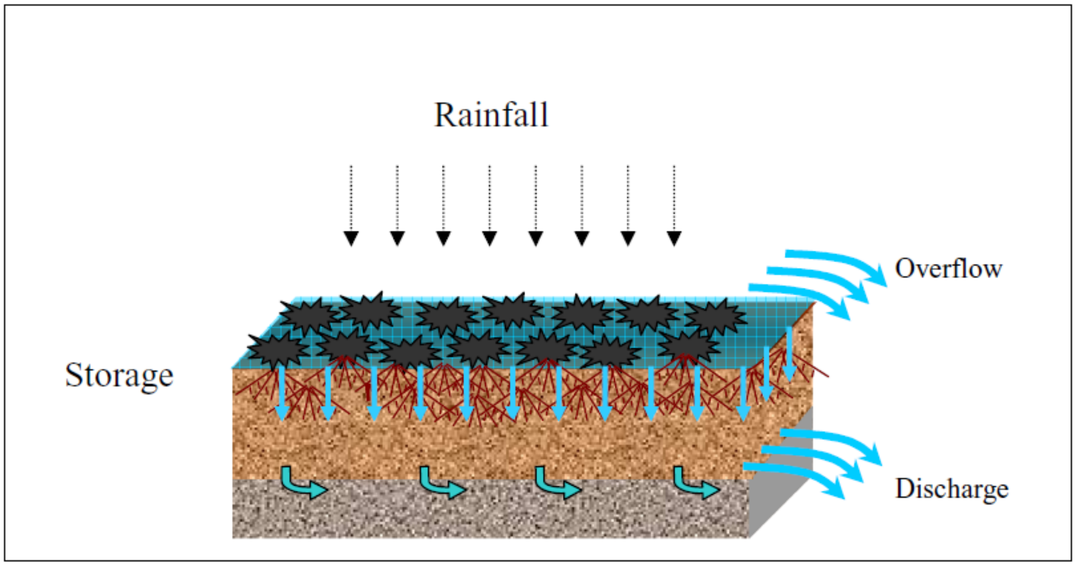

Figure 3-2. A Schematic Drawing of a Simplified Green Roof System (Tetra Tech, 2005)

3.4 Infiltration through The Soil

The water on the soil surface infiltrates though the soil until the soil gets saturated. The infiltration rate changes in the soil depth based on the porosity of the soil and current storage volume of water in each soil layer. The infiltration rate is calculated based on the CN using the following equation:

$$f = \frac{S_m{}^2 \times i}{(P + 0.8S_m)} \tag{3-4}$$

In Eq. 3-4, P presents the total storm depth (in.) and S_m (in.) can be calculated using Eq. 3-1 (Chin, 2006). Eq. 3-4 has a limitation; if i (in./hr) is assumed as the rainfall intensity, then the infiltration stops when the precipitation ends. Hence, it is assumed that S_m and P in Eq. 3-4 remain the same for each run, since S_m depends on the soil depth and soil type, which is constant for all the layers (see Eq. 3-1), and P is the total storm depth, which varies with the return period and rainfall duration.

As the temporal variation of rainfall follows a Type II distribution, the rainfall intensity (i) varies during the storm. For the first time period, the intensity, i, of Eq. 3-

4 equals the rainfall intensity. For subsequent time intervals, the infiltration depends on the depth of storage, which includes the rainfall added to the storage during that time period. As a result, f in Eq. 3-4 changes as i changes. As a time increment of 60 seconds was used (because the rainfall data are given using a one-minute interval), i for the top soil layer is the ponded depth. But i for the second layer is equal to the i for the first layer subtracting the amount of water that was absorbed by the soil in the first layer, i.e., the volume of water in the first layer depends on the porosity of the first layer. In this case, the continuity of mass was used under the assumption that the volume of drainage from the first layer is the input to the second soil layer. A value of the intensity, i, can be calculated and, therefore, the infiltration rate can be found. Calculations proceed from the lowest layer to the top layer so that water drains at a reasonable rate.

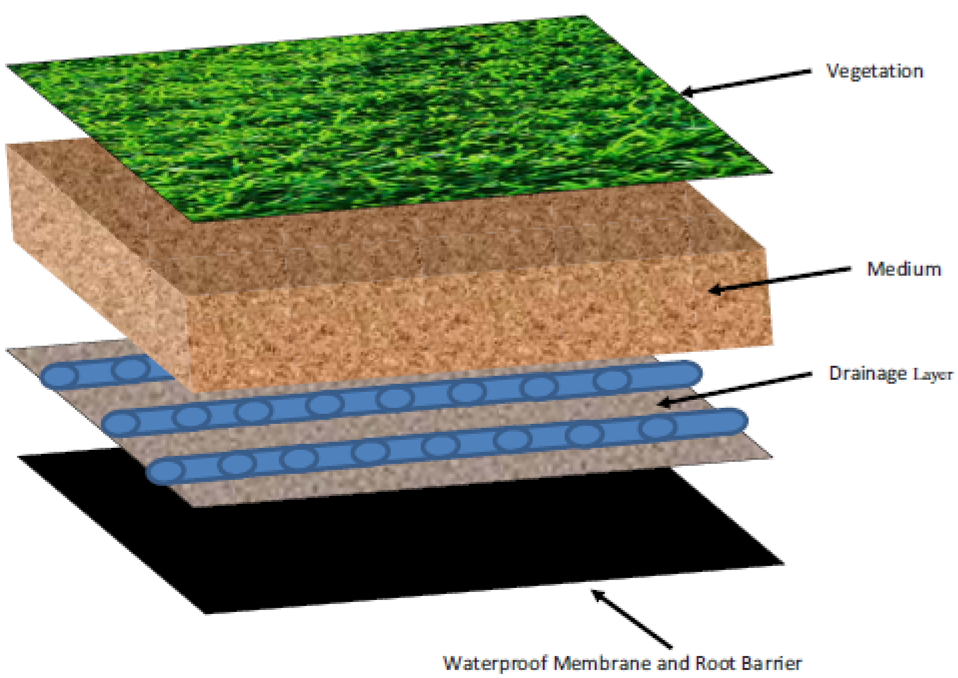

Figure 3-3. Typical Green Roof Profile (She and Pang, 2010)

3.5 Water Movement Through the Soil Layers

After water infiltrates through the soil layers, it goes to the layer beneath it. This subdrainage layer is called hold storage, which physically looks like an egg-carton as shown in Figure 3-1. This sublayer detains a certain volume of water. This is the water that passed through the soil layers and drained from the bottom of the soil mass. When the hold storage is filled, the water overflows through orifices to the roof surface. If the volume of infiltrated water at any time is less than the volume of maximum hold storage, then the hold storage has space for more infiltrated water. Overflow occurs when the hold storage is full.

3.6 Water Movement on The Sod and Roof Surface

After the available storage in the soil is full, the draining water would move onto the roof surface. Then runoff from the roof surface enters the gutter. The velocities with which water moves on the roof and grass surfaces are computed using Manning's equation. In this calculation, the Manning's roughness coefficient for grass was set to 0.15 and 0.02 for the tar (McCuen, 2005). The roof slope is assumed to be 0.0005 m/m. To compute the volume of water that passes from one cell to the next downgradient cell (horizontally), the velocity of the runoff across the roof is multiplied to the time interval (60 seconds) to find the distance the water travels. Then this distance is compared to the cell length to estimate the proportion of water in cell storage that flows into the next downgradient cell (both on roof and grass surfaces).

3.7 Water Movement Through the Gutter

A gutter is located at the end of the roof. Water drains into the gutter both from the grass surface and the rooftop. The gutter width was assumed to be 0.05 m. Flow in gutter and into the downspout is calculated using Manning's equation. To represent the movement of water into the gutter, the gutter slope of 1% (0.01 m/m) is assumed. The Manning's roughness coefficient of 0.023 is used for the metal gutter. Water moves through the gutter the same as it moves on the surface. The water velocity multiplied by 60 seconds to calculate the distance the water traveled in one minute. This calculation continues as the water moves from one cell to another. When all of the cells drain the water through the gutter, the simulation is complete.

Chapter 4: Simulation Results and Data Analysis

4.1 Introduction

The hydrologic responses of different green roof scenarios were analyzed and tested using the computer model. The results were reported in terms of differences in the total volume of runoff, the peak discharge rates, and the depth of runoff. The volume of runoff is used when the effectiveness of a green roof is analyzed. The peak discharge represents the maximum instantaneous discharge within the storm duration. This value can be used in designing the drainage system. The runoff depth is the equivalent depth of water that flows off of the roof during the storm event, which can be used in determining the effectiveness of the roof.

The design parameters of a green roof were varied to study the effect of each factor on green roof effectiveness. Some inputs such as roof characteristics remain constant for most runs, unless their effect is being evaluated. These include the gutter slope, the gutter width, and the gutter roughness coefficient. These variables are set and remain unchanged whether modeling a bare roof or a green roof. Other variables such as the depth and duration of rainfall, the depth and porosity of the soil, the roof slope, and the roughness coefficient of the rooftop were varied to examine these effects.

4.2 Rooftop Characteristics

The rooftop has certain physical characteristics, which were varied in some simulations but held constant for most runs. The number of cells and the width and length of each cell are held constant; as a result, the roof area was constant for all analyses. Furthermore, the downgradient slope, the gutter width, and the roughness coefficients of the rooftop and gutter are fixed, as follows:

- Downgradient slope: 0.0005 m/m (a typical roof slope, often for constructability reasons)
- Number of downgradient cells: 5
- Width of cells: 20 m
- Length of cells: 20 m (giving the roof area of 2000 m^2, which is an area of a moderate sized building)
- Gutter slope: 0.01 m/m (to ensure that water drains from the gutter)
- Gutter width: 0.05 m (a typical gutter width)
- Gutter roughness coefficient: 0.023 (a typical gutter roughness coefficient)

Other input variables represent the green roof characteristics, including the curve number for the cover type, the soil layers and thickness of each layer, the porosity of the soil, and the maximum hold storage per cell. The green roof parameters that are set in most runs (unless varied) are as follows:

- Soil porosity: 0.4
- Maximum hold storage per cell: 4 m^3 (which is equivalent to a depth of 1 cm over the cell area)

4.3 Bare Roof Analyses

By comparing the design characteristics with and without the green roof, the hydrological benefits of green roofs were studied. The criteria used for comparison were the runoff depth and the peak discharge, both of which were compared for the two conditions: the green roof versus the bare roof (roof with no vegetation).

4.3.1 Effects of Bare Roof on Peak Discharge Rates

Peak discharge is an important hydrologic variable because many types of flood damage are associated with the magnitude of the peak of the flood. The peak discharge rates from a bare roof were computed for different storm durations (1 hour, 3 hours, and 24 hours) and different rainfall depths (1.270 mm, 4.572 mm, 9.652 mm, 19.05 mm, and 38.10 mm). The results are shown in Table 4-1. The values show that the peak discharge rates increase as the rainfall depths increase and that they decrease as the storm duration increases. Figure 4-1 shows the relationship between the peak discharge rate and storm duration. The rainfall depth of 38.10 mm provided the highest peak discharge for all storm durations. The largest peak discharge rate occurred when the storm duration was short (1 hour) and the rainfall depth was large (38.10 mm).

Table 4-1. Peak Discharge Rates (m^3/sec) for a Bare Roof and Storms of 1 Hour, 3 Hour, and 24 Hour Durations and depths of 1.270 mm, 4.572 mm, 9.652 mm, 19.05 mm, and 38.10 mm

	Rainfall depth (mm)				
Storm duration (hr)	**1.270**	**4.652**	**9.652**	**19.05**	**38.10**
1	0.000324	0.004652	0.007552	0.020315	0.052264
3	0.000262	0.001930	0.005706	0.014781	0.037180
24	0.000150	0.000982	0.002811	0.007319	0.018826

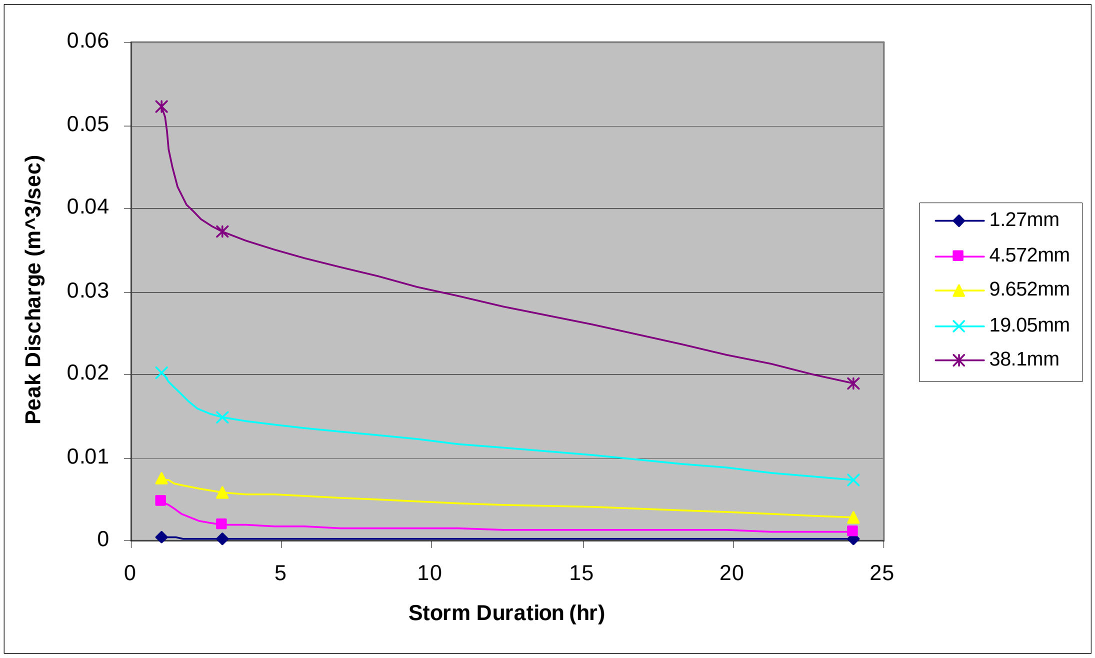

Figure 4-1. Effect of Storm Duration on Bare Roof Peak Discharge Rates (m^3/sec) for Different Rainfall Depths

4.3.2 Effects of Variation of Depth of Runoff on a Bare Roof

Other important criteria in bare roof analyses are the total volume of runoff and the depth of runoff. Tables 4-2 and 4-3 show the total volumes and depths of runoff for the same bare roof conditions. It was understood that as the rainfall depth and storm duration increased, the total volume of runoff increased (see Figure 4-2).

Table 4-2. Total Volume of Runoff (m^3) for a Bare Roof and Storms of 1 Hour, 3 Hour, and 24 Hour Durations and Rainfall Depths of 1.270 mm, 4.572 mm, 9.652 mm, 19.05 mm, and 38.10 mm

	Rainfall depths (mm)				
Storm Duration (hr)	**1.270**	**4.652**	**9.652**	**19.05**	**38.10**
1	0.531	4.216	11.928	28.384	63.599
3	1.327	7.154	16.413	34.184	70.679
24	2.317	8.868	18.661	37.166	74.817

Table 4-3. Depth of Runoff (mm) for a Bare Roof and Storms of 1-Hour, 3-Hour, and 24-Hour Durations and 1.270-mm, 4.572-mm, 9.652-mm, 19.05-mm, and 38.10-mm Rainfall Depth

	Rainfall depths (mm)				
Storm duration (hr)	**1.270**	**4.652**	**9.652**	**19.05**	**38.10**
1	0.27	2.11	5.96	14.19	31.80
3	0.66	3.58	8.21	17.09	35.34
24	1.16	4.43	9.33	18.58	37.41

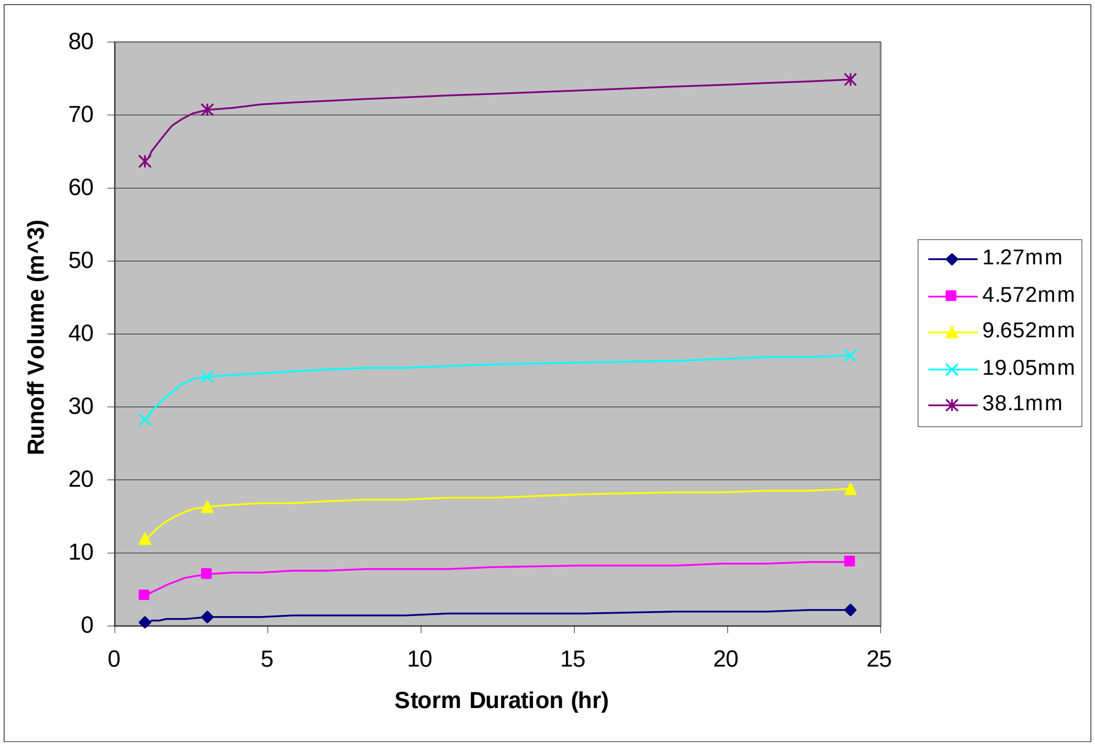

Figure 4-2**. The Effect of Storm Duration on the Total Volume of Runoff (m^3) of Bare Roof for Different Rainfall Depths**

The storm depth of 38.10 mm and storm duration of 24 hours produced a distinctive result. Specifically, this storm characteristic caused the largest volume of total runoff. But for low rainfall depths, the difference in the volume of total runoff in specific storm duration is more significant. For example, for a storm depth of 1.270 mm and a 1-hour duration, the volume of total runoff is 0.531m^3, but this value almost doubles when the rainfall duration is 3 hours, and increased four times for the 24-hour storm duration (compared to a storm duration of 1-hour). However, the increase in the total volume of runoff in other storm depths is not that large. This fact is evident from the slope of the curves in Figure 4-2.

Unwanted ponding at inlets and culverts are the result of an excessive runoff volume at a point. Therefore, the depth of runoff is a useful criterion to evaluate the potential benefit of green roofs. Table 4-3 and Figure 4-3 show the depths of runoff for different storm durations and rainfall depths. This table was produced by dividing the volume of runoff for each event by the roof area. For example, for a rainfall depth of 38.10 mm and a storm duration of 24 hours, the runoff depth is 37.41 mm (74.816 m^3/2000 m^2= 0.03741 m). As the rainfall depth and storm duration increased, the depth of runoff increased (see Figure 4-3). The runoff depth from the bare roof should be influenced by the depth and duration of rainfall. In Figure 4-3, the rainfall depth of 38.10 mm produced the largest depth of runoff for all storm durations. Furthermore, for a storm duration of 1 hour and a rainfall depth of 1.270 mm, the depth of runoff is 0.27 mm, and for a storm duration of 3 hours, the runoff was 0.66 mm; this indicates an increase of 59% when the storm duration increased from 1 hour to 3 hours. The runoff depth increased by 76.7% when the duration of the storm with the same rainfall depth was changed from 1 hour to 24 hours. The increase in depth of runoff during the longer duration storms occurs because the soil is usually saturated during the longer storm durations and the hold storage has been already filled; therefore, water that infiltrated through the soil layer produced rooftop runoff.

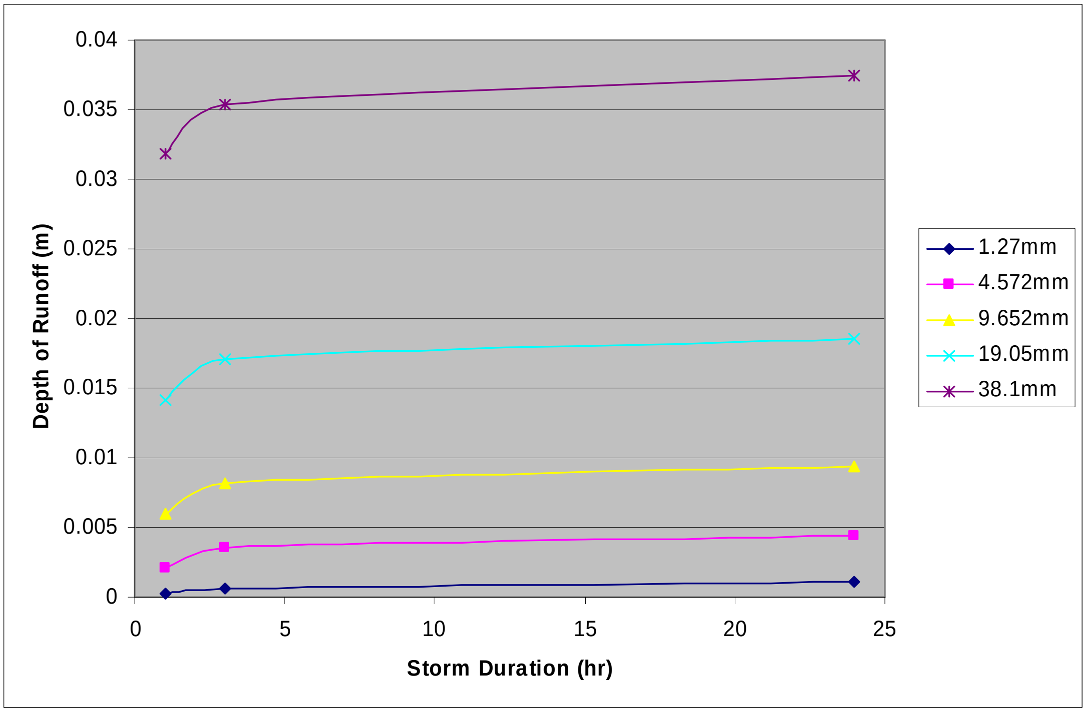

Figure 4-3**. The Effect of Storm Duration on Depth of Runoff on a Bare Roof for Different Rainfall Depths**

Analyses were made to examine the effect of storm duration on the depth of runoff. For the larger rainfall depths, the differences in the depths of runoff were not large even as rainfall depths were increased. The difference in the depth of runoff for a rainfall depth of 38.1 mm and storm durations of 1 hour and 3 hours was only 10% (increasing from 31. 8 mm to 35.3 mm). For the same depth of rainfall (38.1 mm), the runoff depth increased only by 17.6% when the storm duration increased from 1 hour to 24 hours. These results suggested that for the larger rainfall depths, the depth of runoff from the bare roof is not very sensitive to the storm duration. This is expected as most of the rainfall will drain from a bare roof in a short period of time.

4.4 Green Roof Analyses

The peak discharge rates and the depths and volumes of runoff were analyzed for the different green roof scenarios. In these analyses, the responses of green roofs can be compared to the bare roof responses. Figures 4-4 and 4-5 for the green roofs can be compared to Figure 4-1 and 4-3 for the bare roofs, respectively.

4.4.1 Effect of Green Roof on Peak Discharge Rates

The relationship between the peak discharge rate and the storm duration for a green roof is shown in Figure 4-4 for varying depths of rainfall. Peak discharge rates were computed for rainfall depths of 1.270 mm, 4.572 mm, 9.652 mm, 19.05 mm, and 38.10 mm. Figure 4-4 shows that the peak discharge rates that result from a rainfall depth of 38.10 mm are greater than for the other rainfall depths (the same conclusion as analyzing the bare roof results). This shows that, as expected, BMPs are more beneficial for low storm depths and median storm durations (for example, a storm duration of 1 hour and storm depth of 9.652 mm). Under these conditions, the physical processes, i.e., infiltration rates, are influential in limiting runoff.

Table 4-4. Peak Discharge Rates (m^3/sec) for a Green Roof and Storms of 1 Hour, 3 Hour, and 24 Hour Durations and 1.270-mm, 4.572-mm, 9.652-mm, 19.05-mm, and 38.10-mm Rainfall Depths

	Rainfall depth (mm)				
Storm duration (hr)	**1.270**	**4.652**	**9.652**	**19.05**	**38.10**
1	0.000028	0.000248	0.000835	0.002581	0.007960
3	0.000028	0.000244	0.000779	0.002210	0.006393
24	0.000022	0.000164	0.000491	0.001334	0.003631

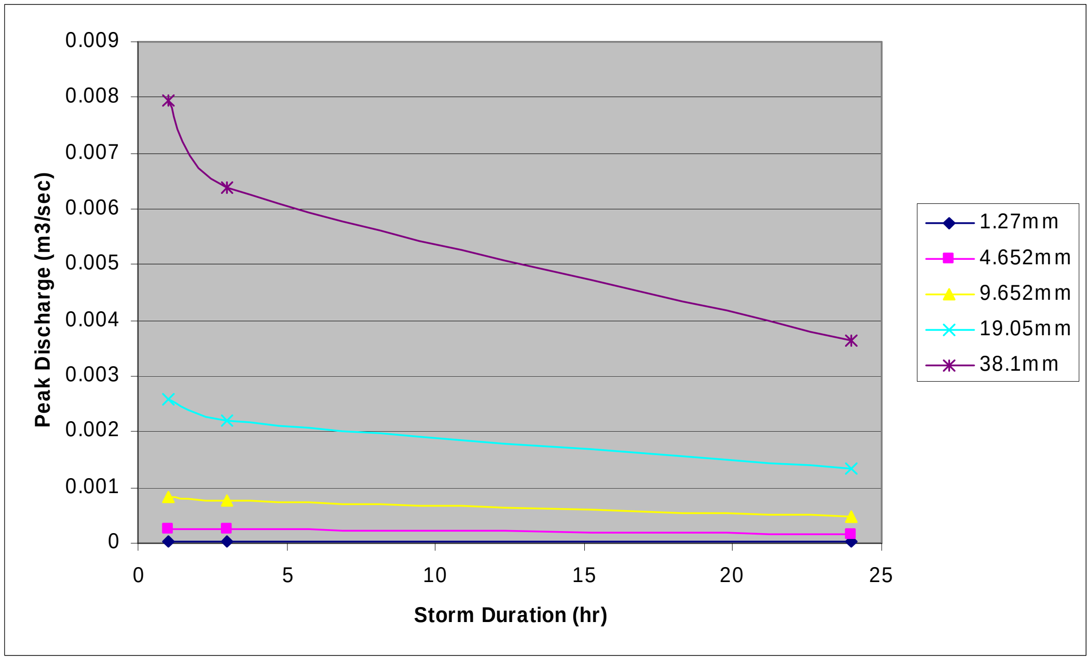

Figure 4-4. The Effect of Storm Duration on Peak Discharge Rates (m^3/sec) from Green Roofs for Different Rainfall Depths

The roughness of a green roof is greater than that of a bare roof. Additionally, a green roof allows for infiltration of rainwater. Thus, peak discharge rates should be affected. The response of the green roof can be compared to that of the bare roof. The peak discharge rates (see Table 4-5) for green roofs are compared to those of a bare roof. The peak discharge rates decreased by as much as 95% for the green roof compared to those from the bare roof. The peak discharge rate from the green roof for a storm duration of 1 hour and storm depth of 38.10 mm was almost the same as that for the bare roof for a 1- hour storm duration and rainfall depth of 9.652 mm. This shows the significant effect that green roofs can have on reducing peak discharge rates.

Table 4-5. Comparing Bare Roof and Green Roof Peak Discharge Rates (m^3/sec) for Different Storms Durations and Rainfall Depths

	Storm duration (hr)								
	1			3			24		
Rainfall depth (mm)	**Bare roof**	**Green roof**	**% Decrease**	**Bare roof**	**Green roof**	**% Decrease**	**Bare roof**	**Green roof**	**% Decrease**
1.270	0.000324	0.000028	91.4	0.000262	0.000028	89.3	0.000150	0.000022	85.3
4.652	0.004652	0.000248	94.7	0.001930	0.000244	87.4	0.000982	0.000164	83.3
9.652	0.007552	0.000835	88.9	0.005706	0.000779	86.3	0.002811	0.000491	82.5
19.05	0.020315	0.002581	87.3	0.014781	0.00221	85.0	0.007319	0.001334	81.8
38.10	0.052264	0.007960	84.8	0.037180	0.006393	82.8	0.018826	0.003631	80.7

The vegetated roof allows for infiltration, delays runoff, and reduces velocities, all of which can contribute to reductions in peak discharge rates. Table 4-5 shows the percentage decrease in the peak discharge rate for the vegetated roof for the smallest and largest storm depths (1.270 mm and 38.10 mm, respectively). For a constant storm duration, the larger rainfall depth generated the larger peak discharge rate. For a constant rainfall intensity, the peak discharge rates decreased for increasing storm durations. Thus, as the rainfall depth increased, the reduction in the peak discharge decreased. This shows that the BMPs are more effective for controlling the peak discharge rates of the smaller rainfall depths.

4.4.2 Effect of Green Roof on Total Volume and Depth of Runoff

Both the total volume and depth of runoff decrease when a green roof is installed. When runoff volumes from the green roof (see Table 4-6) are compared to those from a bare roof (see Table 4-2), decreases are evident. The largest volume of runoff from a bare roof is for a rainfall depth of 38.10 mm and duration of 24 hours, with a runoff volume of 74.82 m^3 (see Table 4-2). This volume is decreased to 53.77 m^3 for the green roof (see Table 4-6). The smallest bare roof volume for 1-hour storm duration and 1.270 -mm rainfall depth was 0.53 m^3 and the smallest runoff volume for a green roof for 1-hour storm duration and 1.270-mm rainfall depth was 0.04 m^3 (see Tables 4-2 and 4-6). The range of total runoff volumes for green roofs is from 0.04 m^3 to 54 m^3, while it is from 0.5 m^3 to 75 m^3 for bare roofs. Such differences would lead to saving in the size and, therefore, cost of drainage infrastructure.

Table 4-6. Total Volume of Runoff (m^3) for a Bare Roof and Storms of 1 Hour, 3 Hours, and 24 Hours Durations and 1.270-mm, 4.572-mm, 9.652-mm, 19.05-mm, and 38.10-mm Rainfall Depths

	Rainfall depth (mm)				
Storm duration (hr)	**1.270**	**4.652**	**9.652**	**19.05**	**38.10**
1	0.04	0.40	1.34	4.16	13.13
3	0.13	1.17	3.90	11.50	32.05
24	0.93	5.25	12.24	25.74	53.77

The percent reductions of the total runoff volume are shown in Table 4-7 for rainfall depths of 1.270 mm and 38.10 mm. The differences in the total volume of runoff from a green roof versus a bare roof were more for the lower rainfall depths. It is evident from Table 4-7 that the total volume of runoff for a 1-hour storm of 1.270

mm decreased by 91.9%; this value shows how effective the green roof can be for short duration storms. The depth of runoff also decreased when the green roof was used. Table 4-8 lists the depth of runoff values for several rainfall depths and durations. Comparing Figure 4-5 to Figure 4-3, these reductions are evident. It is again evident that the depth of runoff is relatively smaller for the lower the rainfall depths and storm durations.

Table 4-7. Percentage Decrease in the Total Volume of Runoff (m^3) for the Green Roof

	Rainfall depth (mm)					
	1.270			38.10		
Storm duration (hr)	**Bare roof**	**Green roof**	**Decrease %**	**Bare roof**	**Green roof**	**Decrease %**
1	0.530557	0.042719	91.9	63.5986	13.1296	79.4
3	1.326912	0.132139	90.0	70.6786	32.0485	54.7
24	2.316991	0.931872	59.8	74.8165	53.76569	28.1

Table 4-8. Depth of Runoff (mm) for a Green Roof and Storms of 1 Hour, 3 Hours, and 24 Hours Durations and 1.270-mm, 4.572-mm, 9.652-mm, 19.05-mm, and 38.10-mm Rainfall Depths

	Rainfall depth (mm)				
Storm duration (hr)	**1.270**	**4.652**	**9.652**	**19.05**	**38.10**
1	0.021	0.198	0.671	2.082	6.565
3	0.066	0.585	1.950	5.751	16.024
24	0.470	2.624	6.120	12.872	26.883

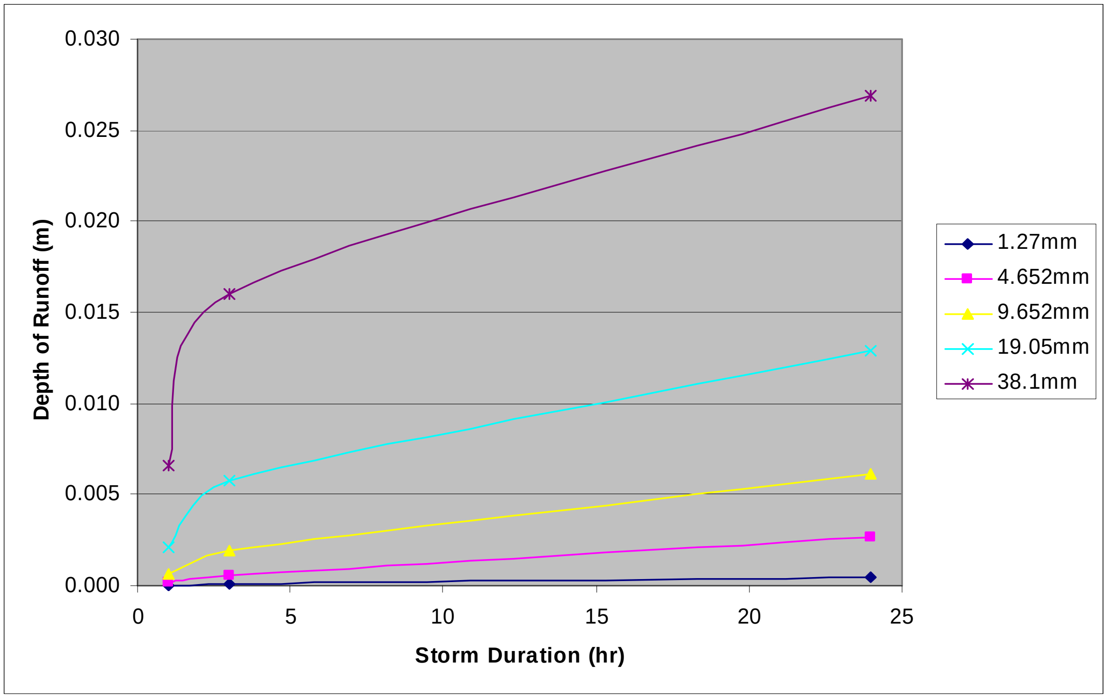

Figure 4-5. Effect of Storm Duration on a Green Roof Total Volume of Runoff (m^3) for Different Rainfall Depths

The percent reduction of the depth of runoff when green roofs can installed are given in Table 4-9 for two rainfall depths. For the longer storm durations and larger rainfall depths, the green roof was less effective in terms of decreasing the depth of runoff. For a 38.10-mm rainfall depth over 24 hours, the green roof decreased the runoff by 28.1%. However, for the 1.270-mm rainfall depth in 1 hour, the percentage reduction was 92.1%.

Table 4-9. Percentage Decrease in the Depth of Runoff (mm) for the Green Roof

	Rainfall depth(mm)					
	1.270			38.10		
Storm Duration (hr)	**Bare roof**	**Green roof**	**% Decrease**	**Bare roof**	**Green roof**	**% Decrease**
1	0.2650	0.0210	92.1	31.799	6.565	79.4
3	0.6630	0.0660	90.0	35.339	16.024	54.7
24	1.1580	0.4660	59.8	37.408	26.883	28.1

The relative sensitivity of peak discharge rates and depths of runoff can be assessed by comparing Figures 4-1 and 4-5. The results show that, when the storm duration decreased, the green roof had a greater effect on reducing the hydrological criteria (peak discharge, volume and depth of runoff). Hence, the 1-hour and 3-hour rainfall durations are used in most analysis. Since water can infiltrate more effectively during the longer storms, a 3-hour storm duration was mostly used in the analyses.

4.5 Effect of Storm Duration

The effects of storm duration on the peak discharge rate and on the depths and volumes of runoff from green roofs were studied. It is known that BMPs react differently to various storm durations, as the effects of infiltration and roughness become more influential. The median rainfall depth of 9.562 mm and soil depth of 0.30 m were chosen as the base values for these series of investigations. Moreover, five downgradient cells each with a length and width of 20 m were assumed.

Storm duration is an important factor. During the longer storm durations, the rainfall depth is distributed over longer periods of time, which allows for more infiltration. During the shorter duration storms, the rainfall intensity is much greater than the infiltration capacity, which limits the potential infiltration.

4.5.1 The Effect of Storm Duration on the Hydrologic Criteria

The analyses for different storm durations showed that, as the storm duration increased for a given rainfall depth, the peak discharge decreased and the depth and volume of runoff increased (see Table 4-10). The ratio of the depth of runoff to the depth of rainfall illustrates the effect of storm duration. The ratio increased by 88.8%

when the storm duration was increased from 1 hour to 24 hours (see Table 4-10). The increase in the total runoff due to an increase in the storm duration was significant (e.g., the volume of total runoff increased from 1.330 m^3 to 12.167 m^3, 89.1% increase, when the storm duration was changed from 1 hour to 24 hours).

Table 4-10. Effect of Different Storm Durations on Peak Discharge Rates, Depths of Runoff, and Total Volumes of Runoff

Storm duration (hr)	1	3	24
Peak discharge (m^3/sec)	0.00083	0.00077	0.00049
Depth of runoff (mm)	0.70	1.90	6.10
Depth of runoff/rainfall depth	0.07	0.20	0.63
Total volume of runoff (m^3)	1.33	3.87	12.17

The relationship between the depth of runoff and the storm duration was studied. Figure 4-6 shows the significant increase in the depth of runoff due to the storm duration. The depth of runoff increased from 0.70 mm to 6.10 mm when the storm duration changed from 1 hour to 24 hours an increase of 88.5%. This change occurs because in one hour all of the rainfall can not drain through the soil layers. Given more time, infiltrated water will have sufficient time to drain.

The changes in the peak discharge rates based on the different storm duration were also studied. The peak discharge rate decreased as the storm duration increased for a specific rainfall depth (see Figure 4-6). As the storm duration increased from 1 hour to 24 hours, the peak discharge decreased by 41.2% for the same rainfall. The decrease in peak discharge occurs because the rainfall is spread over a larger time period, thus allowing for less rainfall input per time period.

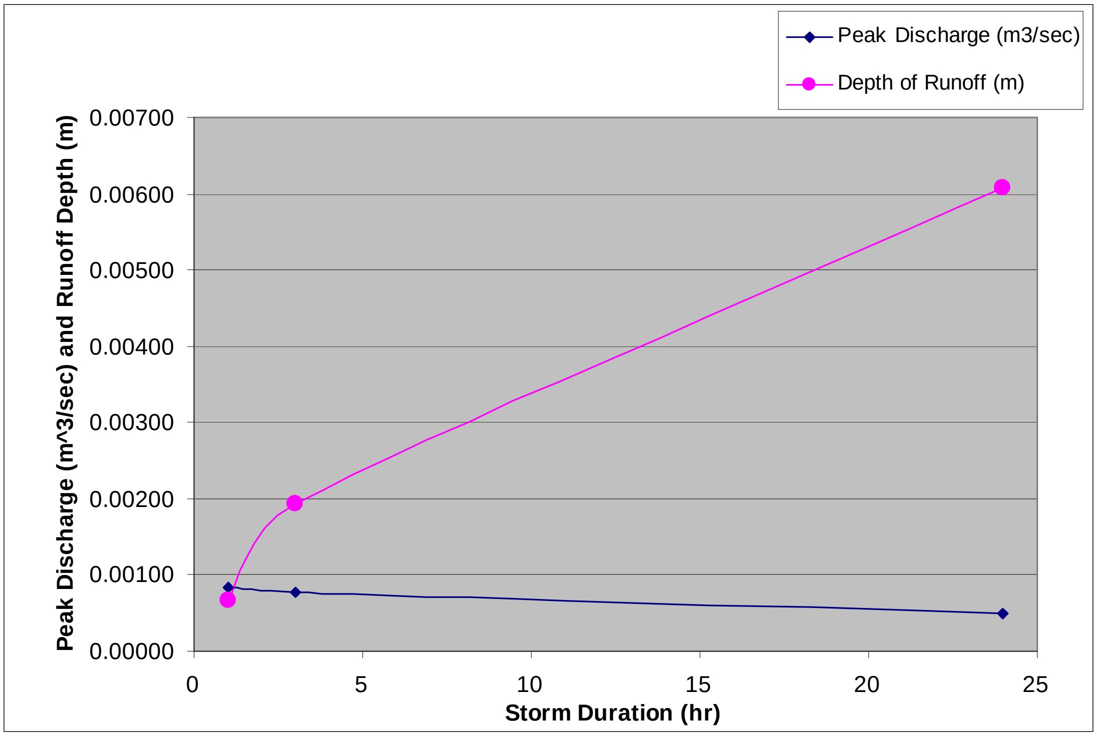

Figure 4-6. Peak Discharge Rate (m^3/sec) and Depth of Runoff (m) Versus the Storm Duration (hr) for 9.652-mm Rainfall Depth

4.6 Effect of Storm Magnitude on Green Roof Response

Flooding is not a function of storm duration alone, as the depth of rainfall is a limiting factor. A green roof will react differently to different rainfall depths. In this section, the effect of storm magnitude was evaluated since each storm event has a unique amount of rainfall. This factor influences the response of the BMP. In these sets of analyses, a 1-hour storm duration, a soil depth of 0.30 m, and a roof area of 2000 m^2 were assumed. The objective was to determine the independent effect of rainfall depth on the hydrologic response of a green roof. When the rainfall depth was increased, the peak discharge and depth of runoff also increased. The increase in peak discharge due to a larger rainfall depth makes physical sense, since in this case a larger volume of precipitation fell onto the roof in each time period. Accordingly, the effectiveness of green roof in controlling the stormwater depends on the rainfall depth.

To better illustrate the changes in behavior of the green roof due to changing rainfall depths, the results are presented graphically. Figures 4-7 and 4-8 show that the peak discharge rate and the depth of runoff increased as the depth of rainfall increased. For the smaller rainfall depths only surface runoff across the grass contributed to the total flow because drainage into the hold storage did not exceed the maximum hold storage capacity. However, for larger depths of rainfall both surface and subsurface runoff occurred as hold storage overflow occurred.

Table 4-11. Effect of Different Storm Depths on Peak Discharge Rate, Depth of Runoff, and Total Volume of Runoff

Total storm depth (mm)	Peak discharge (m^3/s)	Depth of runoff (mm)	Depth of runoff/ rainfall depth	CN based on computed depths of P and Q
1.270	0.00003	0.02	0.016	98
4.652	0.00025	0.20	0.043	95
9.652	0.00084	0.67	0.069	91
19.05	0.00258	2.08	0.109	86
38.10	0.00796	6.57	0.172	79

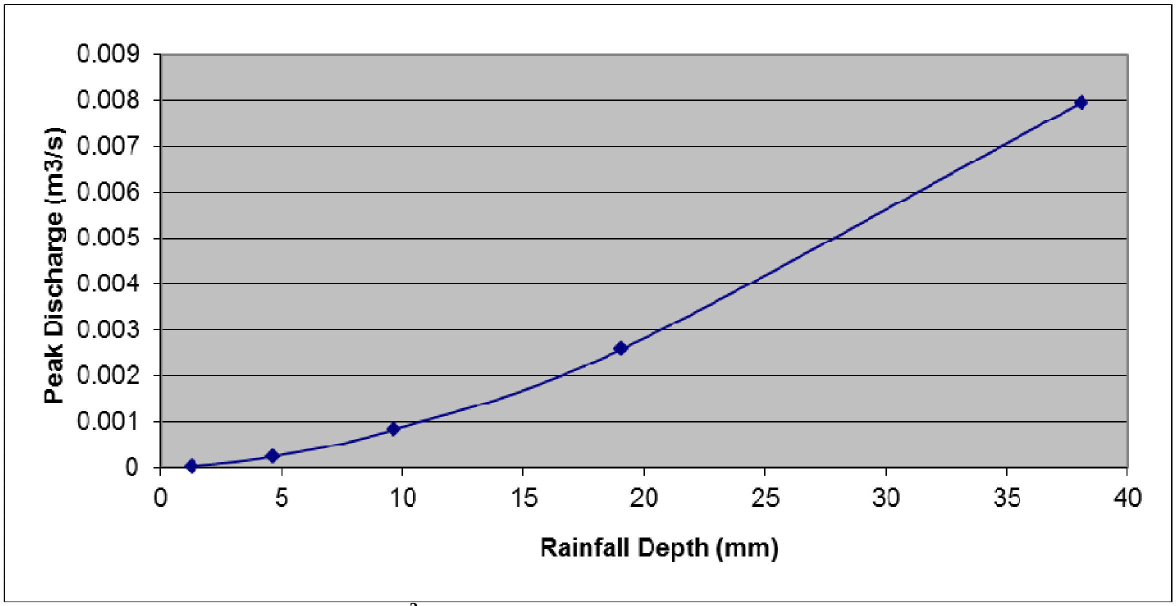

Figure 4-7. Peak Discharge Rate (m^3/sec) Versus the Storm Depth (mm) for a 1-Hour Storm Duration

The behavior of the peak discharge due to different storm depths is shown in Figure 4-7. The peak discharge increased from 0.00003 m^3/sec to 0.00796 m^3/sec when the rainfall depth increased from 1.270 mm to 38.10 mm. This result represents a 99.6% increase in the peak discharge rate for the 1-hour storm duration. The depth of runoff also increased with increasing rainfall depth. Figure 4-8 shows the 99.7% increase in the depth of runoff due to the increase in storm depth from 1.270 mm to 38.10 mm (this value was found by calculating the slope of the curve). Both Figures 4-7 and 4-8 clearly show the importance of rainfall depth in measuring the effectiveness of green roofs.

4.7 Effect of Rainfall Depth on Curve Number

Another benefit of the green roof is reducing the roof curve number. Lower curve numbers were calculated in Chapter 3 to show the effect of green roof soil depths and soil types. Besides this decrease in the green roof, the curve number value also decreased when the storm magnitude was varied.

The curve number changed not only by taking the soil depth and soil type into account, but also by varying the rainfall depth. Decreasing the curve number is one of the objectives of installing green roofs. The curve number decreased by 19.5% when the rainfall depth was increased from 1.270-mm to 38.10-mm (see Figure 4-9). By estimating the change in CN for various storm conditions, the effect of a building as part of a microwatershed can be assessed. For a bare roof, the building would reflect a CN of 98. Installing a green roof would reduce runoff rates, which suggests a CN less than 98. In order to properly account for the green roof, the CN for the building can be reduced from 98 to a value that reflects the design conditions and used to compute a weighted CN for the microwatershed.

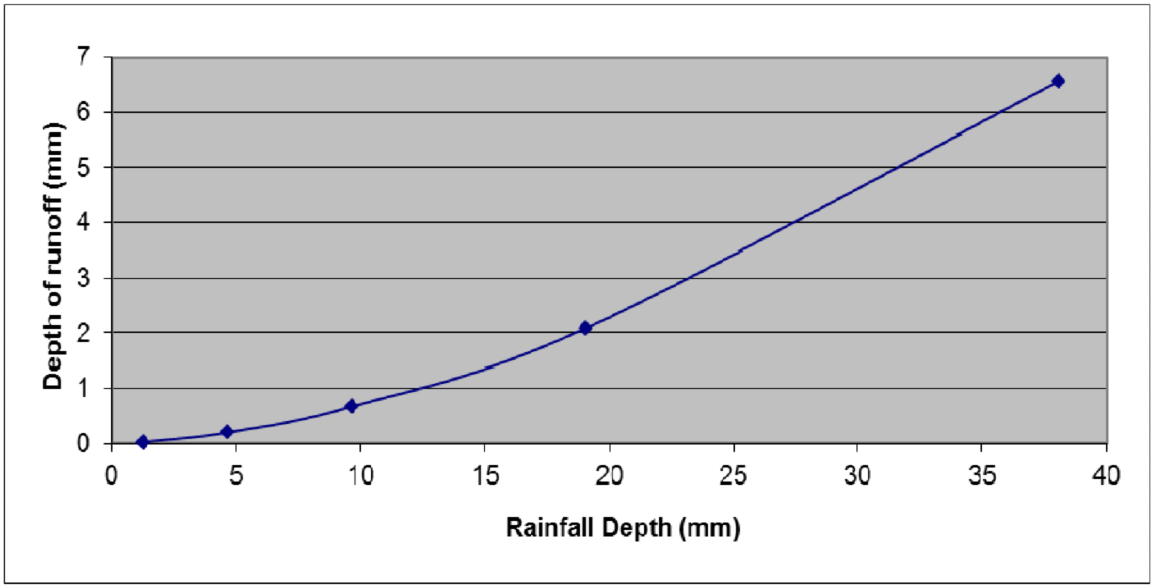

Figure 4-8. Depth of Runoff (mm) Versus the Storm Depth (mm) for a 1-Hour Storm Duration

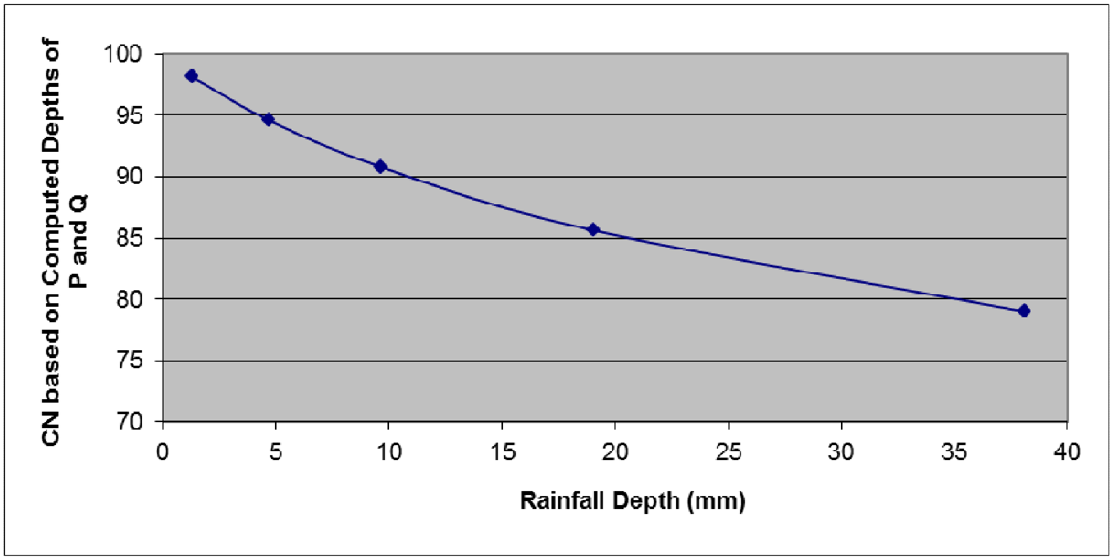

Figure 4-9. CN based on Computed Depths of P and Q Versus the Storm Duration (mm) for a 1-Hour Storm Duration

4.8 Effect of Soil Depth

The amount of soil storage depends in part on the depth of the soil mass, but because of the infiltration rates, all of the soil storage may not be available to infiltrating water. Several soil layers with a different soil depth in each layer were assumed in the green roof model. In these analyses, the 1-hr, 9.652-mm rainfall and a roof area of 2000 m^2 were assumed.

To study the combination of both intensive and extensive green roofs, the soil depths in this analysis were varied from 0.10 m to 0.50 m. The computer model requires the number of soil layers and the depth of each layer as input. For most storms, the peak discharge, depth of runoff, and calculated CN based on computed depths of P and Q were not sensitive to the soil depth (see Table 4-12). As the soil depth was increased, the peak discharge rate with the same input variables did not change when the storm duration was held constant. This result implies that the hydrological impact of using a green roof is significant, while the soil depth variation is comparatively negligible in reducing the peak discharge. Moreover, for the shorter rainfall durations, the CN based on computed depths of P and Q decreased from 98 to 90, but the CN did not change when the soil depths varied. This result occurred because the soil depth was used in calculating he modified curve number. In addition, the depth of runoff increased as the rainfall duration increased (as discussed in section 4.5). Only the depth of runoff into gutter from grass increased as the storm duration increased, and this value was constant for all soil depths (see Table 4-12). The results were rational; the rooftop runoff and peak discharge should not change in different soil depths since increasing the soil depth has little impact on the time required for water to infiltrate through the soil layers.

Table 4-12. Effect of Different Soil Depths and Storm Durations on Peak Discharge Rate, Depth of Runoff, and Curve Number for a 9.652-mm Rainfall Depth

Storm duration (hr)	Soil depth (m)	Peak discharge (m^3/s)	Depth of runoff (mm)	CN based on computed depths of P and Q
1		0.0008	0.7	91
3		0.0008	1.9	94
24	0.10	0.0005	6.1	98
1		0.0008	0.7	91
3		0.0008	1.9	94
24	0.20	0.0005	6.1	98
1		0.0008	0.7	91
3		0.0008	1.9	94
24	0.30	0.0005	6.1	98
1		0.0008	0.7	91
3		0.0008	1.9	94
24	0.40	0.0005	6.1	98
1		0.0008	0.7	91
3		0.0008	1.9	94
24	0.50	0.0005	6.1	98

4.9 Effect of Rooftop Roughness Coefficient

The Manning's roughness coefficient of the rooftop is another variable that influences the velocity and time distribution of runoff from the roof. The model used one roughness coefficient for the grass and a second value for the roof surface below the soil mass. The roughness coefficient for short grass was set as 0.15. The rooftop roughness coefficients of asphalt and tar are 0.012 and 0.02, respectively. Only the two rooftop materials were tested in this section. Analyses were performed for a 0.3-m soil depth and a range of rainfall depths (1.27 mm, 4.572 mm, 9.652 mm, 19.05 mm, and 38.1 mm) for a storm duration of 1 hour with the base roof area (2000 m^2).

An interesting result was observed from Tables 4-13 and 4-14. The peak discharge rates, the volumes of runoff, and the runoff depths were identical for the two rooftop roughness coefficients. This occurred because the velocity of the water was great enough for either rooftop roughness (i.e., 0.012 or 0.02). Thus, for the roof materials considered the outputs are not sensitive to the rooftop roughness coefficient when changed slightly (0.012 and 0.02). However, if the variation in the rooftop roughness coefficient was significant, the result would have been different since the rooftop roughness coefficient dictates the runoff velocity and peak discharge rate.

Table 4-13. Effect of Rooftop Roughness Coefficient on Peak Discharge (m^3/sec)

	Rainfall depth (mm)				
Roughness coefficient of rooftop	**1.270**	**4.652**	**9.652**	**19.05**	**38.10**
0.012	0.04272	0.38395	1.34214	4.16378	13.12960
0.020	0.04272	0.38395	1.34214	4.16378	13.12960

Table 4-14. Effect of Rooftop Roughness Coefficient on Depth of Runoff (mm)

	Rainfall depth (mm)				
Roughness coefficient of rooftop	**1.270**	**4.652**	**9.652**	**19.05**	**38.10**
0.012	0.02	0.19	0.67	2.08	6.57
0.020	0.02	0.19	0.67	2.08	6.57

4.10 Effect of Roof Slope

The slope of the roof is another variable that can be a factor in determining the hydrologic response. The downgradient slope is one factor controlling the velocity of the runoff across both the bare roof and the grass surface. Since the slope is used in Manning's equation, different roof slopes were tested to identify the effect of each on the peak discharge rate and the depth and volume of runoff. Roof slopes of 0.0005 m/m, 0.001 m/m, 0.01 m/m, 0.02 m/m, and 0.05 m/m were tested. Table 4-15 and Figure 4-10 show that the peak discharge increased as the slope increased. The increase is very noticeable, 83.4%, when the roof slope changed from 0.0005 m/m to 0.05 m/m. This result reflects the massing of the runoff at the outlet of the roof due to the higher velocity and smaller travel times. As a result, in designing the roof, it is very critical to consider the importance of roof slope in the design. Lower sloped roofs are needed for stormwater management control and recreation. However, steeper sloped roofs are functional for smaller storm events but they are generally used for aesthetic purposes.

Table 4-15. Effect of Downgradient Slope on Peak Discharge Rate, Depth of Runoff, Total Volume of Runoff, and CN

Downgradient slope (m/m)	Peak discharge (m^3/s)	Depth of runoff (mm)	Total volume of runoff (m^3)	CN based on computed depths of P and Q
0.0005	0.000772	1.933	3.87	94
0.0010	0.001019	2.642	5.28	95
0.0100	0.002573	5.296	10.59	98
0.0200	0.003386	5.847	11.69	98
0.0500	0.004657	6.346	12.69	99

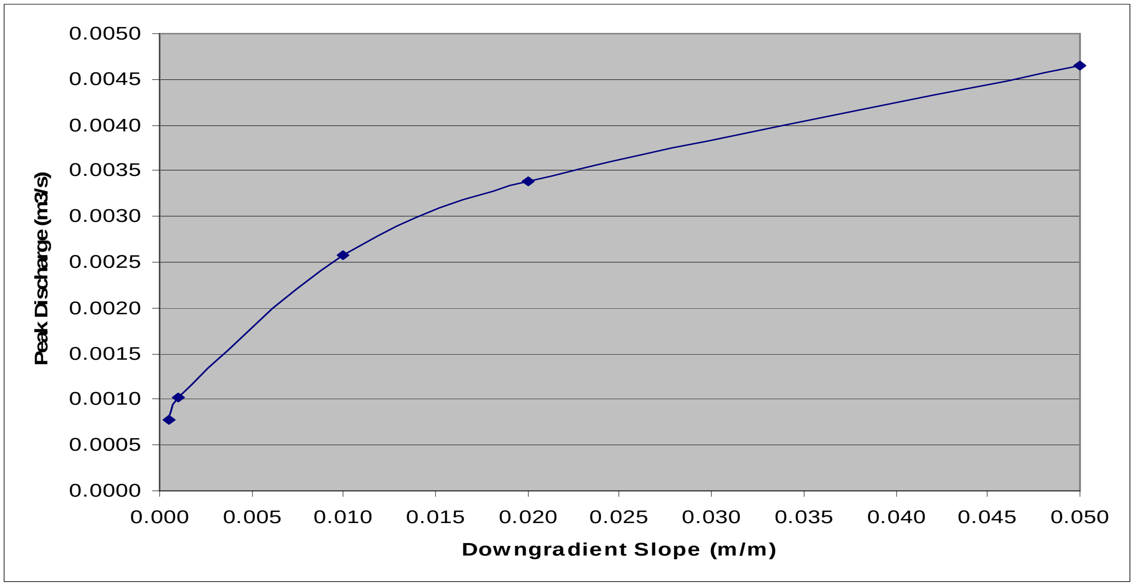

Figure 4-10. Effect of Downgradient Slope on Peak Discharge Rate

As it was noted in Table 4-15, the roof slope influences the depth of runoff. Figure 4-11 shows the 69.5% increase in the runoff depth when the roof slope was changed from 0.0005 m/m to 0.05 m/m. This indicates that the effectiveness of a green roof is sensitive to the slope of the roof. If the roof slope is shallow, the depth of runoff would be very small because much of the water does not immediately drain from the roof. Thus, the slope of the roof is an important design decision.

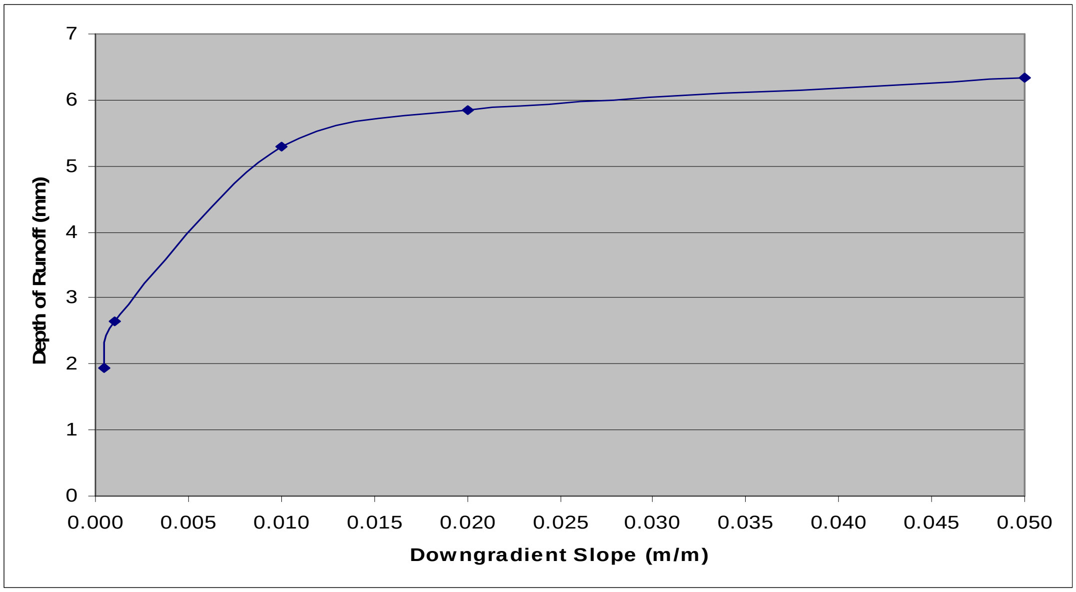

Figure 4-11. Effect of Downgradient Slope on Depth of Runoff

Roof slope also affects the computed curve number. Increasing the roof slope caused a 5 % increase in the CNs as shows in Table 4-15. For the larger slopes, the depth of runoff increases considerably. Since the curve number is directly dependent on the depth of runoff, the slope of the rooftop should be a primary design consideration. Additionally, this could have an effect on the weighted CN for the microwatershed in which the building is located. The effective CN and area of the roof would be part of the computation of the CN for the microwatershed.

Table 4-16 listed the ratio of depth of runoff to the depth of rainfall (9.652 mm) for each downgradient slope. As Figure 4-12 shows, the ratio of depth of runoff to the depth of rainfall increased as the roof slope increased (e.g., there is an increase of 69.7% in the ratio when roof slope changed from 0.0005 to 0.05 m/m). The relationship between the roof slope and the ratio of runoff and rainfall depth was the same as the behavior of the roof slope and depth of runoff (as displayed in Figure 4-

11). This is additional evidence that shows the importance of the downgradient slope in green roof design.

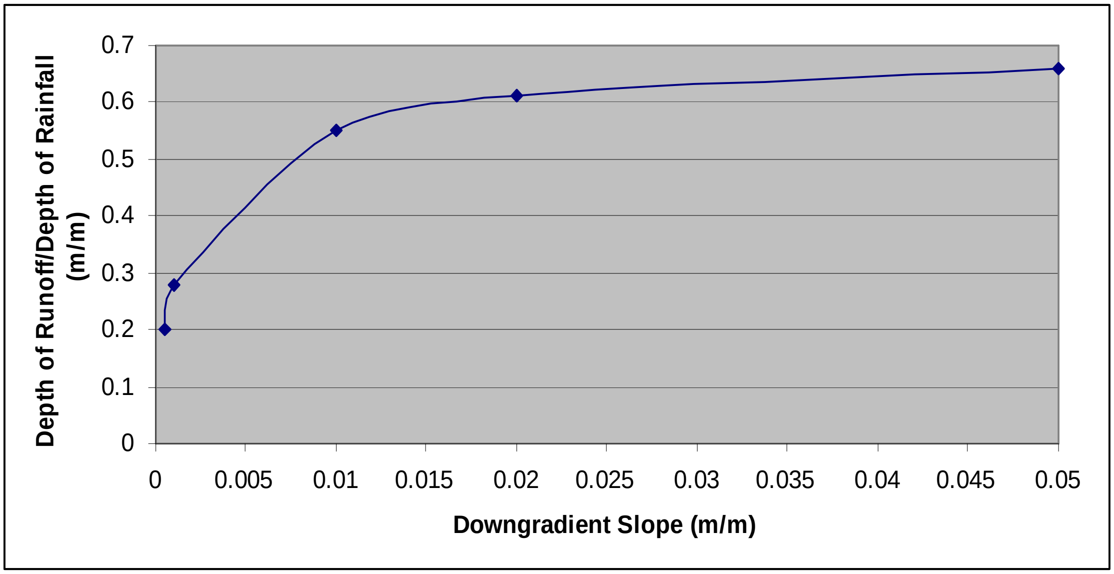

Figure 4-12. Effect of Downgradient Slope on the Ratio of Depth of Runoff and Depth of Rainfall

Table 4-16. Ratio of Depth of Runoff and Depth of Rainfall based on Different Downgradient Slope

Downgradient Slope (m/m)	Depth of Runoff/Depth of Rainfall
0.0005	0.20
0.0010	0.28
0.0100	0.55
0.0200	0.61
0.0500	0.66

4.11 Effect of Number of Downgradient Cells

Other input variables that change the hydrological characteristics of green roofs are the number, width, and length of each downgradient cell. In previous analyses, these design variables were held constant. In this analysis, the roof area (2000 m^2) is the same as in all previous analyses; however, the number of cells, width, and length of cells are design variables. The base rainfall characteristic used in these runs was a rainfall depth of 9.652 mm (as this value is the median value of rainfall depths) and a duration of 1 hour. In addition, the soil depth was set at 0.3 m.

The hydrologic response of the green roof based on a variable number of cells was studied to assess the influence of the model. As it is shown in Table 4-17, the peak discharge rate decreased as the number of cells was increased and the dimensions of the cells varied. In addition, the ratio of depth of runoff to depth of rainfall decreased from 0.18 to 0.03 (83.3%) when the number of cells increased. Figures 4-12 and 4-13 present the output of Table 4-17. Based on the two curves shown in the stated figures, it is realized that the dimensions of the downgradient cells impact the results. As these values represent the model, it shows that the model influences the output. This result occurs because the velocity limits the surface water speed from one cell to the next downgradient cell. As a result, the value peak discharge rate and depth of runoff can vary once the number of downgradient cells varies.

Table 4-17. Effect of Numbers and Dimensions of the Downgradient Cells on Peak Discharge, Depth of Runoff, and Ratio of Depth of Runoff to the Depth of Rainfall

No. of cells	Dimensions of the cell (m^2)	Peak discharge (m^3/s)	Depth of runoff (mm)	Q/P
1	44.72 x 44.72	0.001993	1.773	0.18
2	31.62 x 31.62	0.001579	1.342	0.14
3	25.82 x 25.82	0.001266	1.033	0.11
4	22.36 x 22.36	0.001017	0.82	0.08
5	20.00 x 20.00	0.000828	0.665	0.07
6	18.26 x 18.26	0.000681	0.547	0.06
7	16.90 x 16.90	0.000563	0.452	0.05
8	15.81 x 15.81	0.000467	0.375	0.04
9	14.91 x 14.91	0.000387	0.311	0.03

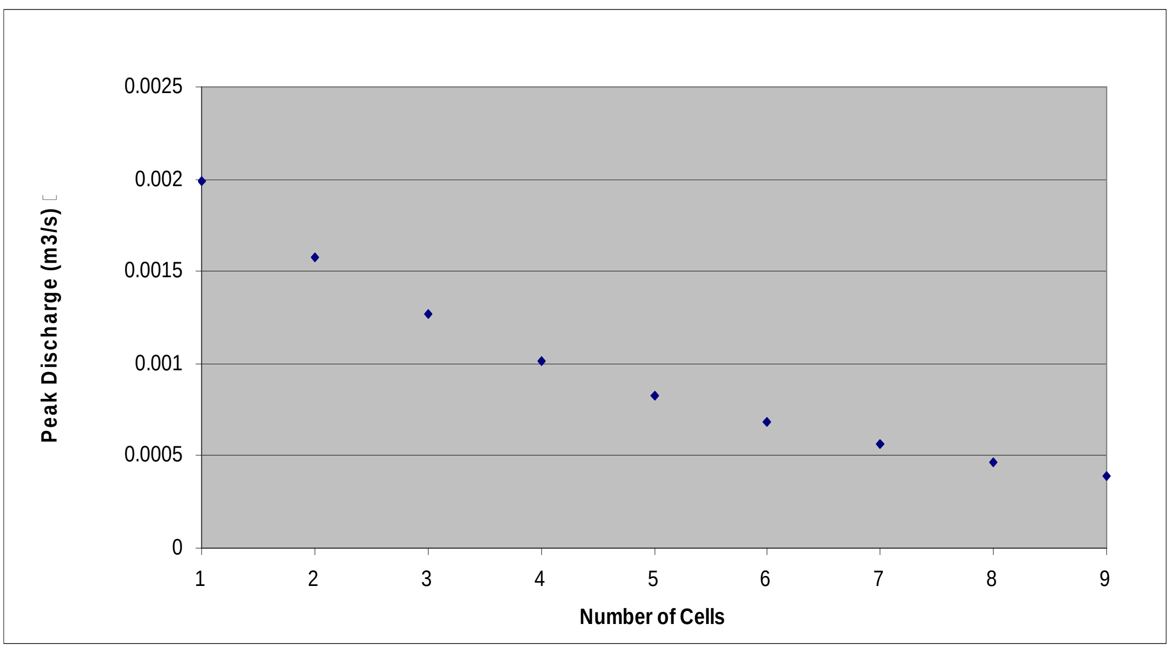

Figure 4-13. Effect of the Number and Dimensions of the Downgradient Cells on Peak Discharge Rate

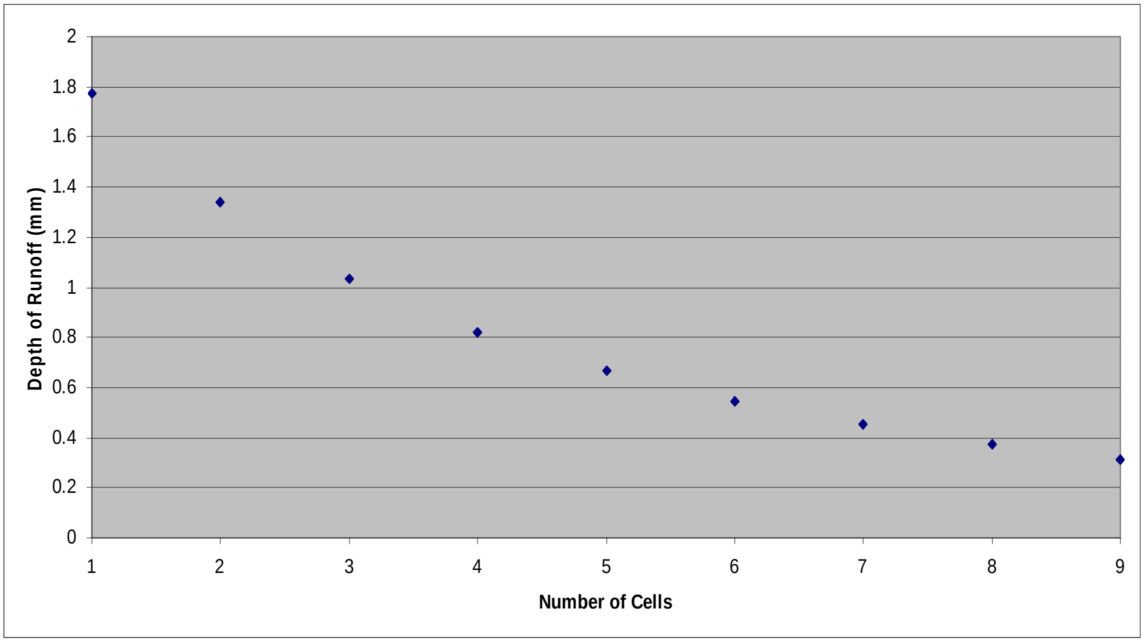

Figure 4-14. Effect of the Number and Dimensions of the Downgradient Cells on Depth of Runoff

Chapter 5: Conclusions and Recommendations

5.1 Introduction

The goal of this research was to evaluate the hydrologic design of green roofs by assessing the variability of their stormwater responses to different rainfall characteristics and physical parameters. Green roofs have many hydrological and environmental advantages, including mitigating the volumes and peaks of stormwater runoff, energy savings, ecological, economical, aesthetical, and psychological benefits. On the other hand, green roofs have disadvantages, such as relatively high construction costs compared to the traditional bare roof (the cost is approximately double), but it should be noted that green roofs last twice as long as bare roofs.

5.2 Conclusions

Storm duration is a rainfall characteristic that affects the peak discharge rates and depths of runoff. In Chapter 4, the results showed that for longer storm durations, but a constant rainfall depth, the peak discharge rate decreased and the depth of runoff increased when compared with the case where the storm duration was shorter. This is the result of the longer storm duration allowing more time for infiltration.

The rainfall depth was another rainfall characteristic that was shown to have a significant impact on the hydrologic response of a green roof. Higher rainfall depths caused increases in both peak discharge rates and runoff depths. This results because runoff results from both the grass surface and the rooftop. For the greater rainfall depths, the water holding capacity of the soil and the hold storage were exceeded, which resulted in runoff from the rooftop. When the runoff from the roof surface was combined with the runoff from the surface of the grass, peak discharge rates increased.

After studying the influences of the rainfall characteristics on the hydrologic response, the hydrologic effects of green roof characteristics were studied. From the stand point of project cost, the depth of soil on the roof is an important design parameter. However, the results showed that varying the depth of soil from 0.10 m to 0.50 m did not have a significant impact on the hydrologic response of the green roof, including both the peak discharge rates and depths of runoff. The rationale behind this result is that low infiltration rates through the soil do not allow for significant depths of rooftop runoff, which is true for either deep or shallow soil layers.

The effect of the slope of the roof was another characteristic that was studied. It was realized that the downgradient slope had a noticeable effect on the peak discharge rate and depth of runoff. As the downgradient slope increased, the peak discharge increased significantly. Moreover, it was realized that the effectiveness of a green roof is more sensitive to changes at the smaller slopes than to changes at the larger slopes. The roof slope should not be either very steep as this could cause erosion or too shallow as this could lead to ponding. For small depths of rainfall, a steep downgradient slope can be practical; otherwise, lower sloped roofs should be used for better BMP performance.

The effect of Manning's roughness coefficient of the tar roof on both the peak discharge rate and the depth of runoff was studied. The peak discharge and depth of runoff did not change as the Manning's roughness of the tar roof was changed. The velocity across the tar roof is sufficiently fast that small changes in the roughness are not important. In cases where the roughness of the surface vegetation varied significantly, the effect of the Manning's roughness would be significant. The Manning's roughness coefficient that was used to calculate the velocity of the runoff from the grass surface was set as 0.15. Since this roughness coefficient is a commonly used value for short grass, it was set and was not a program input variable.

Another variable that was studied in this design was the curve number of the roof. The CN for a standard bare roof is generally 98. A green roof was expected to alter the runoff characteristics with some of the runoff released after the main part of the storm had passed. Therefore, the analyses computed the reduction in CN, ΔCN, that can be used for different conditions (e.g., thickness of roof, infiltration rate of green roof, volume of water storage, etc.). Then a design engineer can get credit for reducing runoff by installing a green roof and reducing the CN by ΔCN when computing the weighted CN for the entire watershed. The modified curve numbers were calculated in this study based on both soil depth and soil type. Furthermore, it realized that curve number decreases when the rainfall depth increases. In addition, roof slope affects the computed curve number. The CN increases as the roof slope increases; this change can influence the surface runoff.

The prototype green roof that was constructed in Pittsburg, Pennsylvania also verified the stated conclusions. Bliss et al. (2009) reported that the monitored green roof reduced the volume of runoff by 70%. Moreover the peak discharge rates as well as depth of runoff reduced significantly (between 5% to 70%). This prototype demonstrated that the time to peak flow extended and the time of runoff delayed. Another prototype that was built in Southfield, Michigan confirmed the results of this research. The green roof held 68.25% of the rainfall volume. Furthermore, from 21 monitored storm events, in 17 of them, the green roof reduced the peak discharge rate by 90% (Carpenter and Kaluvakolanu, 2011). All these conclusions match the results of this research and suggested computer model.

5.3 Recommendations for Future Research

The model and analyses conducted in this research showed that green roofs are a feasible option for stormwater management. The results showed the effectiveness of green roofs in reducing the peak discharge rates and the total runoff depths for different storm and roof characteristics. However, some conditions were not included in the model and the analyses. For further improvement of green roof design, other climatological, regional, and seasonal conditions must be taken into consideration. These conditions may limit the hydrological impact of the green roofs. For example, from the results in Chapter 4, it is evident that the peak discharge reduction depends on the storm intensity and duration. Use of green roofs is practical for low storm intensities and longer storm durations. For storm intensities greater than moderate depths (about 19 mm), a green roof loses its effectiveness in managing the volume of runoff. Different geographical locations have different rainfall characteristics, so specifying a model for a specific region and studying its effectiveness should be done. For example, storm intensities and durations in Nevada are different than those in

Maryland. Therefore, the impact of green roof design characteristics as a function of location should be studied.

Evapotranpiration (ET) was not considered in the model because the model is intended to simulate single storm events; therefore, it is unlikely that evapotranspiration would be a factor during a storm. The impact of ET on the hydrological response of a green roof should be investigated using a multi-storm model. ET effects the initial moisture content of the soil, i.e., the antecedent moisture content. This would influence the antecedent moisture conditions for subsequent storms. Evapotranspiration may contribute in the hydrologic effectiveness of the green roofs by reducing both the surface and subsurface runoff. More research should be conducted to study the impact of wind, temperature, and vapor pressure gradients on a green roof to determine the overall evapotranspiration impact on green roof design.

Types of growing media should be considered in the green roof design. The type of growing media can affect the surface runoff and determine the infiltration rate of the first layer when the surface water is infiltrating to the soil. The growing media would also influence surface roughness. The characteristics of the foliage on the roof can change the Manning's roughness coefficient. Higher roughness rates due to higher grass depths should also be examined for the case where the grass is not mowed. When the maintenance level is low and the height of the grass increases, the roughness will also increase. It is predictable that, when the Manning's roughness coefficient of the grass increases, the water travels at slower rate on the green roof; as a result, there is more time for infiltration, which changes the time distribution of runoff.

5.4 Summary

A primary goal of this research was to develop and use a mathematical model to simulate the movement of water through a green roof and to study the sensitivity of variables that are important in the design of green roofs. To reach this goal, the green roof parameters and input characteristics were varied in each trial, and sensitivity tests were performed to determine the impact of these variations on the design specifications.

This research has highlighted green roofs as a successful urban strategy for mitigating important urban environmental problems, while simultaneously providing green spaces and other important amenities to the urban built environment. It is clear that lots of opportunity exist for further research in this field. The model was developed to simulate rain water movement within the green roof. The two most significant features of this model are consideration of specific yield and using the NRCS infiltration model for the watershed. Initially, water does not drain through the soil to the layer beneath it until the moisture content of the soil reached field capacity. This model rationally assumed that infiltrated water did not drain through all of the soil layers to the underdrain system before the medium was saturated. The use of specific yield enabled more accurate CNs to be developed.

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