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Calibration and Testing of Simple Mass Balance Model for Quantifying Stormwater Management Benefit of an Extensive Green Roof

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Calibration and Testing of Simple Mass Balance Model for Quantifying Stormwater Management Benefit of an Extensive Green Roof

By

Biman Kumar Paudel

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Calibration and Testing of Simple Mass Balance Model for Quantifying Stormwater Management Benefit of an Extensive Green Roof

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ABSTRACT

A simple mass balance based model for quantifying stormwater management benefits of an extensive green roof was developed and tested based on data from Lawrence Technological University. Model simulated green roof runoff peaks and volume agreed with those measured between April – September 2008 within a factor of 0.97 – 1.4 and 0.8 – 1.6 respectively.

The objective of limiting roof runoff peaks from 2 to 100 year design storms to equal or be lower than the corresponding pre-developmental peaks for the tested regional conditions was not met with the green roof alone. Provision of an additional storage of 40 m^3/ 1000 m^2 green roof area in series with the green roof is expected to be able to achieve this objective. The developed procedure is expected to be useful for the assessment of stormwater management benefits of extensive green roofs in other geographical locations.

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ACRONYMS

ASTM	American Society of Testing Materials
BMP	Best Management Practices
cm	Centimeter (s)
CN	Curve number
EPA	Environmental Protection Agency
EPDM	Ethylene Propylene Diene Monomer
ET	Evapo-transpiration
FLL	German Landscape Research, Development and Construction Society
in	Inch (es)
LTU	Lawrence Technological University
L/s	Liters per second
mm	Millimeter (s)
NRC	National Research Council
NRCS	Natural Resources Conservation Service
PVC	Polyvinyl Chloride
SCS	Soil Conservation Service
SGRR	Storm Green Roof Response
TR-55	Technical Release – 55

CHAPTER I: General Introduction

1.1 Green roof definition, components and function

In its simplest form, a green roof is an engineered roofing system that allows plants to grow on top of buildings while protecting the integrity of the underlying structure. A green roof is a surface treatment for rooftops and it involves the addition of layers of growth media and plants to create a controlled green space. It replaces the vegetated footprint that was destroyed when the building was constructed.

The specific materials used for construction of green roofs may vary from project to project, but each has the same essential basic components (Hoffman, 2005). For any green roof to function properly, it must have a waterproofing layer, a root barrier, a water retention layer, growing media and vegetation (Teemusk et al., 2007).

1.1.1 Extensive and intensive green roofs

The green roofs are generally categorized as ‘‘intensive’’ or ‘‘extensive’’ systems depending on the plant material and the planned usage for the roof area. ***Intensive green roofs*** are so named because of their ‘‘intense’’ maintenance needs. They normally imitate landscape found at natural ground level by using a wide variety of plant species, even trees and shrubs needing deeper media thickness (usually >15 cm). Intensive green roofs are often installed as outdoor recreational space with an ability to bear extra weight coming from intense vegetation and human occupancy. With their usually deeper soil medium, intensive green roofs can accommodate a wide range of plants, edibles, shrubs, and even trees requiring regular maintenance and irrigation.

In contrast, ***extensive green roofs*** generally require nominal maintenance. They are normally not accessible to the public. Because of their shallower media depth (<15 cm), plant species are limited to herbs, grasses, mosses, and drought-tolerant succulents such as Sedum. In addition, extensive green roofs can be built upon a sloped surface for proper drainage. They usually require less structural support than intensive ones, and are considered to be more environmentally effective. Figure 1.1 shows the cross sections of these two types of green roofs.

Extensive green roof

Intensive green roof

Figure 1- 1: Cross-sections of Extensive and Intensive green roofs.

(Source: http://www.hydrotechusa.com/garden-projects.htm)

1.1.2 Environmental benefits from green roofs

The accelerated urban growth has affected many of the earth's natural processes. Impervious surfaces like asphalt, concrete rooftops, roads, and parking lots are replacing natural surfaces affecting ecological balances. In order to restore balance to urban ecosystems, there must be ways to bring back depleted green surfaces. City's black rooftops can become new green space without compromising any development. A green roof is installed with the goals of getting major environmental benefits such as reduction of urban heat island effect, improvement of urban ecology, improvement in quality of life and stormwater management.

Reduction of urban heat island effect

Urban heat island effect causes temperatures to be higher in high density cities than in the surrounding areas due to the concentration of heat radiating surfaces and the lack of vegetation. There are two ways to mitigate urban heat island- increasing vegetation, or increasing surface reflectivity. Green roofs accomplish both and consequently reduce individual building energy use (Fang, 2008) and (Bass, 2007).

Improvement in urban ecology

Habitat destruction, pollution, and noise make the urban areas unfriendly to most plant and animal species. Green roofs can support biodiversity and can create healthy thriving habitat in most of the urban landscapes (Hiena, 2007). The vegetation on green roof at the same time attracts different birds and butterflies (Siegler, 2006).

Improvement in quality of life

Green roofs help to reduce patient recovery times. They improve the quality of life for urban dwellers, decrease stress and create space for relaxation and recreation. In addition, they have a number of other economic benefits including growth in real estate values

(Peck, 1999) and (Siegler, 2006). In a long term benefit-cost ratio is always greater than one, justifying the investment on green roof.

Stormwater management

Urban development always disrupts the natural movement of water. Due to impervious surfaces, precipitation cannot infiltrate through, but is converted to runoff potentially creating pressure to city sewage systems. In combined sewerage systems, high rain storms runoff dramatically increases the volume of water in the system. This flood of wastewater can exceed the capacity of treatment plant causing an overflow which then brings the untreated waste into natural waterways.

Green roofs can retain and detain stormwater, reduce runoff volume and slow the rate at which it enters the sewage system. They are a cost-effective stormwater management tool compared to conventional treatment and retention methods (Berghage, 2007). Green roof's contribution towards the stormwater management is its most important benefit. Compared to other local stormwater management solutions, green roofs require no additional space, which is an advantage in urban areas where land can be valuable (Villarreal, 2007).

1.2 Working principle of green roof

In summary, the mechanisms by which any green roof act on stormwater are interception, absorption, evapo-transpiration and runoff. Green roofs provide shade, which reduces solar heat gain through the roof and mitigates the urban heat island effect. Its soil and vegetation layer absorbs and filters rain, preventing it from becoming polluted runoff from the roof's surface. The photosynthesis in green roof vegetation helps to reduce greenhouse gas emissions.

Green roofs absorb, filter, and temporarily store precipitation. These characteristics help to mitigate the impacts of urban stormwater runoff. Volume, peak discharge rates, and associated non point source pollution; primarily sediments and nutrients such as nitrogen and phosphorus are of great concern to the health of watersheds, especially in urban centers. During low intensity periods of rainfall (less than 2.5 cm), green roofs have the potential to completely eliminate runoff as the soil layer absorbs the rain. During longer periods of rainfall, or rainstorms of greater intensity (2.5 to 5 cm or more), green roofs reduce peak flow rates and delay any runoff that might occur later, thus reducing the total volume of water that reaches sewer systems.

The characteristic of hydrograph for a typical storm event due to intervention of green roof is nearly represented as in Figure 1.2. Green roofs are used as a source-control measure because they detain and slowly release rainwater.

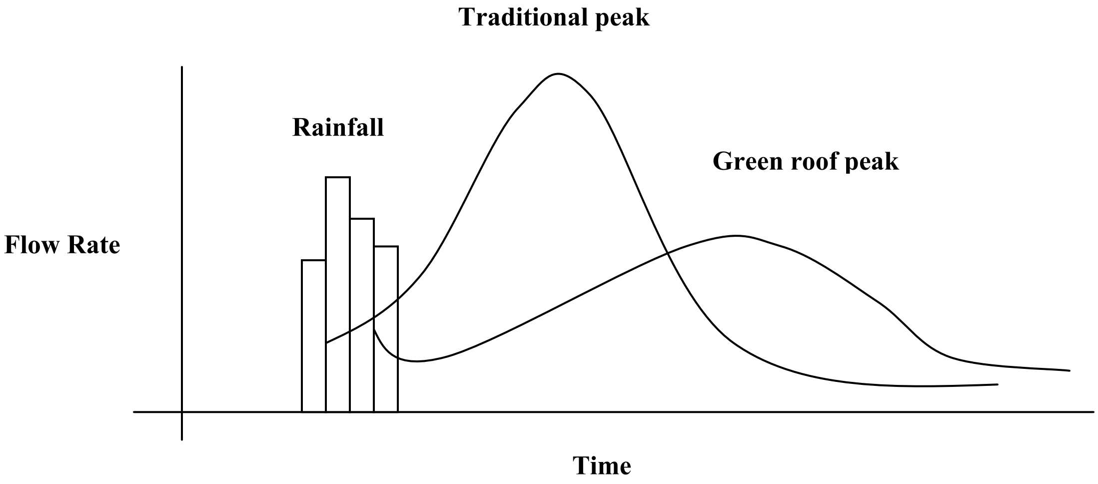

Figure 1- 2: Comparison between traditional and green roof peak for a typical rainfall

1.3 Sources of stormwater

Stormwater is characterized as a runoff from impervious surfaces that enter a sewer before entering into surface waters (Carter, 2006). Besides, other point and non-point sources of pollution, two major areas of concern are the high nutrient loadings and high peak flows associated with rainfall events. The increase of impervious area due to urbanization also increases the volume and rate of urban stormwater runoff. Due to municipal requirements and to aid in the management of stormwater runoff a variety of stormwater BMPs have been developed (Moran, 2002). Green roofs are also being promoted as an optional BMP throughout the regions (Glass, 2007).

1.4 Objectives of study

Green roof technology is emerging as an effective, practical way to increase the energy performance of buildings and limit stormwater runoff. Converting conventional roof surfaces to green roofs is potentially the single greatest way to reduce or delay stormwater runoff on a larger scale. This study therefore focuses only on the stormwater management performance of green roof. Performance of a green roof at one location may not have similar result when applied to another place. It is therefore very essential to study green roof's performance in the particular region of application. This study is done for Windsor-Detroit region by using the extensive green roof constructed at LTU over the A. Alfred Taubman Student Services Center (see Figure 1.3).

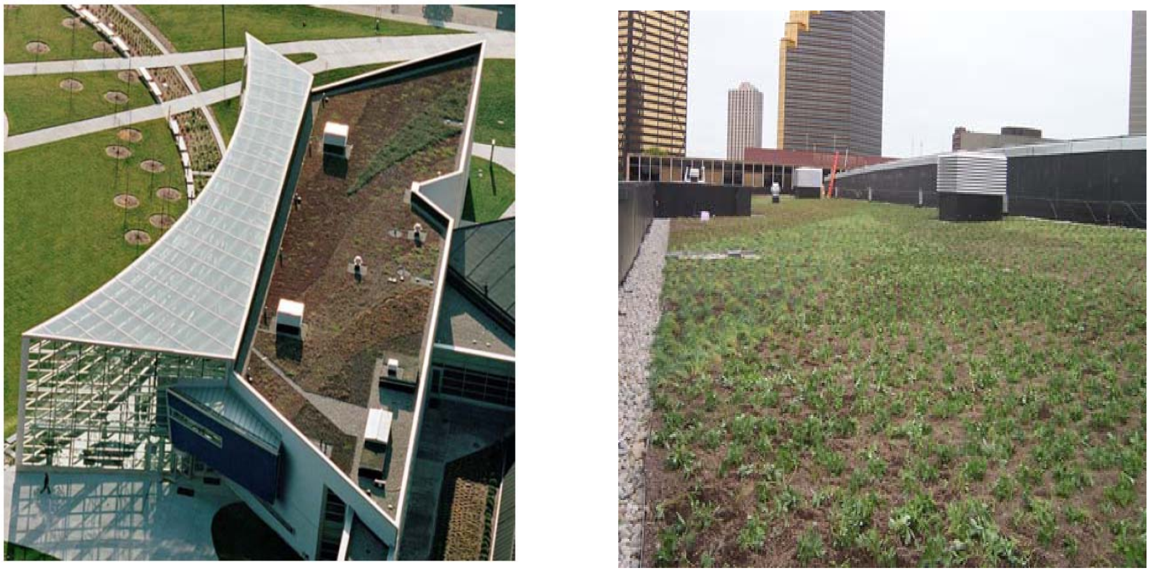

Figure 1- 3: Green Roof on Student Services Center at LTU

(Kaluvakolanu, 2008)

The primary goal of this study is,

- To formulate, calibrate and test a simple mass balance based green roof runoff model using monitored rainfall and runoff data on Lawrence Technological University's (LTU's) extensive green roof.

In addition to this primary goal, specific objectives of this study are,

- To apply this model for simulating peak discharges for a number of design storms in the region with return periods ranging from 2 to 100 years.
- To estimate the effectiveness of the system as a stormwater BMP by comparing the simulated peaks with the pre-developmental peaks in two cases: (i) by green roof itself and (ii) by augmenting the green roof storage capacity with additional storage.

In the context of increasing demands of green roofs in North America, there is a necessity to have dependable methods for predicting green roof's performance (Yiping, 2007) for an actual monitored rainfall and design storms of desired duration and return periods. The green roofs are artificial establishments and depending on the available technology and resources for a location, they may have different characteristics from the actual physical processes involved in any natural watershed. Most of the hydrologic models developed for natural watersheds may not therefore be used in green roof for peak estimation. It is hence expected that the simple mass balance model developed here will be able to predict peak discharges from any storm with acceptable accuracy for the study area.

CHAPTER II: Review of Literature

2.1 Background

Depending on history most green roofs were functional. They were installed on buildings either for amenity or as a sign of elegance and wealth in a community (Kohler, 2004). Since green roof systems are a beneficial way to bring vegetation back into the city and help restore the natural environment, technological improvement is made on the construction aspects of green roofs in the mid-sixties, particularly in Germany and other European nations (Buesching, 2004). They have been a part of European architecture for a long time and are now beginning to take place in North America (Forrester, 2006). As the green roofs are not so publicized in North America, only little data is available on green roof's performance for quality and quantity improvement of stormwater. In this region, it is seen that the benefits of green roof technologies are poorly understood and the market is still immature. In Europe however, these technologies have become very well established (Mentens et al, 2006).

Urban development alters the hydrology of watersheds and streams by disrupting the natural water cycle (Levallius, 2005). Notable effects include increased runoff volumes, changes to stream geo-morphology, impacts to aquatic habitat and water quality impacts. In recent years, green roof as BMPs have been developed to aid in the improvement of stormwater management. However, the use of a green roof as a BMP for stormwater in an area depends on a number of hydrological and climatic factors in that particular location.

Since one of the specific objectives of this study is to have a comprehensive review of the green roof works carried out in North America, this chapter therefore discusses the things apparent from a thorough literature review of a number of documents available on this subject.

On average, traditional rooftops represent about 22 percent of the total land area in major North American cities (Peck, 2005). Since more and more natural areas are being impervious due to urban development, the areas available in these roof surfaces give an opportunity to environmental change, and add a critically important dimension to green roof design. A number of research works illustrate that extensive green roofs have been popular and are gaining acceptance all over North America. Figure 2.1 shows the states and provinces where green roofs exist and research is being done.

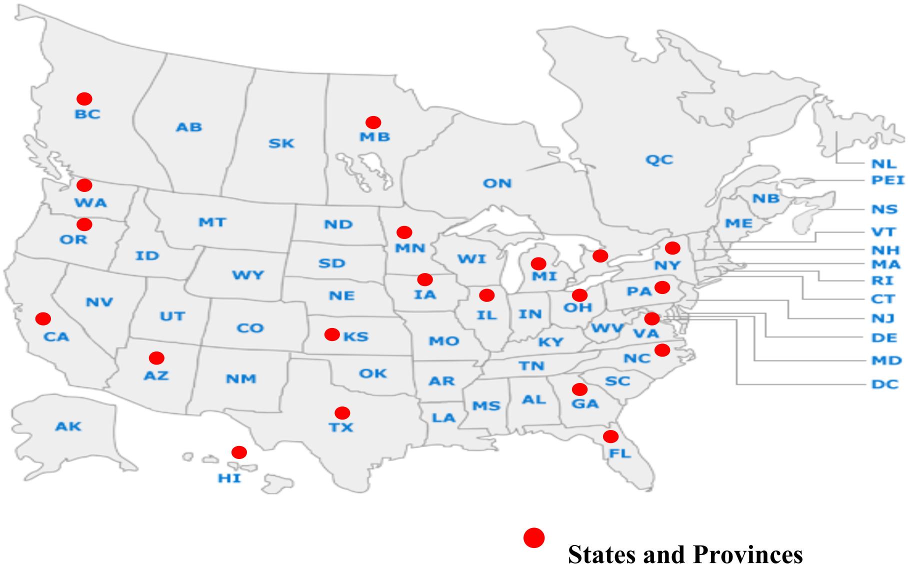

Figure 2- 1: States and Provinces with green roof research works

Due to load restrictions and associated costs, shallow media extensive green roofs are more common (Wong et al, 2003) than deep intensive roofs. The green roof under consideration is an extensive roof and the only type relevant in this study. The literature review is therefore focused only on the extensive green roofs. In the following sections, a number of segments describing the essential components of an extensive green roof are described and the performance of green roofs cited in different works.

2.1.1 Selection of plants

In addition to media, Eumorfopoulou (1998) says plant uptake and transpiration increases the ability of a green roof to hold water from repeated rain events. Maximizing transpiration from the roof may thus enhance the total amount of water prevented from going into the sewer system (Kohler, 2003). The shallow substrates commonly available in extensive green roof result a periodic drought and rapid fluctuation in soil moisture. Thus drought tolerance or avoidance must be the key criterion for the selection of plant species for green roofs (Onmura, 2001).

The most successful green roof plants are low-growing, shallow rooted perennial plants that are heat, cold, sun, wind, drought, salt, insect and disease tolerant (Snodgrass, 2006). Normally, plants that are highly flammable, that develop large root systems or that are excessively “thirsty” should be avoided (Jenrick, 2005). Since most green roof medium is fractured and lack a continuous column of water that facilitates capillary action, green roof plants must be able to withstand periods of dryness and heat, a factor that eliminates most traditional annuals and perennials (Snodgrass, 2006).

Hardy succulents which display CAM (crassulacean acid metabolism) photosynthesis whereby transpiration is reduced during the day to maintain the minimum water loss are therefore the primary plants for low depth roof systems. Different varieties of succulent sedum are then the obvious and in some cases, the only choices for thin substrate, non-irrigated extensive roof gardens in temperate climates (Snodgrass, 2006).

It is therefore suggested that a basic low maintenance extensive green roof should always be planted with perennials and re-rooting plants such as sedums. Sedums are non-invasive, drought resistant, and come in a wide range of colors from blood reds to evergreens (Durhman et al., 2005). They are categorized in terms of foliage and flower color, typical bloom times and the most suitable hardiness zones, the maximum height of plant and the plant's annual spread for coverage in particular location. Once established, they can survive on rainwater alone without any additional irrigation and can withstand high temperatures. Snodgrass et al. (2006) list more than 200 different sedum plants that can be applied in extensive green roofs.

Though different sedum plants are available, selection of a variety in a specific project normally follows a practice of using the previously tried and tested plants (Emilson et al., 2006). It is not appropriate to use the same vegetation mixes everywhere. In some places, the ability to withstand summer drought should be the main factor on plant choice, whereas in regions with severe winters, cold hardiness should play a critical role. With this reason, trialing of different species for their suitability in a particular location should be done (Dunnett et al., 2004) before installing a green roof.

2.1.2 Substrates

Except the English version of FLL guidelines developed in Germany and a couple of ASTM documents dealing with the load requirements in a green roof, there are no current specific regulations in the design of substrates for vegetated roofs in North America. These media are therefore designed as a constant trade-off between system weight requirements, substrate water-holding capacity and oxygen diffusion to plant roots. Extensive green roof systems are designed to optimize the parameters affecting runoff. Designers normally optimize different factors such as water holding capacity, weight, and hydraulic conductivity and maintain the required nutrients and moisture to favor the hardy, drought tolerant plants before recommending the media depths.

Emilsson et al., (2005) while investigating the role of establishment method on the installation of green roofs found that pre-fabricated vegetation mats have higher succulent plant cover than on-site constructed roofs. They also suggested that long-term stability of substrates against decomposition and erosion through water, wind or frost is also an important consideration. The final selection is therefore a compromise between the physical and chemical characteristics with material availability on one side and price on the other. When they analyzed substrates such as commercial soil and two other generic products made from crushed roof tiles with low and high organics, in a certain period they observed higher biomass in commercial substrate due to higher nutrient contents.

It is understood that the substrate or medium in most of the green roof cases is supplied as per the specific demand or need. Most common substrate used is custom-engineered growing medium manufactured from expanded shale, mushroom compost and mineral components. These roof media have 90 percent minerals and 10 percent organics. Whatever the media is, thought should be given on the weight of components used and their composite drainage characteristics. Lightweight aggregate with proper drainage and weed-free properties is often preferred. Table 2.1 accounts for some of the media type that has been used in green roof in North America.

Table 2- 1: Types of media used in some cases of green roof

Media used	**Reference**
40% heat-expanded slate, 40% USGA grade sand, 10% Michigan Peat, 5% Dolomite, 3.33% composted yard waste and 1.67% composted poultry litter by volume.	Vanwoert (2004)
Soil mix with a composition of 55% Perma Till (Stalite 3/8" expanded slate), 30% Rootzone Sand, and 15% approved compost.	Moran et. al., (2005)
90 mm thick substrate medium consisting of 12.5% sphagnum peat moss, 12.5% coir (coconut fiber), 15% perlite, and 60% hydrolite.	Jarrett et. al.,(2006)
Two different types as expanded clay mix (85% mineral and 15% organic) and a tire crumb mix (45% mineral, 40% inorganic and 15% organic)	Hardin (2006)
Media designed has 75% organic and 25% inorganic components.	University of Iowa, IIHR building (2006)
Substrate composed of 15% digested fiber, 25% encapsulated Styrofoam (EPS), 15% perlite, 15% course peat moss and 15% compost.	Multnomah County Ecoroof (2005)
10 cm thick shale	Present study

Ideally, the growing medium or substrate is recommended to have the characteristic of being highly efficient in absorbing and retaining water while at the same time having free-draining properties. This is generally accomplished by granular mineral materials that absorb water and fine particles to which water will cling. Normally artificial soils can be superior to many natural soils, provided they are tailored for the specific type of vegetation they are to support and the location they are to be placed. Light expanded clay granules are widely used on their own or in combination with other materials, and fulfill the requirements of an ideal base for a green roof substrate being lightweight and having some moisture and nutrient storage capability. The most ecologically sound materials are those that are derived from waste or recycled products (Mentens et. al, 2006).

Though a wide media variety is available, the selection however normally depends on the requirement of that particular location based on a number of tradeoff factors. With the deeper medium and more organic contents, more planting options are available, but a predominantly organic medium is not recommended for extensive green roofs (Hoffman, 2005). Though it increases fertility, it also introduces a set of potential problems, including decreased pore space, higher water retention, increased nutrient loading and reduced medium depth over time caused by decomposition. One of the most important aspects of medium is that the depth should be relatively constant over a long period of time, and a highly organic medium makes this impossible.

2.1.3 Drainage layer

The main function of a drainage layer in any green roof is to protect the waterproof membrane (Connelly et al., 2005). It removes excess water or underflow as quickly as possible to prevent over saturation. This drainage layer expels the surplus water on the roof. In some cases, the drainage layer also provides extra storage as the means of irrigating the green roof and providing additional nutrients for the plants grown (Evaluation of green roof, 2007). Snodgrass et al. (2006) also recommend that an efficient drainage is needed to avoid water ponding that could diminish sufficient oxygen for root systems, ultimately leading to root diseases.

The drainage layer must be provided with evaporation holes and they can be made from drainage free materials such as gravel or plastic layers. The commonly available types are granular materials and porous mats. Coarse granular materials include gravel, stone chips, broken clay tiles, clinker, pumice, expanded shale, or expanded clay granules with large amounts of air or pores between them.

Other most common drainage components include Ethylene Propylene Diene Monomer (EPDM) membrane, granular drainage and a low profile perforated conduit, Soprema, Poly Vinyl Chloride (PVC) membrane, light weight gravel drainage medium, rubberized asphalt membrane, geo-textile filter fabric drain, modified bitumen membrane, perforated recycled plastic container drainage and nylon mesh drainage layer (Hoffman, 2005).

2.2 Stormwater quantity performance

There have been a lot of studies conducted in Europe especially in Germany on green roofs for their performance in a number of areas, while this concept in North America is at a very young stage and research is not extensively published (Corrie, 2008; Kohler, 2004). Because of this a very little data exists on the environmental benefits from the implementation of this technology in the region.

Vanwoert (2004) calculates stormwater retention and water use by extensive green roofs. In his work, variables such as roof surfaces, slopes and media depths are used to compare the stormwater retention capacities. Comparison is also made among extensive vegetated roof, extensive non vegetated roof and a gravel media roof. For a period of more than a year, the vegetated roof results retention of 60 percent of cumulative rainfall whereas the media only roof and the gravel roof retain 50 and 27 percent, respectively. He concludes that the two factors that play major role in retention are rainfall intensity and duration of any rainfall. In slope-media thickness variable the most efficient combination for retention comes out to be 4 cm thick green roof with 6.5 percent slope. This study therefore does not support an initial hypothesis of offsetting media slope by depth for more retention. Figure 2.1 shows the corresponding rainfall retention percentage for light, medium and heavy rainfalls.

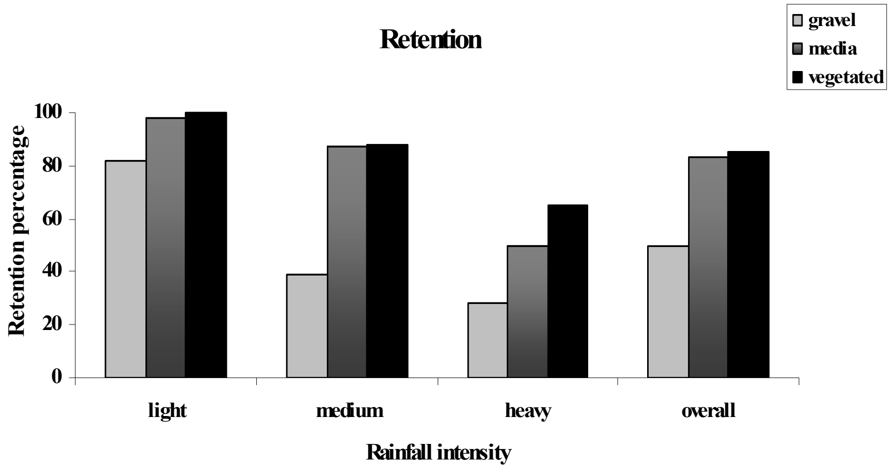

Figure 2- 2: Stormwater retention in percentage by green roof for different rain event (Vanwoert, 2005).

In green roofs with two media depths of 102 and 51 mm, Moran (2002**)** evaluates runoff quantity and plant growth to compare them with a control roof. In dry months, the retention efficiency reached more than 90 percent relative to 60 percent in other seasons. The maximum achieved peak flow reduction is slightly less than 80 percent. Even in this study the depths of green roof media did not play any significant role in stormwater retention and on the values of rational coefficients.

Getter (2006) tries to select the most suitable plant species and makes an observation for the effect of slopes on green roof. Runoff is analyzed from twelve different green roof platforms with varying slopes of 2, 7, 15 and 25 percent. The green roofs retain on average about 80 percent of precipitation. Mean retention is 75 percent for 25 percent slope and 85 percent for 2 percent slope. Getter thus confirms that there is an inverse relationship between retention capacities of green roof with its slope.

Cunningham (2001) evaluates the potential benefits of green roofs on stormwater runoff in the cold climate of Manitoba. Though the plant survival rate in an extremely cold region is very difficult (Wolf, 2008), his research however demonstrates the applicability of green roofs in such harsh climate. Cunningham uses Rational Formula for stormwater runoff estimation taking probability curves (5, 20 and 50 year) for north central United States (TR-55, 1986). The study shows that green roofs achieve a 35 percent reduction in stormwater against existing conditions whereas with the pre-development conditions this value is about 15 percent.

In an establishment believed to be the first of its kind in Canada, Bass (2001) assesses the application of green roof benefits in a local context. A rainfall-runoff modeling with Horton model for infiltration is applied to evaluate the retaining capacity of green roof by simulating two cases for light and hurricane type extreme condition with different soil depth, field capacity and initial moisture condition on the green roof. Both cases confirm that green roof with an appropriate depth of soil plays a role in peak flow attenuation.

In a Southern Illinois University research on evaluation of storm water runoff from a Midwest green roof system, Forrester et al. (2006) determine the depth of substrate for maximum water management. They use different depths such as 5, 10, 15, and 20 cm of growth media with plants. For each independent precipitation it is observed that green roof models with and without plants retain more storm water than the control roofs. The models with and without plants retain almost the same quantity of storm water.

The works discussed so far deal mostly the comprehensive performance of green roof rather than the role of an individual component. Berghage et al. (2007) appraise the relative contribution of media and vegetation on stormwater retention. Researchers in this study have observed the evaporation and evapo-transpiration patterns of water from green roof through three different types of plant species. It is observed that the effect of plants is greatest for initial 5 days after a rainfall event. In these initial days the plants double the media's rate of moisture holding capacity.

The designers (Project Report, 2006) for a green roof project in the University of Iowa building have done water budget calculation using principles of mass balance to estimate the retention capacity of media in different rainfall events. They use two media depths as 2.5 and 5 cm. Figure 2.2 shows that for the same rainfall event the retention level of thicker green roof is higher than that of thinner green roof indicating direct relationship between retention performance and thickness.

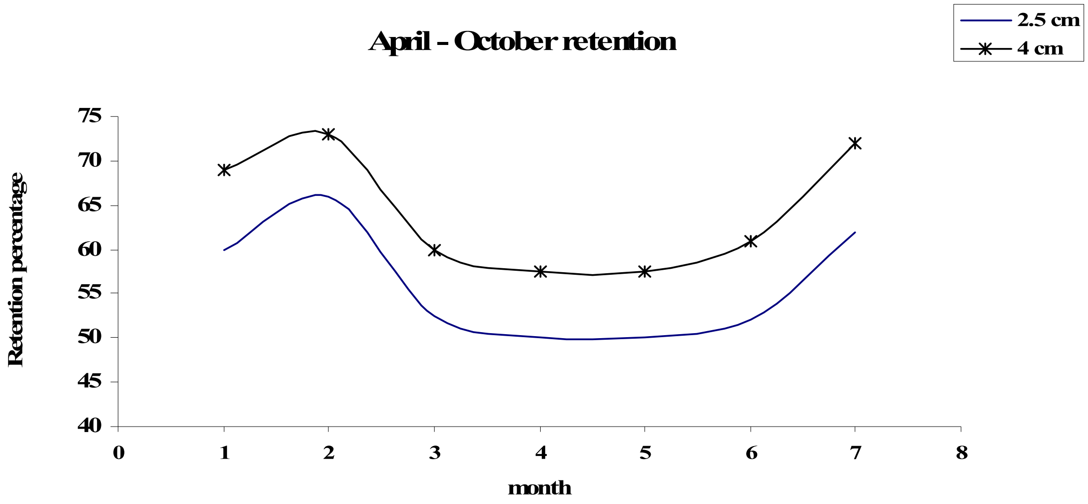

Figure 2- 3: Average percent retention of rainfall (1962-1982)

(Project Report, 2006)

Vanwoert et al., (2005) evaluated the performance of green roofs with different combination of slope, roof surface and media depth to determine the optimal combination for retention performance. They try to find an optimal combination for the best retaining performance. In a number of combinations used, the best performance is achieved by 2 percent green roof slope with 4 cm media depth. For a total of 83 rainfall events collected in 14 month period this combination shows 60 percent retention. This study also indicated that though media thickness and slope are major parameters for retention performance, the best result depends on the intensity and duration of rainfall and initial moisture conditions. Figure 2.3 summarizes their study.

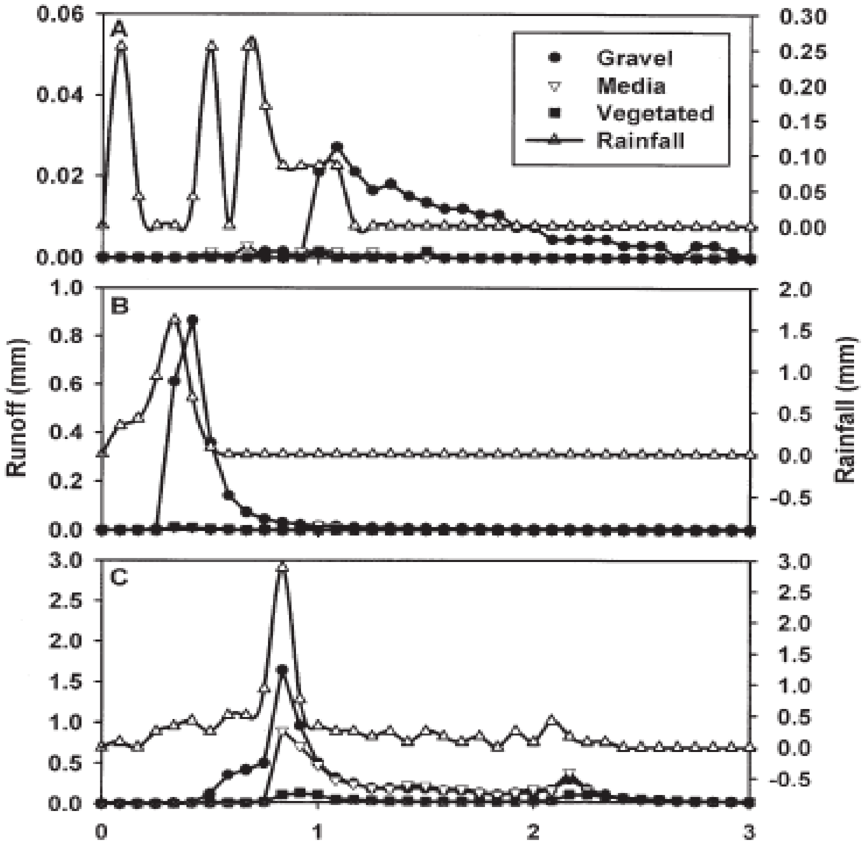

Figure 2- 4: Runoff hydrographs from different sized rainfall events

(Source: Vanwoert et. al., 2006)

Carter and Rasmussen (2006) tried to determine a relation between rainfall size and retention capacity. With the monitoring data, they found an inverse relationship between the rainfall depth and retention percentage. Their study however does not consider any antecedent moisture presence for retention performance estimation.

Hutchinson et al. (2003) found that to achieve the maximum retention, the vegetative coverage should be at least 70 percent of total roof area for any storm event. Banting et al. (2005), while doing cost benefit analysis of green roof's application at municipal level for Toronto, report that there will be a significant level of stormwater flow reduction by extending green roof facility in the existing traditional roofs. This flow reduction will range from 16 to 100 percent depending on the size of rainfall and climatic condition. Shown in the Table 2.2, MacMillan (2004) in Toronto compares the performance of green roof with a traditional control roof on stormwater reduction. He finds that a green roof works better in the spring/summer months than in the fall because of amount of rainfall.

Table 2- 2: Average monthly runoff lag time and coefficient

Year 2003		**Average Runoff lag (min)**		**Average Runoff Coefficient**	
Month	**Total Rainfall (mm)**	**Control**	**Green**	**Control**	**Green**
May	121.8	3.4	88.7	0.8	0.2
June	87.8	4.5	16.5	1	0.1
July	44.2	4	10.8	0.8	0
August	62.6	1.4	4.3	0.9	0.1
September	143.6	1	3	1	0.6
October	55	-2.6	29.6	1	0.8
November	148.8	3.4	17.5	1.2	1

With the results observed it can be concluded that green roof performs better than any traditional roof of the same size on stormwater retaining performance. However, only some of the reviewed works have reported the retention performance values. They are given in the Table 2.3. It is seen that for the varying media depths from 3 to 10 centimeters, the retention ranges from 0.5 to 4 centimeters. It shows that an extensive green roof with 8 to 10 centimeters of media depth will store 2.5 centimeters of rain in average.

Table 2- 3: Summary of green roof stormwater storage

Characteristics	Media	Stormwater	Reference
	cm	cm	
Pre-fabricated sedum vegetated substrate reinforced with polyethylene webbing.	3	1	Berndtsson et. al., 2006
Sedum planted commercial green roof from Gerick Corp., Ohio.	8	3	Berghage et. al., 2007
Characteristics not mentioned.	10	2	Hoffman, 2006
	15	3	
Sedum vegetated commercial green roof.	8	0.75	DeNardo et. al., 2003
	8	0.5	
Commercial green roof, supplier not given.	8	2.5	Federal Energy Management, 2004
	10	2.5	
Pre-fabricated sedum vegetated extensive green roof.	10	2.5	Green Grid Roofs, <www.greenroofs.com>
Sedum grown commercial green roof.	10	4	Jarrett et. al., 2005
Lightweight growing medium supporting a variety of vegetation.	8	1.5	Liu et. al., 2005
Flat roof with Perma Till Lightweight Roof Garden Soil Mix with a variety of sedum.	8	1.5	Moran et. al., 2005
	10	2	
Flat roof with Perma Till Lightweight Roof Garden Soil Mix with a variety of sedum plants.	5	1.5	Moran et. al., 2004
Theoretical perspective.	8	2.5	Miller, 2000
A composite mixture of heat expanded slate, graded sand, Michigan Pit, Dolomite and compost product.	4	0.75	Van Woert, 2005
	5.5	1	
	8	1.5	
Media composition is crushed limestone, crushed brick, sand, clay and organic	4	0.75	Villarreal et. al., 2006

2.2.1 Green roof modeling

Green roof stormwater research includes both model simulations and experimental measurement with full- and pilot scale installations. When the runoff is measured experimentally, it is expected that the combined effect of most of the *in situ* variables is included in the results. Different from these experimental works, some other researchers use either the existing hydraulic-hydrologic models to calculate the runoff or develop models from the experimental data recorded. These developed models after calibration are then used to simulate the runoffs from the storms.

With increasing demand of green roofs' application for stormwater management, it is always essential to have reliable and valid methods for predicting green roof's performance to accommodate a wide range of design approaches and geographical location. It is not feasible every time in every location to go for an experimental measurement to decide on the possible factors. Runoff simulation for any storm event by a logical model is thus one of the convenient approaches for the purpose of determining the performance. Some of the complex models used take into accounts most of the possible variables during simulation but the others are rather simple which may or may not consider these parameters.

It is well understood that the condition in artificially created green roof is different from the actual physical processes involved in any natural watershed; the commonly used SCS unit hydrograph technique in most of the models is thus not well suited for predicting runoff from green roofs (Miller, 2000). There are however a number of modified hydrologic models to predict runoff using historical precipitation and evapo-transpiration data. These models which are so far successful in predicting the hydraulic properties of green roofs are basically in four forms- empirical models, physical models, analytical models and water balance models.

Empirical models though able to make reliable runoff estimation, need analogies between the green roof system and climatic conditions with intended design. Physical models, on the other hand are capable to predict pattern of two-dimensional seepage flow through the green roof. The main problem with this model is its complexity. One-dimensional approach treats runoff from a multi-layered green roof as a cascade from a combination of linear storage elements (Zimmer et al, 1997). This model considering each soil layer as a separate storage element assumes that the flow from each soil layer is proportional to the amount of water stored in that layer.

A reservoir model is the simplest model and treats a green roof system like a simple reservoir and uses a time stepping analysis to account for additions and losses from the system (Miller, 2000). It is based on the principle that no runoff will take place until the water storage capacity of the green roof is exceeded. When the storage capacity is reached, green roof runoff will take place and will imitate the rainfall flow. Hardin (2006) indicates most of the mass balance models are represented by complex equations and they need a large number of variables for a solution. As they are data intensive, these models may not be equally and efficiently applicable in most of the simple green roof situations for different locations.

Robertson (2007) uses the TR-55 model to estimate the existing runoff for different rainfall events. For a given set-up he considers an inventory of the possible and practical areas for green roof. Applying this model in an area with appropriate green roof coverage and an average CN=82, he finds 29 percent reduction in runoff depth compared to existing conditions. The model estimates that even by replacing only eligible traditional rooftops with green roofs, there is a one-third stormwater runoff reduction for a 2-year storm.

Mike Urban hydrological model (Green build-out model, 2007) can be applied for modeling the stormwater management of green roof in any area after adding green roof component to the original model. Application of this model in District of Columbia shows that media storage fluctuates greatly depending on the initial moisture condition and slopes of green roof.

Prowell (2006) tries to estimate the retention performance of modular green roof by using a simple reservoir equation. In this study the maximum field capacity of modular green roof is experimentally measured and the value is used for model calibration. The assumption here is also same as mentioned earlier, for any runoff to occur, the volume of incoming water should always be more than the maximum storage capacity of the media. Only those events with sizes more than storage capacity and capable to produce runoff have been considered for simulation.

Prowell uses a simple reservoir model with input parameters such as potential and actual evapo-transpiration, water holding capacity and soil moistures of the media. The model is found to perform adequately during simulations. This model is capable enough to reasonably predict runoff quantity and timing and takes care of just monthly runoff rates and on the whole monthly runoff volume without giving any consideration for peak reduction. Peak flow simulations using this simplified method cannot be construed as an accurate representation.

Storm Green Roof Response (SGRR) model developed by Jarrett et al., (2005) uses inputs from storm hyetograph and daily ET to understand how a green roof will respond to a specific rain event. The model considered as a routing model is applied to several synthetic storms with 2, 25 and 100-year return period for a designed area at central Pennsylvania. The study shows that the peak runoff rate for all these storms due to green roof intervention comes to a size comparable to an undeveloped parcel of the same size.

In addition to estimating the total runoff volumes this study also calculates decrease in peak flow sizes.

Hardin (2008) deals with an extensive green roof in a completely different way. He uses a case of an irrigated extensive green roof stormwater treatment system. From a water budget experiment and a complex mass balance equation, he develops a continuous stormwater treatment outflow reduction (CSTORM) model and applies this model in design of green roofs in different locations of Florida. With the major inputs as precipitation, irrigation, makeup water and outflow rate the model shows that the efficiency of the system would depend on total precipitation and total outflow. This model can predict the quantity of yearly retention and yearly makeup water requirement for irrigation. It however does not consider the effects of green roof on peak sizes, the most essential factor for any stormwater management project.

Hilten et al. (2006) use Hydrus -1D model to simulate the performance of a modular green roof with the simulation results being verified by the site measured data. The roof's performance is based on inputs like evapo-transpiration, antecedent moisture conditions and a number of other soil hydraulic properties. The model is actually utilized to simulate runoffs for a number of design storms up to 24- hour, 1-year size equal to 7.9 cm. The model does not include other higher values like 2 or 5- year design storms normally considered for a stormwater management program in its simulation exercise. The model is tested for only smaller events and it does not say anything on the performance for its application to larger and extreme sized events. It also requires cumbersome laboratory experiments to determine the model associated with the particular soil type, thereby limiting its applicability for other locations different from the one where tested.

2.2.2 Summary of stormwater management performance

On the basis of the literatures reviewed in this chapter it can be concluded that majority of the works are experiment-based. The runoff values used to calculate the retention and detention performance of green roofs in such establishments are measured experimentally. The physical variables normally considered are slope, depth of the media, installation techniques and selection of plants. The most common climatic variables chosen are initial moisture condition, evapo-transpiration and temperature. The retention and detention performance always vary with location and the number and accuracy of the parameters chosen. Performance of a green roof is totally exclusive and the results from one setting cannot be generalized for another.

Experimental measurement of green roof performance is not feasible every time. A number of models are therefore being used to predict the hydraulic performance of green roof. The models in most of the situations consider a green roof as a natural watershed even though it is artificially built. These models however predict runoffs reasonably comparable to the measured, mostly depending on the precision and number of parameters chosen.

Application of model for runoff calibration and simulation normally includes a long-time precipitation data, evaporation, evapo-transpiration, and antecedent moisture condition of the media. It also needs long term data on other climatic parameters such as temperature, solar radiation and humidity. Most of the models available are therefore data intensive and normally involve heavy resources, both in terms of time and money in their application. To have those data for an isolated and individual location especially to individual household level may not always be viable. These complex models therefore have limited application. In addition, most of these models mainly take care of green roof's performance in volume terms estimating monthly or annual retention. They do not evaluate the green roof's performance on peak sizes, the most essential factor for any stormwater management program.

It is thus essential to have a simple green roof model that can be applied for independent specific rainfall events for any location using minimum number of essential variables involved. This study therefore aims to calibrate and develop a simple green roof mass balance model with only three basic parameters as rainfall, runoff and storage capacity of any green roof. The model once tested for a number of monitoring storms events on LTU's green roof (Hydrotech Garden Roof) is finally used for simulating peak sizes and runoffs from a number of 24-hour 2, 5, 10, 25, 50 and 100-years design storms in the region.

CHAPTER III: Calibration and Verification of Model

3.1 Formulation of green roof model

Most stormwater management programs have the following major objectives; peak flow reduction, reduction of runoff volume and pollutant removal and pollutant source reductions. LTU's green roof which is established as a stormwater BMP is not an exception. Among these objectives, the performance of any stormwater management practice is mainly judged by its effectiveness on peak flow reduction for a given storm event. Different from other data intensive models reviewed earlier, this study is focused to develop and calibrate a simple mass balance green roof model and use this model to simulate the runoff peak flows for different storm events.

The cross section of the extensive green roof installed at the Student Services Center of Lawrence Technological University (LTU) is shown in Figure 3.1. In this study, a simple mass balance model based on water budget for this green roof runoff is developed, calibrated, and tested using the monitoring data available for the roof.

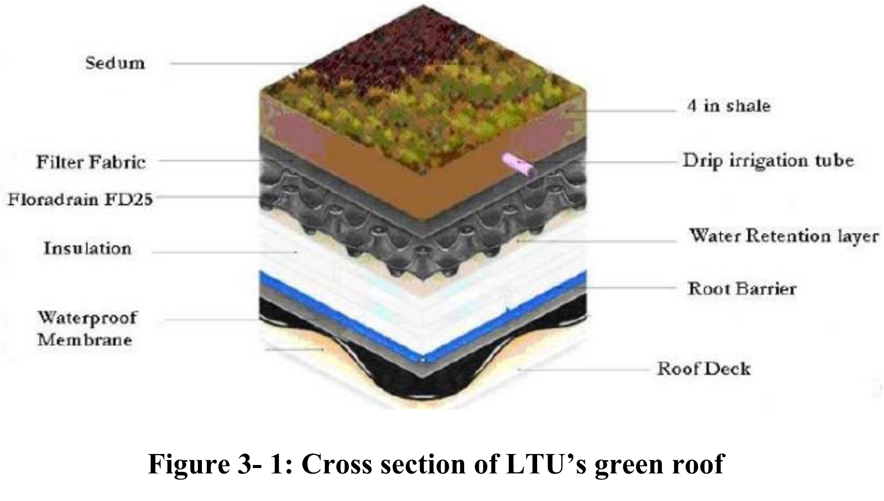

Figure 3- 1: Cross section of LTU's green roof

(Source: Hydrotech USA)

The model being considered in the current study is for simulation of performance of a green roof during a storm event. Uptake, storage, and loss by evapo-transpiration of water in green roof plants during individual storm event are expected to be small and are therefore ignored. Hence, only the green roof system is assumed to be available for water storage. The green roof considered for this study is in its third growing season and, by design it does not need or receive any external supply of water for irrigation. Accordingly, there is no external input of water by irrigation except rainfall. After exclusion of these parameters, the control volume representing the green roof and used for formulation and calibration of model is shown in Figure 3.2.

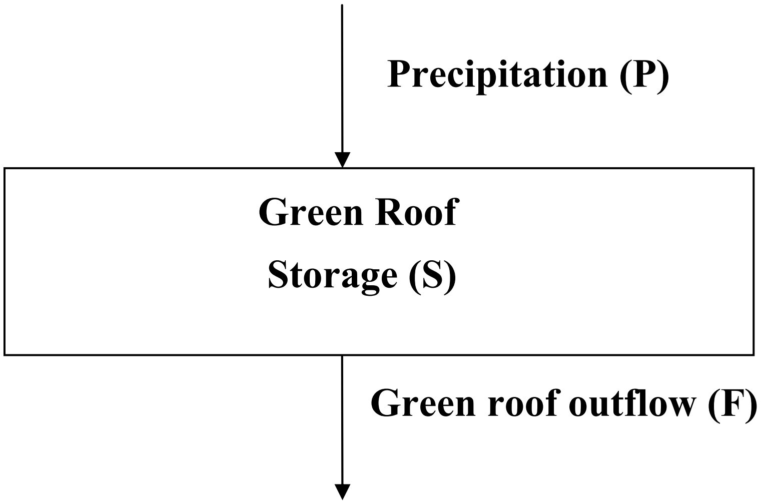

Figure 3- 2: Control volume for simple green roof mass balance model

For the model in Figure 3.2, it is assumed that from the beginning of a storm, the entire precipitation (P) is retained by the green roof media till it reaches to its maximum saturation capacity (S). Once the media reaches saturation, the green roof runoff (outflow) is initiated and is assumed to equal the amount of precipitation (P). Mathematically, this can be represented as follows:

For MS < S

$$\frac{dMS}{dt} = P \qquad (1)$$

Where *dMS* = change in media storage

MS = media storage

S = field or saturation capacity of the media

P = precipitation in volumetric terms

For MS ≥ S

$$F = P \qquad (2)$$

Where *F* = green roof runoff or outflow in volumetric terms.

As such, the overall system's input is the precipitation only and the output is filtrate or runoff from the green roof. Since other parameters are ignored, the system storage in fact accounts for the difference in only the inflow (precipitation) and outflow (runoff) values. Finally, this mathematically represented simple mass balance model is set up in an Excel Spreadsheet to estimate the green roof runoff and corresponding rates of peak discharges from the respective precipitation as inflows. The established setup can be found in Appendix 3-1.

The complexity of the flow through the porous media of the green roof is expected to affect the nature of the green roof runoff. To simulate this effect in the simple model being considered, a moving point average for the runoff over a time period of 30 minutes is considered.

3.2 Rainfall data

Although the actual total area of roof is 943 m^2, the portion instrumented for the research has an area of 325 m^2. Rainfall data on this area is collected from April to September 2008. To collect the rainfall data the following equipments are used. The calculation is then done for a normalized area of 1000 m^2 so as to make this study more convenient for application and comparison with other roofs.

3.3 Monitoring equipment

4 inches Palmer-Bowlus Flumes

Three Palmer-Bowlus flumes of 4 inch diameter are inserted into existing roof drains. When runoff from the roof reaches a certain level in the flume, water is drawn from the flume into the Avalanche Sampler through tubing. Another pipe connects the flume to a bubbler flowmeter, which is inserted on the side of Avalanche Sampler and measures water pressure which is correlated to discharge.

The runoff discharges are calculated on the basis of water level readings in the flumes with the following formula:

$$Q = 1.68 \times H^{1.9}$$

Where Q = Flow in ft^3/s

H = Level reading in flume (ft).

Figure 3- 3: Palmer-Bowlus flume at green roof

730 Bubbler Flowmeter

A 730 Bubbler Flowmeter from Teledyne Isco is connected to the flume through tubing which measures the level of the runoff in the flume based on the pressure necessary to release a bubble air. When a pre-set level is reached (based on discharge), the water is drawn into the Avalanche Sampler. A bubbler flow meter measures the pressure needed to force air bubbles out of the line.

Figure 3- 4: Isco 730 Bubbler Flowmeter

Avalanche Refrigerated Sampler

Avalanche Samplers from Teledyne Isco are installed at the sites. The samplers are enabled to run when the water level in the adjacent flume is equal to more than 0.005 feet. When the water in the flume reaches this level, the sampler is initiated and water is drawn and collected in the samplers in the 14 bottles at a time pace of every 15 minutes. The roof uses the 0.1 inch Teledyne Isco Tipping Bucket Raingauge, which is connected to the sampler and thus the rainfall data is recorded for every 5 minutes. After a storm event, the data is downloaded from the sampler using the Teledyne Isco Flowlink software, which has a USB that connects computer system to the sampler.

Figure 3- 5: Avalanche Sampler

Isco 674 Tipping Bucket Raingauge

An Isco 674 Tipping Bucket Rain gauge has been installed on the roof of boiler room acting as the control roof. The rain gauge connects directly to Avalanche Sampler and uses a tipping bucket for rainfall measurement. It consists of an 8-inch diameter orifice which is factory-calibrated to tip at either 0.01 inch or 0.1 mm of rainfall.

Figure 3- 6: Isco Tipping Bucket Raingauge

Twenty one rainfall events in total were observed during a period of April to September 2008. A measurable runoff for the green roof is generated only for the events with cumulative depth of 1.65 cm or higher. Seven such rainfalls with depth ≥ 1.65 cm have been considered for model calibration and simulations. Out of the other fourteen events with size less than 1.65 cm with no runoff, only seven events whose details were received has been taken for further study. The rainfall data of such fourteen events considered is given in Table 3-1.

Table 3- 1: Rainfall Data

S. No.	Event date	Cumulative Rainfall	
		(in)	(cm)
1	Sept 13	2.94	7.46
2	Sept 14	1.3	3.3
3	July 2	1.27	3.22
4	June 28	0.89	2.26
5	June 10	0.7	1.78
6	May 30	0.69	1.75
7	June 7	0.65	1.65
8	July 16	0.55	1.39
9	July 12	0.55	1.39
10	June 25	0.51	1.29
11	April 10	0.3	0.76
12	April 12	0.2	0.51
13	April 25	0.18	0.45
14	June 23	0.16	0.40

3.4 Calibration of green roof model

The field or saturation capacity (S) for the media may not be easily measured or calculated, and is determined by model calibration. As said earlier, only for events with cumulative rainfall of 1.65 cm or higher, a measurable runoff for the green roof is generated. From Table 3-1, one such event on June 7 is thus selected for model calibration.

For regions that are not arid or dry, the green roof media is expected to have some of its storage capacity occupied by initial moisture content at the beginning of a storm event. The initial moisture content would depend on the climatic conditions, typical rainfall pattern as well as the proximity of the storm event immediately preceding the one being considered. In a previous study, Hilten et al (2006) used actual measured values for their model simulations. Measured values for initial moisture content in the green roof however are not available in the current study. In this case the soil is therefore assumed to be of normal soil moisture conditions (Sorrell, 2008) referred to as Antecedent Moisture Condition II (AMC II) for model testing and simulations.

Several trial values for media saturation capacity are tested at increments of 0.05 cm. This capacity is expressed in terms of cumulative rainfall depth retained by the media to reach saturation. The simulated green roof's outflow rates with the corresponding June 7 rainfall for media saturation capacities of 1.45, 1.5 and 1.55 cm are presented in Figure 3.7. The details of a sample calculation are presented in Appendix 3-2.

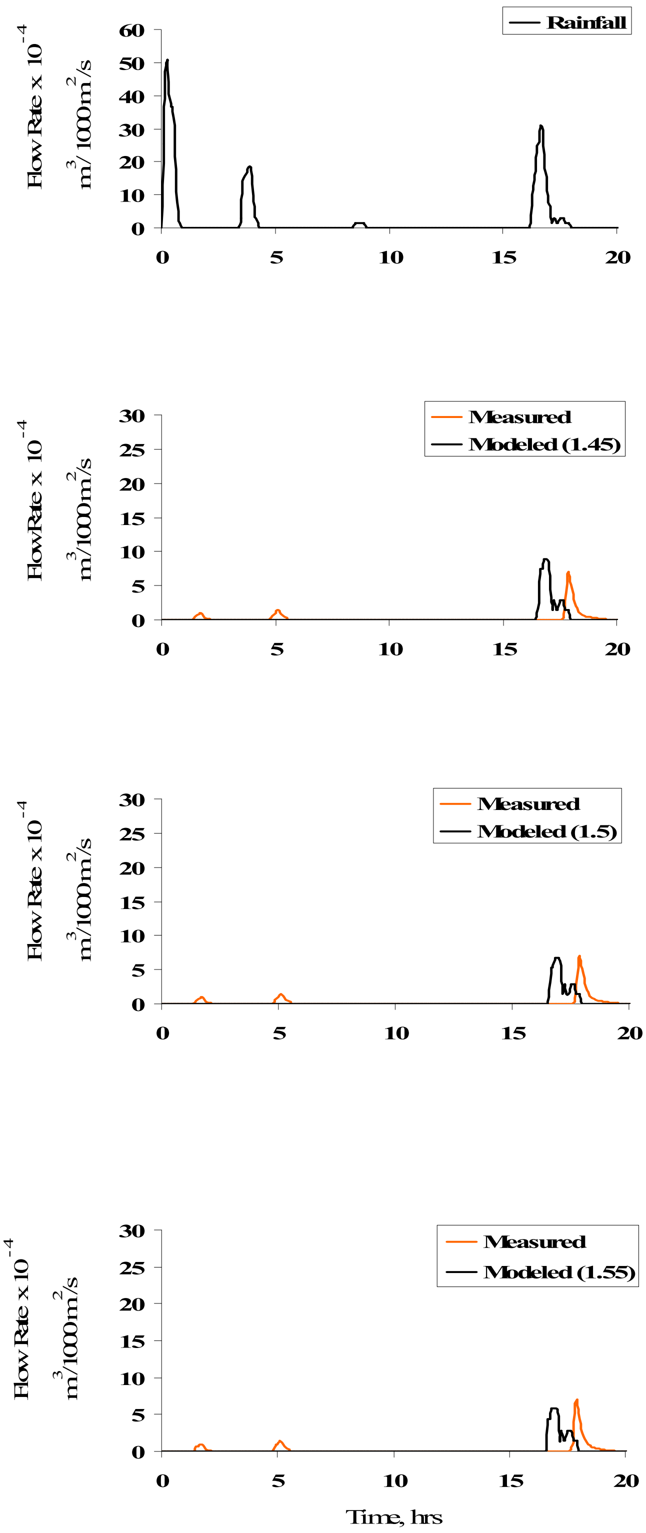

Figure 3- 7: Rainfall, measured and model roof outflow rates for June 7 event

Same green roof simulations have been carried out, but for clarity the three different saturation levels of 1.45, 1.5 and 1.55 cm are respectively represented as Model (1.45) Model (1.5) and Model (1.55) in the hydrographs. From the results, the best agreement between measured and predicted peak flows is obtained for available media storage capacity of 1.5 cm (Model (1.5)). This actually translates to a total available storage volume of 15 m^3 per 1000 m^2 green roof area for normal soil moisture conditions.

The calibrated value of the media storage capacity for this 10 cm deep extensive green roof at LTU is compared against other literature based green roofs with same depth (see Table 3.2). The result here shows that its available 1.5 cm storage capacity is 25 to 40 % lower than 2 to 2.5 cm capacity of other green roofs reviewed. This variation may be due to the differences in the nature of the support medium used in the LTU green roof and also due to difference in residual soil moisture.

Table 3- 2: Stormwater storage capacities for 10 cm deep extensive green roof

Characteristics	**Stormwater storage, cm**	**Reference**
Characteristics not mentioned.	2	Hoffman, 2006
Commercial green roof, supplier not given.	2.5	Federal Energy Management Program, 2004
Pre-fabricated sedum based extensive green roof.	2.5	Green Grid Roofs, <www.greenroofs.com>
Sedum grown commercial green roof.	4	Jarrett et. al., 2006
Flat roof with Perma Till Lightweight Roof Garden Soil Mix with a variety of sedum plants.	2	Moran et. al., 2005
LTU's green roof with shale medium and flora drain	1.5	Present study

3.5 Testing calibrated green roof model

Before applying this calibrated model to predict the runoff responses from a number of design storms (included Chapter 4), it is essential to verify this model and see how it works for other monitoring storm data. From the monitoring data set, one event (June 7th) with size > 1.65 cm was used for model calibration. The other six are considered for testing the model. Each rainfall is routed through the calibrated model and is observed for flow response. Figures 3.8 to 3.10 represent the hydrographs from measured and modeled roof in three cases – June 28, September 13 and September 14 rainfall events.

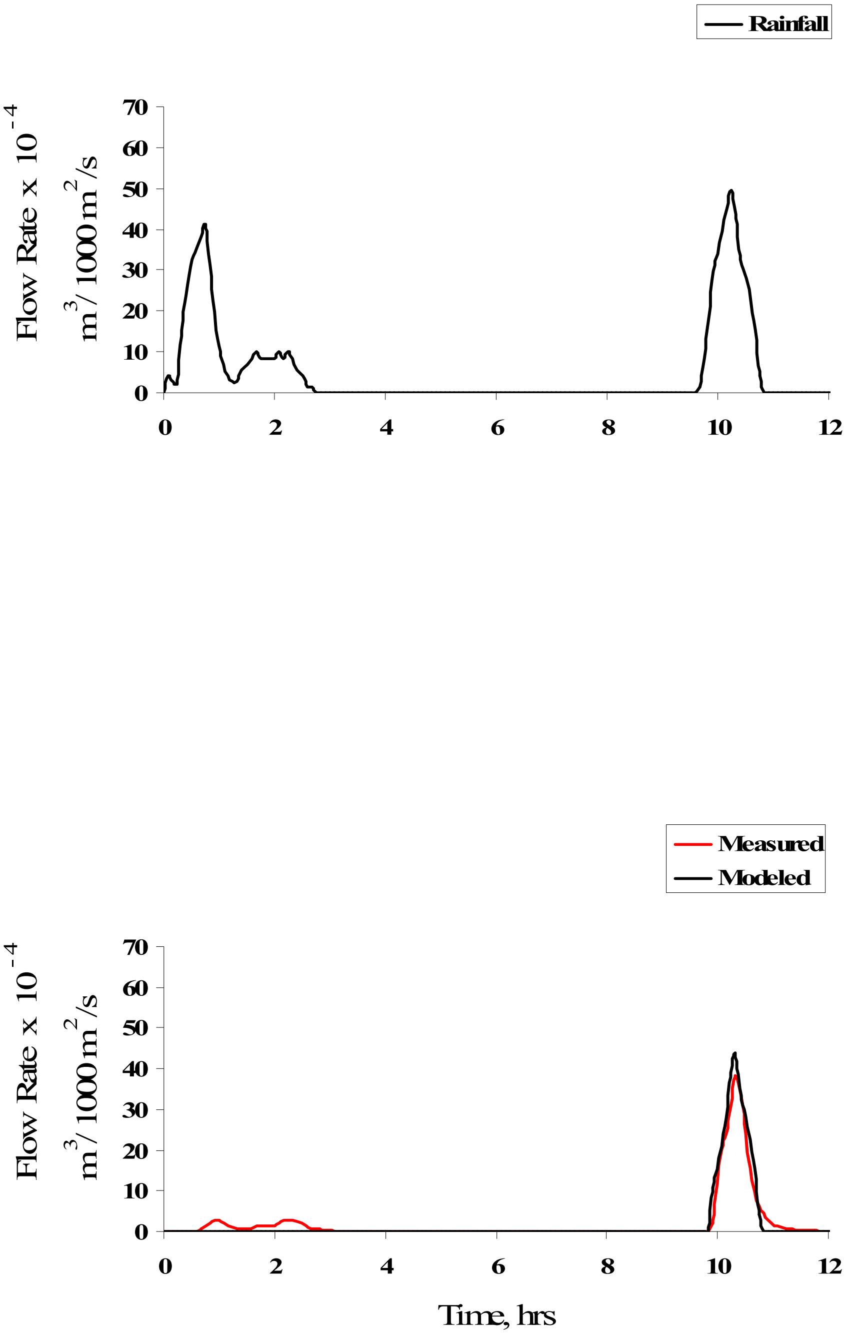

Figure 3- 8: Rainfall, measured and model outflow rates for June 28 event

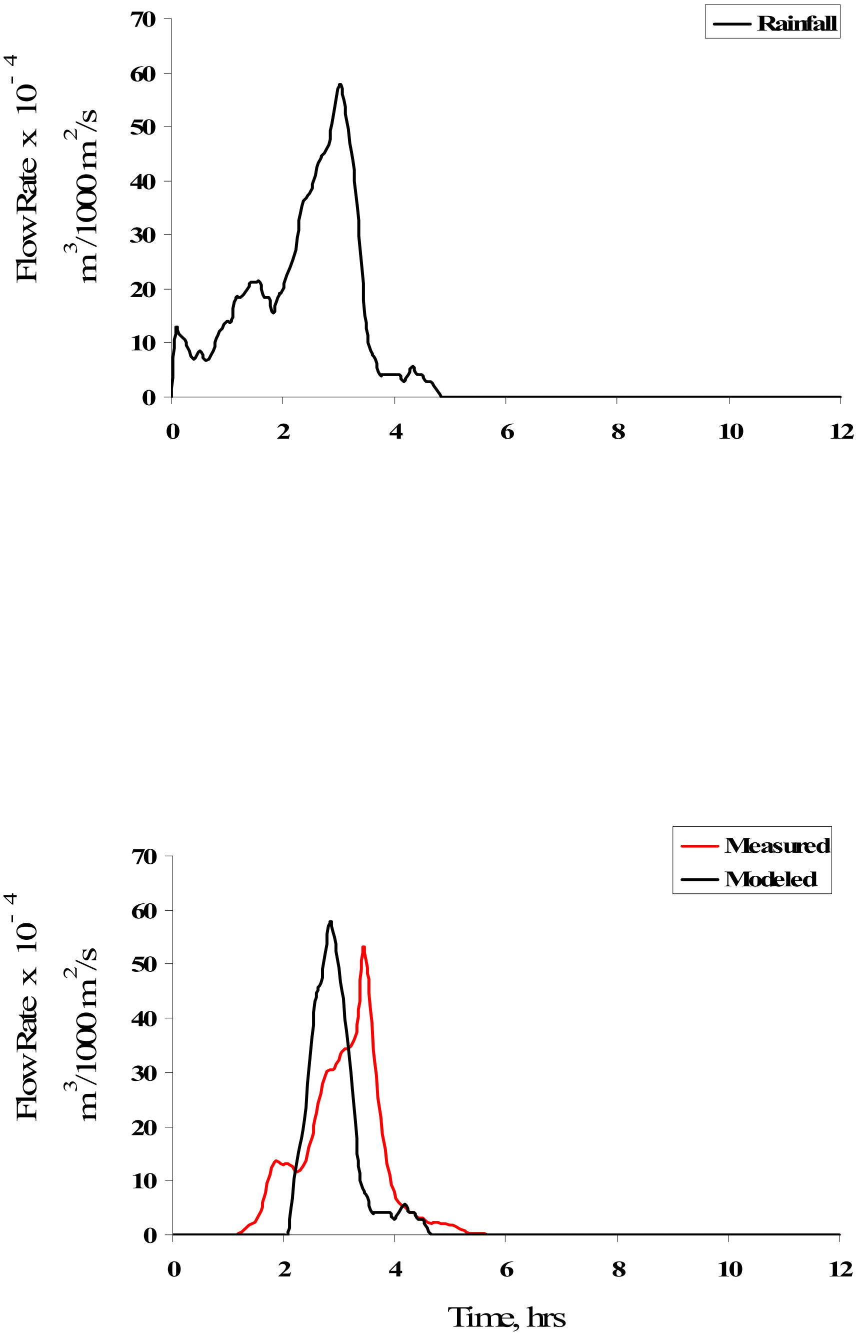

Figure 3- 9: Rainfall, measured and model outflow rates for September 14 event

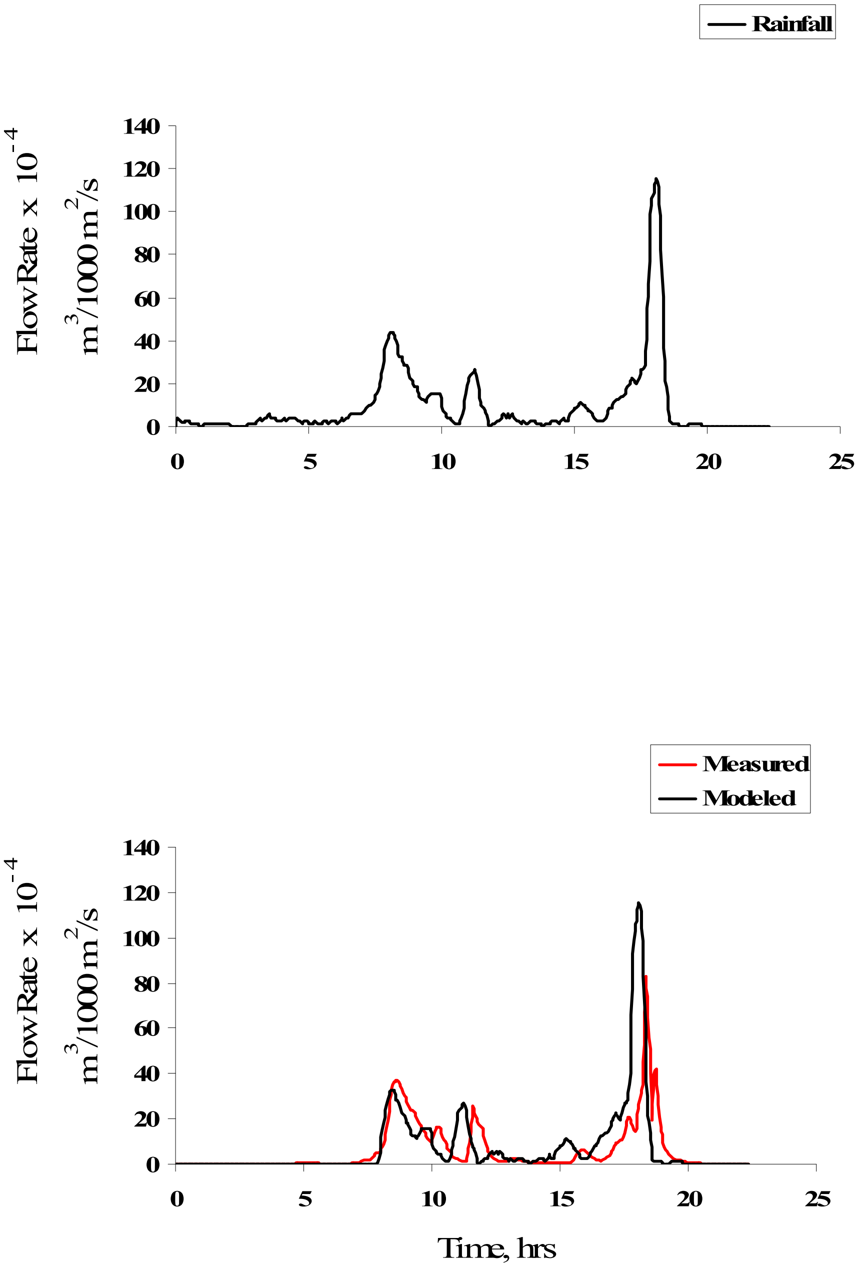

Figure 3- 10: Rainfall, measured and model outflow rates for September 13 event

Since the resulting hydrographs in three events of June 28, September 14 and September 13 appear to match very closely with the measured ones, they have been placed in one group for comparison.

Total rainfall on June 28 is distributed uniformly in two durations, initially in second hour and then at tenth hour. Model roof does not have any runoff for the initial segment of rainfall but measured roof has tiny negligible peaks. However, the modeled runoff closely fits with the measured value. Although the green roof can be expected to have a reasonable level of initial moisture due to earlier rainfalls, the close fittings between the modeled and measured hydrographs indicate that initial moisture level in both the roofs is very close. As represented in Figure 3.8, both measured and model peaks occur at the same time after 10.33 hours from the start of rainfall. The peaks are almost of the same size, with model peak being slightly greater than measured ones by a factor of 1.1. For the rainfall of September 14, the modeled peak (see figure 3.9) is bigger by the same factor of 1.1 from the measured peak. The timing of peaks is however different, the model peak occurs earlier than the measured one even though measured runoff starts immediately after the rainfall whereas the model runoff takes sometimes to occur. This shows that the green roof is already saturated due to rainfall on September 13 and the measured runoff takes place instantaneously once the rainfall occurs.

Another event which generates very identical runoffs and corresponding hydrographs in both the modeled and measured cases is September 13 rainfall. This has the highest rainfall measured in the whole monitoring period. Figure 3.10 shows that both runoffs exactly follow the rainfall pattern with a single maximum and two other smaller peaks depending on the rainfall intensity for different time steps. The nature of runoff curves indicates that both have almost similar initial moisture presence. The model peak is 1.4 times bigger and about 15 minutes earlier than the measured. The results in these three separate storms have been given in final Table 3.3.

There is continuity of rainfalls on September 13 and 14. Since the gap between these two rainfalls is only a few hours, it is appropriate to combine these events and see the model roof's performance in such a combined situation. As shown by Figure 3.11, the runoff hydrographs of both the modeled and measured flows in this situation are very close to each other.

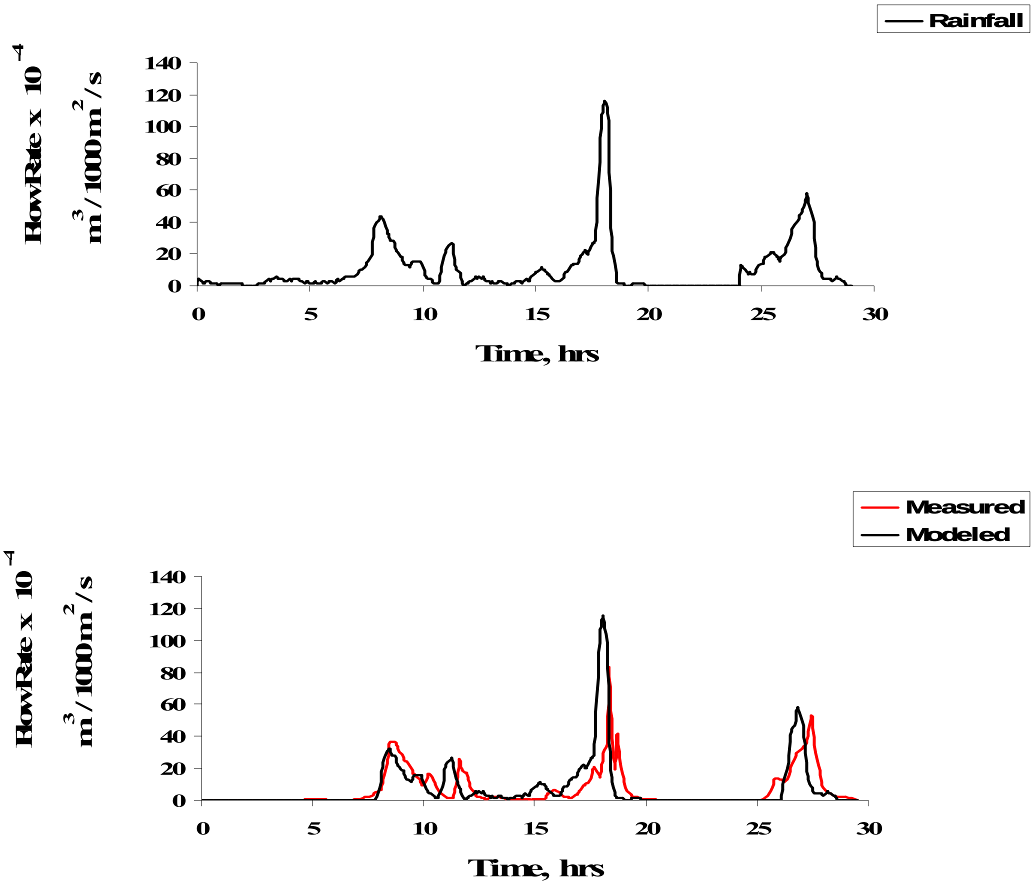

Figure 3- 11: Rainfall, measured and model roof outflow rates for combined September 13 and 14 events

Additionally, runoff simulations for other three remaining larger events of May 30, June 10 and July 2 are also observed. Unlike the earlier events, the shapes of measured and modeled hydrograph in these cases have not followed the similar trends. Hydrographs in Figures 3.12, 3.13 and 3.14 respectively, represent the model and measured outflow rates for these cases.

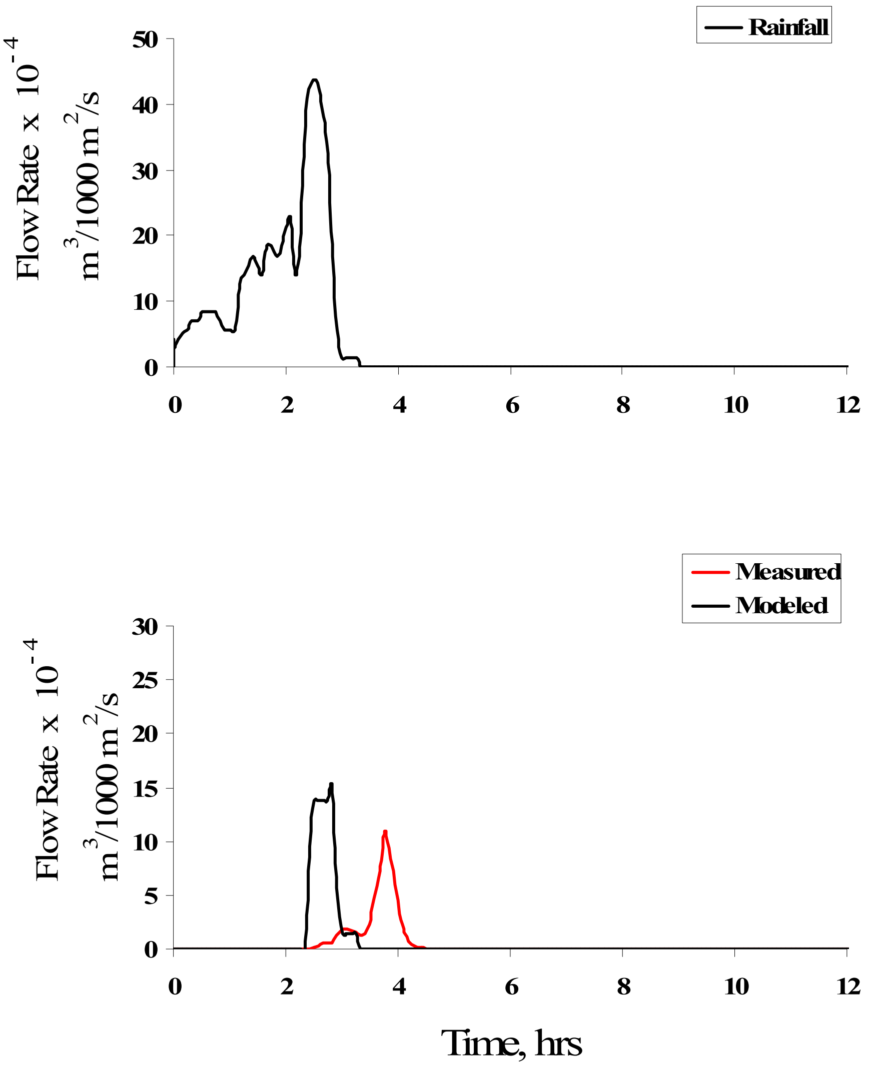

Figure 3- 12: Rainfall, measured and model roof outflow rates for May 30 event

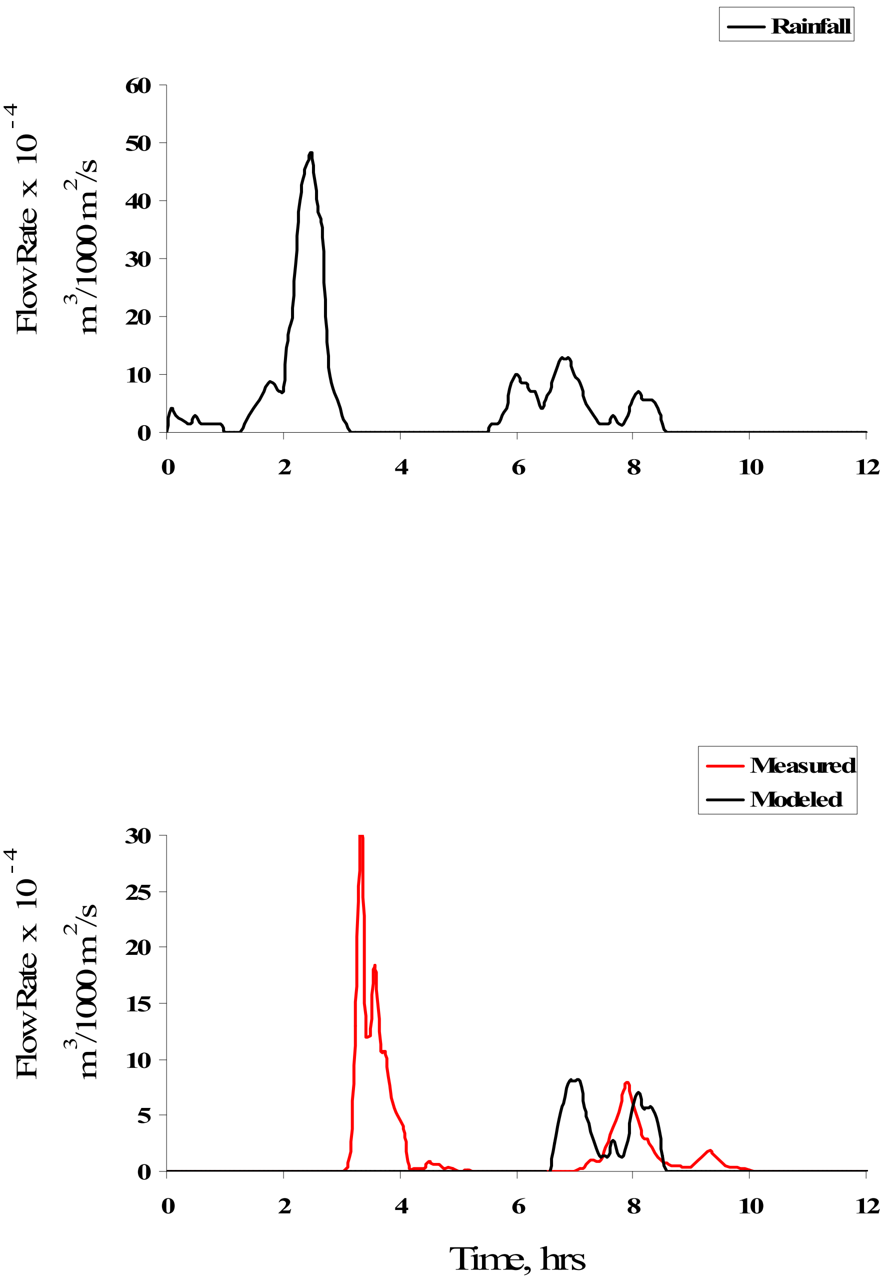

Figure 3- 13: Rainfall, measured and model roof outflow rates for June 10 event

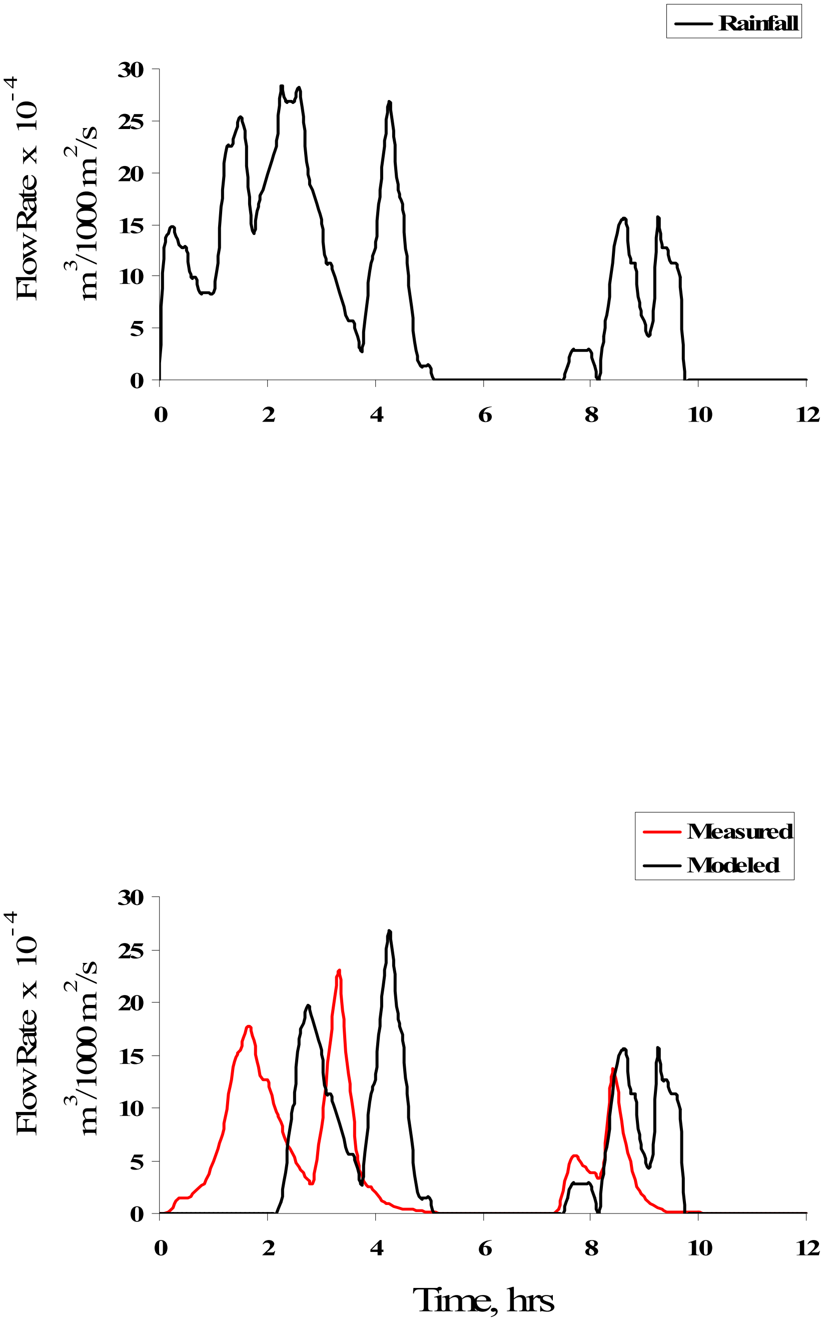

Figure 3- 14: Rainfall, measured and model roof outflow rates for July 2 event

For May 30 rainfall (see Figure 3.12) the model peak is larger and occurs earlier than the measured and this is similar to other three events (June 28, September 13 and September 14) described earlier. The trend of hydrographs however is not identical. Since runoffs in both cases start at the same time, it indicates that both the roofs might have equal initial moisture levels. The model peak here is 1.3 times larger and occurs 50 minutes earlier than the measured peak. For the June 10th event, although the second (smaller) simulated peak is similar to that measured, the first (larger) peak measured is missing in model simulation. This may be due to the actual antecedent moisture condition being wetter than the normal assumed for model simulations due to the significant rainfall event on June 7th.

The nature of runoffs in the case of July 2 rainfall event also does not follow a trend similar to other observations. As seen in Figure 3.14, both the modeled and measured runoffs have three similar peaks at different times depending upon the rainfall patterns. Like other events analyzed earlier in this section, the modeled peaks are greater than measured peaks with an average factor of 1.1 but the measured runoff occurs earlier than the modeled. Possibly, the initial high moisture makes the media saturated, and when there is rainfall the runoff flows instantly.

A comparison of the overall performance by the calibrated model for the larger monitoring storms with size ≥ 1.65 cm against the measured values is summarized in Table 3.3. Comparing the inflow and outflow hydrographs as a common feature, green roof in all cases is seen to retain the initial portion of the rainfall.

Table 3- 3: Rainfall volume, Measured and Modeled Outflow Peaks for the storms with cumulative size ≥ 1.65 cm

Events	Cum. Rainfall	Rainfall vol.	Outflow Volume			Peak flow			Time of peak		
			Msd.	Mod.	Ratio (Mod/ Msd)	Msd.	Mod.	Ratio (Mod/ Msd)	Msd.	Mod.	Diff.
	cm	m^3	m^3	m^3		$m^3/1000m^2/s \times 10^{-4}$	$m^3/1000m^2/s \times 10^{-4}$		hr	hr	hr.
June 7	1.65	16.5	1.4	1.71	1.22	6.9	6.7	0.97	17.91	16.91	1
May 30	1.75	17.5	1.9	2.73	1.6	10.9	15	1.37	3.75	2.83	0.92
June 10	1.78	17.8	6.0	2.9	0.5	31	8	-	3.33	6.91	-
June 28	2.26	22.6	8.2	7.8	0.95	38.3	43.3	1.1	10.33	10.33	0
July 2	3.22	32.2	15	17.4	1.1	22.8	26.8	1.1	3.33	4.25	-
Sep 14	3.3	33	22.2	17.7	0.8	53	58	1.1	3.4	2.8	0.6
Sep 13	7.46	74.6	48.3	60	1.2	83	115	1.4	18.33	18.08	0.25

Notes: Msd. = measured, Mod. = modeled, cum. = cumulative, Diff. = difference

The results in Table 3.3 show that performance of calibrated model to the monitoring storms with size ≥ 1.65 cm for predicting outflow volume and peak flow is in a good range with the measured values. The result for June 10th storm is rather different from other results and it shows a wide deviation from the measured value. Though due to complexity in green roof flow it is very hard to explain this observation, occurrence of an earlier measured peak might be due to presence of initial moisture condition. Whatever the reason, the result of this event is ignored in overall performance study.

Overall, it is seen that the time difference between measured and modeled peaks vary from 0 to 60 minutes, the average calculated as 20 minutes. Due to simplicity of the model, it is difficult to exactly speculate the actual reasons behind this variation in peaks' timing. One of the reasons might be the difference in the initial moisture values in the modeled and the actual green roof in the beginning of any storm event. Despite the fact the average time difference between the modeled and the measured peaks is practically very small.

From Table 3.3, it is seen that except for June 10 rainfall event the modeled peak is larger than corresponding measured peak in all other cases. The difference in sizes of modeled and measured peaks is within a factor of 0.97 to 1.4. The result also shows that after ignoring rainfall of June 10 the modeled outflow volume differs from the corresponding measured values with a factor ranging from 0.8 to 1.6. These resulting values therefore indicate that the simple mass balance model developed in this study predicts both the outflow volume and peak flow for storms within a good range to that of the measured. When this model is used to simulate any typical storm with certain cumulative depth it produces a peak flow within a range of 0.97 to 1.4 times the measured value. In a similar manner, the predicted simulated runoff volumes will be within a factor of 0.8 to 1.6 times to that of the measured values. The model predicted values are always in the higher side. It is therefore to be noted that as the whole process ignores a number of parameters like evapo-transpiration, plant and soil characteristics and other natural variables, model roof is definitely expected to predict larger discharge than the measured.

3.6 Model's prediction for smaller storms with size <1.65 cm

After a number of trials, rainfall on June 7 with cumulative depth of 1.65 cm has been considered for model calibration. This calibrated model is then validated with other rainfalls of size more than 1.65 cm. When this tested model is applied to simulate the runoffs from other monitoring storms smaller than 1.65 cm, no runoff is observed. These storms however have experimentally measured runoffs. Table 3.4 records the inflow and runoff volume of these small storms.

Table 3- 4: Inflow and Outflow volumes from the storms with cumulative size < 1.65 cm

Events	**Cumulative rainfall, cm**	**Inflow, m^3**	**Outflow, m^3**		**Retention, %**	
			Measured	**Modeled**	**Measured**	**Modeled**
July 16	1.39	13.9	0.35	0	97	100
July 12	1.39	13.9	0.07	0	> 99	100
June 25	1.29	12.9	1.26	0	90	100
April 10	0.76	7.6	0.05	0	> 99	100
April 12	0.51	5.1	0.05	0	> 99	100
April 25	0.45	4.5	0.03	0	> 99	100
June 23	0.40	4.0	0.02	0	> 99	100

The table shows modeled roof retaining all the rainfalls. The measured green roofs have more than 99 percent retention for five storms whereas the other two are retained by more than 90 percent. The result therefore confirms that for small storms both roofs behave in a similar manner retaining almost all of the rainfalls falling on to them.

One of the main objectives of any stormwater management program is peak flow reduction. Green roof's performance on peak flow reduction is either estimated experimentally or by model simulation. The simple model developed and tested in this study has been found to be good enough to predict peak flows for any storm size. The model developed behaves in a similar way with the real roof, retaining all water in case of smaller storms with size less than 1.65 centimeters. For the events with size more than 1.65 centimeters, the model can predict the runoffs produced within a range of factors from 0.97 to 1.4.

This simple mass balanced model developed for the purpose of this study and set up in Excel spreadsheet, considering only few variables and with limited numbers of data, can thus be used to simulate runoff from any rainfall including those from designed storms prepared for any location. Simplicity and less data intensive nature are two major characteristics of this model which make it easily applicable for any storm event. Simulation of runoffs from a number of 24-hour design storms with return periods ranging from 2 to 100 years for estimating green roof's capacity to work as a stormwater BMP in the Windsor-Detroit region is performed in Chapter IV.

CHAPTER IV: Green Roof Evaluation as Stormwater BMP

The efficacy of the extensive green roof at LTU as a stormwater BMP is calculated in this chapter. For simulating green roof's performance and estimating generated peak discharge from design storms of various return periods, the model developed in Chapter 3 is used.

Generally for any stormwater device, accepted peak flow criteria are that maximum post-development peak flow rates must not exceed pre-development values for storms with return periods ranging from 2 to 100 years (MOE SWM Design Manual, 2003). For any new urban development, stormwater management programs should therefore be implemented to make post-development peak runoff at least equal to or lower than the corresponding pre-development values. Otherwise, the increased peak flow rates from any storm increases the risks to life and property. This chapter considers this aspect while judging the effectiveness of green roof using the model developed and tested in Chapter III. The pre-development peak runoffs are influenced by regional land-use and meteorological characteristics. Therefore the results obtained are also expected to be region and green roof specific. The region being considered for assessing stormwater management benefit of an extensive green roof similar to that at LTU is Southeast Lower Michigan (in the United States) / Southwest Ontario (in Canada). However the approach presented can be applied to assess the stormwater management benefits of any other extensive green roof at other geographical locations.

4.1 24-hr design rainfall

For the stormwater management purpose, NRCS has developed different rainfall distributions with respect to time for four geographic areas of the United States. For each of these areas, a set of synthetic rainfall distributions have been developed. As shown in Figure 4.1, Type I and IA represent the Pacific maritime climate, Type III represents Gulf of Mexico and Atlantic coastal, and Type II represents the rest of the country. The rainfall distribution taken for LTU's green roof is Type II.

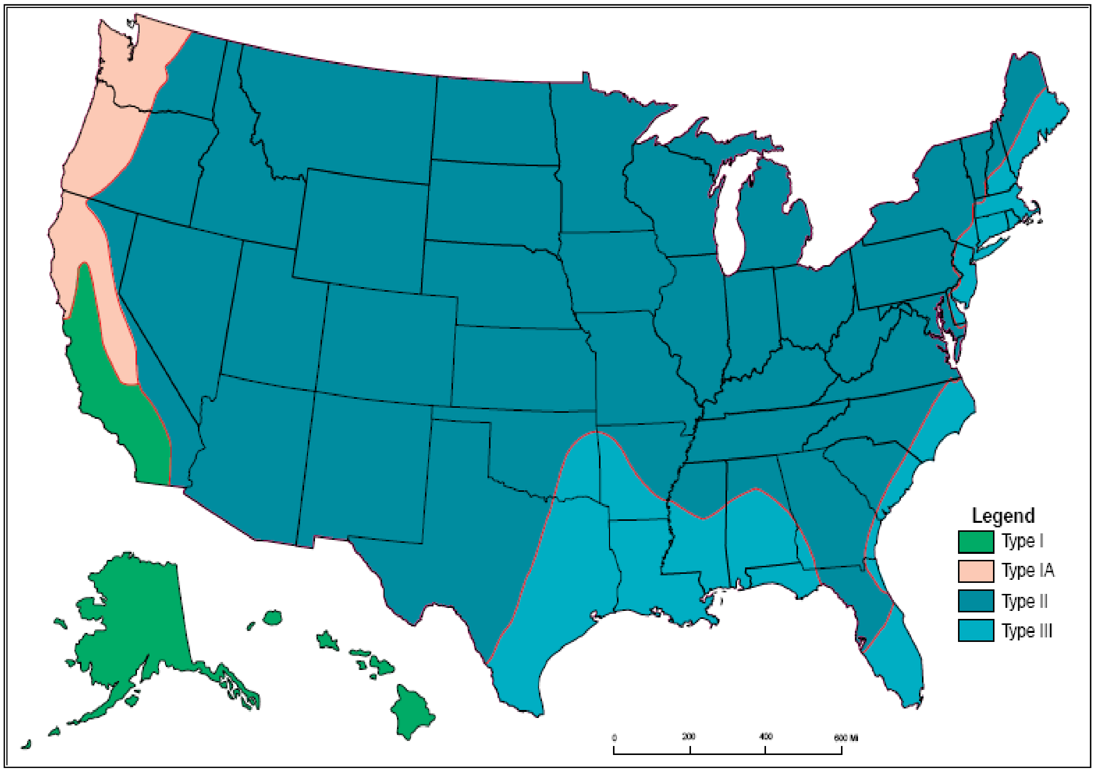

Figure 4- 1: Approximate geographic boundaries for NRCS rainfall distributions

(Source: Agriculture Handbook, 1997)

The NRCS (TR-55, 1986) has also produced a table (Table 4.1) for distributing the total rainfall depth throughout a storm to develop a design storm hyetograph. This table is used to find fractions of the total accumulated rainfall depth for Type II storms with 24-hour durations. This distributed rainfall is then used for simulation and other calculation for this study.

Table 4- 1: SCS dimensionless storm distributions

Time	Type II	Time	Type II	Time	Type II
hr		hr		hr	
0	0	9	0.147	18	0.921
1	0.011	10	0.181	19	0.937
2	0.022	11	0.235	20	0.952
3	0.035	12	0.663	21	0.965
4	0.048	13	0.772	22	0.978
5	0.063	14	0.82	23	0.989
6	0.08	15	0.854	24	1
7	0.098	16	0.88		
8	0.12	17	0.902		

Source: TR- 55, 1986

Type II rainfalls with storm period of 24 hours and recurrence intervals of 2 to 100 years for Southeast Lower Michigan (Huff and Angel, 1992) are chosen for runoff simulation and other relevant calculations for the region being considered. The region under consideration is Zone 10 in the climatic zones map (see Figure 4-2). Since the Huff and Angel study cover more frequencies, its rainfall data is recommended to obtain the design rainfall for the method used here (Sorrell, 2008). The depths of these 24 - hour design storms with 2, 5, 10, 25, 50 and 100 years return periods are 5.74, 6.98, 7.95, 9.14, 10.11 and 11.07 cm respectively. From the fractions for Type II storms (Table 4.1), rainfall distribution for each storm with one hour interval is calculated as given in the Table 4.2.

These one hour time step rainfall distributions later are used for the peak flows simulation so as to evaluate the performance of green roof against the pre-developmental peaks.

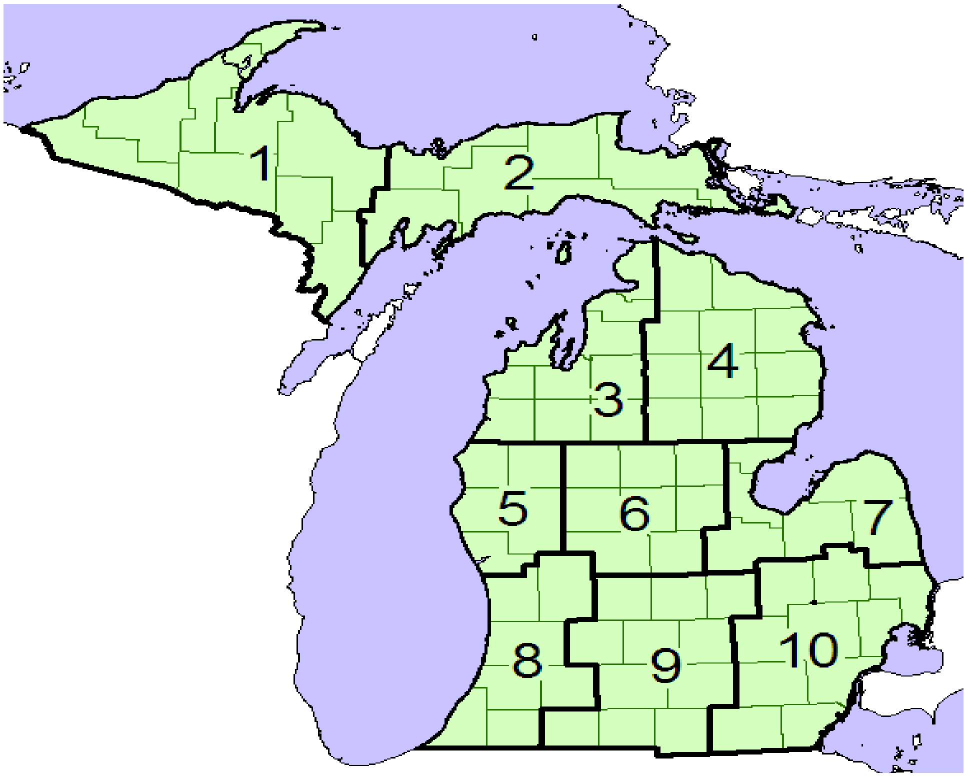

Figure 4- 2: Climatic Zones for Michigan

(Source: Sorrell, 2008)

Table 4- 2: Rainfall Distribution

Time	Fraction	24-hour Rainfall											
		2-year		5-year		10-year		25-year		50-year		100-year	
		P = 5.74 cm		P = 6.98 cm		P = 7.95 cm		P = 9.14 cm		P = 10.11 cm		P = 11.07 cm	
hr		cum	incr	cum	incr	Cum	incr	cum	incr	cum	incr	cum	incr
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.011	0.063	0.063	0.077	0.077	0.087	0.087	0.101	0.101	0.111	0.111	0.122	0.122
2	0.022	0.126	0.063	0.154	0.077	0.175	0.087	0.201	0.101	0.222	0.111	0.244	0.122
3	0.035	0.201	0.075	0.244	0.091	0.278	0.103	0.320	0.119	0.354	0.131	0.387	0.144
4	0.048	0.276	0.075	0.335	0.091	0.382	0.103	0.439	0.119	0.485	0.131	0.531	0.144
5	0.063	0.362	0.086	0.440	0.105	0.501	0.119	0.576	0.137	0.637	0.152	0.697	0.166
6	0.080	0.459	0.098	0.558	0.119	0.636	0.135	0.731	0.155	0.809	0.172	0.886	0.188
7	0.098	0.563	0.103	0.684	0.126	0.779	0.143	0.896	0.165	0.991	0.182	1.085	0.199
8	0.120	0.689	0.126	0.838	0.154	0.954	0.175	1.097	0.201	1.213	0.222	1.328	0.244
9	0.147	0.844	0.155	1.026	0.188	1.169	0.215	1.344	0.247	1.486	0.273	1.627	0.299
10	0.181	1.039	0.195	1.263	0.237	1.439	0.270	1.654	0.311	1.830	0.344	2.004	0.376
11	0.235	1.349	0.310	1.640	0.377	1.868	0.429	2.148	0.494	2.376	0.546	2.601	0.598
12	0.663	3.806	2.457	4.628	2.987	5.271	3.403	6.060	3.912	6.703	4.327	7.339	4.738
13	0.772	4.431	0.626	5.389	0.761	6.137	0.867	7.056	0.996	7.805	1.102	8.546	1.207
14	0.820	4.707	0.276	5.724	0.335	6.519	0.382	7.495	0.439	8.290	0.485	9.077	0.531
15	0.854	4.902	0.195	5.961	0.237	6.789	0.270	7.806	0.311	8.634	0.344	9.454	0.376
16	0.880	5.051	0.149	6.142	0.181	6.996	0.207	8.043	0.238	8.897	0.263	9.742	0.288
17	0.902	5.177	0.126	6.296	0.154	7.171	0.175	8.244	0.201	9.119	0.222	9.985	0.244
18	0.921	5.287	0.109	6.429	0.133	7.322	0.151	8.418	0.174	9.311	0.192	10.195	0.210
19	0.937	5.378	0.092	6.540	0.112	7.449	0.127	8.564	0.146	9.473	0.162	10.373	0.177
20	0.952	5.464	0.086	6.645	0.105	7.568	0.119	8.701	0.137	9.625	0.152	10.539	0.166
21	0.965	5.539	0.075	6.736	0.091	7.672	0.103	8.820	0.119	9.756	0.131	10.683	0.144
22	0.978	5.614	0.075	6.826	0.091	7.775	0.103	8.939	0.119	9.888	0.131	10.826	0.144
23	0.989	5.677	0.063	6.903	0.077	7.863	0.087	9.039	0.101	9.999	0.111	10.948	0.122
24	1.000	**5.740**	0.063	**6.980**	0.077	**7.950**	0.087	**9.140**	0.101	**10.110**	0.111	**11.070**	0.122

Notes: P=Precipitation depth in 24 hours, incr=incremental, cum=cumulative

4.2 Pre-developmental peak flows

There are a variety of methods for estimating peak flows from rainfall data. They are: Rational, SCS and Unit hydrograph methods. In this case, the location being a small ungaged watershed, a unit hydrograph technique as suggested in the "Michigan Department of Environmental Quality" published report for computing flood discharges (Sorrell, 2008) is used. The main advantage of this method is easy to apply and all the physical parameters used are easily determined. This theory assumes uniform rainfall and runoff from the entire drainage basin. The physical description of the watershed includes drainage area, soil type, land use and time of concentration.

Out of all the hydrologic soil groups, as defined by SCS soil scientists the drainage area in pre-development condition (Southeast Lower Michigan/ Southwest Ontario) is considered as group-D soil with a very slow rate of water transmission. The area under consideration is 1000 m^2, which is the same as that being considered for the green roof. For the estimation of runoff the pre-development land area is considered as meadow.

The other significant parameter is time of concentration (T_C), the smallest time for which the entire area is contributing runoff to the drainage outlet. For ungaged watershed like this, T_C is calculated by estimating the velocity through the various components of stream network. There are many methods to estimate the velocity and the method as suggested by Sorrel (2008) and used here is in the form:

$$V = K * S^{0.5} \qquad (5.1)$$

Where K is a coefficient depending on the type of flow, S is the slope of the flow path in percent, and V is the velocity in feet per second. To calculate the velocity, the type of flow is considered as sheet flow, an overland flow not confirming the waterway definition. Value of K for such flow is given as 0.48. The slope of land is taken as 2 %. Using equation 5.1, velocity of the flow comes out to be 0.68 ft/s. Once the velocity is determined, time of concentration is can be computed as:

$$T_C = L / V \qquad (5.2)$$

Where L = length of drainage area under flow in feet

Using equation 5.2 the time of concentration for the drainage area is calculated as 3.6 minutes. Since this time is less than the 1 hour increments at which the design storm data is specified, the T_C value is set at the minimum value of 1 hour.

This time of concentration is then used to estimate the pre-development peak flow for any design rainfall, based on the procedure described in the "Computing Flood Discharges for Small Ungaged Watersheds (Sorrell, 2008). The peak flow is calculated by the equation 5.3.

$$Q = Q_{UP} * SRO * A \qquad (5.3)$$

Where Q = Peak flow in cfs

SRO = Surface runoff in inches

A = Area in mi^2, and

Q_{UP} = Unit hydrograph peak in cfs / mi^2-in

For normal soil moisture conditions, referred to as Antecedent Moisture Condition II SRO is estimated by equation 5.4.

$$SRO = (P-0.2S)^2 / (P+0.8S) \quad (5.4)$$

Where P = Total precipitation in inches

S= Potential maximum retention in inches

S relates to Runoff Curve Number (RCN) for the area by an equation 5.5.

$$S = (1000/RCN) - 10 \quad (5.5)$$

Finally the relation between unit hydrograph peak and time of concentration is given by equation 5.6.

$$Q_{UP} = 238.6 * (T_C)^{-0.82} \quad (5.6)$$

Considering the soil as type D and the land use as meadow, value of RCN is taken as 78. The time of concentration as already explained is considered as 1 hour. With these assumptions and using the method given above, the calculated peak flows for all design rainfalls with return periods ranging from 2 to 100 years come out as tabulated in the Table 4-3. Calculation is given in Appendix 4-1.

Table 4- 3: Pre-development Peak Flows

Rainfall	**Area (mi^2)**	**I (in)**	**S (maximum retention, in)**	**Surface Runoff (SRO, in)**	**Peak discharge m^3/s**
2 yr	0.000386	2.26	2.82	0.637	0.0017
5 yr	0.000386	2.75	2.82	0.955	0.0025
10 yr	0.000386	3.13	2.82	1.222	0.0032
25 yr	0.000386	3.6	2.82	1.574	0.0041
50 yr	0.000386	3.98	2.82	1.871	0.0049
100 yr	0.000386	4.36	2.82	2.178	0.0057

Notes: I= intensity of rainfall

4.3 Green roof runoff simulation

The same design storms which are chosen for determining pre-development peaks are used for runoff simulation. Spreadsheet calculation for the events (2-yr to 100-yr) is given in Appendix 4-2 and the resulting simulations from model green roof are represented in Figures 4.3 to 4.8.

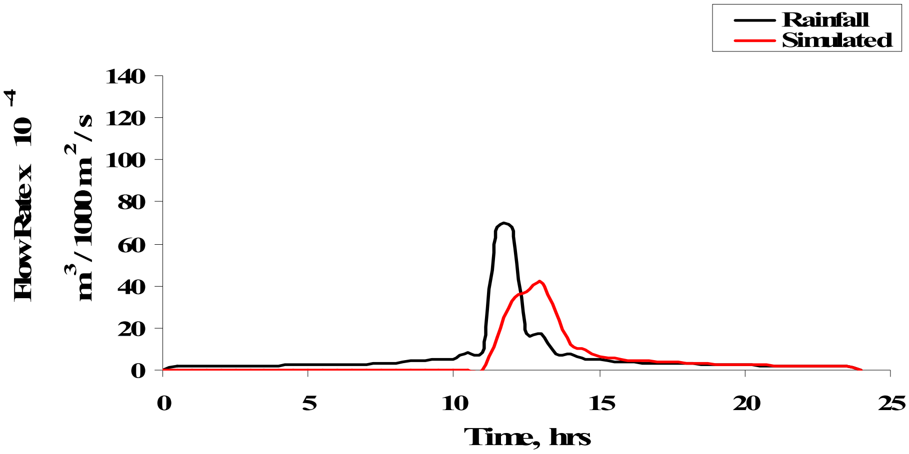

Figure 4- 3: Peak Flow through 2-yr Design Storm

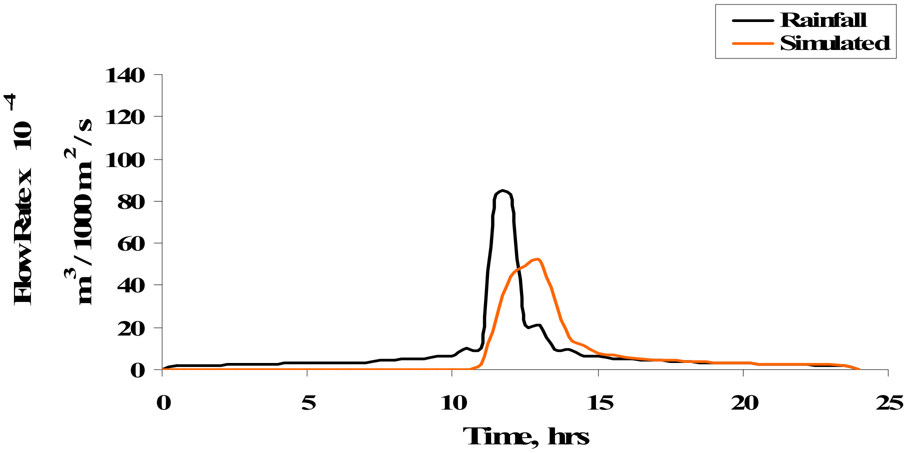

Figure 4- 4: Peak Flow through 5-yr Design Storm

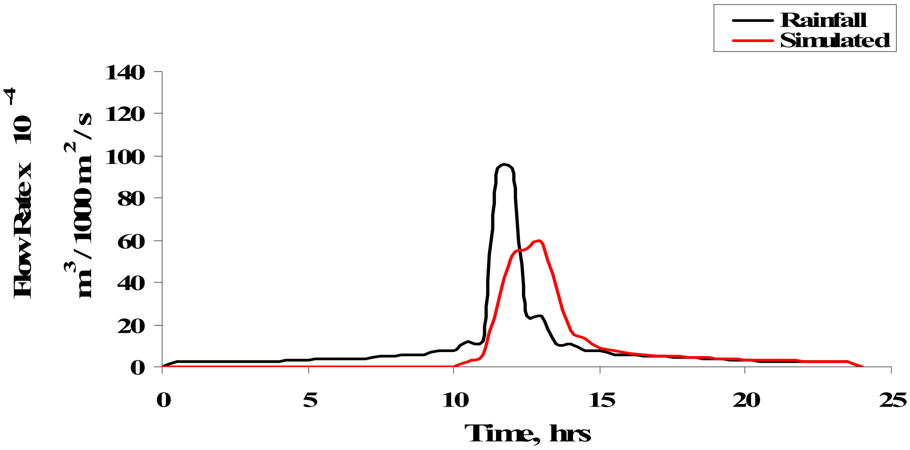

Figure 4- 5: Peak Flow through 10-yr Design Storm

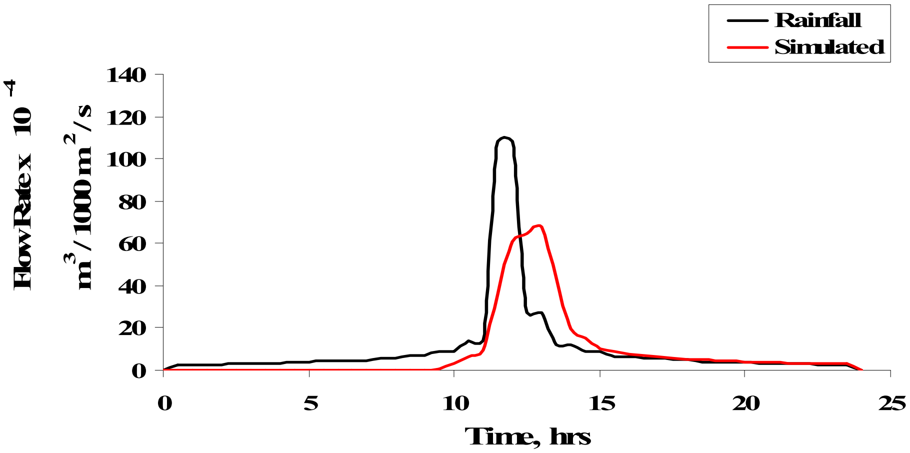

Figure 4- 6: Peak Flow through 25-yr Design Storm

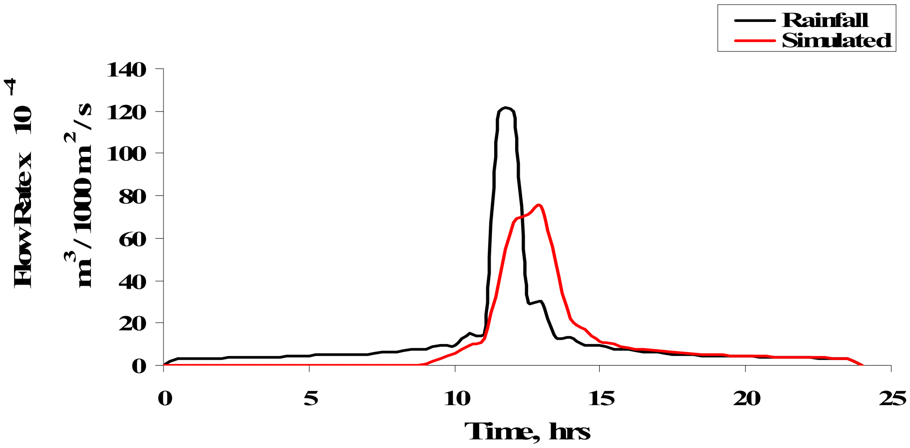

Figure 4- 7: Peak Flow through 50-yr Design Storm

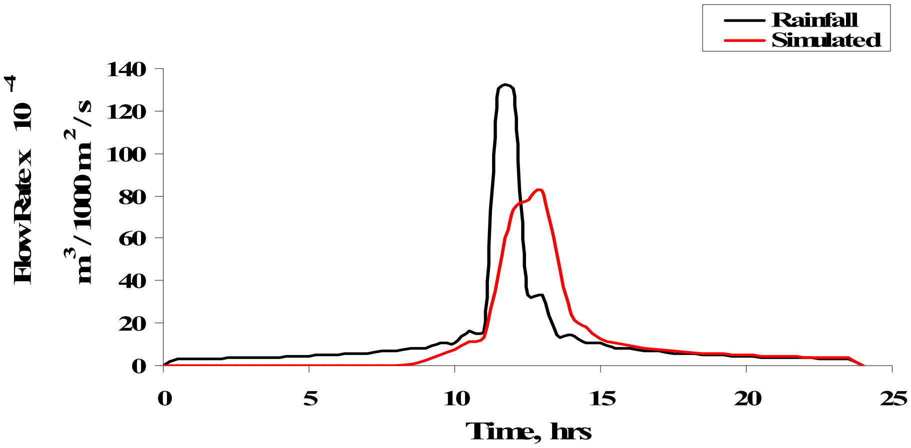

Figure 4- 8: Peak Flow through 100-yr Design Storm

In all the hydrographs plotted above, rainfall curve and simulated curve respectively represent flow rates due to incoming design rainfall and green roof simulation. The final values of these peaks are given in Table 4.4.

Table 4- 4: Rainfall and Simulated Peaks

Rainfall	Peak Flows $m^3/1000\ m^2/sec$	
	Rainfall	Model Simulated
2 yr	0.0068	0.004
5 yr	0.0083	0.0051
10 yr	0.0094	0.0058
25 yr	0.0108	0.0067
50 yr	0.0120	0.0074
100 yr	0.0131	0.0081

Another parameter considered important to evaluate the performance of green roof is its water retention capacity. It is calculated as the percentage difference between rainfall and the simulated runoff volume (see Appendix 4-4), and is tabulated in Table 4.5. This table provides the final details of water retention along with rainfall, model simulated and pre-development peaks.

Table 4- 5: Rainfall, Simulated and Pre-development Peaks and Retention

Rainfall	Peak Flows $m^3/1000\ m^2/sec$			Retention %
	Rainfall	Simulated	Pre-development	
2 yr	0.0068	0.004	0.0017	25.1
5 yr	0.0083	0.0051	0.0025	20.6
10 yr	0.0094	0.0058	0.0032	18.2
25 yr	0.0108	0.0067	0.0041	15.8
50 yr	0.0120	0.0074	0.0049	14.2
100 yr	0.0131	0.0081	0.0057	13.1

In Chapter 3, it has been observed that the flows resulting from storms equal to or less than 1.5 cm size will be retained by the calibrated green roof. For storms greater than this depth, only the initial 1.5 cm will be retained and the rest flows to the watershed. With this consideration, this green roof's application with respect to rainfall distribution in Southwest Ontario (Windsor-Essex) is observed for a certain year based on average rainfall from 1971-2000 recorded in Environment Canada for Windsor. Table 4.6 gives the average number of days per month and year on which a rainfall of certain size occurs in Windsor.

Table 4- 6: Days with rainfall in Windsor, ON

Rainfall	Number of Days												Total
Size (cm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	days
≥0.02	5.7	5.6	9.4	12.2	11.8	11	10.2	10	10.9	10.5	10.6	7.9	115.7
≥ 0.5	1.7	2	4	5	4.9	5.6	4.8	4.4	5	3.9	4.2	3.2	48.8
≥1.0	1	1	1.9	2.9	2.7	3.4	2.8	2.7	3.3	2.2	2.3	1.5	27.7
≥ 2.5	0.13	0.23	0.2	0.37	0.6	0.83	0.6	0.63	1.1	0.4	0.4	0.2	5.7

Source: Canadian Climate Normals 1971-2000, (http://climate.weatheroffice.ec.gc.ca/climate_normals)

The actual days with rainfall size ≤ 1.5 cm, essential for the purpose of this study, is however not presented in the table. A review of the available yearly rainfall data mentioned in Canadian Climate Normals (1971-2000) for a region representative of Southwest Ontario (Windsor-Essex), for a number of years indicates that about 60 % of total days in the range of ≥ 1 cm and ≤ 2.5cm accounts for size ≤1.5 cm and ≥ 1cm, and this is equal to 13 days. Hence the total number of rainfall days with size ≤ 1.5 cm will be 101 days which is equivalent to 87 % of total rainfall days in a year. Based on this calculation, for Southwest Ontario it can be said that if all the rainfalls are considered as single time independent events, the green roof can retain the rainfalls from more than 87 % cases in a year. Considering such a high retention capacity, this green roof can work as a BMP for the majority of rainfall events.

For the remaining rainfalls (13 %) with size larger than 1.5 cm, the roof can retain the initial 1.5 cm of total depth. This retention of initial portion of larger rainfall, called "first-flush" has a great and practical significance in any stormwater management program. The first-flush event occurs after a certain dry spell and its effect is most prominent for sites that are highly impervious. Typically, the peak concentrations of contaminants in any storm water runoff occur at this stage. Capturing this runoff reduces pollutants considerably and reduces substantially the impacts of normal pollutants like TSS, COD and heavy metals like Cu, Mg, Ni, Pb and Zn in the receiving waters.

Retaining the initial part of a storm would also reduce the runoff storage volume needed for the future remaining pollutants. A study by Novotny (1995) shows about 90% of the pollution from a storm in any location is carried out in the first half inch (1.25 cm) of runoff. This is taken as a good reference for stormwater management program that is designed with an objective to treat or remove 90% of the annual pollutant load in a region.

In this study, the retention is the first 1.5 cm depth of any larger rainfall; this value is higher than 1.25 cm as referred above. It is therefore expected that this initial retention of 1.5 cm rainfall reduces more than 90 % contaminants carried by storm in the studied region, ultimately helping to minimize the size of other stormwater treatment structures.

It can therefore be deduced that a green roof has two major benefits - retaining majority of the rainfalls and capturing pollutants from the first-flush component of larger rainfalls. Despite these benefits, Table 4.5 shows that the simulated expected peak flow runoffs by green roof on its own are not equal to or lower than pre-development peak flows for any of the design storms with return periods ranging between 2 to 100 years. As said in the beginning, any acceptable stormwater management device should at least make post-development peak and runoff equal or lower than the pre-development peak and runoff. This condition is not fulfilled here. Green roof by itself therefore is not deemed to be an effective stormwater device and an alternative is to be sought, which in this study is the inclusion of an additional storage device.

4.4 Green roof with additional storage

A schematic of the inclusion of additional storage volume (e.g. tank) combined with green roof is shown in the Figure 4.9.

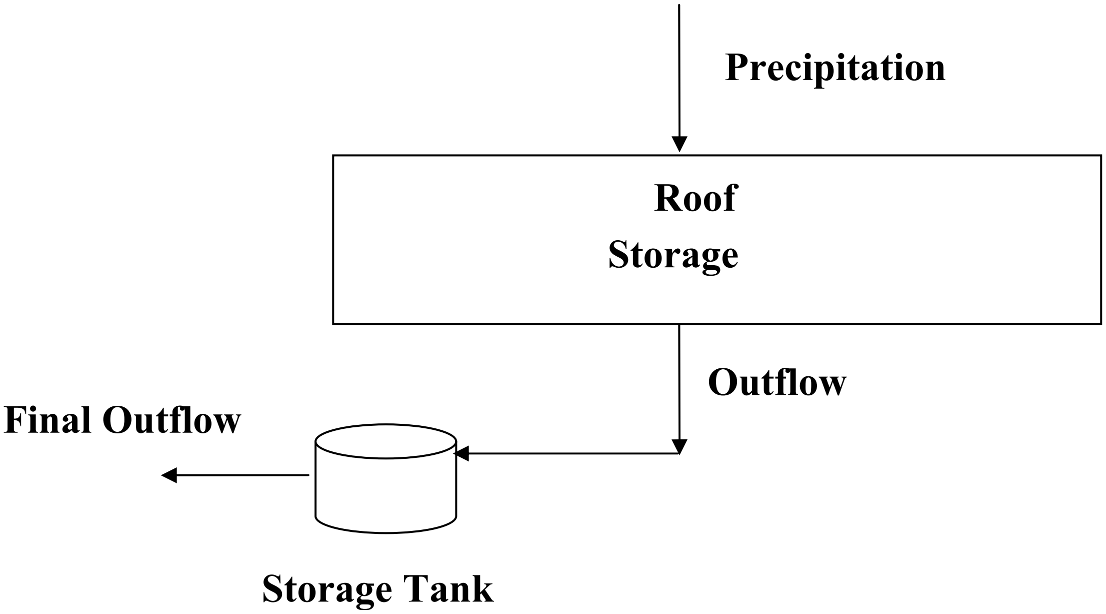

Figure 4- 9: Control volume for runoff simulation from design storms

The spreadsheet model to simulate runoff from the green roof plus additional storage is exactly the same as that for the green roof itself (discussed in Chapter 3). The only difference in this scheme is that the storage available for retention will be augmented by the amount of additional storage available. Model simulation for return periods ranging from 2 to 100 years are carried out for a number of additional storage volumes (considered as trial values). The resulting peaks from the simulation are given in Table 4.7. The results are also represented by Figure 4.10.

Table 4- 7: Simulated Peak Flows (m^3/1000 m^2/s) with storage augmentation

Augmented Storage (m^3)	**Peak Flows** in rainfall periods of					
	2-year	5-year	10-year	25-year	50-year	100-year
0	0.004	0.0051	0.0058	0.0066	0.0074	0.0081
10	0.0029	0.0043	0.0053	0.0066	0.0073	0.0080
20	0.0021	0.0033	0.0042	0.0055	0.0066	0.0076
30	0.0002	0.0023	0.0034	0.0044	0.0055	0.0065
40	0	0.0015	0.0022	0.0036	0.0047	0.0057
50	0	0.0006	0.0014	0.0025	0.0036	0.0046
60	0	0	0.0006	0.0014	0.0025	0.0038
70	0	0	0	0.0003	0.0014	0.0024
80	0	0	0	0	0.0003	0.0013
90	0	0	0	0	0	0.0002
100	0	0	0	0	0	0

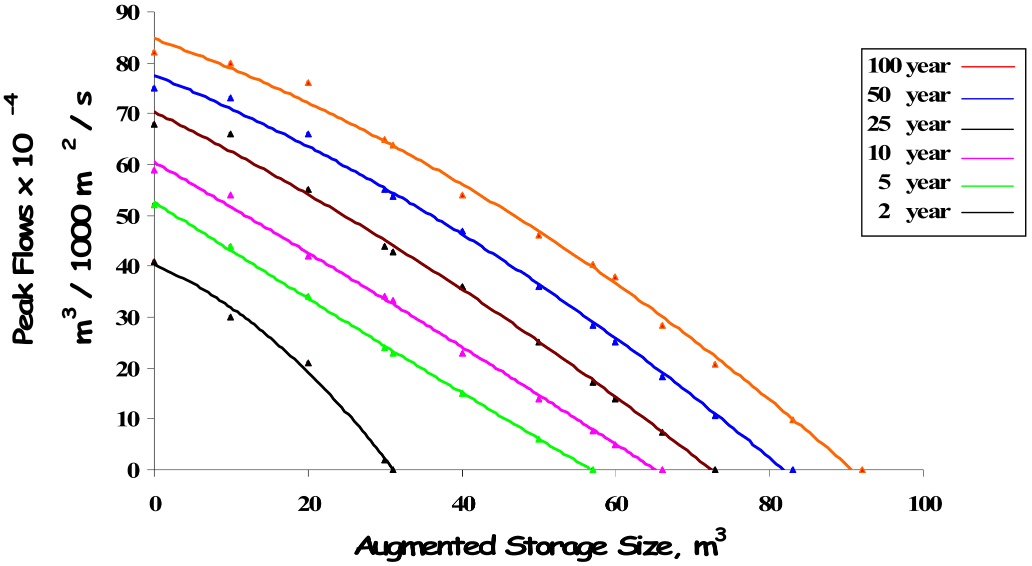

Figure 4- 10: Simulated Peak Flows due to Augmented Storage

Different storage values, starting from 10 m^3 are used in model simulation. Finally, using Figure 4.10, the storage values required to limit the 2 to 100 year storms post-development peaks to corresponding pre-development levels are calculated and shown in Table 4.8. The storage volumes required for complete retention of 2- to 100-year design storm flows are also included in the table.

Table 4- 8: Required Additional Storage to Green Roof

Rainfall	Augmented Storage, m^3	
	for Pre-dev Level	for Complete Retention
2 yr	22	31
5 yr	29	57
10 yr	32	66
25 yr	34	73
50 yr	38	82
100 yr	40	90

Notes: Pre-dev = Pre-development

From the calculation, it is seen that an augmented volume of 22 m^3 would allow the 2-yr design storms post-development peak level to come to pre-development stage. Similarly, for 100-yr, the required size is 40 m^3. Therefore, by adding 40 m^3 storage to the initial storage capacity of green roof would allow the 2 to 100-year design storms post-development peaks to be limited to pre-development levels. An increase in the storage volume by 90 m^3 will retain the entire storm volumes with zero discharge for up to a 100-year design storm.

In conclusion, the Windsor-Essex region in a certain year has about 87 % of the rainfalls with size lower than 1.5 cm, and calibrated green roof can completely retain rainfall lower or equal to this depth. The roof is also capable to retain the most significant first-flush portion of any rainfall greater than 1.5 cm. It shows that the green roof in this region works effectively. It however is not capable of working as a stormwater BMP to produce post-development peak equal or lower than the pre-development peak for any rainfall with return period ranging from 2 to 100 years on its own. This condition being the most essential component of any stormwater management, there is a need to augment the storage capacity of green roof. This study shows that increasing the storage capacity by 40 m^3 the calibrated green roof can fulfill the objective of any stormwater management.

CHAPTER V: Conclusions and Recommendations

5.1 Conclusions

Stormwater management continues to be a growing concern in urban areas. Green roof system serving as a BMP might be one of the solutions to this problem. Before adopting this solution, performance quantification of laid out green roofs needs to be done. Experimental measurement is one of the methods to assess the effectiveness of any green roof. Such methods need, in most of the times, a collection and analysis of intensive data on different parameters. Therefore, this method is not always feasible, economical and convenient in smaller setups such as individual households. Availability of a simple model which can be used to predict the green roof's performance and for a design in any location with the minimum number of parameters is therefore very essential.

The main objective of this study was to calibrate and test a simple mass balance based water budget model to simulate the performance of a 10-cm extensive green roof at LTU for stormwater retention and control. The findings from the study can be summarized as follows:

- The green roof has a calibrated available storage capacity of 1.5 cm and is expected to be able to completely retain runoff from storms with a cumulative rainfall depth of up to 1.5 cm. The roof would be expected to retain about 87 % of the storm events during a typical rainfall year in Southwest Ontario (Windsor-Essex County).

- For storms with a cumulative rainfall depth of 1.65 cm or greater, model predicted peak flows were within a factor of 0.97 to 1.4 of the measured values. The simulated peak flows were always higher than the measured and therefore the predictions are conservative. The total runoff volume simulated was within a factor of 0.8 to 1.6 of the measured values.

- For storms with a cumulative rainfall depth of < 1.65 cm, the model predicted 100% retention of runoff compared to measured values of 90 - > 99 % retention.

- The simulated peak flows for runoff from the green roof were higher than the pre-development flows for the local watershed conditions for all design storms with return periods ranging between 2 to 100 years.

- The green roof with an additional storage of 40 m^3 can meet the stormwater management objective of limiting the peak flow to the pre-development peak flow for 2 to 100 year storms in the region of Southwest Ontario/ Southeast Lower Michigan.

- The additional storage provided can be modified to achieve different stormwater management objectives. An additional storage of 90 m^3 can meet the stormwater management objective of completing retaining runoff flows for up to a 100 year storm in the region of Southwest Ontario/ Southeast Lower Michigan.

5.2 Recommendations

This model considers a case of an extensive green roof which does not need irrigation. It assumes to have only single time-specific storm events during calibration, and therefore the effect of evapo-transpiration is not taken in to account or neglected. This may be acceptable for storms with short duration but in case of long hour rainfalls, evapo-transpiration plays an important role and must be considered. In addition the system may require irrigation if there is a long spell of dry season, and including this parameter would make the model more accurate to estimate stormwater benefits. This is recommended in the future study.

The initial moisture level in the model roof is arbitrarily picked up and is kept constant for all storms. From the results, it seems that variation in performance between the model and the measured value is mainly due to the difference in actual moisture present in the roof and assumed moisture for the model development. It is thus highly recommended to measure the actual moisture in the green roof in the beginning of each precipitation and use this real moisture value in model calibration. The media water storage capacity should also be examined to develop more accurate model.

The model calibration and testing have been carried only with a limited number of storms data available. The accuracy of the model would increase if more storms in all seasons are used while calibration and testing the models.

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Appendix 3- 1: Excel setup for the calculation of peak flow rates

				Moisture, %	**Roof storage, m^3**				
Cumulative time	**Rainfall**	**Rainfall (30 mt.)**	**Inflow**	**Moisture**	**Available storage**	**Retention capacity**	**Cumulative outflow**	**Incremental outflow**	**Flow rates**
hrs	**m**	**m**	**m^3**	**m^3**	**m^3**	**m^3**	**m^3**	**m^3**	**m^3 /1000m^2 /sec**

Notes: area = 1000 m^2, Initial moisture = 20 % of the system storage, Roof storage= number of trial values for calibration, mt. = minutes

Appendix 3-2: Model showing the sample calculation for June 7 rainfall

			Moisture	Roof storage					
			0.2	18 m^3					
			3.6						
Cumulative time	**Rainfall**	**Inflow**	**Moisture**	**Available storage**	**Retention capacity**	**Cumulative outflow**	**Incremental outflow**	**Flow rates**	**Moving point average**
hrs	**m**	**m^3**	**m^3**	**m^3**	**m^3**	**m^3**	**m^3**	**m^3 /1000m^2 /sec**	**m^3 /1000m^2 /sec**
0	0	0	3.6	14.4	-14.4	0	0	0	0
0.083333333	0.001524	1.52439	5.1243902	12.8756098	-12.87560976	0	0	0	0
0.166666667	0.002541	2.54065	7.6650407	10.3349593	-10.33495935	0	0	0	0
0.25	0.002033	2.03252	9.697561	8.30243902	-8.302439024	0	0	0	0
0.333333333	0.000254	0.25407	9.951626	8.04837398	-8.048373984	0	0	0	0
0.416666667	0.000254	0.25407	10.205691	7.79430894	-7.794308943	0	0	0	0
0.5	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
0.583333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
0.666666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
0.75	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
0.833333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
0.916666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.083333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.166666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.25	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.333333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.416666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.5	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.583333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.666666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.75	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.833333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
1.916666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0

2	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.083333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.166666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.25	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.333333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.416666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.5	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.583333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.666666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.75	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.833333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
2.916666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
3	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
3.083333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
3.166666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
3.25	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
3.333333333	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
3.416666667	0	0	10.205691	7.79430894	-7.794308943	0	0	0	0
3.5	0.000508	0.50813	10.713821	7.28617886	-7.286178862	0	0	0	0
3.583333333	0.002033	2.03252	12.746341	5.25365854	-5.253658537	0	0	0	0
3.666666667	0.000254	0.25407	13.000407	4.9995935	-4.999593496	0	0	0	0
3.75	0.000254	0.25407	13.254472	4.74552846	-4.745528455	0	0	0	0
3.833333333	0.000254	0.25407	13.508537	4.49146341	-4.491463415	0	0	0	0
3.916666667	0	0	13.508537	4.49146341	-4.491463415	0	0	0	0
4	0	0	13.508537	4.49146341	-4.491463415	0	0	0	0

Notes: Calculation for initial rainfall period (0-4 hr)

16.08333333	0	0	13.762602	4.23739837	-4.237398374	0	0	0	0
16.16666667	0	0	13.762602	4.23739837	-4.237398374	0	0	0	0
16.25	0.000254	0.25407	14.016667	3.98333333	-3.983333333	0	0	0	0
16.33333333	0.002033	2.03252	16.049187	1.95081301	-1.950813008	0	0	0	0
16.41666667	0.001016	1.01626	17.065447	0.93455285	-0.934552846	0	0	0	0
16.5	0.001016	1.01626	18.081707	-	0.081707317	0.0817073	0.08170732	0.000272358	4.5393E-05
16.58333333	0.000508	0.50813	18.589837	-0.5898374	0.589837398	0.5898374	0.50813008	0.001693767	0.000327687
16.66666667	0.000762	0.7622	19.352033	-	1.35203252	1.3520325	0.76219512	0.00254065	0.000751129
16.75	0	0	19.352033	-	1.35203252	1.3520325	0	0	0.000751129
16.83333333	0.000254	0.25407	19.606098	-	1.606097561	1.6060976	0.25406504	0.000846883	0.000892276
16.91666667	0	0	19.606098	-	1.606097561	1.6060976	0	0	0.000892276
17	0	0	19.606098	-	1.606097561	1.6060976	0	0	0.000846883
17.08333333	0	0	19.606098	-	1.606097561	1.6060976	0	0	0.000564589
17.16666667	0	0	19.606098	-	1.606097561	1.6060976	0	0	0.000141147
17.25	0.000254	0.25407	19.860163	-1.8601626	1.860162602	1.8601626	0.25406504	0.000846883	0.000282294
17.33333333	0	0	19.860163	-1.8601626	1.860162602	1.8601626	0	0	0.000141147
17.41666667	0	0	19.860163	-1.8601626	1.860162602	1.8601626	0	0	0.000141147
17.5	0.000254	0.25407	20.114228	-	2.114227642	2.1142276	0.25406504	0.000846883	0.000282294
17.58333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0.000282294
17.66666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0.000282294
17.75	0	0	20.114228	-	2.114227642	2.1142276	0	0	0.000141147
17.83333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0.000141147
17.91666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0.000141147
18	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
18.08333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
18.16666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
18.25	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
18.33333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
18.41666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
18.5	0	0	20.114228	-	2.114227642	2.1142276	0	0	0

Notes: Calculation for intermediate rainfall period (16-18.5 hr)

22.08333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.16666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.25	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.33333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.41666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.5	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.58333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.66666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.75	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.83333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
22.91666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.08333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.16666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.25	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.33333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.41666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.5	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.58333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.66666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.75	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.83333333	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
23.91666667	0	0	20.114228	-	2.114227642	2.1142276	0	0	0
24	0	0	20.114228	-	2.114227642	2.1142276	0	0	0

Notes:

Sample calculation is done for 1.8 cm storage with initial moisture of 20 % in the media

Calculation for calibration of model with other storage capacity and its testing with different rainfall data has been done in the same way but is not shown here due to the bulk of the data.

In actual calibration the media is considered as normal soil with available storage value only.

Appendix 4- 1: Pre-developmental peak flow calculation

Design Storm	**Rainfall (P), in**	**S, in**	**SRO**	**Q (m^3/sec)**
2-yr	2.26	2.82	0.637	0.0017
5-yr	2.75	2.82	0.955	0.0025
10-yr	3.13	2.82	1.222	0.0032
25-yr	3.6	2.82	1.574	0.0041
50-yr	3.98	2.82	1.871	0.0049
100-yr	4.36	2.82	2.178	0.0057

Where:

Runoff Curve Number (RCN) =78
Maximum Possible Retention $(S) = (1000/78) - 10$
Surface Runoff (SRO) = $(P-0.2S)^2 /(P+0.8S)$
Unit Hydrograph Peak (Q_{up}) $=238.6 * T_C^{-0.82}$
Peak Flow (Q) = $Q_{up} * SRO * A$
A =0.000386 square miles, T_C = 1 hour

Note: Calculation by Unit Hydrograph Peak Method

Appendix 4- 2: Peak-flow simulation of design storms

2 and 5-year storm:

Time, hr	2-yr storm			5-yr storm		
	Rainfall, m	Rainfall rate, m^3/ 1000 m^2 /s	Outflow rate, m^3/ 1000 m^2 /s	Rainfall, m	Rainfall rate, m^3/ 1000 m^2 /s	Outflow rate, m^3/ 1000 m^2 /s
0	0	0	0	0	0	0
0.5	0.00032	0.000175	0	0.00038	0.000213	0
1	0.00032	0.000175	0	0.00038	0.000213	0
1.5	0.00032	0.000175	0	0.00038	0.000213	0
2	0.00032	0.000175	0	0.00038	0.000213	0
2.5	0.00037	0.000207	0	0.00045	0.000252	0
3	0.00037	0.000207	0	0.00045	0.000252	0
3.5	0.00037	0.000207	0	0.00045	0.000252	0
4	0.00037	0.000207	0	0.00045	0.000252	0
4.5	0.00043	0.000239	0	0.00052	0.000291	0
5	0.00043	0.000239	0	0.00052	0.000291	0
5.5	0.00049	0.000271	0	0.00059	0.000330	0
6	0.00049	0.000271	0	0.00059	0.000330	0
6.5	0.00052	0.000287	0	0.00063	0.000349	0
7	0.00052	0.000287	0	0.00063	0.000349	0
7.5	0.00063	0.000350	0	0.00077	0.000427	0
8	0.00063	0.000350	0	0.00077	0.000427	0
8.5	0.00077	0.000430	0	0.00094	0.000524	0
9	0.00077	0.000430	0	0.00094	0.000524	0
9.5	0.00097	0.000541	0	0.00119	0.000659	0
10	0.00097	0.000541	0	0.00119	0.000659	0
10.5	0.00155	0.000860	0	0.00188	0.001047	0.000016
11	0.00155	0.000860	0	0.00188	0.001047	0.000278
11.5	0.01226	0.006812	0.001573	0.01494	0.008298	0.002353
12	0.01226	0.006812	0.003276	0.01494	0.008298	0.004427
12.5	0.00312	0.001735	0.003710	0.0038	0.002113	0.004939
13	0.00312	0.001735	0.004144	0.0038	0.002113	0.005206
13.5	0.00138	0.000764	0.002762	0.00168	0.000931	0.003364
14	0.00138	0.000764	0.001249	0.00168	0.000931	0.001522
14.5	0.00097	0.000541	0.000951	0.00119	0.000659	0.001158
15	0.00097	0.000541	0.000653	0.00119	0.000659	0.000795
15.5	0.00074	0.000414	0.000565	0.00091	0.000504	0.000688
16	0.00074	0.000414	0.000478	0.00091	0.000504	0.000582
16.5	0.00063	0.000350	0.000430	0.00077	0.000427	0.000523
17	0.00063	0.000350	0.000382	0.00077	0.000427	0.000465
17.5	0.00054	0.000302	0.000354	0.00066	0.000368	0.000431
18	0.00054	0.000302	0.000326	0.00066	0.000368	0.000397

18.5	0.00046	0.000255	0.000302	0.00056	0.000310	0.000368
19	0.00046	0.000255	0.000279	0.00056	0.000310	0.000339
19.5	0.00043	0.000239	0.000263	0.00052	0.000291	0.000320
20	0.00043	0.000239	0.000247	0.00052	0.000291	0.000301
20.5	0.00037	0.000207	0.000235	0.00045	0.000252	0.000286
21	0.00037	0.000207	0.000223	0.00045	0.000252	0.000271
21.5	0.00037	0.000207	0.000215	0.00045	0.000252	0.000262
22	0.00037	0.000207	0.000207	0.00045	0.000252	0.000252
22.5	0.00032	0.000175	0.000199	0.00038	0.000213	0.000242
23	0.00032	0.000175	0.000191	0.00038	0.000213	0.000233
23.5	0.00032	0.000175	0.000183	0.00038	0.000213	0.000223
24	0.00032	0.000175	0.000175	0.00038	0.000213	0.000213
24.5	0	0	0		0	0

10 and 25-year storm:

Time, hr	10-yr storm			25-yr storm		
	Rainfall, m	**Rainfall rate, m^3/ 1000 m^2 /s**	**Outflow rate, m^3/ 1000 m^2 /s**	**Rainfall, m**	**Rainfall rate, m^3/ 1000 m^2 /s**	**Outflow rate, m^3/ 1000 m^2/s**
0	0	0	0	0	0	0
0.5	0.00043	0.000241	0	0.00050	0.000278	0
1	0.00043	0.000241	0	0.00050	0.000278	0
1.5	0.00043	0.000241	0	0.00050	0.000278	0
2	0.00043	0.000241	0	0.00050	0.000278	0
2.5	0.00051	0.000285	0	0.00059	0.000329	0
3	0.00051	0.000285	0	0.00059	0.000329	0
3.5	0.00051	0.000285	0	0.00059	0.000329	0
4	0.00051	0.000285	0	0.00059	0.000329	0
4.5	0.00059	0.000329	0	0.00068	0.000379	0
5	0.00059	0.000329	0	0.00068	0.000379	0
5.5	0.00067	0.000373	0	0.00077	0.000430	0
6	0.00067	0.000373	0	0.00077	0.000430	0
6.5	0.00071	0.000395	0	0.00082	0.000455	0
7	0.00071	0.000395	0	0.00082	0.000455	0
7.5	0.00087	0.000483	0	0.00100	0.000556	0
8	0.00087	0.000483	0	0.00100	0.000556	0
8.5	0.00107	0.000593	0	0.00123	0.000683	0
9	0.00107	0.000593	0	0.00123	0.000683	0
9.5	0.00134	0.000746	0	0.00155	0.000859	0.000073
10	0.00134	0.000746	0	0.00155	0.000859	0.000288
10.5	0.00213	0.001185	0.000282	0.00246	0.001365	0.000629
11	0.00213	0.001185	0.000578	0.00246	0.001365	0.000970
11.5	0.01691	0.009392	0.002927	0.01947	0.010819	0.003602
12	0.01691	0.009392	0.005275	0.01947	0.010819	0.006092
12.5	0.00431	0.002392	0.005590	0.00496	0.002755	0.006440
13	0.00431	0.002392	0.005892	0.00496	0.002755	0.006787
13.5	0.00190	0.001053	0.003807	0.00218	0.001213	0.004386
14	0.00190	0.001053	0.001723	0.00218	0.001213	0.001984
14.5	0.00134	0.000746	0.001311	0.00155	0.000859	0.001510
15	0.00134	0.000746	0.000900	0.00155	0.000859	0.001036
15.5	0.00103	0.000571	0.000779	0.00118	0.000657	0.000897
16	0.00103	0.000571	0.000658	0.00118	0.000657	0.000758
16.5	0.00087	0.000483	0.000593	0.00100	0.000556	0.000683
17	0.00087	0.000483	0.000527	0.00100	0.000556	0.000607
17.5	0.00075	0.000417	0.000488	0.00086	0.000480	0.000562
18	0.00075	0.000417	0.000450	0.00086	0.000480	0.000518
18.5	0.00063	0.000351	0.000417	0.00073	0.000404	0.000480

19	0.00063	0.000351	0.000384	0.00073	0.000404	0.000442
19.5	0.00059	0.000329	0.000362	0.00068	0.000379	0.000417
20	0.00059	0.000329	0.000340	0.00068	0.000379	0.000392
20.5	0.00051	0.000285	0.000324	0.00059	0.000329	0.000373
21	0.00051	0.000285	0.000307	0.00059	0.000329	0.000354
21.5	0.00051	0.000285	0.000296	0.00059	0.000329	0.000341
22	0.00051	0.000285	0.000285	0.00059	0.000329	0.000329
22.5	0.00043	0.000241	0.000274	0.00050	0.000278	0.000316
23	0.00043	0.000241	0.000263	0.00050	0.000278	0.000303
23.5	0.00043	0.000241	0.000252	0.00050	0.000278	0.000291
24	0.00043	0.000241	0.000241	0.00050	0.000278	0.000278
24.5	0	0	0	0	0	0.000000

<u>50 and 100-year storm</u>:

Time, hr	50-yr storm			100-yr storm		
	Rainfall, m	Rainfall rate, m3/1000 m2/s	Outflow rate, m^3/ 1000 m^2 /s	Rainfall, m	Rainfall rate, m^3/ 1000 m^2/s	Outflow rate, m^3/ 1000 m^2/s
0	0	0	0	0	0	0
0.5	0.00056	0.000309	0	0.00061	0.000336	0
1	0.00056	0.000309	0	0.00061	0.000336	0
1.5	0.00056	0.000309	0	0.00061	0.000336	0
2	0.00056	0.000309	0	0.00061	0.000336	0
2.5	0.00066	0.000365	0	0.00072	0.000397	0
3	0.00066	0.000365	0	0.00072	0.000397	0
3.5	0.00066	0.000365	0	0.00072	0.000397	0
4	0.00066	0.000365	0	0.00072	0.000397	0
4.5	0.00076	0.000421	0	0.00083	0.000458	0
5	0.00076	0.000421	0	0.00083	0.000458	0
5.5	0.00086	0.000477	0	0.00094	0.000519	0
6	0.00086	0.000477	0	0.00094	0.000519	0
6.5	0.00091	0.000505	0	0.00099	0.000550	0
7	0.00091	0.000505	0	0.00099	0.000550	0
7.5	0.00111	0.000617	0	0.00121	0.000672	0
8	0.00111	0.000617	0	0.00121	0.000672	0
8.5	0.00136	0.000758	0	0.00149	0.000825	0.000040
9	0.00136	0.000758	0.000062	0.00149	0.000825	0.000246
9.5	0.00172	0.000954	0.000301	0.00187	0.001039	0.000506
10	0.00172	0.000954	0.000539	0.00187	0.001039	0.000765
10.5	0.00273	0.001515	0.000918	0.00297	0.001650	0.001138
11	0.00273	0.001515	0.001234	0.00297	0.001650	0.001344
11.5	0.02161	0.012008	0.003998	0.02354	0.013078	0.004354
12	0.02161	0.012008	0.006761	0.02354	0.013078	0.007364
12.5	0.00550	0.003058	0.007147	0.00600	0.003331	0.007784
13	0.00550	0.003058	0.007533	0.00600	0.003331	0.008204
13.5	0.00242	0.001347	0.004868	0.00264	0.001467	0.005301
14	0.00242	0.001347	0.002202	0.00264	0.001467	0.002399
14.5	0.00172	0.000954	0.001676	0.00187	0.001039	0.001826
15	0.00172	0.000954	0.001150	0.00187	0.001039	0.001253
15.5	0.00131	0.000729	0.000996	0.00143	0.000794	0.001085
16	0.00131	0.000729	0.000842	0.00143	0.000794	0.000917
16.5	0.00111	0.000617	0.000758	0.00121	0.000672	0.000825
17	0.00111	0.000617	0.000673	0.00121	0.000672	0.000733
17.5	0.00096	0.000533	0.000624	0.00105	0.000581	0.000680
18	0.00096	0.000533	0.000575	0.00105	0.000581	0.000626
18.5	0.00081	0.000449	0.000533	0.00088	0.000489	0.000581

19	0.00081	0.000449	0.000491	0.00088	0.000489	0.000535
19.5	0.00076	0.000421	0.000463	0.00082	0.000458	0.000504
20	0.00076	0.000421	0.000435	0.00082	0.000458	0.000474
20.5	0.00066	0.000365	0.000414	0.00072	0.000397	0.000451
21	0.00066	0.000365	0.000393	0.00072	0.000397	0.000428
21.5	0.00066	0.000365	0.000379	0.00072	0.000397	0.000413
22	0.00066	0.000365	0.000365	0.00072	0.000397	0.000397
22.5	0.00056	0.000309	0.000351	0.00061	0.000336	0.000382
23	0.00056	0.000309	0.000337	0.00061	0.000336	0.000367
23.5	0.00056	0.000309	0.000323	0.00061	0.000336	0.000351
24	0.00056	0.000309	0.000309	0.00061	0.000336	0.000336
24.5	0	0	0	0	0	0

Appendix 4- 3: Green roof retention percentage

Storm	Rainfall volume, m^3	Outflow volume, m^3	Retention %
2 yr	57.3	42.9	25.1
5 yr	69.8	55.4	20.6
10 yr	79	64.6	18.2
25 yr	91	76.6	15.8
50 yr	101	86.6	14.3
100 yr	110	95.6	13.1

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