A PLANNING TOOL OF URBAN GREENROOFS

By

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Abstract

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Current research does not integrate these benefits in the planning of green roof systems. The objective of this research is to develop a planning tool to evaluate storm water and energy benefits of a green roof structure. To demonstrate the planning tool, a case study of urban green roofs was conducted for three different building scenarios: residential, commercial and industrial buildings. Using the data collected at York University's green roof, the seasonal storm water and energy benefits in dollar values of each scenario were simulated.

The study concluded that it is more important to select a proper soil mixture and type of plant when designing a green roof system. By understanding the stormwater and energy benefits, it is hoped that this research could accrue through the adoption of green roofs in Toronto as well as other Canadian cities.

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Chapter 1

1.1 Introduction

Rooftop surfaces are the most commonly seen spaces in highly urbanized environments. However these spaces have been wasted and their potential environmental function has been neglected for many years. They have been called "the last urban frontier" (Peck, 2002) with their existence just used to provide space for ventilation systems and elevator mechanical infrastructure.

Green roof infrastructure is a proven technology that has become widespread in Europe where vast and vacant rooftop surfaces are being used to relieve numerous ecological problems. After decades of practice, millions of square meters of rooftops are still being transformed into greenery and space-cramped Germans have honed the practice to a fine art. Industry figures suggest that at least 20% of German roofs are now greened.

The residents of cities in North America are facing a considerable number of challenges including air and water pollution, and energy shortages. Green roof infrastructure may provide many of the solutions. Green roofs have begun to be installed across North America, steadily increasing in numbers over the past decade. Active in the greenroof community are Chicago, Illinois; Portland, Oregon; Washington D.C.; Vancouver, British Columbia; and Toronto, Ontario.

Storm water which runs off from roofs, buildings and roads collects grit, sediments, oil, grease, salt and pesticides and has become the primary source of pollution for many lakes and local watercourses. Global climate change has caused warmer average temperature in cities around the world. Many reports (Peck, 2002 and Velazquez, 2000) have identified the negative impacts of the 'urban heat island effect'. Common dark roofing surfaces convert solar radiation into heat during the day, trap the heat and release the heat to the surrounding air most noticeably at night. Rising summer temperatures especially under urban heat island conditions increase the chances of smog formation. More particulate matters circulate in the air and place increasing demands for energy to cool buildings and filter out particulates. More and more research is being conducted at North American universities on the impact of green roofs on the environment, economy, and energy resources (Liu, 2003 and Banting *et al.*, 2005). Researchers have conducted studies on many aspects of green roofs and pointed out two of the most significant benefits for installing green roofs are to mitigate storm water runoff and provide cost-saving benefits through energy use reduction (Liu, 2003 and Banting *et al.*, 2005).

1.2 History of Green Roof Infrastructure

Green roof infrastructure is not a new phenomenon. It has been applied as a standard construction practice for hundreds of years, since green roofs retain heat in buildings during cold seasons and keep the heat out in warm seasons. It also helps to counteract extremes in outdoor temperature both daily and annually. The application of green roofs can be traced as far back as the hanging gardens of Babylon as shown in Figure 1.1 (Pieper, 1987). These terraced structures, constructed around 500 B.C. were built over arched stone beams and waterproofed with layers of reeds and thick tar, then covered by soil and trees. During the Roman Empire, trees were planted on institutional buildings, such as the mausoleums of Augustus and Hadrian (Pieper, 1987).

For ancient Icelanders, green roofs originated from a lack of natural resources, so people had to make do with the local materials such as sod and stone (Magnusson, 1987). Roofs were usually completely covered by dense grasses and the thick walls of the structures contained bottom layers of stone followed by specially cut blocks of sod alternating with strips of thin turf as is found on one of the six sod churches that are still standing in Iceland (Figure 1.2).

Figure 1.1 - Artist rendering of green roofs in Babylon (The Garland Company Inc).

Figure 1.2 – Church in Vidimyri, Iceland (Magnusson, 1987).

roof in La Maison du Diable that was built in 1913 while Wright used rooftop gardens on Hollyhock House and Falling Water and the Horseshoe Inn.

1.3 Definitions of Green Roofs and Rooftop Gardens

A green roof is a continuous layer of vegetation and "soil" on top of a human – made structure. These green spaces are located on top of a structure, mostly on top of a roof. No matter what the location is, the vegetations are not planted in the "ground" which means ground level of a building structure. Green roofs are categorized into two distinct types of systems: extensive and intensive.

They are differentiated mainly by the cost, depth of growing medium and the choice of plants. Most of the green roofs that exist in North America are extensive green roofs, which have thinner and fewer layers. As a result, they are light, inexpensive, and virtually maintenance free. Examples are the Westwood Nature Center (Chagrin, Ohio), the Ford Motor Company's Rouge Assembly Plant (Dearborn, Michigan) and the Heinz 57 Center (Pittsburgh, Pennsylvania). Only a few green roofs are intensive. They are high-profile and provide high thermal and stormwater retention performance (e.g. Fairmount Waterfront Hotel in Vancouver, B.C.). The choices of which type of the green roof to be used depend on site specific factors such as location, structural capacity of the building, budget and plants availability etc.

1.4 Research Objective

Most of the research studies on greenroofs have focused on either stormwater reduction or reduced energy usage; but few studies have addressed both benefits simultaneously. The intent of this research is to develop a greenroof planning tool which addresses both stormwater and energy benefits. This planning tool can be used for the evaluation of green roof design performance in storm runoff reduction and energy saving. The planning tool uses a mathematical model which involves both water balance equations and thermal conductivity equations. The specific objectives of this research are listed below:

1) To determine the maximum loading and depth of soil substrate that can be sustained on existing roof tops by reviewing the loading considerations according to the loading requirements in Ontario Building Code 1997.

2) To formulate and develop a simulation model which simulate hydrological and energy budget of a green roof.

3) To estimate the cost and the potential economic benefits of stormwater and energy reduction for different type of buildings.

By understanding these benefits and costs, it is hoped that this research could accrue through the adoption of green roofs in Toronto as well as other Canadian cities.

1.5 Methodology

A combination of research methods has been used to determine the storm water reduction and energy efficiency benefits of the urban green roofs. A brief description of these methods and their respective chapters are discussed in the sections below.

1.5.1 Literature Review

Different types of green roof systems, their design specifications, and various benefits of green roofs are reviewed. A detailed review of storm water reduction and energy efficiency benefits is emphasized in this chapter as this is the focus of the research.

1.5.2 Components of Greenroof System and Loading Considerations

The first step to consider green roofs is to determine the feasibility of the project. Structural information is needed to determine if the building can support a green roof.

The most important structural information is the loading carrying capacity of the building. To obtain this information, loading capacities have been reviewed under the Ontario Building Code 1997.

Maximum depth of soil substrate can then be calculated by comparing the calculation results to the minimum live loading carrying capacity under the Ontario Building Code. Using the soil samples provided by National Research Council, soil properties and density were determined from geotechnical lab experiments. Total weight of soil substrate can be calculated from the depth and density of the soil. The total weight of the green roof system can be calculated by adding up the weight of each green roof component.

1.5.3 Greenroof Hydrologic/Energy Model

A water budget reflects the relationship between input and output of water through a define control volume. The control volume for our simulation model is the total area of greenroof on York University multiple by the substrate depth. The input of the water balance model is precipitation, while the outputs are evapotranspiration and runoff. It determines the amount of precipitation that can be stored in the growing substrate as well as the amount of runoff that is produced once the storage capacity of the green roof system is reached.

Inputs to the energy model are similar for both greenroofs and conventional roofs. The thermal resistance of each roofing components can be determined from published literature (Bass, 2003). The important feature to note here is the thermal conductivity of the soil substrate. Soil thermal conductivity is determined based on the equation proposed by Vershinin, P.V. *et al.* (1966) in Fundamentals of agrophysics.

1.5.4 Model Calibration and Sensitivity Analysis

The calibration of models consists of changing values of model-input parameters in an attempt to match data collected in the field. In this research, the field data are collected from an extensive green roof located at York University and some input parameters are provided by the TRCA (Toronto and Region Conservation Authority (TRCA).

Soil analyses were conducted on two commonly used green roof soil mixtures: Garland and Sporema. Standard physical properties of soil were measured by conducting sieve Analysis, pH test, Hydrometer test, Specific gravity test, Liquid limit test, Plastic limit test and shrinkage limit test.

1.5.5 Economic Costs and Benefits of Greenroofs

A case study is presented to demonstrate the potential economic benefits of different designs of green roofs. Three different building scenarios: residential, commercial/institutional and industrial buildings were selected for the case study. Land use is the main factor that determines the scales of implementation, types and designs of green roof systems.

Using the data collected from the York University's green roof, the amount of water retaining in the soil substrate as well as the runoff from a green roof are calculated. The seasonal storm water and energy benefits of each scenario are then determined.

The framework used for the following calculations was developed by Kuhn (1999) and the cost of green roof installation was derived from *Bass et al.* (2003). The calculations of the storm water benefits exclude yearly maintenance fees and assume a conservative ten year life cycle. Thus, the benefit per cubic meter of storm water retention by green roof systems is calculated as follows:

1. The measured runoff from the control roof at York University was used for the calculations.

2. The quantity of annual runoff from the control roof is determined by adding up monthly runoff values.
3. The runoff from the green roof is simulated by a hydrologic/energy model.
4. Thus, the volume of storm water retained by the green roof is calculated by subtracting the simulated green roof runoff from the measured runoff from the control roof on a per unit area basis.
5. The approximate cost of an underground storm water storage tank is $1340/m^3 (City of Toronto, 2003).
6. The annual stormwater benefit of the green roof system is calculated by the product of storm water retained by green roof and the cost to build an underground storm water storage tank.

The procedure to determine the best design of green roofs for each land use scenario is listed below:

1. The value of thermal resistance of each roof structure component is determined. The cross section of the roof structure as well as green roof structure is shown in Figure 1.3. Some of the thermal resistance (R values) are adopted from research done by Wong *et.al.* (2002) while others are found from Energy

Company's website such as Colorado Energy Company (Colorado Energy, 2006).

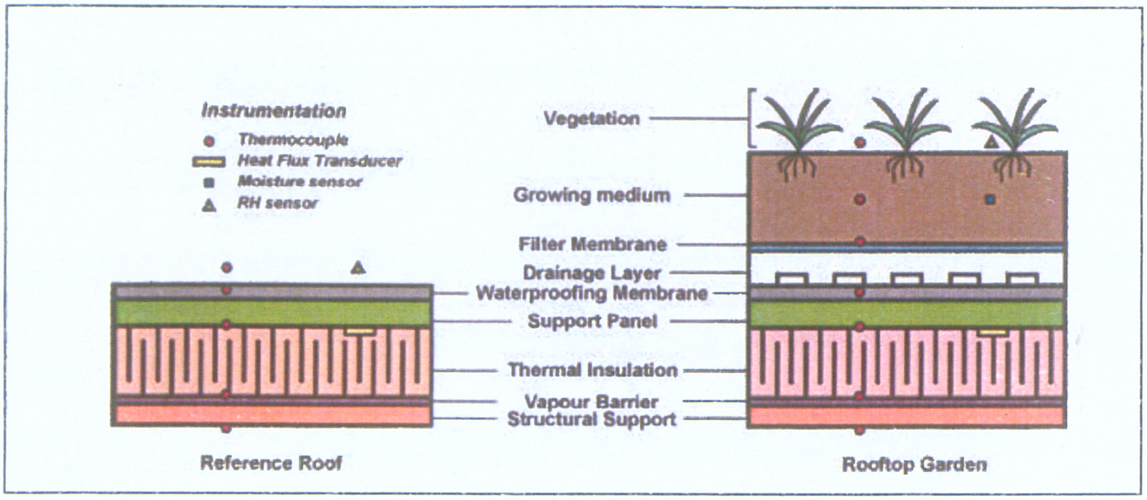

Figure 1.3 – Components of reference roof and green roof (Bass, 2003)

The sum of thermal resistance values (R values) of the reference roof and green roof are determined. The values are shown in Table 1.1.

Table 1.1

Thermal resistance (R value) of the components on reference roof and green roof

Roof components	Roof Resistance	Green Roof Resistance
Concrete Deck	0.12	0.12
Roof Membrane	0.031	0.031
Thermal insulation	0.977	0.977
Filter Fabric	0.075	0.075
Sand	0.094	N/A
Pavers	0.435	N/A
Outside air film	0.36	0.36
Drainage layer (insulcell 50)	N/A	1.429
Filter layer	N/A	0.029
Protection layer (insulflec 25)	N/A	0.002
Vegetation	N/A	0.36
Roof soil substrate	N/A	Determine by numerical energy model
Total Resistance	2.092	3.383

2. Steady-state heat flow is assumed and the rate of heat flow per unit area through a compound element is given by

$$q = \frac{1}{\sum R}\Delta t \quad (1.1)$$

Where

q (W/m^2) = Rate of heat flow per unit area through a compound element.

$\sum R$ (m^2K/W) = The total resistance, which is the sum of the individual resistance.

Δt (k) = The surface temperature difference, which will be the temperature difference of the room and the roof top.

3. The thermal conductivity (k value) of the soil substrate is calculated from the numerical energy model. To determine the thermal resistance of the soil substrate, the k value is divided by the thickness of the soil substrate.
4. The area of the York University's green roof is $241m^2$. By multiplying the roof area to the hourly temperature difference and the roof thermal conductivity of control and green roofs, the amount of heat flow at each roof can be determined.
5. An electricity cost of $0.1017/kWh is assumed (Banting *et al.*, 2005).
6. The annual energy consumption of both roofs in dollar values can be calculated by the product of total heat flow and electricity cost.
7. The annual energy efficiency of a green roof can be determined by subtracting the energy consumption of green roof from the control roof.

1.6 Assumptions and Limitations

In designing a green roof, the substrate type and the LAI (leaf area index) of plants play a critical role in determining the amount of precipitation that is retained within the soil substrate and lost as evapotranspiration. Thus, designers of green roofs will be investigated different combinations of substrate mixture and the LAI. For model calibration, it was assumed that literature values of the soil substrate and the LAI are representative of typical green roof components.

The surface temperatures of the conventional and green roofs are not available at the York University's green roof. Roof temperatures used in the model calibration are from another green roof located at Eastview neighbourhood Community Centre, East York, Toronto. In addition, the amount of solar radiation used for the calculation of cumulative evapotranspiration is based on the field data collected by UTMMS (University of Toronto at Mississauga Meteorological Station).

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Chapter 2

2.1 Green Roof Systems

As noted in the previous chapter, green roof systems can be categorized into two types: extensive and intensive. This chapter reviews the characteristics of extensive and intensive green roofs and their associated benefits.

2.1.1 Extensive Green Roofs

Extensive green roofs are designed to be low profile systems which provide modest thermal and hydrological benefits. Extensive roof systems are inexpensive to install and the capital cost in 2002 varied between $4.00 per square foot to $15.00 per square foot (Peck, 2002). Most of the extensive green roofs are not accessible to the public and they require very low maintenance frequencies (e.g. normally 2 - 3 times per year to remove invasive plant species). Listed below are some of the characteristics of extensive green roofs according to Peck (2002) are:

- Low weight - the saturated weight of an extensive system generally ranges from 70 to 170 kg/m^2.
- Low capital cost - averaging between $4 to $15 per square foot for the system and installation.
- Minimum growing medium - ranging from 5cm to 15cm.
- Low plant diversity - normally only one or two plant species.

- Minimal maintenance requirements - little or virtually no irrigation.

Extensive green roofs are on flat and pitched roofs like the Norwegian sod have as shown on Figure 1.2. They can be used on large flat roofs or surfaces with up to a 30 degree slope (Peck, 2002). The growing medium for extensive green roofs is typically made up of a mineral-based mixture of sand, gravel, crushed brick, peat, and organic mattes; and the range in depth is from 5 to 15 cm (Peck, 2001). The wet roof loads range from less than 72.6 kg/m^2 to approximate 169.4 kg/m^2 (Peck, 2001). Since the growing medium is shallow and flat, plants must be low and not easily destroyed by nesting birds or winds. According to Peck (2002), Prairie flowers and sedum species are the most commonly used plants in North America's extensive green roof systems.

Figure 2.1 – Extensive green roofs locate at Four Seasons Hotel in Boston, MA (http://www.roofmeadow.com/fourseasons.html)

2.1.2 Intensive Green Roofs

Intensive green roofs are designed to be high-profile with high thermal and stormwater retention performance. This type of green roof typically contains a variety of plant types and is designed as a park as shown on Figure 2.2.

Figure 2.2 – Intensive green roofs locate at Coast Plaza Hotel in Vancouver, BC (Rowe *et al.*, 2003)

Intensive green roofs are often accessible to the public. Some of the characteristics of intensive greenroofs are listed below (Peck, 2002):

- Heavy weight - the saturated weight of an intensive system generally ranges from 290 to 960 kg/m^2.
- High capital costs - hard to generalize given the uniqueness of each application.
- Deep growing medium - range from 20cm to 60cm.
- Increased plant diversity to provide wildlife habitat and improve aesthetics and landscape design.

- High maintenance requirements and irrigation systems are involved.

The minimum growing medium depth for intensive green roofs usually ranges from 20 to 60 cm, with a saturated weight ranging between 290 kg/m^2 to 960 kg/m^2 (Peck, 2001). Due to the high load, there are special requirements for the roof design, especially if the roof allows public access.

In addition, the plant diversity can be increased to include trees, flowers and shrub species with a deeper growing medium, which provide a more complex ecosystem. As the plant diversity is increased; maintenance requirements such as watering are also demanding. According to Peck (2001), irrigation systems are required to be installed for intensive green roof systems. Structural and landscaping consultations are also required. Some sites which have incorporated intensive green roofs at their buildings are Atlanta City Hall (Atlanta), North Burnham Park Redevelopment (Chicago) and Coast Plaza Hotel (Vancouver) (Jennings *et al.*, 2003).

Table 2.1
Comparison of Extension and Intensive Green Roof Systems

EXTENSIVE GREEN ROOF	INTENSIVE GREEN ROOF
• Thin growing medium; little or no irrigation; stressful conditions for plants; low plant diversity.	• Deep soil; irrigation system; more favourable conditions for plants; high plant diversity; often accessible.
Advantages: • Lightweight; roof generally does not require reinforcement. • Suitable for large areas. • Suitable for roofs with 0 - 30° (slope). • Low maintenance and long life. • Often no need for irrigation and specialized drainage systems. • Less technical expertise needed. • Often suitable for retrofit projects. • Can leave vegetation to grow spontaneously. • Relatively inexpensive. • Looks more natural. • Easier for planning authority to demand as a condition of planning approvals.	**Advantages:** • Greater diversity of plants and habitats. • Good insulation properties. • Can simulate a wildlife garden on the ground. • Can be made very attractive visually. • Often accessible, with more diverse utilization of the roof, i.e. for recreation, growing food, as open space. • More energy efficiency and storm water retention capability. • Longer membrane life.
Disadvantages:	**Disadvantages:**
• Less energy efficiency and storm water retention benefits.	• Greater weight loading on roof.
• More limited choice of plants.	• Need for irrigation and drainage systems requiring energy, water, materials.
• Usually no access for recreation or other uses.	• Higher capital & maintenance costs.
• Unattractive to some, especially in winter.	• More complex systems and expertise.

Table taken from "Greenbacks from Green Roofs: Forging a New Industry in Canada," (Bass *et al.*, 1998).

2.2 Storm Water Management Implications

The hydrologic impacts of rainfall and snowmelt events in urban areas are typically more problematic than those outside the cities. Under natural conditions, the majority of fallen precipitation is impeded from becoming runoff by vegetation, ground-surface depression storage, and subsurface storage in the form of soil moisture in the unsaturated and saturated zones. Urban landscapes are mostly covered by impervious surfaces which collect the majority of fallen rainfall to surface gutters, underground sewers and engineered channels. Eventually this urban runoff reaches the receiving waters often as a sudden surge (Jennings *et al.*, 2003). Contaminants encountered in the passage of this runoff are carried with the torrent, and these commonly include suspended solids, heavy metals, chlorides, oils and grease etc. as might be expected from the roadways and other surfaces the water has passed over.

Storm water Best Management Practices (BMPs) have provided a number of tools to improve storm water runoff quantity and quality. These include such devices as bio-retention areas, wet and dry detention ponds, constructed wetlands and sand filters. However, many BMPs require a significant amount of land to host them, which is not generally available in busy downtown environments. The opportunity for greenroofs to act as a storm water management practice is logical, since flat rooftops provide space that is not otherwise available on the ground (Jennings *et al.*, 2003).

Unlike some other BMPs, greenroofs may be able to offer controls and improvements on both the quantity and quality of storm water runoff. The Toronto and Region Conservation Authority retained Marshall Macklin Monaghan Ltd. to develop a hydrologic model using the Hydrologic Simulation Program Fortran, to simulate the storm runoff from the York University's greenroof in 2003 to 2004 (Maunder, 2004). The modelling results showed that the extensive greenroof in Toronto is able to reduce up to 25% of the existing peak flow volumes. Graham and Kim (2003) conducted a similar study in Vancouver and showed that suitably designed greenroofs have great potential to protect stream health and reduce flood risk to urban areas. The modelling results for a 50-year watershed retrofit scenario also showed that greenroof re-development on existing buildings could help to restore watershed health over time. Not only are greenroofs able to filter contaminants out of rainwater (Dramstad, 1996), but they can also degrade contaminants, either by direct plant uptake, or by binding them within the growing medium itself (Johnson *et al.*, 1993).

Numerous studies have demonstrated quantitatively that a properly installed and maintained greenroof will absorb water and release it slowly over a period of time, as opposed to a conventional roof where storm water is immediately discharged. Typically, extensive greenroofs, depending on the substrate depth, can retain 60 to 100% of the rain water they receive (Thompson, 1998). The amount retained also depends on numerous factors such as the volume and intensity of rainfall, the amount of time since the previous rainfall event, and the depth and saturation level of the substrate (Monterusso, 2003). Retain means precipitation becomes evapotranspiration instead of runoff.

Several studies that were conducted in Germany have shown that a greenroof with a substrate depth of 2 to 4 cm with a vegetation mix of mosses and Sedum can retain 40 to 45% of the annual rainfall that falls on it (Liesecke, 1998). By increasing the depth of the substrate to 10 to 15cm and changing the vegetation to a mixture of sedum, grasses, and herbs, greenroofs can retain up to 60% of rain water on an annual basis (Liesecke, 1993). Liesecke also indicated that there were noticeable differences between retention in warm weather versus cool weather. In warm weather, a shallow substrate depth can retain 11% more rain water than it can during cold weather (Liesecke, 1993). For deeper substrates, the effect was even more pronounced (20% more in warmer than cooler) cited in Banting *et al.* (2005).

Hutchinson and his team (Hitchinson et al., 2003) demonstrated similar findings: Within their 15-month monitoring period, they found that precipitation retention was approximately 69%. However between December and March the rainfall retention was 59%, while from April to November, rainfall retention was 92%. The differences of rainfall retention between warm weather and cold weather can be seen in Figure 2.3.

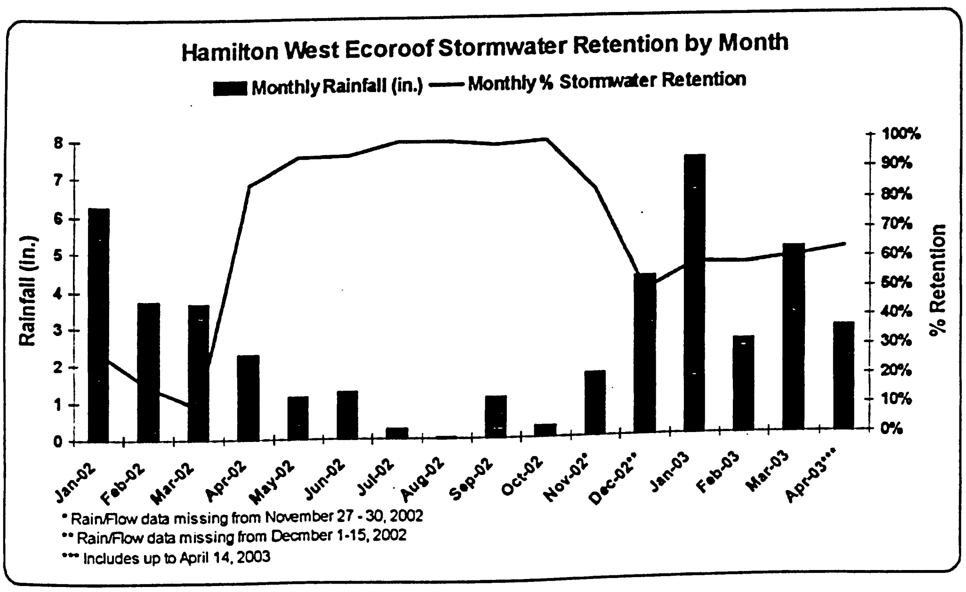

Figure 2.3 - Hamilton West Green Roofs Retention by 15 Months (Hutchinson *et al.*, 2003).

Research that was conducted by Jennings *et al.* in 2003 at North Carolina showed that a greenroof can retain up to 100% of the precipitation that falls on it in warm weather. However the percentage retained for each storm decreased when there had not been an adequate amount of time between storm events. As shown on Table 2.2, the percentage retained for each storm decreased with each respective rain event. The percentage of the storm water retained in their study dropped from 75% to 32%. According to the research results, Jennings *et al.* concluded that the capability of the greenroof retention is highly dependable on the volume, intensity of rainfall and antecedent conditions (Banting *et al.*, 2005).

Storm Event	Rainfall (in)	Greenroof Runoff (in)	Retained (in)	% Retained
7 April 2003	0.89	0.22	0.67	75
8-9 April 2003	1.02	0.57	0.45	44
9-11 April 2003	1.63	1.11	0.52	32

Table 2.2 – April 2003 Hydrologic Retention for the WCC Greenroof in Goldsboro, North Carolina (Jennings *et al.*, 2003).

Rowe *et al.* (2003) found a similar result during their study. Their results showed that on average greenroofs have capabilities to retain 60.6% of total rainfall. During light rain events (<2mm daily), their greenroof retained up to approximately 98% of rainfall, whereas the greenroof was only capable of retaining 50% of the heavy rain events (when rainfall >6mm). According to the experimental data provided by the TRCA (Toronto and Region Conservation Authority, 2003), greenroofs have an average peak flow reduction of 85%, 82%, 68% and 46% during storms ranging in sizes from 10-

19mm, 20-29mm, 30-39mm and ≥ 40mm (TRCA, 2003). TRCA reported that the water holding capacity of the substrate was found to depend on the volume and intensity of the rainfall and antecedent conditions, similar to Jennings *et al.* (2003) concluded. Furthermore, both Jennings *et al.* (2003) and Rowe *et al.* (2003) found that their greenroof was able to reduce the peak flow and the time to peak (by 2 to 4.5 hours) when compared to a standard conventional roof. Liu (2003) also found a storm water-runoff delay on greenroofs. As shown on Figure 2.4, rainfall started at 7:55 am on the 7th of April, 2003 and continued until 2:10 pm. However the runoff didn't start until 12 pm, while the peak of the runoff delayed until 12:55 pm. During a light rain (19mm in 6.5 hours), the greenroof delayed the discharge of storm water for 95 minutes.

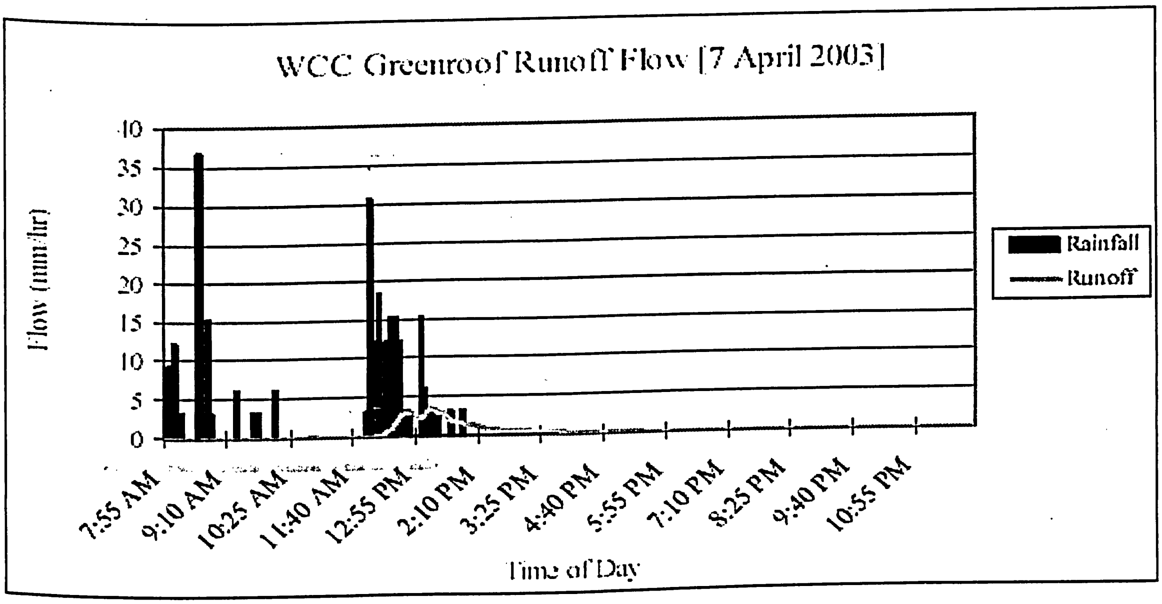

Figure 2.4 - Peak flow reduction of greenroof at WCC Greenroof in Goldsboro, North Carolina (Liu, 2003).

Several studies have shown that in most cases, increasing roof slope does not necessarily increase runoff volume. Liesecke (1999) conducted studies on a greenroof with 9 degrees of slope and found that the annual retention rates range from 55% to 65% which were considered comparable to 2 degrees of slope roofs. Research that was done by Rowe *et al.* (2003) also indicated that retention percentages were unaffected by greenroof slope. Schade (2000) had also reported similar findings that on greenroofs with slopes ranging from 2 degrees to 58 degrees there were constant water retention rates.

2.3 Energy Efficiency Implications

The level of worldwide urbanization has been increasing rapidly. The negative impacts caused by urbanization such as energy shortages, the urban heat island effect due to the changes in the thermal properties of surface materials and lack of evapotranspiration are common problem in many major cities. The best way to solve the problem of energy shortages is to save energy in any way possible. A greenroof can be considered as a tool for energy saving because it works as an insulating layer on top of buildings. A greenroof diminishes the amount of summer heat from solar radiation by the cooling effect from evapotranspiration and helps in reducing energy consumption. Greenroofs also help to reduce the strain on the heating systems and provide benefits during the winter months, the biological activity of the plants roots and bacterial processes in the soil will create heat as a bi-product of their natural processes (Miller, 2003).

Green roofs are basically composed of three layers; all these layers have insulating effects (Köhler *et al.* 2002). The top layer is a layer of plants that shades the surface of the substrate without blocking the air stream. Also biological functions of plants such as photosynthesis, respiration and transpiration can absorb a significant proportion of the solar radiation (Niachou *et al.*, 2001). The middle layer is a layer of 5 to 50cm of substrate. Its effect upon cooling depends on the kind of substrate applied. Usually substrate materials with lighter colour and higher porosity have better insulation ability. Lighter coloured materials allow less heat transfer through them. Materials with higher porosity can retain more air inside. Air is one of the best insulators; more air being trapped inside means the material can give higher insulation ability. The bottom layer includes the filter sheet and the drainage layer. It works as extra insulation to prevent heat gain or heat loss below this is the normal roof support structure.

Niachou *et al.* (2000) reported an experiment on a hotel roof situated in Loutraki region, Athens. They concluded that the green roof contributed to modulation of the air temperature inside of the building. During a typical summer day, lower indoor temperatures were measured in the building with a green roof system even without the operation of an air conditioning system. They also estimated the amount of energy saving for cooling the building with the green roof installed. It was about 37% energy saving for non–insulated buildings per year. It could be increased to 48% energy saving when night ventilation of 10 Air Charge per Hour was applied (Niachou *et al.*, 2001). Similar results are also found by Schmidt (2003) in Berlin where the extensive green roofs transferred 58% of radiation balance into evapotranspiration energy during the summer months. Figure 2.5 shows the daily energy balance on an extensive greenroof in summer months in Berlin.

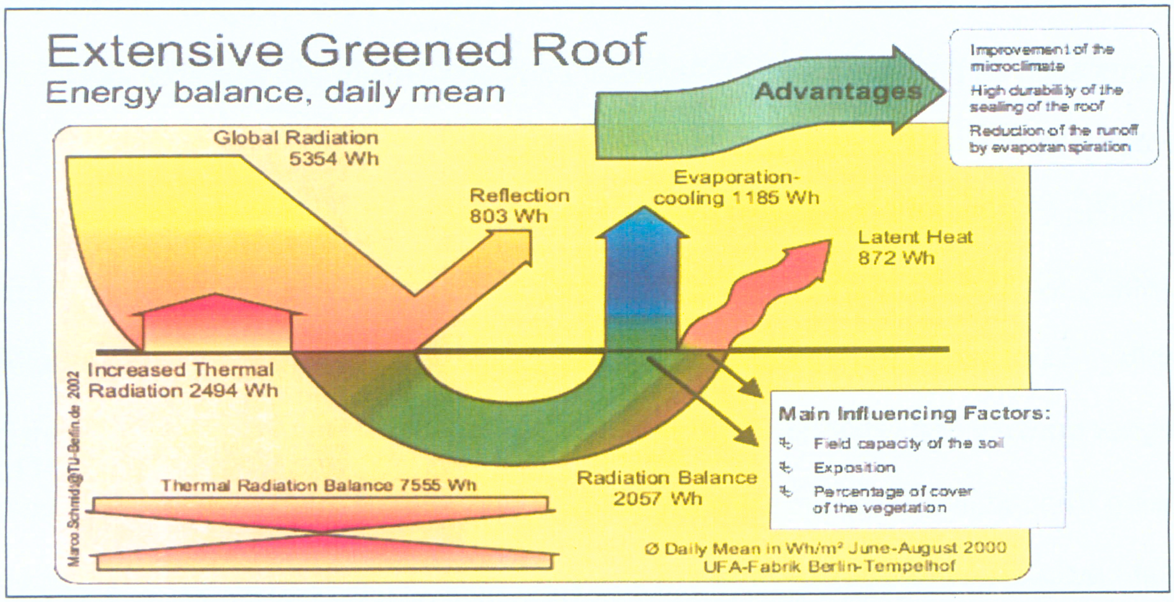

Figure 2.5 – Extensive green roofs transfer 58% of radiation balance into transpiration during summer months, UFA Fabrik in Berlin, Germany (Schmidt, 2003).

McPherson *et al.* (1989) constructed a one-fourth scale green roof model home in Arizona to investigate the relationship between landscape differences and energy consumption. They found that the turf landscape cut air-conditioning energy use by about 25% while the shrubs landscape cut air-conditioning energy use by about 27% (McPherson *et al.*, 1989).

Parker (1983) also had similar findings on a green roof in Miami, Florida. The landscaping was a combination of shrubs and trees. The experimental results showed a saving of 24% in the energy consumption (Parker, 1983).

Furthermore, researchers also found that foliage height and foliage density are strongly related to the effects of the energy phenomena. Theodosiou (2003) had done an experiment on an existing planted roof in the City of Thessaloniki, Greece. He found that by lowering the foliage height, the greenroof was less able to provide a cooling effect. As the foliage height is lowered, the solar radiation that can heat the soil surface and the cooling effects that evapotranspiration may offer will decrease (results shown on Figure 2.6 below).

In terms of foliage density, Theodosiou (2003) concluded that higher foliage density (express in Leaf Area Index – LAI) could provide better cooling capacity of the green roof because higher foliage density could provide higher an evapotranspiration rate. It is shown in Figure 2.7 that the green roof with a foliage LAI equal to three or four acts as a good cooling technique during hot days because high air temperature and low humidity values favour evapotranspiration. Also there is sufficient solar radiation to heat the soil and allow transpiration from the substrate (Theodosiou, 2003).

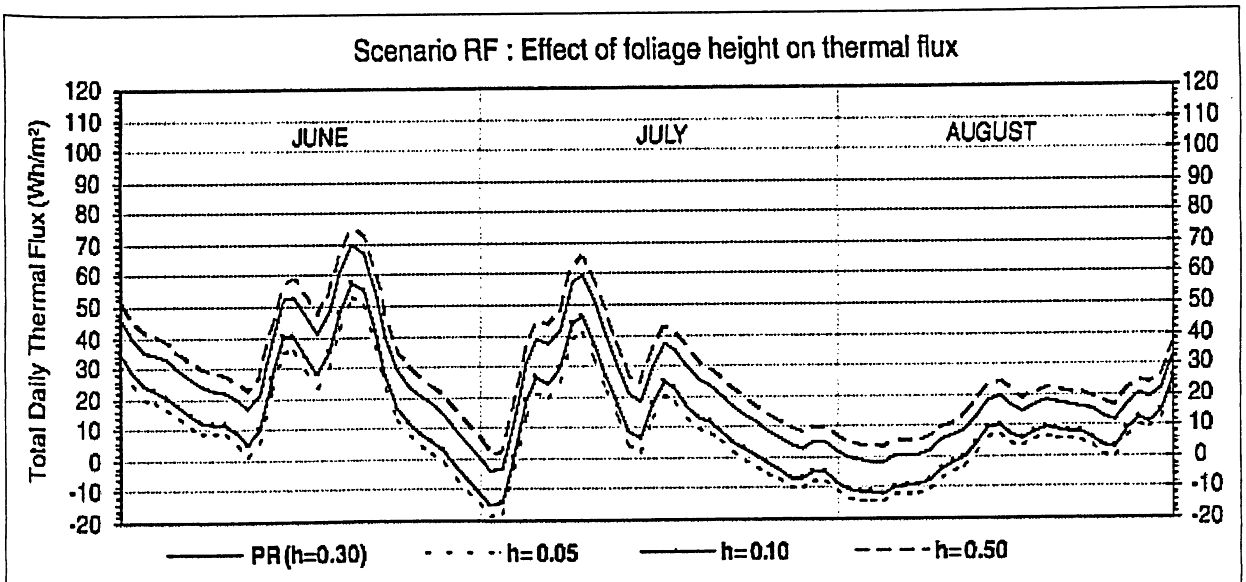

Figure 2.6 – Thermal flux through planted roof for different foliage height values (Theodosiou, 2003).

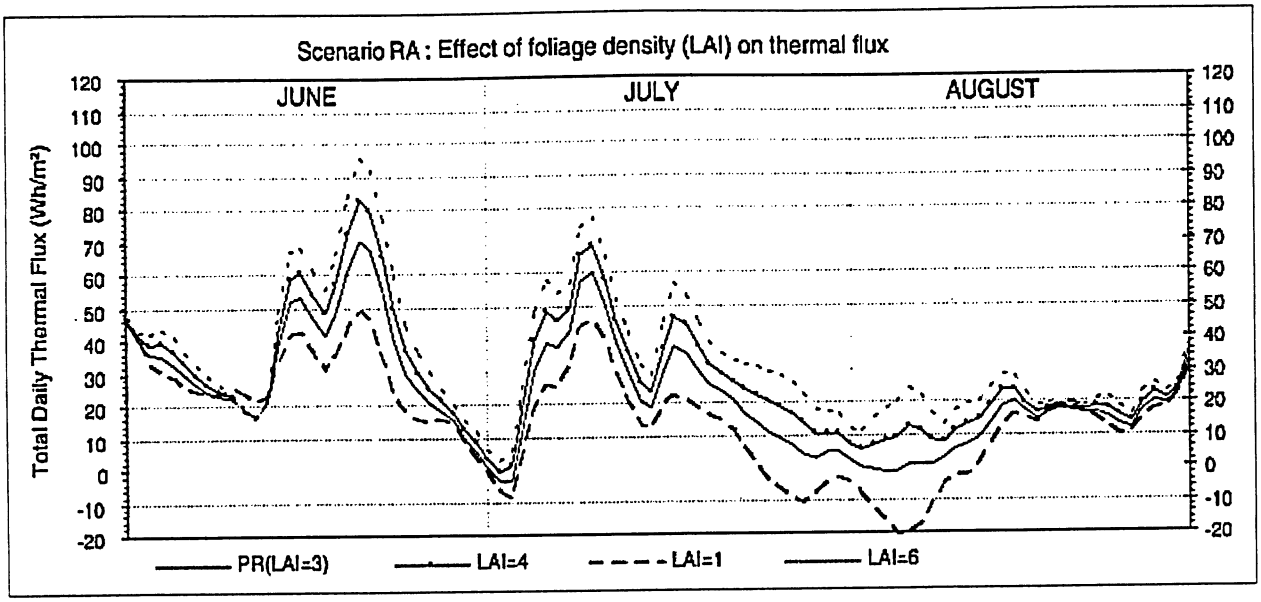

Figure 2.7 – Thermal flux through planted roof for different foliage density values (Theodosiou, 2003).

2.4 Air Quality

Deterioration of urban air quality is an ongoing problem in every city, including Toronto. Heat, sunlight and different pollutants interact to form smog, a harmful "photochemical stew" of ground level ozone which is known to aggravate respiratory problems. Cities are looking for solutions to reduce their air pollution levels. Evidence suggests that green roof systems are capable of improving the air quality within the city.

Green roofs can cool the surrounding air when soil moisture is absorbed by the plants and then released through evapotranspiration (Velazquez, 2000); which means less heat is able to be transferred from the roof top to floors below if buildings are installed with green roof systems. As the surrounding air is cooled, the thermal air movement around the building will be decreased. Velazquez (2000) suggested that by decreasing the thermal air movement around the building the air quality of the surrounding environment can be improved.

In addition, the plant foliage on green roofs rejuvenates the air, producing oxygen and absorbing carbon dioxide and other airborne toxins (Monterusso, 2003). Plants can act as a bio-filter solution as plants are able to filter out fine airborne particles and capture the particles that make up smog. When air moves across the plants gaseous pollutants are absorbed through photosynthesis or trapped on the leaf, branches and stem surfaces. These pollutants will stay on the plants' surfaces until it rains and they are washed into the soil. Velazquez (2000) suggested that about 0.2 kg of air borne particles could be removed annually by every square meter of green roof. People who suffer from asthma or other breathing ailments will benefit by the reduction of smog and other air pollutants (Peck, 1999).

2.5 Urban Heat Island Effect

An urban heat island develops when a high density of buildings raises the ambient air temperature by up to 6.7°C over surrounding rural areas (Osmundson, 1999). Urban areas consist of large impervious reflective surfaces that absorb solar radiation and radiate heat to other surfaces. According to Velazquez (2000), asphalt in parking lots and on rooftops, in particular, can soak up ultra violent radiation and radiate it as thermal infrared radiation. On hot summer days, the surface temperature of urban rooftops climb 50°F (10°C) to 70° F (21°C) hotter than the ambient air temperature. The heat is released after sunset resulting in a dome of higher temperatures over the cities. The ability of solar reflectance of common roofing materials is shown in Figure 2.8. It shows that the commonly used black asphalt rooftops have lowest reflectance ability and can only reflect approximate 6% of the solar radiation.

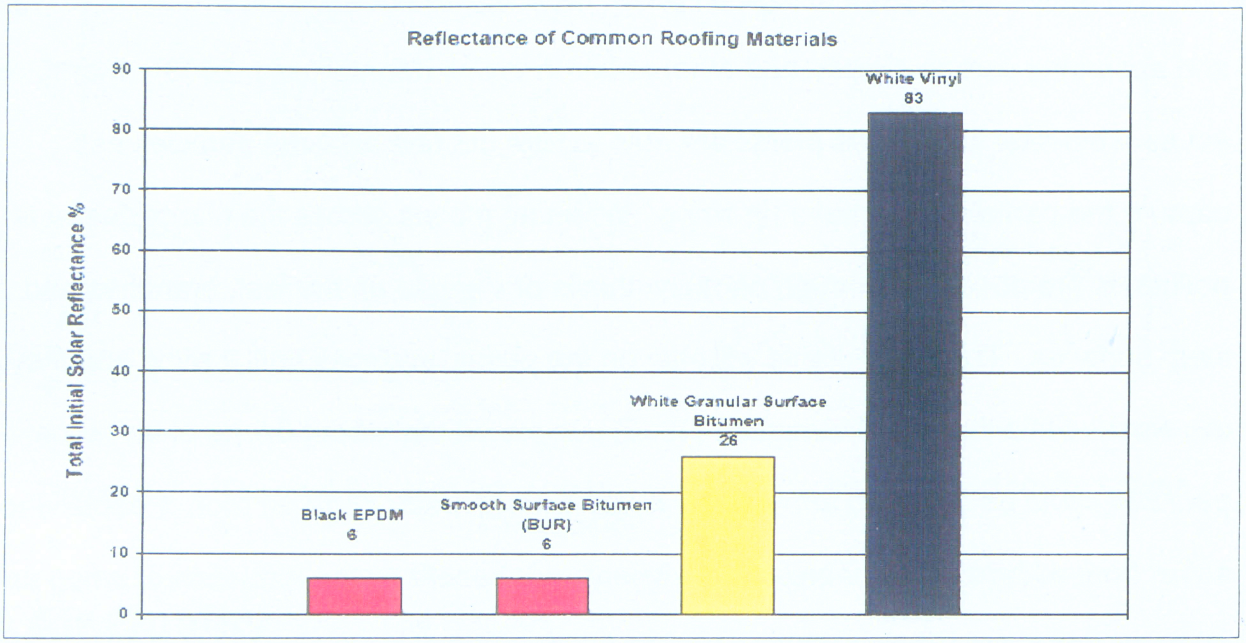

Figure 2.8 – Thermal flux through planted roof for different foliage density values (Theodosiou, 2003).

The canopy of biomass on a greenroof can reduce higher ambient air temperatures in an urban environment since part of the heat energy will be used up during evapotranspiration. Peck and Callaghan (1999) reported that 2% of the energy absorbed by a plant is used in photosynthesis; 48% of the energy is stored in the plant's water system and 30% is transformed into sensible heat. Only the remaining 20% is reflected back into the atmosphere. In comparison with a regular conventional roof, about 70% to 80% of the energy is reflected back into the atmosphere from a green roof.

Wong *et al.* (2003) reported that temperatures were up to 4.2°C lower on a green roof compared to a regular reference roof at a height of 300mm above both surfaces.

Also, vegetation on green roofs can help to reduce the urban heat island effect by absorbing solar radiation. Peck and Callaghan (1999) concluded that green roof systems are capable of regulating the extreme changes in temperature that commonly exist on a normal roof top. Green roofs can absorb heat energy during summer day time, decrease surrounding temperatures, and regulate humidity. During winter or at night, they can release the stored energy and heat from the plants. Thus, green roofs help to decrease the urban island effect by reducing the temperature differences in urban areas (Peck, 1999). Recent studies by the National Research Council of Canada have shown that by just converting 6% of Toronto's rooftops to greenroofs, the city would reduce summertime temperatures by 2°C (Empey, 2003).

2.6 Other Economic Benefits

There are many other benefits associated with green roofs that accrue to different research and experiments. However from a building owner's point of view, the support for using this system, a willingness to build a greenroof will vary depending on the beneficiary's perspective such as costs, amenities and marketability. Green roofs require a larger capital outlay than traditional roofs; however from a life cycle perspective, green roofs may be competitive with conventional roofs. The economic advantages that green roofs can provide to a building owner or developer over a long term are described in the following sections (Weir, 2004):

Extended Life of Roof Membrane

For most of the traditional, exposed conventional roofing systems, the service lives are ranging from 10 to 20 years. The protective benefits of Greenroofs provide extra protection to double and often triple the service life of roofs resulting in long-term savings on roof maintenance and replacement (Velazquez, 2000).

Energy Savings

The thermal insulation offered by green roofs can reduce energy costs for both cooling and heating. According to Environment Canada, an average one-story building with a grass roof and 10cm of growing medium would result in a 25% to 30% reduction in summer cooling bills (Peck, 2002).

Financial Savings from Storm Water Retention

"National Pollution Discharge System" and "Total Maximum Daily Load" regulations under the U.S. Clean Water Act have been recently amended to encourage communities to adopt more comprehensive strategies to manage stormwater discharge (Weir, 2004). Fees will be assessed according to the impervious surface area on a property that drains into a sewer infrastructure. This amended stormwater discharge fees are commonly referred to as "stormwater utility fees" or "impervious surface fees".

In Canada, "Land Drainage Utilities" have been established in year 2003 in Edmonton, Calgary, Strathcona County, Regina, Saskatoon, and Winnipeg (City of Edmonton, 2003). Users and business owners have already begun to look for ways to reduce their stormwater discharge and greenroofs may be a cost-effective measure to reduce these stormwater infrastructure or stormwater fees.

Green roofs can also be used as an amenity space for day care, meetings and recreation; Herman (2003) indicates that green roofs are commonly installed in Germany to replace lost green space due to urbanization. In addition, green roof systems also help to increase the aesthetic appeal, property value and marketability of the building. According to Green Roofs for Healthy Cities (CMHC, 2004), American and British studies show that buildings with accessible green roofs add 6% to 15% to the total market value.

Green roofs can also provide economic benefits of food production (Figure. 2.9).

Figure 2.9 – Urban agriculture with Sedum cucurbita 'Watermelonii' at Michigan State University (Michigan State University).

The Fairmount Waterfront Hotel restaurant in Vancouver boasts its own herb garden, in the midst of downtown Vancouver (CHMC, 2004). The south side of the roof was converted to an herb garden. The green roof herb garden (Figure. 2.10) supplies $20,000 to $25,000 of herbs to the restaurant annually, easily paying back the initial $25,000 construction cost (CMHC, 2004). Annual maintenance costs are approximately $16,000. In addition to herb production, the terraces also provide a desirable amenity to guests. Rooms that open to the south terrace feature with higher ceilings and more elaborate décor, and rent for $80 more per night than other rooms in the hotel (CMHC, 2004).

Figure 2.10 – Herb Garden locate at the Fairmount Waterfront Hotel, Vancouver (Theodosiou, 2003).

2.7 Design Considerations

There are many interacting factors that a green roof designer must take into account in order to achieve optimal performance. The only comprehensive green roof guidelines in existence today are produced by Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL), a landscape industry organization in Germany (Minor, 2005). An English version was issued in 2002 and was entitled as "Guideline for the Planning, Execution and Upkeep of Green Roof Sites". The National Institute of Building Sciences issued a Whole Building Design Guide (WBDG) in 2005, giving out design factors and considerations for designing extensive green roofs.

According to both design guidelines, the general considerations when designing a green roof are as follows:

Green Roof Function

Before the design process, the function of the green roof must be identified. The owner of the building needs to determine the main purpose of the green roof (e.g.

stormwater management, public access or habitat creation) (Velazquez, 2005). The size of the project, budget and degree of accessibility should be taken into the consideration as well.

Structure Loading

One of the major factors influencing the design of green roofs is the load bearing capacity of a roof structure. The load bearing capacity of a roof must consider both dead and live loads. Live load means snow and people - including maintenance workers and any other activities that the roof will need to support. Local snow loading requirement can be found from the local building code.

Vegetation

Vegetation that is able to stabilize soil, quickly repair itself from damage, absorb and transpire water despite extreme conditions of heat and cold, wind and drought should be chosen for greenroof. Also, the cost of the vegetation will be reduced by using local plant species instead of imported plant species.

Growing Medium (Soil)

The growing medium must meet the selected vegetation's nutrient, root aeration, pH and water needs. On the other hand, the structural load capacity of the building often determines the depth and material of the medium, which ultimately determines the vegetation that can be supported (Miller, 2005).

Water Drainage and Storage

The function of the water drainage layer is to move excess water away from the waterproof layer and prevent leaks. Roof drainage design must consider: stormwater management goals, roof slope and the depth and nature of the drainage material.

Currently, there are three main types of drainage material including granular materials (coarse gravel, stone, expanded clay etc.) that have large proportion of open space when packed together, sponge like porous mats that can absorb and hold water, and several types of synthetic drainage modules (Miller, 2005). The selection of the drainage materials and modules depends on the budget, structure loading capacity and local climate such as temperature and rainfall patterns.

Maintenance Requirement

A properly designed green roof should limit irrigation to new vegetation establishment and prolonged periods of drought (Miller, 2005). Typical green roof irrigation methods include: surface spray such as hoses and sprinkler heads, capillary which means mats hold water under the root zone for plants to take up, and standing water which means water is captured from large storms and held for future use. The selection of irrigation system depends on the budget, structure loading capacity and vegetation selection.

Roof Safety and Fire Prevention

If a green roof is designed for public access and/or recreation, it is imperative that safety measures are addressed during the design stage. Adequate protection should be provided in the following areas: safe access, fire escape, edge protection, designated walkway areas and anchorage points for maintenance (Velazquez, 2005).

The risk of fire on green roofs should also be a design consideration. It is important to ensure that an adequate supply of water is available at the greenroof. Plants that are inherently non-flammable should be chosen (e.g. succulents). Additional measures, such as the introduction of fire breaks, gravel areas kept free of vegetation, and strips of gravel around all roof penetrations, can be used to reduce fire risks (Velazquez, 2005).

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Chapter 3

3.1 Designing the Greenroof System

When designing a green roof system, it is vitally important to understand the characteristics of each element within the system. In particular, the structural loading capacity of the roof and the impact on the structural due to the additional imposed loads should be the first consideration.

Before a green roof is installed on a new building, one must start with a structurally sound and damage-free roof. The owners should hire professional structural engineers to design a roof structure that can withstand dead loads (e.g. insulation, waterproofing, vegetation, soil substrate mixture) and live load (e.g. snow and people). If the green roof is retrofitted on an existing building, the sum of dead and live load must meet the loading requirements of the Ontario Building Code.

3.2 Components of Greenroof System

The components that are used in extensive and intensive green roof systems are very similar, except for some variations in vegetation types, growing medium depth and slope. Green roof systems can range from a single layer of pre-grown vegetated mat to the conventional multiple layers of components.

A typical profile of a green roof system includes: a waterproofing membrane, root barrier, drainage layer, water retention layer, growing medium and vegetation. The design is dependent on the suppliers, material availability, budget and local climate. A wide range of materials is available for each profile. The components of a generic green roof system are listed in the following sections in the order of their placement from the top to the constructed roof surface.

3.2.1 Vegetation

The top layer on green roof system is a beautiful amenity which provides urban inhabitants with access to sunlight and fresh air. Scrivens (1999) noted that all plants require light, water, nutrients and mechanical support. Most plants can grow well on a roof if the above requirements can be satisfied. The limitations are climate, structural design and maintenance budgets. Del Barrio (1998) concluded that plants with the ability to provide shade to the roof surface should be selected for green roof systems. Plants with large foliage and/or with a mainly horizontal leaf distribution should also be selected, in order to guarantee low solar radiation transmission between the rooftop and the building.

Plants that are most commonly used are succulents and low-growing plants that are capable of storing water in fleshy leaves, bulbs or roots. Plants successfully used in shallow soil beds on extensive green roof surfaces include various species of sedum, sempervivum, allium, phlox, creeping thyme and aubrietia etc (Emory Knoll Farms, 2005). In North America, sedum (Figure 3.1) has become very popular for green roofs. As recommended by Scholtz-Barth (2001) and Scrivens (1999) a variety of hearty wildflowers and native grass species can also be used on extensive green roofs. Scholtz-Barth noted that native grasses of high drought tolerance are beneficial to rooftop greening. Table 3.1 lists the preferred green roof plant list in North America created by Emory Knoll Farms, Maryland (2005) after two years of researching and testing on several hundred varieties of plants.

Table 3.1 – Preferred green roof plant list in North America

• Allium schoenoprasum
• Delosperma nubigenum 'Basutoland'
• Sedum acre 'Aureum'
• Sedum album
• Sedum album 'Murale'
• Sedum floriferum 'Weihenstephaner Gold'
• Sedum kamtschaticum
• Sedum reflexum
• Sedum sexangulare
• Sedum spurium 'Fuldaglut'
• Sedum spurium 'John Creech'
• Sedum spurium 'Roseum'
• Sedum spurium 'White Form'
• Talinum calycinum

These plants are preferable since they will thrive in a wide range of hardiness zones, soil depths and climatic conditions. Pictures of sedum are shown in Figures 3.1 and 3.2, indicate that sedum has a very dense foliage development which helps to intercept more precipitation as well as reduce solar radiation transmission between the rooftop and the building.

Figure 3.1 – Sedum reflexum, picture from Emory Knoll Farms, MD (2005).

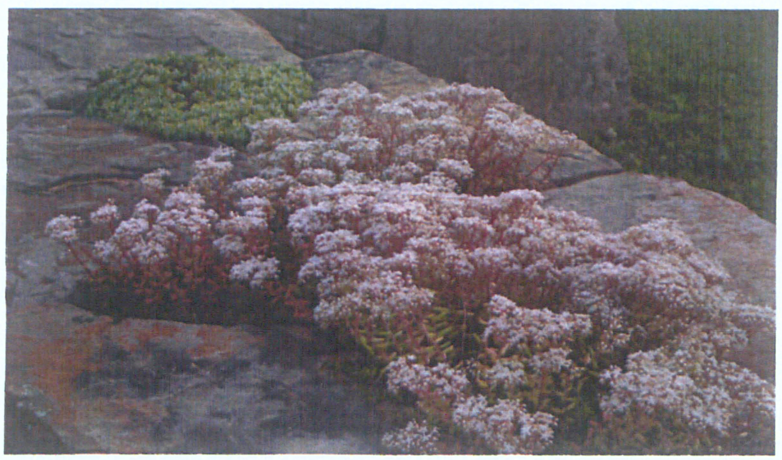

Figure 3.2 – Sedum album, picture from Emory Knoll Farms, MD (2005).

3.2.2 Substrate

The substrate of green roof systems should not be confused with normal planting soil. According to Scrivens (1999) the most important substrate properties are stability, saturated weight, depth, drainage, readily available water, cation exchange capacity (CEC) for nutrient availability, pH and soluble salt buffering. The depth of the substrate is dependent on the type of green roof, vegetation and most importantly the loading capacity of the building. According to Scholtz-Barth (2001), a typical extensive green roof system should have a weight of approximately 15 lbs/foot square which is equal to 73.2 kg/m^2.

Normally a substrate that can hold 25 to 38 percent of its volume in water is considered sufficient. Johnston and Newton (1993) concluded that the ideal substrate should contain 30 to 40 percent firm substance, 35 to 45 per cent water and 15 to 25 per cent air.

Scholtz-barth (2001) recommended the use of stockpiling topsoil from the site prior to construction. In order to increase water retention, this soil should be mixed with expanded clay or slate (a fine-grained rock formed by the metamorphosis of clay). However, Kolb and Schwartz (1986) advised that local topsoil is often subject to severe infestation by weeds and not suitable for use on green roof systems. After investigating five different substrates mixes, Kolb and Schwartz (1986) noted that substrates containing a high proportion of organic matter are subject to volume reductions resulting from mineralization. They determined that all mixes showed a 20% loss in volume due to natural settling (Kolb and Schwartz, 1986).

3.2.3 Filter Layer

Between the growing medium and drainage layer lies a filter which allows water to flow through while retaining the growing medium. Commonly-used filter materials are non-woven material such as glass fibre, water-resistant polyester fibre mats or polypropylene – polyethylene mats which include geo-textiles with a maximum loading of 140 g/m^2 (Davis, 2002).

Peck (2001) advised that the filter layer also serves as a root barrier and one of the filter layers may be treated with a root inhibitor (copper or mild herbicide). A jute mat may be required to prevent substrate erosion into the drainage system if a green roof is installed on a roof with a slope of twenty degrees or more. Drefahl (1998) recommended that a fleece layer should be placed over the drainage layer to assure that water is evenly distributed throughout the roof surface and its loading is evenly distributed.

3.2.4 Drainage Layer

Between the planting medium and the roof membrane is a layer through which water can flow from anywhere on the green roof to the building's drainage system. The main function of a drainage layer is to protect the building's roof structure from being damaged by the weight of accumulated water, to aerate plant roots, and to drain rainfall from the roof. Most of the green roof companies such as Garland and Xero flor Canada Ltd. use a corrugated plastic drain mat with a structural pattern which resembles an egg carton with water storage. Once the mat is fully saturated, excess water can drain out through the perforations on the top of the drain mat. Wark *et al.* (2003) advised that landscape pavers could be used as drainage layers as they would provide sufficient flow and the necessary compression strength.

The thickness of the drainage layer is usually less than 20mm. In some cases, a thicker mat may be required to provide additional insulation and roots restriction (Wark *et al.*, 2003). Kolb and Schwartz (1986) a drainage layer of a 3cm layer of 2-6mm lava or 2-8mm clay granules is recommended. It has the ability to retain 30 to 40% of the precipitation that falls on the roof, resulting in better stormwater reduction benefit.

3.2.5 Protective Layer

The roof's membrane needs protection against building structure movement, temperature changes, damage during the green roof installation and fertilizers. The protective layer can be a slab of lightweight concrete, sheet of rigid insulation, thick plastic sheet, cooper foil or a combination of various materials (Wark, 2003).

The layer lies on top of the insulation layer and works like a root protection barrier covering the insulation layer. If the plants are particularly aggressive, plant roots will follow paths of moisture and perforations in the insulation will become damp. If insulation absorbs as little as 4% moisture by volume, it can lose 70% of its thermal efficiency (McMarlin, 1997). Thus, careful consideration must be taken when choosing the protection layer.

3.2.6 Underlayment (Insulation)

Wark (2003) noted that greenroof systems should have provided sufficient thermal protection. He suggests that there is no need for additional insulation layers in warm or cold climates. According to Part 9 in the Building Code, a level of added insulation is required, regardless of the overall roof design, to increase energy efficiency. As mentioned in the previous section, an insulation layer will lose its thermal efficiency by absorbing moisture. Therefore McMarlin (1997) recommended that cellular glass insulation with a sealed surface and polystyrene board be used for insulation materials as water is unable to accumulate in these products.

3.2.7 Waterproof Roof Membrane

Johnston and Newton (1993) stated that the waterproof roof membrane should "be flexible, have good tensile strength, be easy and efficient to join and be relatively low adhesion to underlying materials."

There are various types of waterproofing systems: built – up roofs, modified bitumen, single – ply, fluid – applied and metal (Scrivens, 1999). Basically, any kind of waterproofing system can be installed for a greenroof system. However in recent years, single – ply membranes have become very popular. Ply membranes such as Thermoset (EPDM – ethylene/propylene rubber) and Thermoplastic (PVC – Polyvinyl chloride & TPO) are plastic or rubber membranes which are typically 39 mils to 60 mils thick (Scrivens, 1999). Wolley and Kimmins (2000) recommended the use of EPDM as it comes with better ratings as environmentally friendly products. In addition, EPDM is one of the most durable membranes over a broad range of temperatures. They indicated that EPDM serves for a longer period of time and gives better economic benefits on a greenroof system.

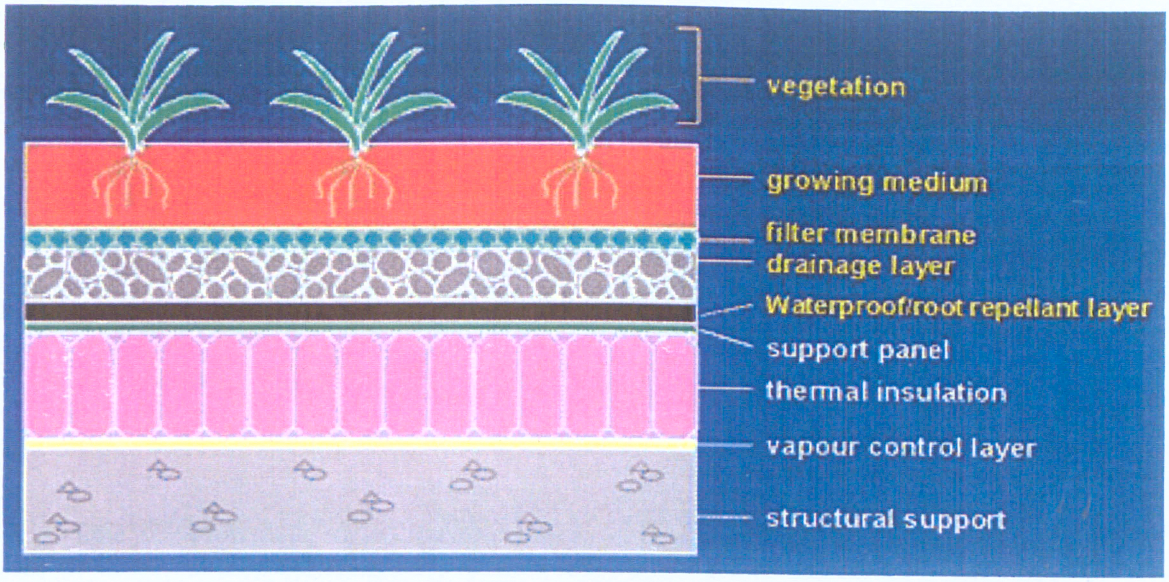

Figure 3.3 – Principal Green Roof Technology Components, (Liu, 2003)

3.3 Loading Consideration

Structure loads are forces applied to a component of a building or to the building. In any building design, loads are always a primary consideration as they define the nature and magnitude of hazards or external forces that a building must resist to provide reasonable performance throughout the structure's useful life. Design loads are influenced by different national, provincial and local codes for types of structures, geographic locations, and a building's intended use (Luebkwman, 1996).

Loading is one of the key factors in designing green roof systems, particularly on existing buildings. It is crucial to have a structural engineer or other capable licensed professional determine the roof's maximum weight loads, in addition to local snow loading requirements (Velazquez, 2005). The magnitude of the design loads will affect the selection of roofing material, soil mixture, vegetation and substrate depth. When designing an optimized green roof, loading consideration must be taken realistically to satisfy both economic and environmental benefits.

3.3.1 Ontario Building Code 1997

A Building Code is a collection of rules, regulations and requirements that specify the minimum acceptable level of safety for constructed objects such as building and non-building structures. The purposes of the code are: to protect the health, safety and welfare of the public and building occupants, to keep construction costs down, to provide consistent standards in construction and to contribute to the well being of a community (International Code Council, 2000). The building code becomes law of a particular jurisdiction when formally enacted by the appropriate authority.

Ontario Building Code 1997 consists of the Building Code Act and O. Reg. 403/97 (July 1, 2005 update containing O. Regs. 245/04, 146/05, 236/05 and 389/05). The Ontario Building Code is a collection of regulations and requirements which pertain to specific subjects that regulate specific practices for construction of all buildings in Ontario. The purpose of the Ontario Building Code is to provide standards and ensure safety for the design and construction of all buildings in Ontario. It also helps to maintain the consistence of quality and durability of construction and construction materials. The Province of Ontario is responsible for the development of the Ontario Building Code, the Ontario Building Code Act and other cost-effective building regulations. The enforcement of the Act and Code is the responsibility of each municipality in the areas that fall within its jurisdiction.

Unlike Germany and other European countries which regulate the construction process, materials as well as loading restrictions on green roof systems, neither the National Building Code of Canada, 1995 nor the Ontario Building Code 1997 discusses anything in regard to the installation of green roof systems (Peck, 2001). The design loadings that are being used in the green roof system loading plans are based on Ontario Building Code 1997 Section 4.1.6.3 - Specified Uniformly Distributed Live Loads on an Area of Floor or Roof (OBC, 1997). Live loadings that apply on the rooftop are assumed to be uniformly distributed across.

3.3.2 Roof Loadings

There are two types of roof loadings: dead and live loads. Dead loads refer to the weight of the roof structure itself and any permanent fixtures situated on the roof such as climate control unit (heating or air conditioning) and light fixtures. These are permanent and stationary loads unless renovation takes place. Live loads are weights imposed by use and occupancy or temporary loads applied to buildings which can change in magnitude (Fiesette, 1997). According to Fisette (1997) live load is defined as “weights imposed by use and occupancy”. Live loads can come from snow, rain, cars or even people.

Buildings are designed with a live loading capacity so as to accommodate any weights beyond the dead load or future load occupancy changes. According to the Ontario Building Code 1997 Section 4.1.6.3 Specified Uniformly Distributed Live Loads on an Area of Floor or Roof, the minimum live load carrying capacity for residential areas is 1.9 kPa (within the scope of Article 2.1.1.2). According to the scope of Article

2.1.1.2, the residential areas are the sleeping and living quarters in apartments, hotels or motels. The minimum live load carrying capacity for commerical buildings (retail, institutional and wholesale areas) and industrial buildings (factories) must meet or exceed 4.8 kPa and 6.0 kPa respectively. The minimum specified loading for the different usage of buildings are summarized in Table 3.2.

Table 3.2 – Summary of minimum specified loading on roof top

Function of the building	Minimum Specified Load, kPa	Minimum Specified Load, kg/m^2
Residental	1.9	193.7
Commerical (retail / wholesale areas / office areas)	4.8	489.3
Industrial (factories)	6.0	611.6

3.3.3 Greenroof Loading Plans

"Regardless of how light a green system may be, the provision must be made for both the weight and dimensions of equipment and material which may be used at various stages of construction and maintenance of the roof" (UK Nature Conservancy Council, 1990). Therefore, loading plans for green roofs should be developed according to the building's function as mentioned in the previous section. Since the minimum live load carrying capacity for residential, commercial and industrial are different, loading plans should be developed for three different scenarios:

- Scenario one – loading plan residential buildings.
- Scenario two – loading plan commercial buildings.
- Scenario three – loading plan on industrial buildings.

Total loadings in each scenario must be less than the minimum specified uniformly distributed live loads carrying capacity. Loading plans for each scenario can be seen in Table 3.3 to 3.5. The total loadings are calculated by adding up the weight of all the green roof elements. Loadings for most of the green roof system components will be the same for all scenarios, except for the vegetation and the soil substrate layer. The minimum specified uniformly distributed live loads carrying capacity of each scenario can be determined from the Ontario Building Code 1997, while loadings for different green roof components can be found on green roof companies' website such as Zinco green roof system (http://www.zinco.de). After making the above determinations, we work our way backwards in terms of accounting for the maximum depth of soil substrate in each scenario. The substrate thickness is then used to estimate the storm water and energy benefits of the green roof (Chapter Six).

Table 3.3 – Scenario one: loading plan on residential buildings

Layer	Thickness (m)	Density (Kg/m^3)	Loading per unit area (Kg/m^2)	Note
Wild flowers	N/A		5	A
Soils (assume 5 cm)	0.05	1250	63.5	B
Drainage layer (FD 40)	0.04		6	C
Filter membrane (polyester)			0.16	D
Protection layer (root barrier)			5	E
Polystyrene Insulation Board	0.037	16	0.592	F
Snow/Rain (Live Load)			101.9	G
		Total	182.2	

Note:

A – Design load according to the Zinco Green roof system

B – Soil assumed to be Sandy loam, wet density is about 1250 Kg/m^3 (Peck, 2001).

C – Design load according to the Zinco Green roof system

D – Design load according to National Research Council Experimental Greenroofs (Liu, 2002)

E – Design load according to the Zinco Green roof system

F – Design load according to Polytechnical University Green roof design system provided by Dr. James Li

G – Design load according to Ontario Building Code 1997, Table 2.5.1.1, Design Data for Selected Locations in Ontario, Snow and Rain Composite Load, Toronto

Table 3.4 – Scenario two: loading plan on commercial buildings

Layer	Thickness (m)	Density (Kg/m³)	Loading per unit area (Kg/m²)	Note
Shrubs and low bushes	N/A		10	A
Soils (assume 15 cm)	0.15	1470	224.0	B
Drainage layer (FD 60)	0.057		35.2	C
Filter membrane (polyester)			0.16	D
Protection layer (root barrier)			5	E
Polystyrene Insulation Board	0.037	16	0.592	F
Snow/Rain (Live Load)			101.9	G
		Total	377.0	

Note:

A – Design load according to the Zinco Green roof system

B – Soil will be Silt loam; Wet weight of soil is about 1600 kg/m3 (Peck, 2001).

C – Design load according to the Zinco Green roof system

D – Design load according to National Research Council Experimental Greenroofs (Liu, 2002)

E – Design load according to the Zinco Green roof system

F – Design load according to Polytechnical University Green roof design system provided by Dr. James Li

G – Design load according to Ontario Building Code 1997, Table 2.5.1.1, Design Data for Selected Locations in Ontario, Snow and Rain Composite Load, Toronto

Table 3.5 – Scenario three: loading plan on industrial buildings

Layer	Thickness (m)	Density (Kg/m^3)	Loading per unit area (Kg/m^2)	Note
Shrubs and bushes up to 1.5m	N/A		20	A
Soils (assume 15 cm)	0.15	1470	224.0	B
Drainage layer (FD 60)	0.057		35.2	C
Filter membrane (polyester)			0.16	D
Protection layer (root barrier)			5	E
Polystyrene Insulation Board	0.037	16	0.592	F
Gravel surfaces			100	G
Snow/Rain (Live Load)			101.9	H
		Total	487.0	

Note:

A – Design load according to the Zinco Green roof system

B – Soil will be Silt loam; Wet weight of soil is about 1600 kg/m3 (Peck, 2001).

C – Design load according to the Zinco Green roof system

D – Design load according to National Research Council Experimental Greenroofs (Liu, 2002)

E – Design load according to the Zinco Green roof system

F – Design load according to Polytechnical University Green roof design system provided by Dr. James Li

G – Design load according to the Zinco Green roof system

H – Design load according to Ontario Building Code 1997, Table 2.5.1.1, Design Data for Selected Locations in Ontario, Snow and Rain Composite Load, Toronto

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Chapter 4

4.1 Greenroof Hydrologic/Energy Model

During the late '80s and '90s a considerable number of research works on the potential water retention by and runoff from green roof systems were done in Germany (Kohler, 1998). Water balance models for green roof systems were also developed. However these models are dependent on the local climatic conditions such as yearly precipitation, temperature and solar radiation etc. It is almost impossible to calculate the storm water retention capacity of green roofs at other locations unless similar local climatic conditions are modelled. Furthermore, since the source codes for the German model are usually unavailable, it is also not possible to modify them to fit North America climatic situations.

4.2 Hydrologic Components

There are various models for simulating rainfall-runoff processes of a greenroof. Most of the models are based on the water balance equation. Each model has its own advantages and disadvantages with regard to data requirements, computing time and resources. The choice of models in this research is highly dependent on the available data and flexibility of model parameters.

4.2.1 Theoretical Basis

According to water budget analysis research that was done at the Watershed Science Centre, Trent University, Ontario (2000), a water budget analysis is a computational technique that balances water input and output while accounting for change in storage. Before going into the concepts of water balance, one has to understand the components of the hydrologic cycle first. The hydrologic cycle describes the processes of motion, loss and recharge of water for a particular site. The processes can be visualized as shown in Figure. 4.1. The cycle may be divided into the following principle components: precipitation, interception, evaporation, transpiration, infiltration, percolation, inter flow, overland flow and groundwater flow.

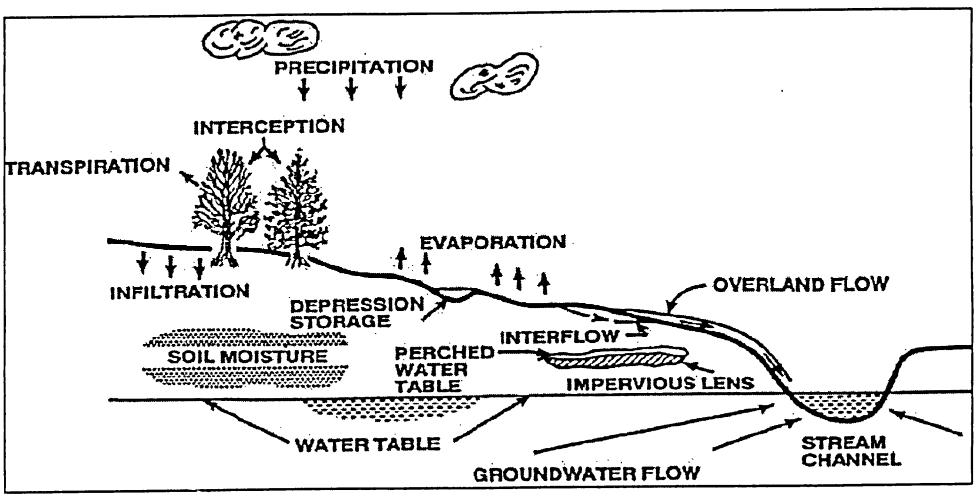

Figure 4.1 - Major pathways of precipitation and the runoff phase of the hydrologic cycle (Wetzel & Likens, 1991)

Any exposed surface may be considered as a unit area on which the hydrologic cycle operates, for example a lake, a river basin or the roof of a building. A water balance is based upon the above noted hydrologic components and is expressed as a mathematical relationship of various hydrologic components.

The general structure of all water balance models is similar and it relates the rates of change of water properties within a control volume to the flow of these properties across the control surface (Xu, 2003). For example, a simple soil water balance model for a control volume drawn around a block of soil (e.g. a green roof system) consists of the input precipitation and output evapotranspiration or runoff as shown in Equation (1)

$$S(t+1) = S(t) + P(t) - AE(t) \qquad (4.1)$$

In which S (t) represents the amount of soil moisture stored at the time t; S (t+1) is the storage at the later time t+1; P (t) and AE (t) represent the precipitation and evapotranspiration respectively for the same time period.

This model simplifies the water balance by using a bucket approach in which precipitation will not create runoff until the field capacity has been reached. The field capacity is a measure of how much water the substrate can hold against the influence of gravitation.

There are two processes that have been incorporated in the green roof hydrologic component of the model: vertical and horizontal. The vertical process of water movement involves vegetation, multi layers of soil, and green roof structural components. This vertical water movement includes interception, throughfall, evapotranspiration, infiltration, soil moisture storage and percolation. The horizontal water movement includes surface runoff. The water movement at a green roof system is shown in Figure 4.2. Details of each process are discussed in the following sections.

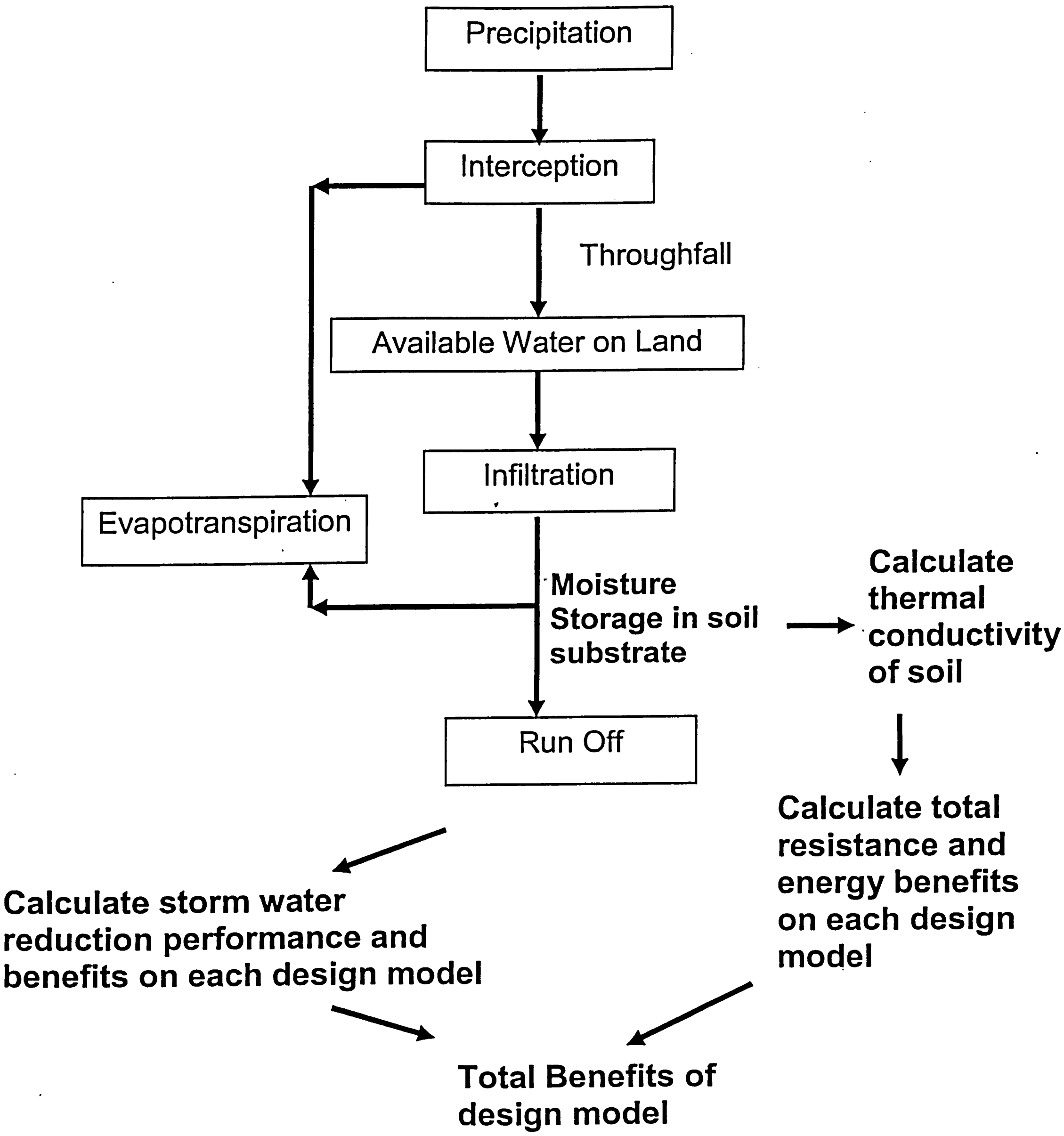

Figure 4.2 - Vertical process of water movement

4.2.2 Formulation of the Hydrologic Model

The purpose of the model is to determine the field capacity of the soil substrate (i.e. how much water the substrate can hold under the influence of gravitation). The computational procedure is listed below:

1. Organize the raw precipitation data (e.g. data collected from York University's greenroof).
2. Input organized precipitation data
3. Calculate amount of interception
4. Calculate amount of throughfall (precipitation minus interception)
5. Calculate amount of infiltration
6. Calculate amount of evapotranspiration
7. Calculate change of soil moisture in each time step (infiltration minus evapotranspiration)
8. Calculate actual soil moisture in each time step
9. Calculate amount of runoff

Details of each step for the case study at York University, Toronto, are described in the following sections.

4.2.3 Precipitation

The York University Rooftop Garden was installed in September 2002, while the monitoring and maintenance started in the following year of April. The green roof is located atop the York University's computer science building, at the southeast quadrant of the roof and over the auditorium. The green roof consists of a 140mm substrate and is vegetated with wildflowers. The substrate is composed of crushed volcanic rock, compost, blonde peat, cooked clay and washed sand and was designed to be light weight, retain water and resist compaction (TRCA, 2005). Also the rooftop garden has a downward slope of about 10% from south to north and covers an area of 241 m^2. A non-vegetated control roof is also designated beside the green roof and its area is 131 m^2, about half the size of the green roof (as shown in Figure 4.3). Precipitation was continuously monitored every five minute in 2003 and 2004.

Precipitation at the site was continuously measured using a Hydrological Services tipping bucket rain gauge. The rain gauge has a measuring range of 0 to 500 mm/hr with an accuracy of +/- 2% at 100mm/hr. To prevent freezing of the rain gauge during winter months and provide water equivalent measurements of snowfall, the rain gauge was wrapped with heat tracing cable (TRCA, 2005). The collected rainfall data were organized and analyzed for all rain events during the study period. Rainfall data were summed and aggregated from a one minute interval to a one hour interval.

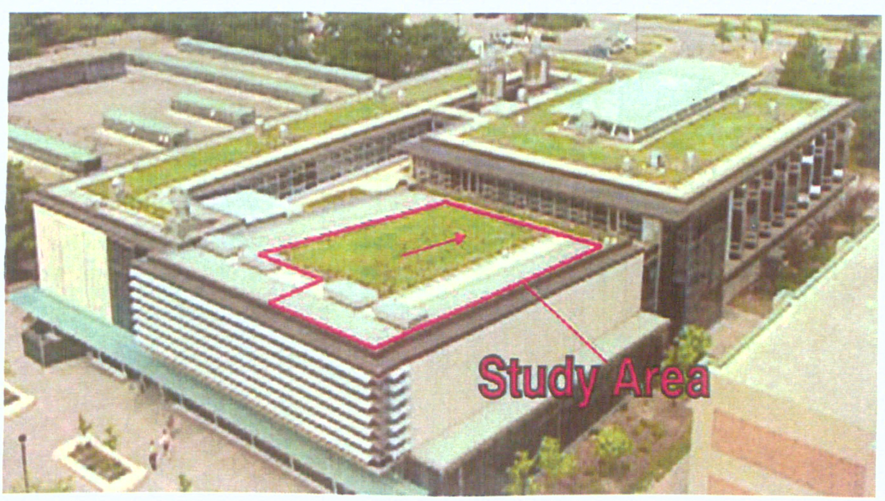

Figure 4.3 - Research site on York University Computer Science Building (TRCA, 2005).

4.2.4 Interception

In the hydrologic component of the model, interception works as a temporary storage of the precipitation by the vegetation or other surface cover. Interception is that portion of the precipitation falling in a watershed that is halted by the vegetation and other above ground objects and evaporates without reaching the ground. Rainfall interception loss can be defined as the residual after subtracting throughfall and stemflow from gross rainfall (Hashina *et al.*, 2002).

The fraction of intercepted precipitation is variable depending on precipitation event duration and magnitude. Normally, a small rainfall event will have a higher interception fraction. As long as the storage capacity of the vegetation is unsaturated, a fraction of precipitation can still be intercepted. When the precipitation exceeds the maximum storage capacity of the vegetation, it becomes throughfall.

Interception by vegetation can be simulated by regarding the canopy as a simple storage, which is described by a combination of cumulative interception with the method of Aston (1979). The equation is as below:

$$S = c_p \cdot S_{max} \cdot \left[1 - e^{-k \cdot \frac{P_{cum}}{S_{max}}}\right] \tag{4.2}$$

In which S is the cumulative interception (mm), P_{cum} is the cumulative rainfall from the beginning of the event (mm); k is a correction factor for vegetation density $(k = 0.046 \cdot LAI)$ which determines the rate with which the S_{max} will be reached, c_p is the fraction of vegetation cover, and S_{max} is the maximum canopy storage capacity (mm).

S_{max} can be estimated as a function of Leaf Area Index (LAI) from the following empirical equation by Von Hoyningen-Huene (1981).

$$S_{max} = 0.935 + 0.498 * LAI - 0.0057 * LAI^2 \qquad (4.3)$$

LAI represents the functional green leaf area of the canopy standing on ground area (Beadle, 1993). The values of LAI that were used in the interception model are taken for turf, shrub, bushes and small trees that locate in North America (Scurlock et al., 2001).

The amount of interception per time step is calculated by subtracting the interception storage and amount of evapotranspiration of the current time step with the interception storage of the previous time step. Interception will only take place for the fraction of the green roofs that was covered by vegetation. To get the value for the actual interception of the green roof system, the amount of interception should be multiplied by the vegetation cover c_p . The vegetation cover varies between 0 and 1.

4.2.5 Throughfall

Throughfall penetrates the canopy directly through spaces between leaves, or by dripping from leaves, twigs and branches when the amount of precipitation falling on the vegetation is in excess of interception storage capacity. The amount of precipitation falling on the vegetation is calculated by:

$$\text{Precipitation on vegetation} = \text{Precipitation} * c_p \qquad (4.4)$$

Where c_p is the fraction of vegetation cover on greenroof which was estimated by randomly selecting five 1m by 1m study areas on the York University green roof. Fraction of vegetation cover on each study area was estimated and an average for the study areas was taken as the vegetation cover on greenroof.

Throughfall is calculated by subtracting the precipitation falling on vegetation with the interception of previous time step and current evapotranspiration.

Throughfall T (t) = Precipitation on vegetation P (t) – interception (t-1) – evapotranspiration (t), If T (t) < 0, T (t) = 0 (4.5)

4.2.6 Infiltration

Infiltration is the process of water entering the soil through the soil surface (Xu, 2003). Infiltration is controlled by many variables including the type of land cover, antecedent moisture, soil texture and structure, soil porosity, surface soil permeability and the rate of water application. Infiltration is assumed to be a strictly downward process in the hydrologic component of the model. Infiltration occurs under two different conditions; they are a ponded condition and non-ponded condition.

Ponded Condition

When water is applied on the land surface such that there is a finite depth of water present on the surface, then such a condition is called ponded infiltration (Hutten, 2001). When a dry soil is ponded, the initial rate of infiltration is extremely high; however, the rate gradually reduces to an asymptotic value after some time when the asymptotic value is the saturated hydraulic conductivity of the surface soil.

Non Ponded Condition

When water is applied at a given rate to a non ponded surface, two possible conditions may happen:

- When the application rate exceeds the asymptotic rate; the surface will infiltrate all the water for a period of time and then ponding will start. Any water applied beyond the time of ponding will become runoff.
- When the application rate less than the asymptotic rate; all the water applied will infiltrate into the soil.

Infiltration models are used in hydrology to estimate the rate of infiltration and the cumulative infiltration of a given soil. There are three infiltration models which are commonly used to estimate the rate of infiltration. They are Horton's model (1933), Phillips model (1962) and the Green-Ampt model (1911).

The Green Ampt model

Although Horton's and Phillip's models can capture the basic behaviour of infiltration, they are applicable for ponded infiltration only. Thus, Green and Ampt (1911) presented an approach that is based on fundamental physics and also allows the user to include different boundary conditions or type of soils in a given scenario. The Green-Ampt model is based on a simple conceptualization of an infiltration front into a dry soil using the sharp interface approximation (Walter, 2004). The approach of Green and Ampt is shown in Figure 4.4 (Walter, 2004).

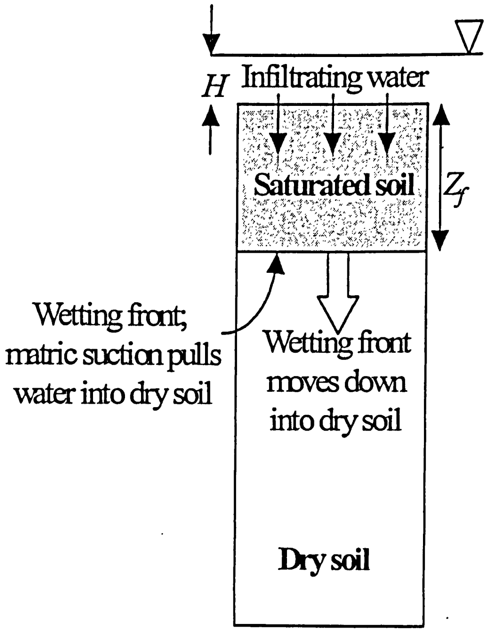

Figure 4.4 – Green-Ampt infiltration model approach

In the simplest form the Green and Ampt equation for infiltration rate f can be written as:

$$f = K_s \frac{\psi_{mf} + Z_f}{Z_f} \tag{4.6}$$

Where:

K_s = Saturated hydraulic conductivity [cm/hr]

ψ_{mf} =Matric-suction at the wetting front [cm of water]

Z_f =The depth of the wetting front [cm of water]

The depth of the wetting front can be related to the cumulative amount of filtration, F [cm]:

$$F = Z_f \left(\theta_S - \theta_i\right) \tag{4.7}$$

Where:

θ_s =Saturated moisture content

θ_i =Initial moisture content

Rearranging equation 4.7 into equation 4.6, the infiltration rate f becomes:

$$f(t) = K_s + K_s \frac{\psi mf(\theta_S - \theta_i)}{F} \tag{4.8}$$

Ponding condition in Green-Ampt model

When the infiltration occurs at a ponding condition and $t > t_p$ (t_p is the time when water begins to pond on the soil surface [hr]), the infiltration rate $f(t)$ becomes:

$$f(t) = K_s + K_s \frac{\psi mf(\theta_S - \theta_i)}{F} \tag{4.9}$$

And the cumulative infiltration, $F(t)$ will become:

$$Kt = F(t) - \psi(\theta_S - \theta_i)\ln\left[1 + \frac{F(t)}{\psi(\theta_S - \theta_i)}\right] \tag{4.10}$$

Non Ponding condition in Green-Ampt model

When the infiltration occurs at a non ponding condition and $t \leq t_p$, the infiltration rate $f(t)$ is given by:

$$f(t) = P \tag{4.11}$$

Where P = rainfall rate [cm/hr]

The amount of water that infiltrates before water begins to pond at the surface, F_p, [cm] can be calculated as:

$$F_p = \frac{\psi m f K_s (\theta_s - \theta_i)}{P - K_s} \qquad t = t_p \text{ and } P > K_s \tag{4.12}$$

The time it takes to have water begin to pond at the surface, t_p [hr], will be:

$$t_p = \frac{F_p}{P} \tag{4.13}$$

4.2.7 Evapotranspiration

Evapotranspiration is one of the processes of the hydrologic cycle and represents the sum of precipitation that changes in phase that is from the liquid or solid state to the gaseous state, near the ground surface and is transferred to the atmosphere during a fix period of time (Yu et al., 1997). Evapotranspiration represents the combination of two separate processes: transpiration and evaporation. Transpiration is the transfer of water from the soil to the atmosphere through vegetation and evaporation is the change of phase of water from soil and intercepted precipitation on the surface of vegetation.

The evapotranspiration process is governed by the meteorological conditions at the site such as air temperature, wind speed, atmospheric pressure, air humidity and exposure to.the sun. It also depends on the type and density of vegetation covering the ground surfaces, soil moisture availability, root distribution and soil properties. If the soil water is not limiting, then evaporation from saturated soil is approximately equal to evapotranspiration from a free water surface and is called potential evaporation (PE) (Thormthwaite, 1948).

There are various methods or approaches for estimating potential evapotranspiration and the following four methods are more recognizable among the others: Penman method (Penman, 1948), Peman-Monteith method (Monteith, 1965), Thormthwaite method (Thormthwaite, 1948) and Priestley-Taylor method (Priestley, 1972). The Priestley-Taylor method is used in the green roof hydrological model not only due to its simplicity; but also because there is a huge limitation on the availability of field data for the models. For example, the latitude of the site and mean dew point temperature that are required in the Peman-Monteith method are unavailable in many areas. Hence it is impossible to use Peman-Monteith in the green roof model without significant uncertainty. The equations for estimating potential evapotranspiration using Priestley-Taylor method are given below:

$$E = \alpha \left(\frac{\Delta}{\Delta + \gamma} \right) * \left(\frac{R_n}{Hv} \right) \tag{4.14}$$

Where:

E = Potential Evapotranspiration (mm)

α = 1.3 is a constant (Chow, 1988), it might be varying from site to site

Δ = Slope of the saturated vapour pressure curve (kPa/C)

γ = Psychometric Constant (kPa/C)

R_n = Net radiation (MJ/m^2)

Hv = Latent heat of vapourization (MJ/Kg)

$$Hv = 2.5 - 0.0022 * T \tag{4.15}$$

Where T = Air Temperature

$$\Delta = \frac{e(a)}{(T+273)} * \frac{(6791)}{(T+273)-5.03} \tag{4.16}$$

$$e(a) = 0.1 * e^{\left(\frac{54.88-5.03*\ln(T+273)-6791}{T+273}\right)} \tag{4.17}$$

$$\gamma = 6.6 * 10^{-4} * PB \tag{4.18}$$

The barometric pressure, PB, (kPa) is given by

$$PB = 101 - 0.0115 * ELEV + 5.44e^{10} - 7 * (ELEV)^2 \tag{4.19}$$

Where ELEV = Elevation (m)

$$G = 0.12 * \frac{T(i)-(T(i-1)+T(i-2)+T(i-3))}{3} \tag{4.20}$$

Where G is assumed to be zero.

Though the Priestley-Taylor method is a simple approach to estimate potential evapotranspiration from a green roof system, sufficient data are still required. Unfortunately, neither net radiation data nor solar radiation data were collected at the weather station of the York University site. Thus, solar radiation data was adopted from The University of Toronto at Mississauga Meteorological Station (UTMMS) Weather Station Data Base. Incoming short wave solar radiation is collected using a Kipp & Zonen model CM 11 solarimeter. The unit of measure for incoming radiation is millivolts. The calibration constant for this solarimeter is 77.276 Watts per square metre per millivolt.

Net radiation (Rn) that require in Priestley-Taylor method will then be calculated by simple computational procedures that used in Arizona Meteorological Network (AZMET), which developed for the California Irrigation Management Information System (CIMIS) by Snyder and Pruitt in 1985 (Brown, 2002). The procedure is listed below:

For Daytime Conditions $\left(SR \geq 0.21 \frac{MJ}{m} * \frac{m}{hr}\right)$:

$$R_{no} = 277.8 * (-0.3 + 0.767 * SR) \tag{4.21}$$

For Nighttime Conditions $\left(SR \prec 0.21 \frac{MJ}{m} * \frac{m}{hr}\right)$:

$$R_{no} = 277.8 * (-0.17 + 0.767 * SR + 0.056 * ea) \tag{4.22}$$

where: SR is the solar radiation expressed in units of MJ/m*m/hr.

The constant 277.8 is a constant used to convert the units of R_{no} from MJ/m*m/hr to W/m*m. Vapour pressure (ea) is computed by multiplying relative humidity (RH) to the saturated vapour pressure (es):

$$ea = es * RH \tag{4.23}$$

$$es = 0.6108 * e^{\left(\frac{17.27 * Ta}{Ta + 237.2}\right)} \tag{4.24}$$

where Ta is the mean hourly air temperature.

The R_{no} computed from Equation 4.21 and 4.22 is in units of W/m^2, whereas R_n is required in Priestley-Taylor Method in units of MJ/m^2. This conversion of units is accomplished by dividing R_{no} by 10^6 and multiplying by 3600 seconds (3600s in 1 hr).

4.2.8 Simulated Runoff

Runoff from a green roof will be dependent upon the volumetric water content contained in the system. To determine the volume of water that a green roof system could retain, the effective percentage of porosity was determined by lab experiments. This percentage was then converted to a depth in millimeter based on the depth of the green roof substrate.

After the maximum field capacity was determined, the following two assumptions were requires before simulating the runoff of greenroof:

1) After a runoff event, the green roof substrate is at field capacity, meaning the volume of water in the block is equal to the maximum water holding capacity.

2) Runoff from a green roof system does not occur until field capacity is reached, and the runoff equation will be:

Soil Moisture from previous time interval + Infiltration $<$ Field Capacity

= No Runoff (4.25)

Soil Moisture from previous time interval + Infiltration $>$ Field Capacity

= Runoff Occurs (4.26)

The hydraulic response was simulated for the period of May - August 2003 and June - August 2004. Simulated values were then compared to measured values. The validity of the model is discussed in Chapter Five. A listing of the hydrologic model inputs and parameters are shown in Table 4.1.

Table 4.1 - List of hydrologic model inputs and parameters

Precipitation	Determine from York University rain gage data
Interception	Von Hoyningen-Huene Equation
LAI	Determined from Worldwide Historical Estimates of Leaf Area Index
Throughfall	= Precipitation – interception of previous time step – evapotranspiration
Infiltration	Green Ampt model
Soil moisture	Storage/ Effective porosity
Saturated Hydraulic Conductivity	Determined from soil type index
Wetting front	Determined from soil type index
Evapotranspiration	Priestley-Taylor Method
Net radiation	Calculated by using UTMMS data and AZMET computational procedures
Air Temperature	Determined from York University Weather Station
Runoff	Storage<Field Capacity = No runoff occurs Storage>Field Capacity = Runoff occurs

4.3 Greenroof Energy Model

Many research studies have shown that green roof systems provide benefits in terms of temperature reduction and energy saving. Simpson and McPherson (Simpson, 1996) showed that tree shade has the potential to reduce annual energy for cooling by 10% to 50% and peak electricity use up to 23%. Research studies such as Bass *et al.* (2003) also point out that the depth of the soil substrate and type of plants chosen would change the insulation values owing to their different U value (heat transfer coefficient). The U value is the reciprocal of thermal resistance of material (W.P. Hickman System Incorporated, 1999). To determine the energy reduction efficiency of green roof systems, total resistance of the roof structure and differences of the surface temperature are required. The thermal resistance values (R values) of green roof system components and normal roof components can be found from different company's website such as (http://www.zinco.de).

4.3.1 Formulation of the Energy Model

The purpose of the model is to find out the difference of energy gain between a conventional roof and a rooftop with a green roof. Details of the computational process are listed below:

1. Determine total thermal resistance of conventional roof components
2. Calculate total thermal conductance of regular roof
3. Determine total thermal resistance of green roof system components
4. Calculate total thermal conductance of green roof

5. Organize raw roof top temperature data
6. Calculate soil thermal conductivity
7. Calculate soil conductance value
8. Calculate total energy gain on a regular conventional roof
9. Calculate total energy gain on a roof that installed greenroof
10. Calculate the difference of total energy gain

4.3.2 Calculations of Thermal Conductivity

The model developed by Vershinin *et al.* (1966) commonly uses to estimate soil thermal conductivity:

$$\lambda(\omega)10^7 = \left[2.1\left(\frac{\rho}{1000}\right)^{(1.2-2\omega)} e^{-0.7(\omega-0.2)^2} + \left(\frac{\rho}{1000}\right)^{\left(0.8+2\omega\right)}\right]\rho c_p(\omega) \qquad (4.27)$$

where:

ρ = Soil bulk density [kg/m^3]

ω = Volumetric moisture content

λ = Thermal conductivity of the soil [$\frac{J}{msK}$]

ρc_p = Thermal capacity of the soil [$\frac{J}{m^3K}$]

$$\rho c_p(\omega) = 4180(0.2+\omega)\rho \qquad (4.28)$$

Soil thermal resistance (RSI) is calculating as:

$$R_{soil} = \frac{T}{\lambda(\omega)10^7} \qquad (4.29)$$

Where:

R_{soil} = thermal resistance of the soil substrate ($\frac{m}{Kw}$)

T = soil thickness (m)

The thermal conductivity specifies the rate of heat transfer in any homogeneous material. If a material has a value of 1 in thermal conductivity, it means that 1 meter cube of material will transfer heat at a rate of 1 watt for every degree of temperature difference between opposite faces (Figure 4.5). Normally the thermal conductivity is expressed as 1 [$\frac{w}{mK}$], where in here it expressed as [$\frac{J}{msK}$].

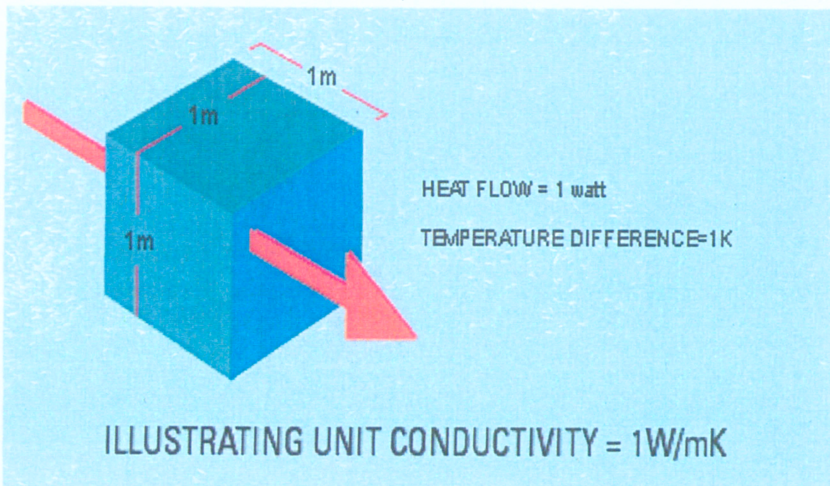

Figure 4.5 – Illustrating Unit Conductivity (Halliday, 1997)

After identifying the thermal conductivity and the depth of the green roof soil substrate, the thermal resistance (RSI) can be determined. Thermal resistance is calculating by dividing the soil thermal conductivity with the soil thickness. The soil conductance (C) is the amount of heat energy transmitted through the unit area of structural component per unit temperature difference between the hot and cold faces and is given by:

$$C = \frac{1}{RSI} \tag{4.30}$$

The value of C is simply the reciprocal of the RSI. A listing of energy model inputs and parameters is shown in Table 4.2.

Table 4.2 - List of energy model inputs and parameters

Soil Thermal Conductivity	Vershinin *et al.* model
Soil density	Determined from soil type index
Soil Moisture Content	Determined from soil storage/ effective porosity and previous soil moisture content

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Chapter 5

5.1 Model Calibration

The calibration of a mathematical model consists of changing values of model input parameters in an attempt to produce outputs that match the field collected data. The purpose of calibration is to improve model predictability. Calibration can be either theoretical (the values are deduced by theory) or empirical (the values are deduced from observing a process and measuring the inputs and outputs). According to Linsley (1982), model calibration is a process of standardizing predicted values. Correction factors are derived by comparing the predicted and observed values for a particular area. These factors can then be applied to generate predicted values that are consistent with observed values. Hydrologic models should be calibrated using observed data in order to confirm the predictability of the model.

Selection of the appropriate calibration method depends on the purpose of the model, the model parameters or variables involved, and most importantly the sensitivity of the parameters. There are several calibration methods for hydrologic models: artificial neural networks method (Elshorbagy *et.al,* 2000), linear method (Cooper *et.al*, 1997), non linear regression method (Ndiritu, 2001) and multiple objective methods (Yu, 2000). Due to the insufficient field data of the case study, none of these formal methods was considered suitable for the calibration of the green roof hydrologic/energy model.

The objective of the model calibration in this study is to demonstrate that the outputs of the green roof model and the measured field data are in good agreement. The hydrologic output is the total monthly runoff from a green roof system at York University.

Some of the input parameters were provided by the Toronto and Regions Conservation Authority (TRCA) while others were estimated. The calibration process is achieved in three steps: (1) the observed runoff values are summed to produce total monthly runoff for the study area; and (2) the model predicts monthly runoff values using a set of parameters; and (3) re-run the model using another set of parameters until the predicted and the observed runoff values are in good agreement.
The calibration parameters are listed below:

1. Field-collected runoff values were organized and summed up as total monthly runoff for the study area.
2. Simulated runoff values were also summed to produce total monthly runoff for each month.
3. Comparison was made between the simulated greenroof runoff and the field-collected runoff values.

5.2 Results and Discussion

There are no universally accepted "goodness-of-fit" criteria that apply in all calibration cases; however, it is important that the difference between model outputs and measured field conditions be minimized. Typically, the percent difference between the model outputs and actual field measurements should be less than 10% (DEQ, 2006).

Using the field measurement at the York University's green roof, model calibration was performed from the time period of May to August 2003 and June to July 2004. The field data include continuous runoff flow records, weather station records and soil moisture records at the York University's green roof for the selected time period. The soil moisture sensor broke down from August 2003 to November 2003; and broke down again in August to November 2004. Thus, the mathematical model can only be calibrated when soil moisture records are available.

Table 5.1 shows the comparison between the simulated and measured monthly green roof runoff in millimetre. In May 2003, the percent of error is 9.3%, while Jun and July 2004, the percent of errors are 7.0% and 5.5% respectively. The percent of errors of these three months are within 10%, which are characterized as a "very good" calibration. The good results may be attributed to the completed field data collected at the York University weather station and the green roof substrate. Results from the simulated and actual field runoff are seen in Figures 5.1, 5.4 and 5.5.

Table 5.1 – York University Green Roof Monthly Simulated and Measured Runoff

Year	Month	Precipitation (mm)	Simulated Runoff (mm)	Field-Colleted Runoff (mm)	Percent Error
2003	May	114.8	42.5	46.9	9.3%
2003	Jun	88.4	19.9	46.6	57.3%
2003	July	44	7.7	20.6	62.7%
2003	August 12th	49.8	8.8	78.8	88.8%
2004	Jun	45.6	10.4	11.2	7.0%
2004	July	174.4	41.6	44.1	5.5%

In general, the runoff simulated by the model is in good agreement with the measured runoff for large storms. On the other hand, the model was unable to calibrate scattered thunderstorms due to their high spatial variability.

The comparisons between the simulated and actual field runoff in June and July 2003 are seen in Figures 5.2 and 5.3. The percent errors of June and July are 57.3% and 62.7% and respectively. August 2003 is the month with the highest percent of error, which is 88.8%. The calibration results of these three months are characterized as a "poor" calibration. The large percent errors between the measured and predicted green roof runoff values occur due to the aforementioned issues. The missing soil moisture data can only be assumed from previous observations resulting in poor prediction of the monthly runoff values. In addition, there are quite a few missing data during these months.

Among the six calibration results, three of them are considered as "good" calibration results while the other are considered as "poor" calibration results. In order to resolve this problem, it is necessary to calibrate the model using a complete set of field collection data.

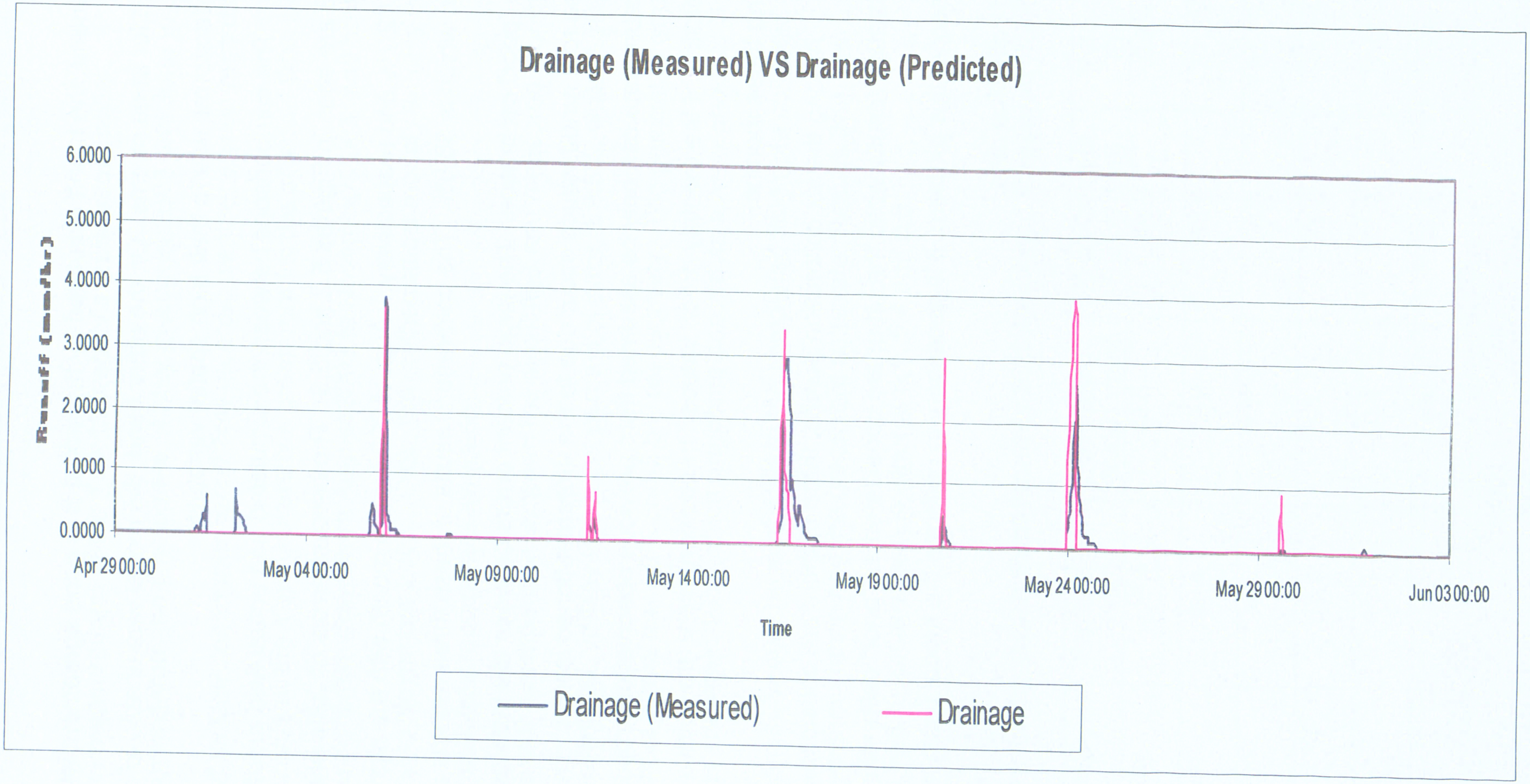

Figure 5.1 – Drainage (Measured) VS Drainage (Predicted), May 2003

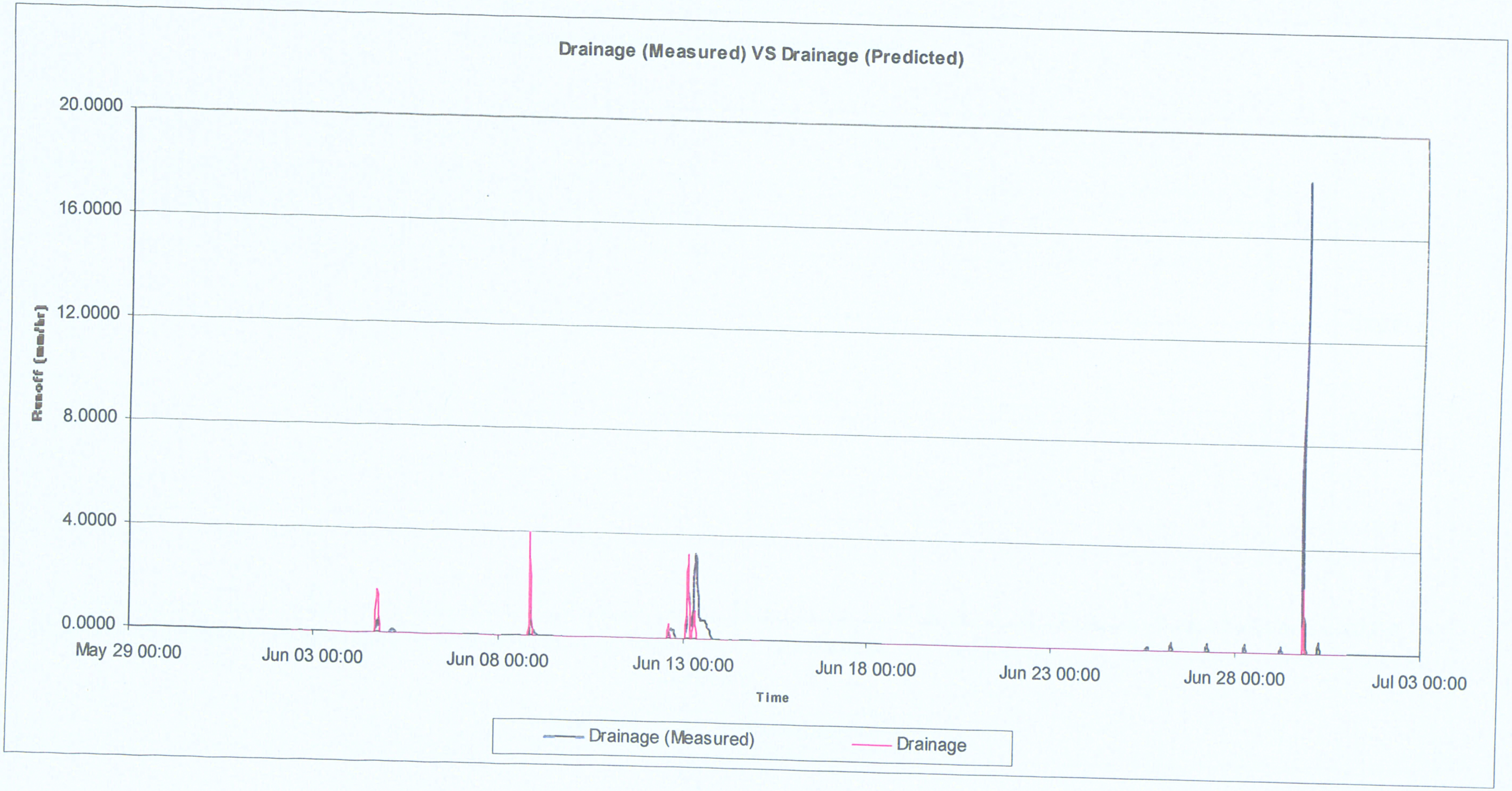

Figure 5.2 – Drainage (Measured) VS Drainage (Predicted), June 2003

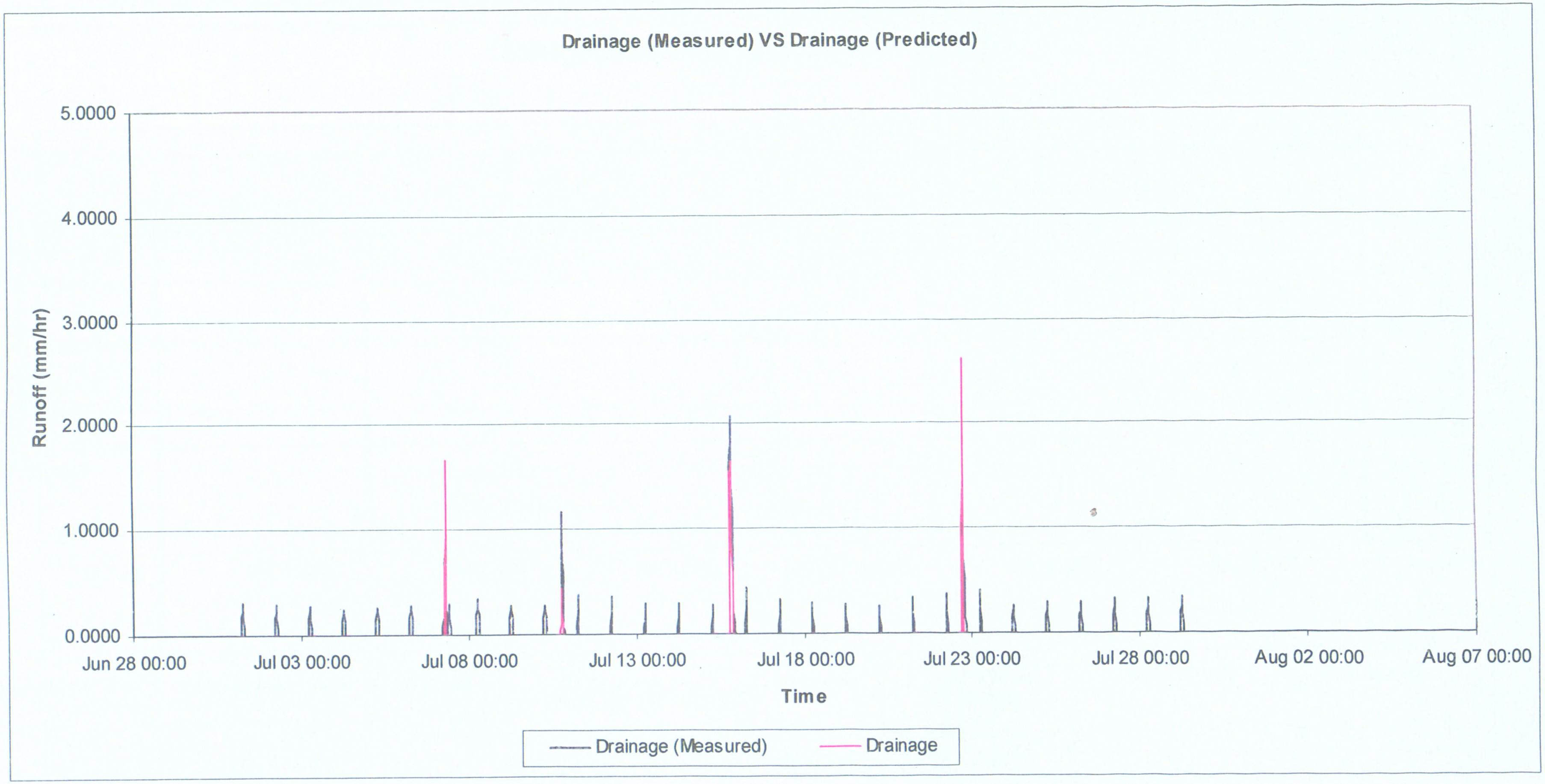

Figure 5.3 – Drainage (Measured) VS Drainage (Predicted), July 2003

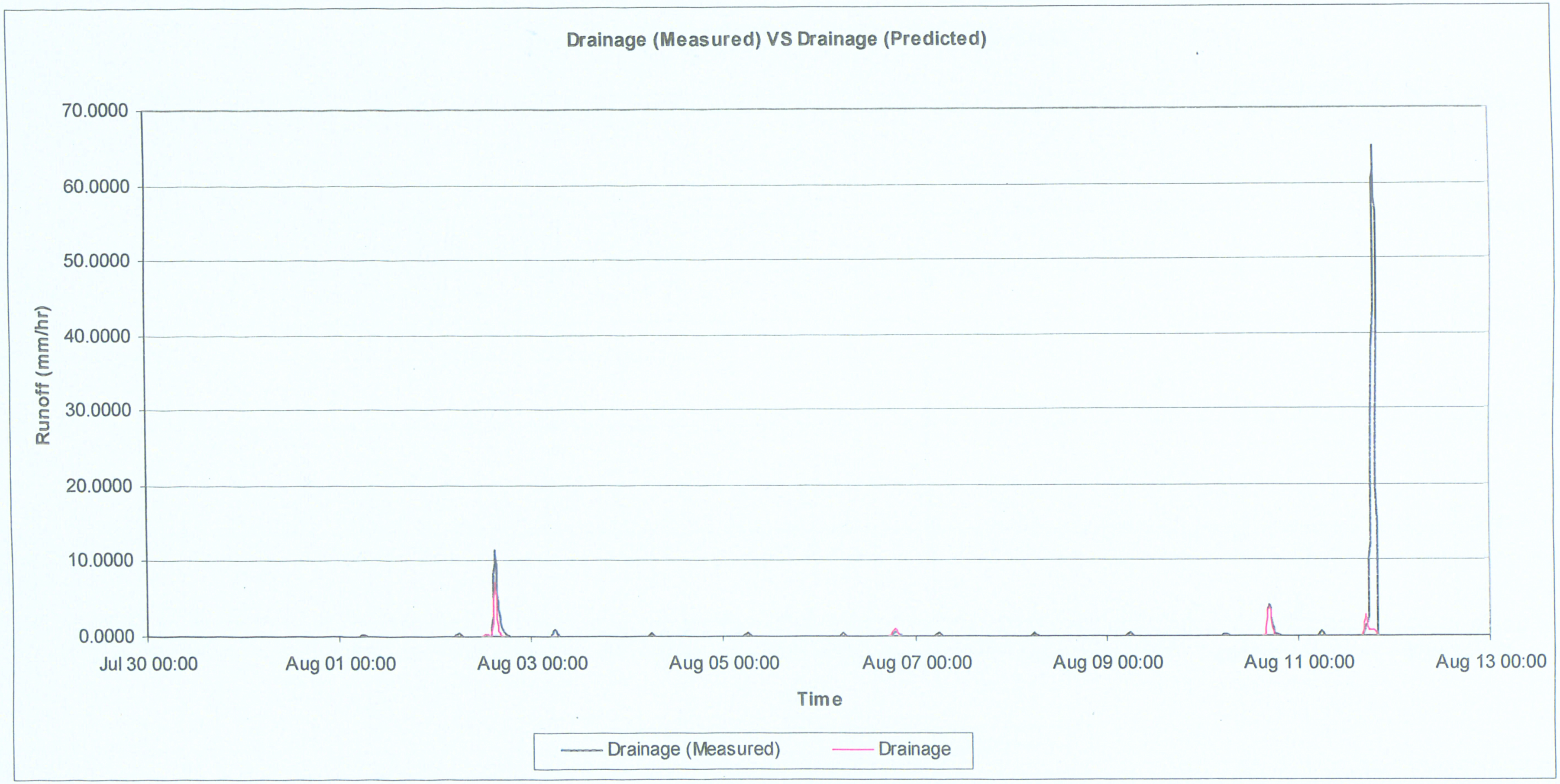

Figure 5.4 – Drainage (Measured) VS Drainage (Predicted), August 2003

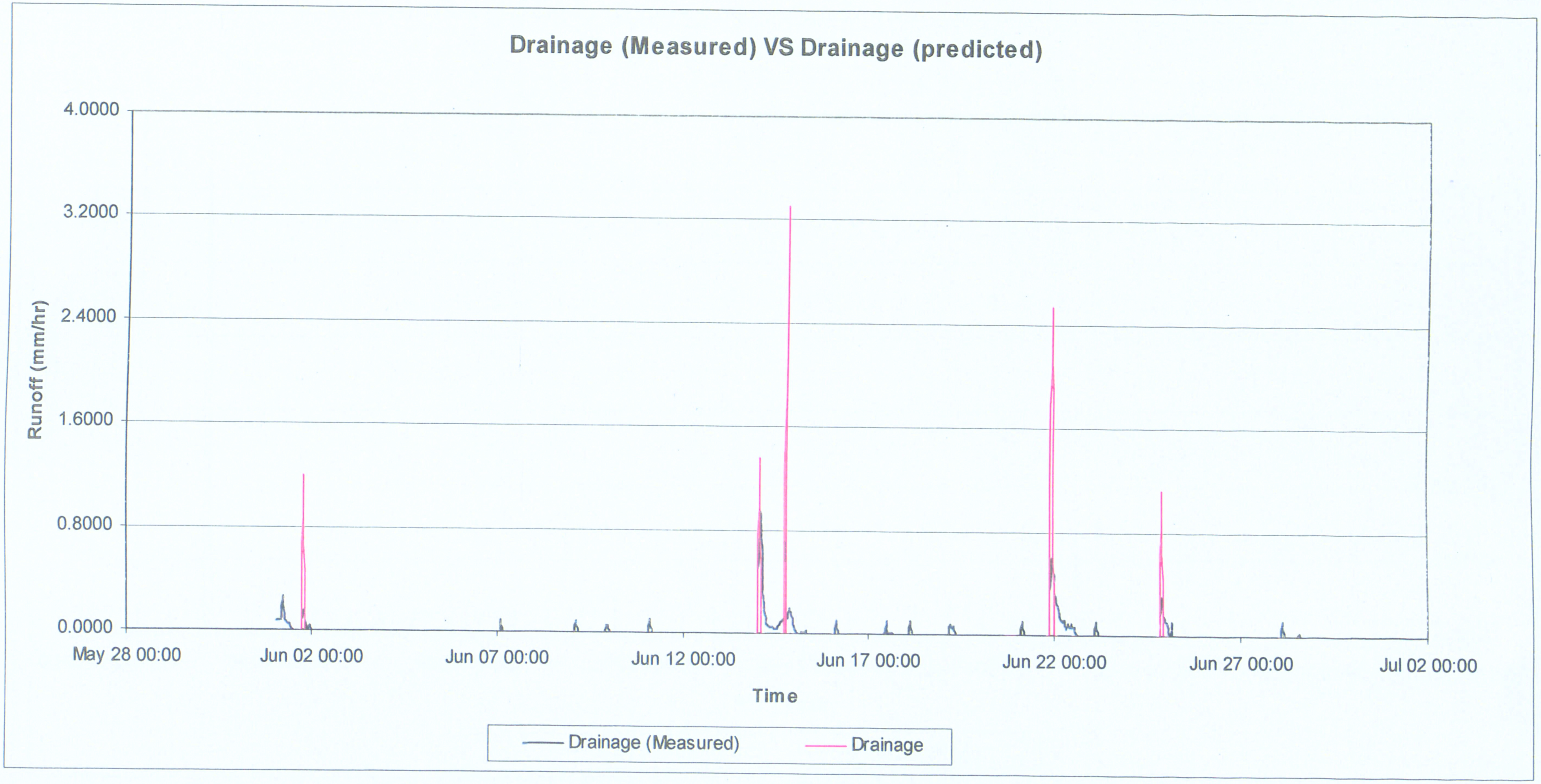

Figure 5.5 – Drainage (Measured) VS Drainage (Predicted), June 2004

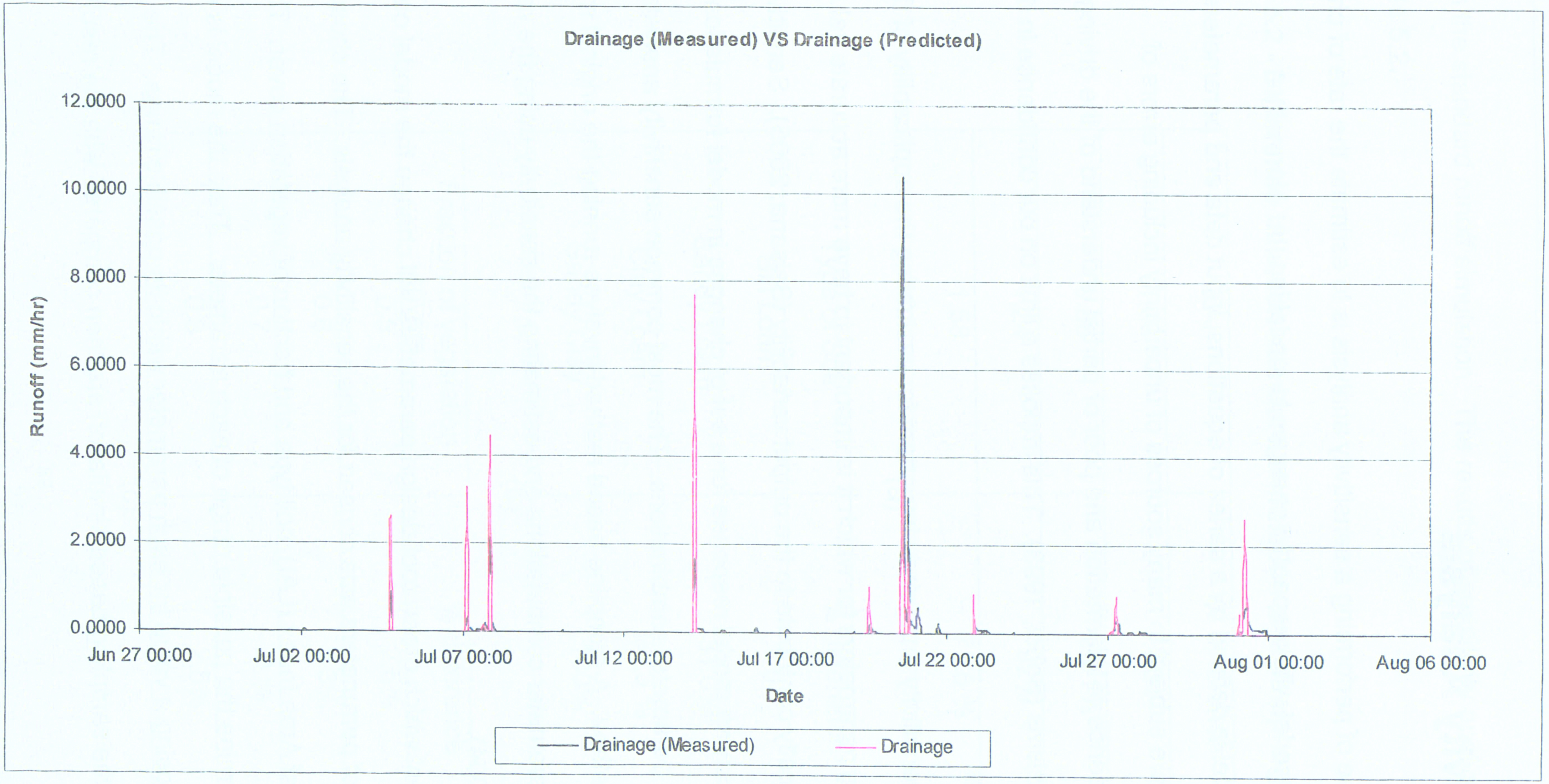

Figure 5.6 – Drainage (Measured) VS Drainage (Predicted), July 2004

5.3 Sensitivity Analysis

The purpose of performing a sensitivity analysis is to estimate the rate of change in the output of a model with respect to changes in model inputs. Normally a mathematical model is defined by a series of equations, input data and parameters, and variables. Inputs are subject to many sources of uncertainty including errors of measurement, absence of information and poor or partial understand of the driving forces and mechanisms (Sobol, 1993). This imposes a limit on our confidence in the output of the model.

Therefore sensitivity analysis is important for evaluating the applicability of the model, determining parameters for which it is important to have more accurate values and factors that mostly contribute to the output variability (Saisana, 2005). Sensitivity testing involves studying model response for a set of changes in model formulation, and for selected model parameter combinations. The most common sensitivity analysis is a sampling based method. A sampling based method involves running the original model for a set of input parameter combinations and estimating the sensitivity using the model outputs (Saltelli, 2004).

To further test which green roof design parameters will change the model outputs significantly, a set of parameters was chosen for the sensitivity analysis. The chosen parameters are Leaf Area Index (LAI), soil type and fraction of vegetation cover. The first step is to determine the possible range of each parameter. Then the model is run many times by choosing a value for each parameter within its possible range. The runoff results from the sampling based simulation are then compared with the results from the standard runoff simulation. The results of sensitivity analysis are shown in Table 5.2.

Table 5.2 - Difference between standard simulation and sampling based simulation

LAI	% difference
1.03	0
0.85	30.1%
1.24	32%
1.58	71.6 %

(a)

Type of Soil	% difference
Silt Loam	0
Sandy Loam	31.0%
Clay Loam	93.3 %
Sandy Clay	100%

(b)

Fraction of vegetation covers	% difference
0.5	2.5%
0.6	1.3%
0.7	0 %
0.8	2.5%

(c)

Soil type is the most sensitive parameter which can cause up to 100% change to the simulated runoff. The findings of the sensitivity analysis are anticipated because the percentage of effective porosity in soil is dependent on the type of soil. The fraction of vegetation covers is the least sensitive parameters which can cause a change in the simulated runoff in the range of 1.3% to 2.5%.

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Chapter 6

6.1 Economic Costs and Benefits of Greenroofs

Most greenroof researchers such as Peck (2001), Wong *et al.* (2003) and Banting *et al.* (2005) have indicated that there are definite benefits for stormwater management and energy savings attributed to the installation of green roof systems. Benefits and costs of green roofs were divided into private and public (Banting *et al.*, 2005). Private costs are those paid for by a building owner, such as green roof installation and maintenance costs while private benefits include energy savings and cost savings associated with the longer service life of a roof membrane (Acks, 2005). Public costs might include some government programs paid for by taxpayers that are aimed at increasing adoption of green roof infrastructure. Public benefits are those experienced by a majority of city residents, regardless of whether the building they live in has a greenroof, and include reduced stormwater runoff and urban heat island reduction (Acks, 2005).

The purpose of this chapter is to give an overview of the costs and financial benefits of green roof systems. A cost and benefit evaluation model for greenroofs has been developed in Excel. The model can explore costs and benefits of green roofs application in: 1) residential, 2) commercial/institutional and 3) industrial buildings. The three scenarios considered represent the land-use categories used in the Ontario Building Code. The seasonal storm water and energy benefits in dollar value were estimated under each scenario. The benefits of a greenroof vary and are highly dependent on the designed greenroof components. A reasonable estimate of the range of required capital investment and the subsequent benefits is necessary before a builder owner can decide whether the green roof is justified.

Field data are collected from the York University's green roof. Due to the limitation of the field data, assumptions were made for some of the input data according to the values suggested by published literature or information that was provided from greenroof companies. It is also noted that the economic benefits of green roof systems are very sensitive to specific design considerations of a building.

6.2 Storm Water Management Benefits

Research done in German municipalities indicates that the widespread installation of green roof systems can result in cost savings in municipal drainage infrastructure (Rowe *et al.*, 2005). Green roofs can reduce the specified size of impervious catchment's zones and storm water drainage pipes. Peck (1999) indicated that green roofs can significantly reduce the cost of retaining storm water in underground tanks and tunnels. A study done by six independent consulting companies for the City of Toronto Department of Works and the Environment and Soprema roofing systems indicates that green roof systems can be a cost-effective storm water management practice (City of Toronto, 1999).

The City of Toronto has developed a continuous simulation model to model Combine Sewer Overflow (CSO) conditions across the city. Using this simulation model, CSO benefits were determined by estimating the reduction of underground storage required after greenroof implementation (Banting *et al.*, 2005). The CSO benefits of greenroofs were determined by the reduction of underground storage for the same level of CSO control and a unit cost of $1,340/m^3 for underground storage (City of Toronto, 2003).

6.3 Energy Efficiency Benefit

Numerous research studies have indicated that green roofs acting as insulators have the potential to save building energy. According to study by NRCC, greenroofs are capable of preventing heat gain in the summer as greenroofs reduce heat gain through shading, insulation and evapotranspiration. However the percentage of energy usage reduction is difficult to estimate as it depends on many factors including insulation of the roof structures, the size and design of the green roof as well as the layout of the building and data for those are not readily available.

Some research indicated that the thicker the soil substrate, the better insulation the green roofs will provide (Rowe *et al.*, 2003). However, whether or not this is universally true is hard to determine as there are insufficient experimental data to support it. In addition to soil thickness; density of soil substrate, type of vegetation and soil moisture can affect the performance of insulation as well. Thus, it is assumed that different combinations of design factors will result in different energy saving values.

Cost of electricity was based on the energy data from NRC (Bass, 2003) which is $0.1017 per kWh. According to Ken Hancock of Physical Plant Services from Queen's University (Dinsdale *et al.*, 2006), over the past five years, the average yearly increase in electricity price has been 7%.

6.4 A Case Study of Greenroof Benefits

A case study of green roof benefits in Toronto has been done on three different types of land use scenarios: residential, commercial/institutional and industrial buildings. Listed below are the data used in the case study:

- The greenroof is $241m^2$ and will have life span of 30 years (Johnston, 2004).
- Study period starts from May 2003 to November 2003.
- Selection of plants is based on the plants that are commonly used on greenroofs in North America and suggestion by Emory Knoll Farms, Maryland (Ed & John, 2002) and Rowe *et al.* (2005).
- Thickness of soil substrate was based on the loading carrying capacity according to Ontario Building Code.
- Two different types of greenroof soil mixture - Soprema and Garland were considered (details of soil properties are shown in Appendix A).
- Materials and installation of the roof cost is assumed to be $\$90/m^2$ (Li, 2006), total capital investment will be $\$90/m^2 \times 241m^2 = \$21690$.
- Maintenance cost is estimated to be $\$1.62/m^2$ (Giesel, 2003)
- CSO benefits of greenroofs is $\$1340/m^3$ (City of Toronto, 2003)
- Cost of electricity is $0.1017 kWh, and a yearly increase of 7% will occur consistently over the 30 years.
- Discount rate of greenroof assumed to be 5% (Kats, 2003).

Different types of plants, depths of the soil substrate and soil mixtures were selected and the associated factors were entered into the hydrologic/energy model described in Chapter Four. By calculating the benefits of each combination of design factors, the combination that gave most benefit in each scenario was determined. The annual benefits of various green roofs are presented in Tables 6.1 to 6.3.

Table 6.1 – Economic benefits on residential buildings

Scenario 1: Residential

Substrate Thickness (cm)	Soil Type	Vegetation Type	Stormwater benefit ($/season)	Energy saving benefit ($/season)	Total economic benefit ($/season)
3.8	Soprema	Shrubs	$113000	$690	$113690
3.8	Soprema	Turfing	$108000	$580	$108580
3.8	Garland	Shrubs	$117000	$690	$117690
3.8	Garland	Turfing	$110000	$580	$110580
5	Soprema	Shrubs	$115000	$690	$115690
5	Soprema	Turfing	$108000	$580	$108580
5	Garland	Shrubs	$120000	$690	$120690
5	Garland	Turfing	$112000	$580	$112580

Table 6.2 – Economic benefits on commercial buildings

Scenario 2: Commercial

Substrate Thickness (cm)	Soil Type	Vegetation Type	Stormwater benefit ($/season)	Energy saving benefit ($/season)	Total economic benefit ($/season)
10.2	Soprema	Shrubs	$118000	$690	$118690
10.2	Soprema	Turfing	$112000	$585	$112585
10.2	Garland	Shrubs	$124000	$690	$124690
10.2	Garland	Turfing	$116000	$585	$116585
15.2	Soprema	Shrubs	$122000	$690	$122690
15.2	Soprema	Bushes	$139000	$620	$139620
15.2	Garland	Shrubs	$127000	$690	$127690
15.2	Garland	Bushes	$144000	$620	$144620

Table 6.3 – Economic benefits on Industrial buildings

Scenario 3: Industrial

Substrate Thickness (cm)	Soil Type	Vegetation Type	Stormwater benefit ($/season)	Energy saving benefit ($/season)	Total economic benefit ($/season)
17.8	Soprema	Shrubs	$124000	$690	$124690
17.8	Soprema	bushes	$139000	$620	$139620
17.8	Garland	Shrubs	$129000	$690	$129690
17.8	Garland	bushes	$146000	$620	$146620
20.3	Soprema	Small trees	$148000	$620	$148620
20.3	Soprema	bushes	$144000	$620	$144620
20.3	Garland	Small trees	$148000	$620	$148620
20.3	Garland	bushes	$148000	$620	$148620

As indicated in Tables 6.1 to 6.3, it is noted that the depth of soil substrate is one of the key factors to achieve maximum economic benefits, especially stormwater management benefits. Stormwater management benefits increase 1.7% to 2.5% in Scenario 1 by increasing the substrate depth. The benefits also increase 2.4% to 3.3% and 1.4% to 3.5% in Scenario 2 and 3 respectively. In addition, type of soil mixtures will affect the greenroof benefits as well. Among all scenarios, soil mixture from Garland seems to havea greater economic benefits than Soprema. The soil mixture from Garland is capable of retaining an extra 10% to 12% of the stormwater resulting in better stormwater management benefits.

The type of vegetation plays an important role on achieving maximum economic benefits. If the depth of the soil substrate permits, vegetation with a higher leaf area index (LAI) should always be chosen. The higher the Leaf area index, the more precipitation the leaf surface can retain, particularly during summer. Less storm water runoff is produced, resulting in increase of storm water benefits.

Based on the case study, the best combination of greenroof design factors for a residential building is 5cm of substrate with soil mixture from Garland and shrubs. The best combination of greenroof design factors for a commercial building is 15.2cm of substrate with soil mixture from Garland and bushes. For an industrial building, 20.3cm of soil with soil mixture from Garland and small trees give maximum economic benefits.

6.5 Cost Analysis

Based upon a total capital investment of $21690 and discount rate of 5% (Kats, 2003), Net Present Value (NPV), breakeven and return on investment (ROI) were calculated. The calculations for this cost analysis can be found in Appendix C.

Net Present Value

The Net Present Value (NPV) of a project or investment is defined as the sum of the present values of the annual cash flows (benefits) minus the initial investment (Dorf, 2005). NPV is commonly used for capital budgeting and profitability analysis of an investment or a project. It describes the current equivalent of the future cash flow of a project at a certain discount rate. The discount rate is the rate at which future cash flow is discounted because of the time value of money (Dorf, 2005). All projects with a positive NPV are profitable and should be accepted. The NPV value for the cost analysis is found to be -$3593. Since this is a negative amount, which means investing in this greenroof is not advisable.

However this does not necessarily mean that greenroof projects should be undertaken since the calculations of NPV only account for private benefits (energy saving) and it does not account for public benefits (stormwater management benefits).

Breakeven

The breakeven point is the point at which costs and benefits are equal. There is no net loss or gain, one has "broken even" (Dorf, 2005). In this cost analysis, the total cost is the expense and the total income is the cumulative savings in energy costs resulting from the greenroof. The breakeven point for this project is approximately 17 years.

Return on Investment

Return on investment (ROI) is the return on past or current investment, or the estimated return on a future investment. ROI is equal to the net income divided by the investment and it is a primary measure of profitability for investors (Dorf, 2005). The net income in this cost analysis is the cumulative energy savings and the investment is the initial capital required for greenroof materials and installion. In this case, cost analysis indicated that the ROI is 100%, which means the investing on greenroof will be profitable.

Even the NPV and ROI results indicate different results on investing on greenroof and make it hard to conclude definitively whether or not installing a greenroof will be profitable or not. However, the NPV calculations only account for the private benefits - energy savings and did not include the stormwater management benefit. In addition, other environmental benefits and amenity enhancement are immeasurable were not incorporated into the calculations of NPV.

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Chapter 7

7.1 Summary and Conclusions

Green roofs are proven technologies that are becoming widespread around the world. The North American roofing industry has adopted them since the last decade. Previous studies have explored the stormwater management and energy saving benefits of green roof systems. However some of the research may not be practical enough for the developers/builders to put green roof on buildings. The lack of government regulations or actual financial gains from installing green roof systems may inhibit the adoption of this technology in North America.

A new planning tool for green roof systems has been developed. It uses an integrated hydrologic/energy model to determine the decrease of runoff and the increase of insulative capacity for a certain green roof design. As a result, different combinations of soil type, soil depth, and plants can be investigated and the combination which gives the largest stormwater and energy benefits can be identified. The planning tool also enables the owner of a building to realize the potential economic benefits and costs of a green roof system.

The case study results also support earlier claims that green roofs retain storm water and provide benefits for storm water management as well as energy savings. For instance, the use of green roofs could reduce storm runoff between 70 to 100%. In addition, analysis of three different land use scenarios in the case study also indicates that one soil mixture could provide a better economic benefit than another mixture for a green roof system. It is attributed to the fact that the soil mixture is capable of retaining an extra 10% to 12% of the stormwater.

The case study also indicates that a larger growing-media depth, in combination with appropriate soil mixture and plants, could generate larger economic benefits. A green roof of 241 m^2 could have a total economic benefit per season ranging from 108,580 to $148,620 for residential, commercial, and industrial buildings. The construction cost of the green roof, including the base system, growing medium, plant material, is about $21,690. The green roof can have a 100% return on investment, which means investing on greenroof is reasonable. It is hoped that the findings in this study can be realized by decision makers in the building construction industry and by roofing companies.

7.2 Suggestions for Further Research

Further research on the long term financial costs and benefits of green roof systems is recommended. Due to the short data available from the York University's green roof, the hydrologic/energy model can not be calibrated properly. Another set of data should be used for a better validation of the mathematical model.

Lastly, the scope of this study can be expanded by investigating a wider selection of plant materials and types of soil mixtures and establishing a clear picture of green roof economic benefits.

7.3 Significance of the Research

Green roof systems have the potential to provide effective storm water management and increase the energy efficiency of a building. However, most studies of greenroof systems have looked at either stormwater management or energy-efficiency benefits. By integrating the storm water management and energy efficiency benefits in one planning tool, this research make a significant step toward the optimization of both benefits at the same time. This research provides a planning tool for green roof systems which in turn "support and encourage a dynamic, growing and environmentally sustainable economy as well as ensure the quality of life and standard of living" (City of Winnipeg, 1996). The planning tool allows green roof designers to investigate various combinations of soil substrate depth, plant selection and soil mixture for residential, commercial and industrial buildings.

Appendix

APPENDIX A

Experimental Results

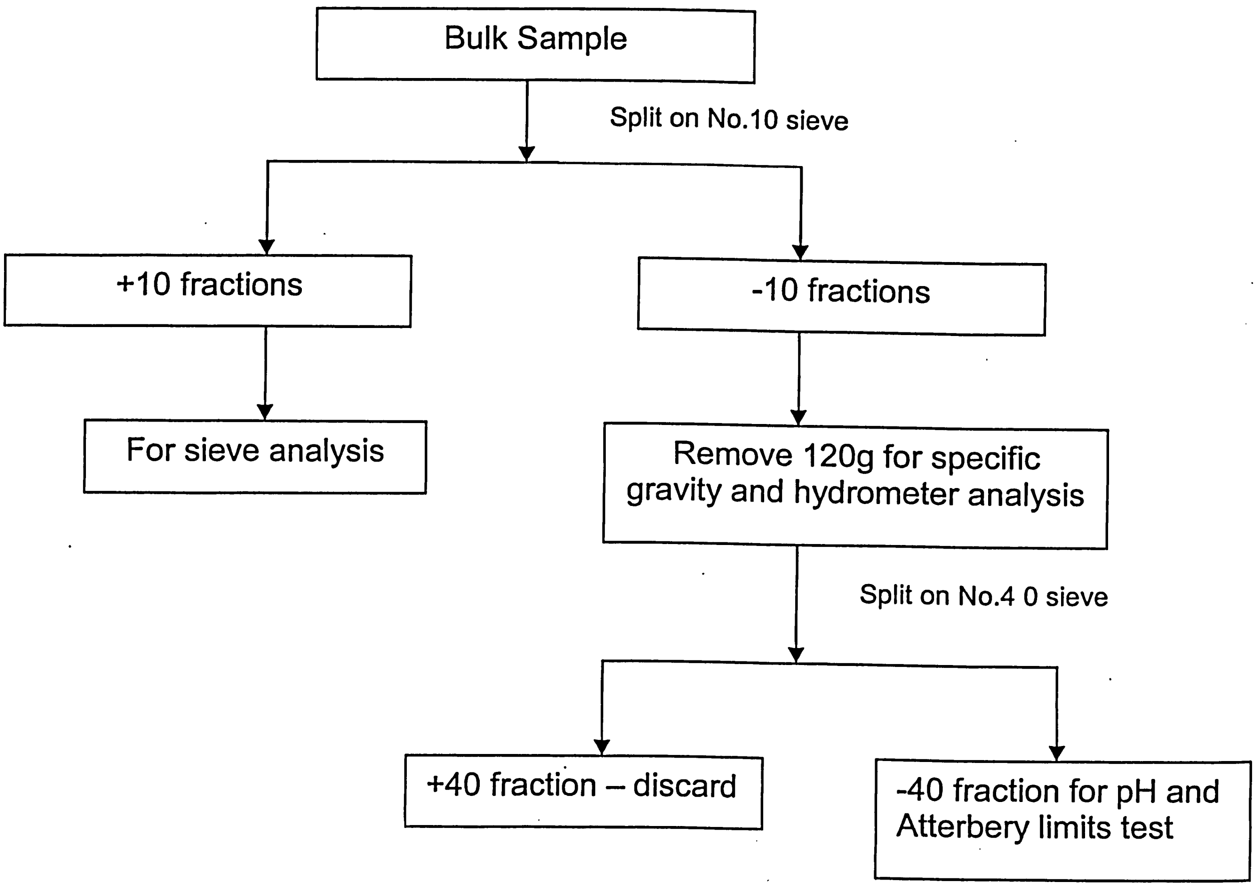
This section describes the soil analysis of two different green roof soil mixtures, Soprema and Garland. These soil mixtures have been used for greenroofs at Eastview Neighbourhood Community Centre, East York, Toronto and NRC (National Research Canada), Ottawa. The soil tests conducted are: Sieve Analysis, pH test, Hydrometer test, Specific gravity test, Liquid limit test, Plastic limit test and Shrinkage limit test.

Preparation of Soil Specimens

Soil specimens were prepared for the tests on grain size, specific gravity, textural classifications, pH, Atterberg limit test (liquid limit, plastic limit and shrinkage limit test). The procedures are described below and shown as a flow diagram in Figure 5.7.

A number of 1000 g soil samples were selected from a bulk sample. The soil samples were sieved by a No.10 sieve, from the -10 fraction; approximately 120g of soil were removed then placed in an oven that set at 105°C for drying. The dried soil specimen was then used for the specific gravity measurement and the hydrometer measurement. The remainder of the -10 fraction was then passed through the No.40 sieve. The soil retained on the No.40 sieve was discarded, while the soil passing the

No.40 sieve was used for the pH and the Atterberg Limits tests. Results of the soil specimens preparation are summarize in following table



Flow diagram for preparation of soil specimens (Salvas, 1977)

Soprema	Garland
Total Mass = 1002.4 g	Total Mass = 1000.35 g
+10 fraction = 493.08 g	+10 fraction = 639.57g
% of Total Mass = 49.19%	% of Total Mass = 63.93%

Table A1 - Summary table of the soil specimens' preparation

pH test

Approximately 50g of soil sample was placed in a 250ml beaker; 150ml of distilled water was then added into the beaker and stirred with a glass stirring rod. The soil and water mixture was allowed to stand for an hour to assure saturation and temperature equilibrium. The pH indicator paper was then used to measure the pH of the mixture in the beakers. According to the pH indicator paper, it was found that Soprema had a pH value of 10 while Garland had the pH values of 9.

Specific gravity test

The mass of the flask was determined to an accuracy of +/- 0.01g. Distilled water was added into the flask to the datum mark and all water from the outside and inside neck of the flask above the datum line was dried with paper towels. The mass of the flask and water as well as the temperature of the water in the flask were then determined, and then the flask was emptied. 50 g of oven dried soil specimen was placed into the emptied flask; distilled water was added into the flask until the water level was approximately 20mm above the surface of the soil.

The flask was then connected to a vacuum source and the vacuum was applied slowly. After shutting off the vacuum, distilled water was added to the flask. Lastly, the mass of the flask with soil and water was determined again. The test results and calculations are presented in following table.

Soil Mixture	Soprema	Garland
Mass of flask	166.39 g	161.16 g
Mass of flask + water	664.17 g	658.65 g
Temperature	21.5 °C	21 °C
Density of Water	0.9979125	0.998023
Volume of flask	500 ml	500 ml
Mass of flask + soil + water	679.84 g	669.61 g
Temperature of water	21 °C	21 °C
Density of water	0.998023	0.998023
Volume of water	464.37 ml	459.36 ml
Volume of soil	35.63 ml	40.64 ml
Mass of soil	50 g	50 g
Specific Gravity of Solids	1.40	1.23

Table A2 - Specific gravity test results and calculations

Grain Size Analysis

Sieve Test

The +10 fraction was used for the sieve test; sieves were stacked with the largest at the top and the smallest at the bottom. The sieves used were 25.4mm (3/4”), 19.0mm (1/2”), 9.51mm (3/8”), No.4 and No.10 and a pan at the bottom. The soil specimens were put on the top sieve and the whole stack of sieves were then put into the shaker for approximately 10 minutes. The results of sieve test are summarized in following tables.

Sieve or Grain Size (mm)	Mass Retained (g)	Percent Retained	Cumulative percent retained	Cumulative percent passing
25.4 mm (3/4")	0	0	0	100
19.0 mm (1/2")	55.61	5.55	5.55	94.45
9.51 mm (3.8")	83.54	8.34	13.89	86.12
No. 4	175.75	17.53	31.42	68.59
No. 10	151.42	15.12	46.52	53.48
Pan	24.89	2.48	49.00	51.00

Table A3 – Result of sieve test (+10 fraction), Soprema
Mass of soil sample, total mass = 1002.4 g

Sieve or Grain Size (mm)	Mass Retained (g)	Percent Retained	Cumulative percent retained	Cumulative percent passing
25.4 mm (3/4")	0.00	0.00	0.00	100.00
19.0 mm (1/2")	0.00	0.00	0.00	100.00
9.51 mm (3.8")	11.57	1.16	1.16	98.84
No. 4	389.44	38.93	40.09	59.91
No. 10	232.15	23.21	63.29	36.71
Pan	5.45	0.54	63.84	36.16

Table A4 – Result of sieve test (+10 fraction), Garland
Mass of soil sample, total mass = 1000.35 g

Sieve or Grain Size (mm)	Mass Retained (g)	Percent Retained	Cumulative percent retained	Cumulative percent passing
No. 20	5.63	5.54	52.06	47.94
No. 40	12.45	12.25	64.31	35.69
No. 60	13.99	13.76	78.07	21.93
No. 80	6.73	6.62	84.69	15.31
No. 100	2.59	2.55	87.24	12.76
Pan	4.60	4.53	91.76	8.24

Table A5 – Result of sieve test (-10 fraction, +200 fraction), Soprema
Mass of soil passing the No.10 sieve = 493.08 g
Mass of soil sample, total mass = 1002.4 g

Sieve or Grain Size (mm)	Mass Retained (g)	Percent Retained	Cumulative percent retained	Cumulative percent passing
No. 20	8.85	11.32	57.84	42.16
No. 40	13.44	17.19	75.02	24.98
No. 60	7.65	9.78	84.80	15.20
No. 80	2.81	3.59	88.40	11.60
No. 100	1.26	1.61	90.01	9.99
Pan	3.69	4.72	94.73	5.27

Table A6 – Result of sieve test (-10 fraction, +200 fraction), Garland
Mass of soil passing the No.10 sieve = 639.57g
Mass of soil sample, total mass = 1000.35 g

Hydrometer Test

By using distilled water, 50 g of the oven dried soil -10 was washed into the dispersion cup. Distilled water was added to the halfway mark of the cup, and the soil water mixture was then mixed in the stirring apparatus for one minute. The soil water mixture was then transferred into a one litre glass cylinder where distilled water was added to bring the water level up to the one litre mark. The palm of the hand was then placed on top of the cylinder containing the soil water mixture. The cylinder was inverted at regular intervals for a period of one minute. The cylinder was then placed on the table; hydrometer and thermometer reading were recorded.

After taking 120 minutes of readings, the cylinder was stored; last reading of hydrometer and thermometer was recorded after 24 hours. After 24 hours of reading, the soil water mixture was decanted through the No.200 sieve. Soil retained on the No.200 sieve was placed into the oven to dry and sieve analysis was carried out afterwards. The results of the Hydrometer test reading and calculations are shown in Tables A7 and A8, while the results of the second sieve test are shown in Tables A5 and A6.

Time of day	Δt (min)	Temp (°C)	Hyd. Rdg.	Comp Corr.	Corr Hyd. Rdg.	Percent Finer, P	L/t	K	D	PF (%)
Initial	0.00	23	5.50	-0.10	5.40	24.880716	0.00	0.0058	0.00	12.24
0.5	0.50	23	5.50	-0.10	5.40	24.880716	307.85	0.0058	0.10	12.24
1	0.50	23	5.50	-0.10	5.40	24.880716	153.93	0.0058	0.07	12.24
2	1.00	23	5.50	-0.10	5.40	24.880716	76.96	0.0058	0.05	12.24
3	1.00	23	5.00	-0.10	4.90	22.576946	51.33	0.0058	0.04	11.11
5	2.00	23	4.50	-0.10	4.40	20.273176	31.12	0.0058	0.03	9.97
10	5.00	23	4.50	-0.10	4.40	20.273176	15.56	0.0058	0.02	9.97
15	5	23	4.00	-0.10	3.90	17.969406	10.40	0.0058	0.02	8.84
60	45.00	23	4.00	-0.10	3.90	17.969406	2.60	0.0058	0.01	8.84
1440	1380.00	24.6	3.80	0	3.80	17.508652	0.11	0.0058	0.00	8.61

Table A7 - Result of Hydrometer test, Soprema

Time of day	Δt (min)	Temp (°C)	Hyd. Rdg.	Comp Corr.	Corr Hyd. Rdg.	Percent Finer, P	L/t	K	D	PF (%)
Initial	0.00	23	10.00	-0.10	9.90	20.161152	0.00	0.0058	0.00	9.92
0.5	0.50	23	10.00	-0.10	9.90	20.161152	292.00	0.0058	0.10	9.92
1	0.50	23	10.00	-0.10	9.90	20.161152	146.00	0.0058	0.07	9.92
2	1.00	23	10.00	-0.10	9.90	20.161152	73.00	0.0058	0.05	9.92
3	1.00	23	10.00	-0.10	9.90	20.161152	48.67	0.0058	0.04	9.92
5	2.00	23	9.00	-0.10	8.90	18.124672	29.60	0.0058	0.03	8.92
10	5.00	23	7.50	-0.10	7.40	15.069952	15.06	0.0058	0.02	7.41
15	5	23	7.50	-0.10	7.40	15.069952	10.04	0.0058	0.02	7.41
60	45.00	23	7.00	-0.10	6.90	14.051712	2.52	0.0058	0.01	6.91
1440	1380.00	24.6	6.60	0	6.60	13.440768	0.11	0.0058	0.00	6.61

Table A8 - Result of Hydrometer test, Garland

Plastic Limit Test

10 g of soil was placed in the mixing dish and mix in sufficient water so that the soil could be formed into a ball. The soil was then classified as plastic state. The soil ball was then placed on the ground side of the glass plate and rolled gently with the palm of the hand. The ball was then rolled into a 3 mm diameter thread without breaking the thread. The soil ball was then re-molded into a ball. The above steps were repeated until the soil thread broke at a thread in 3mm diameter. When the thread broke, the lower limit of the plastic state was achieved. Broken pieces were put on a dish and the water content determined.

Trial No.	1	2
Mass of dish	8.39 g	6.71
Mass of wet soil + dish	8.94 g	7.28
Mass of dry soil + dish	8.65 g	6.81
Mass of water	0.29 g	0.47
Mass of dry soil	0.26 g	0.47
Water Content	111.5%	100%

Table A9 – Result of plastic limit test, Soprema

Plastic Limit = 105.75%

Trial No.	1	2
Mass of dish	8.55 g	8.46
Mass of wet soil + dish	9.15 g	9.05
Mass of dry soil + dish	8.77 g	8.68
Mass of water	0.38 g	0.37
Mass of dry soil	0.22	0.22
Water Content	173%	173%

Table A10 – Result of plastic limit test, Garland

Plastic Limit = 173%

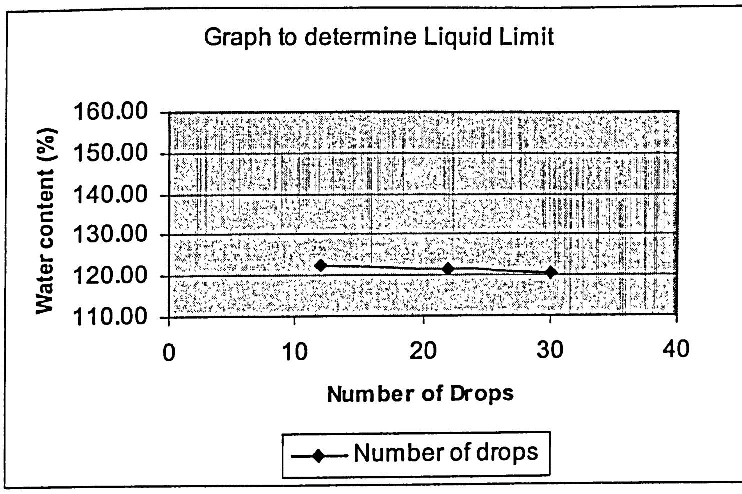
Liquid Limit Test

150g of soil was placed in the mixing dish where distilled water was added into the dish and mixed until it became a stiff paste. The soil paste was then placed in the brass cup and levelled off to a depth of 10mm. A grooving tool was used and a trench was cut in the soil. The crank was turned with the rate of two drops per second, which eventually caused the trench to collapse. Counted the number of drops which the trench was required to collapse for a distance of 13mm along the bottom. Soil was then removed and water content determined. 5 ml of water was then added to the soil and above procedures were repeated until the number of drops required to collapse the trench was less than 10.

Trial No	1	2	3
Number of drops	30	22	12
Mass of dish (g)	8.35	8.59	8.34
Mass of wet soil + dish (g)	10.16	9.52	9.43
Mass of dry soil + dish (g)	9.17	9.01	8.83
Mass of water (g)	0.99	0.51	0.60
Mass of dry soil (g)	0.82	0.42	0.49
Water Content	120.73	121.43	122.45

Liquid Limit = 9.6 %

Table A11 – Result of Liquid limit test, Soprema

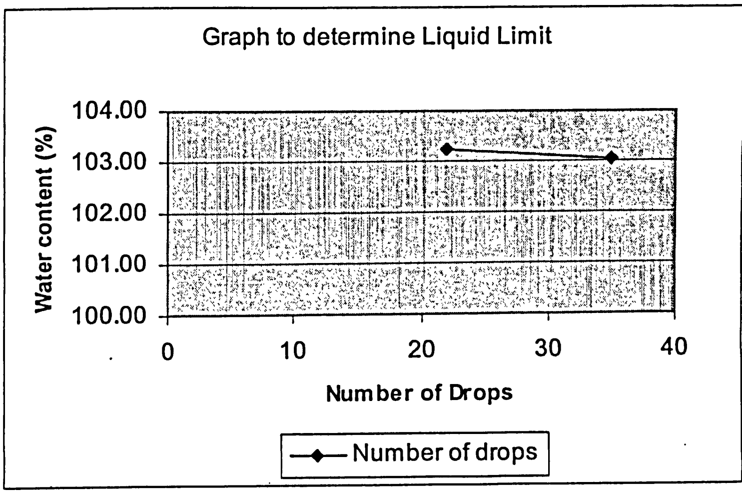


Graph to determine Liquid Limit

Trial No	1	2	3
Number of drops	35	22	13
Mass of dish (g)	15.45	15.30	15.39
Mass of wet soil + dish (g)	16.12	16.56	15.82
Mass of dry soil + dish (g)	15.78	15.92	15.60
Mass of water (g)	0.34	0.64	0.22
Mass of dry soil (g)	0.33	0.62	0.21
Water Content	103.03	103.23	104.76

Liquid limit = 7.86%

Table A12 – Result of Liquid limit test, Garland



Graph to determine Liquid Limit

Shrinkage Limit Test

40 g of soil from the – 40 fraction of "Preparation of soil specimens" was taken out and placed in the evaporating dish. The soil sample was mixed thoroughly with distilled water to form a smooth paste and one half of it was placed into the dish. The dish bottom was tapped to remove the air bubbles inside the soil. The remaining soil paste was then added and repeated the tapped until no more bubbles coming out. The dish was put into the oven for 24 hours until the soil pat was dried. After 24 hours, the soil pat was removed from the dish and attached with a thread before dipping into the melted wax. The entire surface of the soil pat was coated with wax; the mass of the soil pat with wax in air as well as in the water were determined.

Soil Mixture	Soprema	Compox
Mass of soil pat (g)	15.65	25.75
Mass of soil pat + wax in air (g)	26.93	53.03
mass of wax (g)	11.28	27.28
Density of wax (g/ml)	0.91	0.91
Volume of wax (ml)	12.40	29.98
Mass of soil pat + wax in water (g)	28.71	54.73
Volume of soil pat + wax (ml)	28.71	54.73
Volume of soil pat (ml)	16.31	24.75
Specific gravity	1.4	1.23
Volume of soil grains (ml)	11.18	20.93
Volume of voids	5.14	3.82
Mass of water required to fill voids (g)	5.14	3.82
Water content - Shrinkage Limit (%)	32.8168	14.82337

Table A13 – Result of shrinkage limit test

Soil Classification

Two different green roof soil mixtures were classified using the textural soil classification System developed by the U.S. Department of Agriculture (USDA) system. In this system, soil particles larger than 2mm in diameter are disregarded and particles smaller than 2.0mm are divided into three groups: sand 0.05mm to 2.0mm, silt 0.002mm to 0.05mm and clay, less than 0.002mm (Salvas, 1977). By using the USDA soil classification figure, the soil texture can be determined. The textures of the soil mixtures are summarized at the table below.

Soil Mixture	Soprema	Garland
Percent of Sand	51.05 %	26.79%
Percent of Silt	3.67 %	3.31 %
Percent of Clay	8.61 %	6.61 %
Soil texture	Sandy loam to Sandy clay loam	Silty loam to loam

Table A14 – Result of soil classification

<u>Reference</u>

Salvas, R.J., 1977, "Manual for the measurement of soil properties in the laboratory", Department of Civil Engineering, Faculty of Engineering and Applied Science, Ryerson University, Toronto, ON.

Appendix B – Design loads on a green roof, Zinco Green Roof System

Design loads on a green roof

Layers	Build-up height mm	Weight per unit area dry kg/m²	Weight per unit area saturated kg/m²
Protection layer			
Root barrier with protection mat	10	1.0	5.0
Drainage layer			
Floradrain® FD 25	25	1.5	4.5
FD 40	40	2.0	6.0
FD 60 filled with Zincolit	60	6.0	37.0
Floratec FS 75	75	2.0	4.0
Elastodrain EL 200/EL 202	20	12.0	12.0
Vegetation layer (for every 10 l/m²)			
Zincolit	9	10.0	12.0
Extensive soil	8.5	10.0	13.0
Intensive soil	7.5	10.0	14.0
Zincohum	5	6.0	9.0
Plant level			
Sedum, small shrubs and lawn		approx. 5.0	
Shrubs and low bushes		approx. 10.0	
Shrubs and bushes up to approx. 1.5m high		approx. 20.0	
Bushes up to approx. 3.0m high		approx. 30.0	
Large bushes and trees cause a greater concentrated load due to the additional tipping movement under wind pressure.		Individual values must be given	
Examples			
Gravel surface		approx. 90-150	
Paving slabs		approx. 160-220	
Vehicle surface		from approx. 500	
Extensive landscaping		approx. 60-150	
Intensive landscaping		approx. 200-500	

APPENDIX C - Cost Analysis

Roof Area (m^2)	241
Construction cost ($/m^2)	90
Capital Investment	21690
Yearly Energy Save (kWh)	10203.975
Energy Cost ($/kWh)	0.1017

Energy Cost Increase	0.07
Discount Rate	0.05
Life Span (Years)	30
Maintenance Cost ($/m^2)	1.62

Year	Energy Price	Energy Save	Maintance	Total Saving	Cumulative Savings	Cash Flow
0						-$21,690.00
1	$0.1017	$1,037.74	$390.42	$647.32	$647.32	$647.32
2	$0.1088	$1,110.39	$409.94	$700.45	$1,347.77	$700.45
3	$0.1164	$1,188.11	$430.44	$757.68	$2,105.44	$757.68
4	$0.1246	$1,271.28	$451.96	$819.32	$2,924.77	$819.32
5	$0.1333	$1,360.27	$474.56	$885.71	$3,810.48	$885.71
6	$0.1426	$1,455.49	$498.29	$957.20	$4,767.68	$957.20
7	$0.1526	$1,557.37	$523.20	$1,034.17	$5,801.86	$1,034.17
8	$0.1633	$1,666.39	$549.36	$1,117.03	$6,918.89	$1,117.03
9	$0.1747	$1,783.04	$576.83	$1,206.21	$8,125.10	$1,206.21
10	$0.1870	$1,907.85	$605.67	$1,302.18	$9,427.28	$1,302.18
11	$0.2001	$2,041.40	$635.95	$1,405.45	$10,832.73	$1,405.45
12	$0.2141	$2,184.30	$667.75	$1,516.55	$12,349.27	$1,516.55
13	$0.2290	$2,337.20	$701.14	$1,636.06	$13,985.33	$1,636.06
14	$0.2451	$2,500.80	$736.20	$1,764.61	$15,749.94	$1,764.61
15	$0.2622	$2,675.86	$773.00	$1,902.85	$17,652.80	$1,902.85
16	$0.2806	$2,863.17	$811.66	$2,051.51	$19,704.31	$2,051.51
17	$0.3002	$3,063.59	$852.24	$2,211.35	$21,915.66	$2,211.35
18	$0.3213	$3,278.04	$894.85	$2,383.19	$24,298.86	$2,383.19
19	$0.3437	$3,507.51	$939.59	$2,567.91	$26,866.77	$2,567.91
20	$0.3678	$3,753.03	$986.57	$2,766.46	$29,633.23	$2,766.46
21	$0.3935	$4,015.74	$1,035.90	$2,979.84	$32,613.07	$2,979.84
22	$0.4211	$4,296.84	$1,087.70	$3,209.15	$35,822.22	$3,209.15
23	$0.4506	$4,597.62	$1,142.08	$3,455.54	$39,277.76	$3,455.54
24	$0.4821	$4,919.46	$1,199.18	$3,720.27	$42,998.04	$3,720.27
25	$0.5159	$5,263.82	$1,259.14	$4,004.68	$47,002.71	$4,004.68
26	$0.5520	$5,632.29	$1,322.10	$4,310.19	$51,312.90	$4,310.19
27	$0.5906	$6,026.55	$1,388.21	$4,638.34	$55,951.24	$4,638.34
28	$0.6320	$6,448.41	$1,457.62	$4,990.79	$60,942.03	$4,990.79
29	$0.6762	$6,899.79	$1,530.50	$5,369.30	$66,311.33	$5,369.30
30	$0.7235	$7,382.78	$1,607.02	$5,775.76	$72,087.08	$5,775.76
					NPV	-$3,593.06
					Saved Sum	$72,087.08
					IRR for 30 years	7%
					ROI	100%
					Break Even	17 years

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