Evaluating rooftop and vertical gardens as an adaptation strategy for urban areas

Bass, B.; Liu, K. K. Y.; Baskaran, B. A.

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Brad Bass; Bas Baskaran

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Principle Investigators

Brad Bass
Adaptation & Impacts Research Group
Environment Canada

Bas Baskaran
Institute for Research in Construction
National Research Council

Adaptation & Impacts Research

construction Institute for research in construction IRC

Recherche sur les impacts et l'adaptation

Environment Canada Environnement Canada

National Research Council Canada Conseil national de recherches Canada

Executive Summary

Green roof infrastructure has become a multi-million dollar industry in Germany and is gaining popularity in other European countries as well. Green roof infrastructure is more than just soil and plants on a roof, but consists of specialized membranes and drainage barriers to support the growing of vegetation on top of buildings. The benefits of this technology were researched and presented in the Canada Mortgage and Housing Corporation Report *Greenbacks from Green Roofs* (Peck at el., 1999). Many of the advantages of these technologies, such as the reduction of stormwater runoff, the reduction of cooling loads and the reduction of the urban heat island suggested that this technology could play a role in helping Canadian cities adapt to climate change. The goal of this research was to assess these benefits in a Canadian context.

The report also investigated the potential of even a newer technology, vertical gardens, essentially moving the vegetation from the roof to the walls, in an urban environment. Vertical gardens could refer to vine-covered walls, but they could also include additional infrastructure components to support the growing of vegetation on a wall or as part of a window shade. Both technologies were assessed using observations and modelling, and both were assessed with regards to the urban heat island and the reduction of indoor temperatures. The reduction of stormwater runoff was only evaluated for green roof infrastructure.

The performance of green roof infrastructure was studied by field monitoring of an experimental field site, the Field Roofing Facility (FRF), at the National Research Council (NRC) campus in Ottawa. The FRF consisted of two roof sections, a green roof and a modified bituminous roof that is representative of what is typically found on flat roofs in Canadian cities. The two roof sections were identical in principal components and differ only in the green roof components. The roofs were instrumented to measure temperature profile, heat flow, solar radiation and stormwater runoff. The observations were also used to comment upon membrane durability. The thermal performance was also simulated with Visual DOE and a hydrology model was constructed to simulate stormwater retention.

The vertical gardens were tested on the roof of the Earth Science Building at the University of Toronto. The test consisted of comparing the surface temperature of the garden with the surface temperature of a vertical wall and comparing shaded with unshaded temperatures. The thermal performance of the garden was also tested using Visual DOE. AutoCad and LightScape were used to illustrate how one prototype might be adapted to a real building.

The green roof was found to reduce the summer cooling load and the surface temperature of the roof. The Green Roof delayed runoff, reduced the rate and volume of runoff. These results corresponded with the simulation models. The vertical gardens were also shown to reduce summer cooling load, even more dramatically than the green roof. Both technologies reduced surface temperatures sufficiently to suggest that significant reductions of the urban heat island would be attainable if these technologies were adopted on a widespread basis.

There are barriers to more widespread adoption of this technology in Canada. Two of these barriers, the lack of technical and evaluative information for Canada and the lack of awareness were directly addressed by the research in this report.
This work was carried out by a partnership between Environment Canada, specifically the Adaptation and Impacts Research Group, and the NRC, specifically the Institute for Research in Construction. The partnership also included several Canadian Roofing Associations, major roofing companies and the University of Toronto. This work was funded by the Science, Impacts and Adaptation Table of the Climate Change Action Fund, Environment Canada, the NRC and members of the Rooftop Garden Consortium at NRC.

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1 Introduction

The majority of Canadians live in cities, and it is reasonable to assume that their first encounter with the impacts of climate change will occur in urban areas. In 1999, the Science, Impacts and Adaptation Table of the Climate Change Action Fund supported a study to evaluate the potential of adapting urban areas to climate change with rooftop and vertical gardens. The principle investigators in this project were Dr. Bas Baskaran of the Institute for Research in Construction (IRC) at the National Research Council (NRC) and Dr. Brad Bass of the Adaptation and Impacts Research Group (AIRG) within the Meteorological Service of Canada, which is a part of Environment Canada. The research also involved other partnerships with members of the roofing industry and the Faculty of Engineering and the Institute of Environmental Studies at the University of Toronto. Both of the principal research groups were able to build on their experience in evaluating construction material performance under climate variability and the impacts of and adaptation strategies to climate change.

Canadian cities currently face a range of environmental problems; some of them connected to climate. Interviews with chief accounting officers and Heads of Public Works Departments in the Great Lakes Basin revealed that stormwater runoff, water quality and air quality were amongst the most important environmental issues of concern in urban areas. Each of these problem areas can be ameliorated or exacerbated by variations in the climate. Too much precipitation increases stormwater runoff leading to combined sewer overflow (CSO).[1] Higher temperatures can increase the rate of ozone formation, and in combination with heat stress can result in additional deaths or hospital admissions for respiratory problems.

Climate change is expected to result in the more frequent occurrence of extreme temperatures and precipitation events. These changes will heighten many ongoing environmental problems in Canada's cities. Expected changes in precipitation frequency could lead to heavier albeit less frequent rainfall events leading to increased CSO events. The CSO events could exacerbate water quality problems particularly in combination with warmer temperatures and higher rates of evaporation. Higher average temperatures may not be as problematic for air quality and heat stress as a higher frequency and intensity of heat waves that are projected in some scenarios.

[1] Combined sewer overflow occurs because the stormwater drainage system does not exist or has limited capacity. Under heavy rain events, the excess stormwater is channeled through the sewage system. This rush of water can flush pollutants into a receiving body of water before they can be removed at a sewage treatment plant.

Urban areas tend to exacerbate these problems due to the replacement of vegetation with impervious surfaces relative to other land uses. Impermeable surfaces increase the flow of runoff during a storm event and contribute to CSO events. Replacing vegetation with typical urban surfaces also creates an urban heat island (UHI), an elevation of temperature relative to the surrounding rural or natural areas. The UHI occurs because more of the incoming solar radiation is absorbed by dark surfaces such as rooftops and pavement in the city and reradiated as longwave radiation or heat.

Below a certain temperature, the demand for electricity is inelastic. Above this threshold, every degree C increase can increase electricity consumption by 5%, increasing emissions of the fossil fuels required for its generation. Although the UHI may be as small as 2^{o}C, that may be sufficient to move the temperatures above this threshold due the additional demand for air conditioning and requirements for refrigeration. The increased temperatures also increase the aforesaid problems associated with heat stress and the rate of ozone formation.

Vegetation can reduce all of these impacts. It can reduce the stormwater peak by reducing the rate at which rainwater reaches the surface, and vegetated surfaces are highly permeable, which also reduces the amount of stormwater. Vegetation reduces the UHI because of evapotranspiration. Incoming solar energy that is used for evapotranspiration cannot be absorbed and reradiated as heat. Studies in Oregon demonstrated that non-vegetated areas could exceed temperatures of 50^{o}C in July while vegetated areas remain at 25^{o}C (Luvall and Holbo, 1989). Vegetation can also further alleviate air and water quality problems by filtering pollutants through the leaves or the roots. In addition, vegetation in urban areas has been shown to increase mental well being, biodiversity and residential property values.

Planting trees at ground level is the most common strategy for restoring vegetation. In addition to reducing the urban heat island and GHG emissions through reducing energy consumption, shade trees can further offset GHG emissions through the sequestration of carbon in their woody mass. However, higher land use densities or space restrictions in some parts of the city restrict the space required to allow trees to reach their full potential. In these cases, rooftop gardens or green roof infrastructure[2] could provide many of the same benefits, and would take advantage of the unused roof space that is available in most urban areas. In addition,

[2] Within industry, a shift to the term "green roof infrastructure" is occurring as it implies that putting vegetation on a roof involves more than just piling soil and planting seeds. There are multiple layers below the growing medium for drainage and protection from leakage and root penetration through the roof.

depending on its colour, the heat from bare rooftops can exacerbate the urban heat island (Terjung and O'Rourke, 1981a,b) and the associated air quality problems.

Most discussions of the UHI focus on the temperatures of surfaces or the canopy level UHI, which occurs at the level at which most people live. We only feel surface temperatures directly when in contact with these surfaces, but they heat up the surrounding atmosphere. For the canopy level, the primary affect is in the evening. Heat from rooftops affects the temperature of the boundary layer, the layer of the atmosphere extending roughly from rooftop level up to the level where the urban influence is no longer "felt" (Oke, 1976). This additional heating occurs throughout the day and influences the chemistry of air pollution and temperatures above the roof (see below). Nakamura and Oke (1988) found that temperatures in the urban canyon and temperatures in the lower part of the urban boundary layer, are usually very similar. Thus, higher temperatures above the roofs can affect temperatures at canopy level, and in areas with only one or two story buildings, the roofs may be at the canopy level.

Reducing the rooftop temperatures would further reduce the use of energy for space conditioning in both the summer and the winter. In the summer, a typical insulated, gravel-covered rooftop temperature can vary between 60^{o}C and 80^{o}C (Peck et al., 1999). These temperatures increase the cooling load on a building in two ways. Since the internal temperature underneath the roof is typically lower than the temperature above the roof, the heat will always flow through the roof into the building. In addition, modern high-rise buildings are constantly exchanging the internal and external air. Because of the high roof temperatures, the temperature of this external air that is brought into the building's ventilation system may be warmer than the ambient air, requiring additional energy for cooling.

Evapotranspiration from rooftop vegetation could cool the roof, reducing the amount of heat flow into the building through the roof. The lower rooftop temperature would also reduce the temperature of the external air that is exchanged with the building's air. The temperature of this air could also be reduced if the rooftop garden is designed so as to shade the intake valves. Temperatures as low as 25^{o}C have been observed (Peck et al., 1999). During the winter, the rooftop garden would provide additional insulation, which would reduce the flow of heat through the roof.

Green roofs are found throughout Europe. In the early 1960's green roof technology was developed in Switzerland and enhanced in many countries, particularly Germany. In the 1970's, a significant amount of technical research was carried out on root repelling agents, waterproof membranes, drainage, and lightweight growing media and plants. By the year 1996, 10 million square meters of roofs in Germany had been covered with gardens. In European countries such as France, Germany and Austria, green roofs are viewed as an effective strategy for increasing green space in cities, reducing stormwater runoff and achieving other environmental benefits.

An even greater amount of space for vegetation may be available on the exterior walls of the buildings in urban areas, and growing vegetation on walls could create vertical gardens. Vertical gardens increase the amount of vegetative surface in urban areas, increasing evapotranspiration and evaporative cooling, and can be used for direct shading as well. Whereas green roofs directly affect the boundary layer UHI, vertical gardens can reduce the canopy level UHI. In areas that are suitable for trees, they can also to be used to cover windows that cannot be shaded by trees due to the height or specific design features of a building.

Vertical gardening is a comprehensive term referring to any manner in which plants can be grown on, up, or against the wall of a building such as a vine, as part of a window shade, as a balcony garden, or in a vertical hydroponic system. As a window shade, plants can be grown in a planter box installed below a window, or hanging plants can be suspended above a window and used as a part of an awning. To allow some natural light into the room, the vertical garden could be installed on a moveable louver, or installed as part of adjustable awning, so that it could be maneuvered to intercept only direct sunlight. Additional design considerations are also required to cope with high wind speeds for plants and planter boxes located above eight stories.

At a workshop with stakeholders representing the roofing industry, architecture, landscape architecture, engineering and municipal government was held in November 1998 to identify barriers to widespread adoption of green roofs and vertical gardens. One barrier was the lack of information on performance within Canada. This research was developed with three specific objectives as a means to address that barrier. The three specific objectives were to:

- Assess the use of rooftop and vertical gardens as an adaptation strategy in urban areas.
- Assess the durability of the technology with respect to leakage and root penetration.
- Develop partnerships with roofing industry and Green Communities to promote the development and adoption of rooftop and vertical gardens.

The study was divided up into two major and additional minor components. The centrepiece was the construction of a green roof field site, the first of its kind in the world. This site consisted of a small house with a roof that could be reconfigured in a variety of different ways. For this study, half of the roof was built according to standard construction practices while a green roof was installed on the other half.

Both halves were instrumented in a similar manner to measure surface temperature, surface radiation, vertical temperature profiles through the roof, heat flux through the roof and stormwater runoff.

The second major component was the construction of a green roof hydrology model for Canada, which included snow accumulation and melt in order to facilitate a climatic simulation. The model was written with a Windows visual interface so as to increase its utility to other users. Smaller components of the study included a simulation of the insulation and shading potential of green roofs and vertical gardens and a comparison of temperatures between vertical gardens and other urban surfaces in order to assess the potential for reducing the urban heat island.

2 Rational for Green Roof Infrastructure and Vertical Gardens

2.1 Climate Change Impacts

By 2005, 50% of the world's population will live in cities (Bindé, 1998), and in the industrialized world, the figure has already surpassed 80%. The growth in urban populations has and will continue to create a unique set of environmental problems, both within cities and in the surrounding areas, due to the large demands for food, energy and water. Many of these problems are either directly caused or exacerbated by the removal of vegetation to accommodate urban expansion. It is expected that many of these problems will be further exacerbated by climate change, particularly climate change impacts that exacerbate heatwaves and the associated health problems, rapid temperature changes, stormwater runoff, water quality, biodiversity and food security.

Specific climate change impacts in the Great Lakes-St. Lawrence Basin include a net decrease of 46% in basin water supply in the (Mortsch and Quinn, 1996), adverse impacts on unmanaged and managed (e.g. agriculture) ecosystems (Mortsch and Quinn, 1996), an increase in heat-related mortality in Toronto (Chiotti *et al.,* 2002b) and the potential for the re-emergence of malaria (Chiotti *et al.,* 2002b). Some of the findings in the water sector are contradictory: climate change will exacerbate existing problems (Dore and Burton, 2001) or the distribution of water or wastewater treatment are not sensitive and will not be affected by drought (Moraru et al., 1999). While studies of the energy sector (Chiotti *et al.,* 2002a) or the health sector (Chiotti *et al.,* 2002b) demonstrate the relevance of climate change and variability to urban centres, these are preliminary assessments, and part of longer-term projects.

The investment required to cope with climate change should not be minimized. For example, the funding of urban drainage infrastructure is in the order of billions of dollars and annual maintenance is in the order of hundreds of millions of dollars. One important aspect of maintenance is the detection, repair and reduction of leaks as leakage accounts for 10-30% of municipal water supplies (Bruce et al., 2000). Increased occurrences of CSO could put a bigger strain on this infrastructure, partly because the investment in water treatment infrastructure in Ontario's municipalities has been about half the required level during the past 20 years (Fortin and Mitchell, 1990).

Heatwaves, extreme snowfalls, new diseases and water shortages to some extent are already emerging in the Grea Lakes-St. Lawrence basin. Although more people die from cold stress than heat stress in Canada, heat related mortality might become a more frequent part of Ontario's future due to warmer temperatures, and is already a larger problem than cold stress in the City of Toronto. Heatwaves also exacerbate air quality problems by accelerating the formation of smog and increased emissions of pollutants due to increased use of air conditioning and refrigeration. Toronto has already developed a heat-health alert system, and hospitals will need their own contingency plans to deal with the expected increased frequency of heat waves. This section discusses the benefits of urban vegetation, presents an analysis of the radiation balance and the impact of green roofs and vertical gardens and reviews previous work on stormwater management.

2.2 Vegetation and the Energy Balance in Urban Areas

Viewed from the air or from space, with an infrared sensor, the heat signature of a city would be much closer to a rock quarry than a forest. This is significant as summer temperatures in a quarry can reach 50°C while the forest canopy remains at 25°C (Luvall and Holbo, 1989). Vegetation accounts for the temperature difference because it makes moisture available for evapotranspiration, the combination of evaporation of water from plant tissue and the evaporation of water from the soil. Evapotranspiration utilizes a significant amount of incoming solar energy cooling both the leaf surface as well as the air. The energy used for evapotranspiration is embodied in the water vapour, which prevents it from being converted into heat at the surface.

A lower fraction of vegetative cover in the city reduces the available moisture to direct incoming solar radiation towards evapotranspiration. The non-vegetated surfaces absorb the incoming solar radiation and reradiate it as heat. This heat artificially elevates urban temperatures, a phenomenon known as the urban heat island (Sailor, 1998). The higher temperatures increase the demand for air conditioning which pumps more waste heat into the environment, increasing the heat island. Air conditioning requires electricity that is often generated by the burning of fossil fuels leading to increased greenhouse gas (GHG) emissions. Yet, without air conditioning, the higher temperatures will increase the incidents of morbidity and mortality due to heat stress (Kalkstein and Smoyer, 1993).

The evapotranspiration and the associated reduction in surface temperatures indicates that exergy is being used or stored. Exergy is a measure of the quality of the energy, or the amount of energy that is available to do work. Higher amounts of stored exergy are associated with higher levels of ecological integrity (Schneider and Kay, 1994) and higher levels of biodiversity (Bass et al., 1998). Schneider and Kay (1994) proposed that ecosystems develop so as to utilize exergy more effectively. The higher surface temperatures of clear-cut areas, rock quarries and other non-vegetated areas do not utilize exergy as indicated by their higher surface temperatures. Non-vegetated landscapes also only sustain a much lower diversity of life, and raise questions as to whether non-vegetated areas, such as the rock quarry and the clear-cut are appropriate models for urban areas and urban sustainability.

There are other environmental problems associated with the urban heat island and the lack of vegetation in a city. Higher temperatures are associated with increasing severe episodes of ground-level ozone or smog. With increased use of air conditioning comes the increased risk of releasing additional chlorofluorocarbons into the atmosphere, chemical compounds that are responsible for the reduction of the stratospheric ozone that is necessary to protect us from harmful amounts of ultra-violet radiation. The combustion of fossil fuels to generate electricity contributes other pollutants into the atmosphere, such as sulfur dioxide, nitrous oxides and particulate matter, which have been linked to respiratory health problems.

If vegetation is situated so as to cover building surfaces then evaporative cooling can reduce the need for air conditioning by reducing the air temperature immediately adjacent to the building. Artificial evaporative cooling systems have been shown to reduce air conditioning by 20-25% (Abernathy, 1988). Vegetation can further reduce the use of air conditioning through shading and insulating a surface. In previous tests, it has been estimated that shading from trees might reduce energy usage from 20 – 30% (McPherson et al, 1989, Hunn et al., 1993, Akbari et al., 1997). In cold-winter climates, wind decreases energy efficiency by 50%. A row of trees, planted fairly close to a wall improves energy efficiency by reducing contact between wind and the building surface (Minke and Witter, 1982).

Vegetation will reduce energy emissions through reductions in the urban heat island, through shading windows from direct sunlight and through insulation from in both the winter and summer. Reducing energy usage directly on a particular building will reduce emissions of many pollutants into the atmosphere, but the indirect effect of reducing the urban heat island will also have an impact on urban air quality. For example, in Southern California, simulation models have suggested that reducing the urban heat by 2^{o}C would be equivalent to converting half of the motor vehicles to zero-emission electric engines (Taha et al., 1997). A significant reduction in the urban heat island could be achieved in the Los Angeles basin with a 1% increase in vegetation (Sailor, 1995).

Light-coloured surfaces can also reduce the temperature of urban surfaces by reflecting a high percentage of the incoming solar energy so that it is not absorbed and reradiated as heat. However, it is not clear that the potential reductions in the urban heat island are as large as the reductions that could be achieved with vegetation. Reductions in cooling load will probably be greater with green roofs due to the additional shading from the vegetation and extra insulation provided by the growing medium. In addition, the material used to create the light surfaces fades and must be replaced every two to five years, depending on the product. The use of light-coloured surfaces will also not address the other environmental problems that have arisen due to the removal, or are exacerbated by the absence, of vegetation, such as water pollution, lack of habitat for wildlife and stormwater runoff. From a thermodynamic perspective, although the surface temperatures of light-coloured surfaces are relatively lower than is typical for urban areas, these surfaces are not utilizing exergy, and thus are closer to the rock quarry in some respects, than to the forests.

Green roof infrastructure can reduce a building's energy demand on space conditioning through direct shading, evaporative cooling from the plants and the soil, and additional insulation values from both the plants and the growing medium. A 20cm (8in.) layer of growing medium or substrate plus a 20-40cm (8-16in.) layer of thick grass has a combined insulation value equivalent to 15cm (6in.) of mineral wool insulation (RSI 0.14; R 20) (Minke, 1982). Under a green roof, indoor temperatures (without cooling) were found to be at least 3-4°C (5-7°F) lower than hot outdoor temperatures between 25-30°C (77-86°F) (Liesecke, 1989).

Temperature measurements on a 75mm (3in.) green roof at the Fencing Academy of Philadelphia showed that while the bare roof reached 32°C (90°F), the temperature underneath the planting media on the green roof was no higher than 16°C (61°F) (EBN, 2001). A study by Oak Ridge National Laboratory showed that a vegetated roof of 0.46-0.76m (1.5-2.5ft.) of soil reduced the peak sensible cooling needs of a building by about 25% (Christian, 1996). In addition, the green roof did not have a cooling penalty like commercial buildings with high roof insulation levels. A computer simulation of green roofs indicated that they could improve the thermal performance of a building by blocking solar radiation and reducing daily temperature variations and annual thermal fluctuations (Eumorfopoulou, 1998) or by reducing heat flux through the roof (Palomo Del Barrio, 1998).

2.3 Reducing the Urban Heat Island: An Analytical Approach

How Green Roofs and Vertical Gardens Reduce the Urban Heat Island

Surface temperature is considered to be a primary indicator of the urban heat island. Assessing the surface temperature and the reduction in the urban heat island requires sophisticated models of the atmosphere and the land surface. However, the contribution of any surface to the urban heat island and the reductions in surface temperature can be estimated from the radiation balance on the roof and the wall (Brown and Gillespie, 1995). The important components are the incoming solar radiation (R_s) and surface reflectance of R_s, called albedo and often represented by the Greek symbol α.

What produces heat is the longwave or infrared radiation that is reradiated from a surface after it has absorbed the incoming solar radiation. Longwave radiation is also produced in the atmosphere and re-radiated to the surface ($L\downarrow$). The total radiation absorbed (R_{abs}) by a surface without vegetation or moisture is computed as below:

$$R_{abs} = (1 - \alpha) R_s + L\downarrow \qquad [2.1]$$

Assuming a dark surface with an albedo of 0.3, a typical July R_s of 600 Wm^{-2}, the downward longwave radiation is 300 Wm^{-2} at 15^oC (Brown and Gillespie, 1995).

$$R_{abs} = (1 - 0.3)\ 600 + 300 \qquad [2.2]$$

$$R_{abs} = 720\ Wm^{-2} \qquad [2.3]$$

The surface temperature, $T(^oC)$ can be computed with the formula relating energy to temperature developed by Stefan and Boltzmann.

$$\text{Energy}\ (Wm^{-2}) = (5.67 \times 10^{-8}) \times (T + 273)^4 \qquad [2.4]$$

The value of 5.67×10^{-8} is the Stefan-Boltzmann constant, which relates the radiance of a black body to temperature, and is symbolized by the Greek letter σ. T + 273 changes degrees Celsius to degrees Kelvin or K. Thus the Equation [2.4] could be rewritten as

$$E\ (Wm^{-2}) = \sigma \times (T^oK)^4 \qquad [2.5]$$

or

$$R_{abs} = \sigma \times (T^oK)^4 \qquad [2.6]$$

Rearranging Equation [2.6] provides a value for surface temperature.

$$T(^oC) = (R_{abs}/\sigma)^{1/4} - 273 \qquad [2.7]$$

and in this case,

$$T(^oC) = 62.7. \qquad [2.8]$$

This estimate in Equation [2.8] corresponds with the previously reported observations.

If vegetation was affixed to the surface, evapotranspiration could reduce the absorbed energy by as much as one-half. Using a more conservative estimate for R_{abs}, of 420 Wm^{-2} in Equation [2.7], results in a temperature closer to 20°C. This estimate is close to the 25°C reported in the literature, and the lower value is probably due to the value suggested for $L\downarrow$ in Equation [2.1] (Brown and Gillespie, 1995). To estimate the temperature of a wall, and the impact of vertical gardens, it is necessary to reduce the incoming solar radiation, R_s in Equation [1]. Although a precise estimate can be derived based on the use of sine functions, a rule-of-thumb estimate equates six hours of sunshine on a roof to 2.5 hours on a wall which reduces R_s to 250 Wm^{-2}. This produces a surface temperature of 29°C in Equation [2.7], and the corresponding decrease in surface temperature, with a vertical garden, can be derived by reducing R_{abs} accordingly.

Previous observations indicate that vertical gardens do reduce the heat flow into the building, and their surface temperature is lower than a bare wall, which is necessary to reduce the urban heat island. A series of experiments in Japan suggested that vines could reduce the temperature of a veranda with a southwestern exposure (Hoyano, 1988). Vines were effective at reducing the surface temperature of a wall. In Germany, the vertical garden surface temperature was 10°C cooler than a bare wall when observed at 1:30 PM in September (Wilmers, 1988).

A series of observations were collected in South Africa on English ivy, Boston ivy, Virginia creeper and grape vines (Holm, 1989). All the vines were grown at a cover depth of 200 mm to emulate the thermal improvement to a typical South African house. The plants were installed over steel sheets that were compared to black and white panels. Temperatures collected behind all panels were less than the outdoor temperature, but the largest reduction of 2.6°C was behind the vegetated panel. For a building consisting of two 10mm fiber-cement sheets with 38mm of fiberglass insulation, a computer simulation estimated that a vertical garden reduced summer daytime temperatures on the surface by 5°C. These results are not as dramatic as the cooling effect on a horizontal surface, such as a roof, but given the amount of wall space in urban areas, the potential impact of vertical gardening is expected to be quite dramatic.

2.4 Stormwater Management

How Green Roofs Can Reduce Stormwater Runoff

A large component of urban water resource management is moving rainwater and snowmelt away from buildings and roads as fast as possible. The replacement of vegetation by hard surfaces in urban areas has significant impacts on water quantity. Since large parts of the city are now impermeable to water, it has to be diverted through artificial systems, taxing the capacity of the sewage system, or it runs off over the surface. Stormwater runoff has contributed to problems in water quantity and quality and during extreme precipitation events, it can lead to flooding and erosion. Urban runoff can also contain high levels of heavy metals and nutrients. Stormwater can be managed through storage, infiltration and retention. Alternatives to hard infrastructure include downspout disconnection, rain barrels, cisterns, swales adjacent to parking lots, retention ponds, artificial wetlands and living machines, and the use of porous materials for roads, driveways and parking lots as well as urban forestry, rooftop gardens and vertical gardens.

Additional tree cover has reduced urban stormwater runoff by 4-18% (Sanders, 1986) and the pollutants end up being bound in the substrate of vegetation instead of being discharged into the environment. On a rooftop garden, rainwater is stored in the substrate and used by the plants or returned to the atmosphere by evapotranspiration. Observations carried out in Berlin indicate that a substrate depth of 20-40 cm can hold 10 – 15 cm of water, translating into runoff levels that were 25% below normal (Minke and Witter, 1982). Studies in Berlin showed that rooftop gardens absorb 75% of precipitation that falls on them, which translates into an immediate discharge reduction to 25% of normal levels (Stifter, 1997). Generally, summer retention rates vary between 70-100% and winter retention between 40-50%, depending on the rooftop garden design and the weather conditions. A grass covered roof with a 200-400mm (8-16in.) layer of substrate can hold between 100-150mm (4-6in.) of water (Minke, 1982).

Excess water is stored in a drainage layer, and will enter the municipal drainage system, but at a much slower rate and lags the peak flow of runoff, thus helping to reduce the frequency of CSO events, which is a significant problem for many major cities in North America. In Portland, Oregon a rooftop garden with a 7-cm vegetation layer produced no runoff during a three-month summer period although the retention was not as high during a continuous heavy rainfall. A mixed layer of sedum and grass on 51mm (2in.) of soil on the roof of his garage could retain up to 90% of rainfall, and it became less effective only during continuous and heavy rainfall (Thompson, 1998). Preliminary results from Portland, Oregon also indicated that a 100mm (4in.) green roof could absorb a full inch of rainfall during a summer rain event (when the soil started out fairly dry) before water started to runoff (EBN, 2001). This stormwater retention potential of rooftop gardens has led to a bonus density incentive programs in Portland for developers who install a green roof.

Similar statistics do not exist for vertical gardens, but it would vary by design. A vine-covered wall would delay the runoff or allow a slow infiltration into a permeable ground cover. It will be most effective when rain is accompanied by strong winds, and is blown into the wall of a building. A window shade design that involves plants in soil, or another substrate, would have similar benefits to a rooftop garden in that water could be stored in the soil, used by the plants and returned to the atmosphere by evapotranspiration. A hydroponic system might also be designed to capture stormwater.

Rooftop gardens can significantly reduce the cost of retaining stormwater in underground tanks and tunnels (Peck et al., 1999). A rooftop garden composed of sedums and 8 cm of substrate costs \$110.00 Cdn / m^2, or \$11.00 Cdn / m^2 over 10 years and can retain 3 – 4 cm of rainwater. The approximate cost of the roof membrane with a root repellant layer is \$55.00 Cdn / m^2, or \$5.50 Cdn / m^2 over 10 years. In Toronto, the average annual precipitation translates into 80 cm per square metre of roof area or 0.8 m^3 of water. The approximate cost of an underground stormwater storage tank in Toronto is \$500.00 – 1000.00 Cdn per m^3.

The City of Toronto has built a new storage tunnel with a capacity of 85,000 m^3. The tunnel is designed to handle 20 million m^3 of water from April through October, which represents 25 million m^2 of surface area, mostly in the form of roads and parking lots. The approximate cost of the tunnel is \$50 million Canadian, \$588.00 / m^3, or \$58.80 / m^3 per annum over 10 years.

Assuming a retention rate of 85%, over a 10 year period it costs \$16.50 Cdn per annum to retain 0.68 m^3 of stormwater or \$24.26 Cdn / m^3 in a rooftop garden. There are more than 334 million m^2 of roof area in the City of Toronto and 2.4 million m^2 of new roof area will be added over the next ten years. Although not all of this roof space is adequate to support vegetation, and not all of it will have an impact, the amount of available roof space is more than adequate. In addition, the amount of space available for vertical gardens is even larger.

Vertical and rooftop gardens can also be used to improve water quality. Heavy metals such as cadmium, copper, lead and zinc can be bound in the substrate, as much as 95% of (Johnston and Newton, 1996). In Europe both rooftop gardens (Thompson, 1998) and vertical gardens (Johnson and Newton, 1996) are being designed to treat wastewater that would normally be discharged as raw sewage. In addition to delaying and reducing runoff, rooftop gardens can improve the quality of the runoff. Vegetated surfaces can act as natural filters for any of the water that happens to runoff it (North American Wetland Engineering, 1998). Forster (1993) found that the water quality of roof runoff ranged from relatively clean to severely polluted depending on the roof, its location and the particular rain event. Runoff samples obtained from an experimental roof system in Germany indicated the main sources of roof runoff pollution came from local sources (e.g. PAH from heating systems), dissolution of the metal components on the roof and background air pollution (Forster, 1999). Metals such as cadmium, copper, lead and zinc were taken out of rainwater by rooftop gardens (Johnson, 1996).

3 The Green Roof Hydrology Model

3.1 Introduction

A simulation model of a green roof was developed in order to assess the potential reductions of stormwater runoff from different buildings, in different cities across a range of climates. As a green roof is a special type of catchment in terms of soil type, depth and vegetation, the model was based on the simulation of major hydrological processes. The research was designed so as to use observations from a field roofing facility to calibrate the model, and then use the other data to validate the model's performance. Due to the delays in constructing the field roofing facility, stormwater runoff data were not available. Instead, various components of the model were tested individually with other data sets.

The model was developed primarily as a research tool. Beyond this specific research, it is hoped this model could be used for future research and for educational purposes. However, the philosophy from the start has been to build it using a visual programming language so that it could provide the basis for a tool that could be used by other stakeholders to assess the capacity of any particular green roof design. In addition, the evapotranspiration component of the model will hopefully be used to estimate the impact of evaporative cooling on the summer energy consumption for cooling, which is missing from all available energy models.

3.2 The Green Roof Hydrology Model

3.2.1 Modelling Approach

Various approaches are available for simulating precipitation and runoff processes. These software range from the simple water balance to more complicated processes based on distributed hydrologic models. They cover hydrologic processes involving vegetation and single to multi-layer soil processes. In a hydrological simulation, each of these models has advantages and disadvantages over the others with regard to data requirements, computing time and resources. Application of any particular model — empirical, water balance, conceptual-lumped and physically based models — often depends on the specific objectives of the exercise, the need for analytical, future scenario and geographic flexibility and the requirements for precision in the estimates. The choice of models in this research was highly dependent on the need for future flexibility in terms of climate scenarios and geographic region, the differing needs of various stakeholders and the nature of a green roof.

Compared to a natural catchment, a green roof (**Figure 3.1**) has three distinct differences. ***First***, the vertical dimension of the soil profile will be different from that of the natural catchment. In most cases, it will be a mixture of a lightweight growing medium and synthetic components to prevent leakage and root penetration through the roof. ***Second***, the diversity of vegetation in the most common green roof is restricted to various grasses, wild flowers or vegetation that grows well in shallow soils under a range of moisture conditions. ***Third***, some physical processes involved in lateral runoff generation (such as interflow and baseflow) are not as important as they are in larger catchments and are excluded for simplicity, although they could be added at a later time.

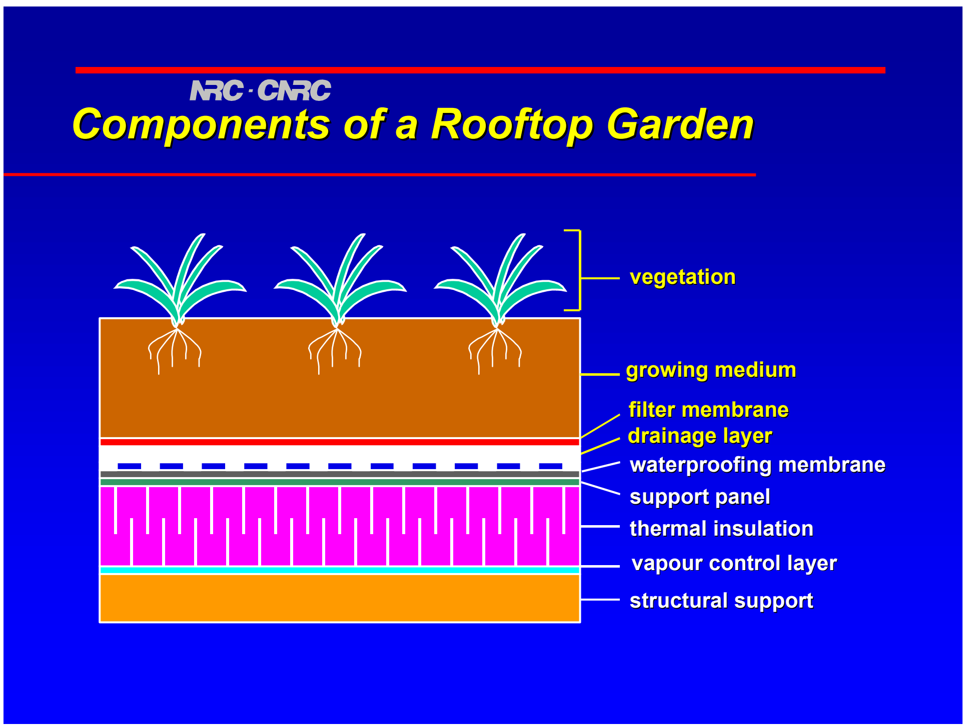


Figure 3.1: Structure of the rooftop garden in the pilot study site in Ottawa

Vertical and horizontal processes have been incorporated in the model. The vertical processes of water movement include interception, storage, evaporation, infiltration, soil-moisture storage, evapotranspiration, percolation or drainage, snowpack accumulation and melt. The horizontal processes only include surface runoff. Components of the vertical and lateral processes are integrated during the simulation run.

3.2.2 Components of the Model

The model has two major components: a snow component (**Figure 3.2**) and a rainfall-runoff component (**Figure 3.3**). The model is divided into two major components because the model is intended for simulating summer runoff, but the winter is required to run multi-year simulations in northern latitudes. However, there are different hydrological processes during winter and summer. These two components are linked in that the summer model receives its initial moisture content from the winter snow model. The two components can be run as stand-alone models to allow the summer model to be used in areas that only experience rainfall. In that case the model will require initial moisture content in the spring.

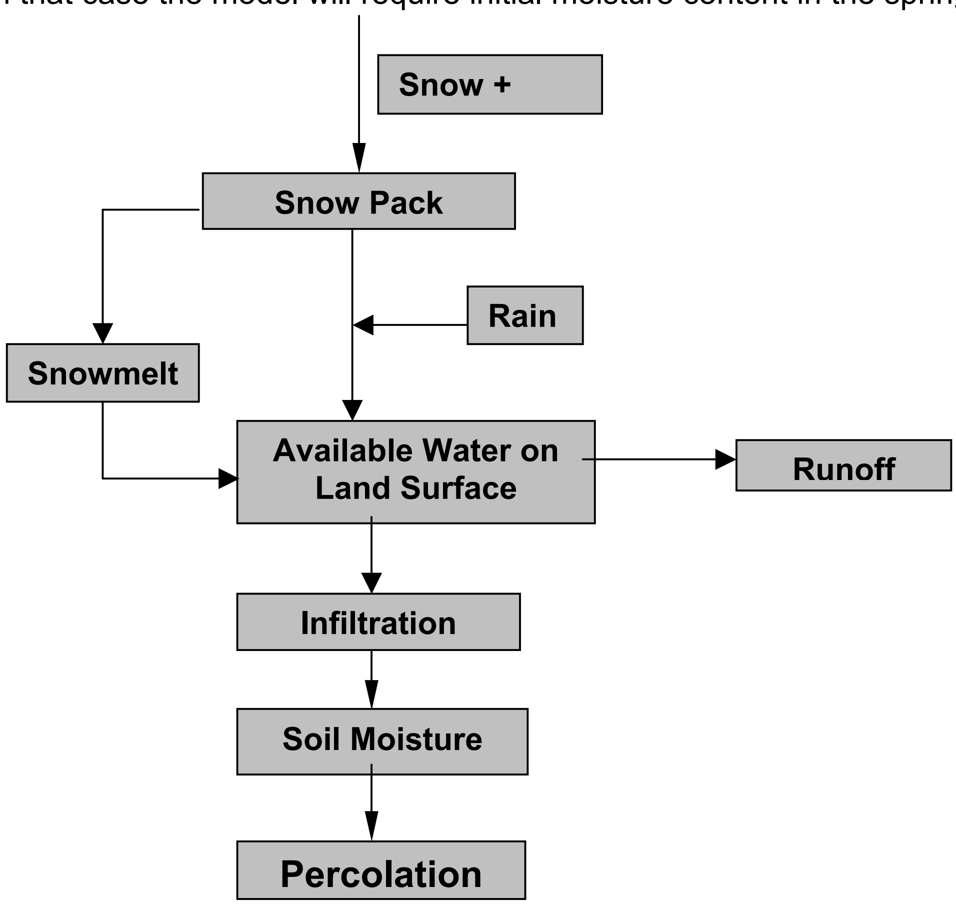


Figure 3.2: The snowmelt – runoff process incorporated in the model

The snow model runs on a daily time-step, and an hourly time-step is used in the summer model. The daily time step for winter is suitable as runoff from snow can involve major storage followed by relatively rapid release, and snow can accumulate over long periods. Release in liquid form depends on the energy available to melt snow, not on the initial precipitation rate. Compared to water that is stored in soil, much of this runoff is shielded from high rates of evapotranspiration as it passes quickly from its frozen state to runoff.

3.2.3 Snowmelt

Runoff from snow requires three conditions. First, snow must warm enough to melt. Second, snow must become wet enough to allow liquid water to drain. At this stage, the snow is said to be “ripe”. Third, soil or surface conditions must allow runoff to occur. The first phase involves the snow’s energy balance. Before melting can start, snow must reach a temperature of 0^oC (32^oF). The amount of energy needed to bring the snowpack up to 0^oC is referred to as its “cold content”, the difference between the snowpack temperature and (0^oC) is its “temperature deficit”. The cold content can be estimated from the amount of snow present (snow water equivalent as mass per area) and its temperature.

Once the temperature of the snowpack has reached 0^oC, the transformation from solid ice to liquid water requires a large addition of energy, 0.3337 MJ per kilogram or 80 calories per gram (the latent heat of fusion for water). Even with a very cold snowpack, much more energy is required to melt the snow than to raise its temperature to 0^oC. When heat is transferred evenly, a snowpack will reach 0^oC throughout its depth before it melts. It is then said to be “isothermal” at 0^oC. Because snow transfers heat relatively slowly, especially at low densities, it is some times possible to have melt at the top or bottom of the pack when other parts are still below 0^oC.

Energy to melt snow can come from several sources: direct solar radiation, energy re-radiated from vegetation, clouds, and other surfaces (longwave radiation) or heat transferred from air, ground, rain or the condensation of water vapour. The relative importance of different energy sources depends on the time of year, the physical setting, vegetation and other cover, weather, and other factors. Seasonal snowmelt associated with spring warming typically reflects increases in solar radiation, re-radiated energy, and heat transferred from warm air. As the snowpack ages and picks up dust and other particles, it reflects less solar radiation and absorbs more energy, adding to the tendency to warm and melt.

Heat transfer from air can be particularly important during periods with sustained, warm winds. When warm, moist air encounters snow, significant energy can be released by the condensation of water vapour. Rain falling on snow can transfer heat to the extent that its temperature is above freezing. Warm, moist air often accompanies rain; during rainy periods, condensation is likely a more important energy source for snowmelt than the rain itself.

Heat conducted from the ground is a relatively minor source of energy, but in autumn it can be important for melting early-season snows. In winter, ground heat may maintain low rates of soil water and ground water recharge. Accumulated over the entire season, this can be significant and may help maintain baseflow in streams.

The amount and type of vegetation strongly influence energy inputs to snow, but the effects can be complex and counter-intuitive. Consider solar radiation gain and longwave radiation gain and loss. With no trees, snow in open areas receives the most direct solar radiation but the least longwave radiation. Snow in areas with high forest cover gains little energy from direct solar radiation, but this loss is compensated by increased longwave radiation from trees.

Energy gain by snow in areas with sparse to intermediate forest cover depends on the degree of shading and amount of energy re-radiated from trees, both of which depend on forest canopy density and form and sun angle. Forest density also affects the transfer of energy by wind. Dense canopies shield snowpack from the wind. In relatively open stands, the presence of some trees may increase turbulence and enhance heat transfer. The net effects of forest cover on snowmelt are debated, but removal of trees by fire or timber harvest generally seems to accelerate melt. Because snow interception decreases and snow accumulation increases, up to a point, with removal of trees, total runoff from snowmelt often increases as well.

The effects of shorter vegetation stands on snowmelt are probably much less than those for forests, but they have received less attention outside of crop and rangelands. These effects probably reflect differences in snow accumulation, though differences in plant water use also affect soil and groundwater recharge.

3.2.4 Water Release and Runoff from Snowmelt

Snow is a porous medium. Like soil, it retains some liquid water in its pores before water drains under the force of gravity. Pursuing this analogy, just as a soil has a field capacity, a snowpack has a “liquid-water-holding capacity”. The liquid-water-holding capacity depends on snowpack density and structure but is generally low (<5% by volume); in a deep snowpack the available storage must be filled before melt water is released. A snowpack that has warmed to 0^{o}C and is at its liquid-water-holding capacity is said to be “ripe”. Any additional melting will release water.

Under some circumstances, sometimes dramatic, runoff over snow can occur. Rain falling on snow may not infiltrate if a low-permeability crust has formed at the surface and if the rainfall rate is high. Snowmelt runoff generated in one part of a landscape may flow over crusty snow or frozen soil that is further downslope. However, the insulating affects of snow allow soils to remain unfrozen if enough snow is deposited early in the cold season, and snow cover remains throughout the winter. Soil is most likely to freeze if snow cover is absent, very thin, or intermittent.

3.2.5 Snowmelt Calculation

(i) Rain-free condition

Empirical Equation: $M = M_f (T_i – T_b)$

Where

M = snow-melt in mm
M_f = snow-melt factor (3.66-5.7 for the Southern Ontario) (Gray and Prowse, 1992)
T_i = index temperature
T_b = base temperature (set as 0^oC).

(ii) During Rain

For a rain event, the melt factor is modified as follows:

$$M_f = (0.74 + 0.007P) (T_i – T_b)$$

Where P = precipitation (in mm).

Snowmelt is calculated by:

$$M = M_f (T_i – T_b).$$

(iii) Cold Content Calculation

Cold content is the energy required, measured in depth of precipitation, to raise the temperature of the snowpack to 0^oC:

$$W_c = SWE * T_s/160$$

Where

SWE = snow water equivalent (cm)

Ts = temperature deficit of the snowpack (^{o}C)

Wc = cold content.

(iv) Calculation of Retention Storage

Retention storage is the total amount of melt or rain that must be added to a snowpack before liquid water is released:

$$S_r = W_c + f(SWE + W_c)$$

Where

Sr = retention storage in cm

f = hygroscopic and capillary force (g/g).

3.2.6 Snow Melt Infiltration Modelling

Infiltration to frozen soils involves the complex phenomenon of coupled heat and mass transfer through porous media; therefore, the process is affected by many factors. The most important include the hydrological, physical and thermal properties of the soil, the soil moisture and temperature regimes, the rate of release of water from snow cover, and the energy content of the infiltrating water (Granger et el., 1984). In the absence of major structural deformations in a profile, e.g., cracks or other macropores, the major physical property of a frozen soil governing its ability to absorb and transmit water is its moisture content. This arises because of the reduction to the hydraulic conductivity caused by the constriction or blockage of the flow of water by ice-filled pores and the effects of these pores on the tortuosity and lengthening of the flow paths and the distribution and continuity of the air-filled pores. The existence of an inverse relationship between infiltration and frozen soil moisture has been demonstrated or postulated by many investigators (Motovilov, 1979; Granger and Dyck, 1980; Kane, 1980).

Following Popov's concerns with long-range forecasting of spring runoff for lowland rivers in the former Soviet Union (Popov, 1972), Gray et al.(1985) grouped completely frozen soils into the following infiltration classes:

Restricted: An ice lens on the surface or at shallow depth impedes infiltration. The amount of meltwater infiltrating the soil is negligible, and most of the snow water goes directly to runoff and evaporation.

Limited: Infiltration is governed primarily by the snow cover water equivalent and frozen water content of the 0 to 300 mm soil layer.

Unlimited: Soils containing many large, air-filled macropores, allowing for the infiltration of most or all of the meltwater.

When evaporation and storage losses are neglected, the runoff coefficients to be assigned to soils whose infiltration potentials are defined as “restricted” or “unlimited” in a practical modelling scheme would be 1.0 or 0, respectively. Thus, the problem remaining is one of defining the relationship between infiltration, snow-cover water equivalent, and frozen soil moisture content for the limited case. Following Granger *et al.* (1984) the following four equations have been incorporated in the snow model to estimate infiltration where SWE>INF.

$$INF = 3.222 * (SWE)^{0.562}$$ (1) [θp: 0.30-0.45]

$$INF = 2.210 * (SWE)^{0.586}$$ (2) [θp: 0.45-0.55]

$$INF = 2.034 * (SWE)^{0.548}$$ (3) [θp: 0.55-0.65]

$$INF = 1.477 * (SWE)^{0.603}$$ (4) [θp: 0.65-0.75]

Where

θp = degree of pore saturation (cm^3/cm^3).

3.2.7 Rainfall-Runoff Modelling

The major processes involved in the rainfall-runoff modelling are evaporation and evapotranspiration, interception, runoff, infiltration and percolation (**Figure 3.3**).

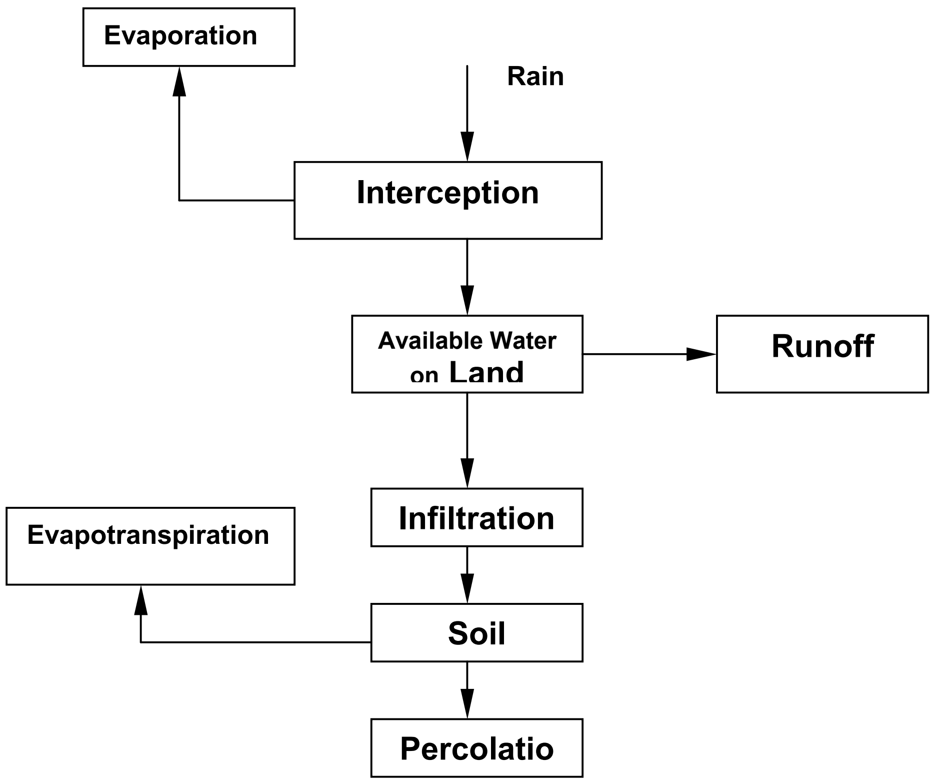


Figure 3.3: Rainfall-runoff process

3.2.8 Interception Model

Interception is that portion of the precipitation falling in a watershed that is intercepted by vegetal cover and other aboveground objects (Singh, 1989). *Interception* covers a variety of processes that result from the temporary storage of precipitation by vegetation or other surface cover. Part of the intercepted precipitation moistens and adheres to these objects and then returns to the atmosphere through evaporation. The interception process that has been incorporated in the model is shown in **Figure 3.4**.

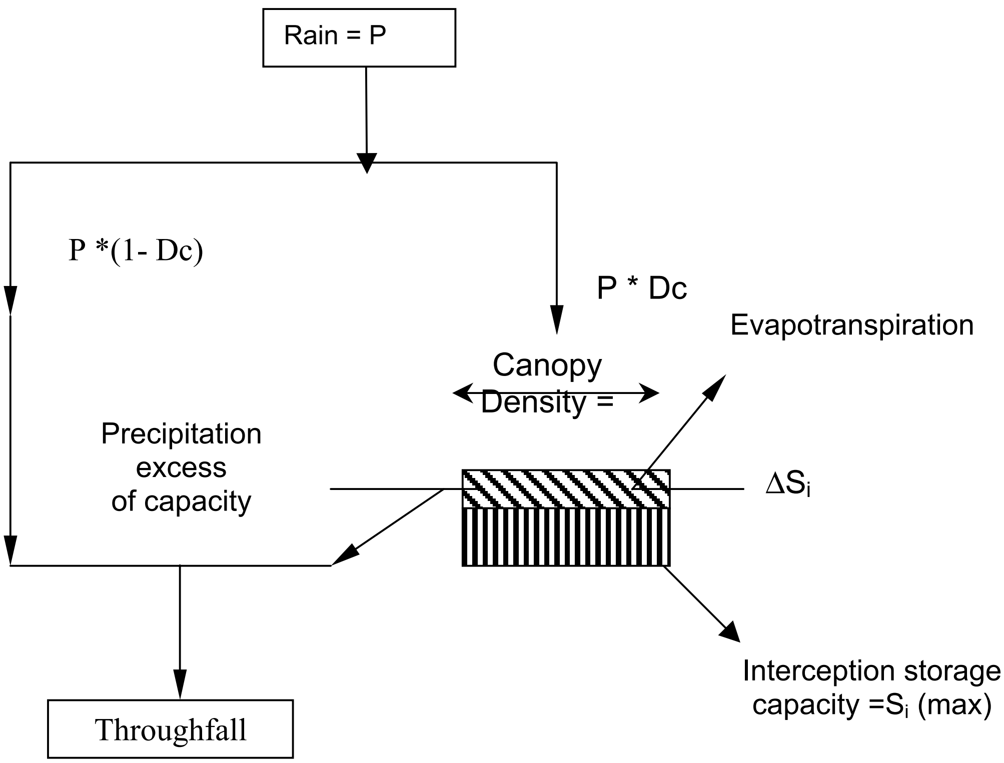


Figure 3.4: The interception process as incorporated in the model

$\Delta S_i =$ (P * Dc) $-E_{in}$

Where

$\Delta S_i =$ change in interception storage per unit area of canopy, when current interception storage is less maximum storage capacity

P = Rainfall per unit area of catchment
$D_c =$ canopy density-area of canopy per unit area of catchment
$E_{in} =$ evaporation and transpiration from interception storage per unit area.

Throughfall in excess of interception storage capacity is estimated by:

$T_{in} = \left|(S_{in(t-1)} + \Delta S_{i(t)} - S_{max}\right|$

$\Delta S_i = (P * Dc) - E_{in}$

ΔS_i = change in interception storage (mm)

P = Rainfall per unit area of catchment
D_c = canopy density-area of canopy per unit area of catchment

E_{in} = evapotranspiration from the interception storage /unit area (mm)

$S_{in\ (t-1)}$ = interception storage at time (t-1)

$\Delta S_{i(t)}$ = increment to interception storage at time t

S_{max} = maximum interception storage capacity

The window from the interception model is shown in **Figure 3.5**. It requires two parameters, the canopy density and the interception storage capacity, which may be similar to turf or grasslands for the standard green roof technology but would change with different uses such as food production and other types of landscapes. *Explain where these are found, provide default values, etc, i.e. what does the user need to know.*

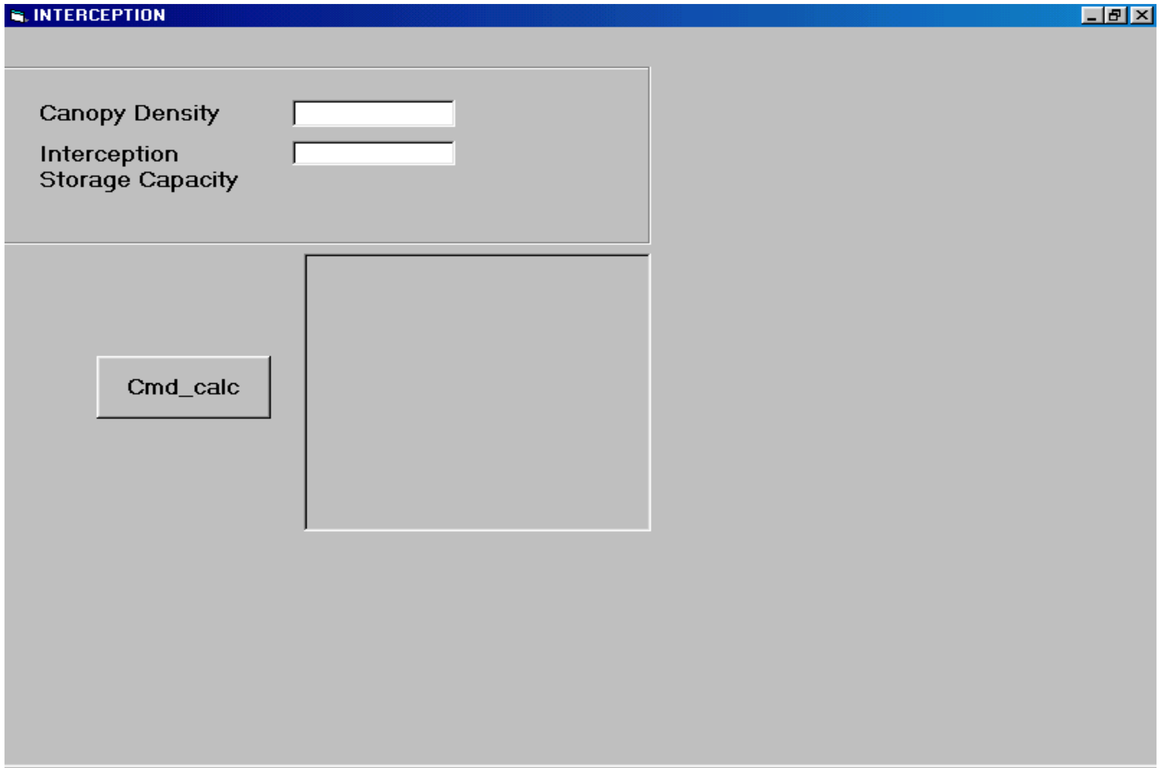


Figure 3.5: Interception Module of the Model

3.2.9 Evapotranspiration Model

(i) Evaporation and Evapotranspiration

Evapotranspiration (ET) is the sum of the volume of water used by vegetation (transpiration) and that evaporated from soil and intercepted precipitation on the surface of the vegetation. In addition to the affect of climate variability on free-water surface evaporation, evapotranspiration is also governed by other soil and vegetative factors (Kristensen and Jansen, 1975).

If the soil water is not limiting, then evaporation from saturated soils is approximately equal to evapotranspiration from a free water surface and is called potential evaporation (PE). When soil water is limited, evaporation is known to occur in several stages and is controlled first by climatic factors and then by soil characteristics; it is called actual evaporation (AE). Likewise, if water is not a limitation and the area is completely shaded by vegetation, then ET occurs at potential rate. Some professionals regard PE and Potential ET as synonymous, although in some practical water-management situations, it may be desirable to differentiate them (Wright, 1982). Penman (1956) defined potential ET as the amount of water transpired at night by a short green crop, completely shading the ground, of uniform height, and never short of water.

Various models are available for estimating potential evapotranspiration. Among them, Penman (1948), Thornthwaite (1948), Peman-Monteith (1964) and Priestley-Taylor (1972) are important and have received a great deal of attention in the literature. The green roof hydrology model uses the Priestley-Taylor Model due to its simplicity and less onerous data requirements.

(ii) Priestley-Taylor Method

If net radiation data are available, then the following simple equation (Priestley and Taylor, 1972) can be used:

$$E = \alpha\left(\frac{\Delta}{\Delta+\gamma}\right) * \left(\frac{R_n}{Hv}\right) \quad \textbf{(1)}$$

E = potential evapotranspiration (mm)

α =1.3 is a constant (Maidment et al., 1988) (may slightly vary from site to site)

Δ = slope of the saturated vapour pressure curve ($kPaC^{-1}$)

γ = psychrometric Constant ($kPaC^{-1}$)

R_n = net radiation (MJm^{-2})

G = soil heat flux ($MJm-^{2}$)

HV = latent heat of vapourization ($MJKg^{-1}$)

$$HV = 2.5 - 0.0022 * T \quad \textbf{(2)}$$

$$e(a) = 0.1 * \exp(54.88 - 5.03 * \ln(T + 273) - 6791 / (T + 273)) \quad \textbf{(3)}$$

$$\Delta = (e(a) / (T + 273)) * (6791 / (T + 273) - 5.03) \quad \textbf{(4)}$$

$$\gamma = 6.6*10^{-4} * PB \quad \textbf{(5)}$$

PB = barometric pressure (kPa)

$$PB = 101 - 0.0115 * ELEV + 5.44e10\text{-}7 * (ELEV)^2 \quad \textbf{(6)}$$

ELEV =elevation (m)

$$G = 0.12 * (T(i) - (T(i-1) + T(i-2) + T(i-3)) / 3) \quad \textbf{(7)}$$

G is assumed to be zero

The window from the evapotranspiration component (**Figure 3.6**) also allows the user to select the Penman and Penman-Monteith algorithms depending on data availability or preference.

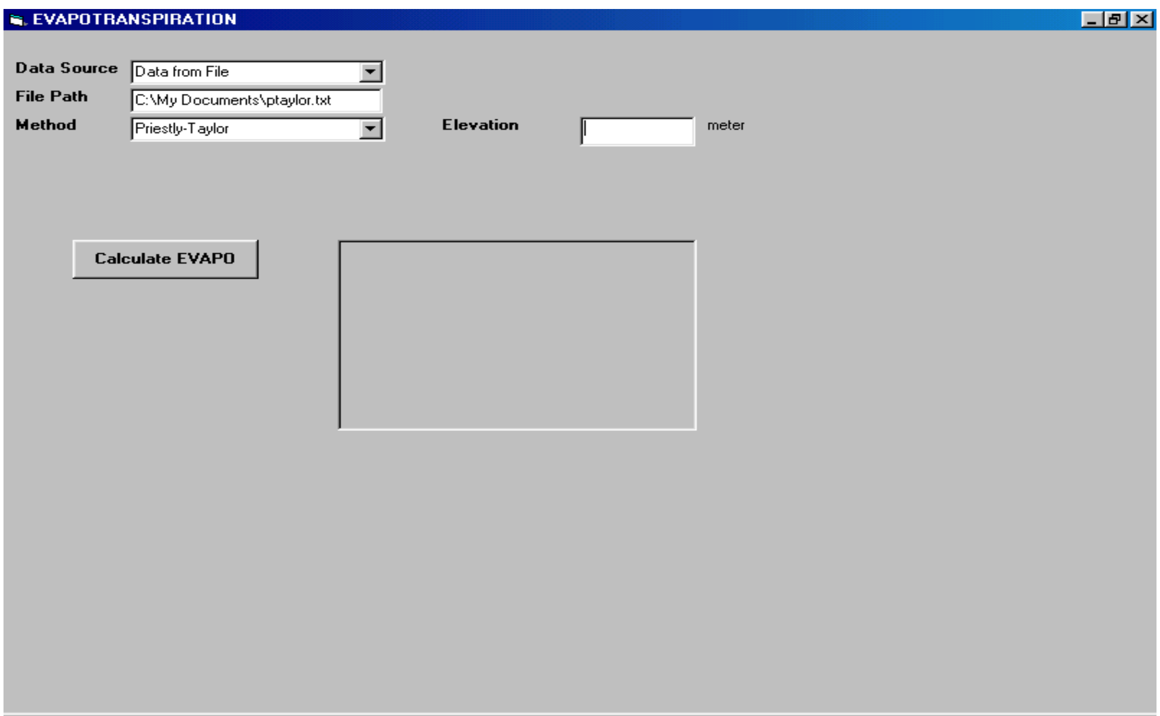


Figure 3.6: Evapotranspiration Module

3.2.10 Infiltration Modelling

(i) Horton equation with soil-moisture accounting

Horton (1933) proposed the exponential decay equation to model the infiltration of water into the soil:

$$f(t) = f_c + (f_o - f_c)\exp(-kt)$$

in which

$f(t)$ = infiltration rate at any time t

f_o = initial infiltration rate

f_c = final infiltration rate

k = exponential decay coefficient.

However, the reduction of the infiltration rate during a storm event may be viewed as reflecting not merely the passage of time but rather the accumulation of water in the soil, a process that continues until the soil becomes saturated. So, rather than considering the infiltration rate as an explicit function of time, it can be considered instead as being dependent on the actual soil moisture content (Tan and O'Connor, 1996).

In order to relate the infiltration rate to the soil moisture content, Tan (1994) has proposed the following equation similar to the equation of Horton (1933). The equation was used in the *spell out in full if available* SMAR conceptual model (Tan and O'Connor, 1995).

$$f = f_c + (f_o - f_c)\exp[-\alpha\,(\frac{S_{act}}{S_{cap} - S_{act}})]$$

From the above equation, it can be seen that when the actual soil moisture content S_{act} approaches the soil moisture capacity S_{cap}, the infiltration rate f tends to a steady rate f_c, and when the soil moisture content S_{act} approaches zero, the infiltration rate f approaches the maximum f_o.

The calculation of the actual infiltration proceeds as follows:

- at t =0, $f^*\Delta t = 0$
- if there is no rain, $f(t).\ \Delta t = 0$
- if rainfall > potential infiltration then actual infiltration = minimum(potential infiltration, soil moisture deficit)

- if rainfall $<$ potential infiltration then actual infiltration =minimum (rainfall, soil moisture deficit).

- The current soil moisture = S_{act} (t-1) + f. Δt

- The Drainage (D_R) rate = fc *(1-(soil capacity-current soil moisture)/(soil capacity-field capacity))^3

- S_{act} (t) =S_{act} (t-1) + f. Δt –E_{act}. Δt -D_R *Δt

- The calculation of actual evapotranspiration in this algorithm proceeds as follows:

- At t =0, E_{act}*Δt =0

- Else if
  - current soil moisture (S $_{currnt}$)(t) > Fc (Field capacity) then E_{act}. Δt =E_{pot}. Δt

- Else if
  - E_{act}*Δt = (S $_{currnt}$)(t)* E_{pot} *Δt/Fc

- The excess runoff is calculated as follows:

- if f. $\Delta t <$ rain. Δt,
  - rainfall_access (R_{access}) = rain. Δt - f. Δt for f. $\Delta t <$ moisture deficit

- if cumulative infiltration satisfies the soil capacity then
  - rainfall_access (R_{access}) = rain. Δt

The window for the modified Horton algorithm, and the required inputs are shown in **Figure 3.7**.

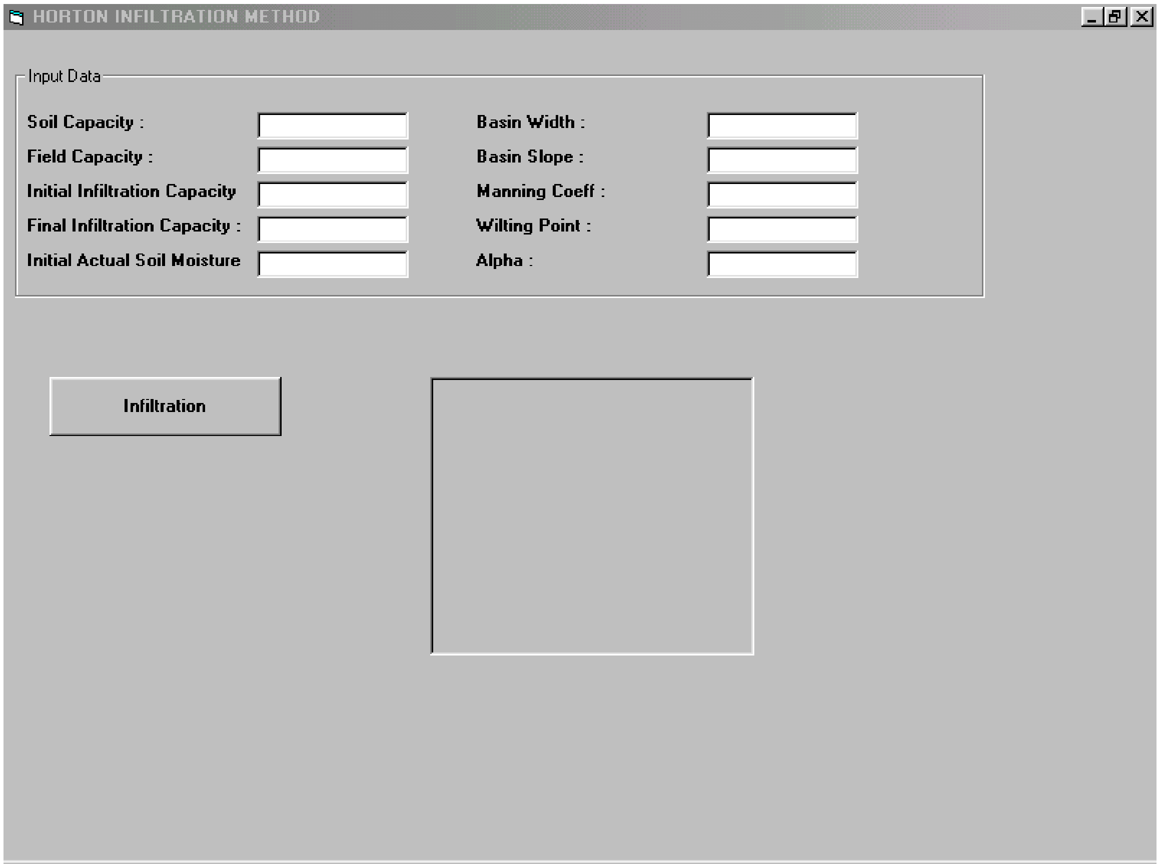


Figure 3.7: Modified Horton infiltration module of the model

<u>(ii) Green-Ampt Method</u>

Based on Darcy's law, Green and Ampt (1911) proposed a simple infiltration mode that is useful for modelling specific events. The model has following five assumptions:

a. The soil surface is covered by a pool whose depth can be neglected.

b. There is a distinctly definable wetting front.

c. The wetting front can be viewed as a plane separating a uniformly wetted infiltrated zone from a totally infiltrated zone. Thus the soil moisture profile is assumed to be a step function (Milly, 1985).

d. Once the soil is wetted, the water content in the wetted zone does not change with time as long as infiltration continues. This implies that the hydraulic conductivity K in the wetted zone does not change with time during infiltration.

e. There is a negative constant pressure just above the wetting front.

The cumulative infiltration is computed using the Green-Ampt Mein-Larson (GAML) model (Mein and Larson, 1973) as presented by Chu (1978) for the case of unsteady rainfall and multiple times to ponding. Chu (1978) computed an indicator, C_u (m) that determines if ponding occurs within a given interval of rainfall intensity given that there is no ponding at the beginning of the interval as

$$C_u = R_i - V_{i-1} - \left[\frac{K\psi\theta_d}{r_{i-1} - K}\right]$$

where

R = cumulative rainfall depth (m)

V = cumulative rainfall excess depth (m)

r = rainfall rate m.s^{-1}

K = saturated hydraulic conductivity (m/hour)

θ_d = soil moisture deficit (m.m^{-1}) = $\eta - \theta_v$

θ_v = initial volumetric content (m.m^{-1})

ψ = matric suction at the wetting front (m).

If C_u is positive, ponding occurs before the end of the interval; if it is negative no ponding occurs. The time to ponding t_p (s) is computed as:

$$t_p = \left[\frac{K\psi\theta_d}{r_{i-1} - K} - R_{i-1} + V_{i-1}\right] * \frac{1}{r_{i-1}} + t_{i-1}$$

t_s is computed from

$$\frac{Kt_s}{\psi\theta_d} = \left[\frac{R_{tp} - V_{i-1}}{\psi\theta_d} - \ln\left\{1 + [R_{tp} - V_{i-1}]/\psi\theta_d\right\}\right]$$

$$R_{tp} = R_{i-1} + (t_p - t_{i-1})/r_{i-1}$$

t is computed from

$$t = t_i - t_p + t_s$$

Cumulative infiltration F_p is computed from

$$F_p = Kt + \psi\theta_d \, In\,(1 + \frac{F_p}{\psi\theta_d})$$

The above equation is solved by successive substitution.

$$f_p = K(\frac{\psi\theta_d}{F_p} + 1)$$

The indicator for the end of ponding C_p during an interval, assuming that the surface was ponded at the beginning of the interval is

$$C_p = R_i - F_i - V_i$$

If C_p is positive, ponding continues, if it is negative ponding ceases within the interval. When there is no ponding within an interval, the cumulative infiltration is computed as

$$F_i = R_i - V_{i-1}$$

The window and the required input are shown in **Figure 3.8**.

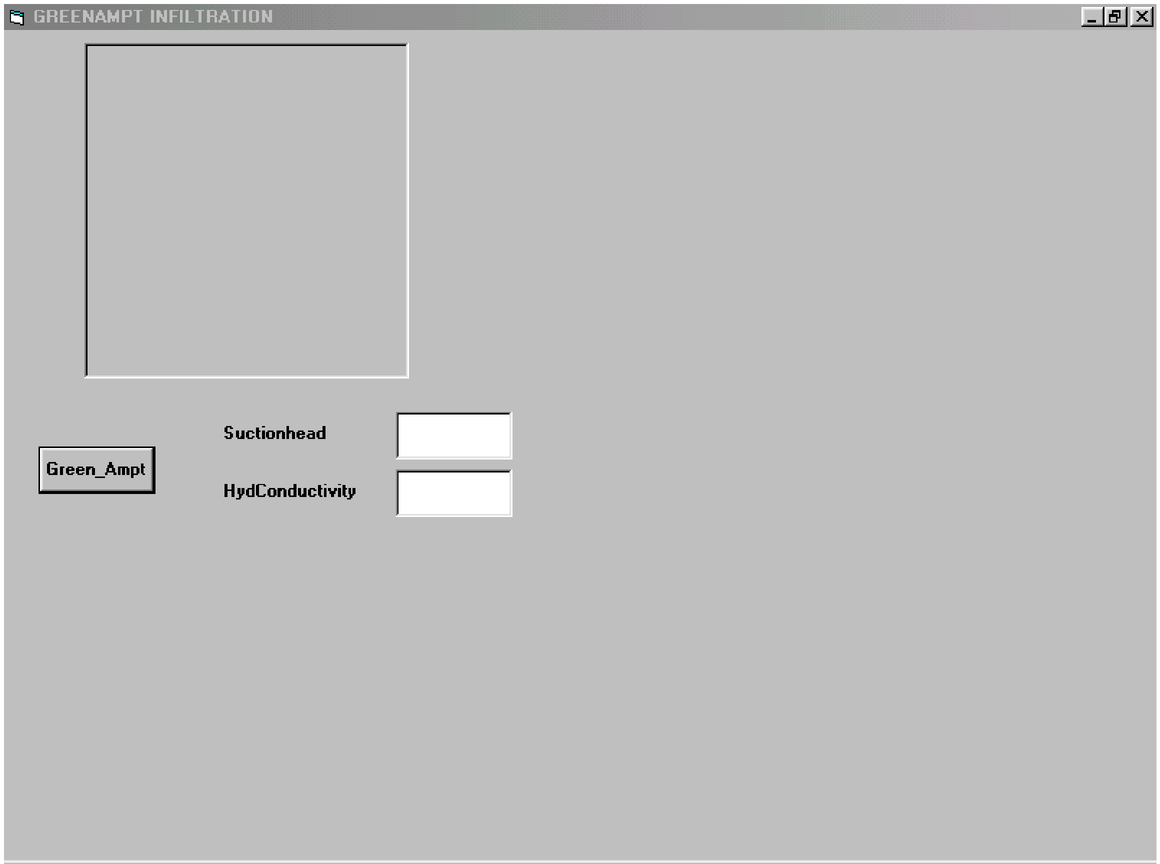


Figure 3.8: Green-Ampt infiltration module of the model

(iii) Process Based Equation

Although the Horton and the modified Horton algorithm can be used for climatological simulations, they do not simulate the actual physical process of infiltration. The physical process is more widely applicable to different regional climates and climate scenarios. It is based on Richard's equations of flow. The Richard's equation for one-dimensional flow can be written as

$$c(h).\frac{\delta h}{\delta t} = \frac{\delta}{\delta z}[k(h).(\frac{\delta h}{\delta z} - 1)]$$

Where

c(h) = soil water capacity can be obtained from soil water characteristics

= $\frac{d\theta}{dh}$

θ = initial water capacity

h = pressure head

The solution of Richard's equation could be explicit and *implicit*.

Explicit solution

$$h_i^{j+1} = h_i^j + \frac{\Delta t}{c_i^j . \Delta z}\left[k_{i+1/2}^j\left(\frac{h_{i+1}^j - h_i^j}{\Delta z} - 1\right) - k_{i-1/2}^j\left(\frac{h_i^j - h_{i-1}^j}{\Delta z} - 1\right)\right]$$

k is the hydraulic conductivity, which can be estimated from by taking arithmetic mean of the two adjacent nodes, and *i* and *j* refer to the spatial and temporal increments.

$$k_{i\pm 0.5}^j = 0.5(k_i + k_{i\pm 1})$$

Implicit Solution

Crank-Nicolson (C-N) Approximation

The C-N approximation averages the space derivatives at the *j+1* and *j*-th time levels to obtain an approximation at the *j +1/2* level. A C-N formulation of the Richard's equation yields,

$$c_i^{j+1/2}\frac{(h_i^{j+1} - h_i^j)}{\Delta t} = \frac{k_{i+1/2}^{j+1/2}}{2\Delta z^2}(h_{i+1}^{j+1} + h_{i+1}^j - h_i^{j+1} - h_i^j - 2\Delta z) - \frac{k_{i-1/2}^{j+1/2}}{2\Delta z^2}(h_i^{j+1} + h_i^j - h_{i-1}^{j+1} - h_{i-1}^j - 2\Delta z)$$

The system of equations generated by the above equation is tridiagonal. Estimates of are obtained by linearization techniques.

$$k_{i\pm 1/2}^{j+1/2} \; and \quad c_i^{j+1/2}$$

Implicit methods generally use much larger time steps than the explicit methods, and their stability conditions have to be determined by trial and error, as they depend upon the nonlinearity of the equations (Havercamp et al., 1977). The programming is also more involved than for the explicit method.

The Initial and boundary conditions for the Richard's equations are

Dirichlet types (constant h or θ)

For example
h(z,0) = -100 cm ($\theta = 0.07903\ cm^3/cm^3$)
h(0,t) = -20 cm (($\theta = 0.269\ cm^3/cm^3$)
h(L,t) =-100 cm

Neuman type

$$q = -(\frac{k\delta h}{\delta z} + k)$$

The window for the process-based model is shown in **Figure 3.9**.

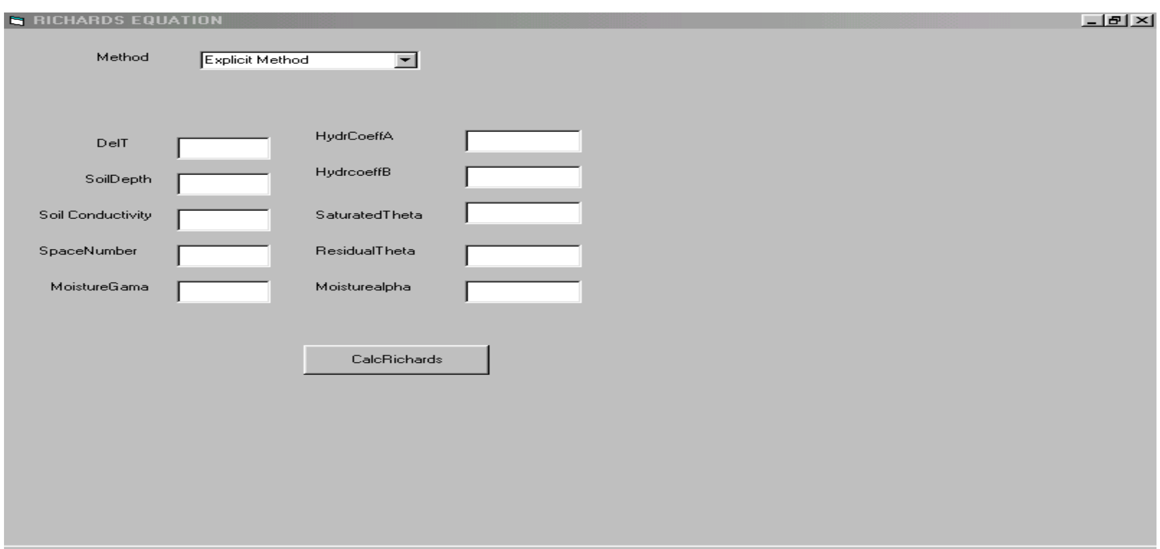


Figure 3.9: Richards infiltration module of the model

DelT = time-step

Soil-Depth = depth of soil/space number

Space-number = number of divisions

MoistureGama = a dimensionless parameter used to calculate moisture content of the soil

SaturatedTheta = saturated soil moisture content

3.3 Programming Progress-Interface Development

After development of all the components of the model, the next step is development of interface. An interface is a group of logically related operations or methods that provides access to a component object. For the model, a multiple document interface (MDI) application is being developed. The MDI allows one to create an application that maintains multiple forms within a single container form.

The approach is to keep the snow model and rainfall-runoff simulations as stand alone models to provide the flexibility to calculate some of the components independently, for example, evapotranspiration or interception. However, for calculating runoff using either the modified Horton or Green-Ampt methods, the relevant windows for potential evapotranspiration and interception will be called.

3.4 Calibration and Validation

Various components of the model such as snowmelt, evapotranspiration, interception and infiltration have been tested against published data and results have been compared. For example, during this exercise, the calibration values for S_{max} and canopy density (D_c) in the interception component were used from the published data. Actual calibration and validation of the model can be done after obtaining sufficient data from a green roof.

3.5 Stormwater Runoff Simulation

The Horton model was used to evaluate the capacity of the green roof to retain stormwater runoff. The roof was parameterized to mimic the field site that was used for the observation studies (following Section 4). The soil depth was set at 150mm (approximately 6 inches), the type of soil was set to sandy loam with a total porosity of 43% by volume or 65mm and a field capacity of 54% by volume or 35mm. The initial moisture content was set to 25mm. The results use the weather observations from Environment Canada for the Broadview station in May, 1956, one of the wettest periods in the climatic data (**Table 3.1**). In the simulation, over four rain events, the roof did not generate any excess runoff and the runoff due to drainage through the infrastructure was 40.06mm (22.06mm) compared to a total rainfall of 70.2mm, less than two thirds (one third) of the total rain event.

Table 3.1: Simulated Runoff from Green Roof, May 1956

Hour	Rainfall (mm)	Potential Evapotranspiration (mm)	Excess Runoff	Runoff as a drainage
0	0	0	0	0
1	4.6	1	0	0
2	0	1	0	0
3	0	1	0	0
4	0	1	0	0
5	0	1	0	0
6	0	1	0	0
7	1.8	1	0	0
8	0.3	1	0	0
9	0	1	0	0
10	0	1	0	0
11	4.8	1	0	0
12	4.1	1	0	0
13	3.3	1	0	0
14	16.5	1		0.24
15	19.3	1		7.98
16	3	1		20
17	11.4	1		1.28
18	0	1		6.98
19	1	1		1.68
20	0	1		0.85
21	0	1		0.47
22	0	1		0.27
23	0.3	1		0.17
24	0.8	1		0.14

These results compare well to the observations of stormwater runoff retention in the following section. The green roof was also evaluated under more extreme conditions that might be equivalent to a hurricane, and in fact are similar to Hurricane Mitch (**Table 3.2**). In this case, the soil depth was doubled to 300mm and the field capacity was increased to 250mm. The initial moisture content was set to 80 mm. The roof generated 734.38mm of runoff through its infrastructure in 16 hours, approximately 71% of the total 1025mm of rainfall, and 75.88mm excess runoff, but only at the end of the event. Thus even in an extreme event, green roof infrastructure, with an appropriate depth of soil, could play a role in mitigating the damage due to flooding.

Table 3.2: Response of the Roof to an Extreme Rain Event

Hour	Rainfall (mm)	Potential Evapotranspiration (mm)	Excess Runoff	Runoff as a drainage
0	0	0	0	0
1	25	1	0	0
2	50	1	0	6.59
3	100	1	0	64.8
4	200	1	0	171.46
5	100	1	0	76.10
6	50	1	0	28.76
7	25	1	0	4.82
8	0	1	0	0
9	0	1	0	0
10	0	1	0	0
11	0	1	0	0
12	25	1	1.58	4.99
13	50	1	20.00	36.01
14	100	1	17.15	80
15	200	1	20.00	180.85
16	100	1	17.15	80

3.6 Future Research

Two important interfaces can be developed for the model. They are GIS and heat transfer and evaporative cooling interfaces. If a rooftop garden has different types of vegetation, a GIS interface may help in understanding evaluating the geographic variability in terms of evapotranspiration, interception, infiltration, runoff and drainage and percolation from various parts of the garden. The heat transfer and evaporative cooling component will enable to calculate heat loss and gain through the garden material and the roof.

4 Field Monitoring of the Green Roof System

4.1 Introduction

One of the barriers to the widespread adoption of green roof infrastructure is the lack of technical data in a Canadian context. Although there are a few green roofs spread across the country, they are not monitored and cannot provide a comprehensive evaluation of thermal performance, stormwater runoff and durability. The Field Roofing Facility (FRF) is the first instrumented site containing both a green roof and a reference roof. Data were collected on the climate of the site, the climate of the roof, the temperature at different levels and at different areas on the roof, the heat flux through the roof and stormwater retention and membrane durability. Due to the difficulties in coordinating the schedules of the different supporting partners, it was not possible to complete construction of the FRF until October 2000. This reduced the observation period to less than one full year, which was insufficient for model calibration; however, additional data will be collected to confirm the initial results and to calibrate the model.

4.2 Construction of the Field Roofing Facility

The FRF is located at the NRC's Montreal Road campus in Ottawa, close to the IRC's natural exposure site on an empty field. There are no tall trees that might provide shading and influence the climatic observations. The FRF is designed to systematically compare the performance of different roofing systems in field service conditions and is the first of its kind in North America. It is 9m (30ft) long, 8m (26ft) wide and 5m (16ft) high. It has an experimental roof area of 70m^2 (800ft^2) and can represent a low-slope industrial roof with high roof-to-wall ratio. The roof of the FRF was divided into two equal sections separated by a 1m (3-ft) parapet. On the north section, a generic green roof was installed and on the south section, a conventional roofing assembly with modified bituminous membrane was installed as a reference roof (**Figure 4.1**). The components of the two roofing systems are summarized in **Table 4.1** and their configurations are shown in **Figure 4.2**.

A 1m (3-ft) parapet surrounds the roof and each section is structurally sloped at two percent towards a central drain. Any runoff from one section would flow towards the central drain in that section by gravity. Each drainpipe is connected to an individual flow meter in the building so that the runoff from the green roof can be measured and compared to the reference roof.

Table 4.1 Components of the roofing systems.

Component	*Reference Roof*	*Rooftop Garden*
Structural support:	Steel / wood structure with a 22mm (7/8 in.) ply wood deck	Steel / wood structure with a 22mm (7/8 in.) ply wood deck
Vapour control layer:	Asphalt-based "peel-and-stick" membrane	Asphalt-based "peel-and-stick" membrane
Thermal insulation:	75mm (3in.) thick mineral fibre board	75mm (3in.) thick mineral fibre board
Support panel:	12.5mm (1/2in.) fibreboard	12.5mm (1/2in.) fibreboard
Membrane:	2-ply modified bituminous membrane	2-ply modified bituminous membrane (cap sheet formulated with root repellent agent)
Drainage layer:	N/A	36mm (1.5in) thick expanded polystyrene panel
Filter membrane:	N/A	Polyethylene/polyester non-woven mat
Growing medium:	N/A	150mm (6in.) light weight soil
Vegetation:	N/A	Wild flower meadow

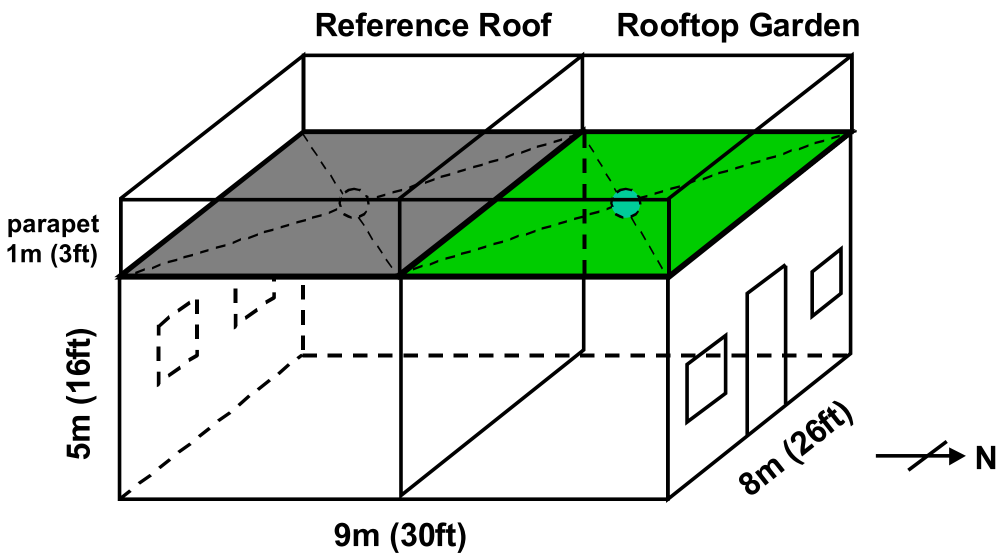


Figure 4.1 Schematics of the Field Roofing Facility (FRF) in the NRC campus in Ottawa.

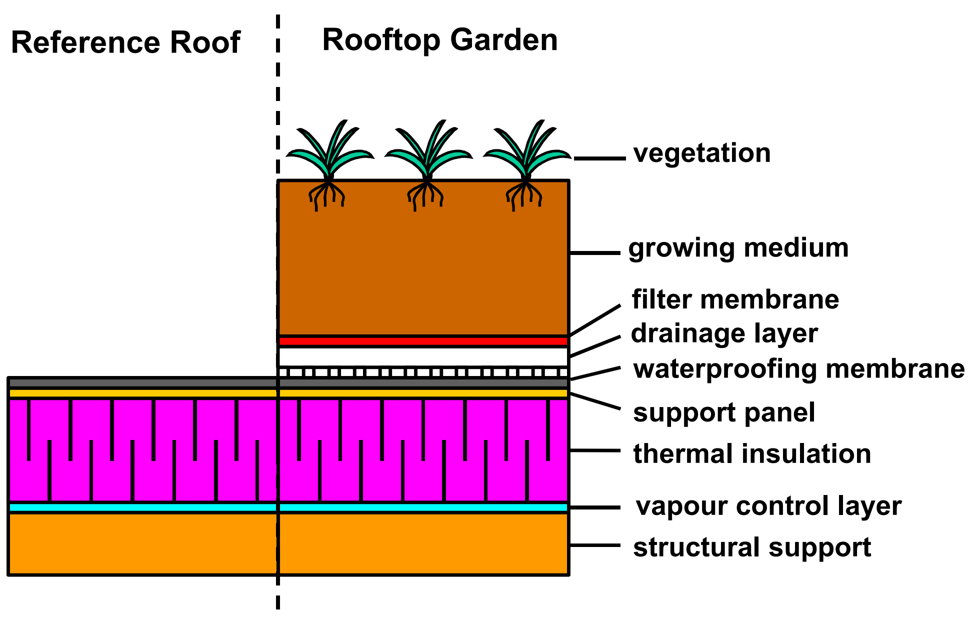


Figure 4.2 Configuration of the roofing systems.

4.3 Planting of Vegetation

The green roof was installed on the north roof section in October 2000. Because of the late completion date, the planting was postponed until the Spring, as the young plants were not likely to develop a root system that would be strong enough to survive the winter. Since the lightweight growing medium was vulnerable to wind erosion due to the lack of vegetation, a single layer of filter membrane was placed on the growing medium to minimize erosion loss. The filter membrane was a thin geo textile material that was permeable to moisture and water but did not provide significant thermal insulation to the roofing system. When the snow melted, the water was allowed to pass freely through the filter membrane into the growing medium. This filter membrane was removed just before planting.

Planting was done in May 2001, about 2 weeks after the last frost. Two 25-g packages of wild flower seeds and annual cut flower seeds were obtained from the Ontario Seeds Company. These plants were either native to Ontario or adapted for the climate zone. Some sedum species were planted as well as sedum is commonly used on green roofs. The various species planted in the garden included S. Kamtschaticum Floriterum, S. Spurium Tricolore, S. Ellacombianum, Pennisetum Alowproides, Aster Alpinus, Bachelor Buttoms, Prairie Coneflower, Cosmos, Little Bluestem, Annual Poppy, Black Eyed Susan, Calendula, Lance Leaved Coreopsis, Helichrysum, Prairie Sandrop, Field Poppy, Sideoats Grama, Crysanthemum, Baby's Breath, Lavatera, Lemon Mint, Xeranthemum, Xinnia.

The seeds germinated in about 4 days. The plants were allowed to grow over the summer, and were irrigated by a household lawn sprinkler. The growing medium was kept moist by irrigation at the beginning to increase survivability of the young plants. When the plants were older (**Figure 4.3**), the irrigation frequency was decreased to once a week and twice a week during the hottest and driest periods of the summer[3]. Watering was usually done in early morning or late in the evening when the temperature was cool, minimizing any sudden temperature drop in the growing medium due to the cooling effects from the evaporation of water.

[3] Although green roofs require very little maintenance, the first two years after installation?

Figure 4.3: The Field Roofing Facility on the NRC campus in Ottawa, June 2001. The median divider separates the Green Roof (left) and the Reference Roof (right). A weather station is located at the median divider.

4.4 Instrumentation

4.4.1 Meteorological Data

Two meteorological stations, maintained approximately 30m (100ft) NW and 6m (20ft) SW from the FRF. These stations provide ten-minute and hourly average observations of temperature, humidity, wind speed and direction, rainfall and solar radiation. A small weather station was also established on the median parapet between the Green Roof and the Reference Roof, at about 1.5m (5ft) above the roof surface. The local meteorological data such as temperature, relative humidity, rainfall and solar radiation on the rooftop were monitored continuously.

4.4.2 Installation of Sensors

Both the Green Roof and the Reference Roof were fully instrumented to monitor temperature profile, heat flow, solar reflectance, soil moisture content, rooftop microclimate and stormwater runoff. Three measurement locations were selected on each roof section to minimize spatial variability and obtain a representative average value (**Figure 4.4**). The three measurement locations selected on the two roof sections are mirror images against the median parapet. Various sensors were embedded between different layers within the roofing system at each instrumentation location (**Figure 4.5**). This allows direct comparison of the measurements obtained from different layers between the two roof sections.

The installation of the instrumentation was designed and executed in such a way that no wire had penetrated the roofing membrane, as its continuity must be maintained to remain waterproof. The roof system was built layer by layer, and the sensors were installed as each layer of roof component was laid. All sensors that were installed below the roofing membrane within the roofing system, the thermocouples (TCs) and the heat flux transducers (HFTs) were tested and collected through a square opening into the building before the roof membrane was applied. The entry point was then sealed using a peel-and-stick asphalt-based vapour control membrane to keep the roofing system airtight. All sensors that were installed above the roof membrane were collected and led into the building through an instrumentation port made from a standard roof protrusion. In total, more than 80 sensors were installed, with over 750m (2500ft) of wires connecting them to the data acquisition system for continuous monitoring.

Temperature Profile

The indoor and outdoor temperature, as well as temperature across both roofing systems were monitored by a network of thermocouples. Thermocouples were installed at different layers within the roofing systems (**Figure 4.5**) to monitor the temperature profile across the thickness of the roofing system and assessing the thermal performance of different roofing components. The outdoor rooftop temperature was monitored by a combined relative humidity and temperature (RH/T) sensor installed inside a radiation shield on the weather station located at the median parapet. The indoor temperature under the Green and the Reference Roofs was monitored by thermocouples placed under the ceiling and along the walls inside the building. The thermocouple network inside the building also monitored any possible thermal gain in one particular direction due to the orientation of the facility.

Heat Flow

The heat flow through the roofing system was measured by six HFTs embedded within the roofing system. They measured the heat flux (energy per unit area per unit time) entering or leaving the building through the roof surface at any point of time. They were calibrated such that a positive reading represents heat entering the building while a negative reading shows heat leaving the building. The heat fluxes over any duration can be integrated to calculate the amount of heat gain or loss through the roof in that period of time.

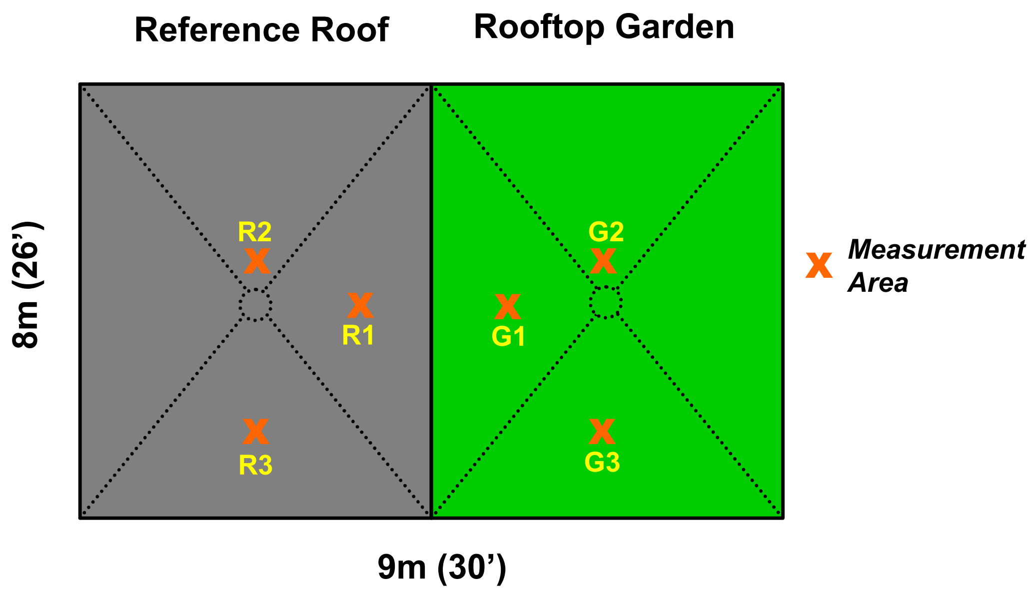


Figure 4.4: Instrumentation locations on FRF (X marks the measurement area).

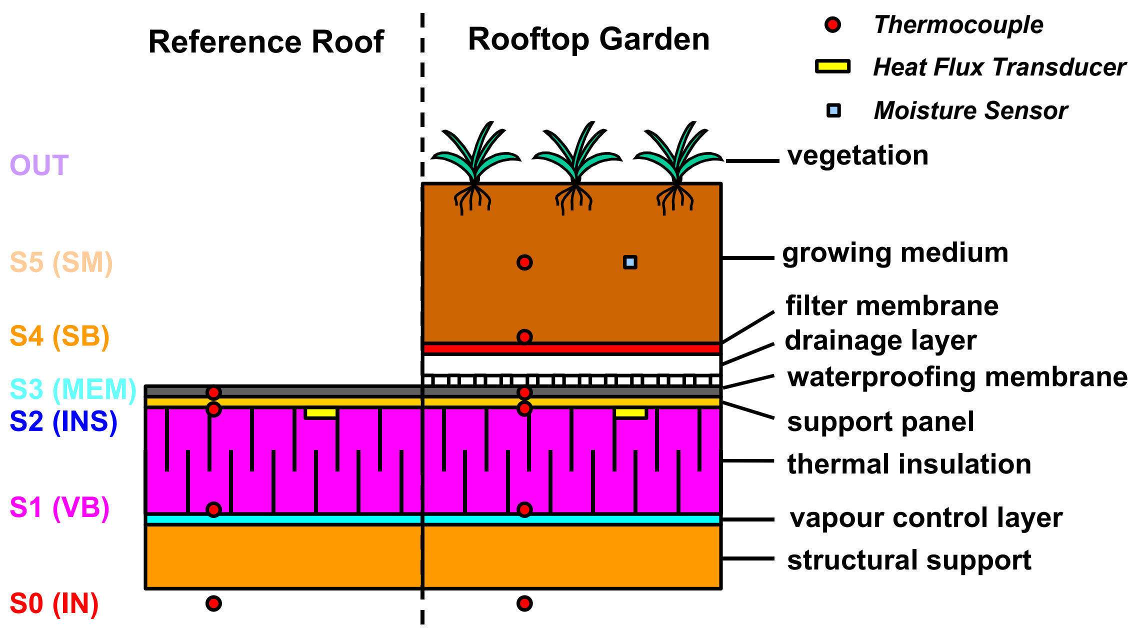


Figure 4.5: Location of sensors installed within the roofing system.

The temperature of the building was maintained by a heat pump that was manually switched to work in a cooling mode during the summer and a heating mode in the winter. A fixed temperature was maintained in the building by a thermostat and the energy required to operate the heat pump was recorded by a power meter connected to the data acquisition system. During the spring and the fall when the outdoor temperature fluctuated around the desired indoor temperature, the heat pump was turned off, as it was difficult to manually switch the heat pump between heating and cooling modes. The indoor temperature was still monitored to provide other data with which to assess the roof performance.

Solar Reflectance

A solar radiation sensor was placed upside down above each roof section to measure the solar radiation reflected from the roof surface. They were located between the drain and the west parapet on each roof section. The solar radiation absorbed by each roof could be derived by the solar radiation incident on the roof (obtained from the weather station) with the solar radiation reflected from the two roofing surfaces (grey granules on the Reference Roof and the vegetation canopy on the Green Roof). Reflected energy cannot be absorbed and reradiated as heat, but it provides an indication as to how much of the absorbed radiation was transmitted through the roof.

Rooftop Microclimate

The outdoor relative humidity (RH) and temperature were monitored by a combined RH/T transmitter installed inside a radiation shield in the small weather station on the rooftop. A RH/T transmitter was also installed in the building to measure the indoor RH. In addition, two combined RH/T transmitters, installed inside radiation shields, were placed just above on the roof surface. One was installed among the plants between drain and the west parapet. It was placed at about 65mm (2.5in.) above the surface of the growing medium in the Rooftop Garden to measure the RH and temperature among the plants.

The other transmitter was installed between the drain and the west parapet – mirror image to the RH/T transmitter on the Green Roof. The transmitter was placed at the same distance above the surface of the roofing membrane on the Reference Roof. These RH and temperature data were compared to the ambient levels recorded by the weather stations to examine how the vegetation may moderate the rooftop microclimate. The readings might also provide data to estimate the evaporative cooling effects of the Green Roof.

Soil Moisture Content

The moisture content of the growing medium was monitored by three granular matrix soil moisture sensors. Soil moisture data would have been useful for irrigation purposes, estimating evapotranspiration and to correlate with the temperature profile of the roofing system and stormwater retention. Unfortunately, the installation of these sensors was delayed and only limited data were available.

Stormwater Runoff

A rain gauge was located with the rooftop weather station. It used a tipping bucket mechanism with a resolution of 0.25mm (0.01in.) of rain per tip. The runoff from the roof passed through a flow-measuring device, which measured the runoff quantity as a function of time.

Most commercial flow meters were designed to measure flow in full pipes under pressure, not partly filled pipes as in our situation. In addition, most industrial flow meters that are designed for flow measurement in large pipes measure high flow rates and do not provide accurate measurements for low flow rates as in roof runoff. To overcome these challenges, a flow measuring system, specially designed to measure roof runoff was built in-house. The flow device consisted of a large plastic barrel with a tipping bucket mechanism. The runoff was collected from a 75-mm (3-in.) pipe from the roof and gradually funneled down to a 25-mm (1-in.) pipe. The tipping bucket mechanism consisted of two buckets arranged side-by-side in the plastic barrel. The runoff was allowed to fill the first tipping bucket in the barrel. Once that bucket was filled, it tipped over, emptied the water and triggered a magnetic switch in the process while the other empty bucket moved under the drainage pipe to be filled. The measured water was emptied into the plastic barrel and allowed to drain out of the building through an opening at the bottom of the barrel. The tipping buckets in these flow devices were designed to provide comparable measurements.

Data Acquisition System

Over 80 sensors were installed in the FRF of which 58 were monitored continuously while the rest – duplicates of thermocouples that were embedded within the roofing systems – were used as backup. All sensors were connected to a HP VXI data acquisition system (DAS), which was programmed to scan all sensors every minute and compute the average every 15 minutes. The 1-minute data and the 15-minute averages were recorded in separate files and stored on the hard drive of a dedicated computer. In most cases, the 15-minute averages were more than adequate for analytical purposes. However, 1-minute data provided more detail when the weather changed suddenly, such as a heavy rain or hailstorm.

4.5 Benchmarking and Verification

The temperature profiles recorded for the two roof sections were compared in the week after the completion of the FRF, September 2000, to ensure that the thermocouples and the HFT's were working properly and the performance of the two roofing systems, before installing the green roof, was identical. Since the DAS was still being debugged at this point, continuous measurement was not possible. Therefore, point measurements were made using a thermocouple reader with two input channels, i.e. two thermocouples could be connected to the reader at the same time.

The temperature recorded by the two thermocouples located at the same spot was shown to be very precise, within ±0.2°C or ±0.4°F. The temperatures obtained between corresponding locations of the two roof sections (e.g. G1 vs. R1) were usually within ±1.0°C (±2°F). A slight difference, within ±2.0°C or ±4°F, was observed across the roof section (e.g. G1 vs G2). This benchmarking exercise confirmed that the performance of the sensors and the two roof sections, prior to installing the Green Roof, were identical within experimental errors. To verify the accuracy of the temperature readings on the weather station on the FRF, the ambient temperature obtained by the FRF's weather station was compared to that recorded by the IRC's weather station in the month of December 2000. The results showed that the temperatures recorded by both stations were in close correspondence (**Figure 4.6**).

4.6 Data Analysis

Final debugging of the DAS was completed and data collection started in November 2000. The data collected from the Green Roof and the Reference Roof were analyzed and compared to assess the thermal performance and stormwater management potential of the rooftop garden. This report summarizes the data, observations and findings during the observation period: November 2000 to September 2001. However, data collection and analysis are to be continued for at least another year.

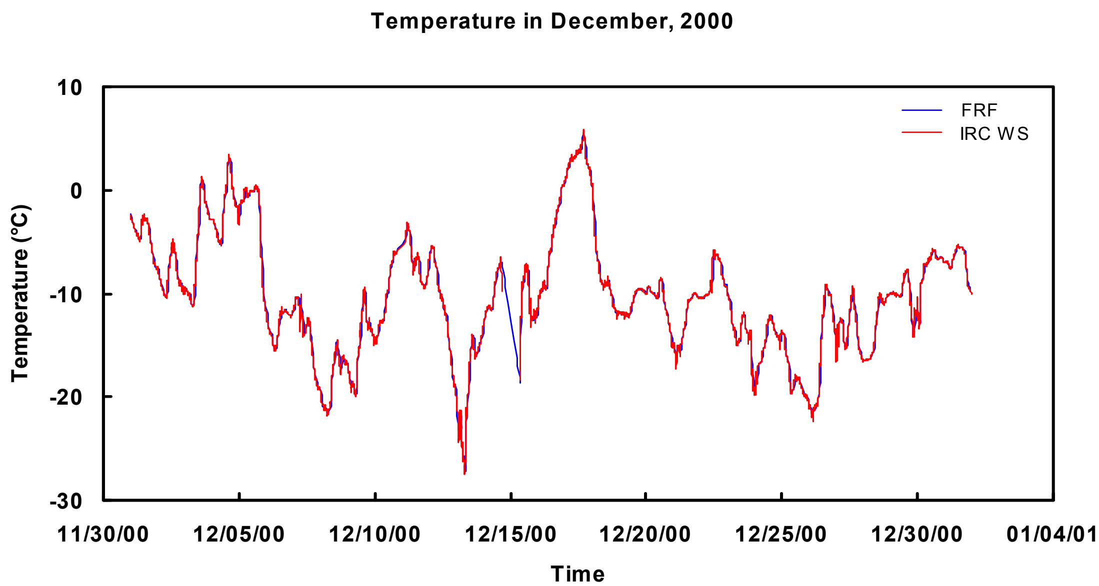


Figure 4.6: The outdoor temperature at the FRF and IRC weather stations.

4.6.1 Temperature Profile

Figure 4.5 shows the location of the thermocouple network installed within the roofing systems. For both roof sections, temperature was measured at four layers (S0-S3) at each measurement location (R1-R3 and G1-G3 in **Figure 4.4**). On the Green Roof, the temperature in the growing medium was measured by two extra thermocouples – one at the bottom (S4) and the other in the middle (S5) of the growing medium (150mm or 6in. deep). The ambient or outdoor temperature (OUT) was measured by the RH/T transmitter on the rooftop weather station. The placement of the thermocouples and the symbols for the layers are described in **Table 4.2**.

Table 4.2 Placement of the thermocouples within the roofing systems.

Layer Symbol	Location Description
S0 (IN)	**Underneath the roof deck, on the ceiling of the FRF**
S1 (VB)	**On the vapour control layer and under the insulation**
S2 (INS)	**On the insulation and under the support panel**
S3 (MEM)	**On the base sheet and under the cap sheet of the 2-ply modified bituminous membranes**
S4 (SB)	**At the bottom of the growing medium (150mm on 6in. deep)**
S5 (SM)	**In the middle of the growing medium (75mm or 3in. deep)**
OUT	**At the rooftop weather station**

Fall and Winter Performance

The data from November 2000 to March 2001 showed that temperature profiles within the roofing system were strongly dependent on the extent of snow coverage on the roof. The temperature profiles observed at the FRF could be divided into three periods based on snow coverage: no coverage, non-uniform coverage and heavy coverage. To illustrate the effects of snow coverage on the thermal performance of the roofing systems, the temperature profiles were selected from a typical day in each of these periods. Note that no vegetation was planted in the garden during the first winter, therefore, the effects observed were solely due to the thermal performance of the drainage layer, filter membrane and the growing medium.

No snow coverage: During late November 2000 and mid December 2000, the weather was cold (the average ambient temperature was -6°C or 21°F), but no snow accumulation was observed on the roofs. **Figure 4.7** shows the temperature profile within the roofing systems on a typical, cool, sunny winter day (December 3, 2000) without snow accumulation on the roof. The outdoor temperature increased from -10°C (14°F) in early morning to just above freezing in the afternoon. The membrane temperature (S3) of the Reference Roof was cooler (-15°C or 5°F) than the outdoor temperature (OUT) in the early morning due to radiation losses.

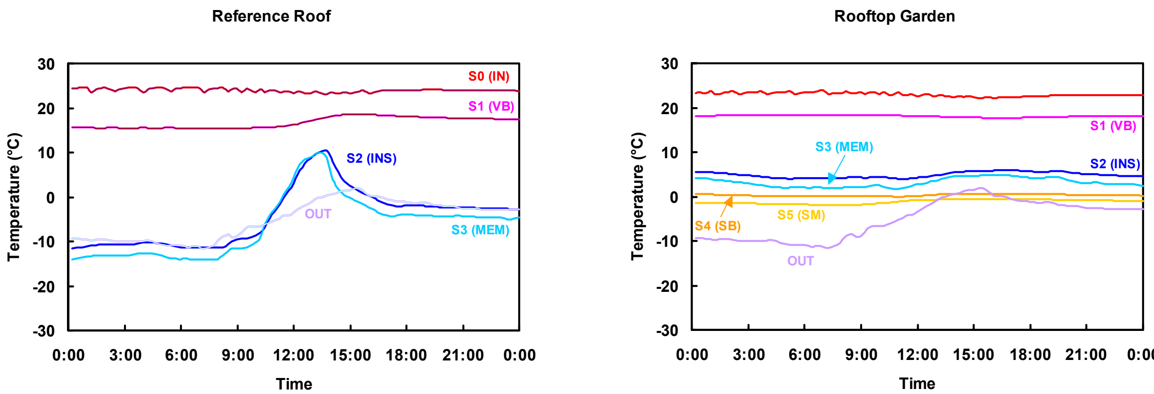


Figure 4.7: Roof temperature profiles without snow coverage (December 3, 2000).

However, it (S3) quickly rose to 10°C (50°F) in the afternoon as the membrane absorbed the incident solar radiation (peak 15-minute average value of 400W/m^2). This pattern was typical for the Reference Roof – the membrane temperature fluctuated with changes in ambient temperatures. On the other hand, the membrane temperature of the Green Roof remained relatively stable between 1 and 5°C (34 to 41°F) throughout the day. The middle (75mm or 3in. deep) of the growing medium (S5), was below 0°C (32°F), but the bottom (150mm or 6in. deep) of the growing medium, (S4), was slightly above 0°C (32°F). The growing medium insulated the roofing membrane and minimised the temperature fluctuations experienced by the membrane.

Non-uniform snow coverage: During the last two weeks of December 2000, snow began to accumulate on the roofs. The snow tended to accumulate near the east parapet, which was expected as the prevailing wind in the winter in Ottawa is about 300-330°. However, the snow accumulation was not uniform between the two roof sections: more snow accumulated on the Reference Roof than on the Rooftop Garden. It was noticed that when the wind blew across the roof, it created a "scooping" action on the snow. The wind scooped up some snow on the west side of the roof section, dropped part of it near the east parapet and blew the rest off the roof.

The amount and depth of snow that the wind could scoop up depended on the geometry of the roof such as the roof area and the parapet height. The parapet surrounding the FRF was 1m (3ft) high. The wind was only able to scoop up some of the snow as it blew across the roof, leaving the bottom part of the snow relatively undisturbed. However, the Green Roof (or Rooftop Garden) components (drainage layer and growing medium) has a combined thickness of about 250mm (10 in.) so the distance between the roof surface and the top of the parapet was effectively reduced by the same amount. Because of this change in geometry, the wind was able to scoop down to the green roof surface (the filter membrane placed on the growing medium to stop it from wind erosion). In addition, more snow was blown off the green roof than accumulated near the east parapet due to the reduced effective parapet height.

Because of the roof geometry and the wind action, the Reference Roof was covered with about 50mm of snow while the green roof remained almost bare for a period of time in late December 2000 and early January 2001. Since snow coverage provides extra thermal insulation value, this difference in snow coverage made it impossible to compare the energy efficiency of the roofs directly as their thermal conditions were different during this period. The non-uniformity of snow coverage between the two roof sections during this period was unexpected and not foreseen in the design of the FRF.

Heavy snow coverage: The roofs were heavily covered with snow from mid-January to March 2001, and the insulating effects of the snow dominated the thermal phenomena observed. On a typical day in that period (January 18, 2001), both roofs were covered with more than 200mm (8in.) of snow. The outdoor temperature (OUT) rose from -20°C (-4°F) before dawn to about -10°C (14°F) in the evening. However, the membrane temperature (S3) of the Reference Roof remained steady at just above freezing throughout the day. The growing medium on the Green Roof was frozen as indicated by the thermocouples at S4 and S5. The membrane temperature (S3) remained steady, between 3 to 4°C (37-39°F) throughout the day. Although the snow coverage was not uniform, it was heavy enough that its insulating effect overshadowed the difference in thermal performance between the Reference and the Green Roofs (**Figure 4.8**).

The growing medium was effective as a windbreak and reduced the convective heat transfer between the roof surface and the surrounding air. On one windy afternoon in December 2000, the membrane temperature on the Reference Roof was approximately 8°C (14°F) lower than that on the Green Roof. However, the membrane temperature recorded at G2 was about 5°C (9°F) lower than those recorded at G1 and G3 (see **Figure 4.4** for instrument locations). This anomaly occurred because G2, being situated next to the drain opening, was affected by the wind, which was able to penetrate under the growing medium for a short distance through the opening, reached G2 and lowered the membrane temperature there through convective heat transfer. The wind was not able affect G1 and G3 as they were too far from the drain opening.

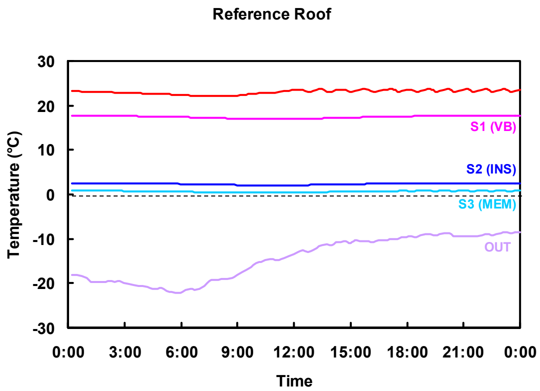


Figure 4.8: Roof temperature profiles under heavy snow (January 18, 2001).

<u>Spring and Summer Performance</u>

On May 20, 2001, a typical Spring day, the outdoor temperature rose quickly from below 10°C (50°F) in early morning to close to 30°C (86°F) in the afternoon (**Figure 4.9**). The peak 15-minute average value of the incident solar radiation was 920W/m^2 on the Reference Roof and the membrane temperature was higher than 55°C (131°F) during the hottest time of the day. On the other hand, the Green Roof membrane temperature remained steady at around 16 to 21°C (61°F to 70°F) due to the insulation and thermal mass effect provided by the growing medium (no vegetation was planted in the garden yet). The temperatures of the middle (S5) and the bottom of the growing medium (S4) were somewhat lower but followed the fluctuations of the outdoor temperature (OUT) with slight time delay.

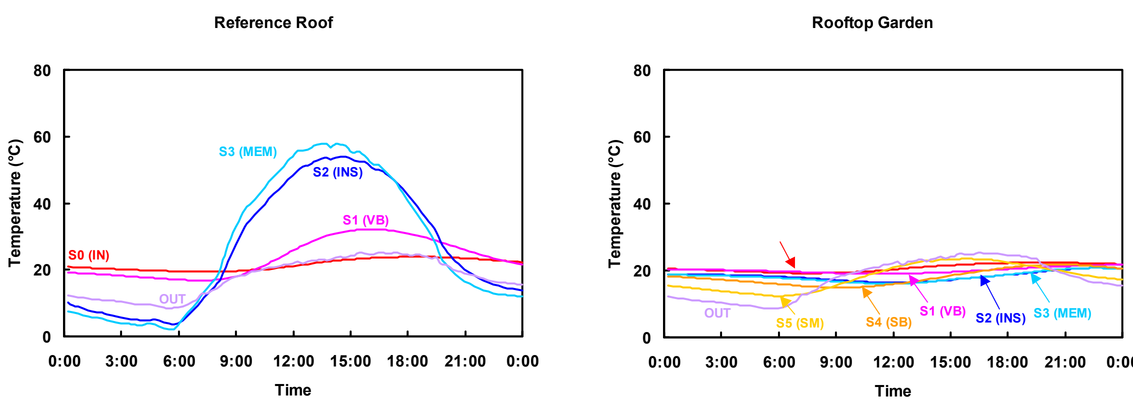


Figure 4.9: Roof temperature profiles on typical Spring day (May 20, 2001).

On July 16, 2001, a typically hot and sunny summer day, the outdoor temperature (OUT) rose from 10°C (50°F) in the morning to 35°C (95°F) in the afternoon (**Figure 4.10**). The membrane temperature on the Reference Roof reached 70°C (158°F) during the hottest time of the day. On the other hand, the membrane temperature on the Green Roof fluctuated around 25°C (77°F) primarily due to the insulation and thermal mass effect of the growing medium as the canopy was not yet dense enough to have a major effect. It is likely that the evaporation of water from the growing medium was involved in the cooling process as well. The temperatures in the middle of the growing medium (S5) and at the bottom of the growing medium (S4) followed the changes of the outdoor temperature with some delay, indicating the thermal mass effect of the growing medium.

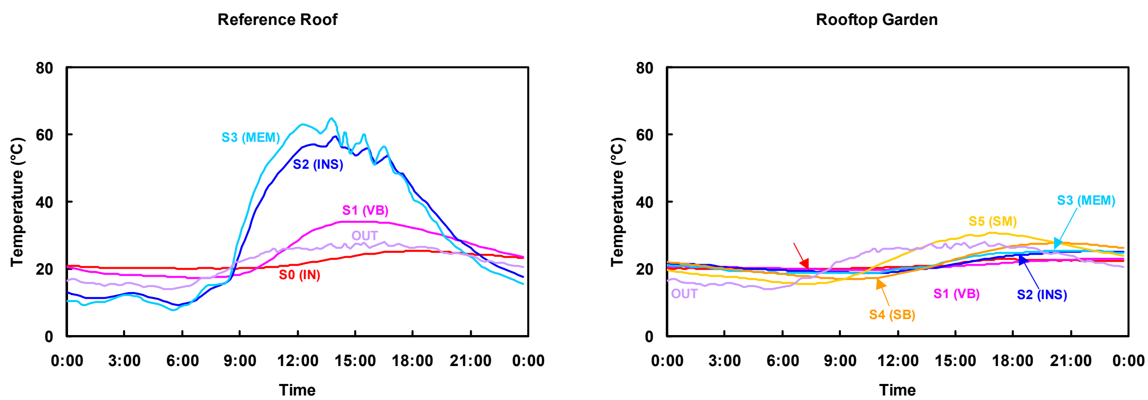


Figure 4.10: Roof temperature profiles on a hot and sunny summer day (July 16, 2001).

4.6.2 Temperature Fluctuations

On the Reference Roof, the membrane temperature fluctuations followed the changes in the ambient temperature (**Figure 4.11**). An exposed membrane absorbs solar radiation during the day and its surface temperature rises. It re-radiates the absorbed heat at night and its surface temperature drops. Diurnal (daily) temperature fluctuations create thermal stresses in the membrane, affecting its long-term performance and its ability to protect a building from water infiltration.

From November to December 2000, when the snow coverage was light, the membrane experienced daily temperature fluctuations (indicated by the vertical distance between the dark blue line and the light blue line) of about 20 to 50°C (36 to 90°F). In January and February 2001, under a heavy blanket of snow, the temperature fluctuation of the membrane was reduced to less than 10°C (18°F). When the snow started to melt in the Spring, the membrane temperature fluctuation increased due to the lack of insulation by the snow. In the summer, the membrane experienced large daily temperature fluctuations (about 50°C or 90°F) due to the absorption of solar radiation during the day and re-radiation at night. The temperature fluctuations experienced by the Green Roof membrane were significantly lower than the Reference Roof membrane (**Figure 4.12**) and also lower than the fluctuation of the ambient temperature throughout the observation period (**Figure 4.13**).

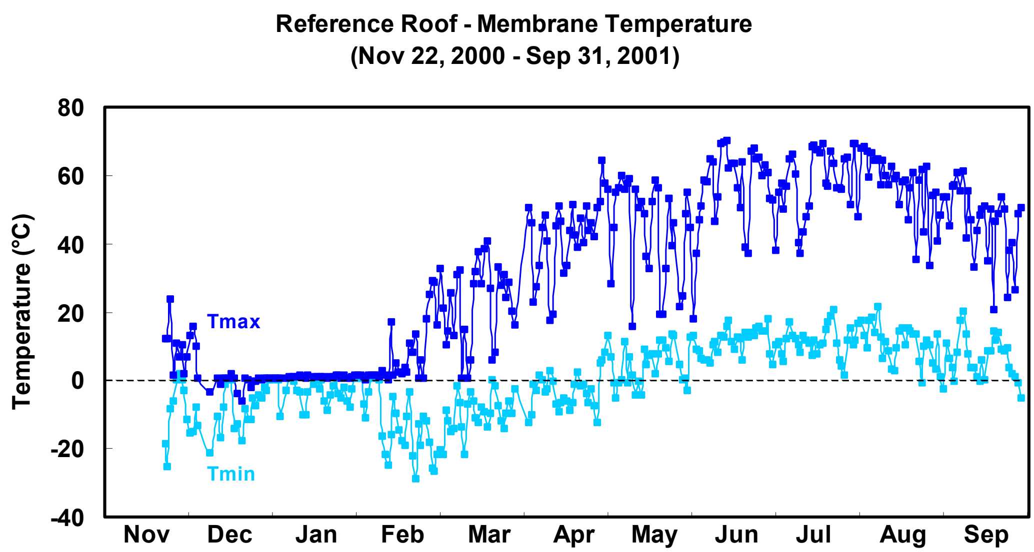


Figure 4.11: The daily maximum and minimum membrane temperature on the Reference Roof (November 2000 to September 2001).

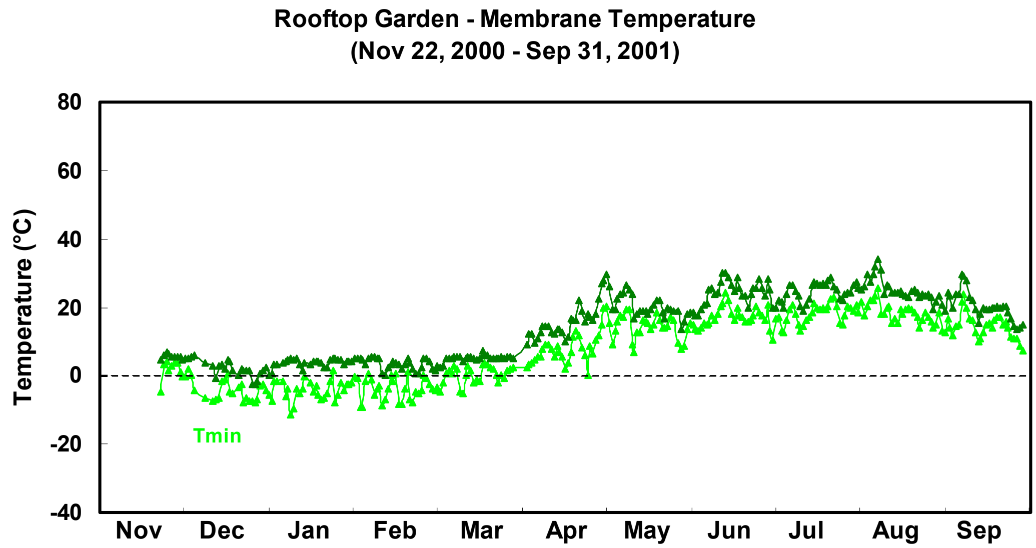


Figure 4.12: The daily maximum and minimum membrane temperature on the Green Roof (November 2000 to September 2001).

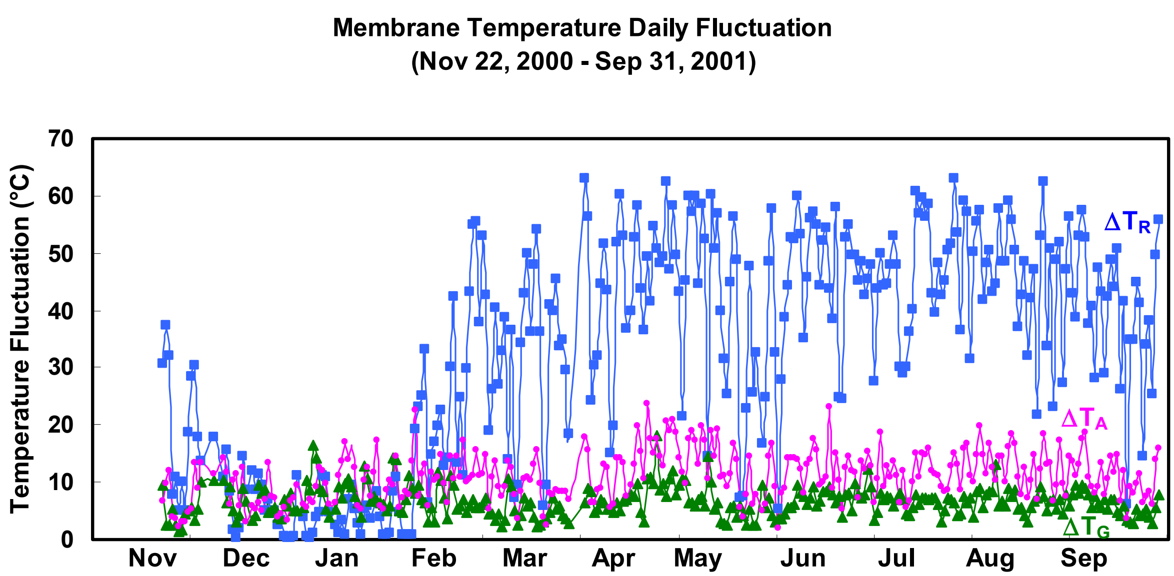


Figure 4.13: The daily ambient temperature (T_A) fluctuation and temperature fluctuations on the Reference (T_R) and Green (T_G) roof membranes (November 2000 to September 2001).

The seasonal median of the daily temperature fluctuation of the ambient and the roof membranes indicates the mid-point of the data meaning that the daily temperature fluctuation was above these temperatures half of the time and below them for the rest of that period (**Figure 4.14**). The seasonal median fluctuation of the membrane temperature on the Green Roof was always lower than that of the Reference Roof and the ambient temperature. This is especially prominent in Spring and Summer: the median daily membrane temperature fluctuation was 46°C (115°F) for the Reference Roof and 6.5°C (44°F) for the Green Roof in this period.

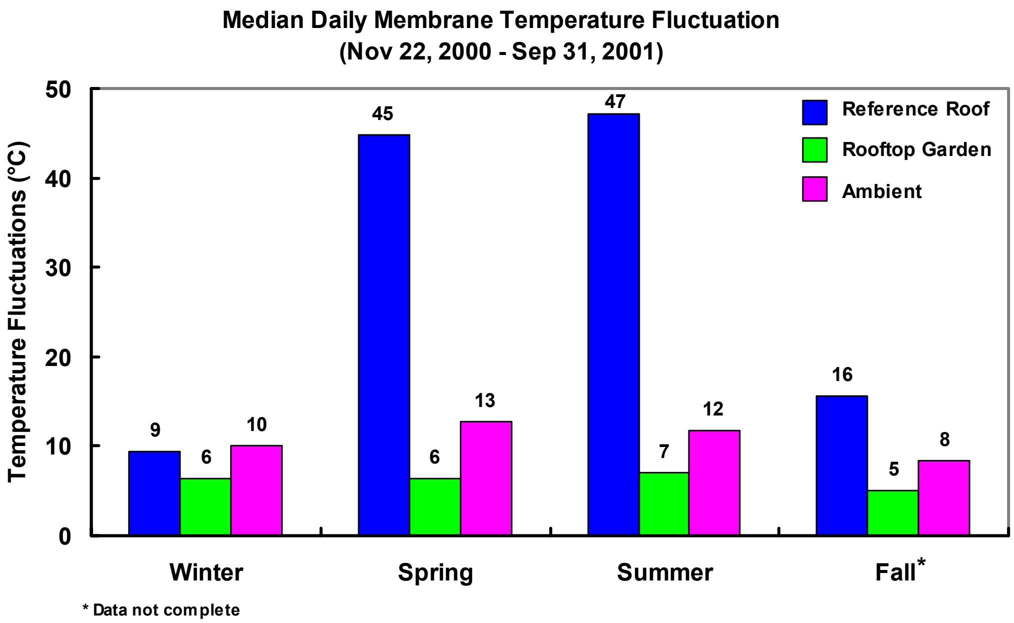


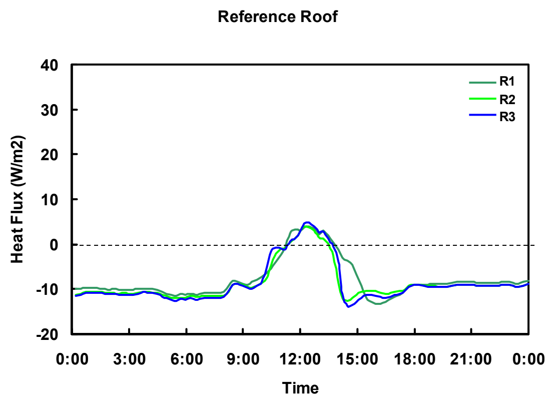
Figure 4.14: The daily median fluctuation of the Reference and Green Roof membrane temperatures and the ambient temperature, by season (November 2000 to September 2001).

4.6.3 Heat Flow

The heat flux through the roof surface was measured by three heat flux transducers (HFT) embedded in the insulation within each roof section. They measured the amount of heat flowing into or out of the building through the roof surface. They were calibrated such that a positive reading represents heat entering the building while a negative reading shows heat leaving the building. The heat flow across the roofing systems was influenced by many factors such as ambient temperature, snow coverage and solar radiation.

Fall and Winter Performance

Since the indoor temperature was kept higher than the outdoor temperature in the winter, the building usually lost heat through the roof as well as through the other parts of the building envelope. Snow cover had an insulating effect and reduced the heat loss through the roofing system during the winter months. The three curves in **Figure 4.15** represent the heat flux recorded by the three HFT embedded in each roof section on December 3, 2000, a typical winter day when no snow was accumulated on the roof.



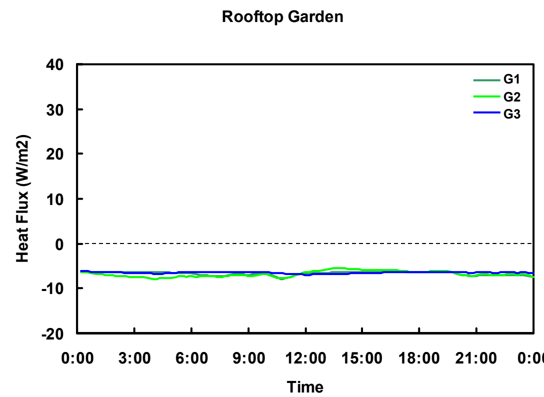


Figure 4.15: The heat flow through the roofing systems on a cold fall day without snow coverage (December 3, 2000).

The Reference Roof lost heat at a rate of 10W/m^2 during early morning and late evening. However, the rate of heat loss decreased during the afternoon as the roof membrane absorbed the solar radiation. During the warmest part of the day, heat entered the building and resulted in positive heat flow for about 2h around noon. On the other hand, the Green Roof lost heat at a steady rate of about 7W/m^2 throughout the day. This rate was steady and was not affected by solar radiation due to the insulation effect from the growing medium, which acted as an effective thermal mass to moderate the thermal performance of the roofing system.

On January 18, 2001, a typical winter day with the roof covered under a heavy blanket of snow the building lost heat through both roof sections at essentially the same rate of 8W/m^2 (**Figure 4.16**). The heavy snow coverage provided extra insulation to the roofing systems and reduced the heat flow through the roofs. This observation was consistent with the stable temperature profiles observed within the roofing systems during heavy snow coverage.

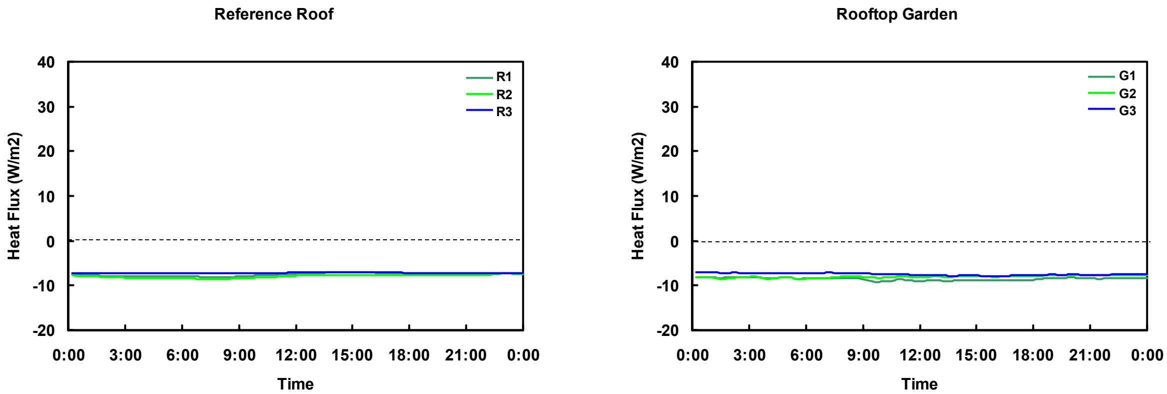


Figure 4.16: Heat flow on a winter day with heavy snow coverage (Jan 18, 2001).

Spring and Summer Performance

Since the indoor temperature was kept lower than the outdoor temperature in the summer, the building generally gained heat through the roof as well as through the other parts of the building envelope. Solar radiation had a strong influence on the heat flow through the roofing systems in this period. On a typical spring day, April 14, 2001, the ambient temperature rose from 0°C (32°F) in the morning to 15°C (59°F) in the afternoon with a peak solar radiation intensity of over 850W/m^2. The Reference Roof lost heat during the early morning and late evening at a rate of 10W/m^2 but it gained heat during the day due to absorption of the solar energy. On the other hand, heat left the building through the Green Roof at a steady rate of 5W/m^2 throughout the day (**Figure 4.17**).

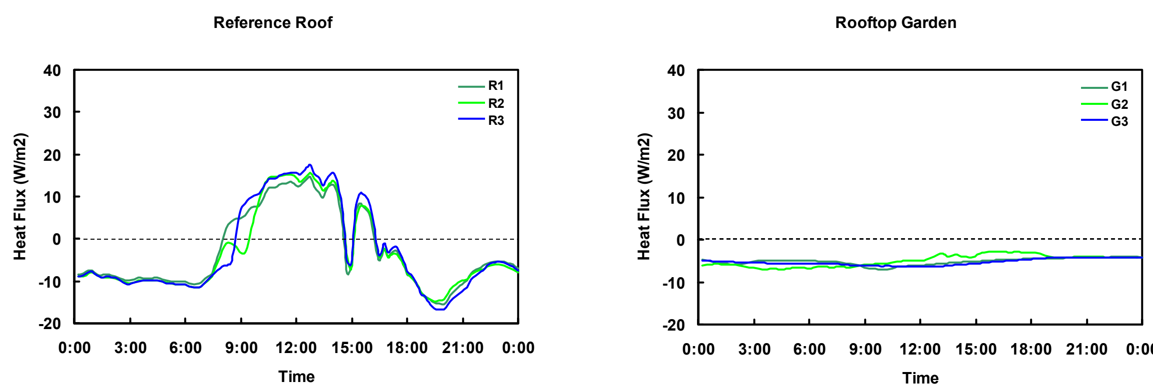


Figure 4.17: The heat flow through the roofing systems on a spring day (April 14, 2001).

On a typical summer day, July 16, 2001, the ambient temperature rose from 18°C (64°F) in the morning to 30°C (86°F) in the afternoon with a peak solar radiation intensity of over 950W/m^2. The peak heat gain through the Reference Roof was over 30W/m^2. The membrane re-radiated its absorbed heat into the surrounding during early morning and at night, creating an outflow of heat from the building at a rate of about 8W/m^2. On the other hand, the heat flow through the Green Roof was close to zero throughout the day. The growing medium and plants acted as a large thermal mass, which moderated the heat flow across the roofing system as is evident from the delayed heat loss/gain displayed by the three heat flux curves in **Figure 4.18**. Examination of additional heat flux data at R3 on two hot summer days shows that the heat flux through the Reference Roof followed the incident solar energy flux, which was recorded by the pyranometer on the rooftop weather station (**Figure 4.19**).

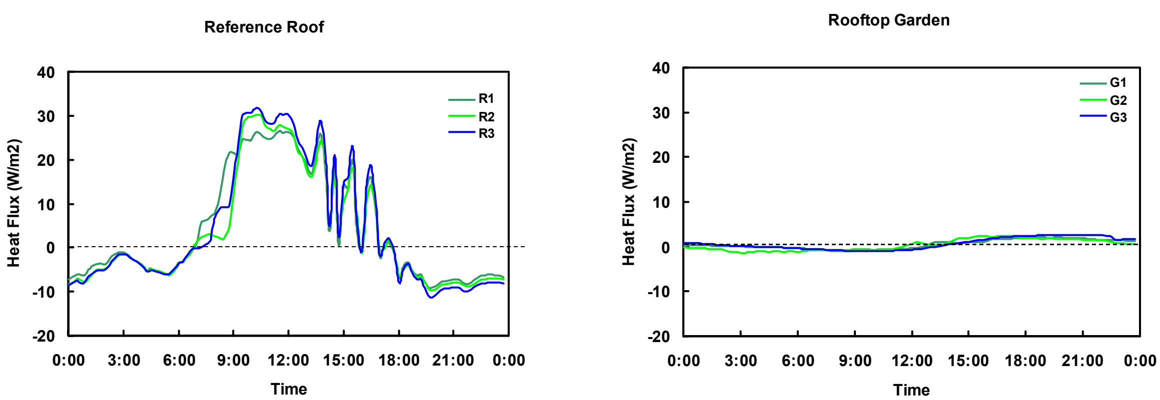


Figure 4.18: The heat flow through the roofing systems on a summer day (July 16, 2001).

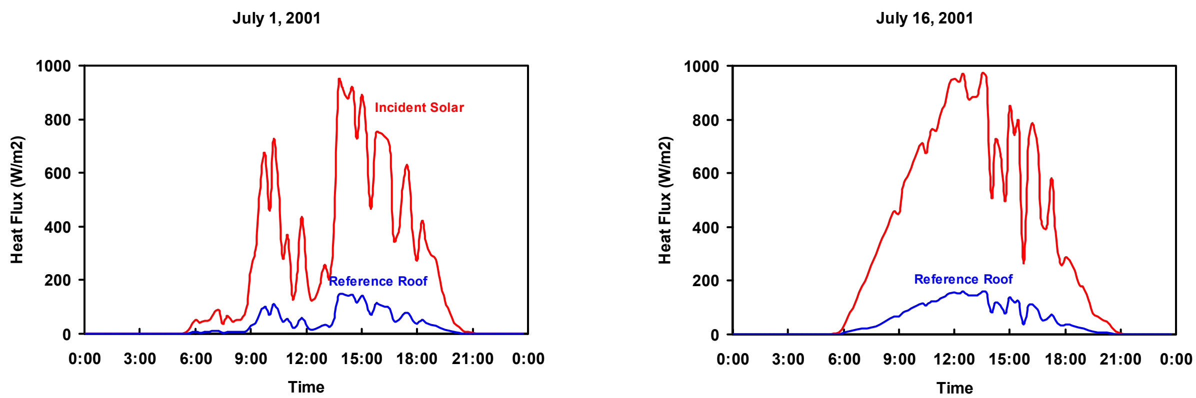
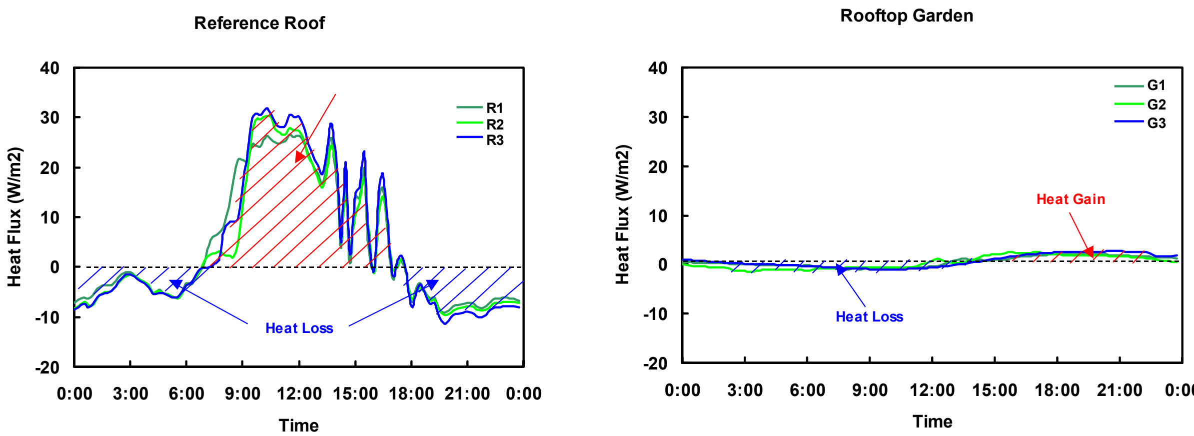


Figure 4.19: Solar radiation and heat flux through the Reference Roof in the summer (July 1 and July 16, 2001).

4.6.4 Energy Efficiency

To compute the heat flow through the Reference and Green Roofs the heat flux curve obtained from each HFT was integrated over time each day to obtain the daily heat flow per unit roof area (kWh/m^2). This is equivalent of calculating the area under a heat flux curves (**Figures 4.15 - 4.18**). The positive areas, heat gain per unit roof area and the negative areas, heat loss per unit roof area, were computed separately (**Figure 4.20**). These numbers were then multiplied by the roof section area (36m^2 or 400ft^2) to obtain the heat flow per day for each roof section in kWh. The daily heat flow through each roof section was then obtained by averaging the individual measurements of the three HFT's and further averaged by each month to smooth out the day-to-day variations (**Figure 4.21**).

Figure 4.21 confirms the earlier results. Heat was lost through both roofs during the winter, approximately 6 to 8kWh per day, and through March 2001, but the Reference Roof also gained 0.5kWh per day on the average in March. From April to September 2001, the building gained heat through the Reference Roof during the day but it also lost heat at night. The Green Roof was found to be most effective during the warmer months (June to August 2001), with less than 1 kWh heat gain during the day and less than 1kWh heat loss at night. As the vegetation canopy was not well developed, (about 60-70% ground coverage) due to the dry conditions, most of the benefits were derived from the growing medium, which



acted as a thermal mass to damp the thermal fluctuations. The shading and evaporative cooling effects of the plants were estimated to be small.

Figure 4.20: Heat flow per unit roof area can be calculated by integrating the heat flux over time. Positive area indicates heat gain by the building while negative area represents heat loss.

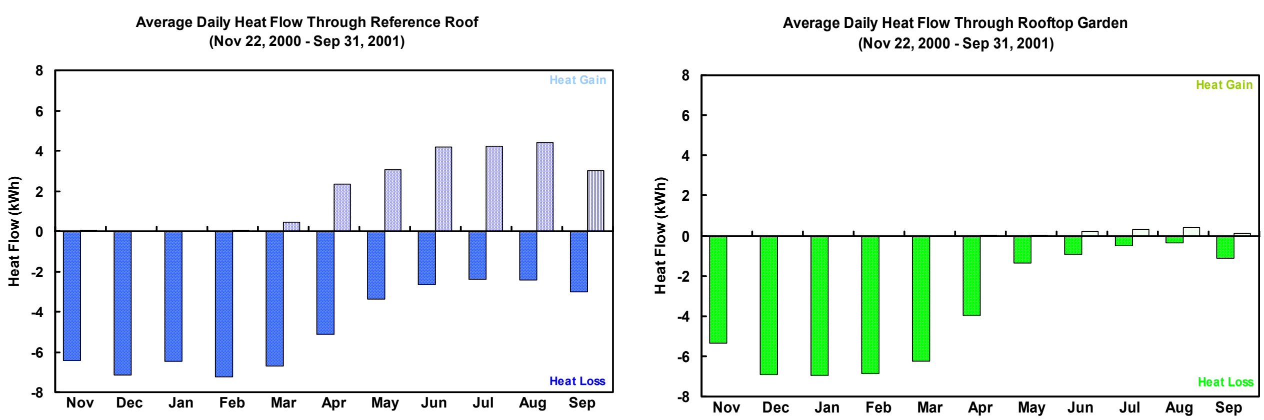


Figure 4.21: Average daily heat flow through Reference and Green Roofs (kWh)

The heat flow between a building and its environment creates energy demand for space conditioning. Assuming we keep the temperature inside the building constant, any heat entering the building has to be removed by the air conditioning unit and any heat leaving the building has to be made up by the furnace. The operation of the heating and cooling devices create energy demand for space conditioning. Therefore, the energy demand for space conditioning due to the roof is the sum of the heat entering and leaving through the roof, or by adding the heat flow through the roof in absolute value. **Figure 4.22** shows the average daily space conditioning energy demand due to heat flow through the roofs. It is calculated by averaging the daily space conditioning energy demand over each month to minimize day-to-day variation. The energy demand due to the heat flow through the Reference Roof remained at about 6.0-7.5kWh throughout the observation period (November 2000 - September 2001). In the cold months (December 2000 – March 2001), the energy demand due to heat flow through the Green Roof was similar to the Reference Roof. However, the building consumed 10-15% less energy for space conditioning on average due to the Green Roof except in January 2001 when the heat loss through the Green Roof increased consumption by 10% above the Reference Roof. The Green Roof significantly outperformed the Reference Roof in the warmer months (April – September 2001). During the hottest months (May – September 2001), the average daily space conditioning energy demand due to the Green Roof was below 1.5kWh, which was 75-90% less than that due to the Reference Roof.

A comparison of the cumulative energy demand due to the two roof sections shows that the energy demand due to both roof sections was essentially the same from November 2000 to March 2001 (**Figure 4.23**). The two curves started to diverge in April 2001, and the difference grew larger through the summer. The difference in space conditioning energy demand was 967kWh over the 11-month observation period. In terms of energy efficiency, the Green Roof system marginally outperformed (~10%) than the Reference Roof during the colder months but it significantly outperformed (>75%) the Reference Roof in the warmer months. More energy savings would be expected if the plant canopy was better developed and provided additional shading and evaporative cooling. Note that the actual dollar saving depends on the type and efficiency of the heating and cooling equipment, which is building specific.

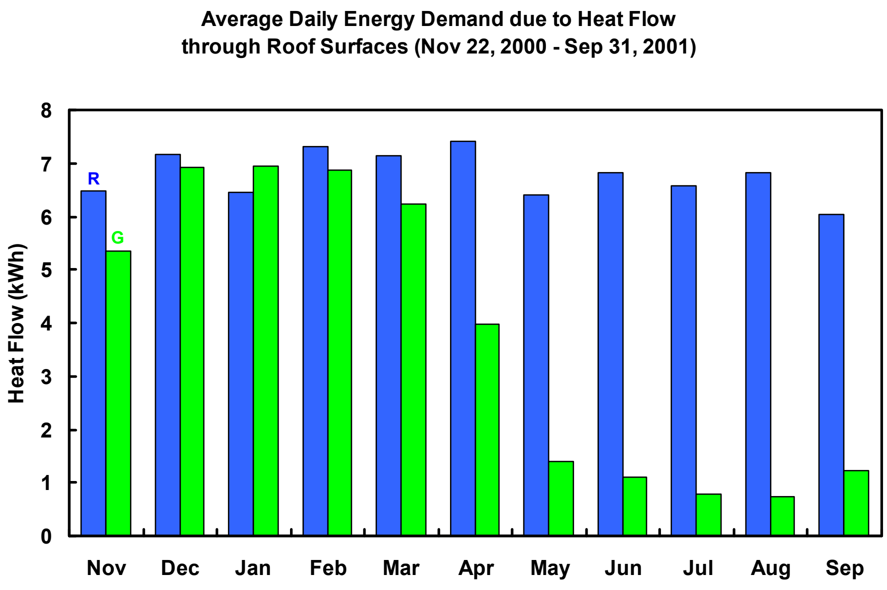


Figure 4.22: Average daily energy requirement due to the heat flow through the roof surfaces.

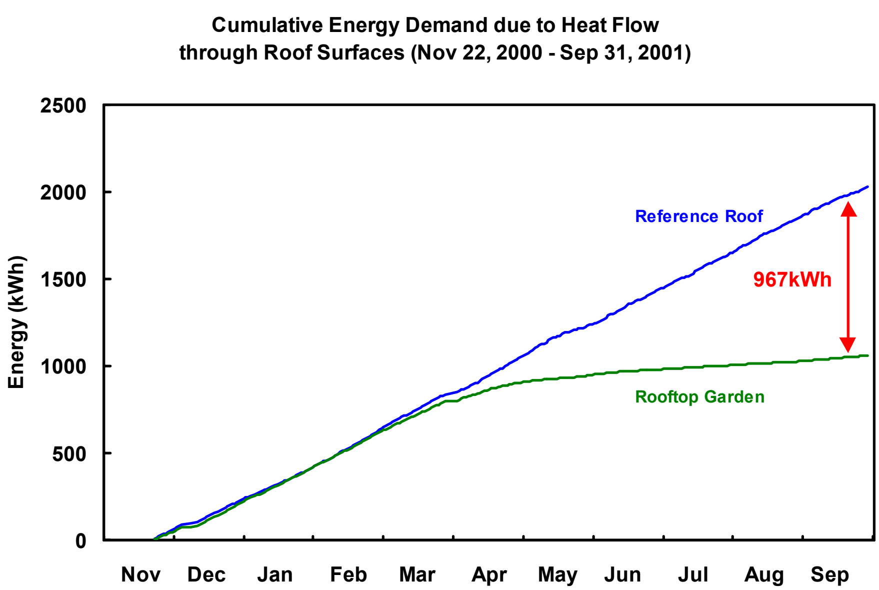


Figure 4.23: Cumulative energy requirement due to heat flow through the roof surfaces

4.6.5 Stormwater Management

The storm water runoff measuring system on both roof sections was installed and calibrated in September 2001 (**Figure 4.1**). The incident rain and the stormwater runoff from the two roof sections were monitored over time and compared for two events that occurred in the Fall, 2001. **Figure 4.24** shows a 34-mm rain event on October 6, 2001. Three of the curves show the cumulative rain/runoff as a function of time: incident rain (Rain: purple), runoff from the Reference Roof (Runoff-R: blue) and runoff from the Green Roof (Runoff-G: green). For easy comparison, the orange curve shows the difference of runoff quantity between the Reference Roof and the Rooftop Garden. The Green Roof retained 8mm(0.3in.) out of the 34mm (1.3in.) of rain, and the runoff from the Reference Roof was equal to the rainfall (**Figure 4.24**).

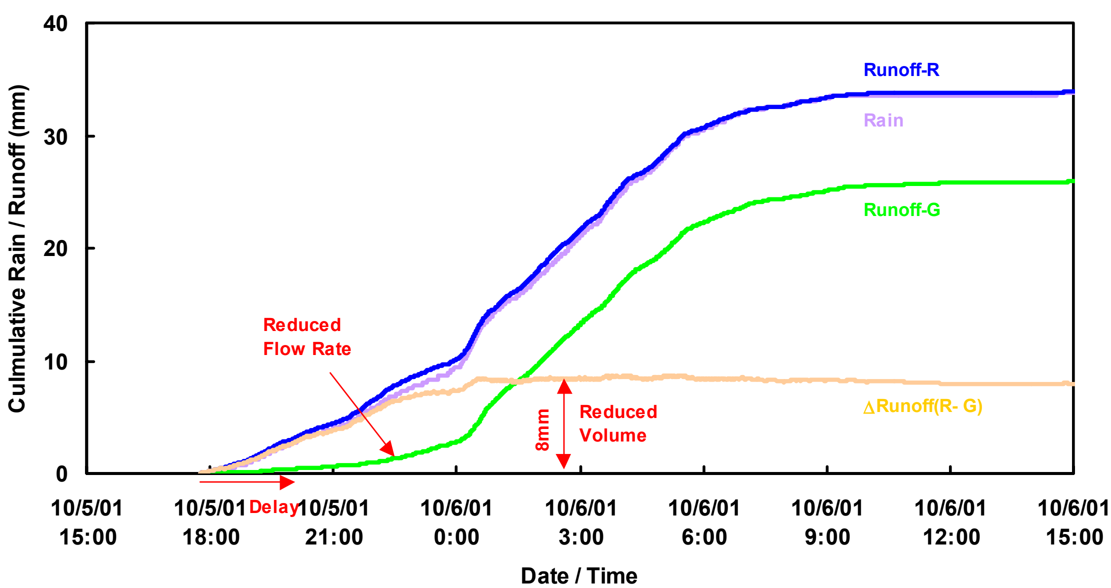


Figure 4.24: Rain event recorded on October 5-6, 2001

From 11pm on October 16, 2001 to 11am on October 17, 2001 there were three 3 rain events over a twelve-hour period: 11:00pm – 2:30am, 3:00 – 5:00 am, 7:30 – 9:15am (**Figure 4.25**). The runoff curve from the Reference Roof follows the Rain curve closely in terms of rate and volume. The runoff amount from the Reference Roof was slightly less than the rain incident on the rooftop. This might have been due to evaporation and adsorption on the roof membrane surface. On the other hand, the runoff pattern from the Green Roof followed a very different pattern. It was delayed by about 45min after the start of the first rain event, likely due to interception by the plants and absorption by the growing medium. The runoff rate was significantly lower than that of the Reference Roof.

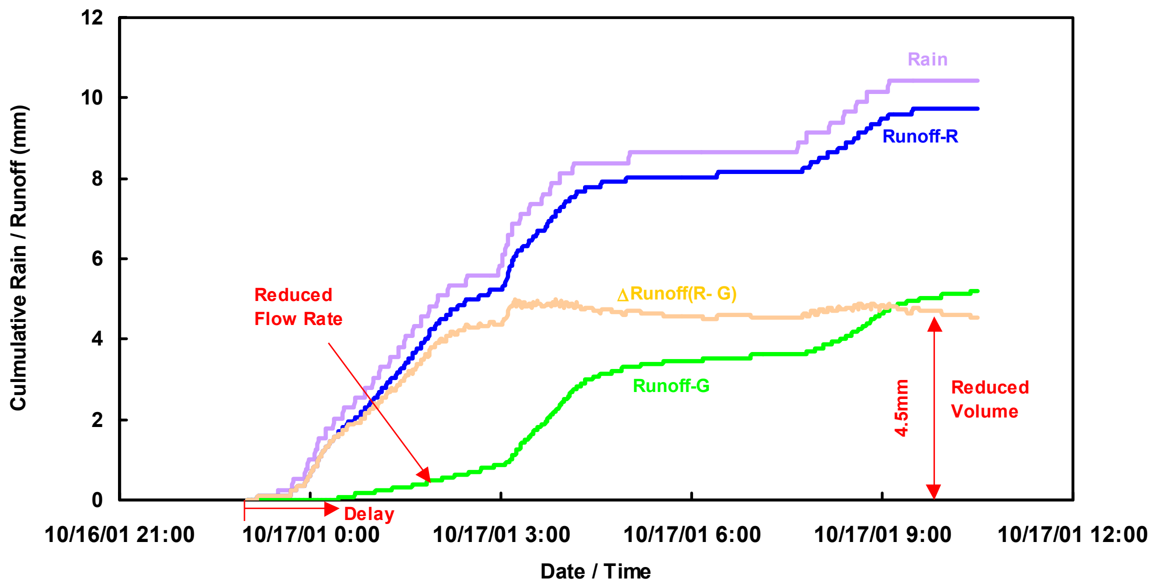


Figure 4.25: Rain event recorded on October 16-17, 2001

During the second rain event, the Green Roof runoff was only slightly lower than that of the Reference Roof, although the cumulative runoff was still low, possibly due to a saturated growing medium. The rain stopped between 5:00 – 7:30am. Water stopped running off from the Reference Roof during this period but water continued to runoff from the Green Roof, as water absorbed by the growing medium started to percolate through the permeable substrate, although at a much reduced rate of 0.12mm/h. During the third rain event, the runoff rates from the two roof section matched closely to the rate of the incident rain confirming that the growing medium was saturated at this point.

Although the runoff from the two roofs was equal during the third event, the Green Roof affected roof runoff in three ways during this second event:

1. It delayed runoff by 45minutes from the start of the first rain event.
2. It lowered the runoff rate. During the first 4h of the rain event, the rain fell at a rate (the slope of the purple curve) of about 2mm/h (0.1in/h). The runoff rate from the Reference Roof (the slope of the blue curve) closely followed the rate of incident rain. However, the runoff rate from the Rooftop Garden was reduced to 0.4mm/h (0.02in./h).
3. It reduced the runoff volume. The Rooftop Garden retained 2mm (0.08in.) of rain before water started to runoff and it retained 4.5mm (0.2in.) out of the 10mm (0.4in.) of rain that fell during this observation period. The growing medium was not dry at the start of the rain event due to light rain in the previous days, which would have reduced the stormwater retention potential of the Green Roof system.

Only limited runoff data were collected in 2001 due to a delay in setting up the stormwater measurement system and the lack of rainfall. However, the data clearly showed that the Rooftop Garden delayed runoff and reduced the runoff rate and volume.

4.6.6 Durability

The membrane on the Reference Roof experienced extremely high temperatures during the spring and summer due to the absorption of the incident solar energy and its reradiation as heat. During the afternoon of a hot summer day, the Reference Roof membrane temperature exceeded 70°C (158°F) when the ambient temperature was only 35°C (95°F). The roof was covered with light grey granules; even higher roof membrane temperatures can be expected for dark colour roofs. High temperatures accelerate the aging and weathering processed, thus reducing the durability of modified bituminous roof membranes.[4]

The Reference Roof also experienced high temperature fluctuations, with a median daily temperature fluctuation of 46°C (115°F) during the spring and summer. Daily temperature fluctuations create thermal stresses in the membrane and affect its long-term performance. The Green Roof reduced the median temperature fluctuation on the membrane experienced to 6.5°C (44°F), a reduction of over 85%.

[4] Heat aging programs are commonly used to artificially weather modified bituminous roof membranes in durability studies (Liu 2001, Puterman 1997, Rodriguez 1993, Dechesne 1991, Baxter 1991, May 1985).

Although it is too early to evaluate the durability of the membrane by mechanical and/or chemical tests, these results suggest that a Green Roof can help to preserve the membrane and prolong its service life by reducing the service temperature (aging) and minimizing the daily temperature fluctuations (thermal stress). Finally, neither membrane experienced leakage during the first year of operation.

5 Vertical Gardens

5.1 Introduction

Throughout history, vertical gardening, or putting vegetation on walls, has been used to control indoor climates or for aesthetics, as much as roof top gardening. The shopkeepers of Pompeii grew vines on their balconies (Jashemski, 1979), and walls of trees were incorporated into Roman mausoleums (Pieper, 1987). The Vikings layered their walls and roofs with turf (Donnelly, 1992), and vertical hanging gardens were used in pre-Columbian Mexico (Goode, 1996), India and in Spanish homes in 16th – 17th century Mexico (Flower, 1937). Examples of vertical gardening can also be found in Russia and other countries that were once part of the Soviet Union (Titova, 1990) and in 18th century France (De Lorme, 1996).

Vertical gardens appear to be a sensible strategy for greening cities, given the preponderance of wall space that is available in urban canyons. As with green roofs, vertical gardens are expected to reduce the urban heat island, energy consumption and stormwater runoff. The discussion in this section focuses on work done on reducing the urban heat island and energy consumption, through observations.

5.2 Surface Temperatures and Shade

Observations have been conducted on vertical garden surface temperatures in different settings at the University of Toronto since 1996 (Bass, 2000). These results have consistently demonstrated that vertical gardens are cooler than light-coloured bricks and walls and black surfaces that are typically found in urban areas. A new round of testing was conducted comparing a vertical garden with a light-coloured metal surface, which is typically found on roofs to shelter equipment. The purpose was not only to compare the temperature of the two surfaces (metal and leaf) but to also assess the shading potential of a vertical garden.

The tests were conducted with *Acanthopanax Sieboldianus* (Fiveleaf Aralia) plants during August 2000. The garden was set up against a slanted metal wall on the roof of the Earth Science Building at the University of Toronto. This location offered three advantages: a southwestern exposure, full sun conditions, and because the metal wall is on a roof, the results are applicable, in a limited manner, to green roofs. The limitation on a direct extension is that a vertical surface receives less direct sunlight than a horizontal surface, although for aesthetic reasons or due to engineering constraints, green roofs may be designed to exhibit varied topography. In addition alpine plants are often used on green roofs, as they are tolerant of drought and dry soils.

Acanthopanax Sieboldianus is and alpine shrub native to plant hardiness zones 4, 5, 6, 7 and 8. It was chosen for its height, which at 1.3 m is idea as a shade for most windows, its economic viability and its recommended use as a shade screen. It grows well in full sun, partly sunny and full shade conditions and can survive in drought and dry soils. The setup was used to compare the surface temperatures of the vertical garden to the surface temperatures of the metal wall, the temperatures of the shaded to the exposed surfaces and the vertical garden to the shaded surface temperatures. The null hypotheses were

- There were no differences between the exposed wall temperatures and the leaf surface temperatures of the vertical garden;
- There were no differences between the exposed wall and shaded surface temperatures;
- There were no differences between the shaded surface and the leaf surface temperatures;

The garden consisted of 4 plants and a control garden was set up consisting of pots with soil but no plants. An aluminum barrier, extending 0.6 m from the wall, was constructed to separate the two gardens from the exposed wall to ensure that minimize the chance that significant temperature differences would be negated by heat conductivity. Measurements were taken with an infrared thermometer on two locations on the wall, the vertical garden and the control garden and three locations on the barrier. Measurements were also taken of the wall behind the vertical garden and the control garden as well as of the surrounding concrete roof tiles. The measurements were taken at 11:30, 13:30, 14:45 and 15:00 on August 24. 2000, under full sun conditions.

The data were compiled and labeled 0, 1, 2 and 3 according to the time at which each observation was made specifically

- the temperature of the wall and the control plots
- the temperature behind the vertical garden and
- the leaf temperature.

The variables were compared using two-way ANOVA tests. Due to the influence of time of day, each pair of variables was compared with an individual t-test.

The maximum surface temperatures of 56 C were recorded on the control garden at 2:46 p.m. while the temperatures of the leaf surface and shaded wall were both 27 C. The average temperatures of the exposed wall, the shaded wall and leaf surfaces were 43 C, 26.8 C and 26.1 C. The temperatures of the concrete roof tiles varied between 48 – 52 C between 2 –3 p.m. The statistical analyses indicated that both the null hypotheses — that were no differences between bare wall and shaded wall temperatures and between bare wall and leaf surface temperatures — should be rejected with a probability > F = 0.0000 (Table 5.1). However, the time of day interfered with both comparisons, particularly the comparison between leaf and bare wall temperatures, and the differences were further analyzed with t-tests at different times. The time of day was a factor because the wall had not yet been exposed to enough sunlight by 11:30 am.

Table 5.1 2-Way ANOVA - Exposed Wall Temperatures (wall) vs Leaf Surface Temperatures (leaf) with interaction of time of day

Number of observations = 76
Root MSE = 2.4571

Source	Partial SS	df	MS	F	Prob > F
Model	6742.33308	5	1348.46662	223.35	0.0000
time	327.187904	2	163.593952	27.10	0.0000
wall_leaf	4800.10674	1	4800.10674	795.07	0.0000
time*wall_leaf	55.0801561	2	27.540078	4.56	0.0137
Residual	422.614286	70	6.03734694		
Total	7164.94737	75	95.5326316		

The comparisons between the bare wall and leaf surface temperatures yielded a probability > |t| = 0.0000 (Table 5.2 provides an example for the results for time 2). Only at time 0, when the entire wall was still shaded, were the differences not statistically significant. Similarly, the probability was > |t| = 0.01 for the bare and shaded wall temperature t-tests at times 1, 2 and 3 (Table 5.3 provides an example for the results for time 2). Both t-tests reinforce the rejection of the null hypotheses, that there were no differences between the shaded and the exposed wall and between the leaf surface and exposed wall.

Table 5.2 Individual t-test comparison between Exposed Wall Temperatures (wall) and Leaf Surface Temperatures (leaf) for Time 2

Variable	Obs	Mean	Std. Dev
wall	22	47.45455	2.939506
leaf	8	27.75	0.7071068
Combined	30	42.2	9.215429

H_0: mean (x) – mean (y) = 0 (assuming equal variances)

t = 16.63 with 29 df

Pr > |t| = 0.0000

95% CI = (14.82147, 18.97853)

Table 5.3 Individual t-test comparison between Exposed Wall Temperatures (wall) and Shaded Wall Temperatures (shade) for Time 2

Variable	Obs	Mean	Std. Dev
wall	22	47.45455	2.939506
shade	6	28.5	1.643168
Combined	28	43.39286	8.363675

H_0: mean (x) – mean (y) = 0 (assuming equal variances)

t = 15.03 with 26 df

Pr > |t| = 0.0000

95% CI = (14.82147, 18.97853)

The comparison of the shaded wall and leaf surface temperatures suggests that the null hypothesis, that the difference is not statistically significant, can only be rejected at the 0.05 level. The probability > F was 0.7647 (Table 5.4). The probability > |t| were 0.065, 0.1085 and 0.2660 for the individual t-tests at times 0, 1 and 2. Thus at 0.01 level, the populations are not statistically significant leading to acceptance of the null hypothesis.

Table 5.4 2-Way ANOVA - Shaded Wall Temperatures (shade) vs Leaf Surface Temperatures (leaf) with interaction of time of day

Number of observations = 53
Root MSE = 1.04461
Differences are significant at 0.05 level

Source	Partial SS	df	MS	F	Prob > F
Model	426.521537	6	71.0869211	65.15	0.0000
time	389.013226	3	129.671075	118.83	0.0000
leaf_shade	7.52410714	1	7.52410714	6.90	0.0117
time*leaf_shade	0.588875155	2	0.294437577	0.27	0.7647
Residual	50.1954545	46	1.09120553		
Total	476.716981	52	9.16763425		

The vertical garden was effective both at shading the surface and reducing the temperature of the surface through shading. This lends support to the use of vertical gardens to reduce the urban heat island, but site-specific experiments will not confirm the specific reductions that could be achieved through the use of vertical and rooftop gardens. Similarly, although the vertical garden was an effective shade, this indicates that it the surfaces are not heating up under the vertical garden. This should reduce the heat flux into a building, and it suggests that a vertical garden would also reduce indoor temperatures, not only through reducing the urban heat island but also directly through shading. However, this would require confirmation with temperature and heat flux measurements in indoor environments.

5.3 A Prototype Design for a Vertical Garden

Unlike the roofing industry, there are no accepted standards for vertical gardens or green wall infrastructure. The experiments conducted as part of this research, and in other studies, have utilized plants in soil beds or vines. The difficulty still lies in adapting these research gardens into a technology that could be used on most buildings and incorporated into window shades, which are effective at reducing energy consumption during the cooling season (see below). A soil-based system must contend with the problem of weight. As with the green roof industry, it might be possible to use a light-weight alternative, but the beds must secured to the building in a manner that would prevent a rupture due to high winds that are typical at higher elevations.

Vines are acceptable for walls, but obviously not for windows as they would block most of the natural light, thereby increasing the need for indoor lighting on all days. Also, there are concerns as to whether vines damage the building envelope. This has not yet been resolved as there are architects who argue that any damage is due to poor construction methods not the vine per se (Peck at al., 1999). In any event, a trellis could be used to separate the vine from the wall. Another alternative is to use an additional structure to support vertical gardens whether they are plants in soil beds or vines. The structure could be designed to allow movement so as to only intercept direct sunlight as needed, but allow for natural light during other times of the day (**Figure 5.1**). If the structure was designed as an awning, it could be used to intercept direct sunlight while allowing indirect sunlight to enter the room (**Figure 5.2**).

Figure 5.1: A vertical garden designed to allow some natural light.

Figure 5.2: A vertical garden designed as a window awning.

Another alternative has been explored for demonstration purposes and to foster further research. It utilizes the principles of hydroponic gardening in the vertical dimension. A hydroponic system eliminates soil and reduces the weight of the garden, and important consideration for any structure that is part of or affixed to the building envelope. The vertical garden was designed to minimize water use through a recycling procedure that allows the same water and nutrient source to be reused for several applications.

The vertical garden is approximately 2 m^2 and can support up to 100 plants (**Figure 5.3**). It consists of ten vinyl columns of ten plants in each column. The basic vinyl column configuration at the heart of this system was based on a design by Franciscus Schryer. A pump lifts the water-nutrient mixture from a reservoir to the top of each column, and gravity is used to circulate the mixture to each plant, and back to reservoir. Although the garden is a prototype, it was designed to make use of inexpensive materials, so as to minimize cost, which is one barrier to adaptation.

The vertical garden a combination of three smaller systems: the recirculating nutrient delivery and aeration system, the support structure for the vegetation and the control system

The *Recirculating Nutrient Delivery and Aeration System* consists of:

- reservoir (80 litre general purpose tote) containing the water/nutrient solution
- submersible electric water pump (rated 535 gallons/hour)
- main distribution tubing (3/4" soft polyethylene) and associated fittings
- in-line filter (Y-type)
- drip lines (1/4" soft polyethylene) and associated fittings
- drippers (1/4" misters)
- return piping (combination of PVC and ABS pipes and fittings)
- aquarium electric air pump
- air supply line (1/4" soft polyethylene) and associated fittings
- two "air stones" (in the reservoir).

The *Vegetative Support Structure*- Consists of:

- brown vinyl eaves trough downpipe (10 main vertical pipes, 100 plant-site sleeves, 2 sloped-horizontal collection/return pipes).
- wooden support frame (1" x 3" and 2" x 3" framing lumber)

The System Control- *consists of:*

- digital electronic timer.

The plants are rooted in rockwool. Rockwool is an inorganic material (made from igneous rock) and has very good moisture and air retention capacities. It is used to anchor the plant and to provide moisture, through contact, by the distribution of the liquid nutrient solution. However, other material such as cocoa fiber or porous extruded polypropylene (P-EPP)™ may be acceptable or even superior rooting media. The cuttings used for the initial planting of the vertical garden were taken, from the pothos (Scindapsus aureus) vine. This plant, although a tropical vine, was used to start the garden due to its hardiness and rapid growth. In the past year, two other plants, impatience and rabbits fern have also been grown successfully in the vertical garden. The vertical garden is located in the Tanz Greenhouse, at the University of Toronto and is open to the public. As the University removed this greenhouse in August 2002, it will be necessary to find a new home for this and future prototypes, to continue research and to continue to provide a demonstration to the public.

Figure 5.3: Hydroponic vertical garden, University of Toronto, Tanz Greenhouse

6 Energy Consumption with Green Roofs, Vertical Gardens

Rooftop and vertical gardens can reduce air conditioning directly by shading roofs and walls and windows from incoming solar energy and through the additional insulation that they provide. The additional insulation can also reduce the amount of energy used for heating. The effect of this additional shading and insulation on energy usage for space conditioning was evaluated using Visual DOE (DOE-2.IE-W83). A scenario was constructed for a one-story office building, approximately 3,000 m^2, for the city of Toronto, Ontario in Canada. The simulation modeled the energy consumption with an insulation factor of R19 on the roof, which is typical for commercial buildings and then with insulation (R30) and shading factors that might be typical of a rooftop garden. The walls were modeled at an insulation of R11, which was increased and were increased to R15, which would be the maximum expected with a vertical garden (Peck et al., 1999).

The rooftop results are reported for the base case scenario (no garden), the shading factor (100%), the insulation (estimated to be R30), the combination of both shading and insulation and the impact of an east-west orientation (Table 1).

Table 1. Electrical End-use (kWh) with Green Roof - Insulation and Shading.

Case	*Lights*	*Equip.*	*Heating*	*Cooling*	*Fans*	*Total*
Base	170,276	63,853	167,652	73,819	51,188	526,788
Shade	170,276	63,853	168,339	70,054	49,235	521,757
R30	170,276	63,853	150,539	72,732	48,049	505,449
Shade & R30	170,276	63,853	151,011	70,210	46,798	521,725
E-W	170,276	63,853	150,600	69,673	46,827	501,229

Table 1 indicates that the additional shading and insulation of a rooftop garden will reduce the energy used for heating by approximately 10% and cooling by approximately 6% (all energy usage converted into kWh). Overall, the total energy usage is reduced by approximately 5%. There are two reasons for the low reductions in cooling. One, the additional insulation of the rooftop garden also slows down the dissipation of heat that is generated inside of the building. Second, the existing insulation in the walls is as effective at reducing the heat flow into the building during the summer as it is in reducing the heat flow out of the building in the winter. When the simulation was run for Santa Barbara, with lower amounts of insulation, the cooling savings were over 10%.

Another scenario compared two roofs with the same insulation, one with soil and one with polystyrene insulation. The roofs were thermally equivalent while temperatures remained stable. When outdoor temperatures fluctuated, the indoor temperatures under the soil-covered roof were more stable than the temperatures under the polystyrene insulation. Under the soil-covered roof, the total energy required to cope with severe temperatures and the peak load decreased by 8% and 15% respectively (Carmody, 1985).

The other issues that emerge are orientation and lighting. First, orientation of the shade has a slight impact. Second, heating and cooling are not the major energy users in northern climates. Rather, lighting is first, followed by equipment and the ventilation system (Fans). It is interesting to note that part of the reduction in total energy was due to the 8.5% reduction in energy usage for the fans. The results for the vertical garden were more promising. The results are presented for cooling as many types of vertical gardens would not be desirable during the heating season due to the high degree of shading. As the insulation had no effect the results are presented for shading, which was fixed at 80% (Table 2).

Table 2. Electrical End-use (kWh) with Vertical Garden - Insulation and Shading.

Case	*Lights*	*Equip.*	*Cooling*	*Fans*
Base	170,276	63,853	73,819	51,188
Shade	170,276	63,853	56,812	40,755

The shading effect of vertical gardens reduces the energy used by cooling by approximately 23% and the energy used by fans by 20% resulting in an 8% reduction in annual energy consumption. The high level of reductions is most likely due to the impact of shading the windows. Although due to the importance of lighting and the lack of any contribution in the heating season, the total energy reductions are quite small.

The impact of green roofs and vertical gardens on air conditioning was compared for the same three-story building across the country. In all cases, vertical gardens reduced the energy used for air conditioning by at least 23%, but this figure was closer to or above 30% in Vancouver or St. Johns. The savings from a green roof were similar across all of the cities, with slightly higher savings being achieved in Montreal and Vancouver.

The DOE software does not provide for the inclusion of evaporative cooling, which would reduce energy even further. For example, simulations of the impact of cooling rooftop temperatures with white roofs indicated that electricity consumption for air conditioning could be reduced between 6-18% in California. The simulations were run for a wide range of buildings in different locations, which accounts for the variation in results. Other studies in the United States indicated savings of 20-30% from shading or evaporative cooling, but they did not account for the use of machinery and other activities.

Although this modelling work is incomplete, in that it did not include evaporative cooling, due to the limitations of the model, it is still possible to obtain modest savings solely due to the insulation and shading of green roofs, even on a multistory building. During the winter, the savings on heating are slightly larger due to the additional insulation. Although the need for heating may decline in Toronto, it still accounts for the largest share of energy consumption in residential and commercial buildings. In buildings without insulation, these savings are even greater. However, significant reductions in air conditioning are possible with vertical gardens, solely due to shading the windows. The energy savings from both technologies would increase if evaporative cooling can be factored into the simulation.

7 Conclusions

7.1 Green Roof Infrastructure

The Field Roofing Facility (FRF), a field research facility that is designed to systematically compare the performance of different roofing systems in field service conditions, was commissioned in September 2000 in the Ottawa campus of the National Research Council (NRC). It was fully instrumented to measure the temperature profile, heat flow, solar reflectance, rooftop microclimate, soil moisture content and stormwater runoff. The roof was divided into two equal sections: a Green Roof was installed on one side and a modified bituminous roof was installed on the other as the Reference Roof. A weather station was also established on the rooftop to monitor the ambient weather conditions. The FRF was monitored continuously from November 2000 to September 2001.

The performance of green roofs was also examined through energy models and a hydrological simulation. The thermal performance was simulated by Visual DOE, and building energy model developed by the United States Department of Energy, which is now an industry standard. A hydrological simulation model was developed with Visual Basic 6.0. The simulation contains various components to model snow melt, interception, infiltration, runoff and evapotranspiration.

Thermal Performance

In the spring and summer, the Green Roof significantly outperformed the Reference Roof. The roof membrane on the Reference Roof experienced extreme temperatures and high diurnal temperature fluctuations due to the dark membrane, which absorbed the solar radiation during the day and re-radiated the absorbed heat at night. On the other hand, the vegetation and the growing medium enhanced the thermal performance of the Green Roof by providing shading, insulation and evaporative cooling. It acted as a thermal mass to dampen the thermal fluctuations experienced by the roof membrane underneath, thus stabilizing the diurnal temperature fluctuations. The median daily membrane temperature fluctuations were 46°C (83°F) and 6.5°C (43.7°F) for the Reference and Green Roofs, respectively. The Green Roof also reduced the heat flow through the roof significantly, most prominently in this period. While the heat flow through the Reference Roof was closely related to the incident solar radiation, the Green Roof moderated the heat flow through the roof and reduced the energy demand for space conditioning. During spring and summer, the average daily energy demand for space conditioning due to the Reference Roof was 6.0-7.5kWh, which was reduced to less than 1.5kWh, a reduction of over 75%, under the Green Roof. Note that this reduction was due to the roof ONLY, other parts of the building envelope were not considered in this study.

In the fall and winter, thermal performance of the Green Roof was slightly better than the Reference Roof because the growing medium blocked the wind and reduced heat loss by convection. However, when the growing medium was frozen, its insulation value was greatly diminished, and heat left the building through both roofs at approximately the same rate. The heat flux and the membrane temperature of the Reference Roof varied with the intensity of the solar radiation when the roof was still bare. Snow coverage provided extra insulation to both roof systems leading to significant reductions in the heat flux through the roof. The fluctuations in the Reference and Green Roof membrane temperatures were diminished under a heavy blanket of snow.

The energy modelling was completed before the FRF was complete, and it was not possible to do a direct comparison. However, the modelling allowed the insulation and shading properties of a green roof to be extended to a three-story building. The model indicated that these particular benefits decrease above one story, although it is still possible to achieve between 5 and 10% savings on both cooling and heating energy including the energy saved on circulating the air through the building.

Stormwater Retention

The Green Roof delayed runoff and reduced runoff rate and volume. During a series of three rain events (10mm in 12h), when the growing medium became saturated, the runoff was delayed runoff by 45min and at least 2mm was absorbed before runoff occurred, retaining 45% of rain and reducing the runoff rate by 75%. When the growing medium was dry, it was able to retain 8mm of water during a rain event. Although only limited data were obtained from FRF, the preliminary data clearly showed that the Green Roof effectively delayed peak flow and reduced the rate and volume of runoff. The Green Roof was an extensive system with wild flower meadow growing in 150mm (6in.) of lightweight soil. It is expected that green roof systems with a deeper soil and more vegetation would have even higher stormwater reduction potential.

The hydrology model confirmed that a green roof, consisting of a minimal soil depth, would significantly reduce stormwater runoff. In the model, the green roof runoff was less than two thirds of the total rainfall, over four events on a partially saturated roof. The roof retained approximately 42% of the rain, which corresponds with the observational data. The same model was also tested on more extreme conditions, such as what might be experienced as a result of a hurricane. Doubling the depth of the growing medium allowed the green roof to retain 30% of the rainfall during conditions that were similar to Hurricane Mitch in Nicaragua.

Durability

High temperature fluctuations accelerate the aging process in asphalt-based roofing membrane and reduces its durability. Diurnal (daily) temperature fluctuations create thermal stresses in the membrane, affecting its long-term performance. The membrane on the Reference Roof experienced high in-service temperature (maximum temperature over 70°C or 158°F) and high diurnal temperature fluctuations (median temperature fluctuation was 46°C or 115°F) during spring and summer. These extreme temperatures affect the durability of asphalt-based roofing materials.

The membrane on the Green Roof experienced lower average in-service temperature (maximum temperature below 35°C or 95°F) and lower daily temperature fluctuations (median temperature fluctuation was 12.5°C or 55°F). Although it is too early to evaluate the durability of the membrane by mechanical and/or chemical tests, it can be expected that rooftop garden can help to preserve the membrane and prolong its service life by reducing heat aging and thermal stress. It should be noted that neither roof experienced leakage during its first year of operation.

7.2 Vertical Gardens

The vertical gardens were evaluated on their potential to reduce the surface temperature of walls either through evaporative cooling or through shading. In the tests that were conducted as part of this research, the vertical garden was effective at reducing surface temperature and as a window shade. In fact, the temperature behind the vertical garden was similar to the temperature of the vegetation canopy. These results confirmed earlier studies conducted at the University of Toronto comparing vertical gardens to dark and light-coloured walls. In these earlier studies, the vertical garden vertical garden was cooling than both surfaces. The differences were quite large and statistically significant under full sun, but even under cloudy conditions, when the differences were much small, they were still statistically significant.

The Visual DOE model was used to test the effectiveness of using vertical gardens to shade building walls and windows on a three-story building. Although the green roof has some impact on the energy consumption of multistory buildings, a great deal of heat flows in through the walls and windows, particularly the windows as many walls tend to be insulated. In the simulation model, using vertical gardens as shades reduced the energy consumption by 23% for cooling by 20% for air circulation. A prototype hydroponic vertical garden was constructed for research and demonstration purposes at the University of Toronto. This design is very lightweight and may provide one means of developing a product for multistory buildings.

7.3 Evaluation of Adaptation to Warmer Temperatures

Green roofs and vertical gardens were proposed as an adaptation to warmer summers and more frequent heatwaves that could occur as a result of climate change. These problems would be exacerbated in cities due to the urban heat island (UHI) effect. The UHI effect not only causes thermal discomfort, but it increases the formation of smog and leads to respiratory problems and heat stress.

An additional health risk may emerge under climate change. Due to the warmer temperatures, Canadians are spending more of the summer indoors in sealed air-conditioned buildings. Indoor air already contains significantly higher levels of volatile organic compounds than the ambient environment. Depending on the location of the air exchangers, the indoor air may also contain higher amounts of other pollutants that are found outdoors, but become more concentrated inside buildings. In addition, many buildings provide suitable environments for the growth of molds and fungi.

Two adaptive strategies are to reduce indoor temperatures and to reduce the ambient temperature by reducing the UHI. Green roofs and vertical gardens are useful components of both strategies. First, in Canada, cooling degree-days are accumulated above 18^{o}C, the point at which air conditioning is used, although the threshold will vary due to personal preferences. The demand for electricity, at least in southwestern Ontario increases by 3% for every 1^{o}C above this threshold (Bass and Mirza, 2002). Air conditioning and refrigeration have a direct economic, but also an environmental cost in terms of pollution and health. Green roofs and vertical gardens have been shown to achieve substantial reductions in this demand. While green roof infrastructure is most effective on one-story buildings or houses, vertical gardens are also effective on multistory buildings.

Second, vegetation has been shown to be effective at reducing the UHI, but many parts of the city lack sufficient space for trees, yet have space for green roofs and vertical gardens. In addition, both roofs and walls can contribute to the UHI. The observations of green roofs and vertical gardens have been shown that these technologies can significantly reduce the surface temperatures of both roofs and walls. However, the extent to which vertical gardens and green roofs could reduce the urban heat island cannot be known with any certainty without further simulations of the weather in urban areas with and with out this technology. One obvious application of vertical gardens is to incorporate them into window shades.

This would have the two-fold effect of reducing incoming solar energy into the interior through shading, reducing heat flow into the building through evaporative cooling, and with widespread adoption, further reductions in heat flow would occur with a diminished UHI.

The fall and winter data suggest that green roofs might also reduce the demand for space conditioning in the winter, although this demand is expected to decline in most regions of Canada. However, if the freezing of the soil is delayed or does not occur, the insulation effect of green roofs will extend through more of the winter. By reducing temperature fluctuations on the membrane, throughout all seasons, the life of this component should be extended, leading to fewer roof replacements. Typically, a roof has a lifetime of 15-20 years, and a green roof is expected to last 25-40 years.

7.4 Evaluation of Adaptation to Increases in Stormwater Runoff

Some scenarios of climate change suggest less frequent but more intense rain events for some parts of the country. The runoff from impermeable surfaces such as rooftops and roadways would generate high peak flow in the storm sewage and sometimes overloads the stormwater system in major cities, increasing the risk of CSO events. Although only limited data were obtained from FRF and detailed analysis was not possible, the preliminary data clearly show that the Green Roof delayed peak flow and reduced the rate and volume of runoff that would otherwise be generated by a roof of that size. Although not measured in this study, the green roof will likely filter out pollutants that would be typically found in runoff from rooftop. In addition, because the surface is cooler, the runoff will be cooler, thus having less of an ecological impact in other water bodies.

The model results were also promising, in that they demonstrated that a green roof will reduce stormwater runoff, but in some cases, all the water can be retained. The amount of retention is a function of the amount and intensity of rain, the depth of the growing medium, the vegetation and the amount of moisture already in the growing medium. The only limit to increasing the depth of the growing medium is the weight-bearing load of the roof and the additional costs associated with the material and strengthening the roof. The hydrology model, run with a 1 metre deep growing medium and hurricane conditions, demonstrated the potential for green roofs to play a role in mitigating the damage to very extreme events if these two barriers can be overcome. This work suggests that municipalities should consider a policy of reinforced roofing for new buildings to accommodate a heavier green roof.

7.5 Other Benefits of Green Roof and Vertical Garden Infrastructure

From a performance perspective, it appears that green roofs and vertical gardens have tremendous potential as an adaptation strategy. Beyond the climate impacts explored in this research, green roofs and vertical gardens are expected to bestow other benefits in urban areas. These include

- improved air quality, due to the reduction in the rate of smog formation and the ability of vegetation to filter or absorb certain pollutants out of the atmosphere,
- improved water quality due to the ability of vegetation to absorb some pollutants from water,
- reduced environmental impact of stormwater runoff due to the lower temperature of water from a green roof versus that from a regular roof,
- increased biodiversity in urban areas,
- increased green amenity space,
- increased mental well-being,
- increased property values and
- increased job opportunities with the growth of a new industry in the economy.

These and other benefits are discussed in Peck et al. (1999).

7.6 Barriers to Widespread Adoption

Peck et al. (1999) discussed four types of barriers to widespread adoption:

- lack of knowledge and awareness,
- lack of incentives to implement,
- cost-based barriers and
- technical issues and risks associated with uncertainty.

This research was designed to reduce the first and fourth barriers. An important aspect of this project has been to communicate the benefits of these technologies to a wider public through lectures and demonstrations. The strategy has been successful in terms of the roofing industry and at the municipal level. For example, in the last year, the City of Toronto included green roofs in the new Environmental Plan and as part of a wider government – industry – academic partnership installed eight demonstration green roof plots at City Hall. The University of Toronto and York University are now committed to some green roof development, and the American Society for Testing and Materials has now struck a committee to develop performance and technical standards for green roofs. During the last year, Toronto was one of only two cities, the other being Tokyo, selected by the Parks

Department in Singapore for a visit to discuss the implementation of green roofs in an urban environment.

Research into these technologies has also increased. Last year, Environment Canada, the University of Toronto, the Department of Public Works and Emergency Services at the City of Toronto, the Toronto Regional Conservation Authority and the Green Roofs for Healthy Cities Coalition co-sponsored the first workshop on green roof research protocols. In June 2001, the National Research Council, Environment Canada, the Green Roofs for Healthy Cities Coalition and other roofing manufacturers sponsored a one-day workshop on green roofs for practitioners as well as members of the growing North American Green Roof research network.

Another important component of this work was the establishment of the Rooftop Garden Consortium at the Institute for Research in Construction (IRC) at the National Research Council (NRC) in April 2000. This is an industry-government collaboration involving various government departments (Environment Canada, National Research Council of Canada, Public Works and Government Services Canada and Oak Ridge National Laboratory in USA), national associations (Canadian Roofing Contractors' Association and Roofing Consultants Institute) and roofing manufacturers (Bakor Inc., EMCO Ltd Building Products, Garland Company Ltd., Hydrotech Membrane Corp., IKO Industries Ltd., Soprema Inc., and Tremco Ltd.). The consortium was established to develop the Rooftop Field Facility that was used for part of this research, to facilitate technology transfer and to raise the awareness of climate change issues in an important industrial group. The primary goal of the consortium is to evaluate the performance of rooftop gardens in the Canadian climate. The consortium agreed that the research on green roof infrastructure would be pre-competitive involving a generic system, which would provide unbiased performance results from an independent source.

The consortium format worked very well for the project. The members not only provided both financial and in-kind contributions (such as roofing materials), they also contributed a wide range of experience and expertise to the project. The members from different groups had different interests and the consortium worked together to design the experiment to best meet the various needs using the resources available. Members of the NRC constructed the green roof and collected the observations. Consortium members were updated with progress of the project through semi-annual consortium meetings. The close relationship established between NRC, Environment Canada and the industry made it possible to facilitate technology transfer in a streamline manner.

The demonstration plots at Toronto City Hall, the vertical garden and the FRF will also be available the public to varying degrees. Based on a market comparison completed by Soprema, Inc., demonstration sites may be one of the best ways of raising awareness in Canada, as Canadians value aesthetics and need to see instant results (Peck at al., 1999). Increasing public awareness is also being addressed through lectures and presentations to general audiences whenever the opportunity arises.

The fourth barrier to adoption has to do with uncertainties about the benefits and the durability of the technology in Canada. Except for Soprema, Inc., which has tested its *Sopranature* product line in Canada, the other claims for green roofs are primarily based on observations of the technology in Germany. This research will contribute to reducing this barrier, both in terms of the benefits and in terms of the durability. The largest potential success in reducing this barrier has been with the roofing industry in Canada, who is fully involved in various research efforts. The results of this research will allow the roofing manufacturers to market green roofs more aggressively in the future. The extent to which this barrier can be further reduced is also tied to the ability to secure additional funding to maintain the data collection and modelling exercises that begun under the aegis of the CCAF.

It is harder to reduce this barrier for vertical gardens for two reasons. Unlike the green roofs, no one industry can be identified as a natural private sector partner. The second reason is the lack of any standard technology, excepting the growth of a vine along the wall. Even if other designs for green roof infrastructure emerge, the current technology in Europe has been the basis of a growing industry for over twenty years. Thus the vertical garden research is concentrating more on the benefits in the hope that products will eventually emerge that can be also be tested for durability to the range of climates found in North America.

The extent to which either of these technologies is adopted may depend on the degree to which the other two barriers can be reduced. The use of legislation has been quite successful at the national level in Germany and fiscal incentives have been introduced by various German cities. In the 1970s, fiscal incentives were used and were to encourage homeowners to install insulation in Canada. Portland, Oregon is the first city in North America to introduce a density-bonus ordinance to encourage the use of green roofs to reduce stormwater runoff i.e., developers can increase the size of new buildings if they include a green roof. The use of government incentives may also be required to overcome the cost barrier, particularly for green roof infrastructure.

The importance of reducing these barriers is illustrated by observing the growth of the market for green roof infrastructure in Germany (Table 7.1). Incentives by state and local governments, supported by legislation at the national level, has expanded the market by an average of 10-15% annual growth throughout the 1980's. In 1989 there were one million square metres of green roof infrastructure, and by 1996 the number had grown to ten million square metres. Green roofs now cover approximately 10% of all of the flat roofs in Germany. A more conservative estimate for the City of Toronto, based on a gradual phase in of the technology by government and modest growth estimates for existing and new building stock over the next ten years, is illustrated in Tables 7.2 – 7.4.

Table 7.1: Growth of Green Roof Infrastructure Industry in Germany

Year	Total Annual Green Roof Infrastructure (m2)
1982	-
1983	20,000
1984	50,000
1985	125,000
1986	300,000
1987	500,000
1988	700,000
1989	1,000,000
1990	1,400,000
1991	2,000,000
1992	2,800,000
1993	4,000,000
1994	5,700,000
1995	7,500,000
1996	10,000,000
1997	9,000,000
1998	10,000,000
Total*	**55,095,000**

Source: Industrieverband Bitumin dach und Dichkungsbhanen, Frankfurt, Germany 1999

* This represent approximately 10% of all of the flat roofs in Germany. Pers. communication, André Bruder, Soprema Inc., Strausborg, Oct. 22, 1999.

Approximately 80% are covered with extensive green roof systems of grass that require less cost and maintenance than intensive systems.

Table 7.2: Projected Green Roof Infrastructure Market Penetration: City of Toronto & Federal Government Building Stock

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Totals
Annual Number of Buildings	20	30	50	100	200	400	800	1,200	1,800	2,700	7,300
Annual New Green Roof Area (m2)	10,000	15,000	25,000	50,000	100,000	200,000	400,000	600,000	900,000	1,350,000	3,650,000

Table 7.3: Projected Green Roof Infrastructure Market Penetration: Toronto, Existing Building Stock

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Totals
% Total Market Penetration #	0.25%	0.35%	0.50%	0.75%	1.00%	1.50%	2.00%	3.00%	4.00%	5.00%	18%
Annual New Green Roof Area (m2)	83,596	117,034	167,192	250,788	334,384	501,576	668,768	1,003,152	1,337,537	1,671,921	6,135,949

Table 7.4: Projected Green Roof Infrastructure Market Penetration: Toronto, New Building Stock

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Totals
% Total Market Penetration #	0.25%	0.35%	0.50%	0.75%	1.00%	1.50%	2.00%	3.00%	4.00%	5.00%	18%
Annual New Green Roof Area (m2)	6000	8400	12000	18000	24000	36000	48000	72000	96000	120000	440400

Thus, only assuming a small penetration it is possible that over ten million square metres of new green roof infrastructure could be constructed in the City of Toronto by the year 2010. This number could probably be increased dramatically with an effort to lower all four of the barriers to widespread adoption.

7.7 Recommendations

The recommendations are divided up into three sections: implementing green roof infrastructure and vertical gardens, recommendations for future research and more general recommendations that could be applied to other types of adaptations. The future research is not research that is planned or is currently funded, but it is recommendation for other types of research to complement and enhance the adoption of green roofs and vertical gardens.

7.7.1 Implementing Green Roof Infrastructure and Vertical Gardens

- Maintain and strengthen the relationship between government and the various industries involve in green roof infrastructure as they will play a major role in the adoption of green roofs. This will require a strong commitment to future research, particularly to completing the tasks set out in this proposal.
- Identify one or more industries that would be suitable and willing partners for vertical gardens.
- Encourage the creation of additional demonstration sites.
- Introduce legislation and incentives at both the federal and municipal level to encourage the use of green roofs and vertical gardens.
- Introduce legislation and incentives at both the federal and municipal level to encourage the construction of roofs with much higher weight-bearing loads to support heavier green roofs.

7.7.2 Future Research

- Evaluate other benefits of green roofs and vertical gardens such as improved air and water quality, food production, protection of the building envelope, increasing amenity space, increasing biodiversity, increasing property values and job creation.
- Evaluate the success of other incentive programs and legislation, either to encourage green roofs in other countries such as Germany or how incentives were used to encourage the adoption of other technologies, such as insulation.
- Undertake a more thorough cost-benefit analysis both for the individual building and for the city including social, environmental and health impacts.

7.7.3 Recommendations for Evaluating Other Adaptation Measures

- Identify relevant groups of stakeholders in industry, government and academia, which might involve looking at the other benefits or uses of the adaptation measure.
- Create a partnership amongst these stakeholders to undertake the research.
- Use a multi-pronged approach that explores the measure in different ways as unexpected problems may reduce the effectiveness of any one particular approach.
- Use the project to raise the awareness and knowledge of the measure to a wider community.

7.8 Future Research

This project has provided the basis for additional research using the facilities, tools and partnerships that have been developed over the past two years.

- The FRF will be used to continue the evaluation of green roof technology, particularly in terms of energy use, stormwater retention, water quality and temperature and durability.
- The FRF will be used to evaluate many other types of green roof designs of varying weights, up to 500 lbs/ft^2.
- A second test site is planned for Toronto to compare to different green roof systems to a conventional roof on a larger building that is currently being used as a community centre.
- A simulation of the impacts of green roof infrastructure on the urban heat island is being developed between Environment Canada and the University of British Columbia.
- A green roof scenario will be incorporated into a regional model of energy demand and supply in the Toronto-Niagara Region under climate change.
- The prototype vertical garden at the University of Toronto will be used to conduct further tests on surface temperatures, the effect shading a window and viability to support a wide range of plants.
- A more thorough analysis of stormwater runoff reduction is planned for a sub-watershed in Toronto.

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