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Centre for the Advancement of Green Roof Technology

British Columbia Institute of Technology

Report to Canada Mortgage and Housing Corporation

BCIT Green Roof Research Program, Phase 1
Summary of Data Analysis

Observation Period – Jan. 1, 2005 to Dec. 31, 2005

This document was prepared under the CMHC External Research Grant.

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Executive Summary

To address a lack of climate-specific performance data and demonstrated feasibility of green roof systems within our region, the British Columbia Institute of Technology (BCIT) constructed and commissioned a dedicated field test site, the Green Roof Research Facility (GRRF), in 2003. The main research objective was to investigate the performance and practical application of extensive green roof systems in Canada's west coast climate.

The GRRF features three roof sections separated by parapets – two green roof sections and one non-green section for reference (REF). Both green roof systems include a root barrier, non-reservoir drainage board and independent filter cloth, and the same growing medium composition. Green Roof 1 (GR-1) contained 75 mm of growing medium planted with sedum species while Green Roof 2 (GR-2) contained 150 mm of growing medium planted with a mix of fescues and grasses. The roof sections were fully instrumented to measure stormwater runoff characteristics and energy efficiency. The roof was monitored and performance data were collected for one full year (January 1 to December 31, 2005). The plants were fully established during this period.

The research facility received 1508 mm of rainfall in 2005. The year can be roughly divided into two periods, dry and wet, based on the rainfall pattern. The dry season occurred from mid-April to the end of September, with 242 mm of rainfall. The remainder of the year was defined as the wet season, with 1266 mm of rainfall. The green roofs delayed the start of runoff and reduced the peak flow and amount of runoff. The extent of these effects varied with the particular rain event and differed for the two green roof systems. In the dry season, GR-2 retained a fraction more rainfall than GR-1, 94% compared to 86%. This was likely due to the higher water retention capacity of the deeper growing medium. However, the performance of the green roofs reversed in the wet season, with GR-1 providing 18% retention and GR-2 providing only 13% retention. It was speculated that the deeper growing medium might take longer to dry and the denser root structure of the fescues/grasses mix on GR-2 might have reduced the water holding capacity in the growing medium. The total annual rainfall retention was 29% for GR-1 and 26% for GR-2.

The green roofs increased the thermal performance of the roofing system and consistently lowered the heat transfer between the building and its environment throughout 2005. Both green roofs were shown to be more effective in reducing heat gain than heat loss; therefore, they were more thermally effective in the summer than in the winter. The green roofs reduced the daily energy demand due to heat flow through the roof by 83-85% in the spring/summer and 40-44% in the fall/winter, with an overall annual reduction of 66%. Despite the difference in growing medium depth and plant species between GR-1 and GR-2, the thermal performance of the green roofs was very similar except during the hottest periods of July and August when GR-2 outperformed GR-1 due to the higher thermal mass of the deeper growing medium. The green roofs also lowered the maximum temperature reached by the roof membrane in the spring/summer from 50°C to less than 30°C and the median membrane temperature fluctuation from 48°C to less than 5°C. These reductions suggested that the green roofs can reduce heat aging and thermal stress on the roof membrane, thus likely increasing its service life.

The first year of observation showed that, within the temperate climate of Vancouver, a green roof system with appropriate plant species in 75 mm of growing medium can provide a similar level of stormwater mitigation and thermal benefits as a green roof system with 150 mm of growing medium. The preliminary findings suggested that buildings in Vancouver could benefit from lighter weight extensive green roof systems.

Acknowledgements

The researchers would like to acknowledge the tremendous support received from BCIT's School of Construction and the Environment. In particular, we would like to thank John English (Dean) and Wayne Hand (Associate Dean) who facilitated the construction of the Green Roof Research Facility through the trades and apprenticeship program, as well as the faculty and students who were committed to the project's completion. Gratitude is owed to Joe Newton and Colin Wilson from the BCIT Technology Centre for the development of the flow meter and data acquisition system during construction and commissioning.

We would also like to acknowledge the financial support and direction provided by the project consortium, which included the Canada Mortgage and Housing Corporation, the Greater Vancouver Regional District, Environment Canada, Georgia Basin Eco System, and Public Works and Government Services Canada. Earth Tech Consulting Engineers and the Roofing Contractors Association of British Columbia provided significant in-kind support, and local suppliers and manufacturers provided materials for the construction of the research facility.

1 Introduction

Green roofs are engineered roof systems incorporating the use of vegetation, which make environmental, economic, and social contributions to urban areas, providing both public and private benefits. Green roofs can lower a building's energy demand for cooling/heating through improved thermal performance. The green roof's plants and growing medium utilize rain water, which delays and reduces the total volume stormwater runoff into the city system, and thereby contributes to the region's stormwater management plan. A green roof can protect the roof membrane from the elements, thus extending its service life.

1.1 Environmental Implications of Green Roofs

The implementation of green roofs has broad environmental implications. At the building scale, a green roof will reduce energy consumption, thereby lowering greenhouse gases. At the urban scale, strategic coverage of rooftops with green roofs will reduce the urban heat island effect **(1)**. Green roofs can become a part of the solution and an action response to the Kyoto Accord**.** Quite apart from their significant contributions as a sustainable construction technology, green roofs are also recognized for their recreational and therapeutic benefits, urban agriculture, biodiversity and habitat, aesthetic attributes, and, overall, their quiet contribution to increasing the quality of life for those Canadians who experience green roofs in everyday life **(2)**.

1.2 Two Types of Green Roofs

In general, green roofs can be categorized into two types of design, intensive or extensive, depending on the plant material and planned usage for the roof area. The design intent is a key factor in determining media depth and plant selection. Intensive and extensive green roof systems can be installed on both conventional and protected membrane roof systems by incorporating additional components, such as a root-resistant layer, a drainage layer, a filter layer and a growing medium to support growth of vegetation.

Intensive green roofs are often referred to as “rooftop gardens,” and, with a depth of growing medium of over 200 mm, irrigation and maintenance can support diverse plant species and dynamic landscape design, and facilitate urban agriculture and amenity spaces.

Extensive systems are commonly referred to as “green roofs,” “living roofs,” and “eco roofs.” An extensive green roof is a vegetative roof system engineered to provide environmental solutions. These roofs are intended to be low maintenance and, therefore, require drought tolerant species that withstand extreme and adverse environmental conditions. The extensive green roof is based on a shallow soil profile of up to 150 mm (6 inches). It can often be installed on buildings without the cost of major structural alterations. Extensive green roofs generally require less maintenance and are less expensive to install than intensive green roofs (Photos 1-2 show two green roofs in British Columbia).

1.3 Opportunities for Use of Green Roofs

Building sustainable communities presents exciting new opportunities for the widespread use of green roofs. With growing awareness of environmental preservation and sustainable development, Canada's building and construction industries are redefining themselves to address the needs of regional and global sustainability. Within British Columbia there is a strong interest in green roofs. This interest is attributed to the favourable climate and the municipal and regional governments' environmental strategies and policy directions. Vancouver has an established inventory of successful intensive rooftop gardens; however, extensive green roof systems based primarily on western European guidelines and specifically designed for environmental solutions are limited.

Vancouver has one of the highest percentage per capita in Canada of individuals living in multi-family housing, and the highest population density per square kilometre in Canada. High profile projects such as the Vancouver Conference Centre Expansion project, the 2010 Olympic Village, and several new multi-family housing and mixed-use developments have invested in green roof technologies. Twenty-five percent of roof areas in the City's new sustainable urban development project along the southeast shores of False Creek are required by Vancouver's *Southeast False Creek Policy Statement* to be vegetated(**3, 4**).

1.4 Establishment of Green Roof Research Facility (GRRF)

In 2002, Green Roofs for Healthy Cities and a regional industry and inter-governmental consortium held a stakeholder workshop in Vancouver. The participants concluded that, although green roofs have been widely adopted elsewhere in Europe, more technical research is required to understand the site level performance and regional scale benefit of green roofs specific to Canada's west coast. Further, such research is critical to establishing standards, policies and programs to support broader implementation (**5**).

The performance of extensive green roofs is different in coastal BC than in other parts of Canada because of the unique rainforest climate. Environment Canada climate normals for Vancouver record the daily mean temperature as 11°C, annual rainfall at 1473 mm and annual snowfall at only 43 mm. The stakeholders identified the major barriers to the implementation of extensive green roofs in the region as the lack of climate-specific performance data, the absence of third party testing and verification of green roof systems, and a lack of demonstrated feasibility. The conclusion of the 2002 workshop was the impetus for the BCIT Green Roof Research Program – Phase 1, which led to the establishment of the BCIT Green Roof Research Facility (GRRF).

The GRRF was constructed and commissioned in 2003 as a field test site to provide demonstration and performance data for the greater Vancouver region. The GRRF is a 100 m^2 building dedicated to research and performance of green roofs, in particular on the stormwater source control and thermal performance of green roofs. The first year of Phase 1 was dedicated primarily to project planning and facility construction, the second year to commissioning, and the third to testing, analysis, and reporting. The initial research program at the GRRF, Phase 1, was partially funded by the Canada Mortgage and Housing Corporation. This report is focused on the research findings in 2005.

The research and resource demonstration programs at the GRRF are designed to better understand and communicate the many public and private benefits of green roofs. The data obtained will also be useful in determining the cost benefits of green roofs based on reduced energy consumption.

The research findings are directly applicable to the future densification of the Lower Mainland. As well, the research findings will contribute to the calibration of a development scenario modeling tool, which was developed for the restoration and protection of the regional watersheds. These watersheds are under continual pressure due to rapid density increase and infrastructure growth in the region (**6, 7**).

2 Green Roof Research Program at BCIT – Phase 1

2.1 Facility Design and Construction

2.1.1 Site Location

The BCIT Green Roof Research Facility was the first project constructed at the new Great Northern Way campus in the light industrial zone of Vancouver, located east of False Creek and the downtown core (Photo 3). The new campus hosts BCIT, the Emily Carr Institute of Art and Design, Simon Fraser University, and the University of British Columbia as an inter-institutional academic consortium. The site location is advantageous to the community for resource demonstrations as well as for green roof performance data acquisition.

The City of Vancouver has released five strategic plans for development of a sustainable community along the southeast shores of False Creek. Green roofs are embedded in the plans as a sustainable construction technology (**7**). Since the construction of the GRRF, the Great Northern Way campus has been included as a key component of the City of Vancouver's Sustainability Precinct, and, with the awarding of the 2010 Olympics, the Olympic Village will be constructed in the Southeast False Creek community.

The microclimates within the Greater Vancouver region vary significantly, relative to elevation and proximity to coastal waters and the mountain zones. The GRRF site is 4 m above sea level and in a microclimatic location that receives rainfall levels close to the average rainfall level throughout the Lower Mainland. However, more critically, the site was selected specifically for construction of an uncompromised research facility. The facility was aligned on geodetic coordinates in a location that provides sufficient setbacks from obstructions to ensure that the roof plane (5.94 m above grade) is free of shading from buildings or trees that would provide shielding of rainfall and also interfere with the acquisition of data on the reflective solar performance and thermal performance of the green roofs (Photo 4).

2.1.2 Construction Process and Details

The GRRF was designed to accommodate three, 33 m^2 research roofs separated by 355 mm high parapets. BCIT faculty and 200 students, along with consultants, contractors, and industry support, designed and constructed the building and installed instrumentation for data collection.

The facility has short spans of 3.6 m; the 38 x 300 mm nominal roof framing can support up to 356 mm of fully saturated growing medium (Photo 5). A plywood slope was installed above the structural deck to provide a consistent 2% slope to drain. The Roofing Contractors Association of British Columbia (RCABC) donated time and expertise to install the two-ply SBS modified bituminous membrane system (Photo 6). The application of the roof above the sloped plywood deck consists of the following layers: kraft laminate vapour barrier, polyisocyanurate insulation with cellulose facers (RSI 4.9), 4 mm rigid asphalt protection board, a 180 gram polyester reinforced thermal fusible base, and a 250 gram polyester reinforced SBS cap sheet. The cap sheet contains root repellent in its formulation to prevent damage from roots.

Each roof is drained independently to the centre for the purpose of measurement of stormwater runoff. The space below the three roofs is one common climatically controlled room. In this manner each roof has an equal environment on the interior side for measurement of heat flow. The method of having one space rather than three segregated rooms mitigates the different heat load that each chamber would receive due to different orientations. The reference roof which is without a green roof system is located in the centre, with a green roof on either side. This was to decrease the migration of species between the two green roofs.

BCIT trades and apprenticeship students involved in the green roof program included steel fabrication, mechanical, electrical, millwork, painting, and finishing students. The involvement of this sector of the construction industry provides a base knowledge of, and confidence in, green roof technology, which is fundamental to the advancement of successful green roof implementation in the region. Based on career demographics, BCIT students will become the leading general contractors and construction managers to advance the BC construction sector over the next 20 years. Additionally, Phase 1 of the green roof initiative included a curriculum integration project assessing the viability of interfacing green roof technology learning outcomes into a wide spectrum of courses and programs in BCIT's School of Construction and the Environment.

2.1.3 Green Roof Systems

The research parameters and options for the green roof systems were selected by the research partners and the funding consortium. The consortium was comprised of regional government organizations, industry associations, and material suppliers. The priority established at the first meeting of the consortium was to collect performance data from the most shallow roof profile thought to be compatible with the coastal climate and applicable to big box retailers and industrial buildings.

Both green roofs have a non-proprietary, non-reservoir green roof system similar to the system (exclusive of growing medium and plants) installed at the Field Roofing Facility (FRF) at the Institute for Research in Construction/National Research Council in Ottawa (**8**). GR-1 has 75 mm of growing medium planted with sedums. GR-2 has 150 mm of growing medium, as per the FRF, and is planted with grasses and fescues. This allows for an analysis of comparable data sets from two significantly different climatic zones within Canada.

The selection of these profiles provides data on both the thermal performance and stormwater mitigation potential of two green roof systems of varying depth of growing medium and with the most appropriate plant species selected for the depth of growing medium. Thus, GR-1 was planted with sedums and GR-2 was planted with grasses and fescues. Therefore, it must be recognized that the real-time performance data of the two green roof profiles are not based solely on the depth of growing medium but rather on the established green roof ecosystem. These research findings have significant implications with respect to the design of extensive green roofs as sustainable technologies to decrease stormwater runoff and increase thermal performance.

2.2 Growing Medium and Vegetation

The landscape architect consultant to the project, Cornelia Hahn Oberlander, specified the growing medium and plant species. The growing medium was a mix by volume of 1/3 white pumice, 1/3 sand and 1/3 organic compost. GR-1 was planted with Sedum acre, Floriferum, and Sedum lydium. GR-2 was planted with Festuca scoparia, Bouteloua gracilis, and Carex glauca. The plants were grown for mid June installation; however, due to a construction delay they were not planted until the middle of August. Irrigation was provided for one full year from planting. Despite the late planting, five of the species survived the summer drought and wintered well with significant root development. The Sedum lydium was replaced in the spring of 2004 with Sedum sexangulare. The exact cause of the Sedum lydium failure was not determined. Thirty percent of the Festuca scoparia plugs were pulled within the first month of planting by black crows. In the spring the most developed of the Festuca scoparia were divided and replanted to continue the planting pattern. Additionally, Hard Fescue was seeded with the three grasses. The decision to inter-seed was made based on the goals of the research plan in which fully established coverage was required for data collection (Photos 7 to 11 and Figure 1).

2.3 Instrumentation and Sensor Locations

The roof of the Green Roof Research Facility was divided into three equal sections. Each section was fully instrumented to monitor the temperature profile, heat flow, solar reflectance, soil moisture content, rooftop microclimate, and stormwater runoff. Three measurement locations (namely, N, W and S) were selected on each roof section to minimize spatial variability and increase the reproducibility of the data (Figure 2). Various sensors were embedded between different components within the roof system at each measurement location (Figure 3). This arrangement allows direct comparison of the measurements obtained from different layers between the three roof sections.

2.3.1 Temperature Profile

A network of thermocouples was installed at different layers within the roof systems to monitor the temperature profile (Figure 3): under the plywood deck (STR), on top of the vapour barrier (VAP), on top of the thermal insulation (INS), and between the 2-ply roof membrane (MEM). For the green roof sections, additional thermocouples were installed in the growing medium: at the bottom (GB), mid-thickness (GM) and on the surface (GS) of the growing medium (Photo 12).

2.3.2 Heat Flow

A heat flux transducer (HFT) was embedded in the top surface of the thermal insulation at each measurement location to measure the heat flow through the roof system. The transducers measured the heat exchange (energy per unit area per unit time) between the building and the outdoor environment through the roof system at any point in time. They were calibrated such that a positive reading represents heat entering the building and a negative reading represents heat leaving the building. The heat flux can be integrated over time to calculate the amount of heat gain or loss through the roof during a time period.

The temperature of the building was maintained at a set point of 21°C using a mechanical forced air convection system and a thermostat. This was designed to simulate the space conditioning of typical multi-residential housings. Since the indoor temperature was relatively constant, the changes in heat flux through the roof were used to estimate the energy demand for the different roof sections (Photo 13).

2.3.3 Solar Reflectance

A solar radiation sensor was placed upside down on a weather pole (WP), 0.4 m above the roof surface on each roof section, to measure the solar radiation reflected from the roof surface (Figure 2 and Photo 14). When solar radiation is incident on a roof, it is either reflected or absorbed. The absorbed energy can transmit through the roof system into the building and increase its energy demand.

2.3.4 Rooftop Microclimate

Vegetation evapotranspirates and modifies the temperature and humidity on the roof surface, creating a rooftop microclimate. To measure these effects, a relative humidity and temperature (RH/T) transmitter placed inside a radiation shield was secured on a weather pole, 0.5 m above the roof surface on each roof section (Figure 2 and Photo 14). The temperature and humidity data would provide information on the cooling effects of green roofs.

To estimate the extent of the cooling effects of the green roofs, temperature measurements were made at different heights above the roof surface by thermocouples secured on the weather pole, 50 mm, 125 mm and 225 mm above each roof section. Note that these were qualitative measurements only. As the thermocouples were exposed to the sun, the temperature would be higher than that of the outdoor air at the same height due to solar gain.

2.3.5 Soil Moisture Content

The moisture content of the growing medium was monitored by three granular matrix soil moisture sensors on each green roof section. The soil moisture data were expected to provide information on evapotranspiration and stormwater retention efficiency. Unfortunately, the field performance of these sensors was poor, so the data could only be used qualitatively.

2.3.6 Stormwater Runoff Monitoring

A rain gauge was installed on the rooftop weather station to measure the rainfall as a function of time. It operates with a tipping bucket mechanism and has a resolution of 0.25 mm of rain per tip.

Most commercial flow meters are designed to measure flow in full pipes under pressure, not partially filled pipes as in a roof drain, and therefore are not suitable for runoff measurements. To overcome this challenge, the BCIT Technology Centre designed and manufactured specialized flow meters to measure the runoff from the roof sections. These flow meters used a tipping bucket mechanism as in typical meteorological rain gauges. Runoff from the roof drain is directed into a horizontal pipe that distributes the water uniformly into a calibrated “tipping bucket” housed in a rectangular glass container (Photo 15). The runoff tips the calibrated bucket, and as it passes the magnetic sensor it sends a pulse signal to the data acquisition system before leaving the building. Flow data would be underestimated in this case, as the overflow was not measured. However, no such heavy rainfall was recorded in 2005. In addition, the resolution of the flow meter was designed to be 10 times that of the rain gauge used on the weather station.

2.3.7 Meteorological Data

A weather station was established next to the reference roof (Figure 2 and Photo 16), about 1.8 m above the roof surface. Local meteorological data on the rooftop, such as air temperature, relative humidity, rainfall, solar radiation, wind speed and direction were recorded.

2.3.8 Data Acquisition System

Over 100 sensors were installed and monitored at BCIT’s GRRF. All sensors were connected to a Campbell Scientific CR23X data acquisition system (DAS). The DAS was programmed to scan all sensors every minute to capture any sudden weather changes. The DAS is programmed to automatically download the data daily into a dedicated computer through the computer network on campus (Photo 17).

3 Results

3.1 Climate Data

The data and discussion are provided as a summary of the first year of observation of the fully established green roof systems at the Green Roof Research Facility. Included in this report are analyses of climate, stormwater retention, membrane temperature profiles, and heat flux. Table 1 provides a climate summary for the research facility site in 2005.

The Environment Canada climate normals published in 2005 are defined as averages of climatological data computed for consecutive periods of 30 years, in this case 1971-2000. The nearest full climatological station is the Vancouver International Airport (YVR). The station is on an exposed ocean site, with an elevation of 4 m above sea level and located 9 km northeast of the research facility. The total precipitation recorded in 2005 at the YVR station is 1183 mm. Climate normals for the YVR site report 1155 mm of precipitation. Greater Vancouver weather stations record significantly different microclimates across the regional district. Climate normals at the White Rock STP station, the most southern municipality in the Greater Vancouver Regional District (GVRD), with an elevation of 13 m, report an annual precipitation of 1102 mm. Climate normals at the residential level station, Redonda Drive in North Vancouver, at the north end of the region, with an elevation of 228 m, report an annual precipitation of 2477 mm.

The research facility is an urban site situated 4 m above sea level. In 2005, the spring and summer climate in Vancouver was characterized by mild temperatures and low precipitation. The average daily temperature recorded at the rooftop weather station was 14.4°C. The fall/winter climate in Vancouver was characterized by cool temperatures and high precipitation. The average daily temperature recorded at the rooftop weather station was 5.7°C. Total precipitation at the research facility in 2005 was 1508 mm. The warmer temperatures and higher total rainfall recorded at the research facility compared to the airport reflect the difference in microclimate and location (Figures 4 and 5).

3.2 Stormwater Retention

In this section, stormwater runoff retention and delay of runoff from the green roofs and the reference roof are discussed. Four rain events are examined in detail. Two events are from the 2005 dry season, a season which straddled the spring, summer and early fall. Two events are from the wet season, just under 7 months, straddling fall, winter and into late spring. Rainfall was measured by a rain gauge located on the weather station on the rooftop. The three roof sections were divided by parapets, and the runoff from each section flowed to a central drain (Figure 2). The data were collected every minute and tabulated on 15 minute intervals for analysis and clarity of plots. In this recorded observation period, the plants on both green roofs were fully established and the irrigation system was not used throughout the full year of data collection. The plant species were selected for drought tolerance capacity, and the plant health was not compromised due to a lack for irrigations.

The research facility received 1508 mm of rainfall in 2005. For definition within this report, the 2005 dry season began in mid April and continued until the end of September. Only 242 mm of rainfall were recorded in the dry season. The remainder of the year is defined as the wet season, in which 1266 mm of rainfall were recorded. The dates defining the start of the dry and wet seasons are derived from weather and rainfall patterns, rather than from the first or the last day of calendar months (Table 2 and Figure 6). Most of the precipitation was in the form of rain. Note that the rain gauge at the rooftop weather station was not equipped to measure snowfall in real time, so the precipitation was recorded when the snow had melted. This only affected 10 days in January 2005.

In order to analyze the green roof behaviour during a rain event, a definition for an event has been defined based on isolation of the event from other rainfall. This is required in order to investigate runoff and delay. Therefore:

- *Event* is herein defined as a discrete period of precipitation separated in time from other recorded precipitation by at least 6 hours before the start of the event and by at least 6 hours after.
- *Runoff* is defined as the amount of runoff from the start of the rain event until 6 hours after the end of the rainfall.
- *Peak flow* is the highest level flow of recorded rainfall intensity or roof runoff (mm/15 min) throughout the rain event.
- *Delay in start of runoff* is the time difference between the start of recorded rainfall and the start of runoff from the green roof.
- *Peak flow delay* is the time difference between the peak flow of rainfall and the peak flow of runoff from the green roofs.

3.2.1 Performance in Dry Season

Climate Characteristics

The dry season in 2005 occurred from mid April to the end of September; 242 mm of rainfall were recorded in the dry season. In total, 25 rain events where recorded in the dry season between April 17 to September 27. Both green roof systems, GR-1 and GR-2, demonstrated a wide range of performance in the dry season.

In this dry season the green roofs had high levels of runoff retention of 90–100% during 20 of the 25 events. The small amount of runoff from short duration events does not provide sufficient data to analyze, with respect to delay and peak flow. Therefore, two long duration events have been selected to illustrate the varying performance within the dry season. These events have similar rainfall amounts; however, the duration and peak flow differ. Most critical for the discussion on runoff retention is the level of moisture in the growing medium owing to rainfall in the preceding days.

Event D1: May 21–22, 2005

Figure 7a–7c shows an event of 19 hr 45 min duration with 18.0 mm of rainfall beginning on May 21. In the 7 days prior to May 21, the site had received 41.9 mm of rainfall. This created a high level of moisture content immediately before the start of the event. This event began in the early evening and continued throughout the night until the afternoon of the next day. At the time of the event the ambient air temperature range was 10°C to 15°C. The temperature range, measured at the middle of the growing medium, was 10°C to 16°C for the 75 mm depth of GR-1 and 13°C to 17°C for the 150 mm depth of GR-2. The rainfall peak flow occurred in the first 4 hours of the event. The runoff from the reference roof was 10% less than the rainfall recorded by the weather station. This can be attributed to the slight ponding of rain on the roof and the parapets, and the higher level of evaporation in the warmer weather. There was no delay in start of runoff from the reference roof.

GR-1 retained 48% of rainfall and delayed the start of runoff by 3 hr 15 min relative to the start of rain and start of runoff from the reference roof. GR-2 retained 87% of the rainfall and delayed the start of runoff by 1 hr 30 min. The runoff from GR-2 was recorded to have occurred earlier than from GR-1; this is due to the tipping bucket design of the flow meters. The start time of the runoff was defined by the first tip of the tipping bucket which was partially full with the GR-2 runoff from the previous day's event. The May 21–22 event runoff from GR-1 and GR-2 continued until the start of the next rain event 7 hours later. The rainfall peak flow was 2.0 mm/15 min. The runoff peak flow reduction relative to rainfall was 8% and 68% for GR-1 and GR-2, respectively. GR-1 did not decrease the runoff peak flow relative to the reference roof, whereas GR-2 decreased the runoff peak flow relative to the reference roof by 63%. The peak flow delay was 15 minutes for both green roofs. Figure 7a illustrates a small first rainfall peak of 3.56 mm (18:00 to 22:00 hrs) and the reference roof runoff. Both GR-1 and GR-2 completely eliminated this small first peak resulting in a decrease capacity to delay the second peak (Figure 7b-7c). This event is typical of dry season events where there has been recorded rainfall in the days preceding the event. The event illustrates a consistent pattern of the higher level of performance of GR-2 over GR-1 in these conditions.

Event D2: June 17, 2005

Figure 8a–8c illustrates an event of 12 hr 45 min duration with 18.0 mm of rainfall on June 17. In the 7 days prior to June 17, the site had received 8.1 mm of rainfall. This created a low moisture content immediately before the start of the event. Rainfall began shortly after midnight and continued until mid afternoon. There was a time period of 5 hours where rainfall was minimal and not recorded by the rain gauge (Figure 8a); however, the reference roof flow meter, which has a resolution 10 times greater than the rain gauge, recorded the minimal rainfall. Thus, this event is a combination of two segments. At the time of the event the ambient air temperature range was 13°C to 16°C. The temperature range, measured at the middle of the growing medium, was 15°C to 20°C for the 75 mm depth of GR-1 and 16°C to 18°C for the 150 mm depth of GR-2, The runoff from the reference roof was 7% less than the rainfall recorded by the weather station. There was no delay in start of runoff from the reference roof.

GR-1 retained 90% of the rainfall. GR-1 delayed the start of runoff by 1 hr 15 min relative to the start of rain and start of runoff from the reference roof. GR-2 retained 93% of the rainfall and delayed the start of runoff by 1 hr 45 min. The June 17 event runoff from GR-1 and GR-2 continued for an additional 5 hr 15 min and 7 hr 00 min, respectively, beyond the rainfall and runoff from the reference roof. The rainfall peak flow was 1.5 mm/15 min. The dramatic reduction in volume of runoff was accompanied by a 90% reduction of runoff peak flow from both green roofs. The peak flow delay was 15 minutes for both green roofs. This event is typical of dry season events where there has been very minimal recorded rainfall in the days preceding the event. The event illustrates a consistent pattern of similar performance in both GR-1 and GR-2 in these dry season conditions.

3.2.2 Performance in Wet Season

Climate Characteristics

The wet season in 2005 is divided into two time periods. The first period was from January 1, 2005 until the middle of April, when the continuous rainfall stopped and Vancouver received 20 consecutive days without rainfall recorded above 2 mm. The second period was from the end of September until December 31, 2005. Coupled together these two wet periods created the 2005 wet season in which 1266 mm of rainfall were recorded. Two long duration events have been selected to illustrate the performance of the green roof systems during the wet season. The first event illustrates a consistently low intensity rain pattern. The second event illustrates high peak intensity.

Event W1: April 5–6, 2005

Figure 9a–9c illustrates an event of 18 hr duration with 17.3 mm of rainfall beginning on April 5. In the 7 days prior to April 5, the site had received 59 mm of rainfall. This event began just after the noon hour and continued throughout the night until the early morning of the next day. At the time of the event the ambient air temperature range was 7°C to 9°C. The temperature range, measured at the middle of the growing medium, was 7°C to 8°C for the 75 mm depth of GR-1 and 8°C to 9°C for the 150 mm depth of GR-2. The runoff from the reference roof was 5% less than the rainfall recorded by the weather station. There was no delay in start of runoff from the reference roof.

GR-1 retained 22% of rainfall and delayed the start of runoff by 1 hr 30 min relative to the start of rain and start of runoff from the reference roof. Runoff from GR-1 continued for 10 hr 30 min after the rain has stopped. GR-2 retained 17% of the rainfall and delayed the start of runoff by 1 hr 45 min. Runoff from GR-2 continued for an additional 11 hr 15 min beyond the rainfall and runoff from the reference roof. The rainfall peak flow was 0.8 mm/15 min at 2 hr 30 min after the start of the event. Otherwise, there was a constant rainfall averaging 0.25 mm/15 min over the remainder of the duration. The runoff peak flow reduction relative to rainfall was 43% and 41% for GR-1 and GR-2, respectively. However, the green roofs did not reduce the runoff peak flow relative to the reference roof, as the green roof growing medium had met field capacity due to the previous 59 mm of rainfall. The peak flow delay was 15 minutes for both green roofs. This event illustrates a consistent pattern of slightly higher level of performance of GR-1 over GR-2 in these climatic conditions presented in the wet season.

Event W2: November 1–2, 2005

Figure 10a–10c shows an event of 11 hr 45 min duration with 17.5 mm of rainfall beginning on November 1. In the 7 days prior to November 1, the site had received 66 mm of rainfall. Rainfall runoff from both green roofs occurred continuously for 5 days. This event began early in the morning and continued until the mid afternoon of the next day. At the time of the event the ambient air temperature range was 7°C to 9°C. The temperature range, measured at the middle of the growing medium, was 8°C to 10°C for the 75 mm depth of GR-1 and 9°C to 10°C for the 150 mm depth of GR-2. The runoff from the reference roof was 6% less than the rainfall recorded by the weather station. The event rainfall peak flow was 2.3 mm/15 min, at 3 hours after the start of the event. Otherwise, there was a constant rainfall averaging 0.25 mm/15 min over the remainder of the duration. There was no delay in start of runoff from the reference roof.

GR-1 retained 11% of rainfall. Runoff from GR-1 continued until the next rainfall event. GR-2 retained 6% of the rainfall and did not delay the start of runoff. Runoff from GR-2 continued until the next runoff event, as well. The runoff peak flow was reduced by 20% for both green roofs, relative to rainfall, and 8% for both green roofs, relative to the reference roof. The peak flow delay was 30 minutes for both green roofs. The event illustrates a consistent pattern of slightly higher level of performance of GR-1 over GR-2 in these conditions.

3.2.3 Runoff Retention Statistics

Dry Season

Table 3 is a table of 13 consecutive events preceding the dry season events discussed in section 3.2.1. This table also represents a range of the green roofs' performance in the dry season with respect to runoff retention and delay in start of runoff. The events represent rainfalls in the range of 2 mm to 18 mm. 100% of the runoff may be retained for short duration, low intensity events, due to the dry condition of the growing medium. The ambient temperature range during the time frame of the 13 events from May 14 to June 17 was 12°C to 23°C. May 15 exemplified a high level of performance with respect to stormwater mitigation during a significant rain event. GR-1 and GR-2 retained 96% and 95%, respectively, of the 15.7 mm rainfall. This was due to the dryness of the growing medium, with a recorded rainfall of only 8 mm in the preceding month. Within this time frame, three events from May 19 to 23 show a reduced performance of the green roofs, with rainfall retention as low as 37%. It is during this 3-day period where GR-2 performs significantly better than GR-1.

In the dry season the green roof with 75 mm of growing medium and sedum species (GR-1) provided a total of 86% rain water runoff retention, where the runoff volume is compared to rainfall. The green roof with 150 mm of growing medium and a mix of fescues and grasses (GR-2) provided a total of 94% rain water runoff retention (Table 2).

Both green roof systems delayed the start of runoff and peak flow for all rain events in the dry season for which runoff occurred.

Wet Season

Tables 4 and 5 are tables of events for the seven days preceding each of the wet season events discussed in section 3.2.2. These tables represent a range of rainfall events with a total volume of 2.8 mm to 39.4 mm. The average ambient temperature during the seven days prior to the April 5–6 event was 4–13°C. The temperature range, measured at the mid point of the growing medium, was 4–15°C for the 75 mm depth of GR-1 and 7–11°C for the 150 mm depth of GR-2. The average ambient temperature during the seven days preceding the November 1–2 event was 5–17°C. The temperature range, measured at the mid point of the growing medium, was 4–13°C for the 75 mm depth of GR-1 and 9–12°C for the 150 mm depth of GR-2.

During events with rainfall of less than 10 mm, the green roofs reduced runoff in the range of 12% to 65% (Tables 4-5). The rainfall retention was not dependent on duration or intensity of the rainfall but on the amount of rainfall in the preceding days and the amount of moisture in the growing medium. During events with rainfall greater than 10 mm, the rainfall retention ranged from 6% to 47%.

In the wet season the green roof with 75 mm of growing medium and sedum species (GR-1) provided a total of 19% rain water runoff retention, where the runoff volume is compared to rainfall. The green roof with 150 mm of growing medium and a mix of fescues and grasses (GR-2) provided a total of 14% rain water runoff retention.

3.3 Thermal Performance

3.3.1 Temperature and Heat Flow Profiles

This section examines the temperature profiles in the roof systems and heat flow data recorded on selected days that were typical of the observation period. The locations and symbols of the thermocouples embedded at different layers within the roof systems are shown in Figure 3. The minute-by-minute data collected were averaged over 15 minutes to minimize variations and enhance clarity of the plots.

Fall and Winter Performance

Climate Characteristics

The fall/winter climate in Vancouver in 2005 was characterized by cool temperatures and high precipitation. The average daily temperature recorded at the rooftop weather station was 5.7°C and the total precipitation was 1092 mm during the fall/winter period (Table 1).

Temperature Profile across the Roof System

Figure 11 shows the temperature profile of the three roof sections on a typical winter day – January 30, 2005. The selected day was overcast: the total daily solar energy incident on the roof was 1.0 MJ/m^2 with a peak 15-minute average solar radiation of 70 W/m^2 (Figure 11a). The rain accumulated to 15 mm over the 24-hr period. The outdoor temperature was hovering around 8–9°C. For the reference roof, the roof membrane in the early morning was slightly cooler (7°C) than the outdoor air temperature (8°C) (Figure 11b). The roof membrane temperature rose slightly at around 09:00 due to the small amount of solar radiation incident on the roof, reaching a peak of 10°C around 13:00. The roof membrane temperature dropped to about 8°C as the incident solar radiation decreased in the afternoon.

The roof membrane temperature of the green roofs (GR-1 and GR-2) was relatively constant at 9–10°C over the 24-hr period (Figure 11c-d). The temperature of the growing medium was 8–9°C. Note that the temperatures of the bottom (GB), mid-thickness (GM), and surface (GS) of the growing medium for each green roof were essentially the same. This was likely due to the high moisture content and therefore high thermal conductivity in the growing medium. Also, despite the differences in the growing medium depth, vegetation type and coverage, the temperature profiles of GR-1 and GR-2 were very similar.

Heat Flow through the Roof System

Figure 12 shows the heat flow through the various roof sections measured by the three heat flux transducers (HFT) on the same winter day. Since the indoor temperature of the building was higher (21°C) than the outdoor temperature (8–9°C), the building lost heat through parts of its building envelope, such as the roof, walls and windows. The HFTs embedded in the roof system measure the heat transfer between the building and its environment through the roof; a negative value indicates heat loss and a positive value indicates heat gain. Figure 12a shows that the reference roof lost heat at a rate of about 2 W/m^2 early in the morning. During the day it absorbed the solar energy, and the heat loss was reduced to about 1 W/m^2. The heat loss returned to around 2 W/m^2 in the evening.

The green roofs lost heat at a relatively constant rate of 2 W/m^2 throughout the day (Figure 12b–12c). Despite of the differences in growing medium depth, vegetation type and coverage, there was little difference in heat flow measured between GR-1 and GR-2 during this period.

Spring and Summer Performance

Climate Characteristics

The spring and summer climate in Vancouver in 2005 was characterized by mild temperatures and low precipitation. The average daily temperature recorded at the rooftop weather station was 14.4°C, and the total precipitation was 416 mm during the spring and summer period.

Temperature Profile across the Roof System

Figure 13 shows the temperature profile of the three roof sections on August 1, 2005, a typical summer day. The selected day was sunny: the daily solar energy incident on the roof was 25 MJ/m^2 with a peak 15-minute average solar radiation of 860 W/m^2 (Figure 13a). The outdoor temperature rose quickly from 18°C early in the morning to 24°C in the afternoon. For the reference roof, the roof membrane in the early morning was cooler than the outdoor temperature due to radiation loss (Figure 13b). The roof membrane absorbed the solar energy during the day and its temperature rose. It reached a peak temperature of 53°C at 14:15, about one hour after the peak incident solar radiation recorded on the rooftop weather station (Figure 13a).

The temperature of the roof membrane under the green roofs was relatively constant in comparison (Figure 13c–d). The roof membrane temperature of GR-1 ranged from 25–28°C over the 24-hr period.

The roof membrane temperature of GR-2 was very stable between 23°C and 24°C. These temperatures indicated that the green roofs were able to reduce heat entering the building and keep the roof membrane cool in the summer. Also, GR-2 was more thermally effective, as indicated by the uniformity in membrane temperature.

Close examination of the temperature recorded at different depths in the growing medium revealed reduction in amplitude and translation of the peaks in GS, GM and GB. When solar radiation reached GR-1, the surface of the growing medium (GS) heated up first and reached a peak of 33°C at 16:00. The temperature of the mid-thickness of the growing medium (37 mm deep) rose slowly and reached a peak of 30°C at 17:45, or 1 hr 45 min after GS. The temperature of the bottom of the growing medium (75 mm deep) also rose slowly and reached its peak of 29°C, 1 hr 30 min after GM. These changes in temperature measured at different growing medium depths clearly demonstrate the thermal buffering effects of the growing medium. GR-2 exhibited similar behaviour. However, the peaks were lower and the lags were longer for GR-2 compared to GR-1, due to the higher thermal mass of the thicker growing medium.

Heat Flow through the Roof System

Figure 14 shows the heat flow through the three roof sections measured by the three heat flux transducers (HFT) on the same summer day. Since the indoor temperature of the building was lower than the outdoor temperature during the day, the building gained heat through parts of the building envelope, such as the roof, walls and windows. Solar radiation had a strong influence on the heat flow through the roof system during this period. Figure 14a shows that the reference roof lost heat at a rate of about 1–3 W/m^2 early in the morning due to radiation loss. However, heat started to enter the roof system at around 08:00 and peaked at about 17 W/m^2 in the afternoon. The heat flow reversed direction again when the solar radiation decreased in the evening.

The heat flow through the green roofs was significantly lower and more uniform over the day (Figure 14b-c). GR-1 showed a very slight heat gain in the evening, again confirming the thermal mass effect. The heat flow through GR-2 was close to zero, indicating it was highly effective in reducing heat flow between the building and its environment in the spring/summer period.

Green roofs can reduce heat gain in the building through the mechanisms of shading, insulation, evapotranspiration and thermal mass. GR-2, with grasses growing in 150-mm thick growing medium, was expected to be more effective in all four mechanisms than GR-1, which consisted of sedums growing in 75-mm thick growing medium. However, for the mild spring and summer weather in Vancouver, the heat flow data showed that the lighter system, GR-1, was able to reduce the heat gain effectively.

3.3.2 Membrane Temperature Statistics

Membrane Temperature Fluctuations

Figures 15 to 17 show the daily maximum and minimum temperatures of the roof membrane on the three roof sections of the GRRF in 2005. The daily extremes of the ambient air temperature are shown in Figure 18 for comparison. The diurnal temperature fluctuation, defined as the difference between the daily maximum and minimum temperatures, was about 10°C in the spring/summer and 5°C in the fall/winter for the outdoor ambient conditions.

Being exposed to the elements, the temperature of the roof membrane on a conventional roof system such as the GRRF is highly dependent on the outdoor conditions. An exposed membrane absorbs solar radiation during the day and its surface temperature rises. It re-radiates the absorbed energy at night and its temperature drops. The surface temperature depends on the surface properties of the roof membrane (solar reflectivity and infrared emissivity), the outdoor temperature, and the solar radiation. Figure 15 shows that the daily maximum temperature of the roof membrane on the reference roof was generally higher than that of the ambient air, with a daily maximum in the range of 40–60°C during spring/summer.

Also, the daily minimum temperature of the roof membrane on the reference roof was slightly lower than that of the ambient air. This creates high diurnal temperature fluctuations in the membrane.

By comparison, the green roofs decreased the daily maximum and increased the daily minimum temperatures of the roof membrane, thus reducing the daily temperature fluctuations that the roof membrane experienced (Figures 16 and 17). The difference between the daily maximum and minimum was higher in the summer than in the winter, due to the higher solar radiation and temperature in the summer. The difference was also smaller for GR-2 than GR-1, due to the deeper growing medium (therefore higher thermal mass) of GR-2.

To minimize the day-to-day fluctuations, the monthly medians of the daily temperature fluctuations of the roof membrane were computed for the three roof sections (Figure 19). The monthly median membrane temperature fluctuations of the green roofs were always significantly lower than the reference roof. In addition, the monthly median membrane temperature fluctuation of GR-2 was lower than GR-1. Figure 20 compares the daily membrane temperature fluctuations by seasons. The median membrane temperature fluctuation for the reference roof was 43–48°C in the spring/summer and 16–19°C in the fall/winter. The green roofs reduced the fluctuation of the roof membrane to less than 5°C in the spring/summer and less than 2°C in the fall/winter. GR-2 was very effective in reducing the temperature fluctuation in the roof membrane to a median temperature fluctuation of less than 2°C throughout 2005.

Maximum Membrane Temperature

Figure 21 shows the distribution of daily maximum membrane temperatures of the three roof sections in 2005. Each bar in the histograms represents the fraction of the year where the daily maximum temperature falls in the temperature range. For example, referring to Figure 21a, out of the 365 days in 2005, the daily maximum membrane temperature for 11% of the days was between 60°C and 70°C. Vancouver is characterized with the mild climate of the west coast; nevertheless, the exposed membrane of the reference roof reached a daily maximum temperature higher than 50°C on 27% of the days in 2005 and higher than 40°C on 43% of the days in 2005. By comparison, the green roofs reduced the daily maximum temperature of the roof membrane to less than 40°C every day in 2005. The daily maximum roof membrane temperature was between 0–30°C, 99% of the time for GR-1 and 100% of the time for GR-2 (Figure 21b–21c). These data clearly demonstrate that the green roofs lowered the temperature of the roof membrane.

3.3.3 Energy Efficiency

To compute the heat flow through each roof section, the heat flux curve obtained from each heat flux transducer was integrated over time each day to obtain the daily heat flow per unit roof area ($kWh/m^2/day$). This is equivalent to calculating the area under a heat flux curve (Figures 12 and 14). The positive areas (above the x-axis), representing heat gain per unit roof area, and the negative areas (below the x-axis), representing heat loss per unit roof area, were computed separately. The heat flow data obtained from the three HFTs on each roof section were averaged to minimize spatial differences across the roof section. The daily heat flow through each roof section was further averaged over a month to smooth out day-to-day variations. The average daily heat gain and heat loss through the three roof sections in 2005 are plotted in Figure 22.

Fall/Winter Performance

During the fall and winter (October to March), the average daily heat loss (0.075 $kWh/m^2/day$) was considerably higher than the heat gain (0.015 $kWh/m^2/day$) for the reference roof (Figure 22a). The green roofs reduced the heat loss from the building to 0.051 $kWh/m^2/day$, and GR-2 lost slightly more heat (8%) than GR-1 during the fall/winter (Figure 22b–22c). No heat gain was observed through the green roofs during this period. This demonstrated that the extensive green roofs were able to reduce heat flow between the building and its environment in the fall/winter, thus lowering the energy demand for space conditioning. The thermal benefit observed was likely derived from the thermal mass of wet growing medium (the total precipitation was over 1000 mm during fall/winter). The data also showed that GR-1 and GR-2 behaved similarly despite the differences in these systems.

Spring/Summer Performance

During the spring and summer (April to September), the heat gain and heat loss through the reference roof were similar, about 0.060 kWh/m^2/day. The green roofs reduced the heat transfer through the roof system. GR-1 and GR-2 reduced the heat gain and loss to less than 0.003 and 0.020 kWh/m^2/day, respectively. This demonstrated that the extensive green roofs were able to reduce heat flow between the building and its environment in the spring/summer, thus lowering the energy demand for space conditioning. The thermal benefits were derived from the growing medium as well as from vegetation (sedums on GR-1 and grasses on GR-2). The heat flow through the two green roofs was similar except for the warmest months of July and August, where GR-2 was thermally more effective than GR-1. This is likely due to the fact that GR-2 had a higher thermal mass (thicker growing medium) and thermal insulation (grasses vs. sedums), which provided better thermal efficiency than GR-1.

Figure 23 compares the heat gain/loss through the roof sections by seasons. It demonstrates that green roofs were effective in reducing heat flow through the roof all year in Vancouver, and the effectiveness was higher in the spring/summer compared to the fall/winter.

Heat Flow Statistics

Heat flow between a building and its environment creates energy demand for space conditioning. The energy demand for space conditioning from the roof can be estimated by the sum of the heat entering and leaving through the roof, i.e. the total heat flow through the roof.

Figure 24 shows the total daily heat flow through the roof sections averaged by month and by season. GR-1 and GR-2 consistently reduced the total daily average heat flow through the roof throughout the year—more in the spring/summer (83–85%, respectively) and less in the fall/winter (40–44%, respectively). The thermal performance of GR-1 and GR-2 was very similar despite their system differences. Figure 25 divides the total heat flow through the roof by heat gain (positive values) and heat loss (negative values) over 2005. About 62% of the total heat flow through the reference roof was due to heat loss. GR-1 and GR-2 reduced the heat loss and gain by 46-50% and 96-100%, respectively. This again confirmed that the green roofs were more thermally effective in spring/summer. Figure 26 shows the percent reduction in heat gain/loss by the green roofs when compared to the reference roof. It clearly demonstrates that green roofs are more effective in reducing heat gain than heat loss.

4 Discussion

4.1 Comparison of Green Roof Systems – Runoff Retention

In the dry season, GR-2 (150 mm of growing medium depth and grasses and fescues) had a higher capacity over GR-1 (75 mm of growing medium depth and sedums) for stormwater runoff retention. This increased capacity of GR-2 over GR-1 diminished as the amount of rainfall increased within the days prior to a recorded event and the moisture content of the growing medium increased. The stormwater runoff retention performance of GR-1 was affected more by the amount of rainfall prior to a recorded event than GR-2.

In the wet season, an inverse in performance between the two roofs was observed, where the depth of growing medium and plant species which provided a performance advantage for GR-2 over GR-1 in the dry season was negated in the wet season. In the wet season GR-1 had a slightly higher water holding capacity than GR-2. The area to volume ratio was higher for the shallower growing medium of GR-1 than for GR-2; however, this does not provide a complete explanation. In both of the time periods of 2005 which defined the wet season, the high volume of rainfall created extended time periods where the green roofs were saturated and runoff was continuous, or where the green roofs had reached field capacity and the delay in runoff was not significant.

Further investigation is required to determine the reasons for the comparative performance between GR-1 and GR-2 with respect to stormwater runoff. The effects on stormwater runoff due to rates of evapotranspiration and the root structure of the different plant species on each of the two green roof systems have not been quantified in this research program. However, observations were recorded at 18 months after the green roofs where fully established with vegetation coverage at 95% to 100%. At that time, the root structure of the sedums in GR-1 extended to mid depth of the 75 mm of growing medium, whereas the roots of the grasses and fescues in GR-2 extended throughout the total depth of the 150 mm of growing medium.

4.1.1 Annual Performance in Runoff Retention

Vancouver is characterized as having a temperate rainforest climate; however in 2005 the urban site of the research facility experienced a 5½ month dry season, recording 242 mm of rain, and a 6½ month wet season, recording the remaining 1266 mm.

The runoff retention of the green roof systems was higher in the dry season (86–94%) than in the wet season (13–18%) due to saturation of the growing medium. The overall annual performance of the green roofs is driven by the rainfall pattern which is delineated by the extreme volume of rainfall in the wet season. When calculated as annual rainfall retention rates, the performance of the two green roof systems is equal. GR-1 reduced runoff by 29% and GR-2 reduced runoff by 26%.

Further, these results highlight that it is not solely the depth of growing medium that affects the stormwater mitigation performance of green roofs but, rather, the overall system design of the growing medium depth and plant species.

Stormwater runoff mitigation is a driving force for green roof implementation. The research findings of the Phase 1 program provide informative data to support shallow profile extensive green roofs as a sustainable construction technology, which will have a broad environmental impact on urban ecology and infrastructure. In terms of annual stormwater runoff retention, the research findings support that an extensive green roof system with 75 mm of growing medium depth installed with the appropriate plant species can provide equal performance in BC’s coastal rainforest climate as a green roof system with 150 mm of growing medium. The 75 mm shallow extensive green roof has the potential to provide higher environmental returns relative to the financial investment in a 150 mm green roof system. Critical in the design decision is the selection of plant species that can be supported within this shallow depth of growing medium. The sedums planted were successful throughout the duration of this research program. Where depth of soil creates a cost impact due to associated loads on long span roof structures or retrofit installations, the research findings support the installation of the shallower system.

4.2 Energy Efficiency and Saving

Heat flow between a building and its environment creates an energy demand for space conditioning. Assuming the indoor temperature is kept constant for normal building operation, any heat entering the building would create a cooling demand for the building and any heat leaving the building would create a heating demand. The heating/cooling demand would create an energy demand for space conditioning equipment, such as an air conditioner and furnace. A green roof is a passive energy technology, which derives its energy saving by reducing heat flow between a building and its environment.

The green roofs were shown to reduce heat flow through the roof, thus reducing the heating/cooling energy demand for the building. Field data at the GRRF in 2005 showed that the total energy demand due to heat flow through the reference roof was 39 kWh/m^2 annually. The green roofs reduced the total annual energy demand by 26.1 kWh/m^2 and 25.9 kWh/m2 for GR-1 and GR-2, respectively. This corresponds to a reduction of about 66%.

Note that the energy demand discussion in this section was estimated based on heat flow through the roof only. Since heat flow through other parts of the building envelope (e.g., walls and windows) was not taken into account, the percent reduction could not be applied to the space conditioning energy demand for the whole building. Also, the analysis assumed that any heat gain or loss through the roof was removed or supplemented by the heating/cooling system in the building, which caused an overestimation of the energy demand, as it did not account for the “comfort window” for the occupants. This comfort window depends on the usage of the building (e.g., factory vs. school) and the occupants. In addition, energy demand is building specific and is dependent on the type and efficiency of the heating/cooling equipment and distribution system.

4.2.1 Seasonal Difference in Thermal Performance

The green roofs were more thermally efficient in the spring/summer than in the fall/winter (Figure 24). They reduced the energy demand due to heat flow through the roof by 83–85% in the spring/summer and only 40–44% in the fall/winter. Green roofs modify the heat flow through the roof system by the mechanisms of shading, insulation, evapotranspiration and thermal mass. In the spring/summer, the green roofs are thermally efficient, as all four mechanisms work together to cool the building. This is indicated by the significant reduction in heat gain/loss through the green roofs compared to the reference roof (Figures 22 and 26). In the fall/winter, the growing medium lost much of its insulation value due to the high precipitation rate in Vancouver, but retained a high thermal mass due to the wet growing medium. Therefore, the thermal efficiency of the green roofs in the fall/winter was largely reduced compared to the warmer and drier months in spring/summer.

4.2.2 Comparison of Green Roof Systems – Thermal Performance

GR-1 and GR-2 differed by their growing medium depth and vegetation. GR-1 contained a sedum mix growing in a growing medium 75 mm thick, while GR-2 contained a grass mix growing in the same growing medium 150 mm thick. Both green roof systems were found to be effective in reducing heat flow through the roof throughout the year, and the effectiveness was higher in the spring/summer than in the fall/winter (Figure 24).

It is interesting to note that the lower profile system, GR-1 (75 mm thick growing medium with sedums), performed almost equally as well as the heavier system, GR-2 (150 mm thick growing medium with grasses), in the spring/summer, except for the warmest months of July and August, when GR-2 outperformed GR-1. GR-2, with a higher thermal mass and capacity for evapotranspiration due to the thicker growing medium, was expected to perform better in the summer. GR-1 was shown to be thermally efficient in reducing heat flow through the roof in the mild summer temperatures of Vancouver. However, during the warmest months of July and August when the heat gain was the highest, GR-2 clearly outperformed GR-1 in reducing the heat flow through the roof system (Figure 22b–22c).

During the fall/winter, the thermal performance of GR-1 and GR-2 was similar (Figure 22b–22c). Since the thermal insulation value of the wet growing medium was low, the thermal effectiveness depended largely on the thermal mass of the growing medium. Again, GR-1 was shown to be thermally efficient in moderating the heat flow through the roof because of the mild climate in Vancouver.

4.3 Implications on Membrane Durability

High temperature accelerates the aging process in bituminous and polymeric roofing membranes and reduces their durability. Diurnal temperature fluctuations create thermal stress in the membranes, which could pull apart seams and flashings and affect the long-term performance of the roof system. Ultra-violet radiation from sunlight also chemically degrades the bituminous and polymeric roof membranes, lowering their physical and mechanical properties. A roof membrane on a conventional roof system is exposed to high temperature, diurnal temperature fluctuations and ultra-violet radiation while in service.

The membrane of the reference roof reached a daily maximum temperature of over 40°C, 43% of the days in 2005, while the membrane under the green roofs was maintained between 0°C and 40°C, 99% of the days in 2005 (Figure 21). In addition, the green roofs reduced the median temperature fluctuation from 48°C to less than 5°C. The growing medium and vegetation also block the ultra-violet radiation from reaching the roof membrane and thereby degrading it. Although it is too early to evaluate the durability of the roof membrane, our data so far showed that green roofs could help to preserve the membrane and increase its durability by reducing the degrading effects of heat aging, thermal stresses and ultra-violet radiation. In addition, the green roof also protects the roof membrane from puncture damage such as rooftop traffic, and therefore helps to extend the membrane's service life.

5 Conclusions

1. The research findings highlight that it is not solely the depth of the growing medium that affects the stormwater mitigation performance of green roofs, but rather the combination of the growing medium and plant species. Both of the green roof systems reduced runoff volume and peak flow and delayed the start of runoff and peak runoff. On an annual basis, there were no appreciable differences between the stormwater mitigation performances of the two green roof systems monitored in Phase 1.
2. The stormwater retention efficiency of the two green roof systems was higher in the dry season (86–94%) than in the wet season (13–18%).This was due to saturation of the growing medium.
3. The average runoff retention of the two green roof systems was 28% in 2005. For the rain pattern in Vancouver, sedums in 75 mm of growing medium were as effective in retaining runoff as grasses in 150 mm of growing medium.
4. The first year observation at the GRRF showed that extensive green roofs with 75–150 mm of growing medium reduced heat flow through the roof, thus lowering the energy demand of the building.
5. The green roofs were found to be more effective in reducing heat flow through the roof in the spring/summer than in the fall/winter due to the different thermal mechanisms involved. The green roofs at the GRRF reduced the heat flow through the roof by 83–85% in the spring/summer and 40–44% in the fall/winter in 2005, with an overall annual reduction of 66%.
6. Despite the fact that GR-2 had a deeper growing medium (150 mm) than GR-1 (75 mm) and different vegetation, their thermal performance was very similar throughout 2005 except for the hottest months, July and August, where GR-2 outperformed GR-1 in reducing heat flow through the roof. The first year of observation suggests that the thermal effectiveness of GR-1 was sufficient for the mild climates of Vancouver.
7. The green roofs reduced the daily maximum membrane temperature in the summer from over 50°C to less than 30°C. They also reduced the median temperature fluctuation from 48°C to less than 5°C. These reductions lower the heat aging rate and the thermal stresses associated with temperature fluctuations, thereby contributing positively to membrane durability.

6 Recommendations and Future Work

The research findings and observations in Phase 1 have provided direction for Phase 2 of the research program at the GRRF. GR-1 and GR-2 differed in growing medium depth and vegetation. To further examine the relative contribution of growing medium depth and vegetation, it would be necessary to isolate the parameters. Phase 2 has two green roof systems installed. As in Phase 1, one green roof system has 75 mm of growing medium and the other has 150 mm of growing medium. However, in Phase 2 both green roof systems have been planted with the same sedum species. Data collection and monitoring will continue in order to further evaluate the stormwater runoff and thermal performance characteristics of the green roof systems. The evaluation of sound transmission characteristic of green roofs will be initiated and there will be an increased focus on plant establishment, maintenance and health.

7 References

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8 Photos, Figures and Tables

Photo 1 BCIT Green Roof Research Facility rooftop,
Great Northern Way Campus, Vancouver, British Columbia.

Photo 2 Margeurite House, Multi-family Development, Vancouver, British Columbia.

Photo 3 BCIT Green Roof Research Facility site,
Great Northern Way Campus, Vancouver, British Columbia.

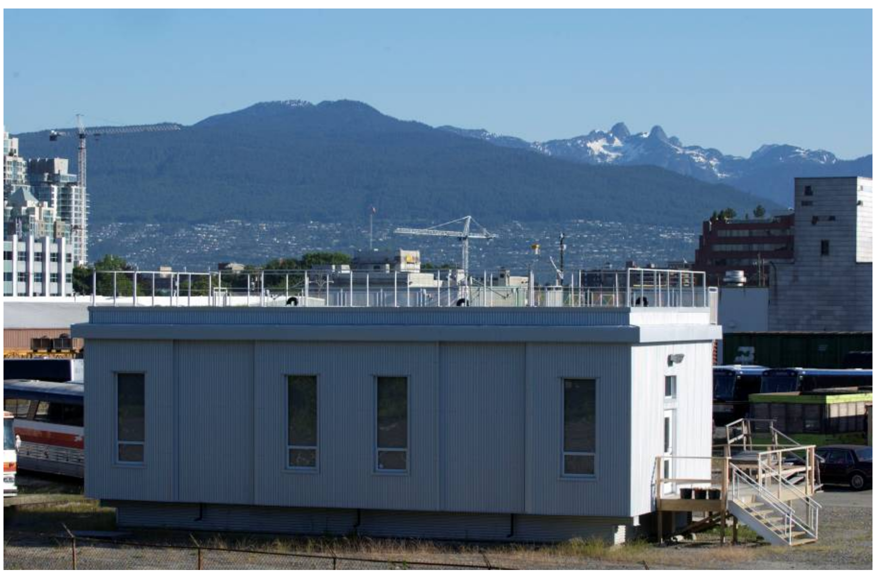


Photo 4 BCIT Green Roof Research Facility,
Great Northern Way Campus, Vancouver, British Columbia.

Photo 5 BCIT Green Roof Research Facility. Prefabricated framing panel installation; built by students; installed by local contractors.

Photo 6 BCIT Green Roof Research Facility, Roofing Contractors Association of British Columbia and regional manufacturers install roof materials.

Photo 7 BCIT Green Roof Research Facility, completion of planting, summer 2003.

Photo 8 BCIT Green Roof Research Facility, Sedum acre on rooftop, spring 2004.

Photo 9 BCIT Green Roof Research Facility, Floriferum on rooftop, spring 2004.

Photo 10 BCIT Green Roof Research Facility, Bouteloua gracilis and Carex glauca on rooftop, spring 2004.

Photo 11 BCIT Green Roof Research Facility, Festuca scoparia on rooftop, spring 2004.

Photo 12 BCIT Green Roof Research Facility instrumentation test point; thermocouples installed in the growing medium.

Photo 13 BCIT Green Roof Research Facility. Researchers interface temperature and heat flow sensors in the roof system.

Photo 14 BCIT Green Roof Research Facility weather pole, including solar radiation sensor, relative humidity and temperature transmitter, and thermocouples.

Photo 15 BCIT Green Roof Research Facility tipping bucket flow measurement system. Designed and built by the BCIT Technology Centre.

Photo 16 BCIT Green Roof Research Facility rooftop weather station.

Photo 17 BCIT Green Roof Research Facility data acquisition system.

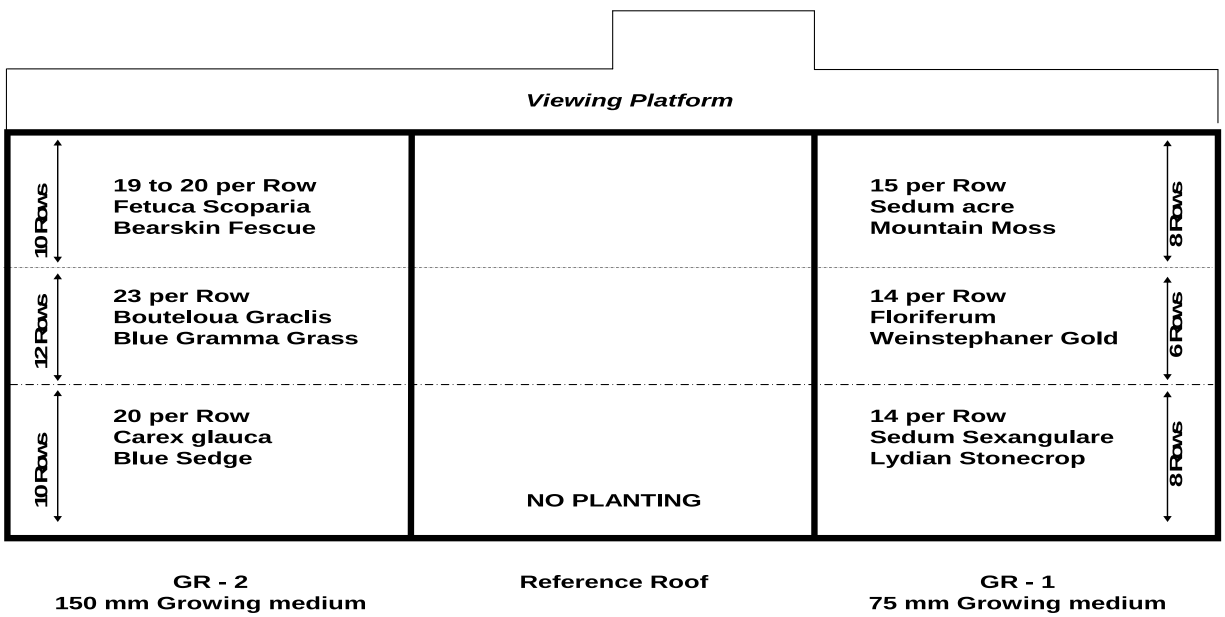


Figure 1 Planting plan at BCIT's Green Roof Research Facility in 2005.

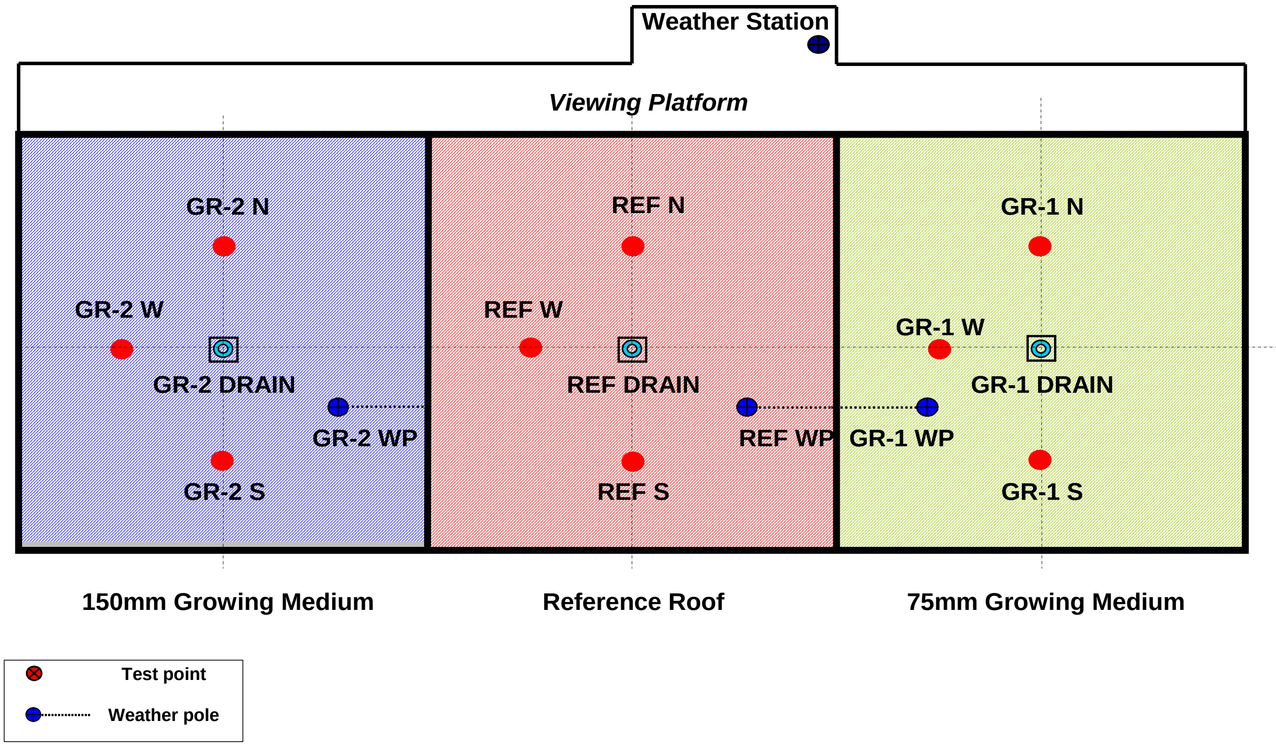


Figure 2 Schematic roof plan of the BCIT Green Roof Research Facility showing instrumentation locations and locations of weather poles and weather station.

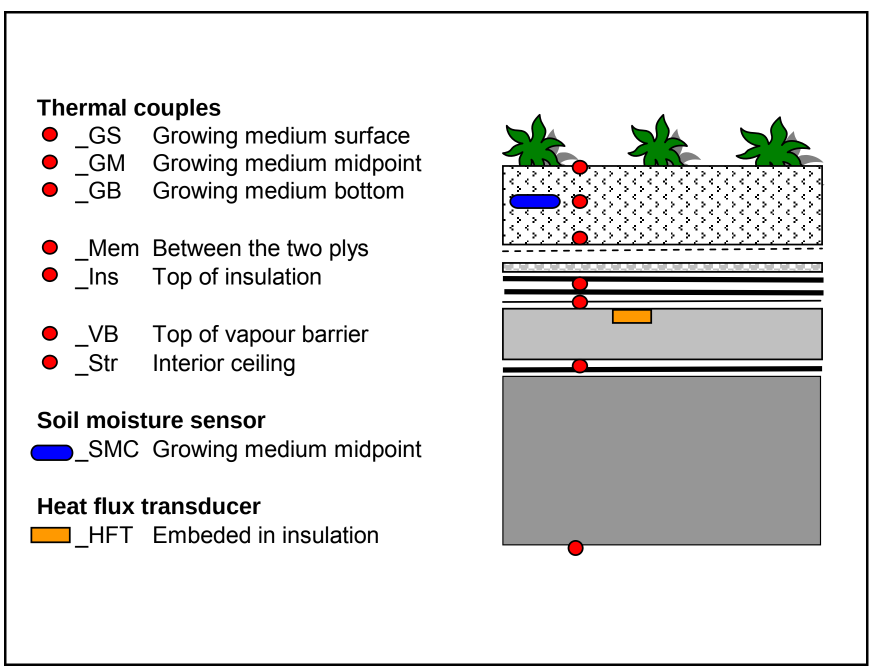


Figure 3 Cross-section of the BCIT Green Roof Research Facility's roofing system showing principal components and location of various sensors.

2005 Climate Summary						
	Air Temperature range					Rainfall
Month	Daily Max[1] (°C)	Daily Min[2] (°C)	Daily Average[3] (°C)	Average[4] (°C)	Average Range[5] (°C)	Total (mm)
Jan	7.9	3.0	5.4	5.3	5.0	323.1
Feb	10.0	2.1	6.0	5.8	7.9	41.7
Mar	12.9	6.4	9.7	9.4	6.5	154.2
Apr	15.3	7.7	11.5	11.4	7.5	112.8
May	19.6	12.0	15.8	15.5	7.5	80.5
Jun	20.0	13.3	16.7	16.3	6.7	62.0
Jul	23.9	15.4	19.7	19.3	8.4	57.2
Aug	24.7	16.0	20.4	20.2	8.7	19.6
Sept	19.5	11.8	15.7	15.3	7.7	83.6
Oct	15.2	9.8	12.5	11.8	5.3	211.3
Nov	8.5	4.5	6.5	6.4	4.0	181.1
Dec	8.3	3.5	5.9	5.6	4.8	181.1
12 Month Totals						1508.0
1	Mean of the maximum recorded temperatures from 00:00 PST to 24:00 PST each day					
2	Mean of the minimum recorded temperatures from 00:00 PST to 24:00 PST each day					
3	Mean is the average of the daily maximum and minimum					
4	Average temperature recorded over the month					
5	The average difference between the daily maximum and minimum					

Table 1 2005 Climate Summary recorded at the BCIT Green Roof Research Facility weather station.

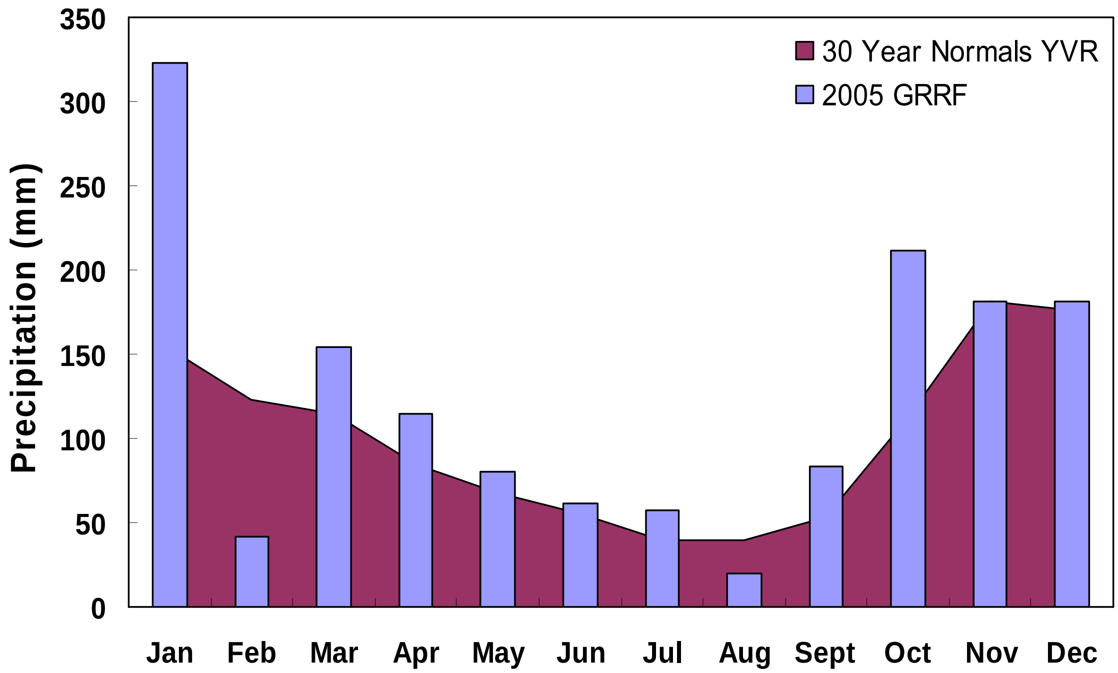


Figure 4 Precipitation at the BCIT Green Roof Research Facility compared to 30 year normals at the Vancouver International Airport.

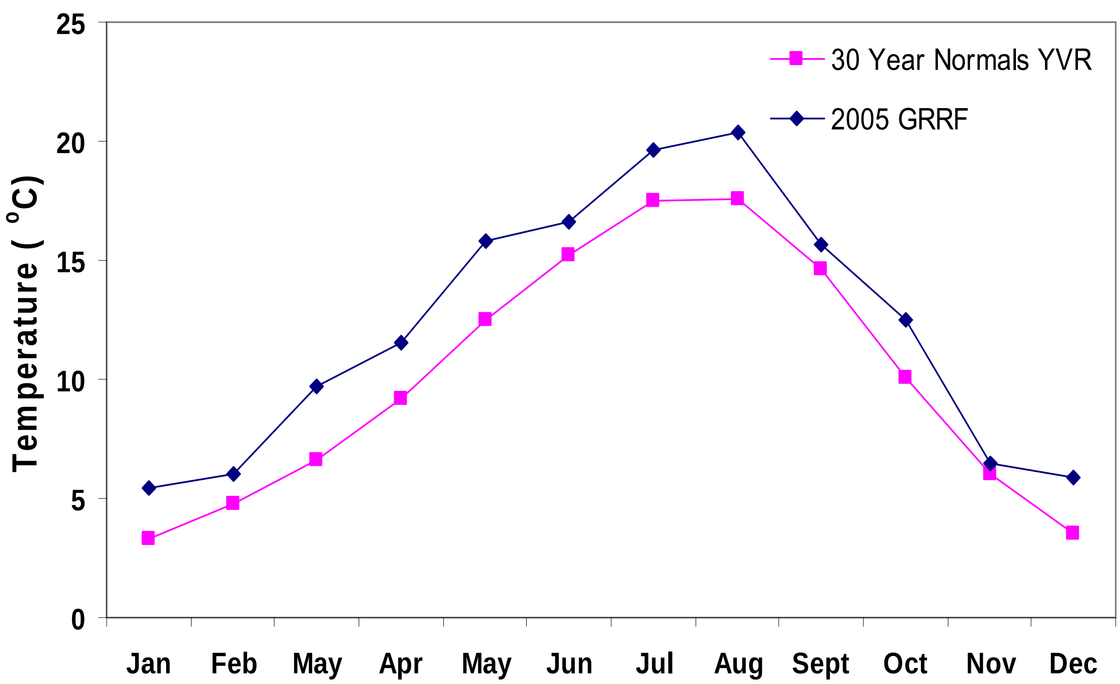


Figure 5 Ambient air temperature at the BCIT Green Roof Research Facility compared to 30 year normals at the Vancouver International Airport.

Season Split Totals

	Period	Rainfall (mm) WS	Runoff (mm) REF	GR-1	GR-2
WET SEASON	January	323.1	301.4	297.0	314.2
	February	41.7	40.9	34.6	31.6
	March	154.2	142.0	108.8	118.2
	April 1 to 17	111.3	105.5	84.7	90.1
Sub total		630.2	589.8	525.0	554.2
DRY SEASON	April 18 to 30	1.5	1.5	0.0	0.0
	May	80.5	73.4	16.1	5.2
	June	62.0	60.1	2.4	1.8
	July	57.2	53.6	13.8	7.4
	August	19.6	18.6	0.2	0.2
	September 1 to 28	21.6	20.1	0.8	0.8
Sub total		242.3	227.2	33.3	15.4
WET SEASON	September 29 to 30	62.0	61.5	47.0	40.8
	October	211.3	199.0	166.3	181.4
	November	181.1	166.0	151.7	163.4
	December	181.1	165.1	150.7	162.1
Sub total		635.5	591.6	515.7	547.7
Totals					
WET SEASON	**(mm)**	**1265.7**	**1181.4**	**1040.7**	**1101.9**
Runoff Reduction			**7%**	**18%**	**13%**
DRY SEASON	**(mm)**	**242.3**	**227.2**	**33.3**	**15.4**
Runoff Reduction			**6%**	**86%**	**94%**
Annual	**(mm)**	**1508.0**	**1408.6**	**1074.0**	**1117.2**
Runoff Reduction			**7%**	**29%**	**26%**

Table 2 Rainfall (including snow melt) throughout 2005 with dry season and wet season comparison.

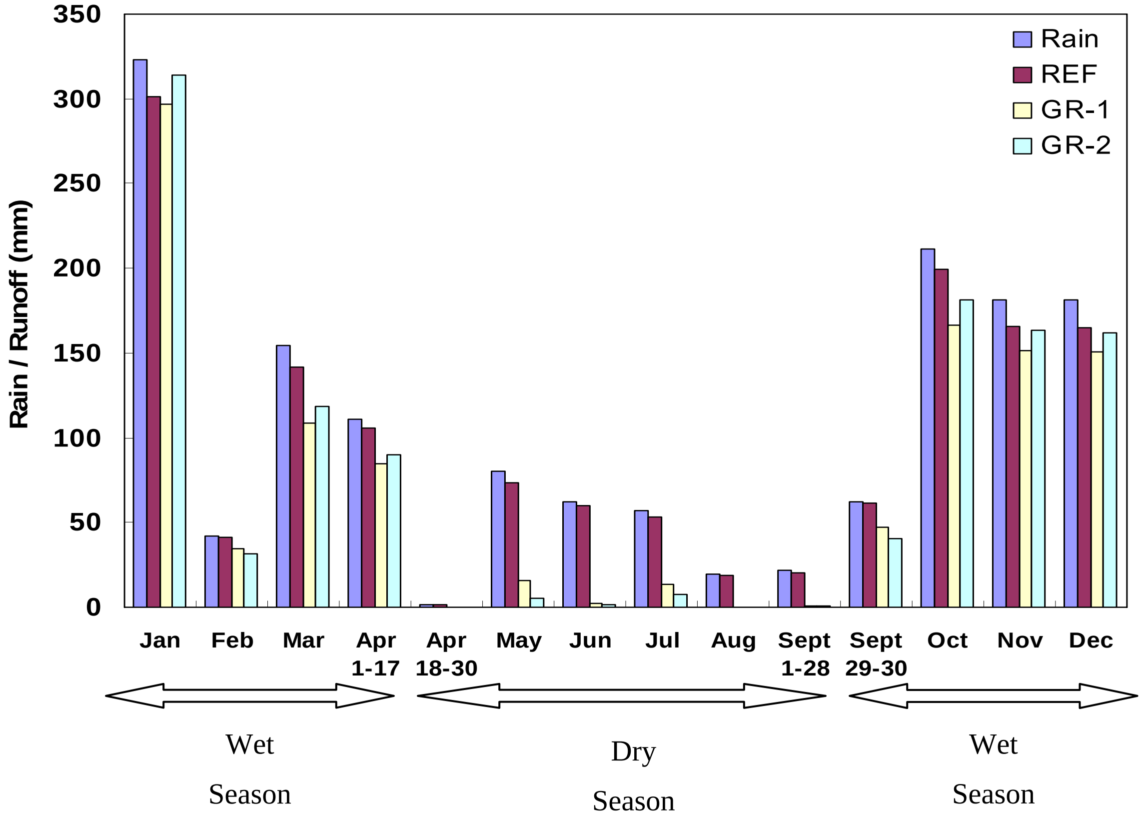


Figure 6 Rainfall and runoff comparison in the 2005 dry season and wet season.

May 21–22, 2005

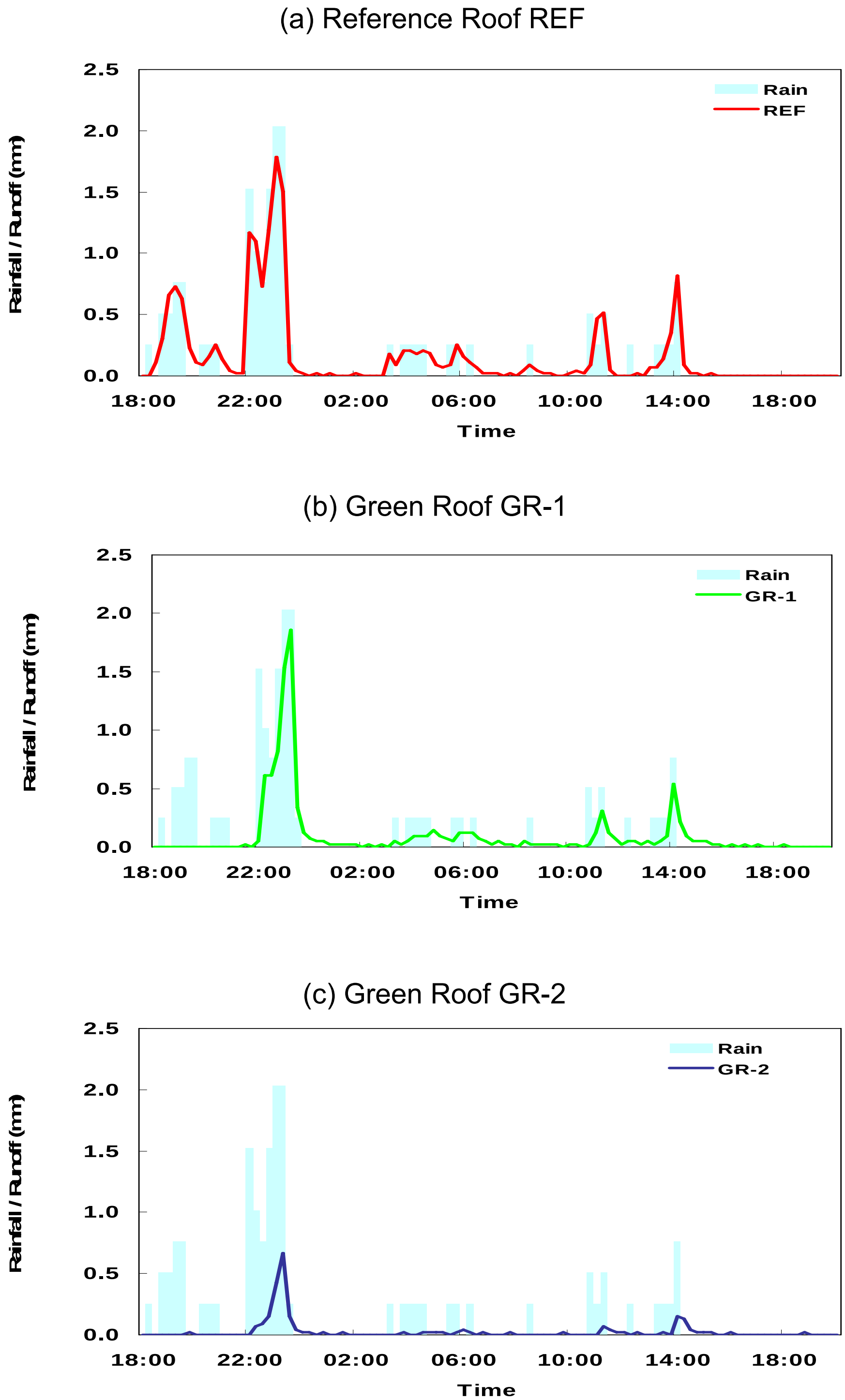
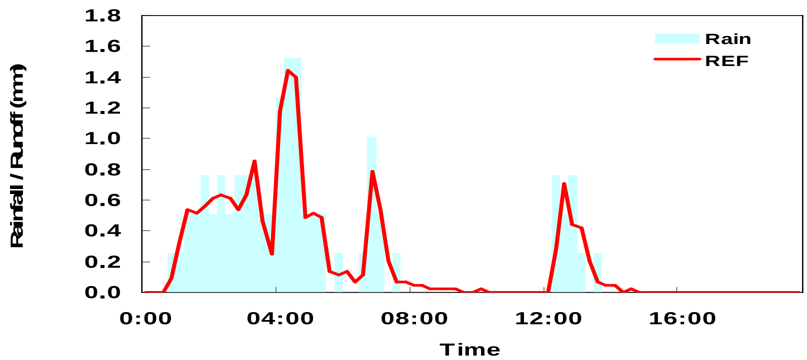


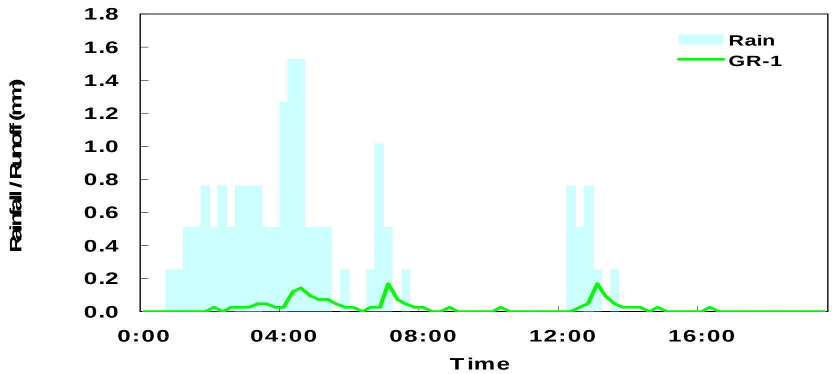
Figure 7 Reference roof and green roof runoff comparison during the May 21–22 rain event. 18 mm of rainfall were recorded over 19 hours and 45 minutes.

June 17, 2005

(a) Reference Roof REF



(b) Green Roof GR-1



(c) Green Roof GR-2

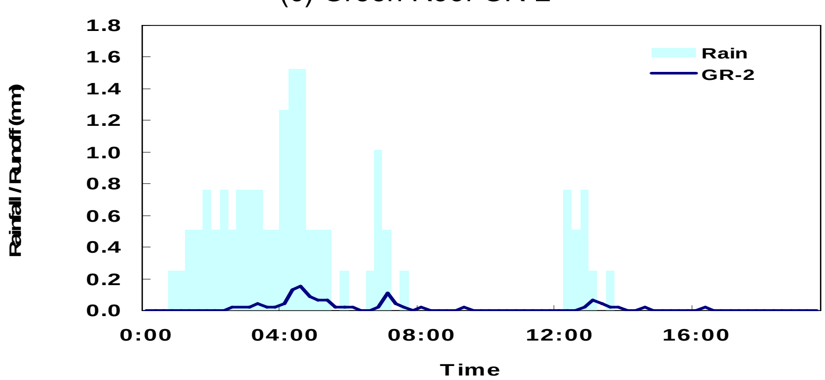
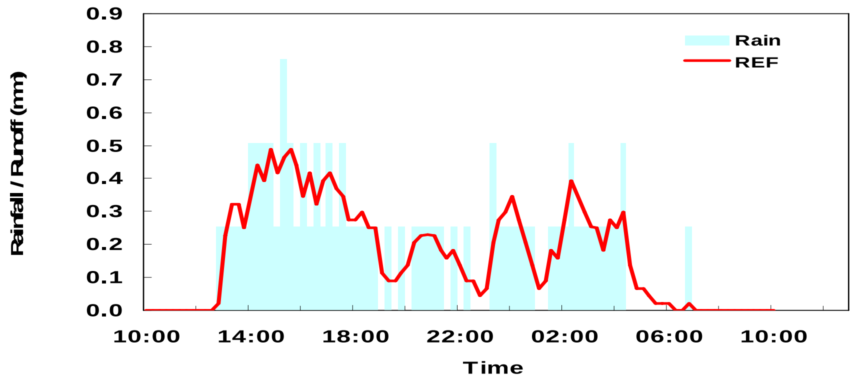


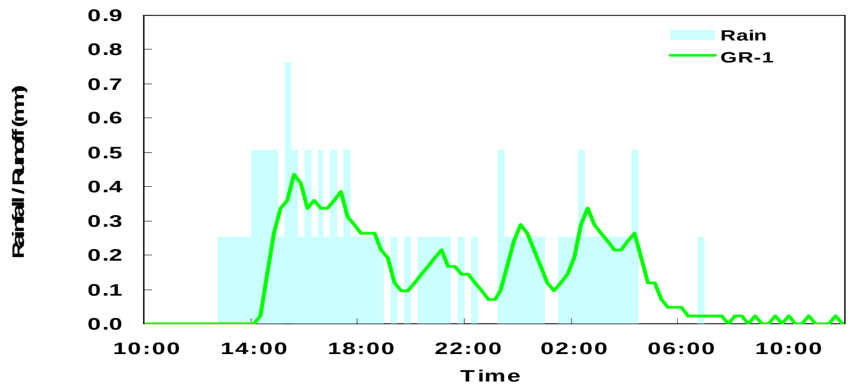
Figure 8 Reference roof and green roof runoff comparison during the June 17th rain event. 18 mm of rainfall were recorded over 12 hours and 45 minutes.

April 5–6, 2005

(a) Reference Roof REF



(b) Green Roof GR-1



(c) Green Roof GR-2

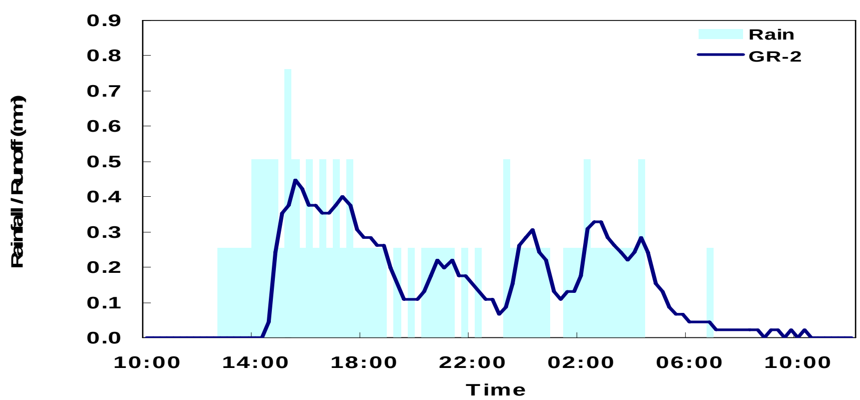


Figure 9 Reference roof and green roof runoff comparison during the April 5–6 rain event. 17.3 mm of rainfall were recorded over 18 hours.

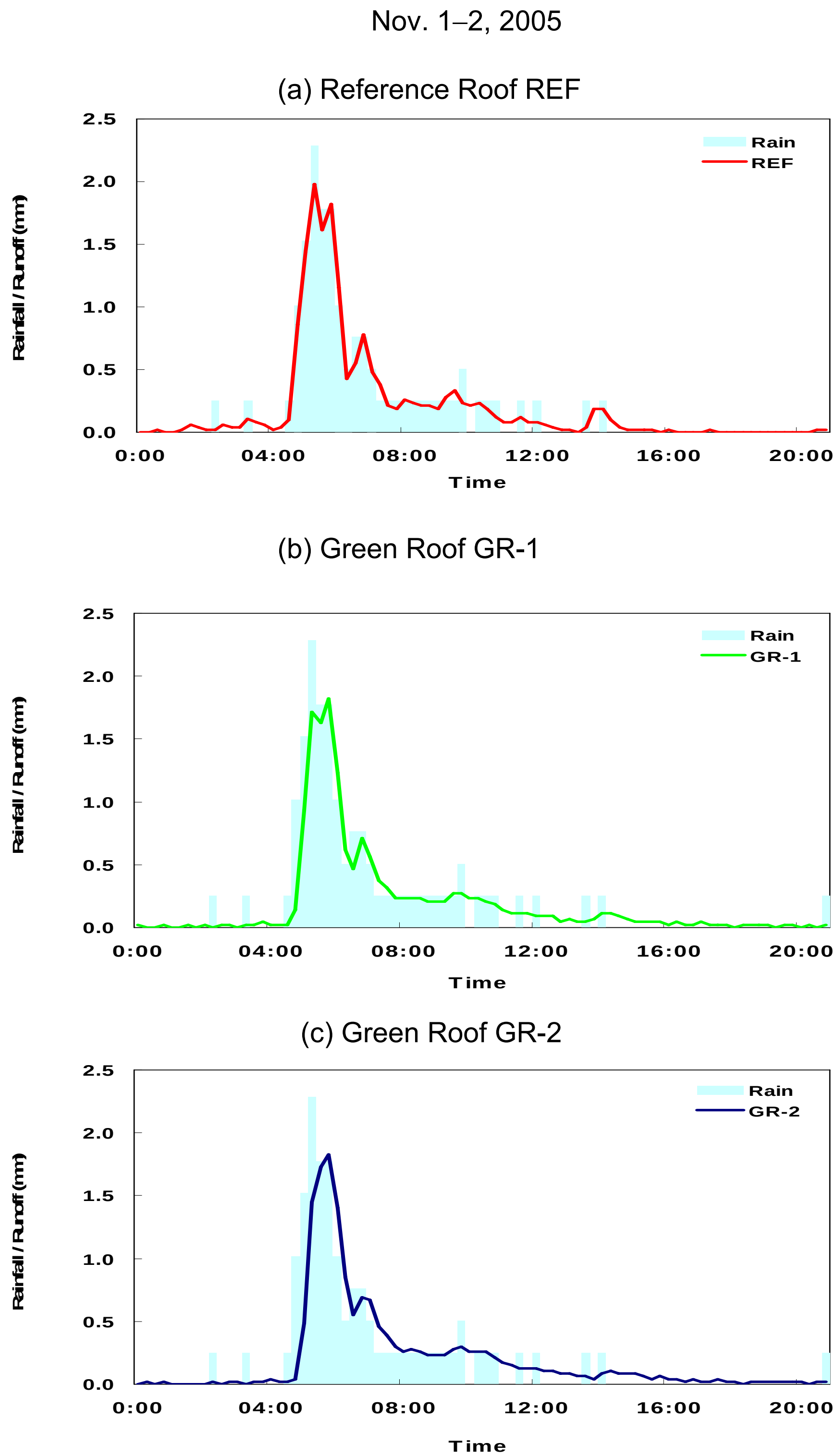


Figure 10 Reference roof and green roof runoff comparison during the November 1–2 rain event. 17.5 mm of rainfall were recorded over 11 hours and 45 minutes.

Storm Events															
Date	**Duration**	**Rainfall**		**% Retained**			**Delay in Start [1.] (minutes)**		**Delay in Peak [2.] (minutes)**		**Reduction in Peak Flow (wrt Rain)**		**Reduction in Peak Flow (wrt REF)**	
		mm	**Peak Flow (mm/15 min)**	**REF**	**GR-1**	**GR-2**	**GR-1**	**GR-2**	**GR-1**	**GR-2**	**GR-1**	**GR-2**	**GR-1**	**GR-2**
MAY 14	3:15	3.8	0.5	0%	100%	99%	na	2:30	na	2:30	100%	96%	100%	96%
MAY 15	14:15	15.8	4.3	*	96%	95%	0:15	0:15	6:00	6:00	96%	95%	93%	92%
MAY 16	4:15	3.6	0.5	3%	99%	99%	4:15	4:15	4:15	4:15	96%	96%	95%	95%
MAY 18	6:45	7.6	1.0	0%	97%	98%	1:45	1:00	1:15	0:30	98%	98%	98%	98%
MAY 19-20	5:30	6.4	1.8	8%	71%	95%	4:30	4:30	0:30	0:30	67%	94%	63%	93%
MAY 21-22	19:45	18.0	2.0	10%	48%	87%	3:15	1:30	0:15	0:15	8%	68%	-4%	63%
MAY 22-23	2:30	2.8	0.8	0%	37%	80%	0:15	1:00	2:30	4:45	72%	99%	49%	98%
MAY 31	9:15	9.9	1.3	5%	98%	98%	1:45	1:30	0:15	0:00	96%	98%	93%	97%
JUN 1	3:45	4.1	1.3	8%	98%	98%	1:30	1:00	0:00	0:00	98%	98%	97%	97%
JUN 5	5:00	8.6	1.8	7%	98%	97%	1:30	1:00	0:00	0:00	99%	99%	98%	98%
JUN 7-8	19:45	6.9	0.5	4%	99%	99%	6:30	6:00	1:30	1:00	95%	96%	95%	96%
JUN 11	10:15	5.1	1.0	5%	100%	99%	na	1:30	na	0:15	100%	98%	100%	98%
JUN 17	12:45	18.0	1.5	7%	90%	93%	1:15	1:45	0:15	0:15	91%	90%	90%	89%

[1.] Time delay between the first tip of the tipping bucket rain gauge and the first measured runoff

[2.] Time delay between the maximum recorded rainfall in a 15 minute interval and the maximum recorded runoff in a 15 minute interval

* Data not available

Table 3 Rain events during the dry season in the 7 days prior to Event D1, May 21–22 through to Event 2, June 17th detailed in Figures 7 and 8.

Rain Events															
Date	Duration	Rainfall		% Retained			Delay in Start [1.] (minutes)		Delay in Peak [2.] (minutes)		Reduction in Peak Flow (wrt Rain)		Reduction in Peak Flow (wrt REF)		
	(hh:mm)	mm	Peak Flow (mm/15 min)	REF	GR-1	GR-2	GR-1	GR-2	GR-1	GR-2	GR-1	GR-2	GR-1	GR-2	
MAR 28-29	12:45	14.7	1.0	8%	25%	14%	0:45	1:15	0:15	0:15	0%	4%	9%	13%	
MAR 31-1	24:45	20.1	0.8	2%	47%	17%	6:45	7:15	0:15	0:15	17%	10%	7%	0%	
APR 1	1:00	2.8	1.3	0%	38%	40%	0:45	1:00	0:00	0:15	58%	56%	43%	41%	
APR 2	4:15	5.6	0.8	3%	16%	12%	0:45	0:15	1:45	1:45	40%	35%	1%	-6%	
APR 3	8:00	17.5	1.0	8%	17%	10%	0:30	1:00	1:45	1:45	15%	15%	9%	9%	
APR 5-6	18:00	17.3	0.8	5%	22%	17%	1:30	1:45	0:15	0:15	43%	41%	35%	39%	

[1.] Time delay between the first tip of the tipping bucket rain gauge and the first measured runoff

[2.] Time delay between the maximum recorded rainfall in a 15 minute interval and the maximum recorded runoff in a 15 minute interval

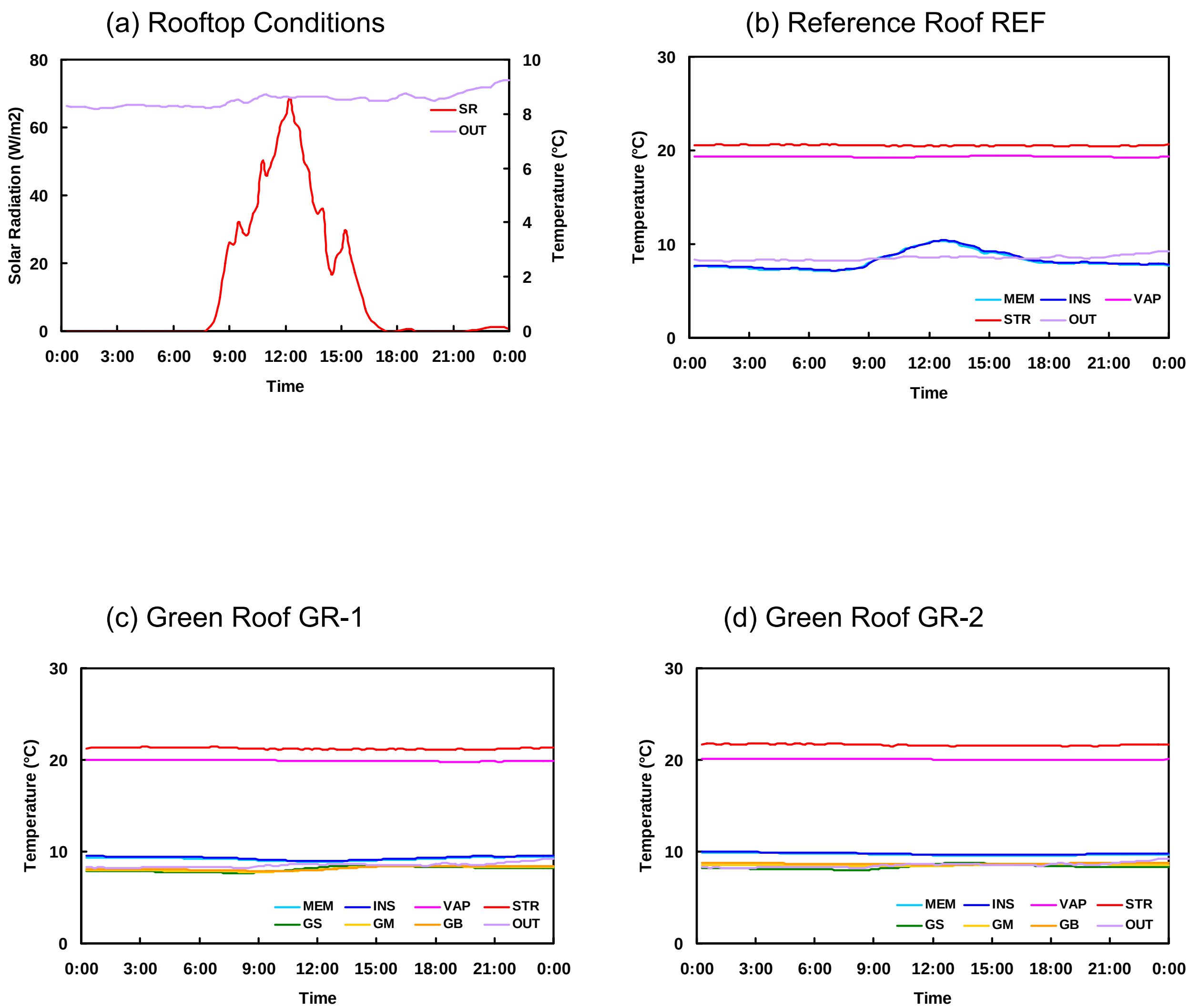
Table 4 Rain events during the wet season in the 7 days prior to the April 5–6 event detailed in Figure 9.

Rain Events														
Date	Duration	Rainfall		% Retained			Delay in Start [1.] (minutes)		Delay in Peak [2.] (minutes)		% Reduction in Peak Flow (wrt Rain)		% Reduction in Peak Flow (wrt REF)	
	(hh:mm)	mm	Peak Flow (mm/15 min)	REF	GR-1	GR-2	GR-1	GR-2	GR-1	GR-2	GR-1	GR-2	GR-1	GR-2
OCT 25-26	3:00	5.1	1.5	6%	65%	54%	2:30	1:30	0:00	0:15	68%	59%	70%	62%
OCT 28	3:00	8.6	1.8	8%	31%	27%	1:15	1:30	0:30	0:30	-6%	5%	18%	-5%
OCT 28-29	12:45	6.1	0.5	7%	19%	16%	0:00	0:15	11:15	11:15	23%	36%	35%	46%
OCT 30-31	23:00	39.4	1.8	8%	16%	10%	0:45	0:45	0:15	0:15	108%	111%	14%	13%
NOV 1	11:45	17.5	2.3	6%	11%	6%	0:15	0:00	0:30	0:30	20%	20%	8%	8%

[1.] Time delay between the first tip of the tipping bucket rain gauge and the first measured runoff

[2.] Time delay between the maximum recorded rainfall in a 15 minute interval and the maximum recorded runoff in a 15 minute interval

Table 5 Rain events during the wet season in the 7 days prior to the November 1–2 event detailed in Figure 10.



Legend:

– MEM	Between the two plys of roof membrane	– OUT	Outdoor environment
– INS	Top of thermal insulation	– GS	Growing medium surface
– VAP	Top of vapour barrier	– GM	Growing medium mid-point
– STR	Interior ceiling	– GB	Growing medium bottom

Figure 11 Weather conditions and temperature profile of the three roof sections at the BCIT Green Roof Research Facility on a typical winter day (January 30, 2005). Refer to Figure 3 for instrumentation location symbols.

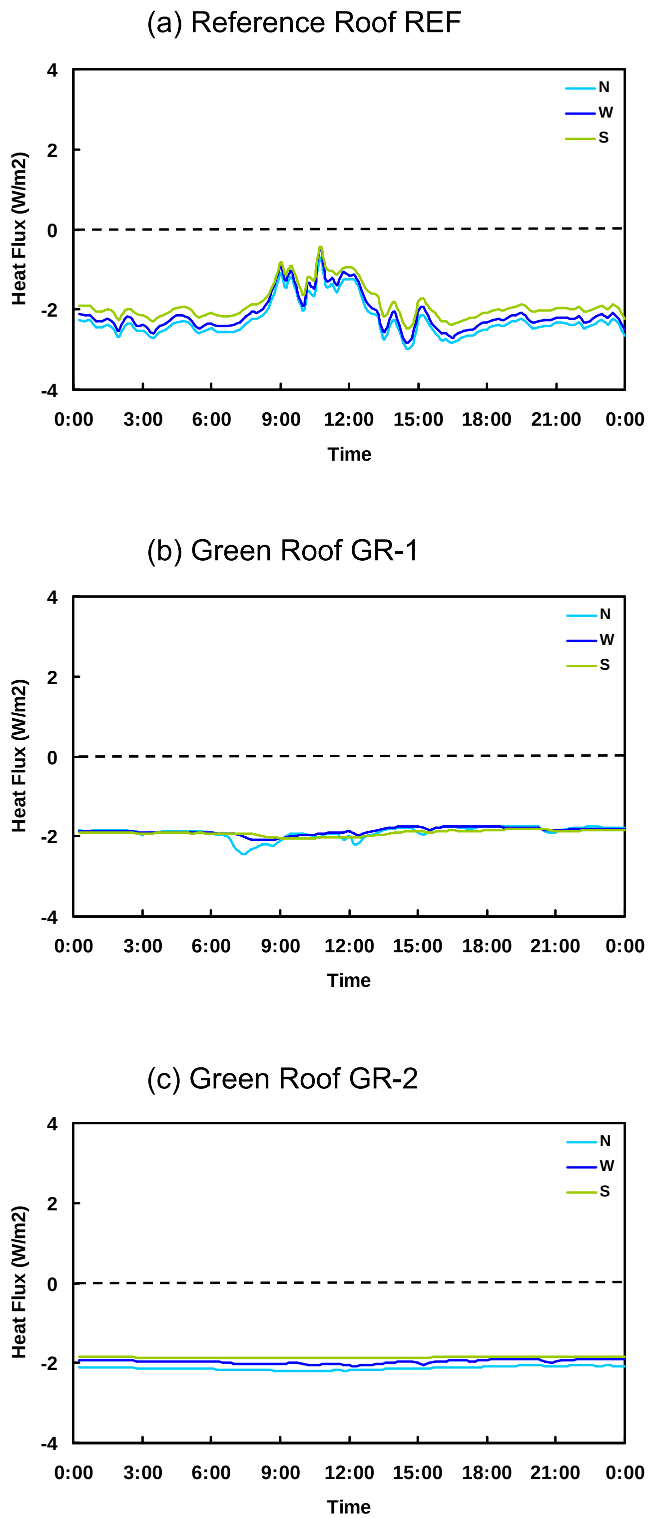
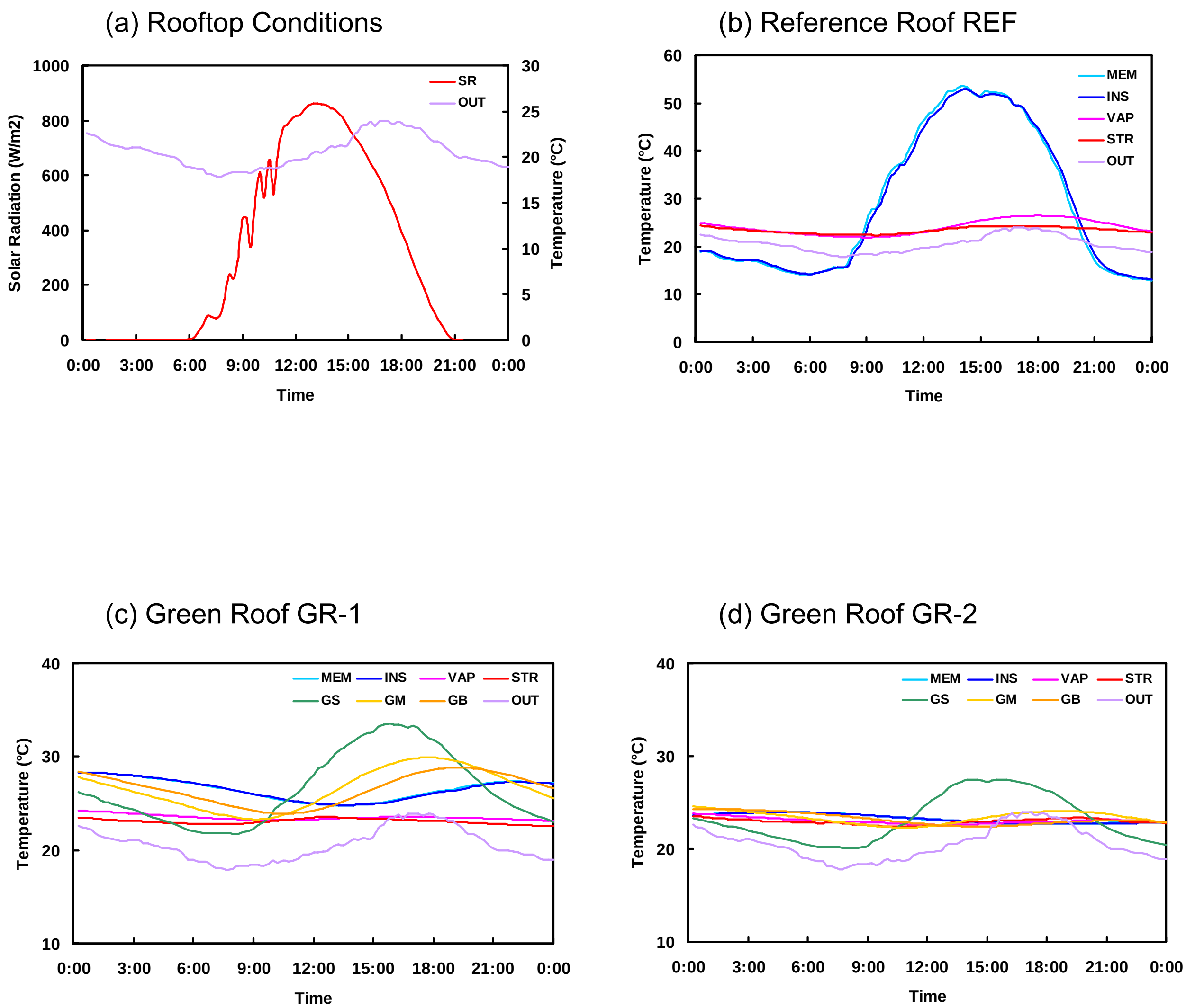


Figure 12 Heat flow through the three roof sections at the BCIT Green Roof Research Facility on a typical winter day (January 30, 2005). Each section contains three sensors – North (N), West (W) and South (S).



Legend:

– MEM	Between the two plys of roof membrane	– OUT	Outdoor environment
– INS	Top of thermal insulation	– GS	Growing medium surface
– VAP	Top of vapour barrier	– GM	Growing medium mid-point
– STR	Interior ceiling	– GB	Growing medium bottom

Figure 13 Weather conditions and temperature profile of the three roof sections at the BCIT Green Roof Research Facility on a typical summer day (August 1, 2005). Note that the temperature scale of the green roof plots was expanded for clarity. Refer to Figure 3 for instrumentation location symbols.

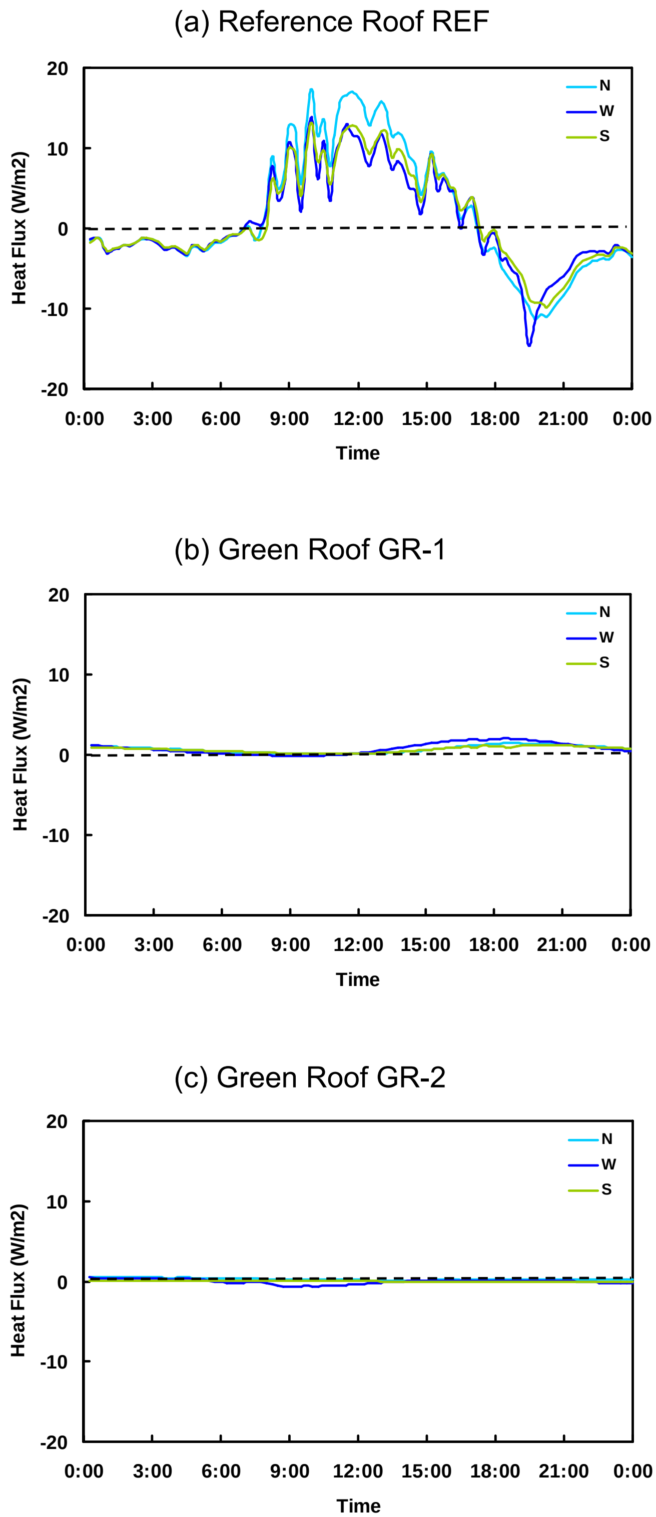


Figure 14 Heat flow through the three roof sections at the BCIT Green Roof Research Facility on a typical summer day (August 1, 2005). Each section contains three sensors – North (N), West (W) and South (S).

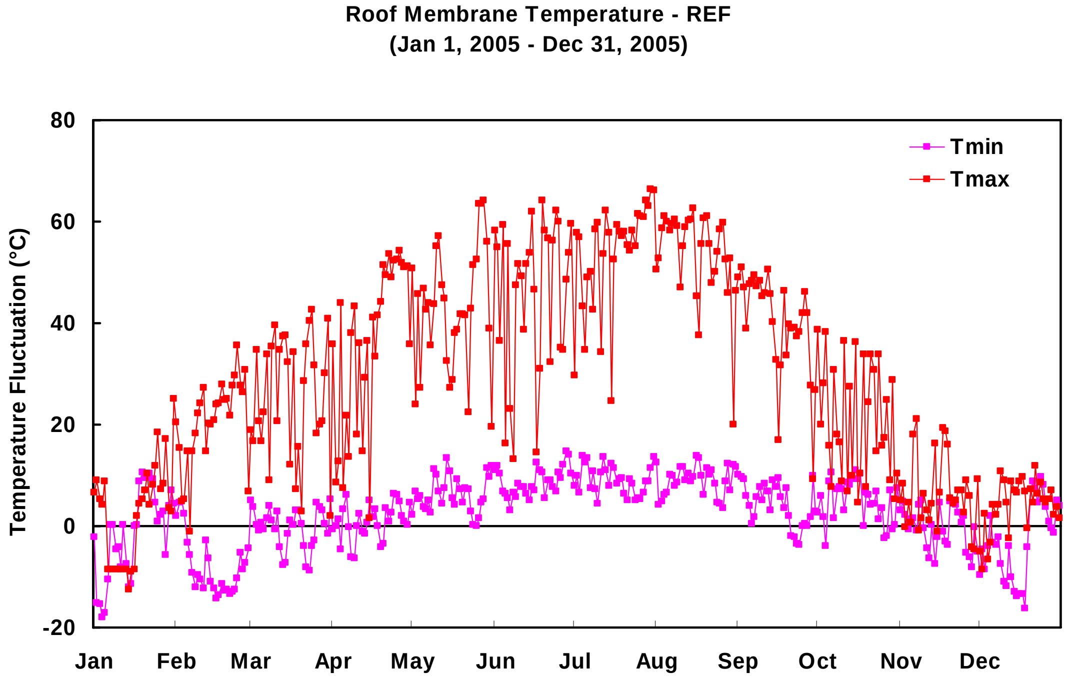


Figure 15 The daily maximum and minimum membrane temperatures measured on the Reference Roof.

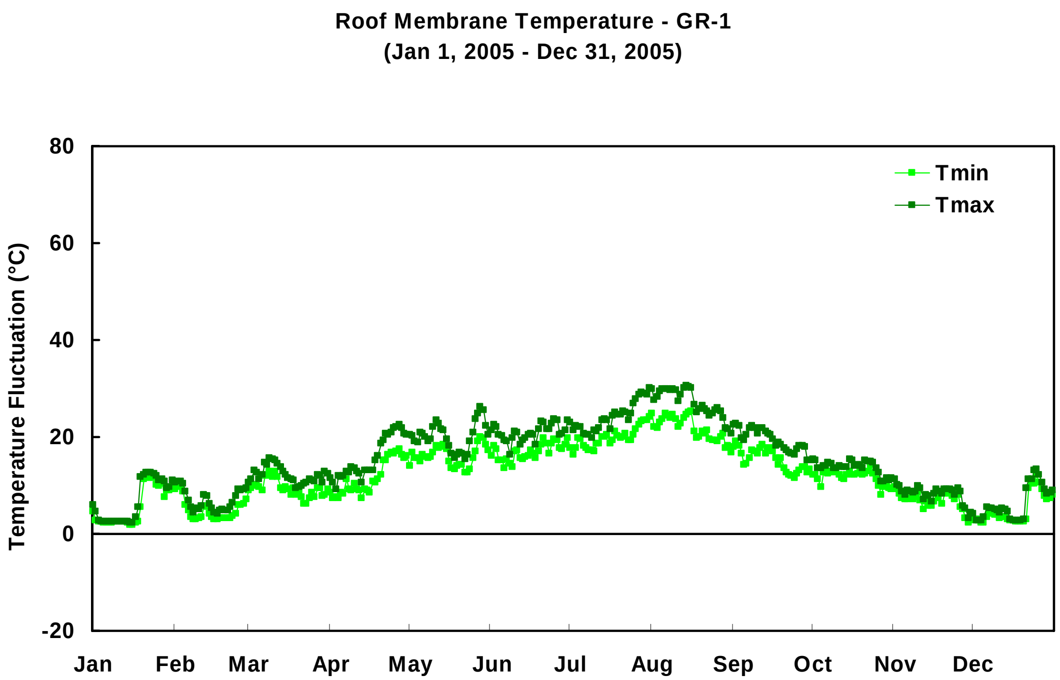


Figure 16 The daily maximum and minimum membrane temperatures measured on Green Roof 1.

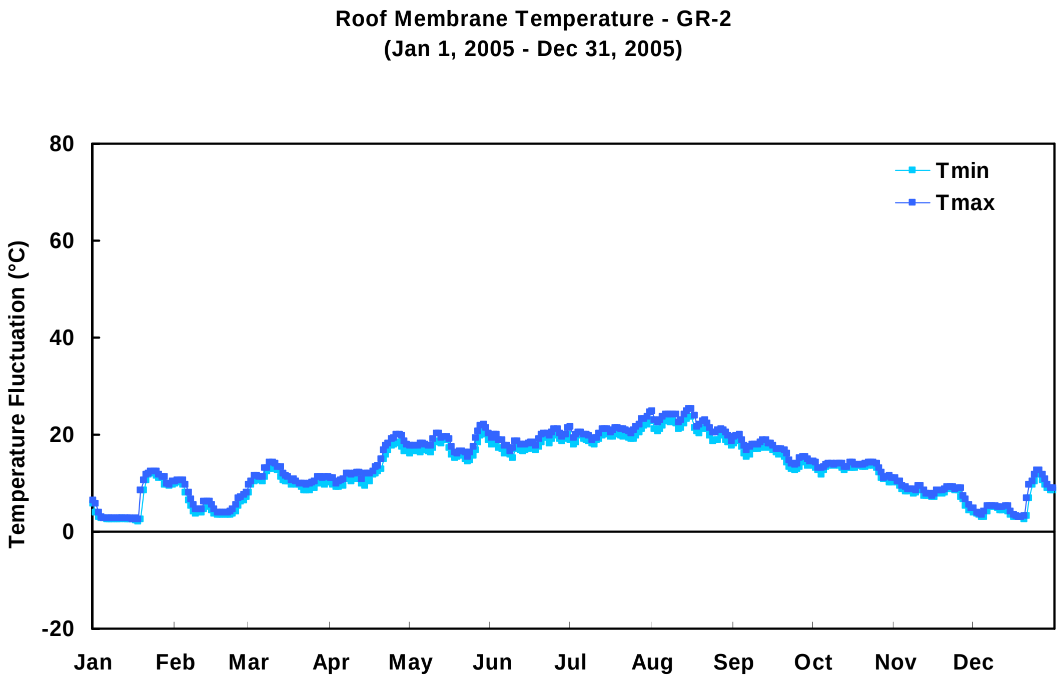


Figure 17 The daily maximum and minimum membrane temperatures measured on Green Roof 2.

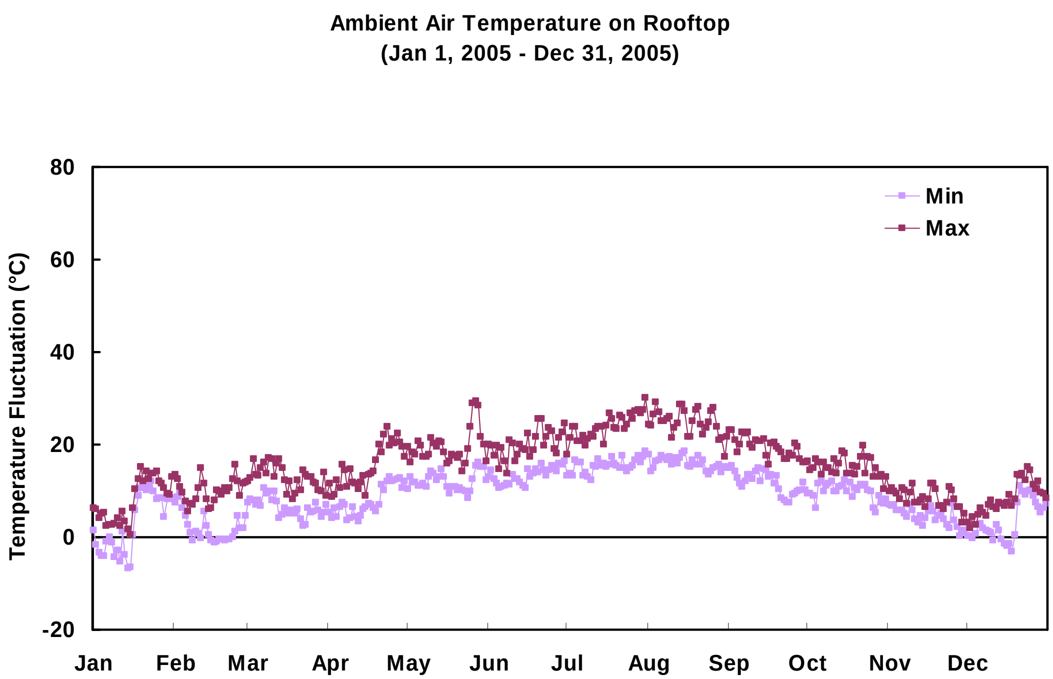


Figure 18 The daily maximum and minimum ambient temperatures measured at the weather station at the BCIT Green Roof Research Facility.

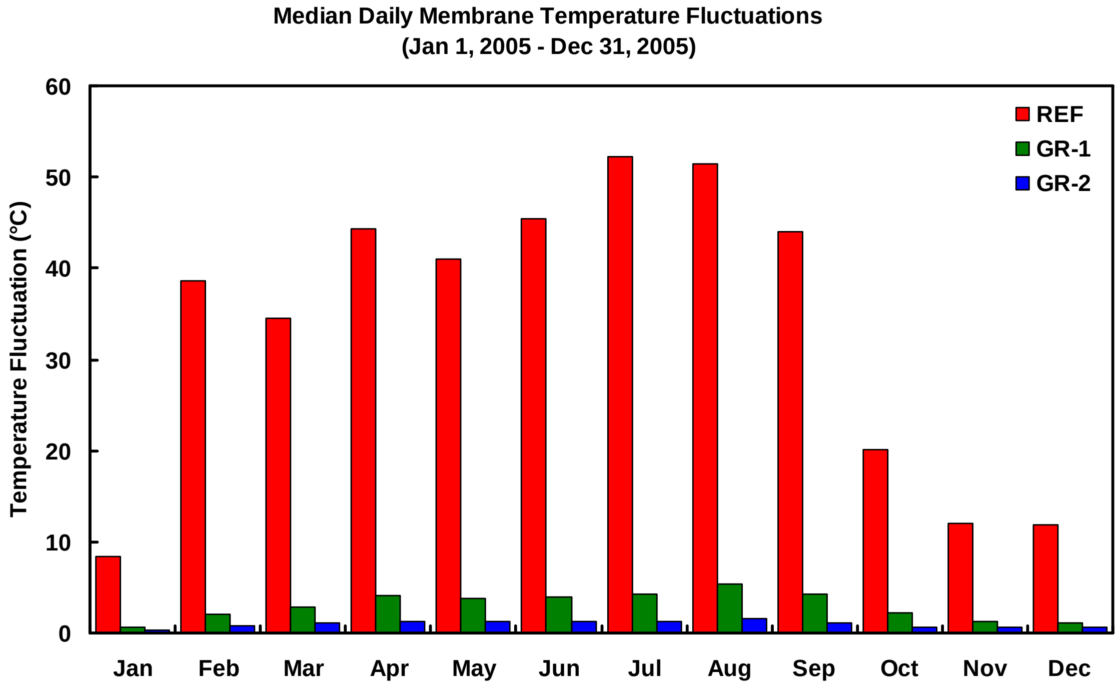


Figure 19 Median daily temperature fluctuation experienced by the roof membrane on the three roof sections at the BCIT Green Roof Research Facility (by month).

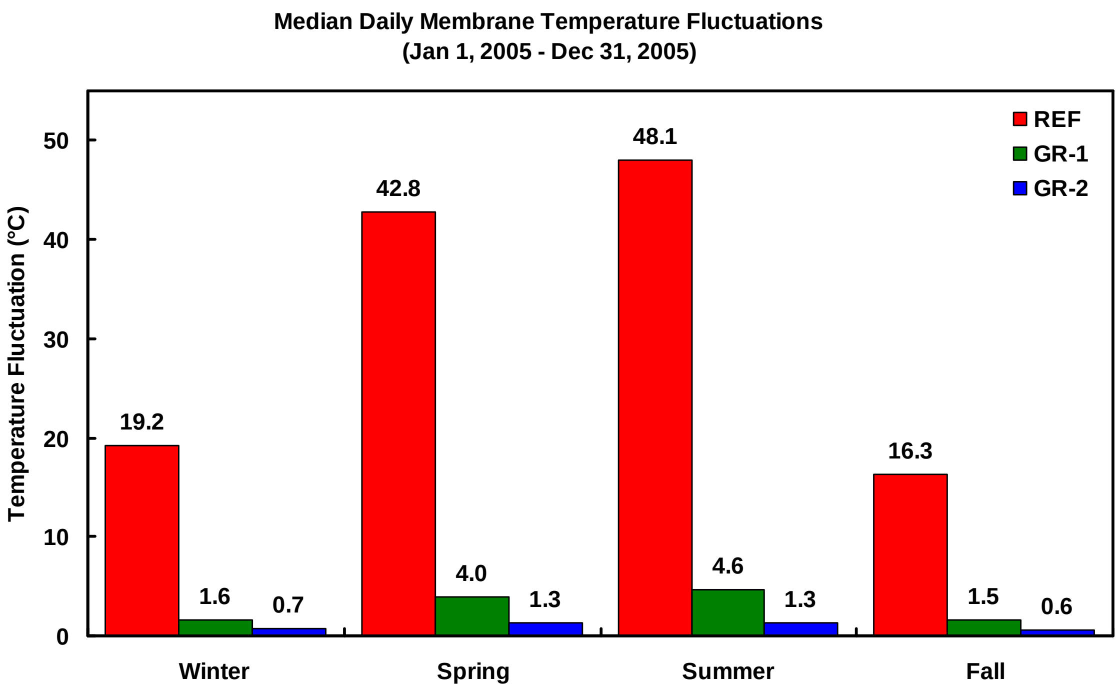


Figure 20 Median daily temperature fluctuation experienced by the roof membrane on the three roof sections at the BCIT Green Roof Research Facility (by season).

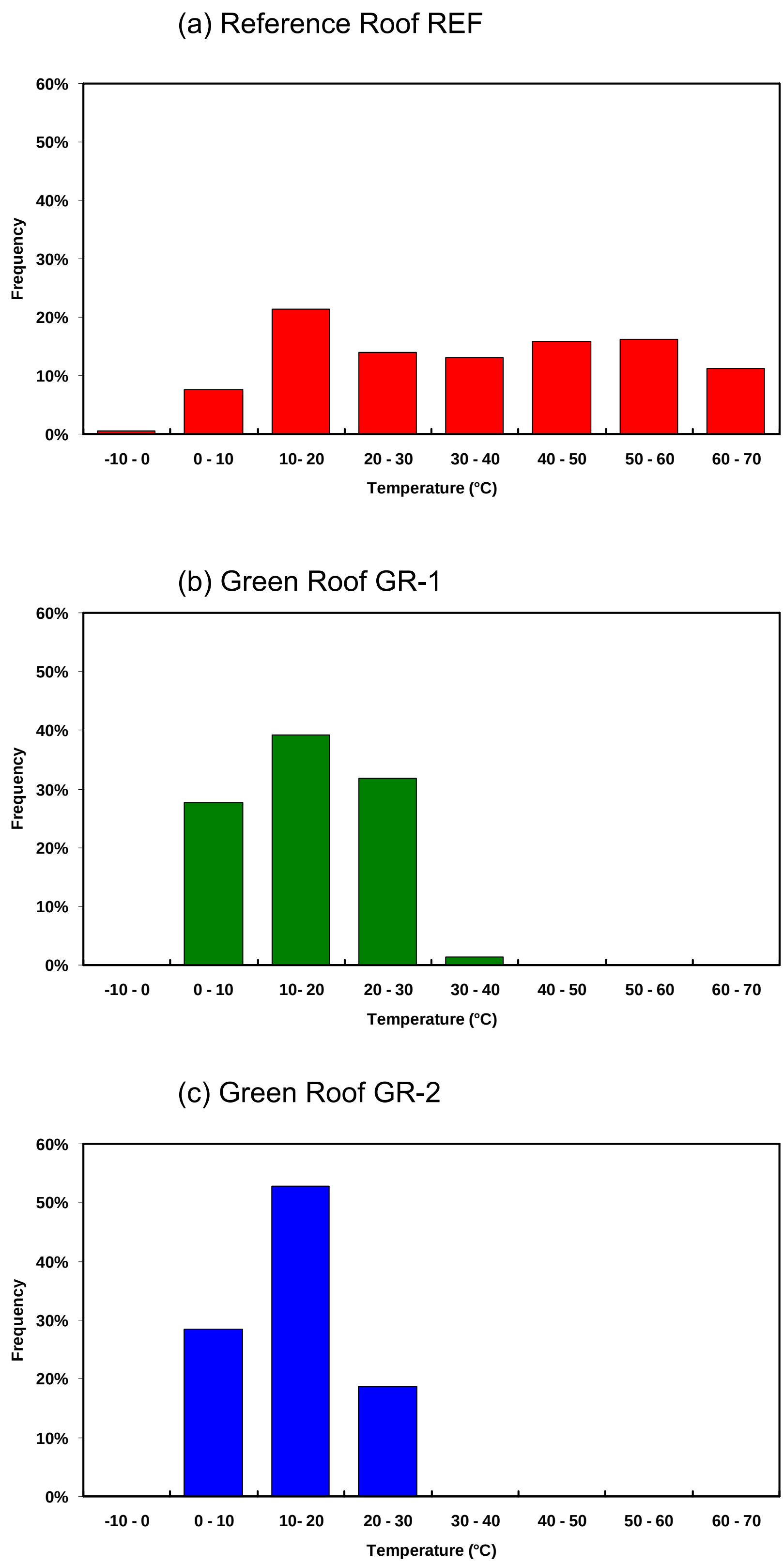


Figure 21 The maximum membrane temperature distribution of the three roof sections at the BCIT Green Roof Research Facility in 2005.

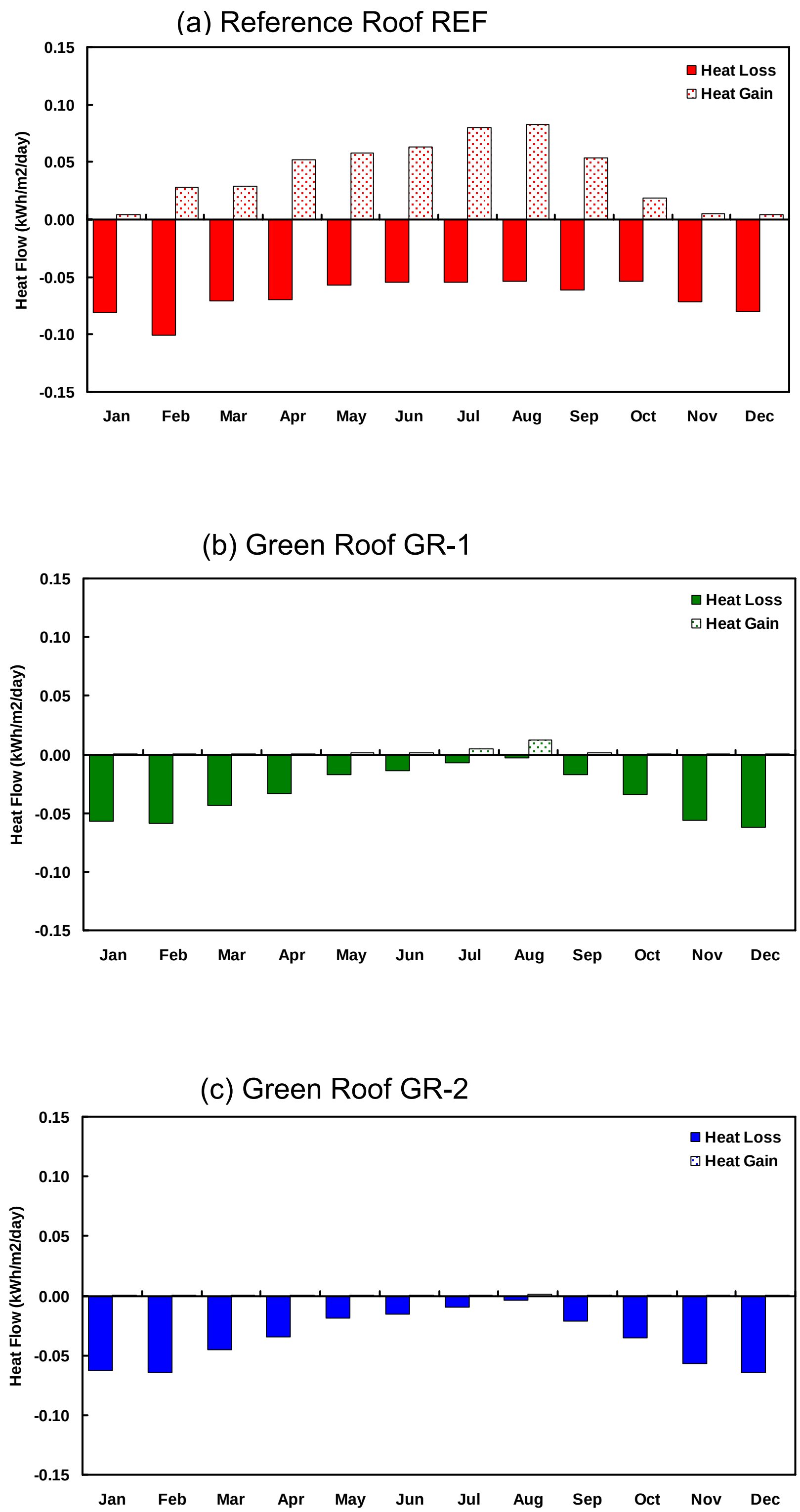


Figure 22 Average daily heat flow through the three roof sections at the BCIT Green Roof Research Facility (by month) in 2005.

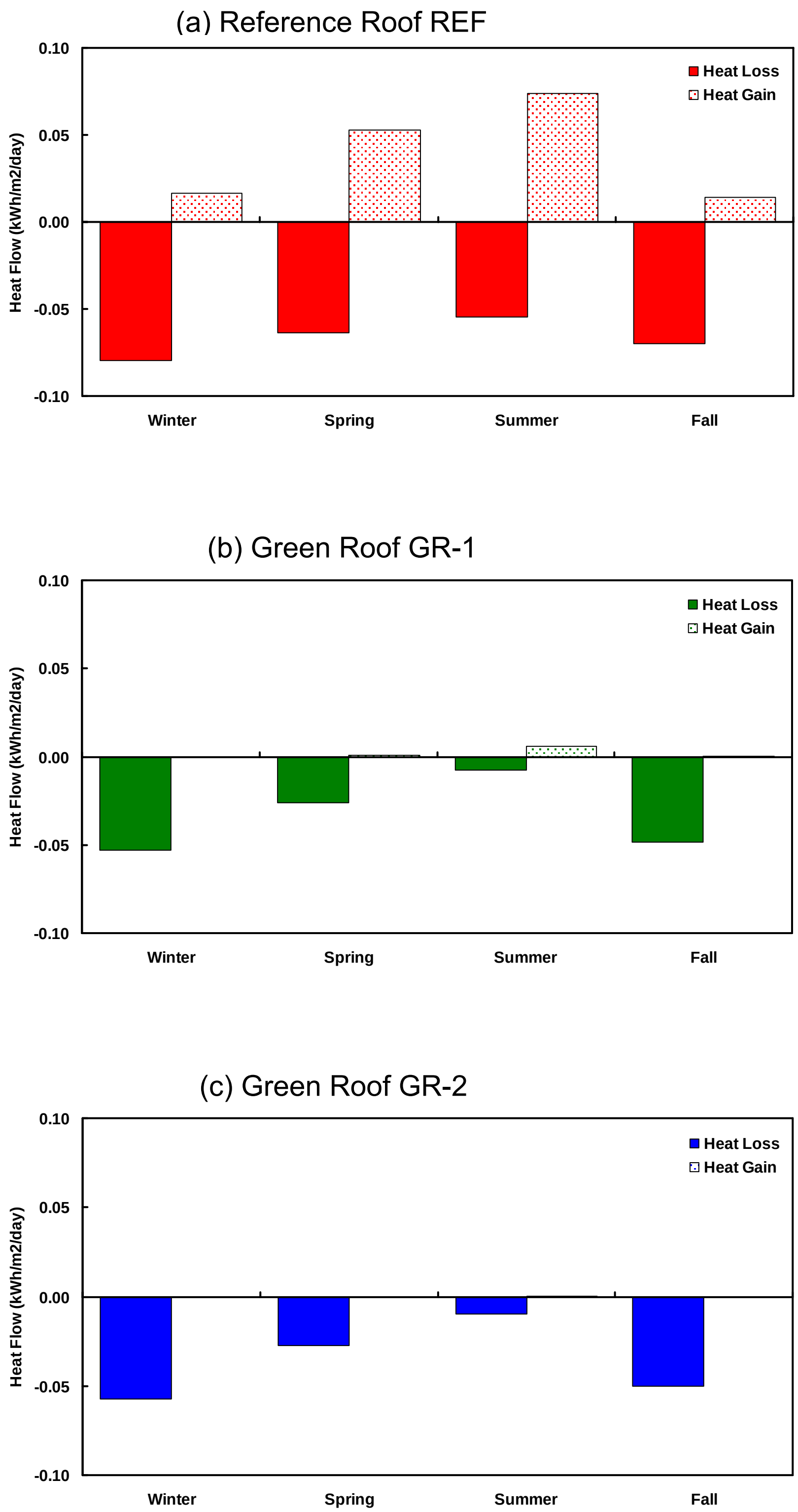
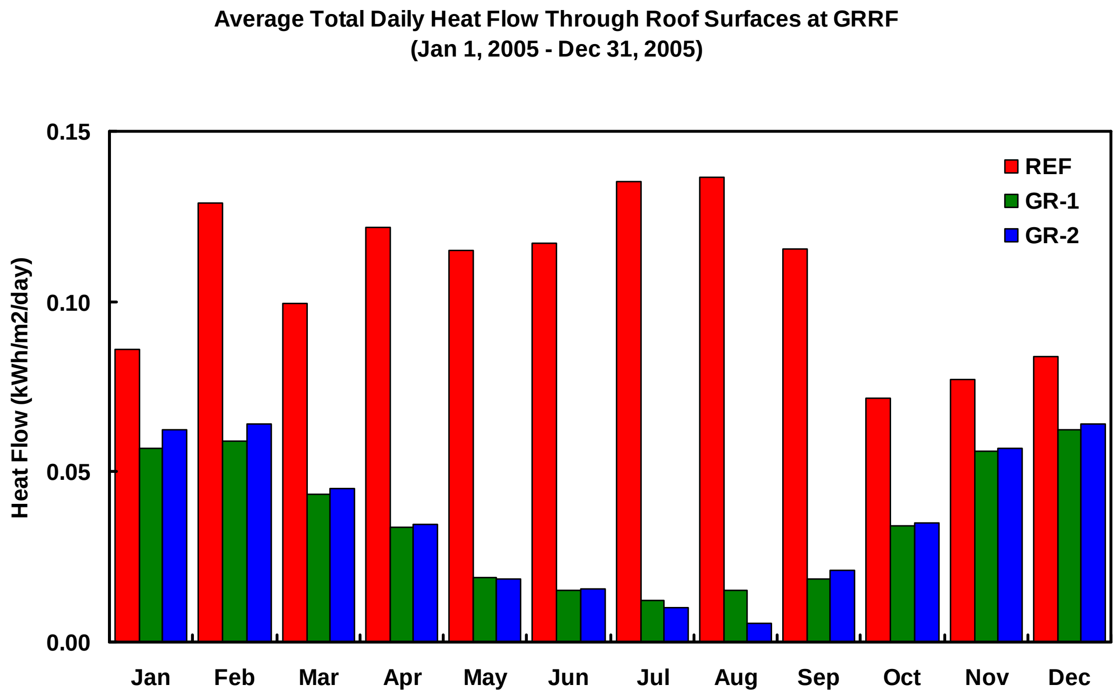


Figure 23 Average daily heat flow through the three roof sections at the BCIT Green Roof Research Facility (by season) in 2005.

(a) by month



(b) by season

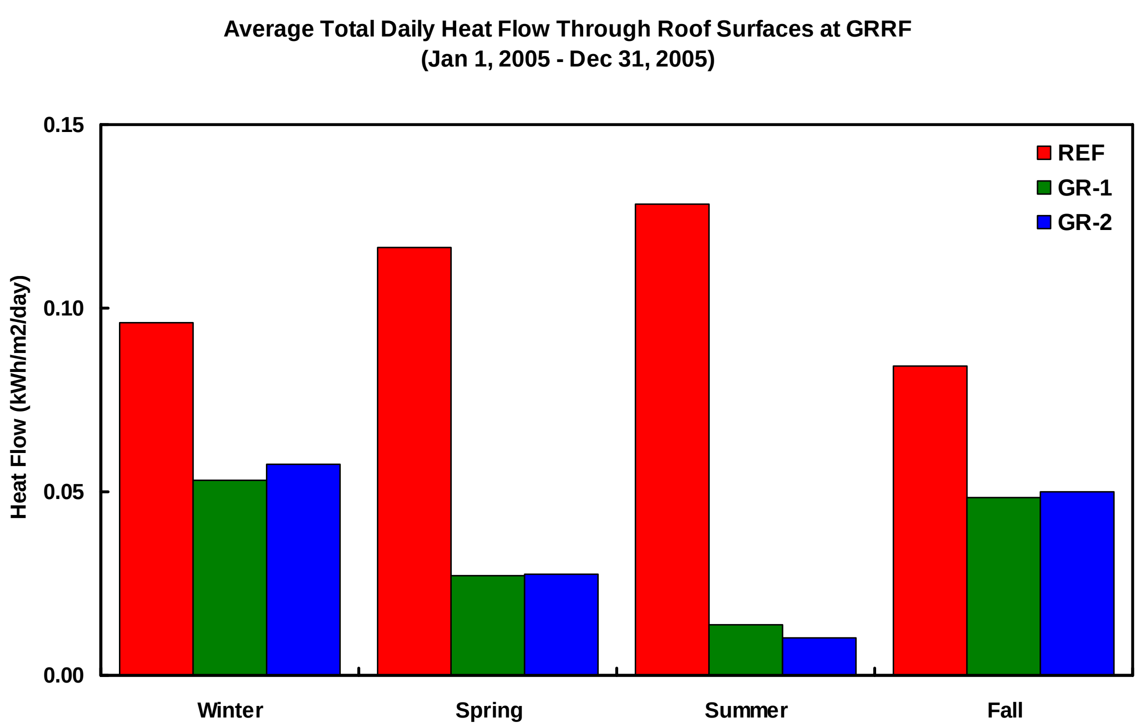


Figure 24 Average daily energy demand due to heat flow through the roof for the three roof sections in 2005 (a) by month and (b) by season.

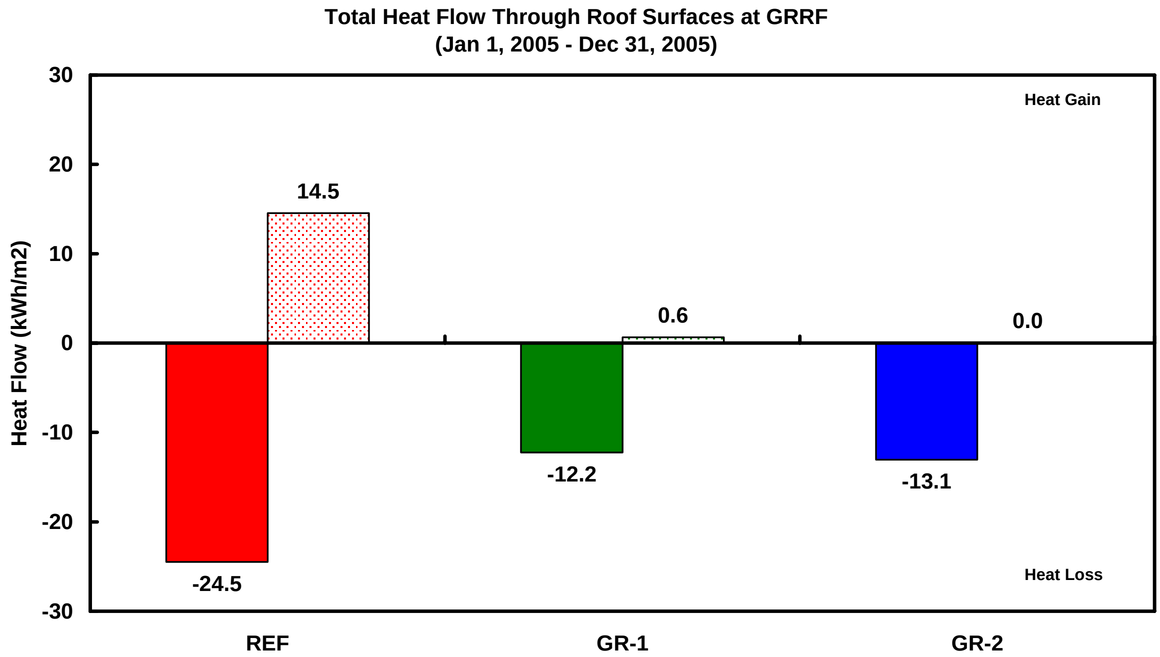


Figure 25 Annual energy demand due to heat flow through the roof for the three roof sections at the BCIT Green Roof Research Facility in 2005.

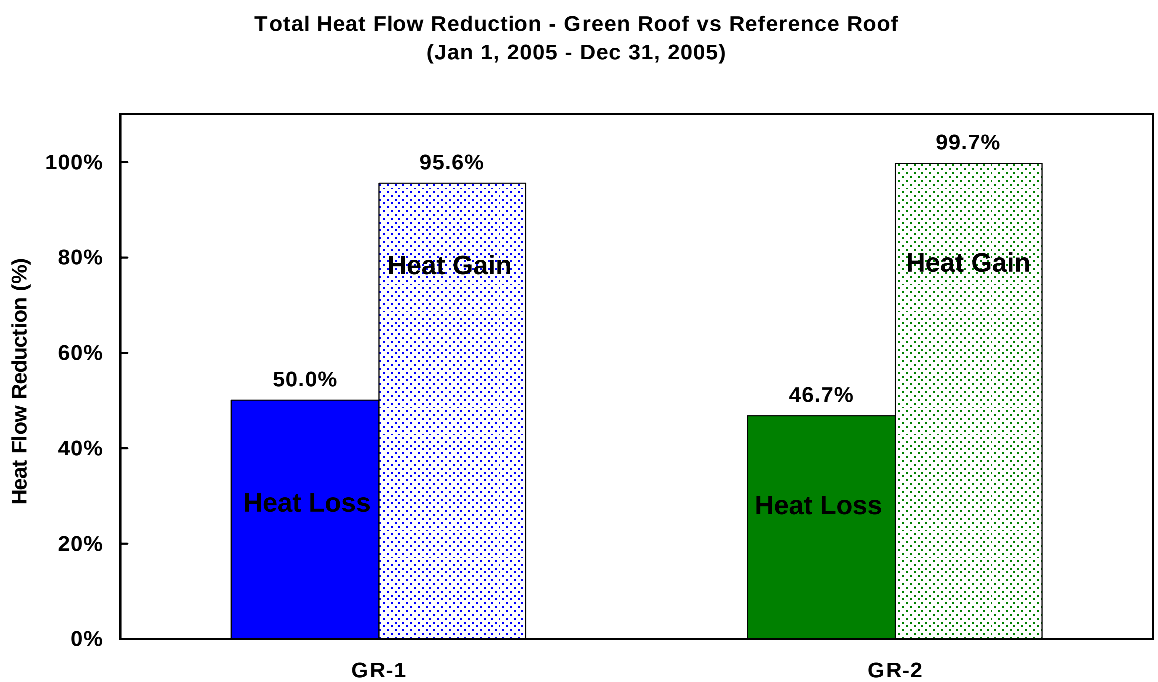


Figure 26 Heat flow reduction by the green roofs (GR-1 and GR-2) compared to the Reference Roof at the BCIT Green Roof Research Facility in 2005.

End of Report