INFLUENCE OF CONSTRUCTION AND DEMOLITION (C&D) WASTE ON GREEN ROOF PERFORMANCE

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

The College of Graduate Studies

(Civil Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Okanagan)

July 2012

Abstract

Green roofs have been used as an environmentally friendly product for many centuries and considered as a sustainable construction practice. Green roofs are built with different layers and variable thicknesses depending on the roof type and/or weather conditions. Basic layers, from bottom to top, of green roof systems usually consists of a root barrier, drainage, filter, growing medium, and vegetation layer. Environmental and operational benefits of green roofs are many. Green roofs must be installed on existing structures to maximize their potential environmental benefits; however, their main disadvantages are cost and weight. New technology enabled the use of light materials such as: low density polyethylene and polypropylene (polymers) to promote their installation. Nevertheless, lifecycle analyses demonstrate that more sustainable products must replace current green roof materials.

This research evaluates indoor air temperature, indoor vapor pressure, water quality, and water retention performance of green roofs built with construction and demolition (C&D) waste. Temperature, vapor pressure, water quality and storm water retention were assessed by comparing the rainwater retained in experimental C&D based green roofs with standard green roofs under the same environmental conditions. Results show that C&D waste, compared to plastics, improves water quality, indoor air temperature and vapor pressure performance; however it reduces the water retention performance. These findings confirm the environmental potential of green roofs. Benefits of installing C&D based green roofs to minimize the impact of construction industry in landfills are potentially enormous.

The Net Present Value (NPV) per unit of area of a green roof was estimated by considering the social-cost benefits that green roofs generate over their lifecycle. The economic analysis demonstrated that green roofs are short-term investments in terms of net returns. In general, installing green roofs is a low risk investment. Furthermore, the probability of profits out of this technology is much higher than the potential financial losses. It is evident that the inclusion of social costs and benefits of green roofs improves their value.

In addition, this study evaluates the influence of green roofs on the seismic response of frame structures. Results from the structural analysis proved that intensive and extensive green roofs do not affect the seismic performance of reinforced concrete frame structures.

Preface

A part of chapter 2 has been published. Bianchini, F and Hewage, K. (2011) How "green" are the green roofs? Lifecycle analysis of green roof materials. Building and Environment 48(0): 57-65. doi: 10.1016/j.buildenv.2011.08.019

A part of chapter 3 has been published. Bianchini, F and Hewage, K (2012) Probabilistic social-cost benefit analysis of green roofs: A Lifecycle approach. Building and Environment 58(0): 152-162. doi: 10.1016/j.buildenv.2012.07.005

A part of chapter 4 has been submitted to Construction and Building Materials Journal. Bianchini, F., Hewage, K., Alam, S., (2012) Influence of green roofs on the seismic response of frame structures.

A part of Chapter 5 has been published in conference proceedings. Bianchini, F and Hewage, K. (2012) Lifecycle Analysis of green roofs. 12th International Environmental Specialty Conference. Canadian Society for Civil Engineering, Edmonton, Canada, June 6-9.

Table of Contents

List of Tables

List of Figures

List of Illustrations

List of Symbols and Abbreviations

AHP	Analytical Hierarchy Process
C&D	concrete and demolition
CDF	cumulative density function
E	modulus of elasticity
f'_c	compressive strength for concrete
f_y	yield strength
GR	green roof
NPV	net present value
LSD	least significance difference
PGA	peak ground acceleration
TSS	total suspended solids

Acknowledgements

I offer my enduring and sincere gratitude to my supervisor and friend, Dr. Kasun Hewage. Without his guidance, this research project could not be completed successfully. His knowledge and mentoring shaped my future. I would like to offer my sincere gratitude to my friends Dr. Cigdem Eskicioglu and Mr. Atul Porwal for all their unconditional help, support, and understanding through this wonderful experience.

Moreover, I would like to recognize the excellent work of Ms. Renee Leboe, Ms. Susan Tingstad, Ms. Karen Seddon, Ms. Teija Wakeman, Ms. Maria Graziano, and Dr. Richard Klukas, who made my academic environment better. I offer much appreciation to my thoughtful and considerate friends and research group: Dr. Rehan Sadiq, Arnaud Houriet, Craig Hostland, Jessica Buriticá, Shani Bishop, Gustavo Aguilar, Navid Hossaini, Priyanjith Mendis, Haibo Feng, and Rajeev Ruparathna.

My most sincere and honest appreciation to the person that changed my life: Mariel Barrantes. Her unconditional support and love encouraged my successful path through this challenging journey. Also, my greatest gratitude goes to Matt and Molly Thurston. Their warm friendship developed a lifelong link. They definitely made my stay in Kelowna one of the best times of my life. I would like to take the opportunity to thank my friends in Costa Rica: Manrique, Alejandro and Diego, who have always cared about my time here.

Most importantly, I would like to pay my innermost thanks to my grandparents and parents, whom I feel to be the source of inspiration for all my achievements.

To my parents

Victor Julio & Damaris

Chapter 1: Introduction

The construction industry is vital to provide the necessary infrastructure to satisfy human development needs. This professional sector provides multiple products to enhance the quality of life (Tam *et al.*, 2004). Importance of the construction industry is seen in its economic significance to the society and its direct social and environmental impacts (Sev, 2009). It is recognized that construction practices are one of the major contributors of environmental problems, particularly due to the utilization of non-renewable materials. The United States Green Building Council (USGBC, 2001) estimated that commercial and residential construction buildings release 30% of green houses gases and consumes 65% of electricity in USA. Due to the well-known environmental issues (i.e. global warming, deforestation, waste generation, etc.), the concept of sustainability has been introduced to the construction sector.

Green construction aims to develop environmentally friendly construction practices that contribute in energy saving, reduction of emissions, re-use, and recycle of materials (Spence and Mulligan, 1995). These concepts are used in different construction applications such as green roofs, ventilation systems, waste management policies, and recycled materials (Zimmermann *et al.*, 2005). Waste reduction is becoming a serious issue around the world. The construction industry is a large contributor of waste material, which has traditionally been dumped into the landfills. There is a growing need to minimize construction waste through environmentally conscientious solutions. The ideal solution would be to reduce the waste material by its reuse, thus diverting it from recycle plants and landfills. Green roofs systems have been developed to respond to the increasing needs of the growing world population. Storm water retention, runoff quality, weather conditions and the use of new materials must be analyzed to ascertain the short and long term effects on the green roofs' performance.

Green roof is a sustainable application that partially replaces the natural landscape destroyed due to the construction of buildings. Grow vegetation on rooftops has been developed as an option to address well-known environmental issues such as: global warming or air pollution (Bianchini and Hewage, 2012). Green roofs can be classified by their purpose and characteristics into two major types: intensive roofs and extensive roofs (Yang *et al.*, 2008;

Czemiel, 2010). Intensive roofs need a reasonable depth of soil and require skilled labor, irrigation, and constant maintenance. They are usually associated with roof gardens (Molineux *et al.*, 2009). Extensive roofs have a relatively thin layer of soil, grow sedums and moss and are designed to be virtually self-sustaining and require minimum maintenance (Molineux *et al.*, 2009). There is a third type of green roofs called semi-intensive. Semi-intensive green roof is a combination of extensive and intensive; however, the extensive type must represent 25% or less of the total green roof`s area (Yang *et al.*, 2008).

Over time, green roofs became a popular construction product due to their environmental benefits; nevertheless, their cost disadvantage has been a challenge to the industry (Nelms *et al.*, 2007). In general, green roof´s experts agree that the reasons for these higher costs are usually due to materials lifting with cranes to the rooftops, expensive labor cost, and high insurance premiums. In addition, depending on the green roof type, more weight can be added to the roof, which may lead to changes in the structural design that can result in a more expensive structure (Clark *et al.*, 2008). Green roof´s experts justify the need to introduce materials like plastics into the market because it can reduce the overall weight and improve the performance of waterproofing layers without compromising the benefits of green roofs.

Green roofs layers and materials are similar among manufacturers; however, each manufacturer has developed its own system. General data about green roofs systems is available; however, specific content of substances, production process, installation process, and engineering technical information is kept as trade secrets in most cases. Usually manufacturers keep this information confidential to achieve competitive advantage.

The demand of using green roofs in new buildings is increasing (City of Portland, 2008); however, to maximize their positive effects on urban settings, green roofs need be installed on existing structures. Installing green roofs on existing structures lead to another challenge where it might be critical to determine their influence on the seismic response of the structure in a seismic risk zone. Additionally, if required, it might be important to determine proper retrofitting methods and their relevant costs.

The seismic retrofit strategy for an existing reinforced concrete (RC) frame may include partial demolition and/or mass reduction, addition of new lateral load resistance system, member replacement, and transformation of non-structural into structural components to enhance the overall seismic performance of the frame by increasing lateral strength, reducing drift and/or increasing ductility (Thermou and Elnashai, 2005; Niroomandi *et al.*, 2010). The retrofitting method should be an applicable, effective, and economic solution; therefore, the selection process is a complex procedure. Thus, selecting, designing and applying the best retrofit solution is merely based on engineering judgment (Baros and Dritsos, 2008).

1.1 Green roof types

Environmental benefits can be maximized by building one type of green roof or the other; however, all three types provide positive environmental benefits. Nevertheless, the installation cost, maintenance, and construction time are depended on the type of the green roof type. Extensive green roofs are light and require low maintenance cost. However, retention and delay of storm water, temperature control, and agricultural space effects can be reduced.

There is a substantial difference of price between the different types of green roofs. While the current cost in British Columbia, Canada for a standard extensive green roof varies from $\$130/m^2$ -$\$165/m^2$ ($\$12/ft^2$-$\$15/ft^2$); the cost of a standard intensive green roof starts around $\$540/m^2$ ($\$50/ft^2$). This fact is one of the major reasons that influence owners' decisions to build one type or the other (Xeroflor, 2011).

1.2 Layers of a typical green roof

Manufacturers offer different green roof systems to the market to cater different weather conditions and user expectations. As shown in Figure 1.1, green roof systems usually have a root barrier, drainage, filter, growing medium, and vegetation (Palla *et al.*, 2009; Czemiel, 2010; She and Pang, 2010).

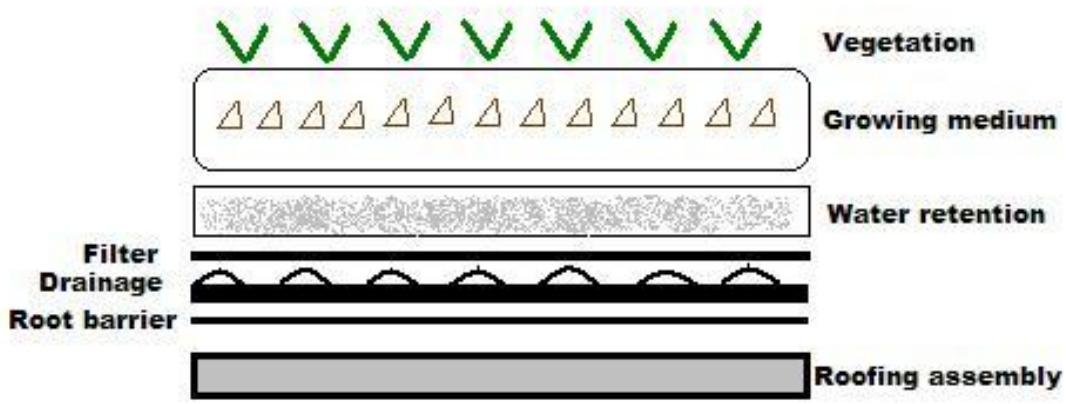


Figure 1.1 Cross section of green roof's layers

1.2.1 Vegetation layer

Vegetation layer is the esthetic layer of green roofs, and perhaps is the symbol that identifies a green roof as an environmental friendly product. Having a bloom and healthy vegetation is the goal of many designers and owners; however, the purpose of growing plants on roof tops, besides esthetic, are to mitigate urban heat effect, improve air quality, replace displaced landscape, and enhance biodiversity (Clark *et al.*, 2008; Tabares-Velasco and Srebric, 2009). Moreover plants play an important role in regulating storm water runoff (Schroll *et al.*, 2010) by retention and evapotranspiration processes (Oberndorfer *et al.*, 2007). Nevertheless, Dunnet *et al.* (2008) stated that changes in the physical characteristics of plants influence their environmental contribution.

Environmental conditions at rooftops are different than at ground level; therefore, it is recommended to use Crassulacean Acid Metabolism (CAM) plants. CAM plants open their leaf pores to exchange oxygen and carbon dioxide in the darkness allowing the conservation of water under drought conditions (Getter and Rowe, 2006). Such characteristics reduce the range of plants that can be used on the rooftops; however, Berghage *et al.* (2007) showed that sedums and mosses meet all such requirements. Therefore, these plants are the most popular type of vegetation on green roofs. Not like sedums, mosses are green and need less care to maintain their physiological functions (Villarreal and Bengtsson, 2005). Generally these plants do not exceed 10 cm of height.

One of the major goals of intensive green roofs is to provide an open and accessible space for users to enjoy a different environment within the building (Molineux *et al.*, 2009). Generally plants like grasses, herbs, shrubs, small trees and even small fruit trees or vegetables that can vary their height from 10 cm to more than 100 cm are used in intensive green roofs (Cavanaugh, 2008).

1.2.2 Growing medium layer

This layer contributes to thermal performance and water retention (Teemusk and Mander, 2007); besides it supplies nutrients and water that plants need for their biological functions. (Jim and Tsang, 2011). Additionally, it provides space for plant roots to settle and strengthen, to withstand wind force and other rough weather conditions on the rooftops. It is important to consider the content and age of the medium since it affects directly the performance of the layer (Schrader and Böning, 2006).

The natural growing medium is regular soil. However, the soil can have clay and organic particles that may be heavy when saturated. Weight limitations of green roof systems led several manufacturers to develop their own growing mediums. Generally, growing medium has a high content of porous minerals and a low content of organic matter to maintain the balance between weight and performance (Clark *et al.*, 2008). Nevertheless, the content of the medium can be modified to meet the natural requirements of the selected vegetation.

The thickness of the growing medium layer is related to the vegetation as well. Small vegetation like mosses requires less depth of medium to their roots than the depth a shrub may require (Villarreal and Bengtsson, 2005). The thinnest growing medium in the Canadian market is of 2.5 cm for an extensive green roof system. Intensive green roof systems are designed to grow different types of plants, thus the medium can vary between 20 cm to 120 cm (Yang *et al.*, 2008).

1.2.3 Water retention layer

The main objective of this layer is to retain water for runoff control (Teemusk and Mander, 2007) and keep the growing medium layer moist (Jim and Tsang, 2011). Water is a natural source of nutrients for plants and help vegetation to be healthy to survive on rooftops. In addition, storm water retention by green roofs decreases and delays the runoff water in the city´s storm water sewage system (Czemiel, 2010). The retention capacity depends on the type of green roof, vegetation, building´s roofing assembly, weather conditions, and previous soil´s saturation (Mentens *et al.*, 2006; Teemusk and Mander, 2007; Nicholson *et al.*, 2009; Czemiel, 2010). Stored water in the roof adds an additional weight that the roof structure may not hold; consequently the roofing assembly is the first limitation to select materials and thickness of the water retention layer. Extensive green roofs require less water holding capacity than intensive since the thickness of the growing medium and vegetation is less. On the contrary, intensive green roofs use bigger vegetation with stronger roots that need more water and nutrients to survive and bloom (Soprema, 2011; Xeroflor, 2011).

Unlike the other layers, water retention layer is a mat made out of mineral wool or polymeric fibers and is installed just above the filter layer. The thickness of this layer varies, due to the factors discussed above, affecting retention performance and saturated weight. The depth of each mat can vary from 1.0 cm to 6.5 cm (Soprema, 2011; Xeroflor, 2011). Mats can be combined, installing one above the other, to meet the needs of different green roofs.

1.2.4 Filter layer

Regardless of the green roof system, the purpose of the filter layer is to prevent the particles of the upper layers from draining with water runoff and blocks the drainage layer (Teemusk and Mander, 2007). This layer prevents fine material infiltration to lower layers during the draining process. In addition, the filter layer maintains the integrity of the growing medium and vegetation.

Materials such as polymeric fibers or polyolefins are used to manufacture thin and light filter layer. The filter is bonded to the drainage layer to facilitate easy installation. Since filter layer information is shown as a part of the drainage layer, there is no technical information available to specify its thickness and weight (Soprema, 2011; Xeroflor, 2011).

1.2.5 Drainage layer

Green roofs have a water retention capacity; however, it is important to provide an empty space between the layers to allow the excess water to freely move out of the roof (She and Pang, 2010). It decreases the risk of water leaks to the roofing assembly. In addition, water adds an extra weight to the roof assembly; therefore, it is essential to ensure a good drainage to maintain structural capacity of the roof assembly. Effective drainage protects the root barrier from the excess water that can be accumulated in the membrane. Excess water in root barrier encourages plant roots to grow and damage the root barrier and roofing assembly (Getter *et al.*, 2007).

Drainage materials and material shapes can be different depending on the chosen green roof system, weather conditions, and roofing assembly. Light and thin materials, as polyethylene and polypropylene, are preferred to build extensive green roofs due to weight limitations. Interviewees of green roof manufacturers stated that their preference for polymer based relays are due to its' flexibility to transport in rolls, easy installation, high strength, durability, and low production cost. Usually, the polymer material is bonded to one or both sides of a geotextile that prevents small particles of the growing medium to migrate and block the drainage. Depending on the green roof system and type of drainage, thickness of the layer can vary from 1.0 cm to 1.5 cm (Soprema, 2011; Xeroflor, 2011).

Intensive green roofs are designed to hold higher loads than extensive; therefore, the drainage layer can be heavier and simpler. Generally the layer is composed of round pebbles, which are a natural drainage and filter. The thickness of the layer can be 4 cm or more (Soprema, 2011; Xeroflor, 2011).

1.2.6 Root barrier layer

The root barrier is the first layer above the buildings´ roofing assembly that generally is built out of traditional materials like concrete. The main purpose of this layer is to provide a waterproof membrane to the roofing assembly (She and Pang, 2010). Leak prevention is one of the most important objectives of any green roof system design. In case of a leak in an operating green roof, all the layers needed to be removed to locate the leak.

Another purpose of this layer, as the name suggests, is to protect the buildings´ roofing assembly from plant´s roots that could penetrate from green roof˝s upper layers (Soprema, 2011; Xeroflor, 2011). Roots grow, strengthen, and move through soil seeking water and nutrients for the plant (Getter and Rowe, 2006). Over time, without proper protection, roots can penetrate the roofing assembly resulting in cracks and holes where water infiltrates.

There are two different types of root barriers in the market: physical and chemical. Physical barriers consist of a thin layer (usually about 0.05 cm) of a low-density polyethylene (LDPE) or polyethylene (PP) material that is placed above the roofing assembly (Soprema, 2011; Xeroflor, 2011). Chemical barriers use toxins like copper based products to inhibit root penetration.

1.3 Benefits of green roofs

Environmental and operational cost-benefits of vegetated roofs are several and can be listed as follows: reduction of energy demand for heating and cooling, mitigation of urban heat island, reduction and delay of storm water runoff, improvement in air quality, replacement of displaced landscape, enhancement of biodiversity, provision of recreational and agricultural spaces, and insulation of a building for sound (Santamouris *et al.*, 2007; Yang *et al.*, 2008; Molineux *et al.*, 2009; Currie and Bass, 2010; Czemiel, 2010).

1.3.1 Heat island effect

The heat island effect explains why urban areas have a higher temperature than rural areas. The reason for this effect is mainly due to dark colors of the buildings´ rooftops (Nelms *et al.*, 2007). Roofs with dark colors absorb energy from the sun and can reach temperatures higher than the ambient temperature. High temperatures on the roof result in increases of energy demand, higher air conditioning costs, and heat-related illnesses (United States Environmental Agency of Protection, 2011a).

Rural areas are not exposed to this problem due to vegetation. Trees and plants help to control the ambient temperature by evapotranspiration (Sailor *et al.*, 2008). In open areas plants use solar energy to control temperature by releasing vapor and contributing to the water cycle, while in urban areas there is not enough vegetation to cool down the environment (Sailor *et al.*, 2008; Newsham *et al.*, 2009).

Installing green roofs in urban areas can mitigate heat island effect. Rosenzweig *et al*., (2006) suggested that if New York City covers 50% of roof tops with green roofs, the temperature difference between the city and its surrounding may decrease by 0.8 ºC.

1.3.2 Storm water retention

Impermeable surfaces in cities are increasing due to urban developments, resulting in decrease stormwater infiltration (Czemiel, 2010). Green roofs have a water retention capacity that contributes to control the quantity of runoff water that can go into the city´s sewer system (Clark *et al.*, 2008; Currie and Bass, 2010). Compared to regular roofing systems, green roofs drain runoff water at a lower rate allowing the city's stormwater sewer system to have enough time to transport runoff to the disposal body of water, which reduces the risk of flooding (Teemusk and Mander, 2007; Rajendran *et al.*, 2009; Wu and Low, 2010).

The amount of water that can be harvested from rain is important; however, the quality of that water is very important as well (Czemiel, 2010). Some research studies noted the effect of the roof's materials over the quality of runoff water. Such studies show that regardless of the roofing system, current roofing materials add chemicals or metal compounds to the runoff water (Teemusk and Mander, 2007; Getter *et al.*, 2007; Czemiel, 2010; Nicholson *et al.*, 2010; Mendez *et al.*, 2010). Mendez *et al.* (2010) and Nicholson *et al.* (2010) stated that every artificial roofing material affect the runoff, however, the water studied from sample green roofs added less chemical compounds and usually met the US EPA standards. However, it is important to note that the Mendez *et al.* (2010) research did not consider the possibility of adding fertilizers and pesticides to protect and enhance plants growth by ordinary owners, resulting in more chemicals in runoff water.

1.3.3 Air pollution

Pollution management focuses on controlling the sources that release toxic chemicals in the air (Schnelle and Brown, 2002), but does not consider the pollutants that are already in the air (Yang *et al.*, 2008). Urban areas usually have higher levels of toxics in the air (Mayer, 1999), and urban vegetation may be part of the solution to reduce air contamination to an acceptable level.

Green roofs contribute to reduce air pollution in two ways: (1) controlling temperature variations of a building reduces heating and air conditioning demand, hence less carbon dioxide is released from power plants; and (2) plants´ photosynthesis sequester carbon dioxide from the air and store it as biomass (Getter *et al.*, 2009). Yang *et al.* (2008) quantified the annual air pollution reduction (1835.23 metric tons of all pollutants) for the City of Chicago completely covered with green roofs. Currie and Bass (2005) estimated that 109 ha of green roofs in Toronto could annually reduce 7.87 metric tons of air pollution.

1.3.4 Reduction of energy demand

Green roofs can improve the insulation properties of a building; hence reduce annual energy consumption. Green roofs act to reduce the heat loss from the building in winter and heat gain into the building in summer,but also adds thermal mass to help stabilize internal temperatures year round. Castleton *et al.* (2010). Liu and Baskaran (2003) demonstrated that the installation of green roofs reduce A/C energy demand in 75% during warmer months. Moreover, Niachou *et al.* (2001) estimated that the impact of green roofs in energy savings in well-insulated buildings is 2%, while for non-insulated buildings can be up 37%.

1.3.5 Insulation of building for sound

Little scientific research to determine the acoustical effects of vegetated rooftops has been conducted. Basically, green roofs can reduce sound propagation in two ways: (1) by providing increased insulation of the roof system and (2) by absorbing sound waves diffracted over roofs (Renterghem and Botteldooren, 2010). Renterghem and Botteldooren (2010) measured sound diffraction and propagation in situ. Results demonstrated that green roofs could lead to consistent and significant sound reduction at locations where only diffracted sound waves arrive.

1.3.6 Replacement of displayed landscape

Increasing urbanization has transformed natural landscape into cities. The installation of green roofs replaces standard roof surfaces with vegetation that can mimic native displaced landscape. For instance, prairie grassland habitat creation is one of the few examples of a specific landscape that has been successfully re-created on North American green roofs (Currie and Bass, 2010). Tall grass prairies are important habitats for several species of migratory birds (Gedge, 2003), and these habitats on green roofs could play a similarly important role in any Canadian city.

A landscape ecology approach to the design of green roofs would advocate for planning beyond an individual roof and moving to a framework of green roof aggregations, where these networks of green roofs can effectively facilitate the movement of species (Currie and Bass, 2010). The potential advantages of developing a green roof network could lead to synergistic effects created when a certain number of roofs are clustered in an area.

1.3.7 Enhancement of biodiversity

Biodiversity refers to the independent and dependent variations within all life forms, from the smallest molecular organizations in soils to the unabated complexities of life forms within entire ecosystems (Wilson, 1999). Green roofs are one tool for enhancing biodiversity in urban areas. The vegetation layer can support a multitude of different plant species, depending on the depth and composition of the growing medium. Thus, green roofs' vegetation layer helps to extend existing ground level habitat by establishing habitat in areas where it would not otherwise exist (Currie and Bass, 2010).

Green roof habitats may not be as abundant or as high quality as those at ground level. However, green roofs can provide suitable habitat for animal and plant species that are not able to adapt and survive in urban settings (Currie and Bass, 2010). Therefore, green roofs can be designed to mimic almost any type of habitat to preserve species (Currie and Bass, 2010).

1.4 Research objectives

The research project focused on developing better sustainable green roofs with reused C&D waste materials. The main objective of this research project is to experimentally test and analyze the potential of using construction waste materials in green roofs. Following are the sub-objectives of the performed research:

- Lifecycle analysis (LCA) of current green roof materials and layers.
- Determine the feasibility, economic, and socio-environmental impacts of re-using Construction and Demolition (C&D) waste in green roofs.
- Investigate the influence of green roofs over the seismic performance of structures.
- Experimentally compare the performance of C&D waste green roofs with standard commercial green roofs.

1.5 Research methodology

The research objectives were developed under each chapter following a specific methodology. In chapter 2, the advantages and disadvantages of using current green roof materials were investigated. The entire lifecycle of green roofs from the material extraction to decommissioning were analyzed using the software SimaPro 7.1. The environmental benefits of current green roofs were evaluated by comparing emissions of NO_2, SO_2, O_3 and PM_{10} in green roof's material manufacturing process, such as polymers, with the green roof´s pollution removal capacity. In addition, different scenarios were modeled to estimate the emissions released due to different green roof types.

Inappropriate C&D waste management during construction may lead to economic and environmental impacts. In chapter 3, a comparative analysis was conducted to balance socio-environmental and financial costs of green roofs. A lifecycle net benefit-cost analysis, with the social dimension, was performed. This objective is based on an extensive literature review in multiple fields and reasonable assumptions for unavailable data. The Net Present Value (NPV) per unit of area of a green roof was estimated by considering the social-cost benefits that green roofs generate over their lifecycle. Two main types of green roofs – i.e. extensive and intensive - were analyzed. Additionally, an experimental extensive green roof, which replaced roof layers with construction and demolition waste (C&D), was assessed. A probabilistic analysis was performed to estimate the personal and social NPV and payback period of green roofs. Additionally, a sensitivity analysis was also conducted to identify the most important for the NPV and payback calculations. In both cases, the software MS Excel was used to perform the different analyses.

The effects of green roofs in seismic properties of buildings such as time period, inter-storey drift, roof drift and base shear were analyzed. Chapter 4 evaluated the influence of green roofs on the seismic response of 3, 6, and 8 storey reinforced concrete ductile moment resisting frames, which were designed according to current seismic standards, however, not designed for green roofs. For each frame, three different types of roofs were considered: gravel flat roof, extensive green roof, and intensive green roof. Nonlinear dynamic time history analysis using an ensemble of twenty real earthquake records was performed to determine the inter-storey drift demand, roof drift demand, and base shear demand for each frame. Eigenvalue analysis was also performed to determine the impact of green roofs weight on the elastic and cracked periods of the structure. The software SeismoStruct was used to performed the different structural analyses.

Chapter 5 experimentally compared the performance of C&D waste green roofs. To determine the environmental performance, six C&D green roofs were compared with two standard commercial green roof systems under the same environmental conditions. Indoor air temperature, relative vapor pressure, retention of storm water, and runoff water quality were measured and analyzed. The C&D waste green roofs were compared with standard commercial green roof systems and natural rainfall. Moreover, pH, total suspended solids (TSS), and electro conductivity were measured to compare runoff water quality. The experiment was conducted for a 10 months period.

Evaluation of the performance and durability of waste based green roofs will help the construction industry to practice out-of-the-box approaches. The findings identified methods to effectively incorporate construction and demolition (C&D) materials into green roof systems, which not only improve their sustainability but also reduce their costs. Green roofs are designed as a long-term solution due to their natural capacity to adapt to environmental conditions. Facilitate and expand their installation on new and existing buildings is a mandatory step in green design and construction.

Chapter 2: Lifecycle analysis of green roof materials

The importance of this chapter relays in determining the sustainability of green roofs, by estimating the number of years that a regular green roof takes to balance the pollution released in its' material production, with the pollution removed by the green roof's plants in the operation phase. The analysis was performed for the polymers, since all the layers, except for the growing medium and vegetation, are generally made out of polymer materials.

This chapter has two main objectives:

(1) Discuss the importance of different layers of green roof with related materials properties.

(2) Discuss the amount of pollution released to the air due to the production process of polypropylene and polyethylene (in green roof materials) and compare with Yang *et al.* (2008) green roof´s air pollution removal results.

2.1 Physical characteristics of the materials

Green roof´s materials usually use polymers for all the layers except for the growing medium. Growing medium should have enough organic matter and porous materials to meet the weight and growing requirements.

The lifecycle analysis performed in this chapter is limited to the green roof's manufacturing and operational phases. Transportation and decommission of materials were not considered in the analysis. Additionally, the estimated emissions are restricted to the lifecycle analysis' software database.

2.1.1 Polymers

Weight limitations in green roofs demanded light but durable materials like polypropylene and polyethylene. The goal of decreasing the weight of green roofs is to facilitate their installation in existing buildings and avoid excessive construction costs of new buildings due to large structural elements. The use of polymers motivated the construction of extensive green roofs, because it allows the roof to decrease thickness and weight, while maintaining environmental benefits similar to intensive green roofs at a lower cost and maintenance.

Lower layers of green roofs are exposed to high stresses due to heavy loads above them. In addition, plant roots of upper layers may damage the water retention and drainage layer. Therefore, materials in these layers should have high tensile and puncture resistance, which polymers are capable of (Sperling, 2006).

The broad use of polymers in different industrial applications is due to their multiple beneficial characteristics such as: versatility, low weight, durability, corrosion resistance, insulation capacity, low cost, and ability to be tailored (Sperling, 2006). Additionally, thin and long layers can be produced and packed in rolls that facilitate transport and installation. Moreover, polymers also seems like an environmental attractive material because its' re-using and recycling potential. Generally, drainage and filter layers are manufactured of 40% recycled polypropylene and water retention layer of 100% recycled polymeric fibers (Soprema, 2011; Xeroflor, 2011).

2.1.2 Growing medium

Manufacturers carefully keep confidential the growing medium specific content. The growing medium content may vary depending on the type of chosen vegetation. All plants need organic matter to grow; nevertheless, some types need more than others. Larger plants like small trees and shrubs require more nutrients present in the growing medium. The growing medium for intensive green roofs may have up to 45% of organic content, while extensive may have up to 30% (Getter and Rowe, 2006).

Organic content usually is composed of soil with peat moss, bark, sawdust, or leaves to provide enough nutrients to the plants; however, decomposing of the organic matter reduces the volume of the growing medium. It may cause harmful exposure of plant´s roots (Palla *et al.*, 2009). To counteract this problem, the non-organic part of the growing medium should be a mixture of sand, scoria, and porous minerals that are light. It will decrease the consolidation of the medium as well (Palla *et al.*, 2009; Schrader and Böning, 2006). The ultimate goal of manufacturing growing medium is to maintain a proper balance among weight, nutrients for plants, thickness, and durability.

2.2 Lifecycle analysis of green roof layers

There were many previous cost-benefits analysis of green roofs (Currie and Bass, 2005; Getter *et al.*, 2009; Yang *et al.*, 2008) by analyzing initial construction costs, reduction of energy demand (to mitigate urban island effect), control and delay of storm water runoff, and removal of air pollution. All the reviewed previous studies noted overall benefits of green roofs. Kosareo and Ries (2006) compared green roofs types with a conventional stone ballasted roof, nevertheless, this investigation did not focus on analyzing the environmental impacts of manufacturing the materials used in green roof layers. Green roofs are catalogued as a sustainability practice; however, the production process of polymers is highly polluting.

2.2.1 Production process of polymers

Polymers are manufactured in four different processes: 1. continuous extrusion, 2. injection molding, 3. blow molding, and 4. thermoforming. All of these processes have three basic steps: i.e. 1. melting of the raw material, 2. shaping of the molten material, and 3. solidification of the molten to the desired shape (Chung, 2000). Regardless of the method to produce the polymer, it needs high amount of energy to increase the temperature, to more than 120°C, to melt the raw material to facilitate the shaping. After providing the desired form, the material must be cold down to accelerate solidification (Giles *et al.*, 2005). The energy sources and chemicals in the manufacture process of polymers release toxic substances to the air. Air pollution and energy consumption are essentials in lifecycle analysis.

2.2.2 Input of the lifecycle analysis software

The lifecycle analysis presented in this chapter used SimaPro 7.1 software. The damage oriented method Eco-Indicator (H) V2.06 was applied. This method quantifies the amount of raw materials and substances released to different media, such as air, water and soil, to produce 1 kg of polymer. The software was used to analyze two options: i.e. recycled and non-recycled materials. Polyethylene low density (PE-LD) production mix at plant (RER) and polypropylene granulate (PP) production mix at plant (RER) were selected as the specific polymer materials for the root barrier and drainage, filter, and water retention layers. The recycling process includes mixing the polymer with chemical additives. Nevertheless, these substances don´t produce any considerable effect on the durability and life span of the polymers (Seymour and Carraher, 1995). Therefore, using non-recycled or recycled materials as green roofs layers depends just on their availability and price in the market. Polymers take long time to biodegrade in landfills (Chung, 2000), hence it is preferable to recycle and introduce them again in the market, than produce new ones.

For the lifecycle analysis of low-density polyethylene and polypropylene, densities of 0.92 g/cm^3 and 0.95 g/cm^3 respectively in 20°C., were used (Seymour and Carraher, 1995). The drainage layer (polymeric fibers) typically has same density and production process of polypropylene. Hence it was analyzed as polypropylene.

2.2.3 Output of the lifecycle analysis software

Table 2.1 and Table 2.2 rank the amount of substances used in the production process of LDPE and PP for non-recycled and recycled process respectively.

Table 2.1 Substances needed and released due to the production process of non-recycled polymers (Based on SimaPro results)

LDPE				PP			
Substance	Media	Unit	Amount released	Substance	Media	Unit	Amount released
Radon-222	Air	Bq	298	Radon-222	Air	Bq	198
Noble gases, radioactive, unspecified	Air	Bq	134	Noble gases, radioactive, unspecified	Air	Bq	91
Heat, waste	Air	MJ	27	Heat, waste	Air	MJ	21
Hydrogen-3, Tritium	Water	Bq	6	Hydrogen-3, Tritium	Water	Bq	4
Carbon dioxide, fossil	Air	kg	2	Carbon dioxide, fossil	Air	kg	1.7
Energy, potential (in hydropower reservoir), converted	Raw (input)	MJ	0.9	Oil, crude, in ground	Raw (input)	kg	1
Oil, crude, in ground	Raw (input)	kg	0.9	Gas, natural, in ground	Raw (input)	m^3	0.6
Gas, natural, in ground	Raw (input)	m^3	0.8	Energy, potential (in hydropower reservoir), converted	Raw (input)	MJ	0.30
Energy, gross calorific value, in biomass	Raw (input)	MJ	0.4	Energy, gross calorific value, in biomass	Raw (input)	MJ	0.2
Coal, hard, unspecified, in ground	Raw (input)	kg	0.1	Coal, hard, unspecified, in ground	Raw (input)	kg	0.08

The column “media” shown in Table 2.1 identifies the amount of substances that are released to the environment, or the amount of raw materials needed for the production process. The first five released substances are the same for both polymers. Data shows that the production process of polymers is highly pollutant, where 2 kg and 1.7 kg of carbon dioxide (CO_2) is released to produce 1 kg of LDPE and PP respectively. The amount of mass of CO_2 released doubles the amount of product manufactured.

In addition, the amount of raw material and energy to manufacture 1 kg of polymers is considerably high. Energy (from different sources) in the production process needed for extrusion, blow molding, injection molding, and thermoforming. All these processes require high pressures and temperatures. Crude Oil represents the biggest raw material contributor to manufacture polymers. To produce 1 kg of LDPE and PP, 0.8 kg and 1 kg of crude oil is required respectively, which is on 1:1 relation. Use of this fossil source causes extreme pollution in production process (United States Environmental Agency of Protection, 2011b).

Table 2.2 Substances needed and released due to the production process of recycled polymers (Based on SimaPro results)

LDPE				PP			
Substance	Media	Unit	Amount released	Substance	Media	Unit	Amount released
Radioactive species	Air	Bq	3639724	Acids	Raw (input)	kg	317
Radioactive species	Water	Bq	33441	Waste in bioactive landfill	Solid waste	kg	21
Radon-222	Air	Bq	297	Phosphate	Water	kg	1.8
Noble gases, radioactive, unspecified	Air	Bq	133	Formaldehyde	Air	kg	0.5
Heat, waste	Air	MJ	27	Fluoride	Air	kg	0.40
Hydrogen-3, Tritium	Water	Bq	6	Boron	Water	kg	0.10
Energy, potential (in hydropower reservoir), converted	Raw (input)	MJ	3.5	Hydrocarbons, aliphatic, unsaturated	Air	kg	0.08
Carbon dioxide, fossil	Air	Kg	2	Glyphosate	Soil	kg	0.05
Oil, crude, in ground	Raw (input)	Kg	0.9	Phenol	Air	kg	0.02
Gas, natural, in ground	Raw (input)	m^3	0.8	Radioactive species	Water	Bq	0.01

Table 2.2 shows that the same amount of oil and gas are needed for the non-recycled and recycled processes of LDPE. In addition, the same amount of carbon dioxide, radon 222, noble gases, and heat are emitted to the air in both processes. However, the recycled process releases other substances, such as scandium and phosphate, which are not released in the non-recycled process. Even though many emissions and input of the recycled and non-recycled process are the same, the recycled process can be considered more polluting for

specific media and substances, since it releases much more radioactive substances to air and water.

Recycled PP doesn´t need the same amount of oil and gas as an input compared to non-recycled PP; however, the process requires additives and acids. Additionally, large quantities of acids and waste (bioactive landfill) are produced to manufacture 1 kg of the recycled polymer. Compared to the non-recycled material, the recycled is generating more waste in the overall production process. Although the recycling of polymer results in the release of some radioactive materials that are not released in non-recycled polymer production, overall recycled polymer production has a lower environmental impact.

2.2.4 Application of data to different scenarios

To have a comparative analysis in this chapter, the same problem addressed by Yang *et al.* (2008) is considered. Yang *et al.* (2008) investigations quantified the air pollution removal of green roofs for the entire area of the city of Chicago. This chapter analyses the air pollution created due to the production process of the polymers, which are used to manufacture green roof´s layers. Yang *et al.* (2008) considered the air pollution removal in four substances: 1. Nitrogen Dioxide (NO_2), 2. Sulfur Dioxide (SO_2), 3. Ozone (O_3), and 4. particles of 10 micrometers or less (PM_{10}). For comparative purposes this chapter analyzes the same substances with two scenarios:

(1) Green roof materials are manufactured with non-recycled polymers.

(2) Drainage and filter layers are manufactured with 40% recycled polypropylene and water retention layer is manufactured with 100% recycled polymeric fibers (Soprema, 2011; Xeroflor, 2011).

The city of Chicago has an area of 588.3 km^2 (58830 ha) and 27.86% of that area is roof surfaces (Gray and Finster, 2000). Yang *et al.* (2008) estimated 0.198 km^2 (19.8 ha) of the roof area are green roofs, moreover noted that 32.58% of that area represents extensive green roofs (and 67.42% to intensive/semi-intensive green roofs).

Yang *et al.* (2008) investigation quantified the air pollution removal by assuming all the roof tops of the city of Chicago as green roofs. To model the roof area that is not currently considered as a green roof (remaining roof area) Yang *et al.* (2008) analyzed three scenarios:

(1) the remaining roof area has the same current ratio of extensive and intensive green roofs

(2) the remaining roof area has extensive green roofs, and

(3) the remaining roof area has intensive green roofs.

Table 2.3 shows the distribution of areas organized by the type of green roofs under three scenarios.

Table 2.3 Area of green roof for the different scenarios (Based on Yang *et al.*, 2008)

	Area (ha)		
	First scenario	**Second scenario**	**Third scenario**
Extensive	5339.86	16376.70	6.45
Intensive/semi intensive	11050.20	13.35	16383.60
Total	**16390**	**16390**	**16390**

The weight of polymers used to build a typical green roof is needed to estimate the amount of pollutants released to air due to the production process of polymers. As mentioned, this chapter analyses the polymer materials in root barrier, drainage, and water retention layer, of green roofs (shown in Figure 1.1). Properties of the materials and the thickness of each layer considered for the lifecycle analysis are shown in Table 2.4.

Table 2.4 Materials and properties considered for green roof`s layers

			Thickness (cm)	
Layer	**Material**	**Density (g/cm^3)**	**Extensive**	**Intensive**
Root barrier	Low density polyethylene	0.92	0.05	0.05
Drainage	Semi-Crystalline polypropylene	0.95	1.5	4.0
Water Retention	Polymeric fibers	0.95	1.0	1.5

The volume of polymers was obtained by multiplying the areas shown in Table 2.3 with the thickness shown in Table 2.4. The weight of each layer, shown in Table 2.5, was calculated by multiplying the volume with the density of each layer (shown in Table 2.4).

Table 2.5 Weight of polymers for each layer

		Weight (ton)		
		First scenario	**Second scenario**	**Third scenario**
Extensive	Root barrier	24563.36	75332.82	29.67
	Drainage	760930.05	2333679.75	919.13
	Water Retention	507286.70	1555786.50	612.75
Intensive/semi intensive	Root barrier	50830.92	61.41	75364.56
	Drainage	4199076.00	5073.00	6225768.00
	Water Retention	1574653.50	1902.38	2334663.00

Pollution is mainly caused by the emissions in the production process of polymers; therefore, Table 2.6 shows the weight shown in Table 2.5 organized by polymer type.

Table 2.6 Total weight of polymers under different scenarios

		Weight (ton)		
		First scenario	**Second scenario**	**Third scenario**
Extensive	Low Density polyethylene	24563.36	75332.82	29.67
	Polypropylene	1268216.75	3889466.25	1531.88
Intensive/semi intensive	Low Density polyethylene	50830.92	61.41	75364.56
	Polypropylene	5773729.50	6975.38	8560431.00

Results in Table 2.7 show the amount of substances released to the air for each kilogram of recycled and non-recycled polymers. SimaPro 7.1 was used for the analysis.

Table 2.7 Amount of substances released to the air per 1 kg of polymer (Derived from SimaPro results)

		Weight (kg)			
		Non-recycled		Recycled	
Substance	**Unit**	**LDPE**	**PP**	**LDPE**	**PP**
NO_2	Kg	3.80E-03	3.30E-03	2.22E-03	6.75E-260
SO_2	Kg	5.03E-03	3.79E-03	5.03E-03	0
O_3	Kg	4.16E-09	2.88E-09	4.16E-09	6.75E-260
PM_{10}	Kg	4.75E-04	4.06E-04	4.75E-04	6.75E-260
	Total of pollutants (kg)	9.31E-03	7.49E-03	3.29E-03	2.03E-259

Table 2.7 shows that low-density polyethylene´s production process, for both recycled and non-recycled polymer, is more pollutant than polypropylene´s. Polyethylene is used to manufacture the layer that requires the lowest quantity of material (root barrier). The total amount of substances released to the air for the option of non-recycled polymers is calculated by multiplying the information in Table 2.6 and Table 2.7. Calculations for the recycled polymers option was more complicated since the drainage and filter layers have 40% and 100% recycled PP respectively.

It is assumed that 60% of the total weight of drainage layer is produced with non-recycled polymers and the remaining with recycled polymers. The amount of pollution released is calculated by multiplying the 60% of the drainage layer weight (Table 2.5) with the amount of toxic substances shown in Table 2.7. Similarly, the remaining was estimated by multiplying the remaining weight (40%) with the toxic substances shown in Table 2.7.

The same process was followed for every scenario. Obtained results are shown in Table 2.8.

Table 2.8 Total amount of pollutants released to the air (Derived from SimaPro results)

		Weight (ton)					
		First Scenario		Second Scenario		Third Scenario	
		Non-recycled	Recycled	Non-recycled	Recycled	Non-recycled	Recycled
Extensive	NO_2	4272	1598	13103	4900	5	2
	SO_2	4927	1853	15110	5682	6	2
	O_3	3.8E-03	1.4E-03	1.2E-02	4.3E-03	4.5E-06	1.7E-06
	PM_{10}	526	197	1615	604	6.36E-01	2.38E-01
Intensive/semi intensive	NO_2	19219	8495	23	10	28495	12595
	SO_2	22123	9798	27	12	32801	14527
	O_3	1.7E-02	7.5E-03	2.0E-05	9.0E-06	2.5E-02	1.1E-02
	PM_{10}	2368	1047	3	1	3511	1552
	Total (ton)	53436	22988	29880	11210	64819	28679

Table 2.9 shows the amount of pollution released for the two options described above.

Table 2.9 Amount of pollutants released (Derived from SimaPro results)

		Pollution released (ton)	
	Air pollution removal (ton/yr) Yang *et al.*, 2008	Non-recycled materials (option 1)	Recycled materials (option 2)
First scenario	1835.2	53435.80	22987.73
Second scenario	1405.5	29880.49	11210.08
Third scenario	2046.9	64818.54	28679.10

Table 2.10 shows the number of years required, in the operation phase of the green roofs, to balance the air pollution in the materials' production phase.

Table 2.10 Years needed to balance pollution.

	Years		
	Non-recycled materials	Recycled materials	Non-recycled/recycled
First scenario	29	13	2.23
Second scenario	21	8	2.62
Third scenario	32	14	2.28
		Average	2.37
		Variance	0.05

2.3 Discussion

Results of the total pollutants released show that non-recycled LDPE releases 2.8 times more toxic substances to air than recycled LDPE (Table 2.7). Additionally, the recycling process removes NO_2 from the air than releasing it because it is required in the production process. Analyzing just the amounts of the four toxic substances (NO_2, SO_2, O_3 and PM_{10}) released from the recycled LDPE is lower than the emissions of non-recycled process.

Toxic emissions released to air decreased by the use of layers manufactured out of recycled polymers in 2.3, 2.7 and 2.2 times for the first, second, and third scenario respectively. Pollution is considerably decreased; if 100% recycled PP is used in the drainage layer (instead of using 40%).

Yang *et al.* (2008) estimated that the total amount of air pollution removal per year for every scenario. Table 2.9 shows the amount of pollution released for non-recycled and recycled polymers for every selected scenario. It is evident that the manufacturing process of non-recycled polymers pollutes more than the recycled polymers.

Toxic substances released to air are 1820 kg per ha and 3960 kg per ha for extensive and intensive green roofs, with the non-recycle option, respectively (shown in Table 2.9). The recycled option released 680 kg per ha for extensive green roofs and 1750 kg per ha for intensive green roofs. These rates are compared with the air pollution removal rate of green roofs reported by Yang *et al.* (2008); which is 85 kg per ha per year in Chicago. Currie and Bass (2005) reported the air pollution removal rate of green roofs as 72 kg per ha per year in Toronto. These removal rates allowed calculating the amount of years required to balance pollution for every scenario and option analyzed in this chapter. From the results in Table 2.9, it is notable that the non-recycled materials need more time to balance pollution created in the material production. Table 2.10 evidences that the use of non-recycled polymers increase toxic releases to the environment.

Extensive green roofs release least amount of toxic substances for both, recycled and non-recycled materials. This result was expected since the layers of extensive green roofs are thinner than the intensive type; hence less material is required. In terms of 4 toxic substances (NO_2, SO_2, O_3 and PM_{10}, extensive roofs manufactured with recycled plastics are the best option. Kosareo and Ries (2006) determined, that intensive green roof is the best option from a lifecycle perspective. However, the only difference between the extensive and intensive green roof used for their study is the thickness of the growing medium. Variations in the growing medium won´t affect the toxic emissions of the manufacturing process of the polymers. This chapter considered different thickness for the drainage and water retention layer, which is the reality. These variations directly affect the toxic substances released to the air in the manufacturing process.

In terms of SO_2, Kosareo and Ries (2006) determined that intensive green roofs are better than extensive. This suggests that they used different plants for intensive green roofs and for extensive green roofs in the analysis. This study used the same type of plants for both types of green roofs, since the air pollution removal rate reported by Yang *et al.* (2008) is an average rate for green roofs. The air pollution removal depends on the air pollution concentration, weather, type, and age of the plants (Yang *et al.*, 2008). Intensive green roofs usually have bigger plants that sequester more contaminants from air due to their natural metabolism (Berghage *et al.*, 2007). Therefore, intensive green roofs will have a higher air removal rate and have a better performance in the lifecycle analysis.

Differences in above results show uncertainties in green roof performance. Weather, thickness of layers and types of materials and plants are characteristics that vary among green roofs. The choice of these characteristics affects the pollution released in the manufacturing process and influences the environmental performance of green roofs.

Lifespan of green roofs depends on the maintenance, type of green roof, and weather conditions. Acks (2005) noted the expected operating life of green roofs as 55 years, while Kosareo and Ries (2006) as 45 years, Saiz et al. (2006) as 50 years, and Clark et al. (2008) as 40 years. Based on these studies, it can be concluded that green roof˝s lifespan varies between 40 to 55 years. All the analyzed three scenarios, for the two studied options, balanced the pollution created by material manufacturing process in the full lifespan of green roofs. However, it required almost 2/3 and 1/3 of the lifespan of green roofs, with non-recycled and recycled materials, respectively.

The typical disposal phase of green roofs includes dissemble of all the layers and transport them to landfills. The growing medium can be easily re-used in any other purpose and plants biodegrade fast; but not the polymers. Polymers degrade very slowly (Chung, 2000) and on a volume basis represent the 20% of landfills input (Seymour and Carraher, 1995). Therefore, recycling or reusing these materials becomes an attractive option. Additionally, recycling and reusing avoid the production of new materials. From an environmental point of view, it is recommendable the use of recycled polymers as green roofs layers; even though the recycling process has a negative environmental impact.

It is still beneficial to install green roofs with polymers; however, it is essential to explore materials that can replace the current use of polymers to enhance overall sustainability of green roofs. Some industrial and construction processes discard materials that do not meet the designed quality or intended purpose. Introduce these waste materials into green roof construction is the next immediate challenge.

Chapter 3: Social cost-benefit analysis of green roofs

Responsible construction management requires quantitative estimates of costs and benefits of the alternative uses of the environment (Brookshire *et al.*, 2006). Kosareo and Ries (2006), Clark *et al*. (2008), and Carter and Keeler (2007) have proven the economic advantages of green roofs. However, a lifecycle benefit-cost value represent a unit of area of a green roof is still not available. This chapter focuses on filling the gap with best available data with reasonable assumptions. Data related to lifecycle social-cost benefits of green roofs is extremely rare and mostly qualitative (difficult to quantify). The analysis presented in this chapter is based on an extensive literature review in multiple fields, such as forestry, engineering and plant biology.

This chapter estimates the present worth value of a green roof, by assigning a monetary value to the social-cost benefits that standard commercial green roofs generate over their lifecycle. Furthermore, results are compared with the NPV of an extensive, construction and demolition (C&D) waste based, experimental green roof. A probabilistic analysis was performed to estimate personal and societal costs/benefits. Additionally, a sensitivity analysis was conducted to calculate the payback period.

The results and the probabilistic analyses performed in this chapter are restricted to North America. An extensive literature review found that some economic green roof benefits (i.e. tax abatements) are only available in Canada and United States. In addition, the dollar values used as input data are subject to the North American market.

3.1 Materials and methods

Many studies have already been conducted to estimate the costs and benefits of green roofs in urban scenarios. Kosareo and Ries (2006), Clark *et al.* (2008), and Carter and Keeler (2007) focused their research on analyzing specific benefits of green roofs. They compared the initial construction cost, energy reduction, storm water management, and air quality of green roofs over conventional flat roofs, by estimating the net present value (NPV). Costs and benefits of green roofs vary depending on many characteristics such as: green roof type, weather conditions, or location of the structure. The location of a green roof in a building is also a factor that affects the NPV. Inflation, discount rate, labor, green roof efficiency, cost of materials, and energy consumption/savings are factors that vary between countries and regions. A generic methodology that takes into consideration these uncertainties (of green roofs), within an acceptable confidence level, is required to estimate lifecycle cost-benefits. Hence, a Monte Carlo simulation was conducted (US EPA, 1997).

The analysis was conducted for three main green roof types: (1) extensive green roof, (2) intensive green roof, and (3) C&D waste based extensive green roof. Cost and benefits of green roofs are divided in two categories in this paper: i.e. (1) personal and (2) social. Moreover, the functional unit used in the NPV analysis was dollar per square meter ($\$/m^2$). Personal costs and benefits of green roofs are those that obtained just by the owner or developer of the system. Consequently, social benefits are those that are obtained by society. Three analysis scenarios were performed to calculate NPV investment for each green roof type:

(1) NPV by considering only personal costs and benefits,

(2) NPV by considering only social costs and benefits, and

(3) NPV by considering both, personal and social costs and benefits

The three analyses considered the same variability of discount rate and inflation. The discount rate was assumed to vary from 2% to 8% (Statistics Canada. 2011). Similarly, based on Statistics Canada (2011), inflation has varied in the last decade from 1% to 4%. The maximum lifespan of a green roof is about 55 years (Acks, 2005); while, the minimum has been estimated about 40 years (Clark *et al.*, 2008). Hence, time variance in the Monte Carlo simulations was considered between 40 years and 55 years. In some cases a uniform distribution was assumed.

3.2 Theory and calculation

Economic analysis conducted in this paper considered variations in green roof performance related to: rainwater retention, air pollution removal, and energy reduction. Additionally, the input prices were gathered from different published and reliable sources, as noted in the following section. All dollar amounts have been converted to year 2012 valuations using the consumer price index (Statistics Canada, 2012).

As described in Table 3.1, uniform and triangular functions were used to model the analyzed parameters. Uniform distribution was used when data within the same range have the same probability. For instance, air quality improvement varies depending on many conditions. Thus, green roof air pollution removal cannot be described as a deterministic value. Differently, the landfill cost is related to the weight of the polymeric layers. The plastic layers weight of an intensive green roof varies depending on the thickness of each layer; however, one specific overall thickness is often repeated in many intensive green roofs. Therefore, a triangular distribution was used.

3.2.1 Personal costs and benefits

Many environmental benefits of green roofs can be taken as personal benefits. Retention and delay of storm water or energy consumption reduction are characteristics that may modify the structural and mechanical design of any building (Carter and Jackson, 2007; Mentens *et al.*, 2006). Nevertheless, in order to take advantage of these benefits, an initial investment is required to install a green roof.

3.2.1.1 Initial construction cost

There is a significant difference between green roof prices. The current costs in British Columbia, Canada for a standard extensive green roof varies from $\$130/m^2$-$\$165/m^2$ ($\$12/ft^2$-$\$15/ft^2$). The cost of a standard intensive green roof starts around $\$540/m^2$ ($\$50/ft^2$) (Bianchini and Hewage, 2011). Installation price depend on many factors such as labor and equipment costs. This study considers a uniform distribution that varies from $\$165/m^2$ to $\$540/m^2$ for intensive green roofs, while for extensive and C&D waste based extensive green roof vary between $\$130/m^2$ and $\$165/m^2$.

3.2.1.2 Property value

Natural landscapes benefit homeowners and investors by increasing the market value of properties. There is no direct literature to note property value increase due to green roofs. The value of an average house could increase by 7.1% if it is close to a woodland cover (Garrod, 2002). The Council of Trees and Landscape Appraisers (CTLA, 2003) found that provision of trees/greenery could add from 15% to 25% to the total value of properties. Furthermore, the Commission of Architecture and the Built Environment (CABE, 2005) showed that properties increase their price by 7% in locations landscaped with trees. Green roofs do not provide the same benefits as woodlands and forests. Thereby, this study conservatively considered that extensive green roofs and C&D waste based extensive green roofs could increase properties price by between 2% to 5%. While, intensive green roofs increase may vary between 10% and 20%. The total value of a property depends on many factors such as: area, location, structure type or proximity to public services. This benefit was estimated as an increase of the initial cost of green roofs. Therefore, for extensive and C&D waste based green roofs, the lower and higher range initial cost value was increased by 2% and 5% respectively. Similarly, for intensive green roofs, the lower and higher initial cost increased by 10% and 20%, respectively.

The analysis considered that extensive green roofs and C&D waste based extensive green roofs increase property value from \$132/m^2 (\$12/ft^2) to \$174/m^2 (\$16/ft^2). Commercially available standard intensive green roofs increase could vary between \$181.5/m^2 (\$16.8/ft^2) and \$648/m^2 (\$60/ft^2). This benefit is capitalized at the time of property sale.

3.2.1.3 Tax reduction

The City of New York enhanced installation of green roofs by allowing one-time tax abatement. The building owner can benefit with a tax reduction of \$48/m^2 (\$4.5/ft^2), if the green roof covers at least 50% of the total roof area (New York City, 2010). The maximum tax abatement is \$100,000. Both extensive and intensive green roofs are eligible for this reduction. This benefit is not available in all the cities of the world. Thus, this analysis considered that benefits vary from \$0/m^2 to \$48/m^2 (\$4.5/ft^2), for each green roof type.

3.2.1.4 Storm water retention

Storm water runoff due to the construction of impervious areas is a public concern since impervious areas in cities increase, more rainwater drain through public sewers (Mentens *et al.*, 2006). Vegetation and growing medium of green roofs contribute to retain and delay the amount of storm water (Schroll *et al.*, 2011). The city of Portland (2008) charged a monthly fee of \$7.91/1000 ft^2 (\$85/1000 m^2) for impervious areas to support its storm water system. However, the City offers a 35% discount for those properties that reduce effective impervious area. Green roofs qualify for the full discount; therefore, the building owners could save \$0.38/m^2 annually. Since not every city offers this discount, this probabilistic analysis considers that the benefit ranges between \$0/m^2 and \$0.38/m^2 (\$0.034/ft^2), for each green roof type

3.2.1.5 Avoided storm water in drainage system

Storm water retention potential of green roofs positively affects the drainage system/capacity of buildings. Similarly to the storm water retention benefit, as more rainwater is retained, less water drains through the building's drainage system. According to a two-year study conducted in Seattle, Washington by Post (2007), installation of green roofs allowed developers to reduce storm water infrastructure. Post (2007) estimated these savings structure as 30% to 60% of the green roof's initial cost. Therefore, the analysis conducted in this paper considered that extensive and C&D waste green roof avoided storm water infrastructure benefits between \$39/m^2 (\$2.8/ft^2) and \$100/m^2 (\$9.3/ft^2). For intensive green roofs this benefit varies between \$100/m^2 (\$9.3/ft^2) and \$324/m^2 (\$30/ft^2).

3.2.1.6 Energy reduction- cooling and heating benefit

Liu and Baskaran (2003) assessed the thermal performance of green roofs. Their study stated that green roofs work as an insulation layer for buildings. Thickness of the growing medium and plants protects rooftops from fluctuations in weather conditions (Sailor *et al.*, 2008). Lee *et al.* (2007) estimated that green roofs save between 1.8 kW/m^2 (0.17 kWh/ft^2) to 6.8 kWh/m^2 (0.63 kWh/ft^2) in cooling energy. Green roofs save 0.22 therms/m^2 (0.02 therms/ft^2)

in heating (natural gas) energy (City of Portland, 2008). Prices for cooling and heating can be estimated as \$0.1/kWh and \$1/therm, respectively (Lee *et al.*, 2007). Energy savings could vary among green roof types; however, there is no available data to quantify this difference. Thereby, this study accounted that the annual economic benefit of green roofs in heating is \$0.22/m^2 (\$0.02/ft^2); and for cooling vary between \$0.18/m^2 (\$0.017/ft^2) to \$0.68/m^2 (\$0.064/ft^2) for each type of green roof.

3.2.1.7 Longevity benefit

The expected lifespan of green roof varies from 40 to 55 years (Acks, 2005; Kosareo and Ries, 2006; Saiz *et al.*, 2006; Clark *et al.*, 2008), while the life of conventional roofs is about 20 years (City of Portland, 2008). The re-roofing cost of a conventional roof is estimated as \$160/m^2 (\$15/ft^2) (City of Portland, 2008). Hence, the owner of the building has to pay this cost in every 20 years. Since green roofs have a higher lifespan than conventional roofs, reduced cost of replacing a conventional roof is considered as a benefit. If the probabilistic analysis (Monte Carlo) randomly selected a time frame of 40 years, the cost of replacing was considered as \$160/m^2. Furthermore, if the Monte Carlo simulation randomly selected a time frame of more than 40 years, an owner would have to replace the conventional roof at least two times. In such a case, the benefit is estimated as double of the benefit of one conventional roof replacement. Therefore, a benefit of \$320/m^2 (for green roofs) was used to estimate the NPV.

3.2.1.8 Operation and maintenance (O&M) cost

Economic and environmental benefits of green roofs depend on their performance (Rosenzweig *et al.*, 2006). Consequently, operation and maintenance of green roofs are extremely important to ensure its positive impacts. Acks (2005) estimated that annual O&M cost of green roofs to be between \$0.7/m^2 (\$0.06/ft^2) to \$13.5/m^2 (\$1.25/ft^2). A uniform distribution was assumed to model the variability of O&M cost for each green roof type.

3.2.2 Social costs and benefits

Green roofs contribute to minimize many well-known environmental issues. Mitigation of urban heat island effect and improvement of air quality are examples of externalities that benefit the society (Kosareo and Ries, 2006; Getter *et al.*, 2009). Social costs and benefits of green roofs need to be quantified to determine their importance and promote their installation.

3.2.2.1 Air pollution

Green roofs materials manufacturing processes release toxic substances to soil, air, and water. Bianchini and Hewage (2011) estimated that 1 kg of polymer production (for green roofs); releases 2 kg of carbon (CO_2) and 3.8E-3 kg of nitrates (NO_x). Bianchini and Hewage (2011) considered only key air pollutants; however, more toxic substances may release to different media.

The amount of polymers used in extensive green roofs varies between 2.07 kg/m^2 to 3.27 kg/m^2 (Xeroflor, 2011). For the case of intensive green roofs, Xeroflor (2011) technical specifications fall into a triangular distribution. The plastics volume fluctuates between 0.87 kg/m^2 and 2.07 kg/m^2, with a most probable value of 1.17 kg/m^2 (Xeroflor, 2011). Intensive green roofs have thicker growing medium that can substitute some polymeric layers in extensive roofs. The goal of C&D waste based green roofs was to replace current polymer based green roof layers with reused construction waste. The only plastic material typically used in C&D green roof was the root barrier; therefore, the amount of polymers required is 0.47 kg/m^2.

Clark *et al.* (2008) estimated that the NO_x emissions tax as \$3375/ton, while the Kyoto protocol (1997) estimated the carbon tax as \$20/ton. Thus, this analysis considered that the carbon cost of commercial/standard extensive green roofs varying uniformly between \$0.083/m^2 and \$0.131/m^2; and for C&D waste based green roof as a constant value of \$0.019/m^2. In terms of the plastic volume, for the case of commercial/standard intensive green roofs the carbon cost fluctuates triangularly between \$0.035/m^2 and \$0.083/m^2, with a most probable value of \$0.045/m^2. Similarly, this study considered that the nitrates cost of commercial standard extensive green roofs varies uniformly between \$13.98/m^2 and \$22.07/m^2, and for C&D waste based green roof would be a constant value of \$3.17/m^2. In the case of commercial standard/intensive green roofs the carbon cost fluctuates triangularly between \$5.87/m^2 and 13.98 \$/m^2, with a most probable value of \$7.6/m^2.

The probabilistic analysis considered total air pollution cost as the sum of carbon and nitrates cost. Therefore, for extensive green roofs, the total air pollution cost varies uniformly between \$14.06/m^2 and \$22.20/m^2, while for C&D waste based green roof the cost is a constant value of \$3.20/m^2. In the case of intensive green roofs the carbon cost fluctuates triangularly between \$5.90/m^2 and \$14.06/m^2, with a most probable value of \$7.65/m^2.

3.2.2.2 Carbon reduction

Different types of plants can be grown on green roofs. Generally, Crassulacean Acid Metabolism (CAM) plants are preferred due their water conservation capacity under drought conditions (Getter and Rowe, 2006). Evidently, the oxygen-carbon dioxide exchange rate differs between plant types. Nevertheless, previous investigations have shown that 1 ha of green roofs remove between 72 kg to 85 kg of pollutants (Currie and Bass, 2005; Yang *et al.*, 2008). The carbon reduction tax is estimated as \$20/ton (Kyoto Protocol, 1997); therefore, the conducted probabilistic analysis considered that the annual benefit of carbon reduction varies from \$1.4E-4/m^2 (\$1.3E-5/ft^2) to \$1.7E-4/m^2 (\$1.6E-5/ft^2) for each green roof type.

3.2.2.3 Air quality improvements

Green roofs have been distinguished as an air pollution control technology (Schnelle and Brown, 2002). Air quality is related to the amount of dust, particulates, and nitrates (NO_x) in the air (Peck *et al.*, 1999; Carter and Keeler, 2007). The NO_x emissions credit is estimated as \$3375/ton (Clark *et al.*, 2005). Thereby, considering the green roofs air pollution removal range described in section 3.2.2.2, the improved air quality benefit would range between \$0.025/m^2 (\$0.002/ft^2) and \$0.03/m^2 (\$0.003/ft^2) for each type of green roof.

3.2.2.4 Reduction of infrastructure improvement costs

Storm water retention can be considered as a social benefit. As mentioned in section 3.2.1.4, green roofs absorb more rainwater; hence less water drains through public storm water systems. The city of Portland (2008) invested \$30/ m^2 (\$2.7/ft^2) per year to manage the storm water originated by impervious areas. Actual green roof water retention performance varies from 25% to 86% (Mentens *et al.*, 2006). From the available data, this study considered that the annual social benefit would fluctuate between \$8/m^2 (\$0.8/ft^2) and \$26/m^2 (\$2.4/ft^2).

3.2.2.5 Reduction of flood risk

Impervious surfaces in urban areas increase the volume of storm water runoff. Severe floods cause high economic losses, which adversely affect the national economy. The cost to the national economy of England and Wales, due to urban flooding, is estimated as £270 million (\$428 million) per year (Parliamentary Office of Science and Technology, 2007). The total area of England and Wales is 151,175 km^2 (Britain Tourism Board, 2012). Hence, England and Wales expend \$2831/km^2 (\$2.8E-3/m^2) annually for flood control. Green roofs reduce the risk of flooding by retaining and delaying the amount of runoff rainwater that enters the public sewage system (Forest Research, 2010).

As discussed in section 3.2.1.4, green roofs have the capacity to absorb 25% to 86% of rainwater. Therefore, green roofs could save from \$7.1E-4/m^2 (\$6.6E-5/ft^2) to \$2.4E-3/m^2 (\$2.3E-4/ft^2). However, flood risk varies from region to region. To include cities with low flood, this probabilistic analysis considered that the benefits of reducing of flood risk due to green roofs fluctuates between from \$0/m^2 to \$2.4E-3/m^2 (\$2.3E-4/ft^2).

3.2.2.6 Habitat creation

Habitat creation and protection is extremely important to mitigate the adverse effects of urban settings. The City of Portland (2008) invested \$275,000 per acre to purchase land and then restore it as a natural habitat. Green roofs replace impervious roof top areas with plants and soil, which attracts small animals such as butterflies, birds, bugs, and bees. In the case of insects, the growing medium in green roofs can provide a similar habitat to the habitat protected or restored in the city context (Schrader and Böning, 2006). This characteristic represents an avoided cost; thus, it can be considered as a social benefit. It is important to note that green roofs do not provide the same level of benefits as natural habitats. Therefore, this analysis assumed that an appropriate transfer of benefits would be 15% for extensive green roofs, and 30% for intensive green roofs. Habitat creation is not a common investment in many cities. Therefore, benefits that range from $0/m^2 to $10.2/m^2 ($0.94/ft^2), and, $0/m^2 to $20.4/m^2 ($1.8/ft^2), were used for extensive and intensive green roofs, respectively.

3.2.2.7 Aesthetics

Aesthetics are important in the designing and operational phase of structures; however, an objective estimation of its economic impact on the structure is difficult. Aesthetics can be valued with a stated preference method. This methodology asks individuals for their willingness to pay extra for a given good or accept compensation for a given harm (Wise *et al.*, 2010). For the particular case of structures, stated preference methods asks how much more is a consumer willing to pay, if the same structure is located in a different area. That willingness to expend more can be identified as the value of esthetic. CABE (2004) reported that buildings and houses that have a park nearby increased their price by 6%, while the structures that have view of the park increased their price by 8%. Furthermore, CABE (2005) found that the average premium of properties with direct view or within close proximity to local parks was 11.3% and 7.3% higher than other properties, respectively.

Green roofs do not provide the same level of benefits as local parks. This study assumes that the aesthetics benefit obtained from extensive green roofs varies from 2% to 5% of property value. For intensive green roofs the aesthetics benefit is considered that varies from 5% to 8% of the property. This social benefit was estimated as a percentage of the initial cost of green roofs. Therefore, this analysis considered that extensive green roofs and C&D waste based extensive green roofs increase property value from $2.6/m^2 ($0.24/ft^2) to $8.3/m^2 ($0.77/ft^2); while commercial standard intensive green roofs value addition could vary between $8.3/m^2 ($0.77/ft^2) and $43.2/m^2 ($4/ft^2).

3.2.2.8 Provision of recreational space

Intensive green roofs are also known as park-like roofs due to their similarities with public parks (Molineux *et al.*, 2009). Intensive green roofs provide recreational spaces in urban areas if they are designed for public use. A study conducted by De Sousa (2002) in Toronto found that the average investment cost of turning brownfields into parks is about \$200,000/ha (\$20/m^2). Since, intensive green roofs do not provide the same level of benefits as a public park, this study assumed that an appropriate transfer of benefits could vary between 30% and 70%. Therefore, the amount of public investment saved uniformly fluctuates between \$6/m^2 (\$0.55/ft^2) and \$14/m^2 (\$1.3/ft^2). Extensive green roofs do not provide this benefit.

3.2.2.9 Mitigation of urban heat island effect

Albedo is the reflection potential of any surface (Susca *et al.*, 2011). Dark surfaces reflect less solar radiation. Hence, absorb more energy. Urban areas have dark surfaces with low albedo such as concrete and asphalt. The combination of dark surfaces and lack of vegetation increases urban air temperature during summer months (Rosenfeld *et al.*, 1995). Temperature increase leads to an increase of energy demand due to the use of HVAC systems. Akbari *et al.* (1992) have found that peak urban electric demand in six cities in United States increased from 2% to 4% for each 1°C rise in daily maximum temperature, above the threshold of 15°C to 20°C. It is estimated that heat island effect increases electrical consumption by about 1 GW to 1.5 GW per year in the Los Angeles Basin (Akbari *et al.*, 2001). Los Angeles Basin has an area of 1,212 km^2 (United States Census Bureau, 2010); thus, the City's electrical demand varies between 0.83 kWh/m^2 to 1.24 kWh/m^2. Zinzi and Agnoli (2011) estimated that green roofs save 10% to 14% of the electrical energy consumed in cooling residential buildings. By considering the price of electricity as \$0.1/kW (Lee *et al.*, 2007), this analysis considers that green roofs can reduce urban temperature, represented as a benefit, between \$8.3E-3/m^2 (\$7.6E-4/ft^2) and \$1.2E-3/m^2 (\$1.6E-4/ft^2).

3.2.2.10 Landfill cost

The disposal phase of green roofs has different options. Materials can be recycled, re-used, or landfilled. Water retention, drainage, and root barrier layers are manufactured out of recycled polymers, which can be recycled again when green roof lifespan ends. However, many cities do not have the required technology to undertake the recycling process. Hence, this analysis considered the worst-case scenario: green roof layers are landfilled without any treatment process. Landfill operation and maintenance costs depend on many characteristics such as: size, technology, location and remaining capacity (Chang and Wang, 1995; Chang *et al.*, 2005; Jamasb and Nepal, 2010). Chang and Wang (1995) estimated that the average operation maintenance cost for landfilling without energy recovery is $55.75 (in year 1992). Jamasb and Nepal (2010) estimated a cost of €9.12/ton ($12.5/ton) of waste for the United Kingdom (UK). Similarly, Tsilemou and Panagiotakopoulos (2006) estimated that the operation and maintenance cost varies in Europe from €3.2/ton ($4.3/ton) to €45/ton ($61.7/ton).

As explained in the section 4.2.2.1, the amount of polymers used in extensive green roofs varies from 2.07 kg/m^2 to 3.27 kg/m^2, while for intensive green roofs the amount fluctuate between 0.87 kg/m^2 and 2.07 kg/m^2, with a most probable value of 1.17 kg/m^2 (Xeroflor, 2011). The only plastic material used in C&D waste based green roofs is the root barrier with a weight of 0.47 kg/m^2. Therefore, for extensive green roofs, the landfilling cost varies uniformly between \$8.9E-3/m^2 and \$0.20/m^2; while for C&D waste based extensive green roof varies from \$2.0E-3/m^2 to \$0.03/m^2. In the case of intensive green roofs, this cost fluctuates triangularly between \$2.7E-4/m^2 and \$0.13/m^2, with a most probable value of \$0.07/m^2. Tables 3.1-3.3 summarize the costs and benefits used for the probabilistic analysis.

Table 3.1 Data input for the personal probabilistic analysis

		Extensive green roof			C&D waste based green roof			Intensive green roof				
		Value ($/m2)		Function	Value ($/m2)		Function	Value ($/m2)		Function	Type	Time frame
Personal	Initial cost	130	165	Uniform	130	165	Uniform	165	540	Uniform	Cost	one time
	Property value	132.6	174	Uniform	132.6	174	Uniform	181.5	648	Uniform	Benefit	one time
	Tax reduction	0	48	Uniform	0	48	Uniform	0	48	Uniform	Benefit	one time
	Water retention	0	0.38	Uniform	0	0.38	Uniform	0	0.38	Uniform	Benefit	annual
	Cooling	0.18	0.68	Uniform	0.18	0.68	Uniform	0.18	0.68	Uniform	Benefit	annual
	Heating	0.22		Constant	0.22		Constant	0.22		Constant	Benefit	annual
	Avoid infrastructure cost	39	100	Uniform	39	100	Uniform	100	324	Uniform	Benefit	one time
	O&M cost	0.65	13.46	Uniform	0.65	13.46	Uniform	0.70	13.50	Uniform	Cost	annual
	Longevity	161.46		Constant	161.46		Constant	161.46		Constant	Benefit	every 20 years

Table 3.2 Data input for the social probabilistic analysis

		Extensive green roof			C&D waste based green roof			Intensive green roof				
		Value ($/m2)		Function	Value ($/m2)		Function	Value ($/m2)		Function	Type	Time frame
Social	Air pollution released	14.06	22.20	Uniform	3.20		Constant	5.90	14.06	Triangular	Cost	one time
	Carbon reduction	1.44E-04	1.70E-04	Uniform	1.44E-04	1.70E-04	Uniform	1.44E-04	1.70E-04	Uniform	Benefit	annual
	Improvement of air quality	2.65E-02	3.13E-02	Uniform	2.65E-02	3.13E-02	Uniform	2.65E-02	3.13E-02	Uniform	Benefit	annual
	Reduction of infrastructure improvement	8	26	Uniform	8	26	Uniform	8	26	Uniform	Benefit	one time
	Reduction of flood risk	0	2.4E-03	Uniform	0	2.4E-03	Uniform	0	2.4E-03	Uniform	Benefit	annual
	Habitat creation	0	10.20	Uniform	0	10.20	Uniform	0	20.40	Uniform	Benefit	one time
	Provision of recreational space	-	-	-	-	-	-	6	14	Uniform	Benefit	one time
	Mitigation of urban heat island effect	8.3E-03	1.7E-02	Uniform	8.3E-03	1.7E-02	Uniform	8.3E-03	1.7E-02	Uniform	Benefit	annual
	Aesthetics	26	8.3	Uniform	26	8.3	Uniform	8.3	43.2	Uniform	Benefit	one time
	Landfill cost	8.9E-03	0.2	Uniform	2.0E-03	0.03	Uniform	2.7E-04	0.13	Triangular	Cost	one time

Table 3.3 Economic data input for the probabilistic analyses

		Value		Function
Economic	Year	40	55	Uniform
	Discount rate (%)	2	8	Uniform
	Inflation (%)	1	4	Uniform

3.3 Lifecycle probabilistic analysis

This study considered manufacturing, construction, operation, and decommissioning phases of green roofs. Therefore, a cradle-to-grave lifecycle analysis was performed. It was assumed that green roof materials would be landfilled after decommissioning.

3.3.1 Probabilistic analysis

Monte Carlo analysis was performed to calculate the lifecycle NPV of green roofs. For each scenario mentioned in section 3.2, the analysis was conducted for 10,000 simulations, to ensure that all the possible combinations for every cost/benefit were randomly selected.

3.3.1.1 Extensive green roof

Figures 3.1-3.3 depict the histograms and cumulative density function (CDF) for the 3 analyzed scenarios.

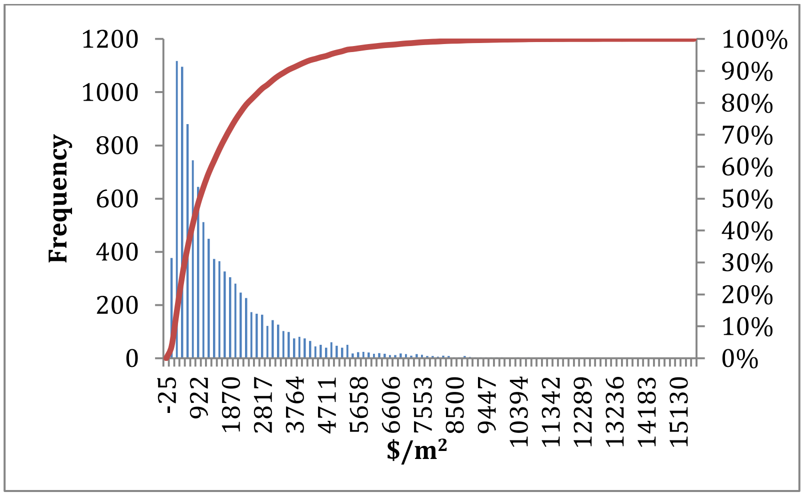


Figure 3.1 Extensive green roof personal NPV

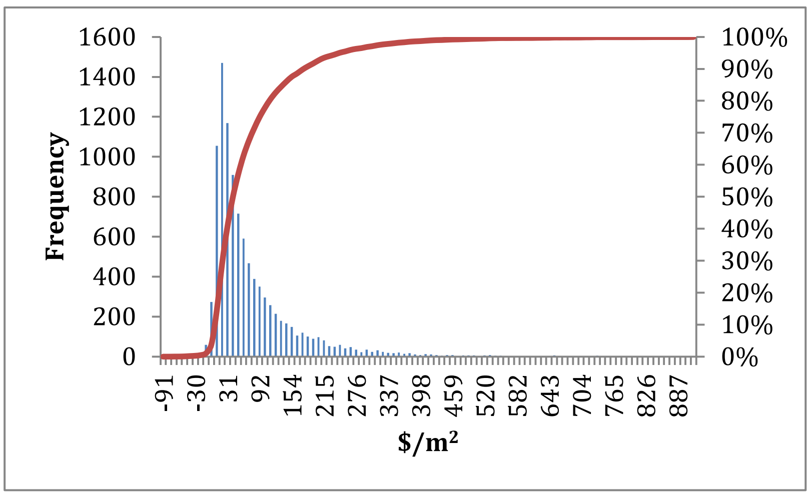


Figure 3.2 Extensive green roof social NPV

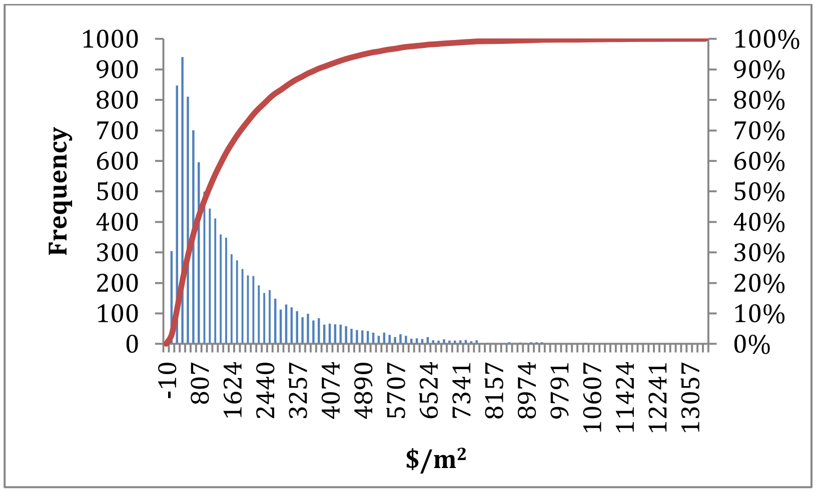


Figure 3.3 Extensive green roof personal and social NPV

As per the results shown in Figure 3.1, with 90% of confidence, the personal sector will obtain a benefit of up to \$3606/m^2 (\$331.75/ft^2). However, the most probable NPV benefit is \$291/m^2 (\$26.77/ft^2). Additionally, there is a probability of 1.0% that the NPV result a cost, not a benefit. Therefore, there is 0.82% confidence that extensive green roofs could cause losses up to \$25/m^2 (\$2.3/ft^2)

Similarly, as per Figure. 3.2, green roofs represent a social benefit of up to \$184/m^2 (\$17.12/ft^2), with a most probable benefit of \$21/m^2 (\$1.95/ft^2), with a 90% confidence. Additionally, there is a probability of 1.1% that the NPV results in a cost, not a benefit. Thus, there is 1.1% confidence that extensive green roofs could cause losses of up to \$91/m^2 (\$8.46/ft^2).

The third scenario considered the NPV calculation including the costs and benefits for both personal and social sectors. Figure 3.3 shows that the overall lifecycle benefit of installing extensive green roofs could be up to a maximum of \$3802/m^2 (\$352.04/ft^2), with 90% confidence. Additionally, the most probable benefit resulted is \$400/m^2 (\$/37.03ft^2). Moreover, there is a probability of 0.34% that the NPV results in a cost, not a benefit. Thereby, there is 0.34% confidence that extensive green roofs could cause losses of up to \$10/m^2 (\$0.93/ft^2).

3.3.1.2 C&D waste based extensive green roof

The personal benefits of extensive and C&D waste based green roofs are the same. Therefore, Figure 4.1 shows the CDF for the personal scenario of C&D waste based green roofs as well. Figure 3.4 shows the histogram and CDF for the social scenario; while, Figure 3.5 shows both, personal and social scenarios.

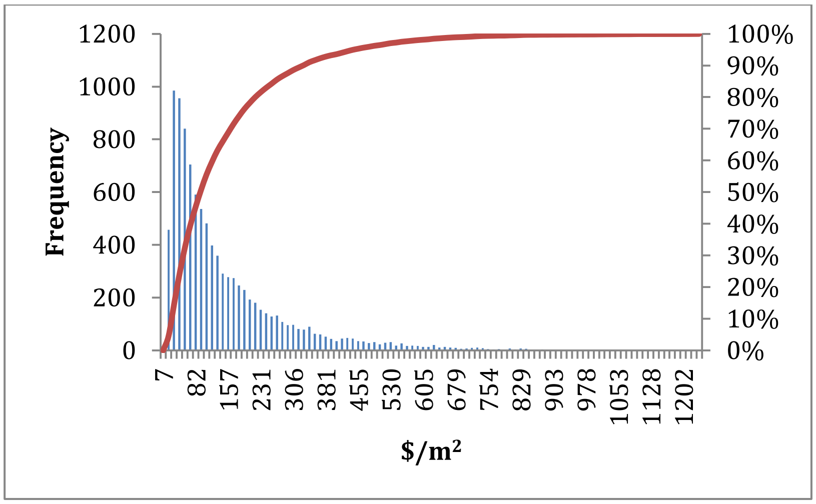


Figure 3.4 C&D waste based extensive green roof social NPV

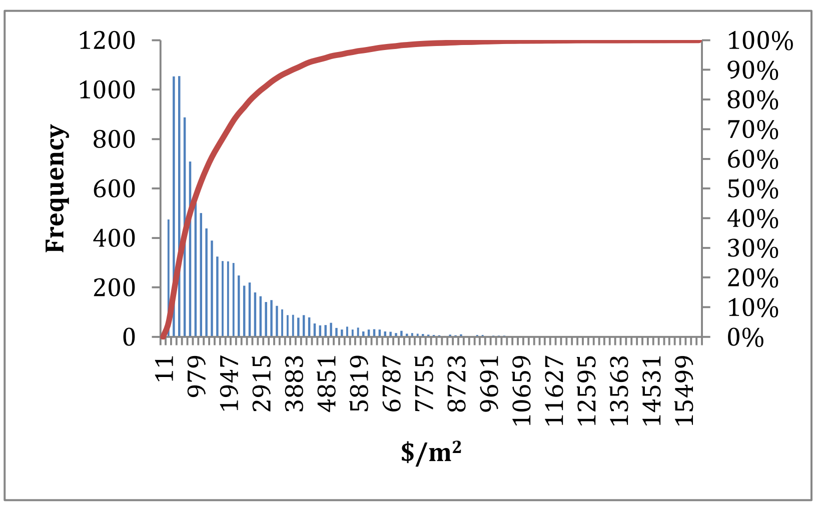


Figure 3.5 C&D waste based extensive green roof personal and social NPV

As discussed in section 3.3.1.1, Figure. 3.1, shows that the most frequent NPV is $291/m^2 ($26.77/ft^2). Additionally, there is a 90% confidence that the personal sector obtains a maximum NPV of \$3606/m^2 (\$331.75/ft^2). Furthermore, as per Figure 3.4, 90% confidence level indicates that green roofs represent a social benefit of up to \$331/m^2 (\$30.56/ft^2), with a most frequent benefit of \$32/m^2 (\$2.96/ft^2). The NPV calculation with costs and benefits for both personal and social sectors is shown in Figure 3.5. The most probable overall lifecycle benefit of installing C&D waste based green roofs is \$495/m^2 (\$45.83/ft^2). Moreover, benefits could be as high as \$3883/m^2 (\$359.53/ft^2), with 90% confidence.

3.3.1.3 Intensive green roof

Figures 3.6-3.8 depict the histograms and CDF for the 3 analyzed scenarios: (1) personal (2) social and, (3) both personal and social.

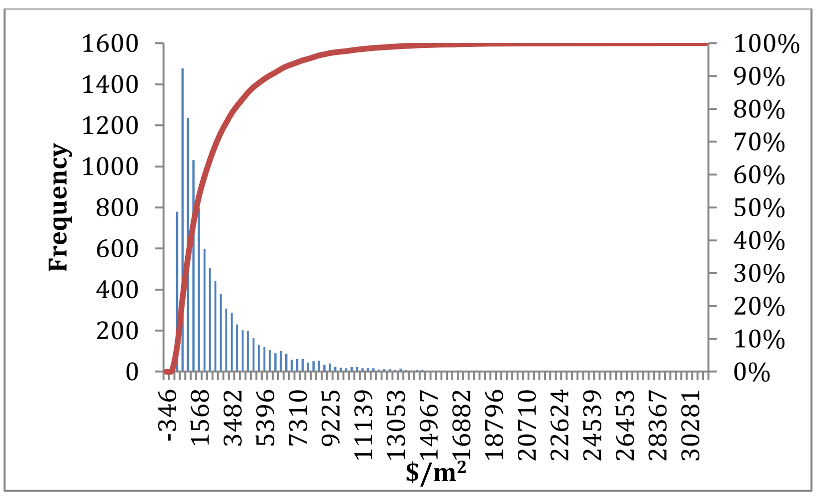


Figure 3.6 Intensive green roof personal NPV

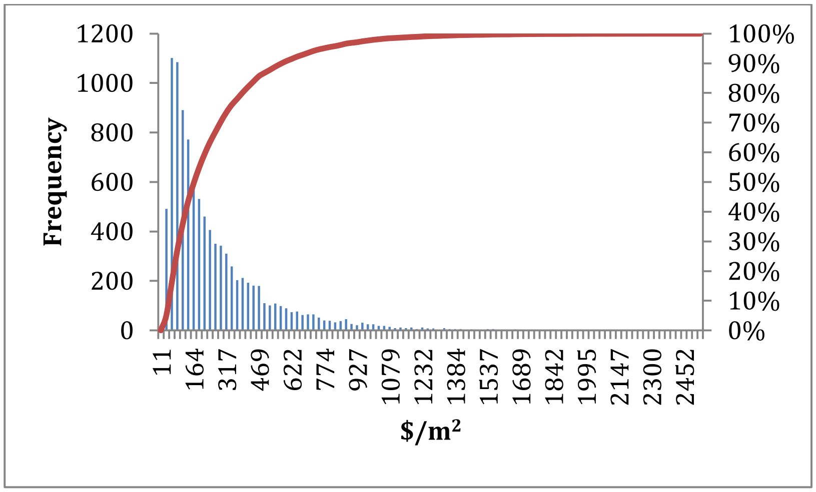


Figure 3.7 Intensive green roof social NPV

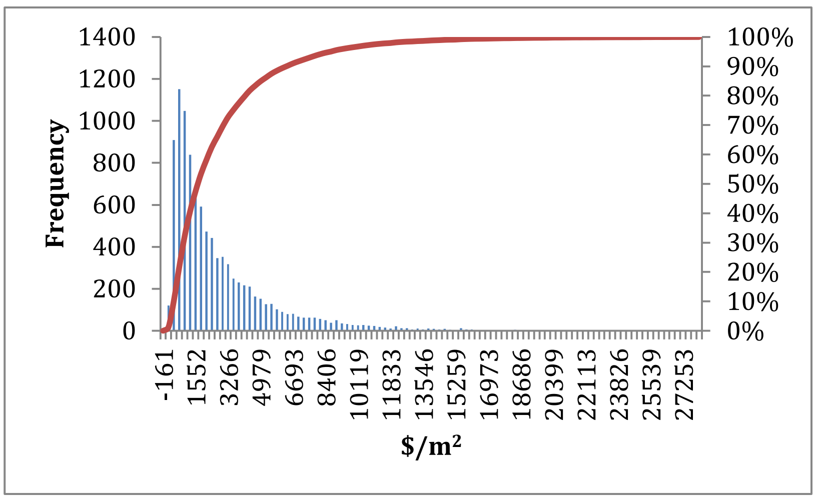


Figure 3.8 Intensive green roof personal and social NPV

Figure 3.6 indicates that, with 90% of confidence, the personal sector obtains a NPV of up to $5715/m^2 ($531.62/ft^2). Nevertheless, the most likely benefit is $611/m^2 ($56.84/ft^2). Additionally, there is a probability of 1.0% that the NPV results in a cost, not a benefit. Therefore, there is 1.0% confidence that intensive green roofs could cause losses of up to $346/m^2 ($32.19/ft^2). Figure 3.7 shows the social benefit of intensive green roofs. The most probable social benefit is $62/m^2 ($5.77/ft^2) and the maximum possible benefit could be $571/m^2 ($53.11/ft^2), with a 90% confidence. The combination of personal and social factors represents the overall economic benefits of installing intensive green roofs. Figure 3.8 shows that the most probable benefit of intensive green roofs is $696/m^2 ($64.74/ft^2).

Moreover, with 90% confidence, intensive green roofs benefits could be as high as \$6407/m^2 (\$596/ft^2). In addition, there is a probability of 0.03% that the NPV results in a cost, not a benefit. Therefore, there is 0.03% confidence that intensive green roofs could cause losses of up to \$161/m^2 (\$14.98/ft^2). Table 3.4 summarizes the results obtained from the probabilistic analyses.

Table 3.4 Results from the NPV probabilistic analyses

	NPV (\$/m^2)					
	Personal		Social		Social and personal	
	Maximum	Most probable	Maximum	Most probable	Maximum	Most probable
Extensive	3606	291	184	21	3802	400
C&D waste	3606	291	331	32	3883	495
Intensive	5715	611	571	62	6407	696

3.3.2 Payback period

The payback period is the time required to return the initial investment. In this particular case, the initial investment is the green roof construction cost while the return consists of all costs and benefits in green roof lifecycle. The payback period, by considering personal costs and benefits was estimated for each type of green roof. Additionally, influence of both personal and social cost and benefits on the payback period was also calculated.

3.3.2.1 Extensive green roof

Figure 3.9 shows the histogram and CDF of the personal payback. Figure 3.10 shows the payback period for both personal and social sectors.

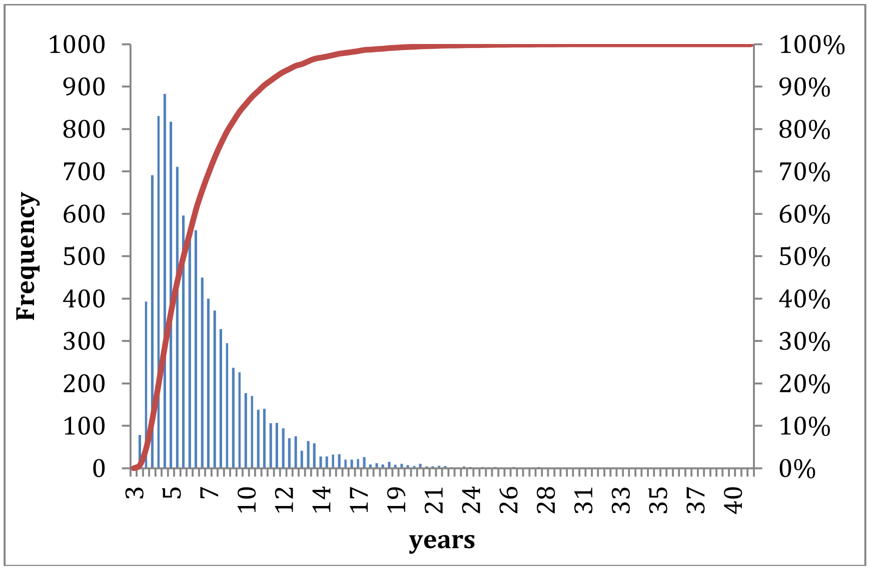


Figure 3.9 Payback period for personal NPV of extensive green roofs

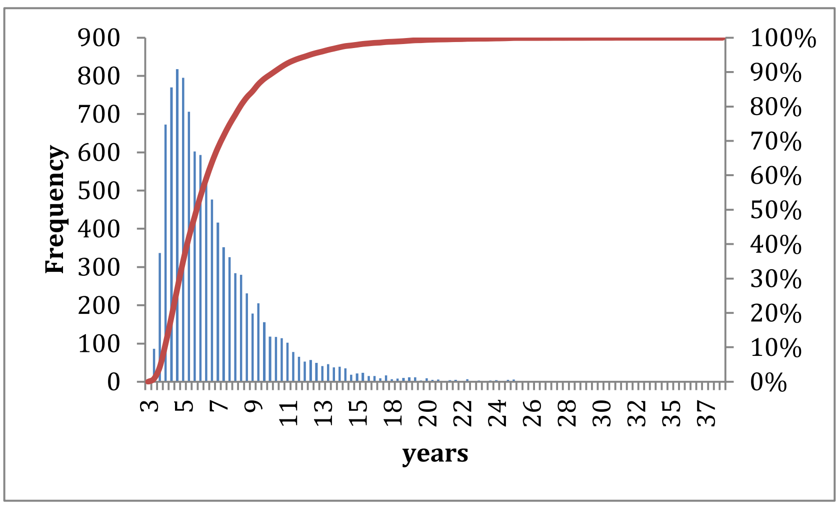


Figure 3.10 Payback period for personal and social NPV of extensive green roofs

The payback period, by considering only the personal costs and benefits could be up to 10 years with 90% confidence, and the most probable payback period is 4.6 years (55 months). If the social costs and benefits are included in the payback estimation, the most probable return is reduced to 4.2 years (51 months). Additionally with 90% confidence, the maximum payback is reduced to up to 10 years (120 months).

3.3.2.2 C&D waste based extensive green roof

The CDF of return of investment both personal and social sectors, are shown in Figure 3.11. The histogram and return of investment for the personal sector is shown in Figure 3.9, since the input for extensive and C&D waste based green roofs is the same.

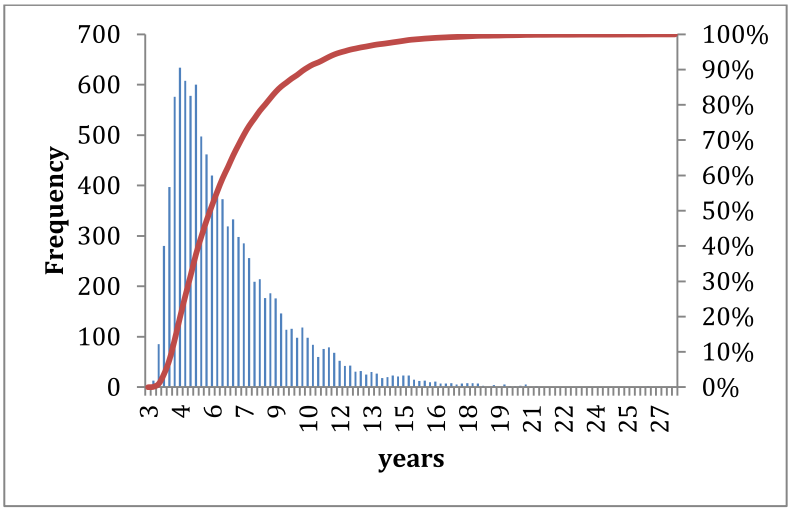


Figure 3.11 Payback period for personal and social NPV of C&D waste based green roofs

Equally as extensive green roofs, the maximum expected payback period, with only personal costs and benefits, is 10.4 years (124 months) with 90% of confidence. However, payback period is most likely to be 4.6 years (55.2 months). Similarly, with 90% confidence, costs and benefits for both social and personal sector, results in a maximum payback period of 9.7 years (116 months). Nonetheless, the return period is most likely to be 4 years (48 months).

3.3.2.3 Intensive green roof

Figure 3.12 shows the histogram and CDF for the personal payback, and Figure 3.13 shows the return of benefits for both personal and social sectors.

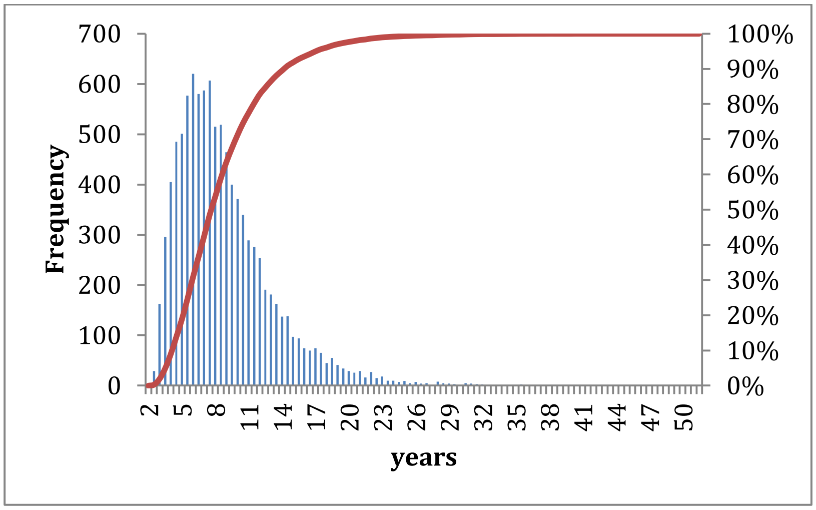


Figure 3.12 Payback period for personal NPV of intensive green roofs

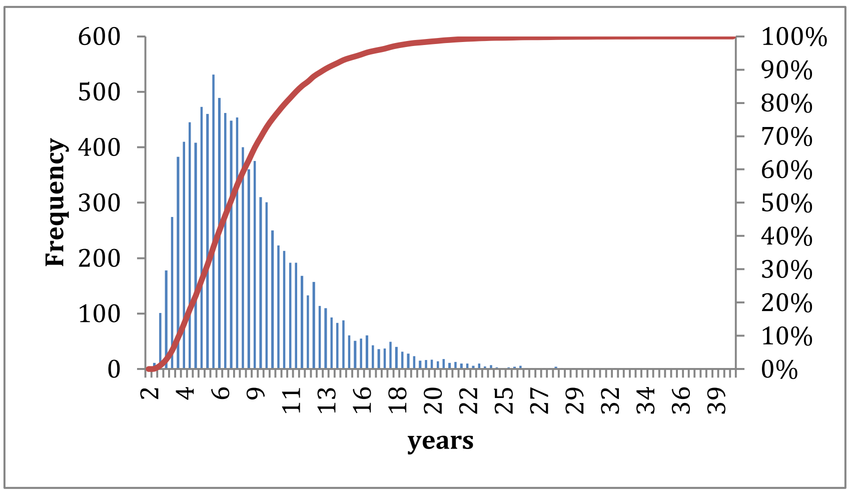


Figure 3.13 Payback period for personal and social NPV of intensive green roofs

The payback probabilistic analysis shows that the investment will be most probably returned in 6 years (72 months). The payback period can be as high as 14 years (90% confidence), for the personal sector. However, if the social costs and benefits are included in the calculation, the maximum return period could decrease to 12.8 years (154 months). In addition, the addition of social benefits reduces the most probable payback return period to 5.7 years (68 months).

Table 3.5 summarizes the results from the payback probabilistic analyses.

Table 3.5 Results from the payback period probabilistic analyses

	Payback (years)			
	Personal		Social and personal	
	Maximum	Most Probable	Maximum	Most Probable
Extensive	10.4	4.6	10	4.2
C&D waste	10.4	4.6	9.7	4
Intensive	14	6	12.8	5.7

3.3.3 Sensitivity analysis

NPV and payback calculation depends on all the factors shown in Tables 3.1-3.3. A sensitivity analysis was performed to determine which costs or benefits cause significant impacts in the overall NPV estimation. The sensitivity analysis was performed for all the green roof types; however, all the analyses showed the same finding: all green roof types are sensitive to the same parameters. Hence, Figure 3.14 depicts how a variation from -20% to 20% in the personal and economic factor affects the final NPV result of any green roof type. Similarly, Figure 3.15 shows how a variation in the social factors affects the final NPV estimation.

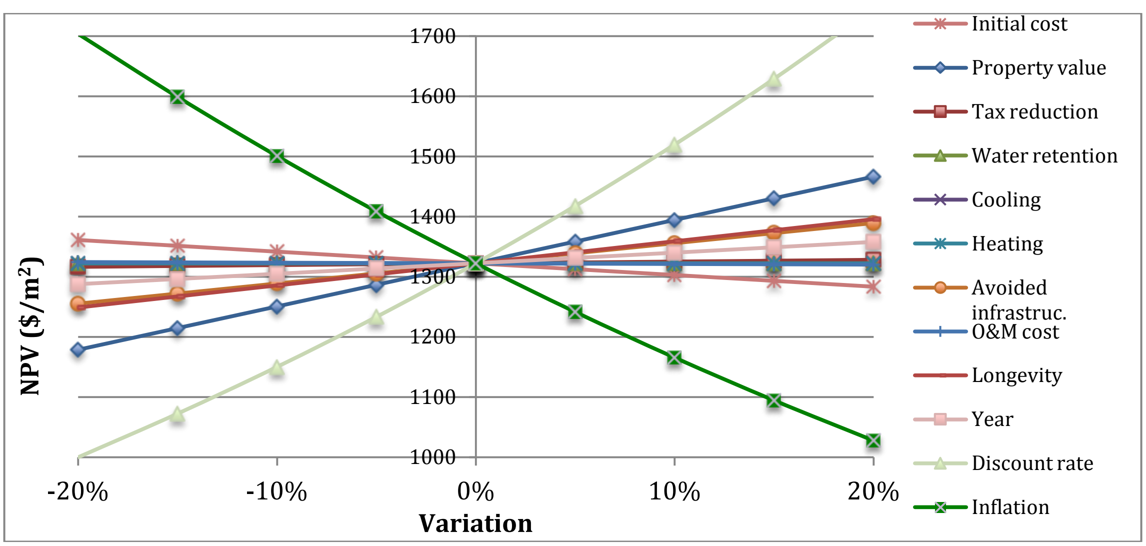


Figure 3.14 Sensitivity analysis for the personal and economic factors

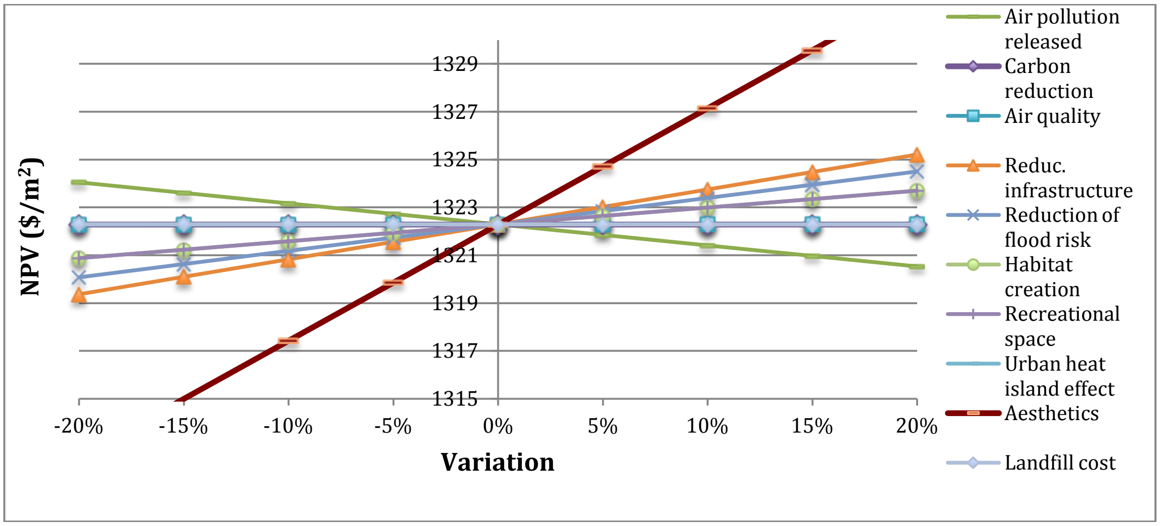


Figure 3.15 Sensitivity analysis for the social factors

As per Figure 3.14, the NPV calculation is sensitive to, in descendent order, inflation, discount rate, property value, longevity, avoided infrastructure cost, and initial cost. Moreover, Figure 3.15 shows that the NPV calculation is sensitive to, in descendent order, aesthetics, air pollution released, reduction of infrastructure improvement, and reduction of flood risk.

3.3.4 Break even analysis

A break even analysis was performed to the most sensitive values reported in Figure 3.14. Figure 3.16 and Figure 3.17 show the break even analysis of the economic factors and personal factors, respectively. The break even analysis was not performed to the social factors due to their small impact in the NPV calculation.

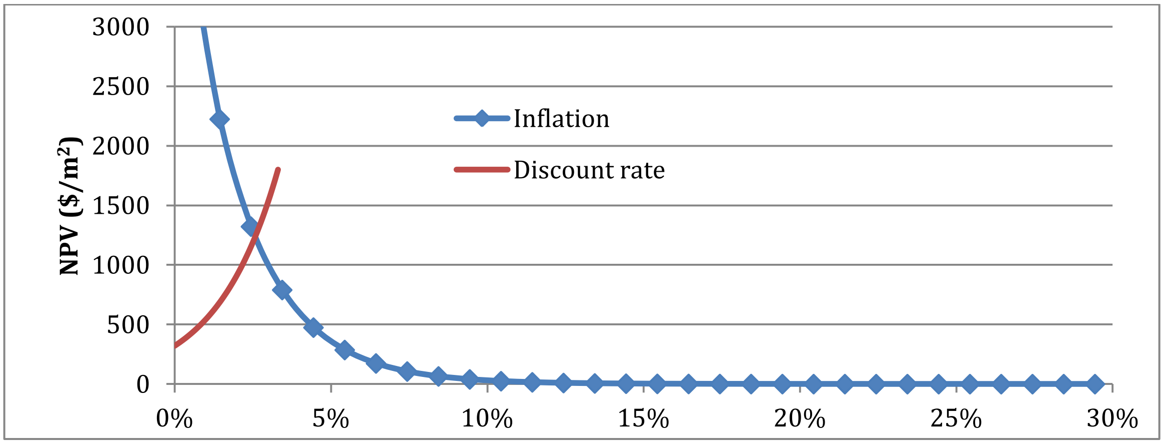


Figure 3.16 Break even analysis for the economic factors

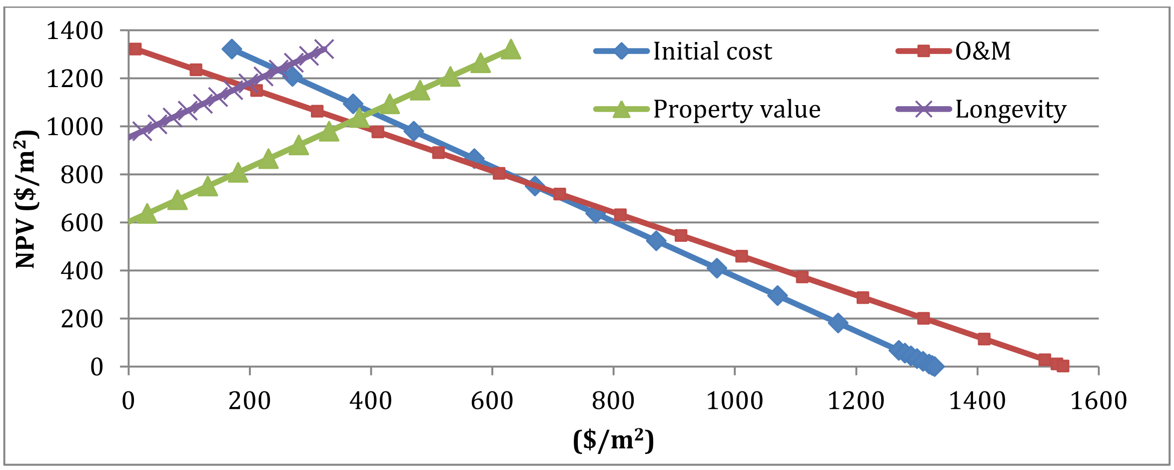


Figure 3.17 Break even analysis for the personal factors

Figure 3.16 show that inflation should be as high as 30% to reduce the NPV estimation to $\$0/m^2$. In addition, the analysis suggests that a reduction of the discount rate can never decrease the NPV to $\$0/m^2$. Equally, Figure 3.17 depicts that longevity and property value cannot reduce the NPV to $\$0/m^2$. Moreover, Figure 3.17 shows that the initial cost and O&M should as high as $\$1330/m^2$ and $\$1540/m^2$/year, respectively, to minimize the NPV to $\$0/m^2$.

3.4 Discussion

Data analysis demonstrated the potential economic advantages and disadvantages of building green roofs (per unit area). The probabilistic analysis considered three different scenarios for each green roof type. As shown in Figures 3.4 and 3.7, the social scenario resulted only in benefits for installing green roofs. Similarly, as per Figure 3.5, with 100% probability, the NPV of green roofs represented only benefits for both personal and social costs and benefits. The three scenarios analyzed for extensive green roofs may result in cost or benefits. While, for C&D waste based green roofs, only the personal scenario can result in cost or benefits. Moreover, the personal, and personal and social scenarios may results in cost or benefits for intensive green roofs. However, the NPV cost was low compared to the possible benefits.

As per Figures 3.1, 3.2, 3.3, 3.6 and 3.8, there is a probability that the NPV could be below $0/m^2 is of 0.82%, 1.1%, 0.34%, 1.0% and 0.03%, respectively. This means that there is, on average, a probability of 98% that the NPV will result in benefits for the personal sector. The highest frequencies shown in the histograms of Figures 3.1, 3.2, 3.3, 3.6 and 3.8 indicate the most probable values of the personal NPV. Hence, the most probable benefits for extensive green roofs are $291/m^2, $21/m^2 and $400/m^2 for personal, social, and personal and social scenarios respectively. For the case of C&D waste based green roofs is $291/m^2. Moreover, in the case of intensive green roofs the most probable benefits are $611/m^2 and $696/m^2, for the personal, and the personal and social scenarios respectively. In all cases, only the most probable return benefit of the social scenarios did not exceeded the initial installation cost. Similarly, the most probable payback period, if only personal cost and benefits are considered, is 6 years for intensive green roofs and around 4.6 years for extensive and C&D waste based green roofs.

Adding social benefits to the analysis improved NPV and payback results for all green roof types. When social benefits are considered, the financial losses of intensive green roofs become insignificant. Social benefits exceed social costs, since the main financial investment (installation cost) is paid by the personal sector. Adding social benefits to the analysis increased the NPV benefit by 5.5%, 7.8%, and 12.1% for extensive, C&D waste based, and intensive green roofs, respectively. Additionally, the analysis confirmed that green roofs are long-term investments with short-term returns. The highest most probable return of investment for both social and personal NPV is around 5.7 years. In the best-case scenario, lighter green roofs can reduce the payback period to 4 years.

Extensive and C&D waste green roofs mainly differ in the materials used as layers. From the personal perspective, C&D waste green roofs should be cheaper than extensive green roofs, since C&D waste can be easily obtained from any construction project. However, due to the lack of data, this benefit was not considered in the analysis. As shown in Table 3.4, the main advantage of C&D waste green roofs, over extensive green roofs, is their social benefits. Re-use of C&D waste to replace polymeric materials was included in the social lifecycle analysis. For instance, extensive green roofs create a higher manufacturing and landfill cost for society. In comparison to extensive green roofs, C&D waste based green roofs increased the most probable economic benefits by 2.2%. Thus, the re-use of materials is a profitable environmental solution.

The sensitivity analysis shows the costs and benefits that influenced the NPV and payback calculation. The economic factors that influenced NPV and payback period are discount rates and inflation, which will vary depending on economic conditions. The main non-economic factors influencing the NPV are the initial construction cost, longevity, property value, air pollution released and aesthetics. The importance of beautifying cities was justified in the analysis, as aesthetics plays an important role in NPV sensitivity. This finding suggests that society cares about landscape transformation, since it is willing to pay more to enjoy a natural view.

Energy prices, emission credits, and tax abatements are all factors that encourage friendly environmental technologies. At present low energy prices and modest emission credits and tax abatements provide weak incentives. However, as time passes energy price may increase due to scarcity. Similarly, air quality will become a priority if society continues to pollute the environment. In such a case, carbon and nitrate credits would become much more robust. Any of these scenarios would result in improved the NPV and payback.

As this analysis has shown green roofs have many social benefits. However, assigning an accurate dollar value to each one remains a challenge. Enhancement of biodiversity and purification of rainwater are a few examples of benefits that require further research. There is no question about the potential of these environmental benefits; however, they were not represented in the NPV and payback calculation due to the unavailability of data.

This analysis has shown multiple cost and benefits related to green roofs. However, it is important to note that the reported costs and benefits might reasonably be expected to change across different climate zones, particularly with reference to temperature. Additionally, tax abatements vary depending on local laws. This particular benefit might not even exist in many cities.

Chapter 4: Influence of green roofs on the seismic performance of structures

There is no available/published literature that depicts the performance of existing buildings by incorporating green roofs. Hence, this chapter evaluates the effects of green roofs on the seismic performance of existing frame buildings.

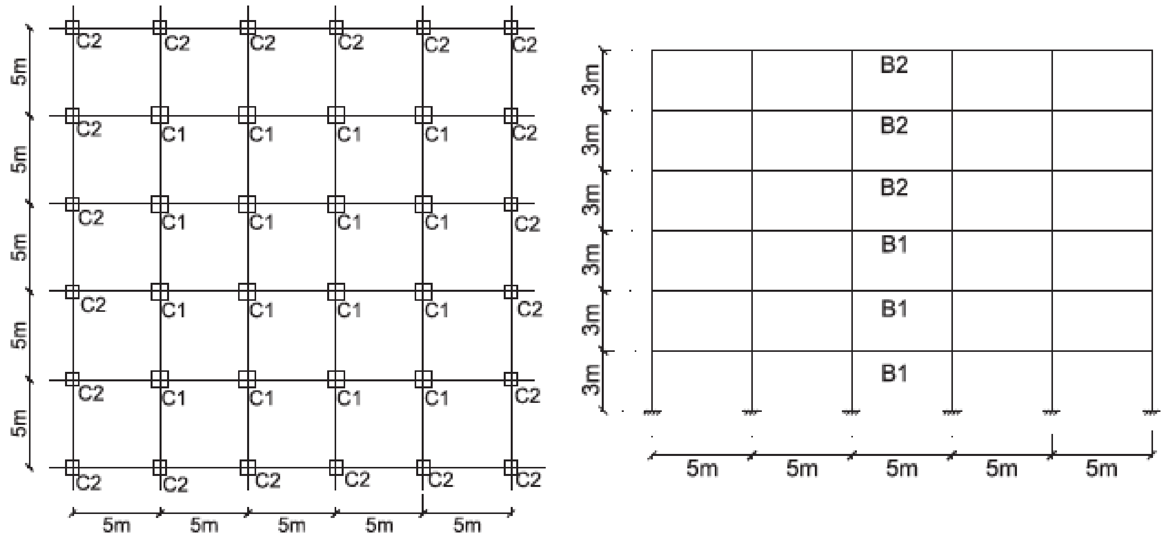
To have a comparative analysis in this chapter, 3 regular reinforced concrete (RC) buildings of different stories, designed according to current seismic standards, have been considered as per Alam *et al.* (2012). These buildings were not designed to support green roof on the top. Here, green roof was applied in each building with three different types; thus, nine RC frame buildings were analyzed. This chapter illustrates that without much modification or retrofitting, green roofs can be potentially installed in existing frame buildings, if they are designed according to current seismic standards.

The analyses performed in this chapter are subject to the following restrictions:

- The analyzed structures are frame type. The seismic behavior of wall type structures due to the installation of green roofs was not studied.
- The obtained results are limited to reinforced concrete frames. Steel and wood frames were not analyzed.

4.1 Properties and modeling of the structures

The typical plan and elevation of the steel RC buildings are shown in Figure 4.1a and Figure 4.1b. The structures were analyzed as per NBCC (2005) and designed as moderately ductile moment resisting frames based on equivalent static force procedure according to CSA A23.3-04 (2004). The strain peak stress, compressive (f'_c) and tensile strength for concrete is 0.2%, 35 MPa and 3.5 MPa respectively. Steel was modeled with a modulus of elasticity (E) of $2x10^5$ MPa and yield strength (f_y) of 400 MPa, while the strain hardening parameter was considered as 0.5%. For further details of the building design process the reader is referred to Alam *et al.* (2012).



(a) (b)

Figure 4.1 Typical building configuration (a) Plan, and (b) Elevation

4.1.1 Structures and roof modeling

The seismic behavior of the structures was modeled using SeismoStruct (Seismosoft, 2004a). Nine frame structures were modeled as planar frames. The program was used to determine the structural demands in the frame elements due to the application of the combination of loads and earthquake accelerations. The material properties, element sections, and loads were input in the software. The slabs were modeled as a distributed mass on the beams. Gravel flat roofs and green roofs are considered installed on the same roofing assembly. Therefore, to simplify the model, they were represented as dead loads. These different types of roofs were modeled as uniformly distributed mass on the roof beams.

The weight of each type of green roof varies with the material and water saturation. Fully saturated green roofs were considered as the worst-case scenario. Additionally, the thickest intensive green roof and the thinnest extensive green roofs available in the market were analyzed. Table 4.1 shows the materials, layers and weight considered in the analysis (Xeroflor, 2011). In addition, the weight of each RC frame considering the different types of roofs was estimated and is shown in Table 4.2.

Table 4.1 Weight of the different types of roofs (Based on Xeroflor 2011)

	Saturated weight (kg/m^2)		
Layers	Gravel flat roof	Extensive green roof	Intensive green roof
Root Barrier	-	0.47	0.47
Drainage and filter	-	0.80	0.80
Water retention	-	10.3	2.65
Growing medium and vegetation	-	37	225
Gravel	30	-	-
Total	30	48.57	228.92

Table 4.2 Weight of the RC frames

	Weight (kN)								
	3 storey			6 storey			8 storey		
	Gravel	Extensive	Intensive	Gravel	Extensive	Intensive	Gravel	Extensive	Intensive
Roof	18.39	29.77	140.36	18.39	29.77	140.36	18.39	29.77	140.36
Slab	1472			2943			3924		
Beams 1	238			265			265		
Beams 2	0			265			441		
Columns 1	119			343			565		
Columns 2	38			76			101		
Total	1886	1897	2008	3911	3922	4033	5315	5327	5437
Green roof weight contribution (%)	-	1.57	7.00	-	0.76	3.48	-	0.56	2.58

4.2 Dynamic time history analysis

Twenty real earthquake records were selected to conduct dynamic time-history analyses for each frame to predict and compare their seismic performances. The spectrum-compatible real accelerograms were randomly selected from the Pacific Earthquake Engineering Research Center (PEER, 2007) strong motion database. The ground motion data is detailed in Table 4.3.

The ground motions presented in Table 4.3 were scaled, assuming 5% damping, using the computer program SeismoMatch (Seismosoft, 2004b). The unscaled records are plotted with respect to the design spectral acceleration for Vancouver (NBCC, 2005) as shown in Figure 4.2.

Table 4.3 Ground motion records (Source: PEER strong motion database, http://peer.berkeley.edu)

Record	Event	Year	Station	M[a]	R[b] (km)	PGA (g)
1	Northridge	1994	Beverly Hills - 14145 Mulhol	6.7	9.4	0.430
2	Cape Mendocino	1992	Cape Mendocino	7	7	13.478
3	Victoria, Mexico	1980	Chihuahua	6.3	19	0.118
4	Coyote Lake	1979	Halls Valley	5.8	33.8	0.043
5	Hector Mine	1999	Amboy	7.13	43	0.198
6	Kobe, Japan	1995	Takarazuka	6.9	19.1	0.670
7	Loma Prieta	1989	Corralitos	6.9	3.9	0.498
8	Nahanni, Canada	1985	Site 2	6.7	4.9	0.389
9	San Salvador, El Salvador	1985	Geotech. Investig. Center	5.8	6.3	0.556
10	Sierra Madre	1991	LA-Obregon Park	5.61	27.4	0.203
11	Managua, Nicaragua	1972	Managua-ESSO	6.2	4.1	0.418
12	New Zealand	1987	Matahinia Dam	6.6	16.1	0.282
13	Gilroy	2002	Dublin	4.9	87	0.0069
14	Gilroy	2002	Foster City - Bowditch School	4.9	86.4	0.007
15	Parkfield	1966	Cholame - Shandon Array #12	6.2	17.6	0.0614
16	Norcia, Italy	1979	Cascia	5.9	4.6	0.171
17	San Fernando	1971	Borrego Springs Fire Station	6.6	214.3	0.0096
18	San Fernando	1971	Buena Vista	6.6	112.5	0.0117
19	Palm Springs	1986	Desert Hot Springs	6.1	6.8	0.309
20	San Francisco	1957	Golden Gate Park	5.3	9.6	0.111

[a] Magnitude

[b] Closest distance to fault rupture

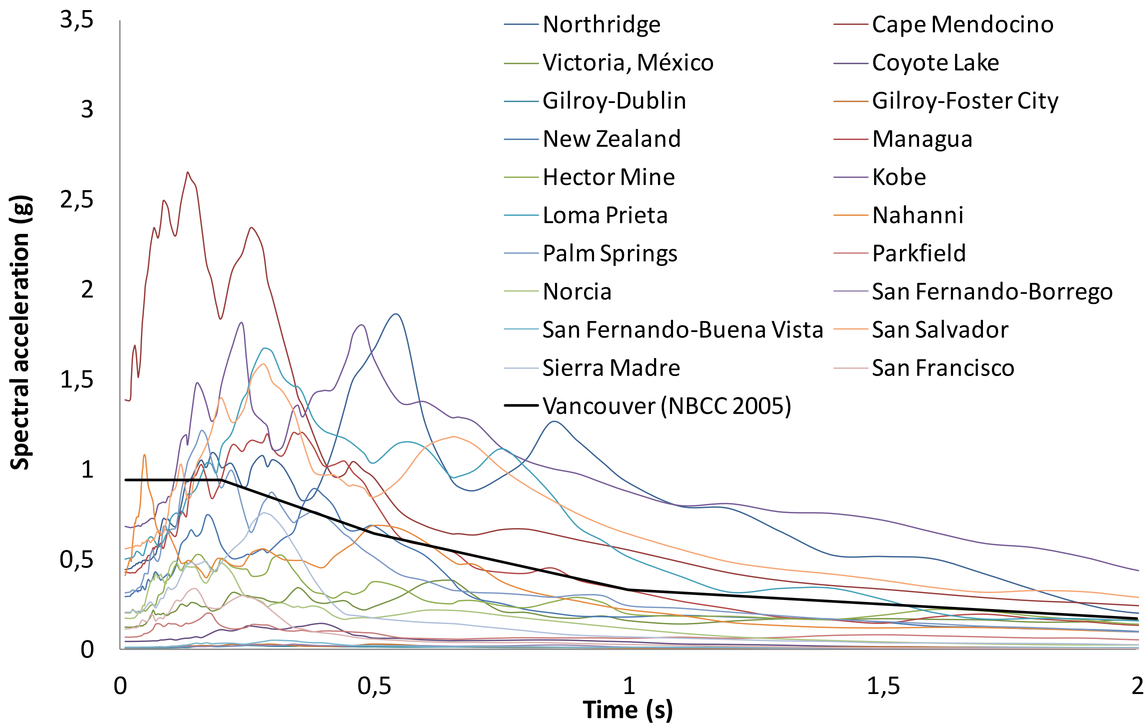


Figure 4.2 Variation of spectral acceleration with the period of structure

4.2.1 Time period

The fundamental periods of the structures was determined by considering both cracked and uncracked sections. The elastic cracked period was estimated by reducing the inertia of beams and columns. The American Concrete Institute (2008) suggests the use of modification factors 0.3 and 0.7 for rectangular beams and columns, respectively; to decrease the inertia of each element and model cracked sections. Table 4.4 shows the elastic period of the structures for uncracked and cracked condition. Additionally, Table 4.4 provides the code prediction values for period (T_1) as per the National Building Code of Canada (NBCC, 2005).

Table 4.4 Elastic cracked and uncracked period of structures

	Gravel roof			Extensive			Intensive		
Frame storeys	3	6	8	3	6	8	3	6	8
T_1 from Code	0.390	0.655	0.813	0.390	0.655	0.813	0.390	0.655	0.813
Elastic (sec)	0.452	0.692	0.873	0.454	0.694	0.875	0.478	0.713	0.893
Cracked (sec)	0.4929	0.745	0.933	0.495	0.747	0.935	0.520	0.767	0.954
	Variation elastic (%)			0.59	0.33	0.25	6.32	3.48	2.64
	Variation cracked (%)			0.62	0.36	0.26	6.82	3.74	2.81

The elastic periods of the structures were close to the code prediction. However, the 6 storey frame with gravel roof was the closest to the code prediction. Additionally, for all the frames, the cracked period compared to the corresponding elastic period, is slightly higher.

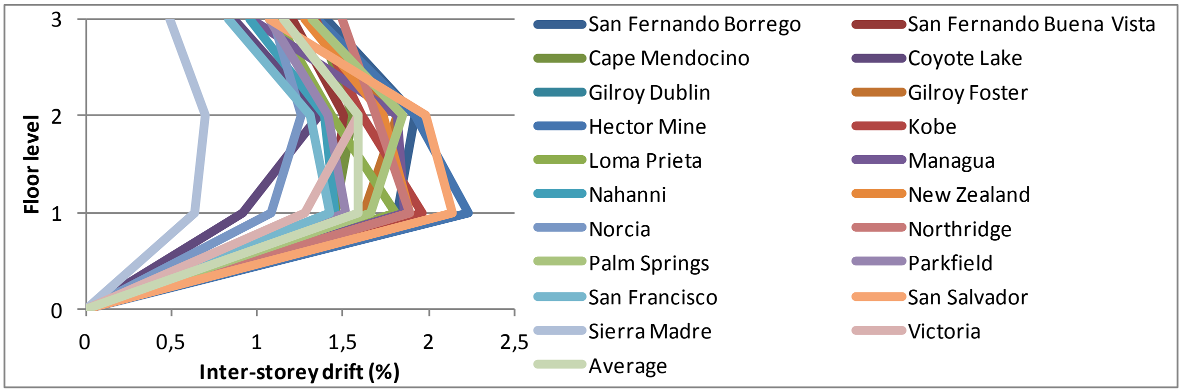
The analyses results show that the installation of green roofs increases the fundamental period of the structure in comparison to the structures with gravel roof. As the mass increases, the period of the structure increases. Furthermore, results show that the differences between the fundamental periods of the buildings with gravel flat roofs, extensive and intensive green roofs decrease with the increase in number of stories. For instance, in the case of 3, 6 and 8 storey structures with intensive green roofs, they had 6.32%, 3.48% and 2.64% higher elastic period, respectively compared to those with gravel roofs. Cracked periods followed similar trend.

4.2.2 Inter-storey drift demand

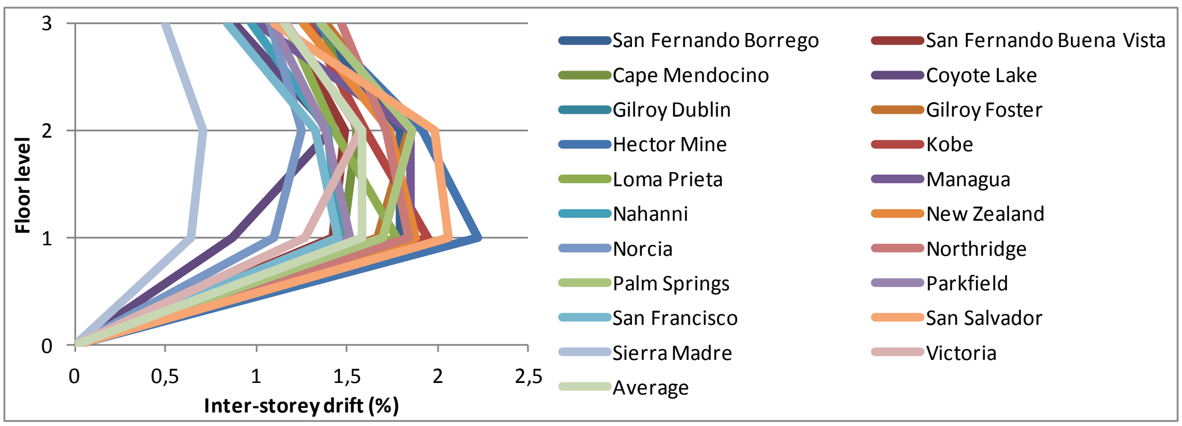
The inter-storey drift demand was computed from the dynamic analysis output. Results are shown in Figures 4.3-4.5. The results show that for all roof types, the maximum demand is in the same floor level. For the 3 storey frame, on average, the maximum inter-storey drift is experienced in the first and second floor, while for the 6 and 8 storey the maximum drift takes place, on average, in the forth and fifth floor, respectively. For the 3 storey frames, the average maximum demand is 1.58% for all the roof types; while for the 6 storey frames, the average maximum demands are 1.29%, 1.3%, and 1.32% for the gravel flat roof, extensive green roof and intensive green roof, respectively (Figure 4.3 and Figure 4.4). In the case of 8 storey frames, the average maximum demands are 1.20%, 1.21 and 1.24% for the gravel flat roof, extensive green roof and intensive green roof, respectively (Figure 4.5). In general, extensive and intensive green roof types increase the inter-storey drift compared to that of gravel flat roof type; however, this difference is minimum. For instance, intensive green roof increased the maximum inter-storey drift demand from 0.77% to 0.83%, while extensive green roof increased from 2.32% to 3.33%.

None of the inter-storey drifts exceeded the NBCC (2005) limit of 2.5%. The low inter-storey drift values indicate that the installation of green roofs do not pose any detrimental effect on the seismic behavior of the structural system. The stiffness of the RC frames is strictly related to the mechanical properties of the materials used for the structural elements. The results obtained are consistent with this well-known structural characteristic.

(a)



(b)



(c)

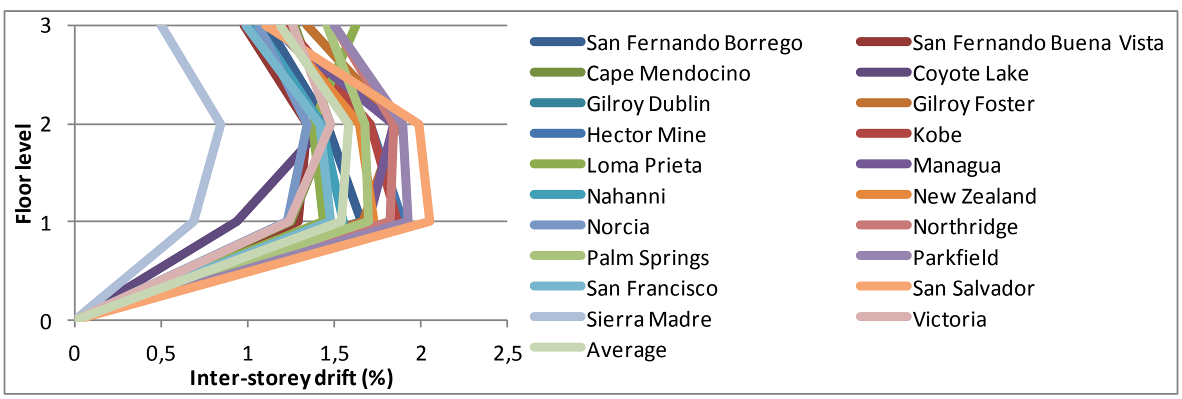
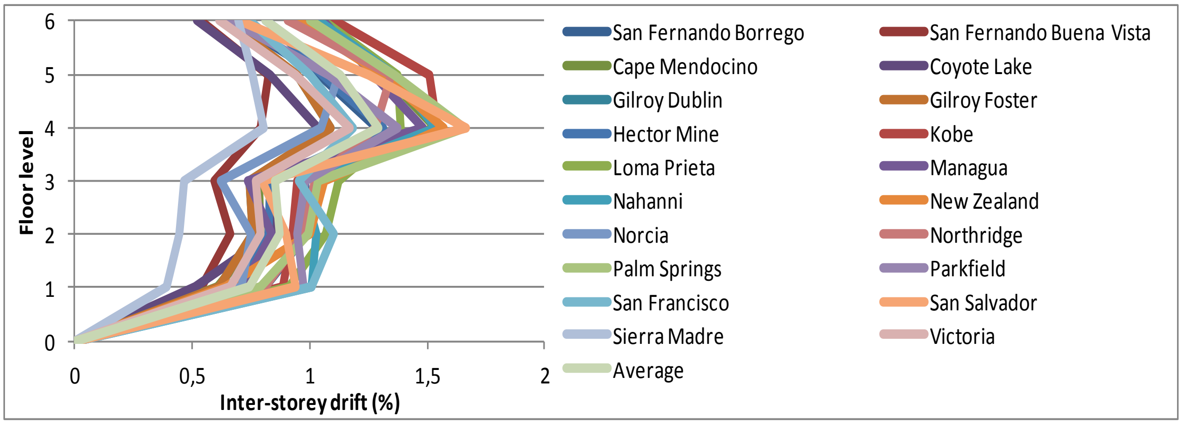


Figure 4.3 Inter-storey drift demand of 3 storey (a) gravel roof, (b) extensive and (c) intensive green roofs.

(a)



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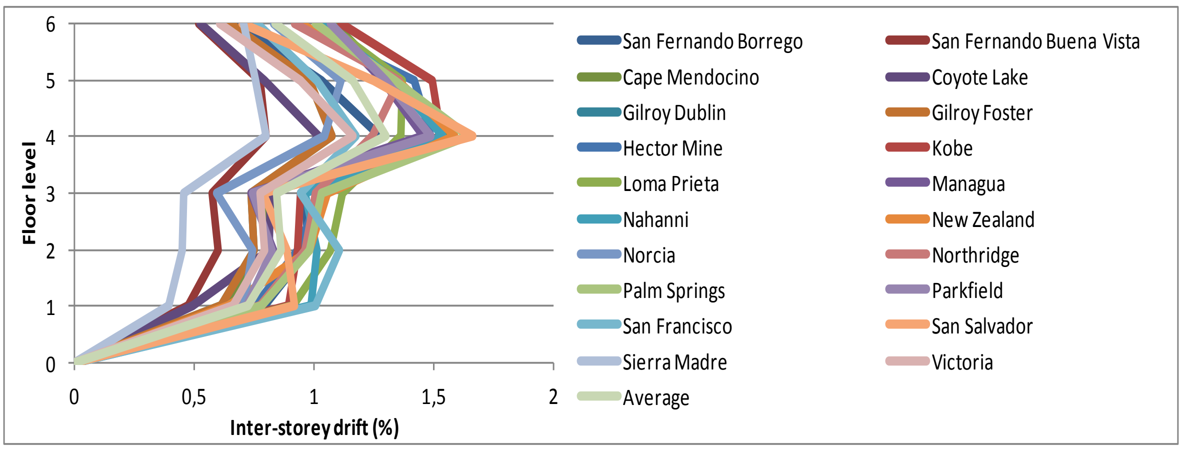


(c)

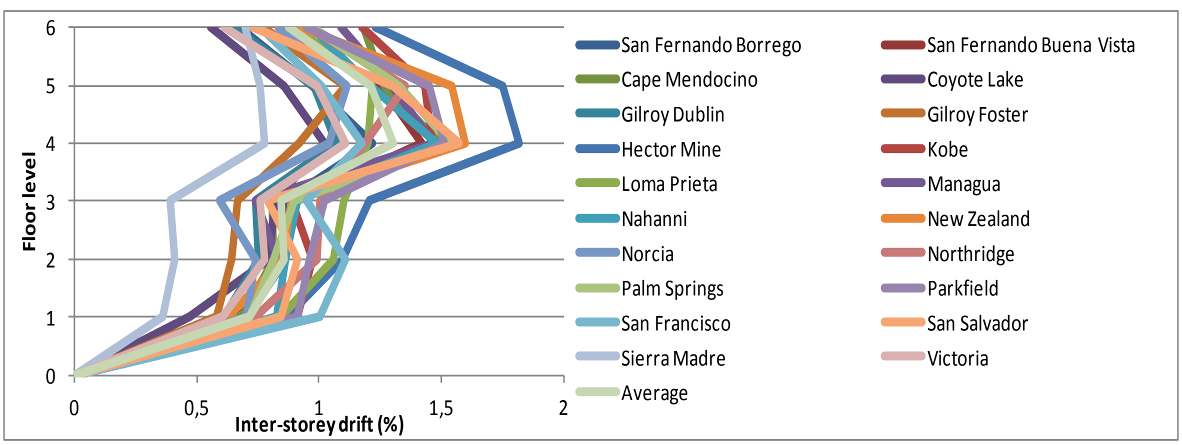
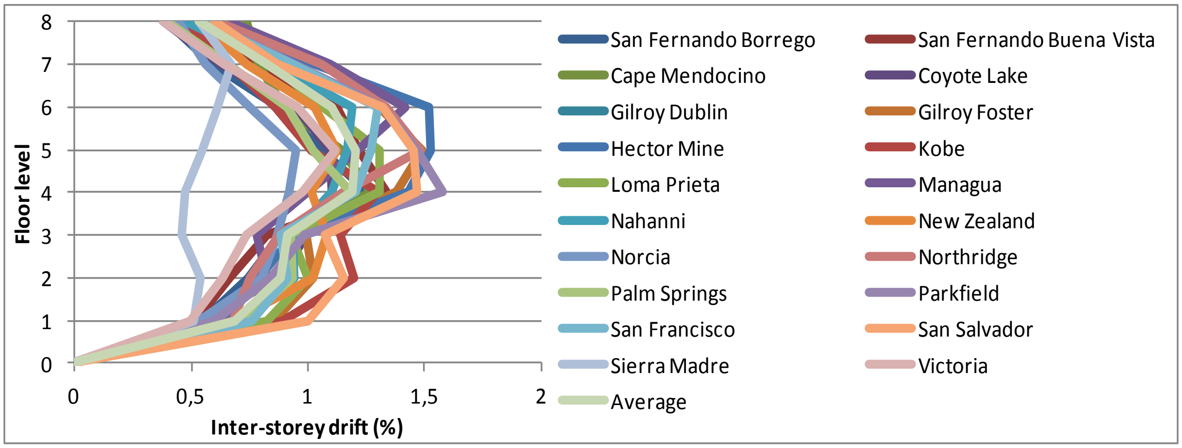
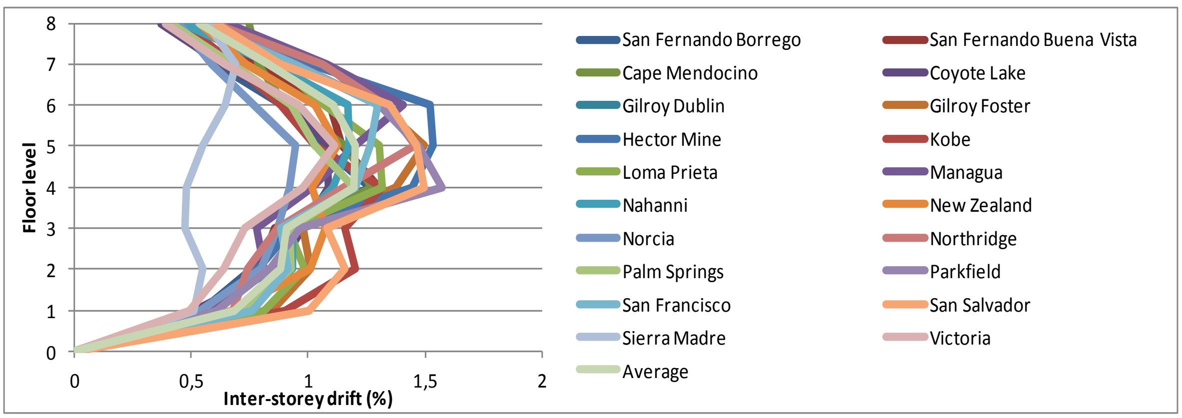


Figure 4.4 Inter-storey drift demand of 8 storey (a) gravel roof, (b) extensive and (c) intensive green roofs.

(a)



(b)



(c)

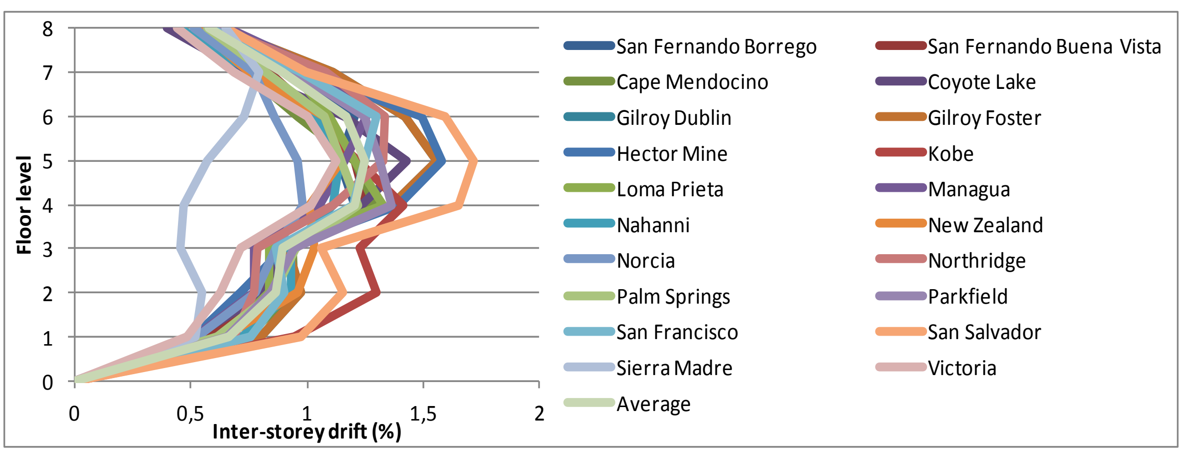


Figure 4.5 Inter-storey drift demand of 6 storey (a) gravel roof, (b) extensive and (c) intensive green roofs.

4.2.3 Roof drift demand

Figure 4.6 shows the roof drifts obtained for all the frames with different roof types under the selected earthquake motions. In the case of 3 storey frames (Figure 4.5a), on an average, intensive green roof caused the highest roof drift compared to those with other roof types. Similar results were obtained for the 6 and 8 storey frames (Figure 4.5b and Figure 4.5c).

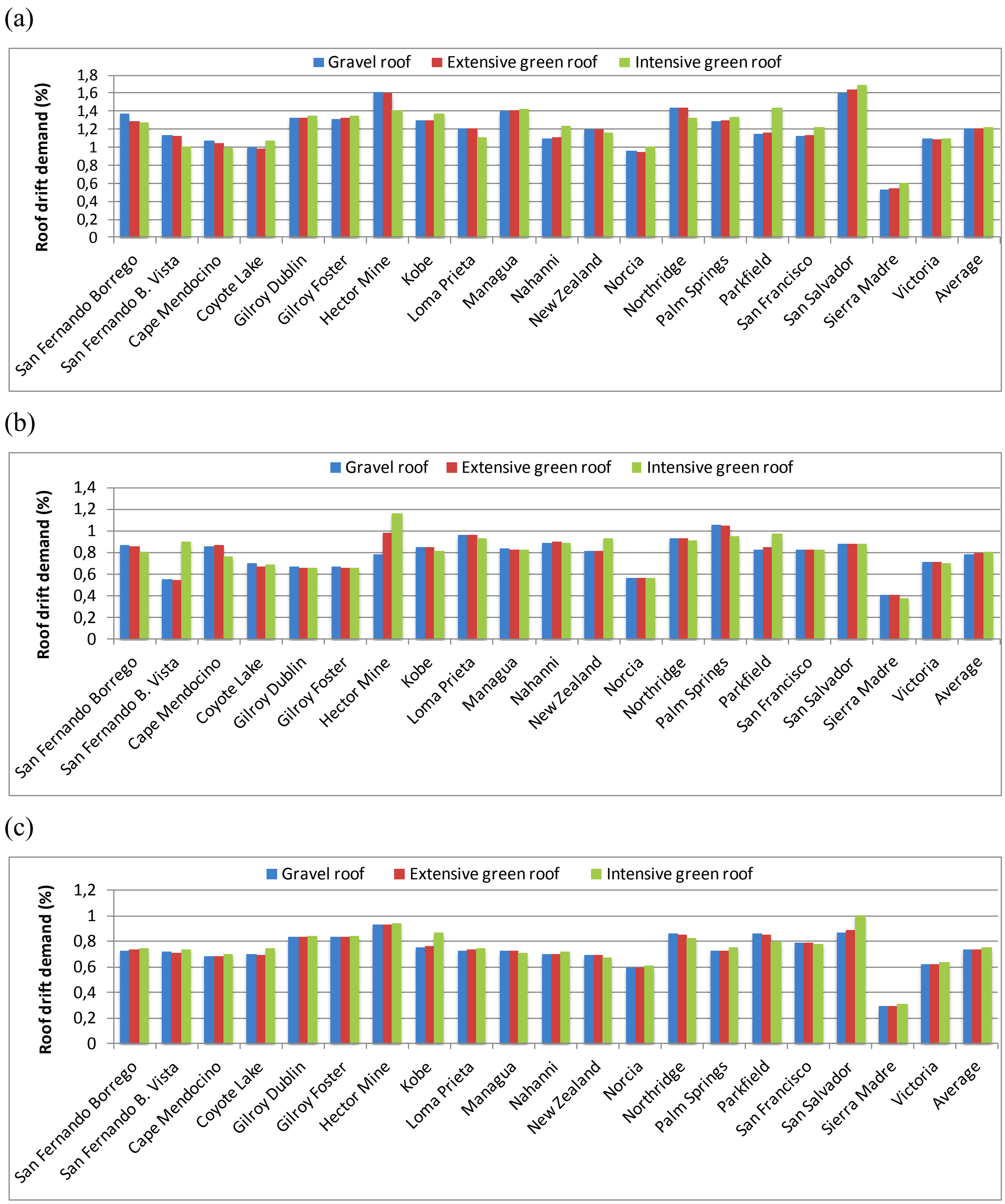


Figure 4.6 Roof drift demand for (a) gravel roof, (b) extensive and (c) intensive green roofs.

From Figure 4.6 it can be observed that in the case of 3 storey frame, the roof drift demand, compared to gravel flat roofs, is 0.14% lower and 1.14% higher for extensive and intensive green roof, respectively. In the case of the 6 storey frame, extensive and intensive green roofs increase the roof drift 0.90% and 3.45% respectively. The 8 storey frame follows the same trend as that of the 6 storey frame. Compared to gravel flat roofs, extensive and intensive green roofs increase the roof drift 0.1% and 2.46%, respectively. In general, as shown in Figure 4.5, as the frame height increases the roof drift demand decreases. Additionally, the difference between roof drift demands of the same storey frame with different roof types is not significant.

The seismic performance should be evaluated by comparing the capacity of the RC frames with that of the demand that those frames experience under a seismic event. The roof drift and base shear capacity are determined from a pushover analysis, while the demand is estimated by a dynamic time history analysis. Static pushover (SPO) method uses single degree of freedom (SDOF) models to determine the capacity of multidegree of freedom structures (MDOF). Incremental dynamic analysis (IDA) shows that MDOF structures increase their system capacity under an earthquake (Vamvatsikos and Cornell, 2002); therefore, an incremental factor should be used while utilizing the SPO results. The capacity curve discrepancy factor (CCDF) defines the difference between forces and moments of the SPO curve and the dynamic pushover curve (Papanikolaou *et al.*, 2006). On average, dynamic pushover results are 31.25% higher than the SPO (Zeus, 2004). Table 4.5 summarizes the capacity obtained from SPO analysis conducted by Alam *et al.* (2012).

Table 4.5 Base shear and roof drift capacity

	3 storey	6 storey	8 storey
Maximum displacement (m)	0.169	0.207	0.393
Base shear capacity (kN)	600	922	1050
Base shear capacity with CCDF (kN)	788	1210	1378

Figure 4.7 shows the roof drift capacity/demand ratio for all the frames with different roof types. Results show that the capacity/demand ratio for intensive green roof is slightly lower than the other roof types; however, this difference is minimum. In the case of 3 storey frames, the extensive green roofs, compared to gravel flat roofs, have 0.15% higher capacity/demand ratio; while in the cases of extensive green roofs of the 6 and 8 storey

frames, the ratios are 0.90% and 0.04% lower, respectively compared to those of gravel flat roofs. Compared to gravel flat roof, the intensive green roof capacity/demand ratio is 1.1%, 3.3% and 2.4% lower for 3, 6 and 8 stories, respectively. In addition, the results show that for all the frames have a higher roof drift capacity compared to its demand during an earthquake.

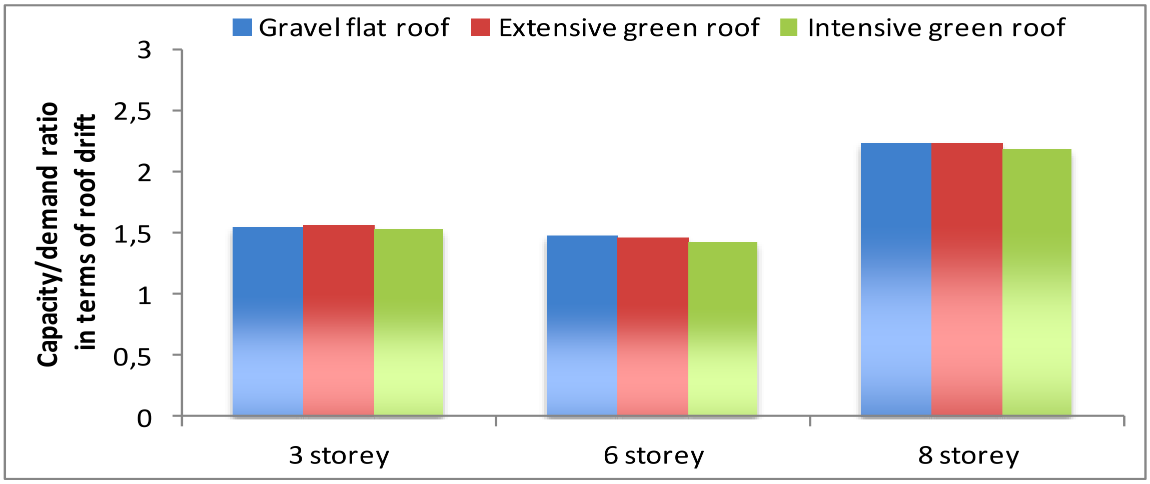
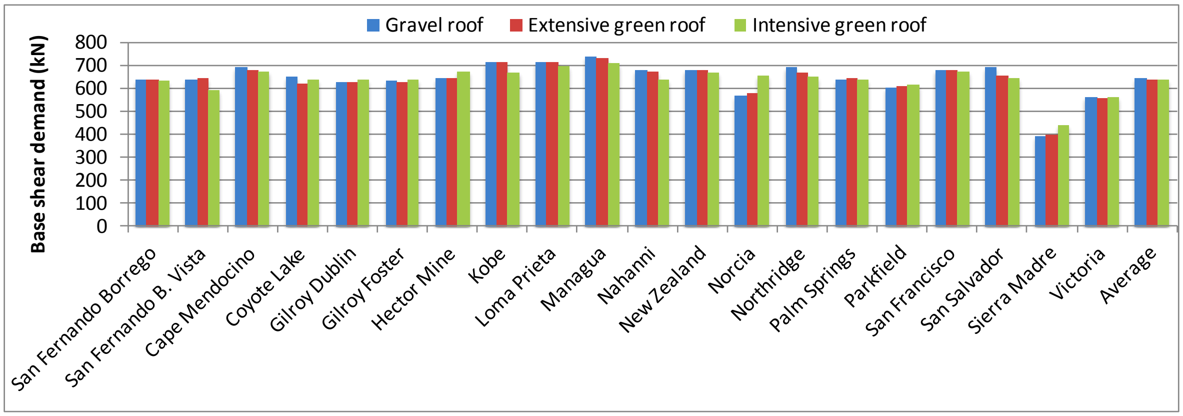


Figure 4.7 Roof drift capacity/demand ratio

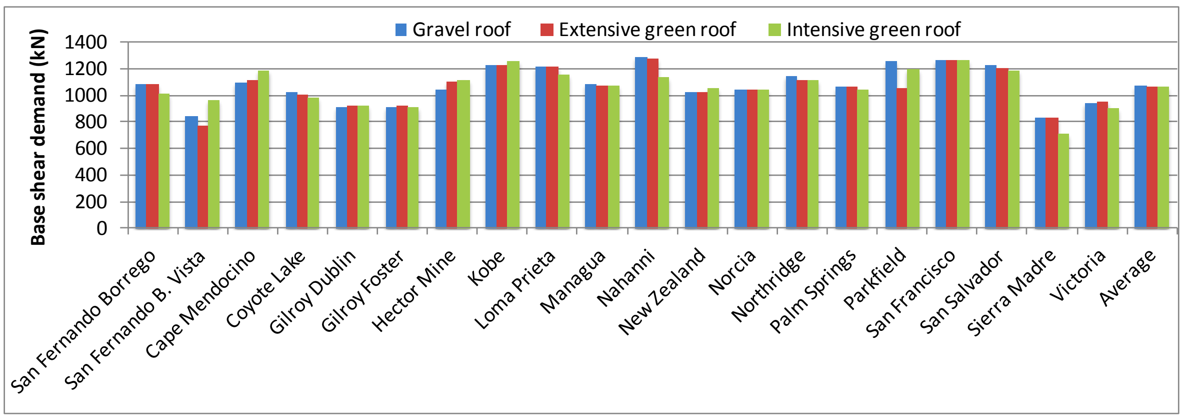
4.2.4 Base shear demand

Figure 4.8 shows the base shear demand for all the frames with different roof types under the selected ground motion records. In the case of 3 storey frames (Figure 4.8a), the intensive green roof caused the highest base shear. Similar results were obtained for 6 and 8 storey frames (Figure 4.8b and Figure 4.8c).

(a)



(b)



(c)

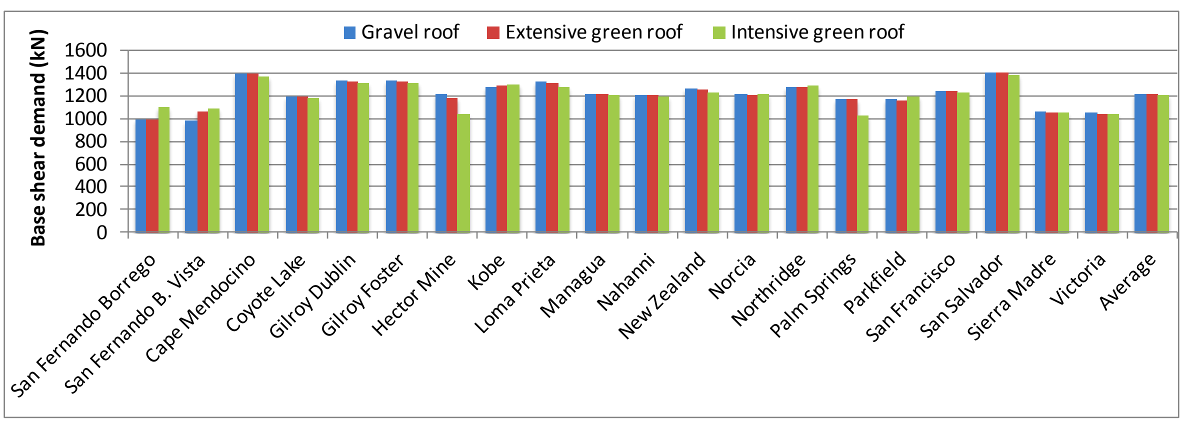


Figure 4.8 Base shear demand for (a) gravel roof, (b) extensive and (c) intensive green roofs.

From Figure 4.8 it can be observed that on an average the base shear demand decreases as the roof weight increases. However, these differences are very small. Compared to gravel flat roofs, extensive green roof reduces the base shear demand by 0.85%, 1.20% and 0.20% for 3, 6 and 8 storey frames, respectively. Similarly, compared to gravel roofs, intensive green roofs reduce the base shear demand by 1.10%, 1.40% and 1.3% for 3, 6 and 8 storey frames, respectively.

Figure 4.9 shows the seismic base shear capacity/demand ratio for all the frames with different roof types. Results show that all the frames possess a higher base shear capacity compared to its demand during a seismic event. Additionally, the capacity/demand ratio gradually decreases with the increase of storey numbers because of higher demand for taller frames. Furthermore, Figure 4.9 depicts that the capacity/demand ratio for the same frame height increases with the increase of the roof weight. Nevertheless, these differences are negligible. Compared to gravel flat roofs, extensive green roof increases the base shear capacity/demand by 0.82%, 1.23% and 0.13% for 3, 6 and 8 storey frames, respectively. Similarly, compared to gravel roofs, intensive green roofs increase the capacity/demand ratio by 1.06%, 1.41% and 1.16% for 3, 6 and 8 storey frames, respectively.

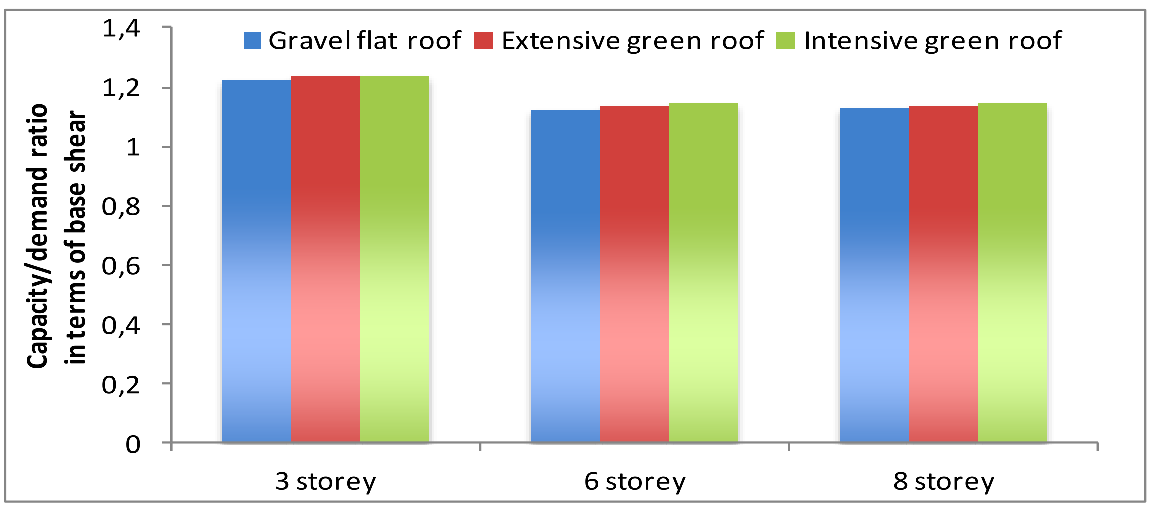


Figure 4.9 Base shear capacity/demand ratio

4.3 Discussion

Results obtained from the time history analyses show that the green roofs increase the period of the RC frames, inter-story drift and roof drift demand; however, reduces the base shear demand. It was expected that green roofs increase the base shear because they add more weight to the structure.

The base shear experienced by a structure during an earthquake depends on the Weight (W) and spectral acceleration ($S(T_a)$) at the time period of the structure. As the weight increases, the base shear increases. Similarly, the base shear proportionately increases/decreases with the spectral acceleration. Green roofs impact both, weight and spectral acceleration of the structure, but in opposite directions. Green roofs clearly add weight to the structure; however, increases the time period, which in turn reduces the spectral acceleration. Therefore, although a green roof is adding weight to the structure, it is increasing the time period, thus reducing $S(T_a)$. The combination of these impacts compensates the estimation of the base shear (V). For the particular RC frames addressed in this chapter, the effect of decreasing the spectral acceleration is higher than the extra weight effect.

Additionally, Figure 4.9 depicts that as the height of the frame increases, the base shear capacity/demand ratio decreases; hence, the base shear demand is higher for higher stories. For each type, green roof weight is constant regardless the structure type, but the weight of each frame increases with the height increase. Green roof extra weight contribution, as a percentage of the total weight, is minimum and decreases when the weight of the structure increases (Table 4.2). Similarly, the impact of green roofs on the time period compared to gravel roofs becomes insignificant as the frame height increases. Results show that the impact of green roofs in the time period is higher than that of the impact from the extra weight contribution (percentage). Thus, the influence on the $S(T_a)$ is higher. The combination of these effects results in a reduction of the base shear demand.

Chapter 5: Experimental performance of construction and demolition (C&D) waste based green roofs

This chapter focused on analyzing the reduction of green roofs' environmental footprint by replacing current polymeric materials with construction and demolition (C&D) waste. Quantifying the effects of C&D waste on green roof performance is important to ensure its application. Therefore, an experiment was conducted to determine the environmental performance. Six C&D waste green roofs (C&D-GR) will be compared with two standard commercial green roof systems. Indoor air temperature, indoor relative vapor pressure, retention of storm water, and runoff water quality are the main factors that will be measured and analyzed. The experiment was conducted from August 2011 to July 2012.

Results obtained in this chapter are subject to the following limitations:

- The experimental green roofs studied are restricted to extensive green roofs.
- The C&D waste used to build the experimental green roofs are limited to concrete, brick and foam. Expanded shale was used in one green roof; however, it is not considered as a waste product of the construction process.
- The experimental roof platforms were not perfectly sealed at the edges. Therefore, ambient air temperature and vapor pressure could affect platforms' indoor conditions.
- The experimental roof platforms were built with plywood. Platforms' indoor air temperature could be affected by ambient temperature due to conduction and convection
- Experimental data was collected for a 10 months period. Ideally, the experiment should be conducted for at least a year to determine green roofs' performance under the four weather seasons.
- The experimental set-up was located in an open area surrounded by trees. Direct sunlight on green roofs' plants may have been affected due to the height of surrounding vegetation.

- Runoff water samples were analyzed on a weekly basis. Part of the sample could be lost due to ambient conditions such as: frost-defrost and evaporation.
- Water quality tests are limited to: pH, electro conductivity and TSS. A complete water quality assessment requires more specialized and complex tests.

5.1 Materials and Methods

5.1.1 Site and experimental green roofs

Eight roof platforms were constructed at The University of British Columbia (UBC), Okanagan campus. The Okanagan valley's climate is characterized as semi-arid with four seasons (City of Kelowna, 2012). Moreover, the valley experiences dry and hot summers and mild winters (City of Kelowna, 2012).

Each experimental roof platform has dimensions of 0.9m x 1.8m (3ft x 6ft). Plywood sheets of 1.27 cm (1/2 inch) thickness were used to enclose the perimeter of the platforms. Each green roof has a slope of 10% and the upper end of platform has a height of 0.92m (3ft). Additionally, aluminum sheets were installed at the low end of the slope to canalize runoff storm water to the water-collecting devices. Moreover, black plastic was installed over the gutters to avoid that rainwater could drop directly on the drainage system.

Two platforms replicated commercial standard extensive green roofs, while the remaining six platforms replaced different current material layers with C&D waste. Each platform was covered with the same waterproofing membrane. The Xeroflor XF112 root barrier was installed on top of the waterproof membrane. Additionally, the eight green roofs used Xeroflor XF301 vegetation mat as the vegetation layer (Xeroflor, 2011).

Furthermore, each platform sits on 2.54 cm (1 inch) thick insulation layer. This insulation layers have to purpose of sealing the bottom of the experimental structures. The joints and edges of the experimental structure were sealed with silicon. Appendix A shows the design details of the experimental platforms.

5.1.2 Experimental green roofs' layers

Concrete, brick and foam were the selected C&D waste to perform the experiment due to the availability of resources. At the time that the experimental structures were built, the Engineering building was under construction. The construction company in charge of the project donated the C&D waste used in this experiment. Additionally, expanded shale was used in one experimental green roof. The three waste types were crushed to a size that varies between 1cm and 5cm, while the expanded shale size varies from 0.5cm to 1.5cm. Table 5.1 specifies the materials and the saturated weight of each green roof system and Illustration 5.1 shows the experimental set-up.

Illustration 5.1 Experimental set-up

Table 5.1 Layers and weights of experimental green roofs

		Root barrier	Drainage and filter	Water retention	Growing medium	Vegetation	Total
GR1	Material	Poly-ethylene	N/A	Polymeric fibers	Pre-vegetated mats		-
	Thickness (cm)	0.05	-	2.5	3		5.55
	Weight (kg/m^2)	0.47	-	23.92	37		61.39
GR2	Material	Poly-ethylene	N/A	Polymeric fibers	Pre-vegetated mats		-
	Thickness (cm)	0.05		2	3		5.05
	Weight (kg/m^2)	0.47	-	20.60	37		58.07
GR3	Material	Poly-ethylene	Crushed concrete	Polymeric fibers	Pre-vegetated mats		-
	Thickness (cm)	0.05	1-5	1	3		5.05-9.05
	Weight (kg/m^2)	0.47	16.27	10.30	37		64.04
GR4	Material	Poly-ethylene	Crushed concrete	N/A	Pre-vegetated mats		-
	Thickness (cm)	0.05	1-5	-	3		4.05-8.05
	Weight (kg/m^2)	0.47	15.06	-	37		52.81
GR5	Material	Poly-ethylene	Crushed foam	N/A	Pre-vegetated mats		-
	Thickness (cm)	0.05	1-5	-	3		5.05-9.05
	Weight (kg/m^2)	0.47	1.81	-	37		49.58
GR6	Material	Poly-ethylene	Expanded Shale	Polymeric fibers	Pre-vegetated mats		-
	Thickness (cm)	0.05	0.5-1.5	1	3		4.55-5.55
	Weight (kg/m^2)	0.47	12	10.30	37		59.77
GR7	Material	Poly-ethylene	Crushed concrete + crushed brick + crushed rigifoam	Polymeric fibers	Pre-vegetated mats		-
	Thickness (cm)	0.05	1-5	1	3		5.05-9.05
	Weight (kg/m^2)	0.47	19.28	10.30	37		67.05

		Root barrier	Drainage and filter	Water retention	Growing medium	Vegetation	Total
GR8	Material	Poly-ethylene	Crushed concrete + crushed brick + crushed rigifoam	N/A	Pre-vegetated mats		-
	Thickness (cm)	0.05	1-5	-	3		4.05-8.05
	Weight (kg/m^2)	0.47	19.28	-	37		56.75

5.1.3 Data collection

Temperature and vapor pressure inside each experimental green roof were measured and recorded by wireless sensors (La Crosse TX60U). Experimental data was collected every half hour, while ambient air temperature was measured every hour. Experimental ambient air temperature and vapor pressure readings were compared to those measured in the Kelowna`s International airport total weather station (Environment Canada, 2012). The airport is 3km (1.9 miles) away from the experimental set-up. Due to the frequency of data collection, temperature and vapor pressure results were considered as continuous data.

Water retention was measured by collecting the runoff storm water of each green roof. The difference between the runoff storm water and the natural precipitation is the amount of water absorbed by each green roof. Water retention was measured on a weekly basis (7 days). Therefore, precipitation and runoff storm water was collected and accumulated every day. Then it was measured at the beginning of the seventh day. The amount and the quality of the collected runoff water were analyzed at the UBC Okanagan campus environmental laboratory. Illustration 5.2 shows the water samples before the laboratory analysis.

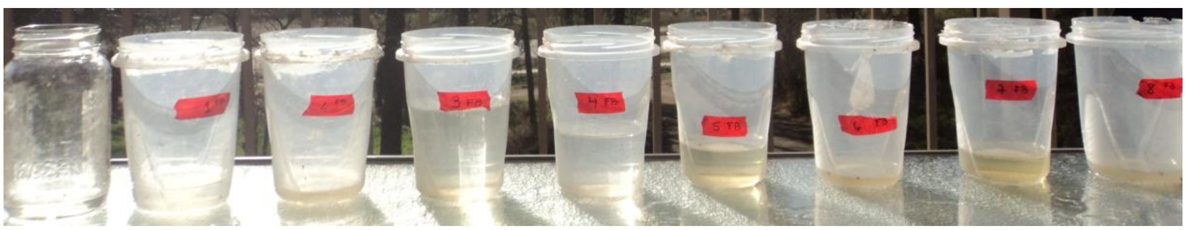


Illustration 5.2 Runoff storm water samples

Electro conductivity, total suspended solids (TSS) and pH tests were performed to the runoff water samples. TSS is the amount of suspended particles present in water (US EPA, 1999). Similarly, electro conductivity estimates the total amount of dissolved salts present in water (US EPA 1994). Therefore, for both tests, as more particles and salts are present, the worst the water quality is. The pH test measures how acidic or basic is a substance (US EPA, 2007). The pH scale ranges from 0 to 14, where a pH of 7 is neutral. A pH of less than 7 is acid, while a pH higher than 7 is basic.

Electro conductivity and pH were directly measured with specialized sensors, while a qualitative technique was used to measure TSS. A spectrophotometer was set at a wavelength of 550nm to determine the amount absorbance present in the runoff water samples. Different concentrations of green roof's growing medium were used to make a calibration curve. The calibration curve was used to estimate the concentration of suspended solids (mg/l) present in the storm water runoff.

5.1.4 Data analysis

Indoor temperature and vapor pressure data were compared among green roofs to determine the effect of materials in these parameters. Additionally, data from each green roof was compared to the ambient air temperature to determine the green roof with the best overall performance. When ambient temperature is high (summer), green roof with indoor temperature lower than ambient air temperature is preferable. On the other hand, when ambient temperature is low (winter), green roof with indoor temperature higher than ambient air temperature is preferable. Transition seasons (fall and spring) are important to identify the effects of the materials used as layers under freezing and defrosting conditions. Therefore, the analysis organized data in four seasons: spring, summer, fall and winter. This paper assumes the following months for each season:

- Spring: April, May, and June
- Summer: July, August, and September
- Fall: October, November, and December
- Winter: January, February, and March

Temperature and vapor pressure data were analyzed in two ways. In the first, an analysis of variance (ANOVA) was used to determine if there is a significant difference between the average daily temperatures and vapor pressure of each green roof. Similarly, in the second way an ANOVA was used to determine if there is significant difference between the average seasonal temperature and vapor pressure under each green roof. A 95% confidence level was used for both analyses.

Likewise, an ANOVA model was used to compare the performance of every green roof in terms of water retention, pH, TSS, and electro conductivity. Data for these four parameters was analyzed as one set, instead of the seasonal division used for temperature and vapor pressure. Furthermore, electro conductivity, pH, and TSS were compared with Environment Canada regulatory limits for drinking and storm water. The Least Significant Difference (LSD) is a method for comparing treatment groups mean after the ANOVA null hypothesis has been rejected using the ANOVA F-test (Carmer *et al*., 1989). When there was statistical evidence that the analyzed data was significantly different, the Least Significant Difference (LSD) method was used.

5.2 Results

5.2.1 Temperature

Continuous data of indoor temperature of each green roof and ambient temperature was collected and analyzed. Figures 5.1-5.4 show the thermal performance under each green roof.

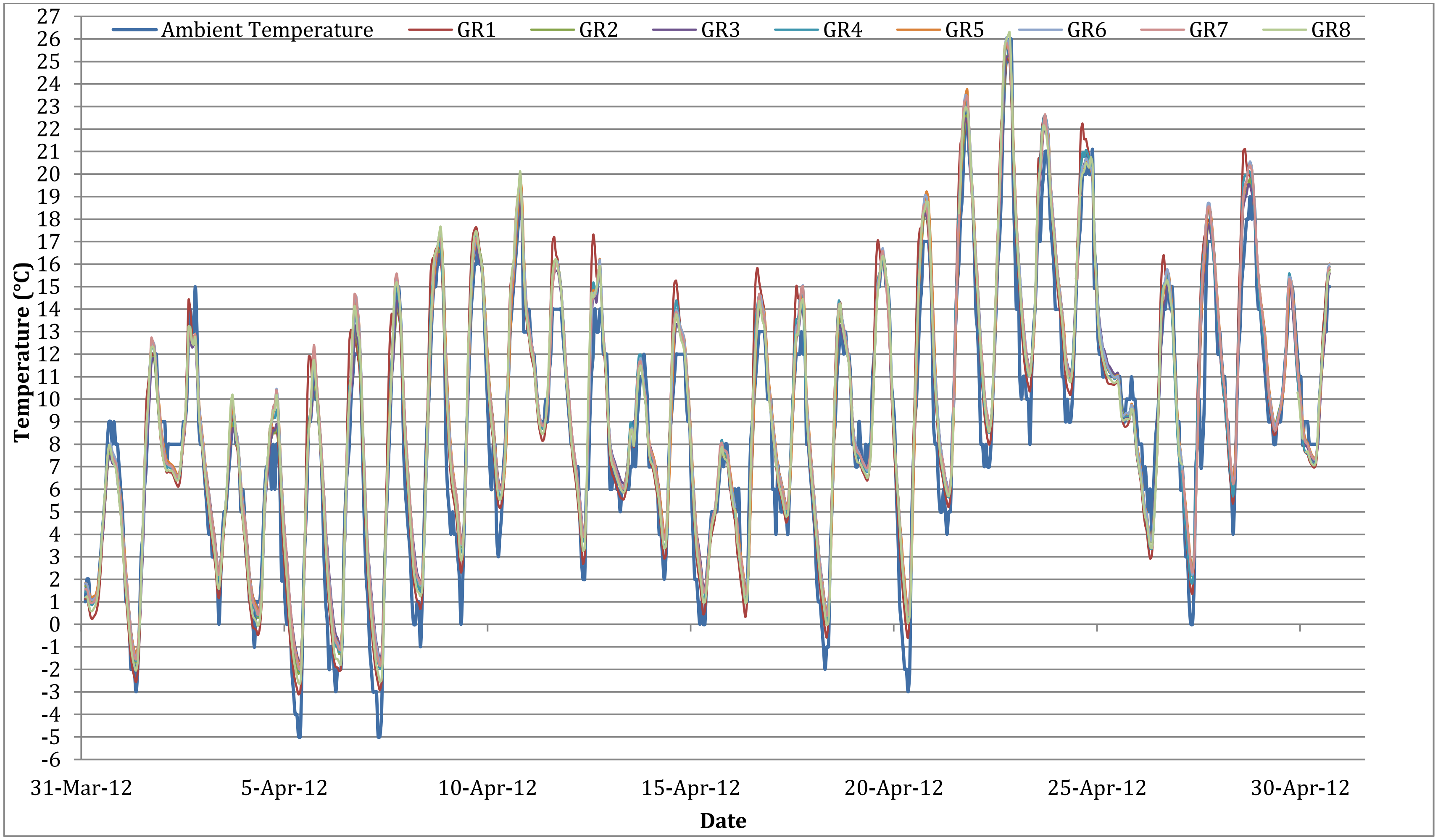


Figure 5.1 Indoor air temperature of experimental green roofs for spring season

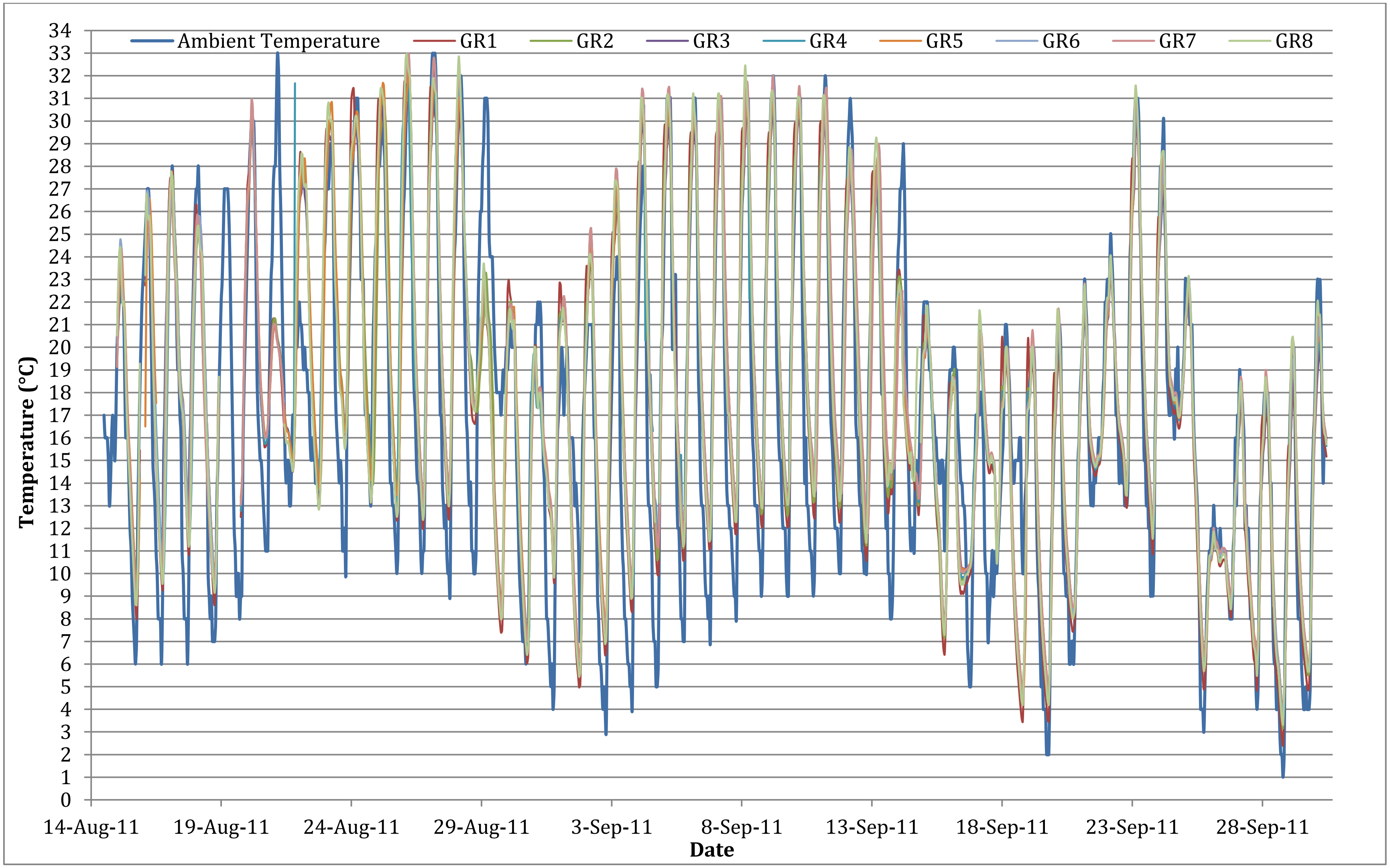


Figure 5.2 Indoor air temperature of experimental green roofs for summer season

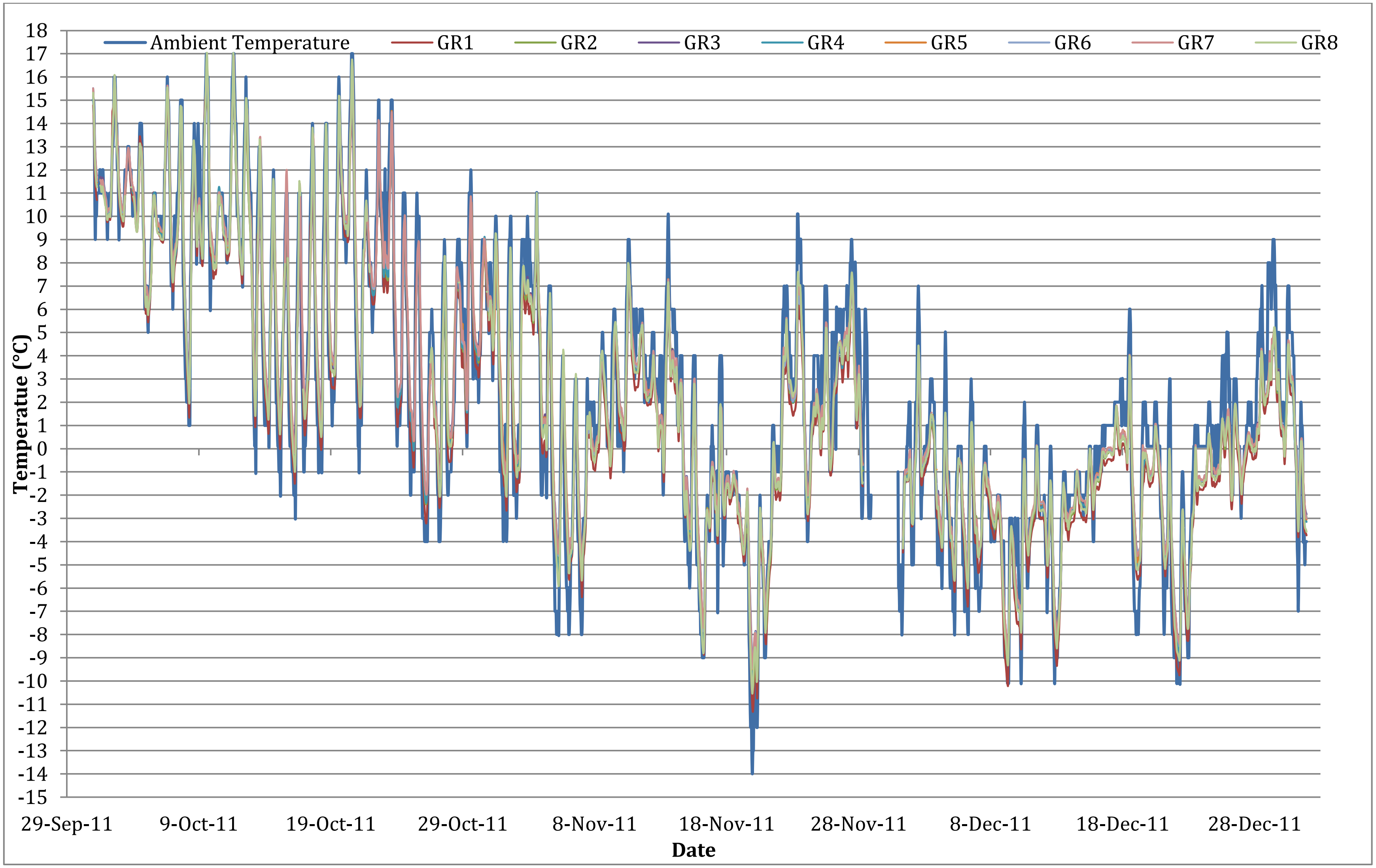


Figure 5.3 Indoor air temperature of experimental green roofs for fall season

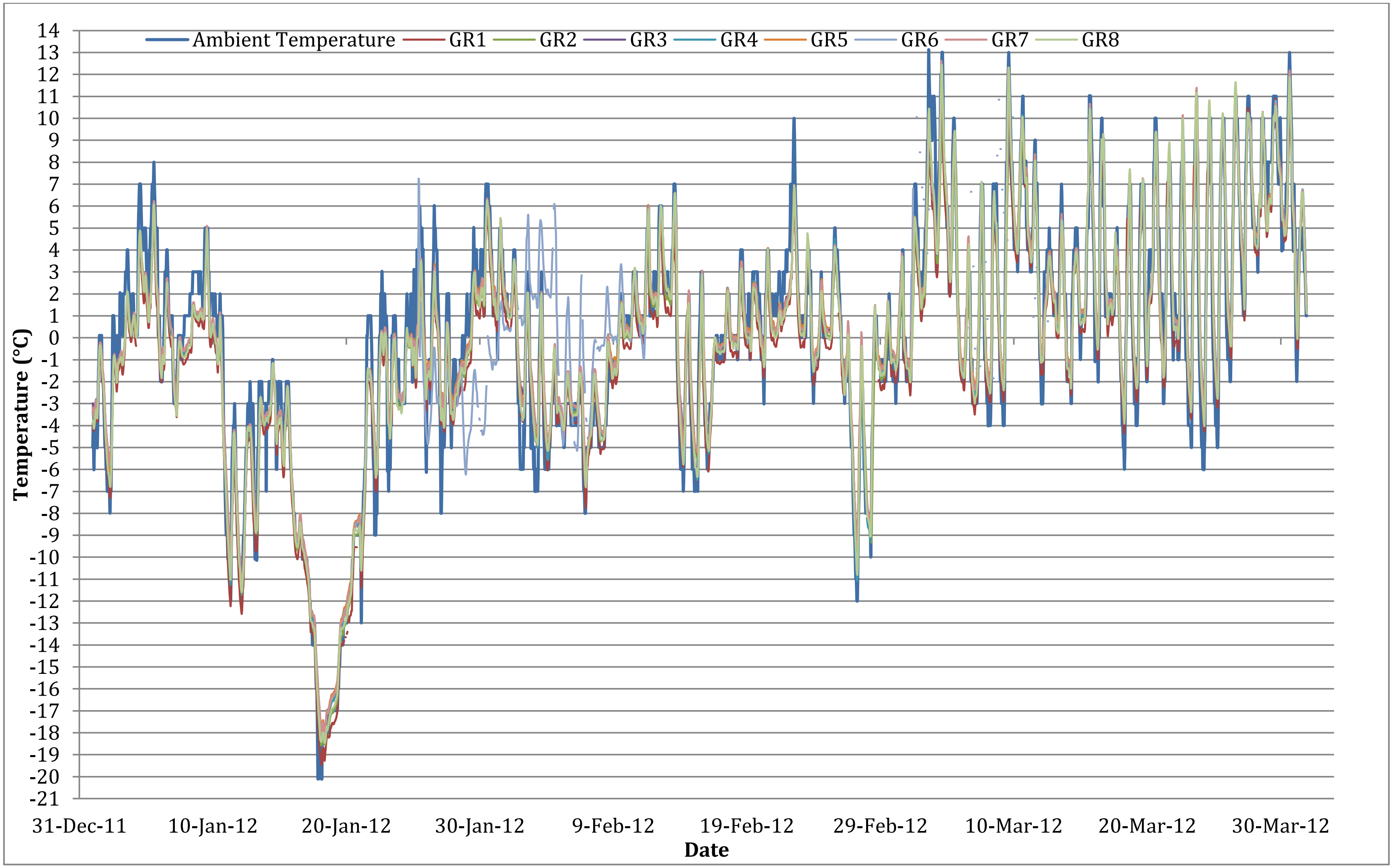


Figure 5.4 Indoor air temperature of experimental green roofs for winter season

Figures 5.1, 5.2, 5.3, and 5.4 show the indoor air temperature and ambient temperature under each green roof for spring, summer, fall and winter, respectively. Moreover, ambient temperature changes are evident and correspondent to each season. The lowest recorded ambient air temperature was -22°C, while the highest was 33°C during winter and summer, respectively. It is evident that green roofs respond slowly to ambient temperature sudden changes. Green roofs' indoor air temperatures were always in between the daily lowest and highest peak ambient air temperature.

Figure 5.5 depicts temperature data organized by seasons. Additionally, the average air temperatures of each season under each green roof are shown in Table 5.2.

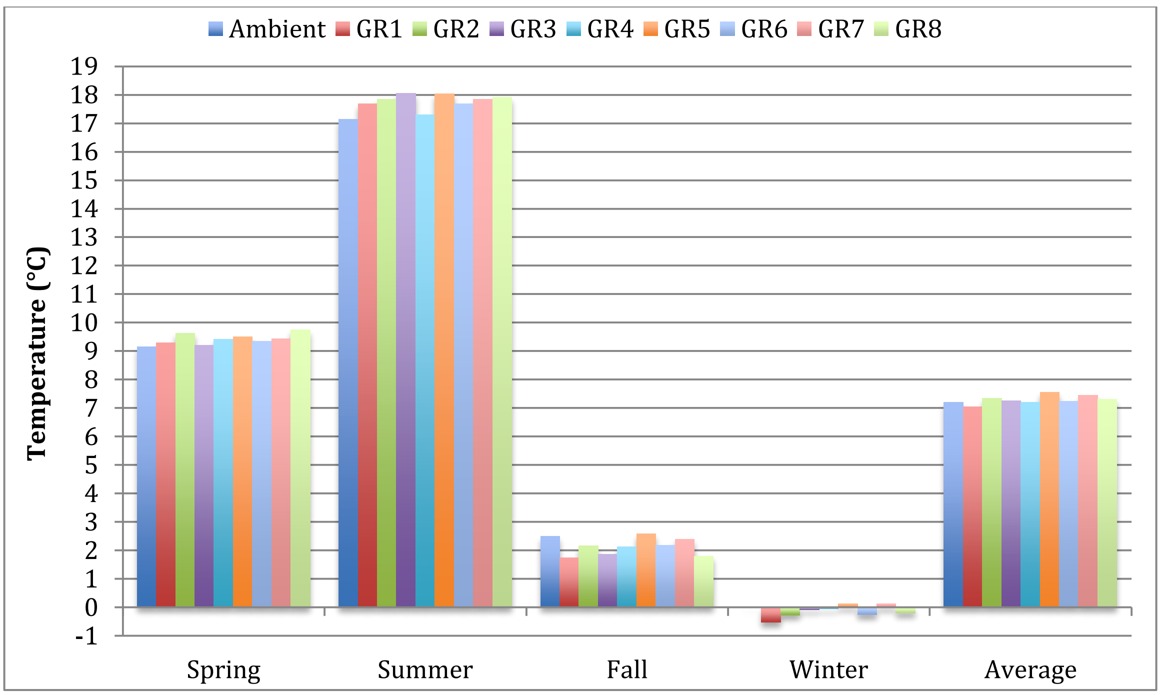


Figure 5.5 Ambient temperature and green roofs' indoor temperature by seasons

Table 5.2 Ambient temperature and indoor air temperature of experimental green roofs

Temperature (°C)					
GR ID	Spring	Summer	Fall	Winter	Average of seasons
Ambient	9.14	17.13	2.50	0.01	7.20
GR1	9.29	17.68	1.74	-0.53	7.05
GR2	9.63	17.83	2.15	-0.27	7.33
GR3	9.20	18.05	1.87	-0.09	7.26
GR4	9.41	17.29	2.12	-0.06	7.19
GR5	9.50	18.03	2.57	0.12	7.56
GR6	9.34	17.68	2.18	-0.27	7.23
GR7	9.42	17.83	2.39	0.12	7.44
GR8	9.74	17.91	1.80	-0.20	7.31

Results shown in Figure 5.5 and Table 5.2 compare average ambient air temperature with green roofs' average indoor air temperature. For spring and summer, average ambient air temperature was lower than green roofs' indoor air temperature. However, average ambient temperature was higher for fall and winter. It was expected that for warm seasons, such as spring and summer, green roofs were going to have a lower indoor air temperature. Nevertheless, as shown in Figures 5.1-5.2, green roofs did have a lower indoor temperature when ambient temperature was over 25°C. Similarly, green roofs' indoor air temperature is higher when ambient temperature was lower than 8°C (Figures 5.5 and 5.6). Therefore, the average temperatures shown in Table 5.2 do not clearly represent the daily green roofs' behavior.

ANOVA was performed to identify statistical differences between green roofs' indoor air temperature and ambient air temperature. Additionally, ANOVA average temperatures of each season were compared. Results are shown in Table 5.3.

Table 5.3 ANOVA results for ambient temperature and green roofs' indoor air temperatures

Source	Sum of Squares (SS)	Degrees of freedom	Mean SS	F	P-value	F critical
Experimental green roofs	0.71	8	0.08	1.46	0.047	2.35
Season	1751	3	583.92	9556	4.72E-37	3.01
Error	1.46	24	0.04			
Total	1753.97	35				

Results from Table 5.3 compare significant differences between average indoor air temperature of green roofs and average ambient air temperature. Moreover, compares if it is a significant difference among seasons. If the F value is higher than F critical, then there is statistical evidence that the samples are different. Any other case means that the samples are not significantly different. In this case of experimental green roofs there is statistical evidence that are not different. Thus, the average indoor temperature of green roofs is the same. For the case of seasons, F is higher than F critical. Therefore, data between seasons is significantly different.

Results from Table 5.3 demonstrated that average temperature between seasons is different to each other. Therefore, LSD was used for pairwise comparisons among seasonal ambient temperature and green roofs' indoor air temperature means. Table 5.4 summarizes data that is significantly different.

Table 5.4 LSD results for significant different seasonal ambient temperature and green roofs' indoor air temperatures

Spring-Summer	Spring-Winter	Summer-Winter
Spring-Fall	Summer-Fall	Fall-Winter

LSD results identifies which data is statically significant different to each other. In this case, average temperature for all seasons is different to each other. For instance summer average temperature (18°C) is significantly different to winter average temperature (0°C); therefore, Table 5.4 shows "Summer-Winter". This result is logical and correspondent to the collected data.

5.2.2 Vapor pressure

Continuous data of indoor vapor pressure of each green roof and ambient vapor pressure was collected and analyzed. Figures 5.6-5.9 show the performance under each green roof.

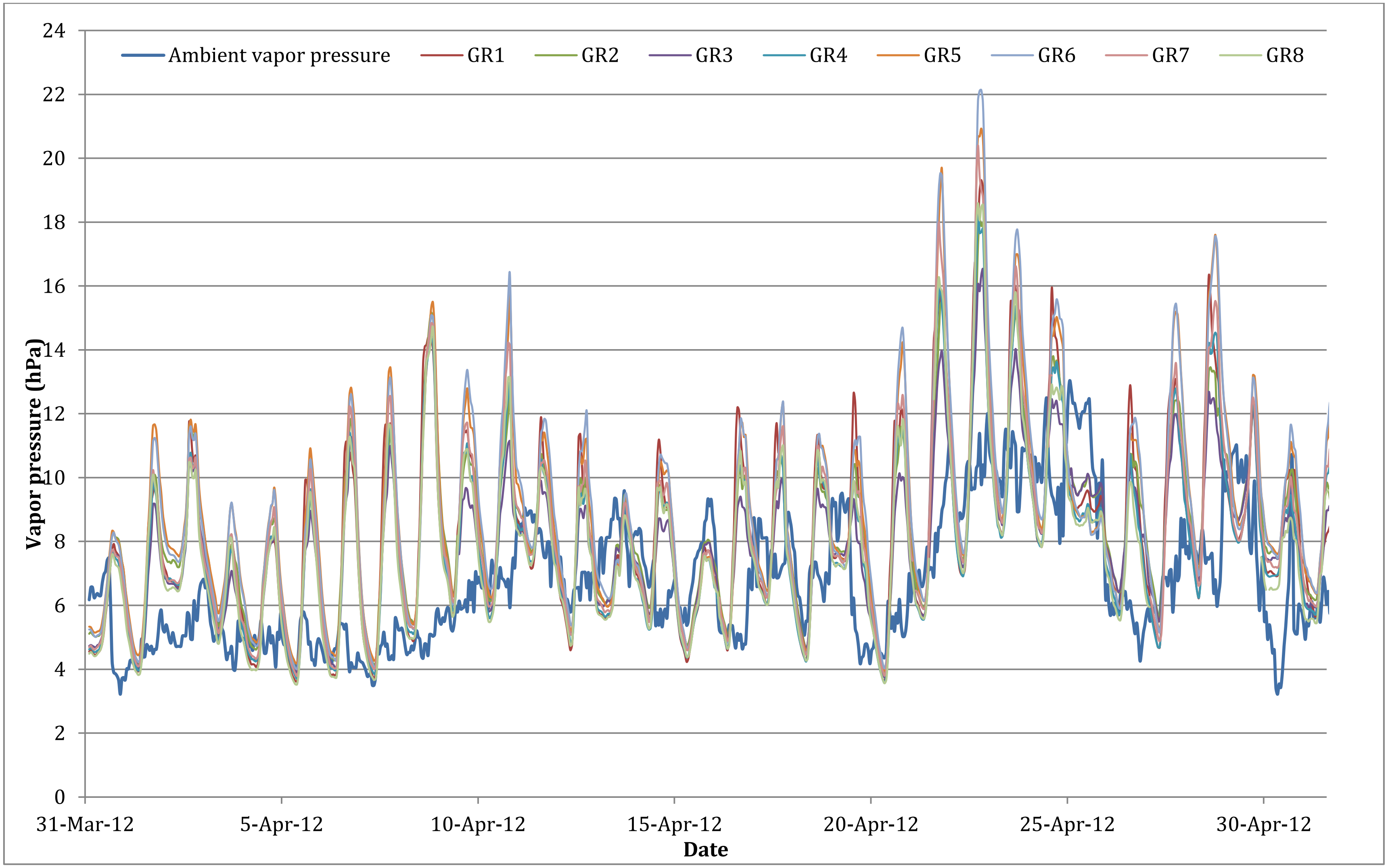


Figure 5.6 Indoor vapor pressure of experimental green roofs for spring season

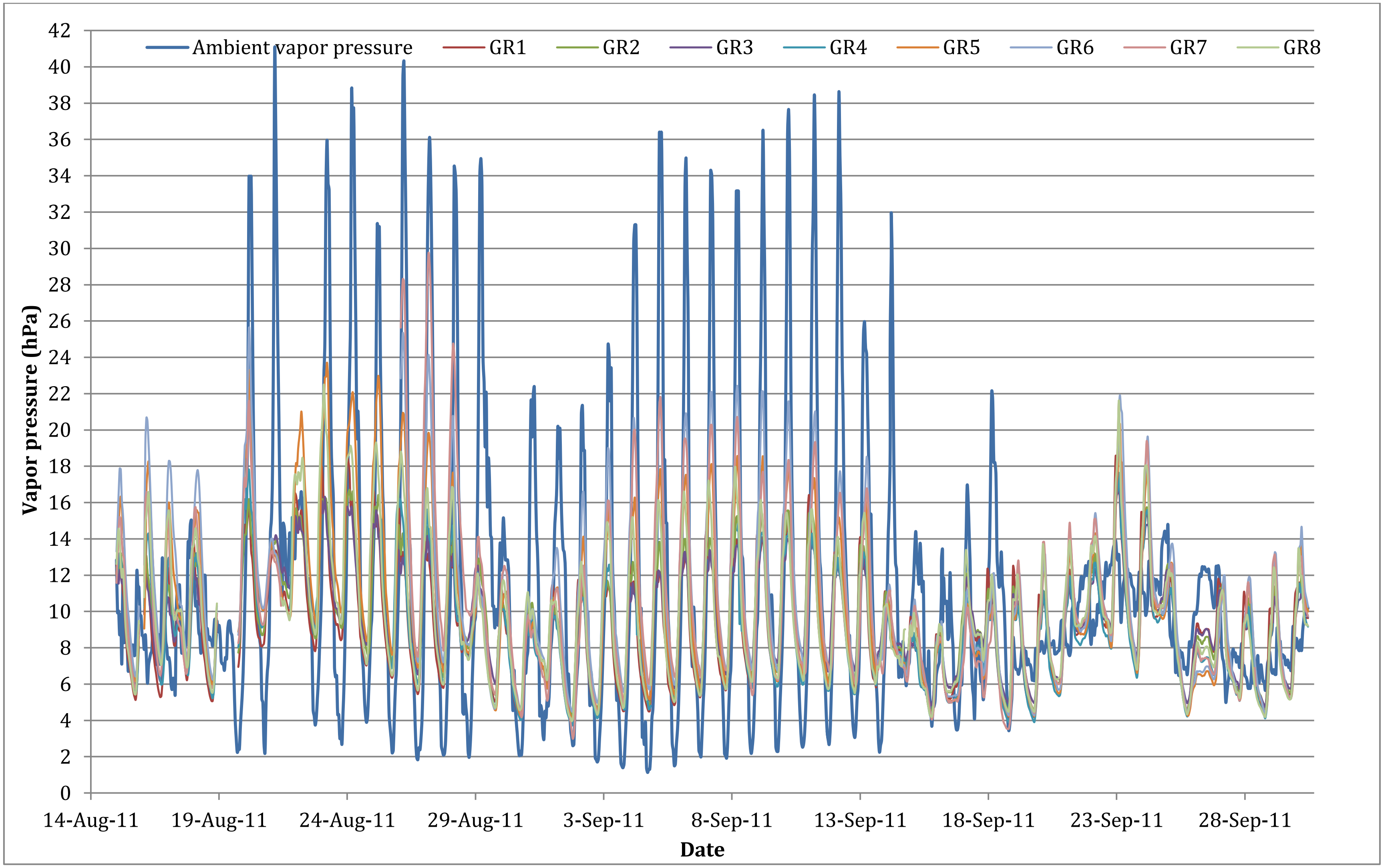


Figure 5.7 Indoor vapor pressure of experimental green roofs for summer season

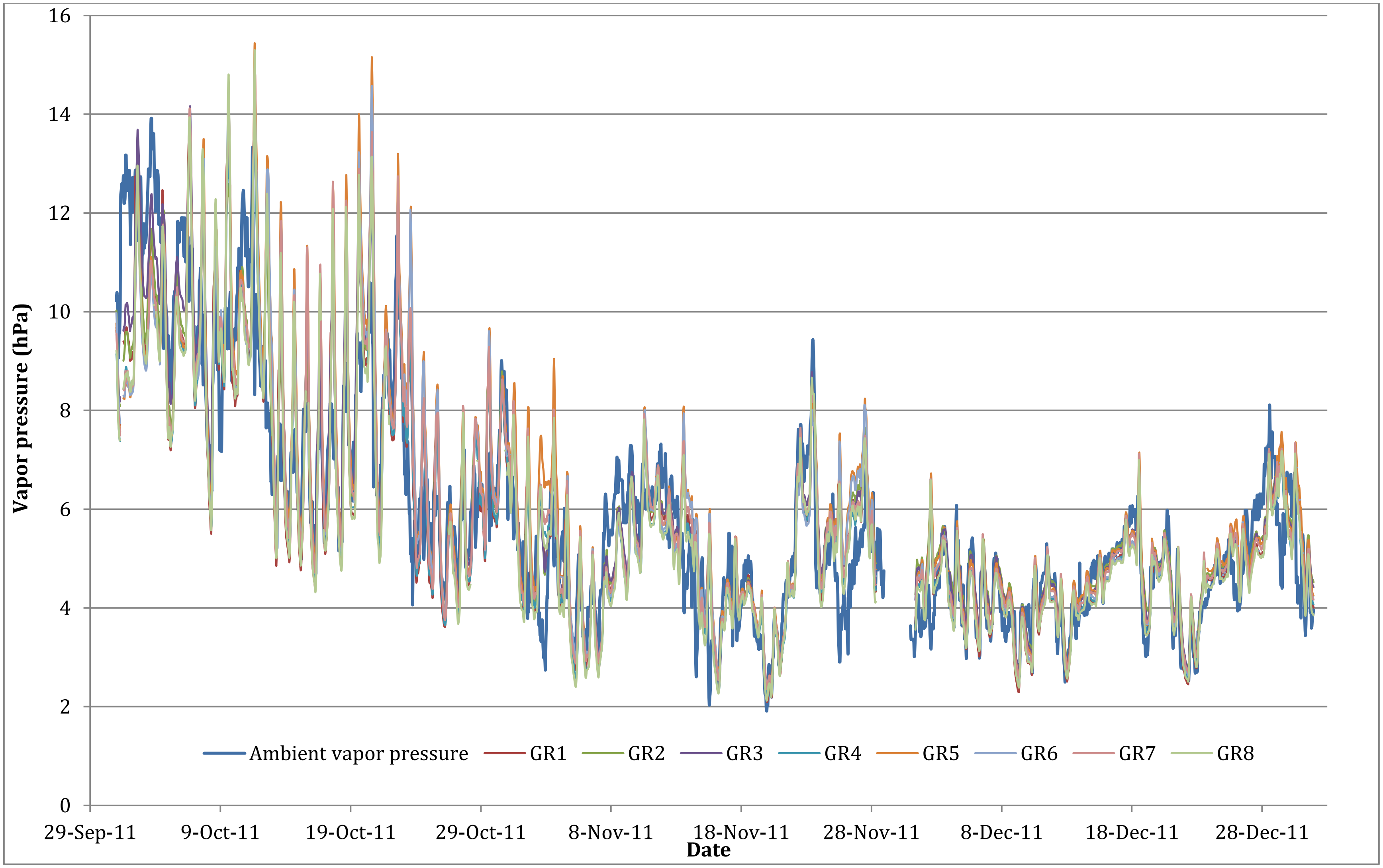


Figure 5.8 Indoor vapor pressure of experimental green roofs for fall season

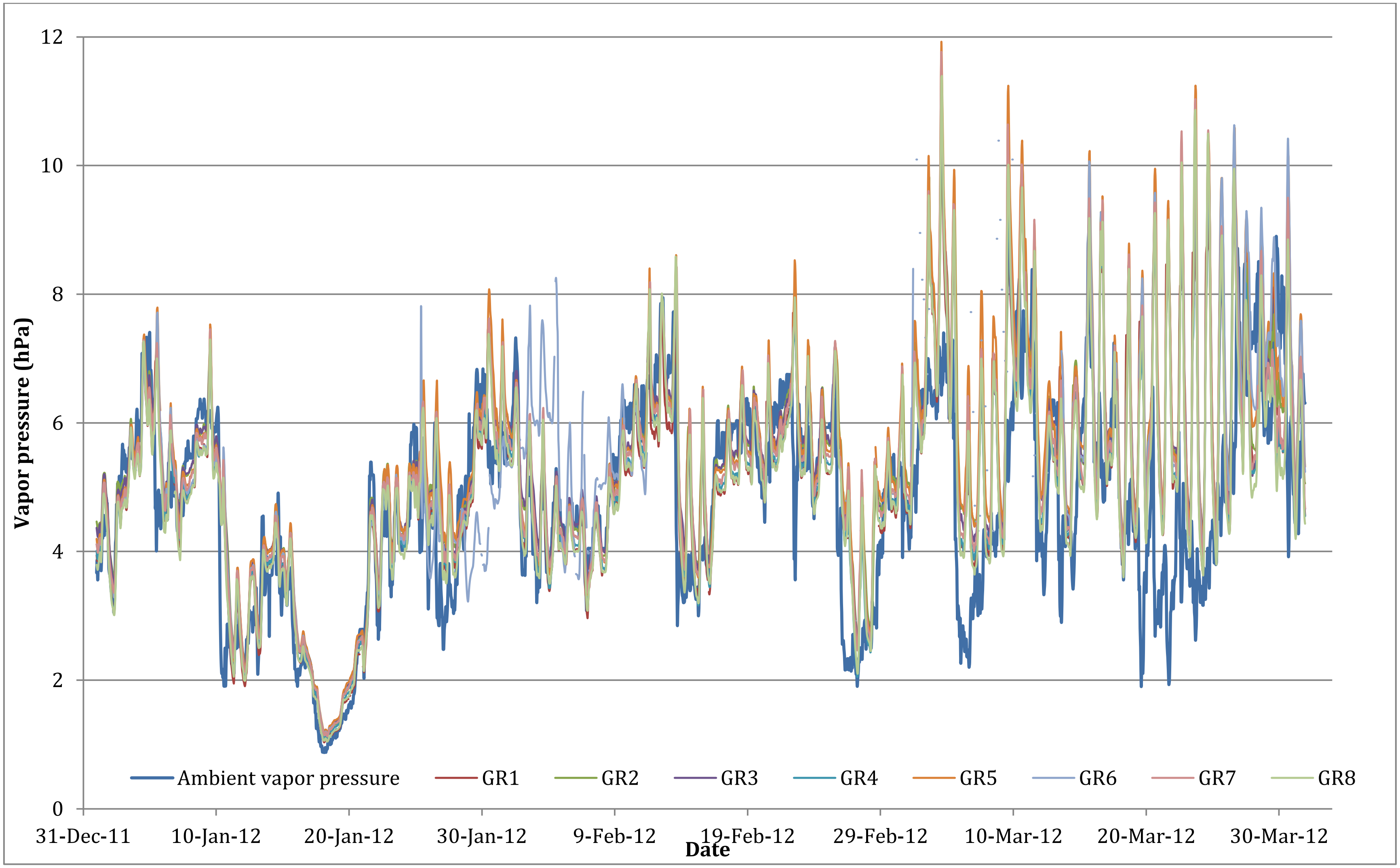


Figure 5.9 Indoor vapor pressure of experimental green roofs for winter season

Figures 5.6, 5.7, 5.8, and 5.9 show the indoor air vapor pressure and the ambient vapor pressure under each green roof for spring, summer, fall and winter, respectively. Moreover, ambient vapor pressure variations are evident and correspondent to each season. For instance, as winter arrives and temperatures decrease, vapor pressure decreases due to the presence of snow. The lowest recorded ambient air vapor pressure was 1 hPa, while the highest was 30 hPa during winter and summer, respectively. Similarly as temperature results, it is evident that green roofs respond slowly to sudden vapor pressure changes. Green roofs' indoor air vapor pressure was always in between the daily lowest and highest peak ambient air vapor pressure.

Figure 5.10 depicts vapor pressure data organized by seasons. Additionally, the average vapor pressure of each season under each green roof is shown in Table 5.5.

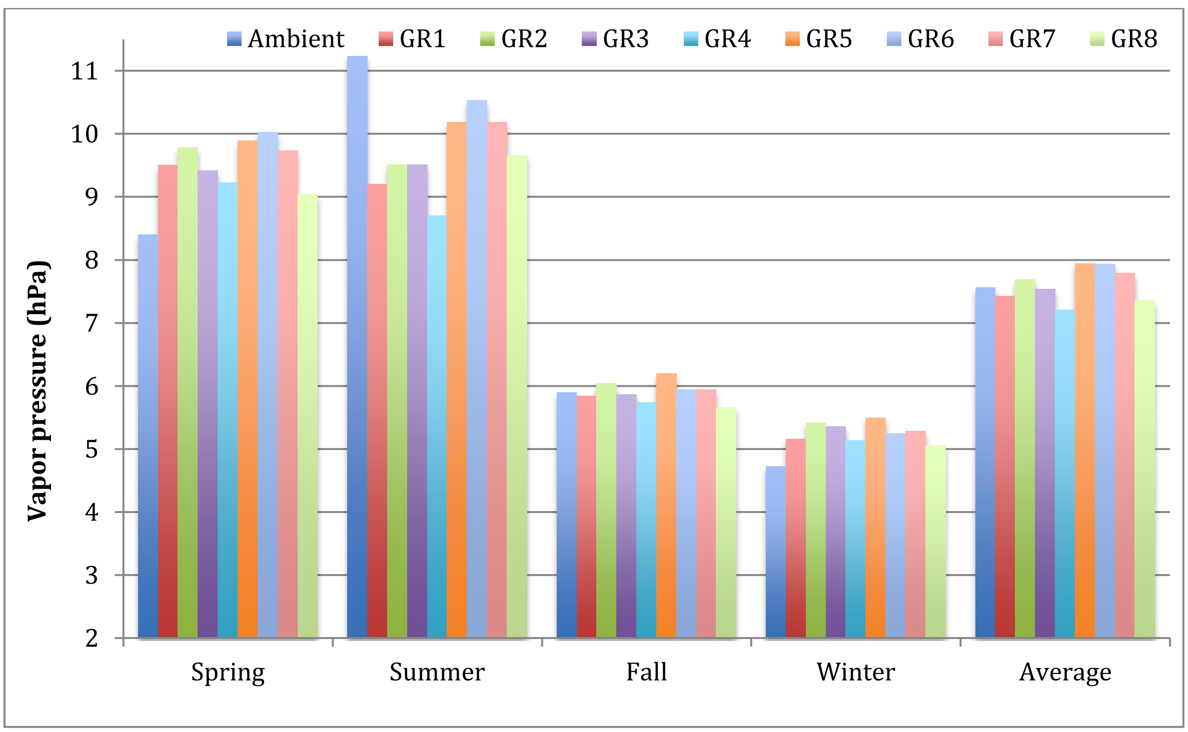


Figure 5.10 Ambient vapor pressure and green roofs' indoor vapor pressure by seasons

Table 5.5 Ambient vapor pressure and indoor vapor pressure of experimental green roofs

Vapor pressure (hPa)					
GR ID	Spring	Summer	Fall	Winter	Average
Ambient	8.40	11.23	5.90	4.73	7.56
GR1	9.50	9.20	5.84	5.16	7.43
GR2	9.78	9.51	6.04	5.41	7.69
GR3	9.41	9.51	5.87	5.36	7.54
GR4	9.23	8.70	5.74	5.14	7.20
GR5	9.89	10.18	6.20	5.49	7.94
GR6	10.03	10.53	5.95	5.25	7.94
GR7	9.73	10.18	5.95	5.29	7.79
GR8	9.04	9.66	5.66	5.06	7.35

Results shown in Figure 5.10 and Table 5.5 compare average ambient air vapor pressure with green roofs' average indoor air vapor pressure. For spring, fall, and winter average ambient air vapor pressure was lower than green roofs' indoor air temperature. However, average ambient vapor pressure was higher only for summer. As discussed before, Figure 5.10 clearly demonstrates that as cold seasons arrive, vapor pressure is lower.

ANOVA was performed to identify statistical differences between green roofs' indoor air vapor pressure and ambient air vapor pressure. Additionally, ANOVA average vapor pressure of each season was compared. Results are shown in Table 5.6.

Table 5.6 ANOVA results for ambient vapor pressure and green roofs' indoor vapor pressure

Source	Sum of Squares (SS)	Degrees of freedom	Mean SS	F	P-value	F critical
Experimental green roofs	2.11	8	0.26	1.24	0.32	2.35
Season	153.93	3	51.31	240.10	5.01E-18	3.01
Error	5.13	24	0.21			
Total	161.17	35				

Equally as section 5.2.1, results from Table 5.6 compares if it is a significant difference between data. In this case for seasons, F is higher than F critical. Therefore, data between seasons is significantly different. There is statistical evidence that indoor vapor pressure of experimental green roofs and ambient vapor pressure are not different. Similarly as section 5.2.1, LSD was used for pairwise comparisons among seasonal ambient vapor pressure and green roofs' indoor vapor pressure means. Table 5.7 summarizes data that is significantly different.

Table 5.7 LSD results for significant different ambient vapor pressure and green roofs' indoor vapor pressure

Spring-Summer	Spring-Winter	Summer-Winter
Spring-Fall	Summer-Fall	Fall-Winter

Equally as temperature results, LSD results identified that average vapor pressure for all seasons is different to each other. For instance spring average vapor pressure (9.44 hPa) is significantly different to fall average vapor pressure (5.90 hPa); therefore, Table 5.7 shows "Spring-Fall".

5.2.3 Water retention

The amount of storm water drained by each green roof due to the Okanagan`s natural rainfall is shown in Figure 5.11. In addition, Figure 5.11 shows the average precipitation.

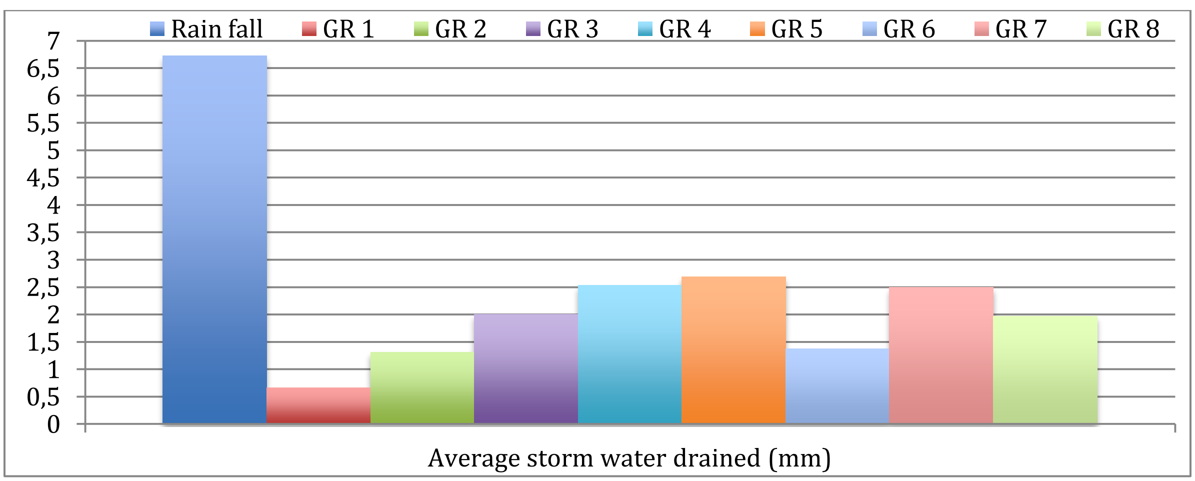


Figure 5.11 Average precipitation and storm water drained by each green roof

Figure 5.11 demonstrates green roofs´ water retaining capacity. The retention capacity could vary depending on the intensity of the rain events. The Okanagan valley`s precipitation has a moderate intensity; therefore, amount of storm water drained by each green roof is low. The average water retention performance of each green roof is shown in Figure 5.12.

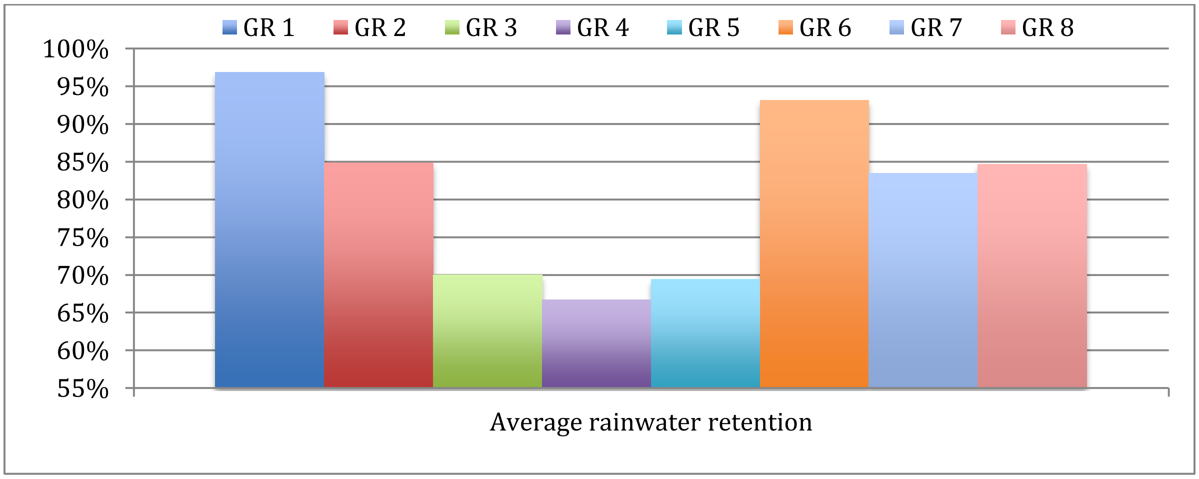


Figure 5.12 Average water retention performance of green roofs' runoff

It is evident from Figure 5.12 that standard commercial green roofs (GR1 and GR2) had the best water retention performance. In addition, expanded shale resulted to have higher water retention potential than the rest of C&D waste based green roofs. C&D waste based green roofs that used crushed concrete had the poorest performance.

To determine if results are statically different an ANOVA was performed. Results are shown in Table 5.8.

Table 5.8 ANOVA results for water retention

Source	Sum of Squares (SS)	Degrees of freedom	Mean SS	F	P-value	F critical
Between group	2.02	7	0.289	3.28	2.76E-3	2.07
Within Group	14.08	160	0.088			
Total	16.10	167				

Results from Table 5.8 compares if it is a significant difference between green roofs` water retention performance. For this case, F is higher than F critical; therefore, there is a significant difference between the water retention performances of green roofs. LSD was used for pair wise comparisons to determine which data is significant different. Table 5.9 summarizes data that is significantly different.

Table 5.9 LSD results for significant different water retention performance

GR1-GR3	GR1-GR5	GR4-GR6
GR1-GR4	GR3-GR6	GR5-GR6

Similar to sections 5.2.1 and 5.2.2, LSD results identified that some green roofs have a different water retention performance. For instance GR1 average water retention (96%) is significantly different to GR4 average water retention (66%); therefore, Table 5.9 shows "GR1-GR4". Moreover, "GR1-GR2" is not present in Table 5.9, hence water retention performance for GR1 and GR2 is statically the same.

5.2.4 pH

Figure 5.13 compares the average green roofs' storm water runoff pH with rainwater's pH.

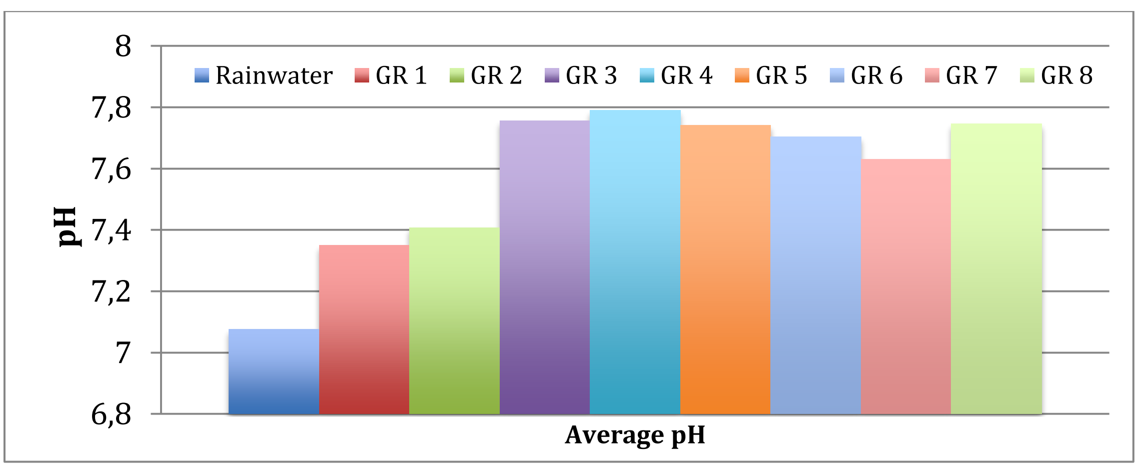


Figure 5.13 Average pH of rainwater and green roofs' runoff

Neutral pH is 7; however, it is considerate that a neutral pH ranges between 6 and 8. Results from rainwater and green roofs' storm water runoff pH test felt within the neutral range. However, Figure 5.13 clearly shows that green roofs tend to increase natural rainwater's pH. Figure 5.13 shows an evident pH increase from GR3. Therefore, it is clearly shown that C&D waste based green roofs have a higher impact on rainwater's pH than commercial standard green roofs.

ANOVA was performed to determine if it is statistical evidence that pH results are significantly different. Results are shown in Table 5.10.

Table 5.10 ANOVA results for storm water pH

Source	Sum of Squares (SS)	Degrees of freedom	Mean SS	F	P-value	F critical
Between group	10.78	8	1.35	5.09	1.07E-5	1.99
Within Group	44.98	170	0.26			
Total	55.77	178				

Results from Table 5.10 compares if it is a significant difference between green roofs` storm water runoff pH. ANOVA results in an F higher than F critical. Consequently, there is a significant difference between the pH of natural rainwater and the pH of green roofs` storm water runoff. Table 5.11 summarizes data that is significantly different.

Table 5.11 LSD results for significant different rainwater and storm water pH

Rainwater-GR2	Rainwater -GR7	GR1-GR6
Rainwater -GR3	Rainwater -GR8	GR1-GR8
Rainwater -GR4	GR1-GR3	GR2-GR3
Rainwater -GR5	GR1-GR4	GR2-GR4
Rainwater -GR6	GR1-GR5	GR2-GR8

Similar to previous sections, LSD results identified that green roofs' runoff pH and rainwater's pH are different. For instance GR2's pH (7.4) is significantly different to GR8's pH (7.7); therefore, Table 5.11 shows "GR2-GR8". Moreover, Table 5.11 demonstrates that rainwater's pH is different to all the green roofs' runoff pH, except for GR1 (commercial standard green roof).

5.2.5 Total suspended solids (TSS)

Figure 5.14 compares the average TSS of green roofs' storm water runoff with rainwater's TSS.

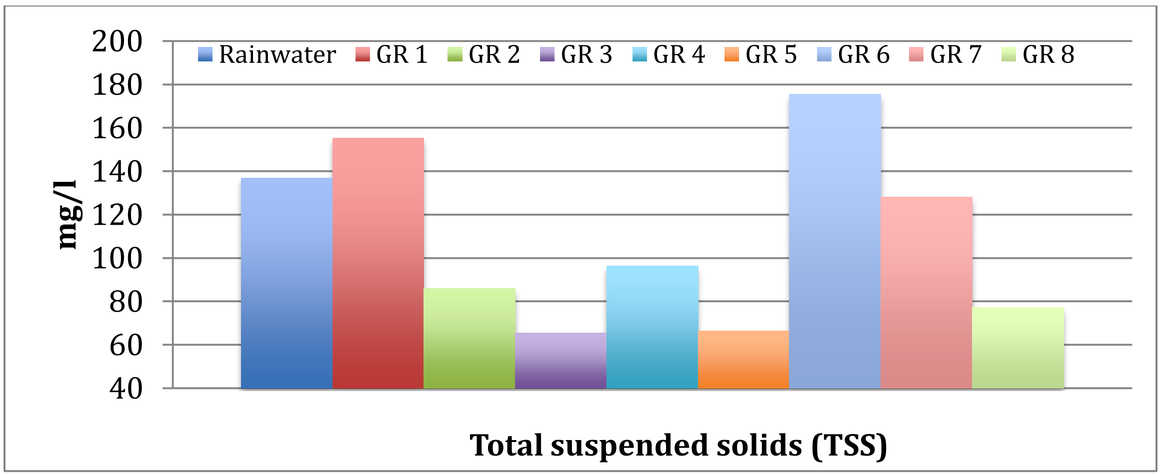


Figure 5.14 Average TSS of rainwater and green roofs' runoff

In general, from Figure 5.14, green roofs reduced rainwater's TSS. Nevertheless, only GR1 (commercial standard) and GR6 (expanded shale) increased rainwater's TSS. Moreover, C&D waste based green roofs had the best performance. C&D waste based green roofs reduced, on average, rainwater's TSS content in half. Equally as previous sections, an ANOVA was performed. Results are shown in Table 5.12.

Table 5.12 ANOVA results for storm water TSS

Source	Sum of Squares (SS)	Degrees of freedom	Mean SS	F	P-value	F critical
Between group	2.55E5	8	3.19E4	1.89	6.37E-2	1.99
Within Group	2.90E6	163	1.68E4			
Total	3.15E6	171				

The F value is lower than F critical; therefore, there is not a significant difference between the TSS of natural rainwater and green roofs' runoff TSS. Moreover, there is no significant difference among green roofs' runoff TSS. Hence, the LSD method was not performed.

5.2.6 Electro conductivity

Figure 5.15 compares the average electro conductivity of green roofs' storm water runoff with rainwater's electro conductivity.

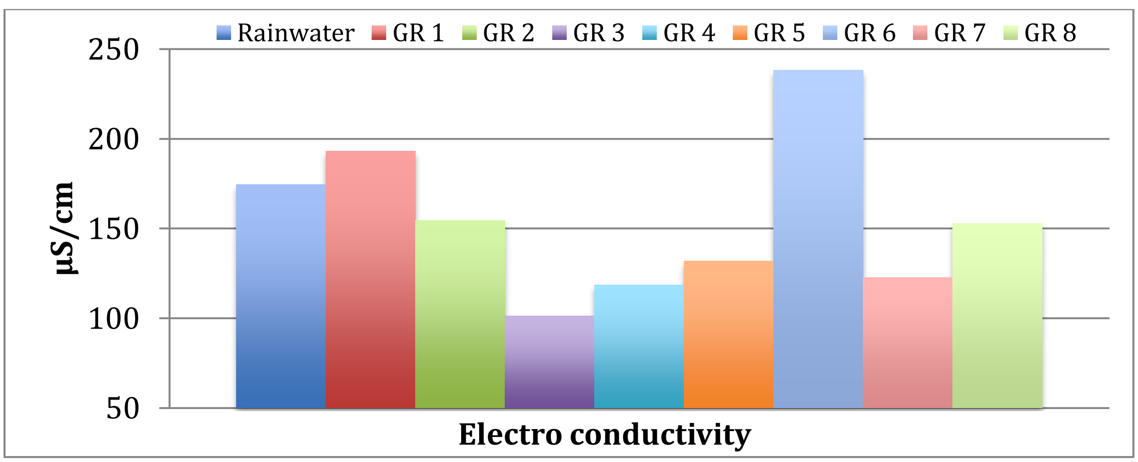


Figure 5.15 Average electro conductivity of rainwater and green roofs' runoff

Figure 5.15 shows, in general, that green roofs reduce rainwater's electro conductivity. Equally as TSS, only GR1 (commercial standard green roof) and GR6 (expanded shale) increased the amount of electro conductivity present in rainwater. The ANOVA results are shown in Table 5.13.

Table 5.13 ANOVA results for storm water electro conductivity

Source	Sum of Squares (SS)	Degrees of freedom	Mean SS	F	P-value	F critical
Between group	1.59E5	8	1.99E4	2.50	1.83E-2	2.06
Within Group	6.22E5	78	7.98E3			
Total	7.81E5	86				

The ANOVA concludes that there is a significant difference between the electro conductivity of natural rainwater and the electro conductivity of green roofs` storm water runoff due to the difference between F and F critical. Table 5.14 summarizes LSD results.

Table 5.14 LSD results for significant different rainwater and storm water electro conductivity

Rainwater-GR3	GR1-GR5	GR4-GR6
Rainwater-GR4	GR1-GR7	GR5-GR6
GR1-GR3	GR2-GR6	GR6-GR7
GR1-GR4	GR3-GR6	GR6-GR8

Similar to previous sections, LSD results identified that green roofs' runoff electro conductivity and rainwater's electro conductivity are different. For instance rainwater's TSS (175 μS/cm) is significantly different to GR3's TSS (101 μS/cm); therefore, Table 5.14 shows "Rainwater-GR3".

5.3 Discussion

Data analysis compared the performance of commercial standard green roofs with C&D based green roofs. In terms of indoor air temperature, the statistical analysis concluded that there is no significant difference among green roofs (Table 5.3). Moreover, there is no significant difference between green roofs' indoor air temperature and ambient temperature. Table 5.3 demonstrated that seasonal average temperatures are significant different, while Table 5.4 shows that data is significant different from season to season. In addition, the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 2012) suggests that comfort indoor air temperature varies between 18°C and 24°C. Results from Table 5.2 shows that every green roof has, on average, a lower temperature than the advisable comfort temperature.

Figures 5.6-5.9 show that green roofs' indoor air vapor pressure tends to be stable. However, ambient vapor pressure experiences sudden changes during the day. Results in Figures 5.8-5.11 report that ambient vapor pressure can be as high as 40 hPa and be as low as 5 hPa in the same week. Nevertheless, Table 5.5 demonstrates that the average ambient vapor pressure is similar to green roofs' average vapor pressure. Therefore, the ANOVA resulted that vapor pressure among green roofs is not significant different, while data among seasons is significant different (Table 5.6). Additionally, Table 5.7 shows that data from all the seasons is different from each other. The Canada Mortgage and Housing Corporation (CMHC, 2004) suggests that comfort indoor air relative humidity ranges from 30% to 55%. Therefore, if it is considered an average indoor temperature of 21°C, The CMHC suggests a comfort indoor vapor pressure that ranges from 7.45 hPa to 13.65 hPa. Results from Table 5.3 shows that every green roof has, on average, a lower vapor pressure than the advisable comfort vapor pressure.

Figures 5.1-5.4 and Figures 5.6-5.9 demonstrate that green roofs are not sensitive to sudden changes in environmental conditions. Green roofs' response to sudden increase or decrease of ambient conditions is slow. For instance, Figure 5.6 shows that a sudden increase of ambient vapor pressure causes an increase in green roofs' indoor vapor pressure. However, green roofs' vapor pressure increase at a much lower rate than ambient vapor pressure. The same behavior is noted when ambient vapor pressure suddenly drops down. Temperature results show the same green roof's response behavior. Root barrier, growing medium and vegetation layers are exactly the same for the experimental set-up. From them, the only layer capable of adapting to environmental conditions is vegetation. Therefore, green roof's plants play an important role regulating indoor conditions. Additionally, the growing medium's thickness provides an important insulation for any structure.

Results shown in Figure 5.12 demonstrate that the layer's material type affect the green roof's rainwater retention capacity. These results prove that green roof's rainwater capacity is not just dependent of the vegetation and growing medium layers, but also in the subsequent layers. The statistical analysis in Table 5.8 confirms that there is a significant difference between green roofs' water retention performance. Additionally, Table 5.9 identifies which green roofs have significant different rainwater retention potential. The two best green roofs, in terms of water retention, are GR1 and GR6. GR1 is a standard commercial green roof with the Xeroflor XF107 water retention layer, while GR6 replaces polymeric layers with expanded shale. Concrete and rigid foam were the materials that resulted in the poorest water retention performance (GR3, GR4 and GR5). Both materials have small pores. Hence, this physical characteristic allows materials to absorb just little amounts of water. On the other hand, expanded shale has bigger pores that allow the absorption of more water. Similarly, polymers can be specially designed to absorb fluids.

GR1 (standard commercial green roof) has water retention performance of 97%, while GR4 (crushed concrete) absorbed, on average, 67% of rainwater. The water retention potential difference between these green roofs is 30%. If it is compared with other green roofs, the performance of crushed concrete is poor. However, compared with any other standard roof, a 67% of rainwater absorption is a huge benefit.

The only physical difference between GR7 and GR8 is that GR7 has a thin polymeric water retention layer (XF159). However, GR8 has 2% higher water retention potential. Equally, GR3 differs from GR4 in that GR3 has the XF159 polymeric water retention layer. In this case, GR3 has 3% higher water retention potential. Table 5.9 does not show GR7-GR8 and GR3-GR4; therefore, this pair of couples are not significant different. This result probes that not all the polymeric water retention layers increase green roof's water retention potential.

Health Canada (2010) demands that drinking water must have a pH between 6.5 and 8.5. Results in Figure 5.13 show that the average pH for rainwater and green roofs' samples are within the Canadian law range. Additionally, samples' pH results fall into the neutral range. In general commercial standard green roofs and C&D waste increase rainwater's pH in 2% and 10%, respectively. Table 5.10 statically probes that there is a significant difference between green roofs runoff's pH. Table 5.11 identifies which green roofs' samples are different to each other. Moreover, Table 5.11 shows that rainwater's pH is significant lower that all the green roofs' samples. However, the pH increase is not enough to change rainwater's pH from neutral to basic. Average rainwater's pH resulted to in the lower limit of the law's range. Moreover, Figure 5.13 clearly demonstrates that green roofs increase rainwater's pH. Green roofs' capacity of increasing rainwater's pH is particularly important in places with acid rain. In such a case, green roofs could change rainwater's pH from acid to neutral.

The amount of TSS present in raw water must be between 45mg/l and 330mg/l (Health Canada, 2010). Results obtained from rainwater and green roofs samples are within the Canadian law range (Figure 5.14). In general, Figure 5.14 shows that green roofs act as a rainwater filter. Rainwater's TSS tends to be higher than many green roof's samples. However, Table 5.12 demonstrates that there is no statistical difference between the obtained results. C&D waste based green roofs resulted to have, on average, the least amount of suspended solids. Nevertheless, is important to note that expanded shale green roof (GR6) and one commercial standard green roof (GR1) resulted in the only green roofs that add particles to rainwater. Since there is no statistical difference between green roofs' average TSS content, results suggests that the vegetation and growing medium layers work as a rainwater filter.

The statistical analysis resulted in that samples' electro conductivity are significant different (Table 5.13). Additionally, Table 5.14 identifies the samples that are different to each other. Drinking water electrical conductivity should be 1ower than 500μS/cm (Health Canada, 2010). Similar as pH and TSS, Figure 5.15 shows that all electro conductivity results satisfy Health Canada's law limit. In general, green roofs tend to reduce rainwater's electro conductivity. C&D waste based green roofs' runoff samples have, on average, the least amount of inorganic salts (Figure. 5.15). Moreover, equally as TSS, GR1 and GR6 were the only green roofs that increase and deteriorate rainwater physical properties. Therefore, this result suggests that a main portion of GR1 and GR6 TSS's particles are inorganic salts.

Chapter 6: Conclusion

As urbanization increases, it is critical to find a balance between human development requirements and environmental concerns. This study represents a small contribution towards the reduction of the green roof`s environmental footprint. Additionally, the conducted research encourages green roof installation by demonstrating its economic and structural positive effects on buildings.

This thesis has identified important characteristics that should be taken into account to compare green roofs with conventional roofs. Additionally, explores the possibility of using C&D waste to replace current green roof layers. The proposed green roof can reduce green roof's environmental footprint and improve social economic benefits. It will also guide engineers to find and re-use a more effective material in terms of water retention. The methodology can be applied to any green roof type and system with very little modifications.

Results of chapter 2 demonstrate that there are more advantages than disadvantages of building green roofs to reduce air pollution. Positive environmental impacts emphasize the importance of green roofs as a sustainable option for the construction industry and society. The analysis presented in this paper considered four main polluting substances (NO_2, SO_2, O_3 and PM_{10}); however the production process of polymers releases more toxic substances to different media. Investigations needed to be conducted to enhance the overall air pollution potential of green roofs.

Green roofs can balance the pollution released to the air due to the polymer´s production process in long term; however it is important to point that the manufacturing process of low-density polyethylene and polypropylene has high negative impacts to the environment. The analysis in chapter 3 concluded that it is still beneficial to install green roofs with polymers; however, it is essential to explore materials that can replace the current use of polymers to enhance overall sustainability of green roofs.

Green roofs provide personal and social benefits. The probabilistic NPV analysis in chapter 4 determined that there is a low financial risk for installing any green roof type. Additionally, from a personal perspective, the potential profit of an intensive green roof is much higher than its potential losses. Green roofs are a personal investment. However, over the lifecycle of these roofs, both personal and social sectors derive economic benefits. In fact, when social costs and benefits are considered in the NPV estimation, the profitability of the investment is assured. Installing green roofs would be an even more attractive business, if social benefits were partially transferred to investors. Society should promote green roof construction by reducing insurance premiums and public maintenance costs. These incentives will enhance green roof construction on new and existing buildings, hence, improving social environmental benefits.

The analysis in chapter 3 demonstrated the financial benefits of re-using waste materials in green roof construction. The main social costs of green roofs were found to be in the manufacturing and decommission phases of their lifecycle. Furthermore, green roofs should be seen as a part of a suite of environmentally friendly construction practices. Green buildings must be considered as economically feasible construction systems. The economic feasibility of every possible element is important to increase the market value of green technologies. Innovation and further research is required to decrease the carbon footprint of green technologies over their lifecycle.

Dynamic time history analyses were conducted on all the frames described in chapter 4 to determine the capacity/demand ratio in terms of base shear and roof drift. Three different storey RC frames (e.g. 3, 6 and 8) with 3 different roof types have been analyzed. Results demonstrate the impact of green roofs on the seismic performance of the frame structures, which increases the time period, inter-storey drift, and roof drift demand; additionally, reduces the base shear demand. In the case of 3 storey frames:

- On average, the maximum inter-storey drift is experienced in the first and second floor. The average inter-storey maximum demand is 1.58% for all roof types.
- The roof drift caused by intensive green roof is 1.14% and 1.28% higher than that of gravel flat roof and extensive green roof, respectively.
- The base shear demand for gravel flat roof is 0.82% and 1.07% higher than that of extensive and intensive green roof, respectively.

In the case of 6 storey frames:

- On average the maximum inter-storey drift takes place on the forth floor. Intensive green roof causes the average maximum inter-storey demand (1.32%).
- The roof drift caused by intensive green roof is 3.45% and 2.53% higher than that of gravel flat roof and extensive green roof, respectively.
- The base shear demand for gravel flat roof is 1.24% and 1.43% higher than that of extensive and intensive green roof, respectively.

In the case of 8 storey frames:

- The average maximum inter-storey drift experienced is 1.24% in the fifth floor for the intensive green roof.
- The roof drift caused by intensive green roof is 2.46% and 2.42% higher than that of gravel flat roof and extensive green roof, respectively.
- The base shear demand for gravel flat roof is 0.13% and 1.17% higher than that of extensive and intensive green roof, respectively.

The dynamic time history analyses reveal that green roofs have some impact on the dynamic behavior of frame structures, which were designed according to current seismic standards; however, the differences are insignificant/ negligible. Results also indicate that the base shear demand does not exceed the capacity of the structure; therefore, they can be installed on existing buildings. Based on the findings, no retrofitting technique is required to increase the lateral strength and increase ductility.

Analysis in chapter 4 indicates that if frame structures are properly designed according to current seismic design guidelines, one may install green roofs on the existing roof without any compromise to the performance of the structure at the designed seismicity level. Before implementing green roof, analysis is also required to determine the capacity of the structural elements to resist the increase in gravitational loads due to the extra weight from the green roof. Further research is required to determine the seismic performance of frame structures in the case of partial green roofs on plan dimensions and arrangements.

Eight different experimental green roofs with different material types have been analyzed in chapter 5. Indoor temperature, indoor vapor pressure, water retention capacity and runoff water quality were measured to determine each green roof performance. Results in chapter 5 demonstrate the impact of the materials used as layers in green roof's performance. In the case of indoor temperature:

- There is no significant difference between experimental green roofs' average indoor air temperature and average ambient air temperature.
- Average indoor air temperature and ambient air temperature are significant different among seasons.
- On average, C&D waste based green roofs tend to have higher indoor air temperature than commercial standard green roofs.

In the case of indoor vapor pressure:

- There is no significant difference between experimental green roofs' average indoor air vapor pressure and average ambient air vapor pressure.
- Average indoor air vapor pressure and ambient air vapor pressure are significant different among seasons.
- On average, C&D waste based green roofs tend to have higher indoor air vapor pressure than commercial standard green roofs.

In the case of water retention:

- Average water retention capacity is significant different between experimental green roofs.
- Commercial standard green roofs have higher water retention capacity than C&D waste based green roofs.
- The average maximum water retention is 97% (GR1), while the average minimum water retention is 67% (GR4).

In the case of pH:

- Strom water runoff's pH is significant different among green roofs.
- On average, commercial standard green roofs and C&D waste based green roofs increase rainwater's pH in 2% and 10%, respectively.

In the case of total suspended solids (TSS):

- There is no significant difference between experimental green roofs' average indoor air temperature and average ambient air temperature.
- In general, green roofs reduce rainwater's TSS content.
- On average, commercial standard green roofs have 15% more TSS than C&D waste based green roofs.

In the case of electro conductivity:

- Average electro conductivity is significant different between experimental green roofs' runoff and rainwater.
- In general, green roofs reduce rainwater's electro conductivity.
- On average, commercial standard green roofs' runoff samples have 17% more electro conductivity than C&D waste based green roofs.

The analyses presented in chapter 5 reveal that materials below the growing medium and vegetation layers impact on green roof`s performance. However, for indoor air temperature, indoor vapor pressure and TSS the differences are insignificant/negligible. Results also indicate that green roofs can improve rainwater's quality. Therefore, green roof's storm water runoff could be used for non-drinking purposes, such as: irrigation or flushing toilets.

Chapter 5 probes that the use of C&D waste to replace current green roof's polymeric layers is feasible. The use of C&D waste improves green roof's environmental footprint and the potential economic benefits without significantly compromising green roof's environmental benefits. Therefore, the installation of green roofs with C&D waste materials is beneficial.

The performed methodology for green roof assessment can yield guidelines for the decision makers in designing and installing green roofs on existing and new structures. However, to achieve that goal this thesis recommends:

- The study focuses on replacing green roof current polymeric layers with C&D waste. Further research is required to develop a more environmental friendly growing medium layer.
- Develop a green roof code and construction guideline.
- Experimentally compare different green roof types such as intensive or semi-intensive.
- Explore the use/re-use of different waste materials as green roof layers
- Study the best suitable plants for the Okanagan valley weather.
- Further research is required to understand the environmental benefits of green roofs. For instance, Yang *et al*, (2008) determined the amount of four pollutants that green roof ̓s plants can remove from the air. However, the analysis presented in Chapter 2 demonstrated that different industrial processes released more than four pollutant substances to the air. Moreover, polluting substances are released to water and soil as well.
- Assign an economic value to green roof's social benefits such as enhancement of biodiversity or rainwater purification.
- A complete water quality assessment is needed to determine the impact of C&D waste on the storm water's quality. Moreover, identify any possible negative effect of current and alternative materials in green roof's vegetation layer.
- Study the role of green roofs in bioremediation.

There is a greater need to implement clean technologies that enhance quality of life and save energy. Green roofs represent an engineering effort that contributes towards environmental friendly practices. Facilitating and expanding their installation on new and existing buildings through academic research is an imperative step in green design and construction.

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Appendices

Appendix A Design details of the experimental set-up.

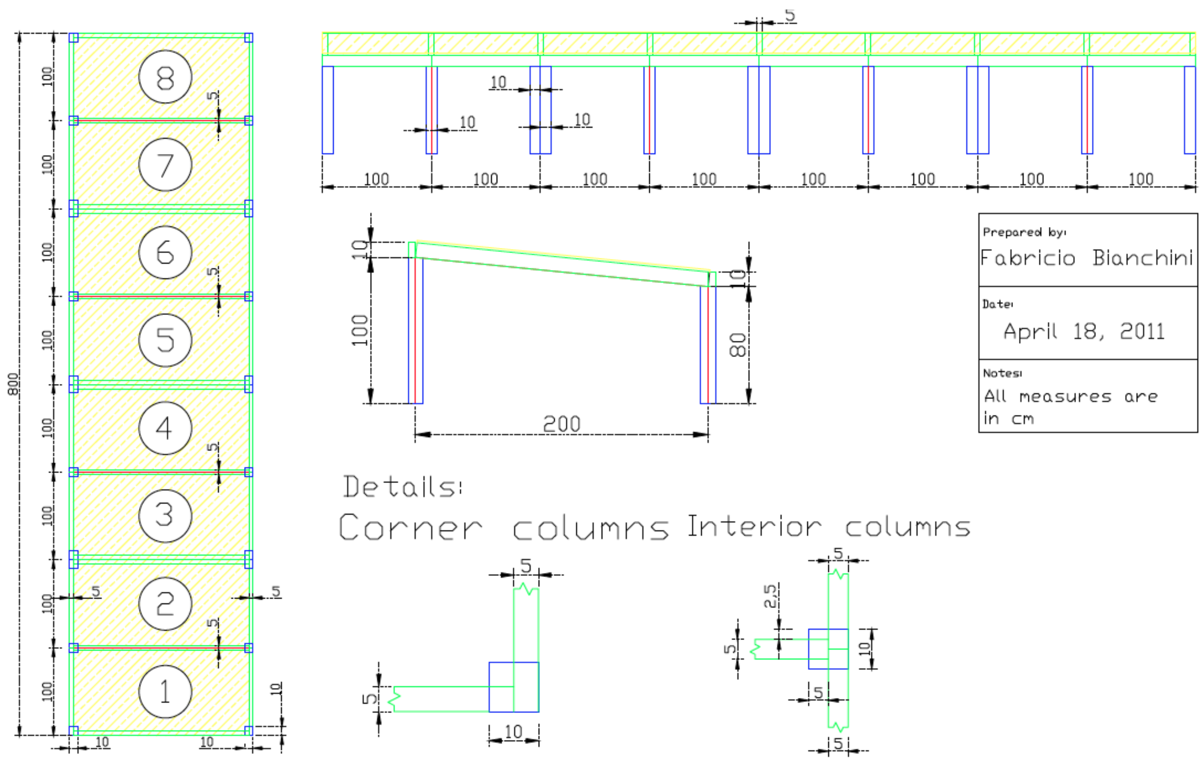

Illustration A.1 Runoff storm water samples