WATER QUALITY AND LIFECYCLE ASSESSMENT OF GREEN ROOF SYSTEMS IN SEMI-ARID CLIMATE

by

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Abstract

Non-point source pollution contributes significantly to stormwater contamination in urban areas. Low impact development (LID) techniques and technologies are developed as a response to these challenges. Green buildings incorporate environmentally responsible and resource-efficient technologies to reduce environmental impacts over their life cycle. Green roof systems are broadly recognized as LID practices that may improve urban environmental quality by reducing stormwater runoffs. Potential impact of green roofs on the quality of runoff may be a deterrent to wider application of green roof systems. Organic and inorganic fertilizers in growing media, for example, may contaminate runoff and generate non-point source pollution. Recently, various environmental assessment methods have been developed to assess the environmental performance of green building technologies. Methods developed to date, however, are insufficient for accurate quantitative estimation and evaluation of triple-bottom-line (TBL) sustainability performance objectives (i.e. economic, environmental, and social) in the context of green building technologies. This study has two main objectives. First, it aims to investigate the performance of green roofs in the context of runoff water quality in the semi-arid environment of Kelowna, British Columbia, Canada. An experimental investigation has been conducted to enhance green roof performance by addition of a supplemental filtration layer. Runoff and precipitation samples were analyzed for water quality parameters including pH, nitrate and ammonia. In the next step, a quantitative sustainability evaluation framework for green building technologies was developed. The proposed framework integrates fuzzy-analytical hierarchy process (FAHP) integrated with a ‘cradle-to-grave’ life cycle assessment to address interactions and influence of various TBL criteria. The experiment results showed that the generic green roofs runoff is acceptable for domestic reclaimed water used under Cnadaian guidelines for domestic reclaimed water. The analysis shows that green roofs are able to reduce non-point source nitrate and ammonia concentrations. The installation of extensive green roofs could decrease a large amount of non-point source nitrate and ammonia emissions in an urban area during their lifespan. The utility of the FAHP approach is demonstrated by comparing sustainability performance of two generic green roof systems with a conventional roof. The results show that an ‘extensive’ green roof system is a more desirable option in terms of long-term sustainability performance criteria.

Keywords: Green roofs, stormwater runoff quality, low impact development (LID) practices, non-point source pollution, Performance assessment, fuzzy-analytical hierarchy process (FAHP), life cycle assessment (LCA).

Preface

Parts of Chapter 2 and Chapter 3Chapter 4 have been submitted as follows:

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Glossary

Symbol	Definition (Unit)
AHP	Analytical Hierarchy Process
Cd	Cadmium
CF	Coconut Fiber
CIRS	Centre for Interactive Research on Sustainability
Cr	Chrome
EC	Electrical Conductivity
EPDM	Ethylene Propylene Diene Monomer
FAHP	Fuzzy-AHP
Fe	Ferrous
G	Gravel
GAC	Granular Activated Carbon
GB	Gravel Ballasted Roof
GHG	Green House Gas
GR	Green Roof System
GWP	Global Warming Potential
K	Potassium
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LID	Low Impact Development
Mn	Manganese
NO_3-N	Nitrate-Nitrogen
NH_4-N	Ammonia-Nitrogen
ORP	Oxidation Reduction Potential
Pb	Lead
PO_4-P	Phosphate-Phosphorous
S	Sand
T	Crushed Tile
Tot- N	Total Nitrogen
TSG	Crushed Tile +Sand + Gravel
WB	Wood Bulk
Zn	Zinc

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Dedication

To My Loving Parents

Chapter 1 : Introduction

This chapter highlights the motivation for this thesis. A brief history of green roof systems and the environmental impacts of conventional roofing systems have been described in Sections 1.1 and 1.2, respectively. Following this, the motivation and objectives of the study have been presented in Sections 1.3 and 1.4. The research methodology outline in the context of thesis organization has been provided in Section 1.5. Finally, the thesis structure is demonstrated in Section 1.6.

1.1 A Brief History of Green Roof Systems

Green roofs have been used in buildings for many years. The first historical use of green roofs was found in the region of Mesopotamia located between the Tigris and Euphrates rivers around 500 BC (Osmundson 1999). Implementation of green roof as a modern means of architectural design for best management practices started in German-speaking countries 50 years ago (Osmundson 1999). However, green roofs have been used as a stormwater best management practice in North America only in the last decade.

By widespread acceptance of “green building” principles symbolized by constructing high profile housing projects called the Hundertwasser-Haus in Vienna, Austria, roof gardens and facade greening became the center of attention for urban landscape architects, building companies, and environmental researchers (Osmundson 1999). The Research Society for Landscape Development and Landscape Design in Germany, or in German *Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau* (FLL), developed a branch to study various benefits and impacts of green roofs on the buildings and environment in the 1970s (Dunnett and Kingsbury 2008). This organization is responsible for developing guidelines and standards for green roofing systems. The *FLL guideline* is frequently referenced in North America due to the absence of specified guidelines developed for the US or Canada.

Green roof systems can be categorized based on the depth of the growing medium: extensive green roofs and intensive green roofs. Extensive green roofs, also called eco-roofs or performance roofs have the growing medium almost less than 150 mm, whereas intensive green roofs growing medium is 150 mm and higher (Bianchini and Hewage 2012a).

In North America, practitioners and building contractors tend to incorporate green roof systems into their projects. Research has shown that green roof system implementation dramatically increased every year e.g. 115% in 2011, and 24% in 2012 (Green roofs for healthy cities 2013a). The US Green Building Council's Leadership in Energy and Environmental Design (LEED) program, and other green building initiatives and incentives designed for building owners and contractors are the primary motivations for such a dramatic growth of retrofitting and constructing green roof systems.

1.2 Environmental Impacts of Roofing Systems

Roofing system depreciation is the most frequent phenomenon in building systems. Roofing elements deteriorate due to harsh conditions in winter and summer seasons. In the context of roofing deterioration, a conventional building in the United States requires roof replacement at least four times during its lifespan, which produces a large amount of solid waste (Coffelt and Hendrickson 2010). This situation could be worse in Canada due to harsher winter seasons and significant variation of temperature during summers.

High volume of wastes from roofing systems can greatly increase the environmental impacts of the building industry (Bianchini and Hewage 2012b). Various techniques have been developed to minimize waste generation and environmental impacts and maximize the environmental performance of a roofing system over its lifespan. Green roof systems offer a wide range of environmental and ecological benefits and improve the quality of indoor and outdoor environments. Advantages and disadvantages of green roof systems are discussed in detail in Chapter 2.

1.3 Research Motivation

A comprehensive experimental investigation is required to assess claimed environmental benefits of green roof systems. The results of this experiment can assist architects and designers in comparing different roofing alternatives in the context of a specific project. Although green roof systems are known as best management practices (BMPs) or low impact development (LID) technologies, some aspects of the environmental performance of green roof systems have still not been comprehensively studied. The basic application of green roof systems is for stormwater management. Green roof systems can reduce stormwater volume and delay the peak hour by capturing a portion of precipitation. Previous studies on green roofs runoff quality were controversial. Some studies showed that the water quality of green roofs runoff is lower than that of conventional roofs. Lower water quality of runoff may increase the amount of non-point source pollution in urban areas. Since the type of plants and soil formulation applied in green roof systems vary from one plant to another, it is necessary to conduct runoff quality field sampling for a plant before the implementation of the green roof system. The runoff water quality analysis can be used for further policy making and urban design for providing a plan for non-point source pollutant management in a city.

Lack of proper implementation of green roof systems in local construction industries, building codes, and other important regulations and guidelines prevent designers, architects, and engineers from making an informed decision during the design process. Building components last for decades and require a large investment for construction, operation and maintenance (O&M), and disposal (Nelms et al. 2007). Therefore, decisions in this industry are costly and require a wide range of criteria to be considered. As a result, developing a framework for assessing the sustainability of roofing systems is necessary.

1.4 Objectives

The focus of this research is developing a decision support tool for green roof systems' selection based on the sustainability triple bottom line (TBL). The main objective of this study is to experimentally investigate the performance of green roofs on runoff water quality.

An extensive green roof system pilot was constructed near the Engineering, Management and Education (EME) building located at the University of British Columbia–Okanagan campus (UBC-O), Kelowna, Canada. The pilot was run from June to December 2012 and the result of the analysis was implemented on developing different scenarios for non-point source nitrate removal in downtown Kelowna. In the next step, a framework for assessing the sustainability of roofing systems was developed based on the existing knowledge base and experimental study results of green roof systems. The framework helped to compare sustainability of extensive and intensive green roofs with gravel ballasted roof systems for the EME building located at UBC-O, Kelowna, Canada.

Following are the specific objectives of the current research project:

- Explore the effect of additional filtering materials added to green roof layers on the runoff water quality.
- Life cycle assessment (LCA) of an extensive green roof and an intensive green roof with a gravel ballasted roof.
- Develop a comprehensive sustainability assessment framework based on the FAHP coupled with LCA to estimate a relative sustainability index (RSI) for roofing systems.

1.5 Research Methodology Outline

The research methodology to achieve the objectives of the study is illustrated in Figure 1-1. The methodology is comprehensively described in Chapter 3Chapter 4 and Chapter 4.

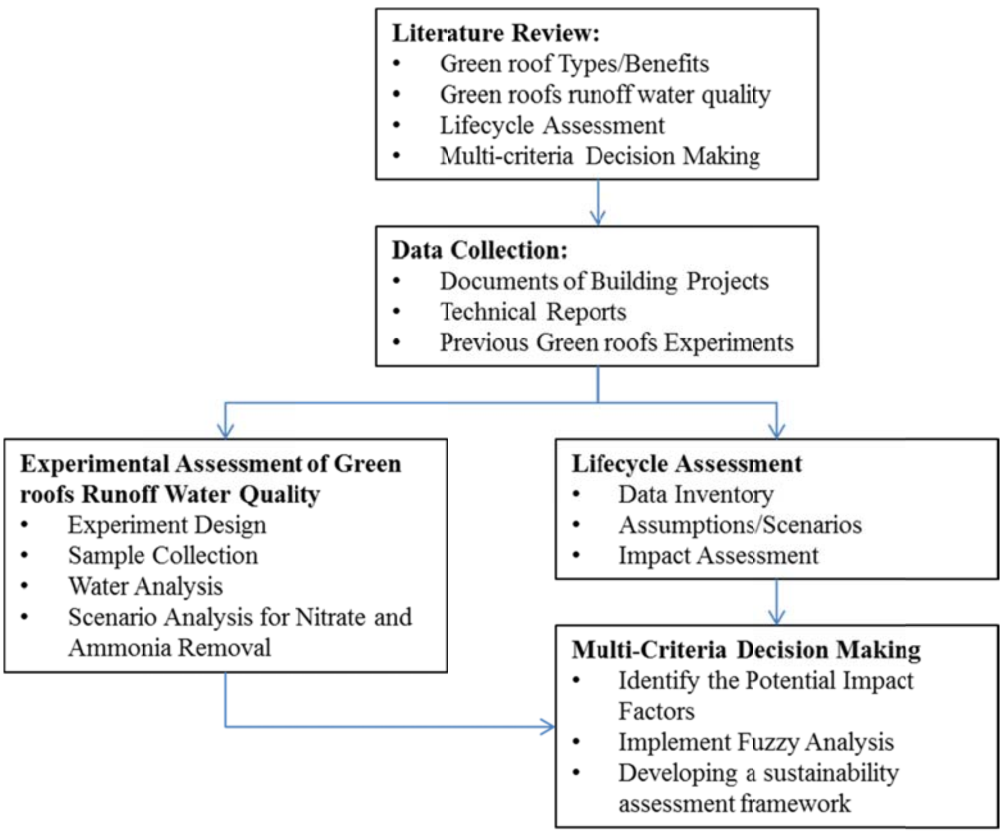

Figure 1-1: Research Methodology Outline

The research started with a comprehensive literature review focused on the green roof systems. The information and data was collected based on the previous studies, building documents, and technical reviews. This information was used for experiment design, lifecycle assessment, and developing the sustainability assessment framework.

The experiment was designed in order to conduct the runoff water quality assessment. The analysis was performed based on natural rain events, and the main water quality characteristics were assessed. The results were compared with fresh water and reclaimed water guidelines.

In the second step, a sustainability assessment framework was developed for assessing the sustainability of roofing systems. The framework was based on the FAHP and LCA. Important criteria influencing the sustainability of a roofing system were identified. The framework evaluated extensive and intensive green roofs and compared the results with conventional roofing systems.

1.6 Thesis Structure

The thesis consists of five chapters as shown in Figure 1-2. The research methodology was developed based on the objectives discussed earlier. In Chapter 2, detailed background information required for this research has been provided. The advantages and disadvantages of green roof systems have been discussed. Issues related to runoff water quality of the green roof systems have also been discussed in detail. The life cycle methodology and its limitations as well as multi-criteria decision making methods are discussed in relation to the current research.

In Chapter 3, an experimental investigation of extensive green roof systems has been provided. The experiment is performed based on natural rain sampling of 2012. While the experiment sampling was completed, the effluent quality was compared with the effluent of control roofs. Moreover, an additional pre-treatment layer was added to green roof systems. The runoff quality of the enhanced green roofs was analyzed and compared with the generic green roof systems. Optimistic and conservative scenarios for retrofitting a part of Kelowna’s downtown buildings with an extensive green roof were performed to estimate the amount of non-point source nitrate and ammonia removal.

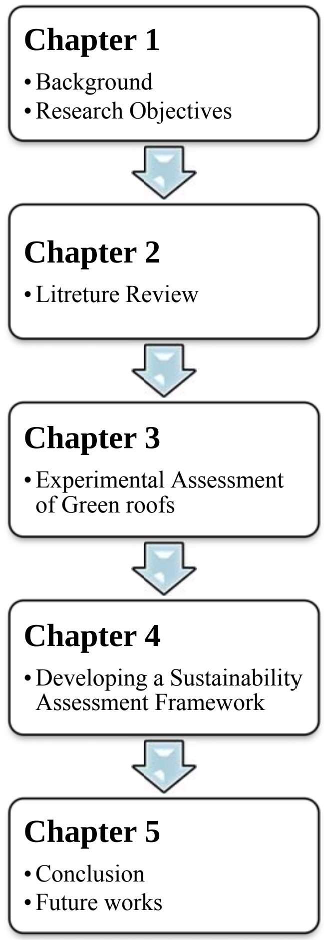

Figure 1-2: Thesis Structure

In Chapter 4, a relative sustainability index (RSI) was developed for assessing the sustainability of building technologies based on the TBL criteria. For this purpose, the entire lifecycle of extensive and intensive green roofs was analyzed and compared with a gravel ballasted roof. When the LCA emissions were performed, the RSI framework was constructed based on the TBL criteria. TBL criteria consist of economic, environmental, and social criteria. For this purpose, various sub-criteria were defined for each TBL criterion, and then the roofing systems were evaluated and assessed using the Fuzzy Analytical Hierarchy Process (FAHP) method.

Finally, a summary and conclusion of the current research project is presented in Chapter 5.

Chapter 2 : Background

This chapter provides the background information for this thesis. The literature review covers the following main topics in this chapter:

- Green roof systems including their components, types, environmental benefits, disadvantages, and costs.
- Life cycle assessment (LCA) definition, steps, limitations, and its application in green roof systems.
- Multi-criteria decision making (MCDM) with a specific focus on AHP.

2.1 Green Roof Systems

Non-point source pollution in urban areas is responsible for significant water quality deterioration in North America (USEPA 2009a; Brezonik and Stadelmann 2002). Wash-off of impervious surfaces such as roof surfaces, and direct discharge of pollutants, fertilizers, and pesticides are sources of non-point pollution in urban areas (Gregoire and Clausen 2011; Brezonik and Stadelmann 2002; Egodawatta et al. 2009). While impervious roof surfaces coverage is about 12% in residential areas and 21% in commercial areas (Ellis 2013; Chester and Gibbons 1996; Boulanger and Nikolaidis 2003; Gregoire and Clausen 2011), it is necessary to manage the additional emission of these surfaces.

Low impact development (LID) technologies have been developed as an appropriate response to non-point source pollution management in urbanized areas (Ellis 2013; Dolowitz et al. 2012). LIDs incorporate land use planning and engineered designs with the natural features of materials to infiltrate, filter, store, and detain runoff close to its source (McHarg 1995). Various LID practices such as bio-retention cells, green roofs, and grassed swales have been developed in recent years (Dietz 2007; Gregoire and Clausen 2011).

Green roofs are increasingly used by urban and environmental planners to mitigate different environmental impacts of urban development. These roofs are covered with vegetation and growing medium equipped with a filtration layer. There are two types of green roofs: intensive and extensive. Intensive green roofs have a thick growing medium and may be planted with trees and shrubs, whereas extensive green roofs have thinner growing medium ($\leq$ 10 cm) and are planted with drought tolerant vegetation such as *Sedum* and *Delosperma* (Berndtsson et al. 2009; Gregoire and Clausen 2011; USEPA 2009b).

2.1.1 Green Roofs Components

A green roof is a roof with additional, high quality water proofing and a root barrier system, a drainage system, filtration layer, a growing medium, and vegetation (Green roof for healthy cities 2013). Figure 2-1 depicts a generic green roof and illustrates different layers in its orientation. Water proofing membranes used in green roofs are thicker and able to support the additional weight of green roofs. Waterproofing membranes should be installed with a high standard of care in furnishing and installation of materials. Roof drainage systems in conjunction with green roofs should be designed to supply green roof components. Green roof systems drainage supportive components are designed to stand the additional load of the green roof growing medium.

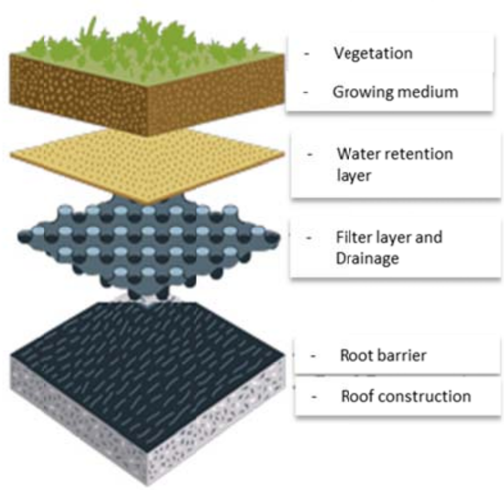

Figure 2-1: Typical cross section of a generic green roof

Regardless of those interactions, green roofs are modular in the majority of cases and can be retrofitted on the basic roofing system (Green roof for healthy cities 2013). For this reason, each layer of green roofs will be investigated and layers below the water proofing layer are not considered in this research.

i- Vegetation

Vegetation is the most important element that distinguishes green roofs from other types of roofing systems. Selection of a proper vegetation type is one of the challenging tasks in green roofs design. Each plant type has a different weight, benefits, and maintenance procedure. There are several requirements for plant type selection including non-invasive roots, not dropping large quantities of leaves or fruits, and not exceeding the load capacity of the structure (Osmundson 1999). Plant types should be resistant to climate conditions (wet or dry) and freezing in winter, and should be compatible with soil used in green roofs (Osmundson 1999). Moreover, plant types should tolerate temperature extremes and high winds, should quickly cover the growing medium, and should self-repair (Dunnett and Kingsbury 2008; FLL Guidelines 2002).

Plant selection for extensive green roofs is almost limited to *Sedum* or grass mixes due to the conservative nature of the building industry. Limited plant types meet the requirements. These plants naturally grow in harsh, rocky environments with shallow soil. However, there is a question whether a broader range of plant types with the potential benefits to local bio-diversity might be appropriate for use in green roofs. Plant types can influence runoff quantity by providing a better evapotranspiration rate and use of supplemental growing medium for a range of plant species (Dunnett et al. 2005).

ii- Growing medium

The growing medium is the layer that supports plants and provides the most environmental benefits of green roofs. Growing medium porosity and density can impact hydraulic conductivity of green roofs and structure design reinforcement. The growing medium must support the needs of plants; it must be light and provide an optimized balance between water retention and drainage. Growing medium can significantly change the runoff flow and saturated hydraulic conductivity (Poulenard et al. 2001).

iii- Filter layer

The filter layer in green roofs prevents clogging of both the green roof drainage layer and the roof drainage system. The filter layer prevents washed particles of the growing medium and plant matters from entering the drainage layer. The filter layer should be water permeable, durable, portable, inexpensive, and tough (Osmundson 1999). In most green roofs a semi-permeable propylene fabric is used (Osmundson 1999; Dunnett and Kingsbury 2008).

iv- Drainage layer

The drainage layer is a porous material that conveys the free water to the roofing drainage system (DeNardo et al. 2003). The drainage layer provides two critical factors for green roof systems: First, green roofs and especially extensive green roofs are planted with drought-tolerant plants. A drainage layer is required to convey the excess water during storms and avoid drowning the roots of these plants. Second, the drainage layer is required to maximize the thermal performance of the insulation layer (Dunnett and Kingsbury 2008). Granular drainage layers are simple and traditional methods, while other lighter materials like spongy materials, plastics or polystyrene modules, and recently recycled construction materials can be used as a drainage layer (Bianchini and Hewage 2012a).

v- Root barrier

The root barrier sits between the drainage layer and the water proofing layer. Plant roots naturally seek water and may cause roof membrane punctures and leaks. There are two main strategies to protect the waterproof membrane. The first is implementing a roll of PVC or waterproofing membrane as a root-impervious layer. Another strategy is implementing plastic or metal sheets to effectively isolate plant roots from the waterproofing layer (Dunnett and Kingsbury 2008). In addition, there are several other methods for protecting waterproofing methods, such as chemical root inhibitors (Peck and Kuhn 2001). The roof membrane material acts as a root barrier itself (Osmundson 1999).

2.1.2 Environmental Benefits of Green Roofs

Green roof systems are among the technologies receiving increased attention for their potential to mitigate negative environmental impacts of the construction industry. Green roof systems may contribute to stormwater management (Berndtsson 2010; Teemusk and Mander 2007; Rajendran, Gambatese, and Behm 2009; City of Toronto 2010), reducing urban heat island effect (Nelms et al. 2007; Newsham et al. 2009; Rosenzweig, Stuart, and Lily 2006; Peck and Kuhn 2001), reducing the system’s energy consumption (Jaffal, Ouldboukhitine, and Belarbi 2012), and decreasing the total cost of systems over their lifespan (Castleton et al. 2010; Rowe 2011). Green roof systems can also improve building aesthetics and the overall building value (Getter and Rowe 2006; Long et al. 2006). Green roofs provide better protection with additional insulating layers and may prolong the roofing system lifespan to at least 40 years, compared to conventional roofing systems with a 20 year lifespan (Kohler et al. 2001; Carter and Keeler 2008).

i- Reducing energy consumption

Green roofs' impacts on energy consumption have been investigated widely. The insulation effects of additional materials reduce energy demand for cooling and heating the building during summer and winter (Jaffal et al. 2012; Newsham et al. 2009).

Eumorfopoilou and Aravantinos (1998) examined thermal behavior of green roofs by applying mathematical calculations and stated that about 27% of the total solar radiation absorbed by the green roof is reflected and 60% is absorbed by plants.

Green roofs can reduce the surface temperature and the temperature fluctuation of the roof. Onmura et al. (2001) conducted an experiment on green roofs' surface temperature and compared them with white roofs in Japan. The results showed that green roofs reduce the surface temperature to 28-30ºC, while the surface temperature on conventional roofs is about 60ºC. Sonne (2006) studied the surface temperature of a roof with 50% green roof and 50% without green roof. The study showed that green roofs are able to reduce temperature fluctuation on the roofs' surface. The surface temperature variation on a part without green roof was about 28°C, while the temperature fluctuation on a green roof was about 1.2°C.

Experiments on green roofs show that green roofs increase the energy performance of a building. Liu and Baskaran (2003) argued that green roofs can reduce the energy demand for the building to about 75%. Santamouris et al. (2007) studied the energy performance of green roofs installed on a building in Athens, Greece. Santamouris et al. (2007) elucidated that green roofs significantly reduce the energy demand of a building cooling system during summer. This reduction varied from 6-49% for the whole building and 12-87% for the last floor. However, they argued that green roofs' influence on a building heating load in winter is insignificant. Fioretti et al. (2010) explored green roofs' impact on energy performance of a building in two different case studies. The results showed that green roofs have a better performance than conventional roofs and reduce daily energy demand for the building. Chan and Chow (2013) simulated the energy performance of green roofs and argued that a green roof with a thicker soil medium and plant height provides a better thermal insulation effect.

ii- Stormwater management

Green roofs retain precipitation and gradually evapo-transpire it, whereas conventional roofs immediately drain stormwater into the downstream. Runoff peak flow can be reduced by temporary stored water in the vegetation and soil medium, which can extend the "time-of-concentration" and reduce local urban flooding (Gregoire and Clausen 2011). Despite the fact that green roofs have been recognized as a means of reducing the quantity of stormwater runoff, lack of sufficient evidence on the impacts of green roofs on stormwater runoff quality deters sustainable implementation of them.

Green roofs can be used as an effective stormwater management tool in urban areas, because they are able to decrease the quantity of stormwater. Green roofs impact stormwater runoff through lowering and delaying the peak runoff. A study conducted in Vancouver, BC showed that a well-designed green roof is able to protect stream health and reduce the risk of flood in urban areas (Graham and Kim 2003).

Green roofs are able to reduce runoff up to 100% in warm weather. However, the percentage of retained water in green roofs diminishes when there is not adequate time between each storm event (Moran, Hunt, and Jennings 2004). According to the experimental results, the retention capacity of green roofs is highly dependent on the volume and intensity of precipitation (Moran et al. 2004).

Teemusk and Mander (2007) conducted an experiment on stormwater retention potential of green roofs. The results showed that green roofs are able to reduce light rainfall runoff up to 86%. In the case of heavy rainfalls, green roofs can only delay the runoff up to half an hour, and their impact on runoff volume is insignificant. Green roofs are able to reduce the runoff volume up to 18.9% in high density areas (Gill et al. 2007).

iii- Urban heat island effect

Buildings in high density areas reduce the amount of long wave radiation heat loss at night and increase the ambient temperature; this phenomenon is called the urban heat island effect (Oke

1995). Hard surfaces in urban areas prevent rainwater percolation into the soil and decrease evaporation, which may amplify the ambient temperature heating up.

Green roofs can reduce this impact by increasing vegetated areas. Energy is used to evaporate water stored in green roof media, thereby reducing the ambient temperature. Quantifying the influence of green roofs in urban heat island reduction is difficult (Köhler and Schmidt 2003). Previous study results declare that by accounting for wind and precipitation, the effect of green roofs is still noticeable and green roofs are able to reduce ambient temperature of building by around 0.24°C (Bass et al. 2002; Pompeii 2010).

iv- Improved air quality

Different solutions are proposed for decelerating the declining air quality in cities. Green roofs are able to reduce local air pollution by decreasing summer extreme temperatures, and capturing particulates and gases (Rosenzweig et al. 2006). Green roofs reduce the ambient temperature of urban areas, which can directly reduce the reaction of NOx with volatile organic compounds (Rosenfeld et al. 1998). Moreover, Yok and Sia (2005) stated that green roofs reduce sulfure dioxide by 37% and nitrous acid by 21% in the ambient air. However, the overall nitric acid and particulates increased due to green roofs components and materials in the soil medium.

2.1.3 Green Roofs Concerns

Although green roofs would bring various benefits to urban areas, there are some barriers that hold planners, developers, and building owners back. These barriers include the following:

i- Economic consideration

The costs of green roofs can be divided into four main categories: costs of green roof design, structural reinforcement, capital cost of green roof procurement, and operation and maintenance (O&M) costs.

The initial costs of green roofs vary significantly. The initial costs of extensive systems in British Columbia, Canada varies from $\$12/ft^2$-$\$15/ft^2$, while for intensive systems it starts from $\$50/ft^2$ (Bianchini and Hewage 2012a).

The O&M costs vary significantly by green roof type and materials. Annual O&M costs are estimated to be $0.75-$1.50 per square foot (Bell et al. 2008).

Design fees are about 5% to 10% of the green roofs cost. The structural reinforcement costs vary significantly based on green roofs type and weight. While extensive green roofs can be retrofitted on existing buildings without any additional reinforcement, intensive green roofs require complete structural redesign and reinforcement.

2.2 Purposes of Green Roof Runoff Quality Assessment

The quality of green roof runoff is an important aspect of the performance of green roofs, especially when a green roof is combined with an open stormwater system (Berndtsson et al. 2009). Since the volume of runoff from green roofs is lower than from conventional roofs, it is generally assumed that green roofs improve the quality of runoff as well. Most of the previous studies emphasized the poor water quality of green roof runoff. For example, Berndtsson et al. (2006) studied heavy metals and nutrients including Cd, Cr, Fe, K, Mn, Pb, Zn, NO_3-N, Tot-N, and PO_4-P in green roof runoff and demonstrated that green roofs can be a source of contaminants. Similarly, other studies showed that the organic matter and nutrients in green roof runoff are higher than conventional roofs (Vijayaraghavan et al. 2012; Moran et al. 2004). Teemusk and Mander (2007) reported that a greater amount of nitrogen and phosphorus that had accumulated in green roofs washed away during heavy rainfalls and contaminated source water. In addition, utilizing fertilizers, especially on extensive green roofs, can be detrimental to runoff water quality. The mineralized nutrients from the fertilizers can be rapidly leached from the substrates and can impact runoff water quality. Although this effect can be reduced by using controlled-release-fertilizers, the nutrient leakage from green roofs is still higher than that of other roofs (Shaviv 2001).

In the past, few studies have been conducted on developing effective media for improving the green roof runoff quality. A study at Pennsylvania State University elucidated that applying an additional filtering medium in green roof systems may improve the runoff quality (Long et al. 2006). In this study, several advanced filtration media such as granular activated carbon (GAC), zeolites, and polymers were used. Long et al. (2006) stated that while applying GAC media in green roof systems might increase capital costs and maintenance expenditures, the runoff quality can be improved, especially in zinc removal.

2.3 Life Cycle Assessment (LCA) for Environmental Impact Analysis

Building performance assessment tools have been developed to evaluate the performance of newly designed technologies and unconventional build processes. In general, two types of assessment tools are developed for the building sector. The first group is green building rating systems (GBRS) such as BREEAM, LEED, CASBEE, and SB-Tool. GBRS include tools that mainly focus on alternatives evaluation based on specific criteria (Reza 2013). In GBRS a number of selected criteria are evaluated on a scale ranging between low and high environmental performance. However, GBRS are based on scoring and weighting criteria that are not always efficient, which may lead to unrealistic and subjective results (Ali and Al Nsairat 2009). In addition, GBRS evaluation methods are based on a number of pre-defined criteria and applications of an innovative building design, new materials, and products, which might not confirm their environmental performance. Since GBRS are based on qualitative assessments, results might lead to an overestimated performance assessment of a new technology and thereby misinform the decision maker.

The second group of building performance assessment tools consists of tools that use LCA in their methodology, such as BEES, Athena, Beat, EcoQuantum, and KCL Eco. LCA is an environmental technique to assess the "life cycle" environmental impacts of a product. LCA has been applied in a variety of systems and technologies from the 1990s. Based on the ISO 14000 series on environmental management, LCA is a systematic tool for investigating the environmental impacts of a product or service from the extraction of raw material to the end of life (Klöpffer 2005). The most important feature of LCA is that the product or service's environmental impacts are evaluated over its life cycle, which is usually defined as "cradle-to-grave" analysis. This feature helps decision makers to gain a complete picture and comprehensive description of the environmental impacts of the objective. According to the ISO 14044 (2006) standard, a typical LCA consists of four phases:

- Goal and scope definition
- Life cycle inventory (LCI) analysis
- Life cycle impact assessment (LCIA)

- Life cycle interpretation

2.3.1 Goal and Scope Definition

The goal of the LCA study should be defined in the first step. Based on the goal, the system function and functional unit are defined. After that, the boundary for the LCA analysis is specified. Also, processes studied in the LCA are described. A cradle-to-grave analysis considers manufacturing, transportation, construction, operation, maintenance, and demolition phases of both systems (ISO 14044 2006).

2.3.2 LCI Analysis

In this step, an inventory of materials inflow to the system and outflow back to the environment is analyzed. The inflows to the system are resources, raw materials, and energy used in the system. Outflow of the system is energy and emissions released to the environmental compartments including air, water, and soil media (Rebitzer et al. 2004).

The main inventory of alternatives is performed by considering the life cycle phases of alternatives including manufacturing, transportation, operation & maintenance, and end-of-life phases. It should be noted that there is little reliable data available on the life span of building components (Kellenberger and Althaus 2009).

2.3.3 Life Cycle Impact Assessment (LCIA)

The inflows and outflows of the roofing system life cycle are simulated by SimaPro[1] software. This software is able to utilize various databases regarding different materials' life cycle inventory from cradle to grave. Raw material extraction/acquisition, material processing, product manufacture, product use, and end-of-life are the life cycle stages considered by SimaPro. Associated environmental impacts are assessed using the IMPACT 2002+ method. The IMPACT 2002+ method considers the mid-point of impacts for modeling the environmental impacts

[1] It is a well-known eco-invent database used for applications such as carbon footprint calculation, product design, and eco design. The databases include eco-invent v.2, US LCI, ELCD, US Input Output, EU and Danish Input Output, Dutch Input Output, LCA Food, and Industry data v.2.

(Jolliet et al. 2003) and categorizes the environmental impacts to 9 categories including (Appendix A: Impact Category Description):

- Carcinogens
- Respiratory Inorganics
- Ozone Layer Depletion
- Respiratory Organics
- Land Occupation
- Aquatic Acidification
- Aquatic Eutrophication
- Global Warming Potential
- Non-Renewable Energy Consumption

After the impact assessment process, a more environmentally friendly roofing system is the one that produces low level of these adverse effects.

2.3.4 Life Cycle Interpretation

The LCA results are discussed; the uncertainties and study limitations are identified and analyzed, the implications of the LCA study are established, and recommendations are proposed. The interpretation phase is often after the LCIA, however, it is not only restricted to that level and important conclusions may arise before the study is completed.

There are several LCA studies on green roof systems. However, the results of different LCA studies cannot be compared directly with each other due to different goal and scope definitions, system boundaries, data sources, LCI analysis, assumptions, and uncertainties (Reza 2013). Accordingly, the conclusion is inconsistent.

Some researchers argue that LCA contains uncertainties as a result of choosing different databases and life cycle impact assessing methods (Steen 1997; Lloyd and Ries 2008). Since LCA results are prone to uncertainty and vagueness (Harwell et al. 1986), deterministic results of LCA-based tools might not be very reliable. LCA results might overestimate or underestimate the environmental impacts of a technology, which is not desirable. Therefore, LCA-based tools can be integrated with multi-criteria decision-making (MCDM) techniques in order to select the most sustainable solution.

2.3.5 LCA for Green Roof Systems

The LCA of green roof systems has been comprehensively investigated in previous studies. Saiz et al. (2006) studied the LCA of extensive green roofs and compared their associated environmental impacts with those of standard roofs. Saiz et al. (2006) evaluated the LCA based on the energy consumption of an eight story building by implementing extensive green roofs. They argued that extensive green roofs reduce the environmental impacts by between 1% and 5.3%. Kosareo and Ries (2007) studied the life cycle environmental cost of intensive and extensive green roofs compared with conventional roofs. The LCA was performed based on the different life stages of all three roofing systems including fabrication, transportation, installation, operation, maintenance, and end of life. The study showed that green roofs can significantly reduce the life cycle environmental impacts of a building by decreasing the energy use.

Life cycle cost analysis on green roof systems showed that green roofs are not the most economical alternative for the private sector. Some environmental scientists suggest that other environmental benefits of green roof systems should be considered. Blackhurst et al. (2010) argued that since the green roofs are not the best energy saving techniques and the life cycle cost analysis should consider both private and social benefits. Bianchini and Hewage (2012b) analyzed the life cycle cost-benefit of green roof systems based on the probabilistic net present value (NPV). The result showed that the payback period for extensive green roofs is about 4-5 years considering social and private benefits.

Moreover, most LCA studies on green roof systems contain uncertainty on the analysis of the environmental impact contribution of the system (Peri et al. 2012). LCA studies ignored the environmental contribution of the small parts of the system without proper justification. Peri et al. (2012) declared that the extensive green roofs substrate, including fertilizers, have an environmental impact contribution during the green roof system lifespan. Green roof systems' substrate and fertilizer provide NOx and N_2O emission rates (Zaman et al. 2008; Shepherd et al. 1991).

The LCA of green roof systems' specific materials or applications are also explored in previous LCA studies. The LCA analysis of low density polyethylene and polypropylene (polymers) materials used in the drainage layer showed that these materials produce higher amounts of NO_2, SO_2, O_3, and PM_{10} emission during a lengthy green roof lifespan (Bianchini and Hewage 2012a). The additional air pollution due to the polymers' manufacturing phase requires 13-32 years to be balanced (Bianchini and Hewage 2012a). Wang et al. (2013) highlighted the importance of the system condition and characteristics on the cost and benefits of the system. Their study stated that green roof systems can balance out the additional economic costs through environmental improvements.

2.4 Multi-Criteria Decision Making (MCDM)

MCDM is the method of categorizing various non-dominant solutions for approaching a decision-making problem with multiple and conflicting criteria. Different methods of MCDM with various mathematical sensitivity analysis result in different or Pareto solutions for an individual decision-making problem (Bottero et al. 2011).

MCDM methods are gaining credibility in sustainability-oriented development and green building technology choice, due to their capacity to support decision making in complex socio-economic systems at their intersection with the multi-faceted concept of sustainability (Wang et al. 2009). MCDM methods enable decision making to navigate through complexity to select most sustainable options. MCDM helps decision makers to resolve uncertainty-inducing conflicts among criteria, and to reconcile multiple objectives and perspectives (Wang et al. 2009; Sarkis and Talluri 2002).

MCDM is a useful tool for environmental management as it is able to convert complicated and often conflicting interests and priorities of a decision maker into a more simplified and sequential process (Kholghi 2001). MCDM techniques can be used to balance the demands of Triple-Bottom-Line (Haimes 1992). "Sustainability" is generally considered a vague term in the decision-making process (Muga and Mihelcic 2008). MCDM can be applied to simplify the term "sustainability" into criteria and quantitative indicators (Tesfamariam and Sadiq 2006; "OECD " 2001; Palme et al. 2005).

Reliable decisions can be made by selecting relevant decision criteria and indicators as well as by selecting the most appropriate MCDM methodology (Rosén 2009; Kruijf 2007). There are various MCDM methods developed for decision-making problems and systems, but there is no agreement on the "best" method for solving a particular decision-making problem in different conditions (Brunner and Starkl 2004; Schilling 2010).

2.4.1 Analytical Hierarchy Process (AHP)

One of the most popular decision making frameworks is the analytical hierarchy process (AHP) (Dabaghian et al. 2008; Tesfamariam and Sadiq 2006). The AHP method ranks different alternatives based on the pair-wise comparisons to demonstrate the weights for each criterion. The AHP method was initially developed by Thomas L. Saaty in the 1970s (Saaty 1980). AHP has since gained currency in environmental and sustainability decision making such as sustainable energy decision making (Pilavachi et al. 2009; Hobbs and Horn 1997; Aras et al. 2004; Chatzimouratidis and Pilavachi 2009), water and wastewater management (Galal 2013; Dabaghian et al. 2008; Jaber and Mohsen 2001; Chung and Lee 2009), and built environment and technology selection (Wedding and Crawford-Brown 2007; Tupenaite et al. 2010; Reza et al. 2011; Medineckiene et al. 2010; ALwaer and Clements-Croome 2010; Ali and Al Nsairat 2009).

The AHP method provides a platform for complex decision-making problems using objective mathematics to express systematically the subjective preferences of an individual or a group of decision makers (Saaty 1980; Mofarrah et al. 2013). The complex problem can be handled by structuring a hierarchy and the pair-wise comparisons are carried out between each two criteria. Normally, the pair-wise comparisons rank from 1 to 9, where 1 represents equal importance and 9 represents the extreme importance of one criterion over another (Tesfamariam and Sadiq 2006; Dabaghian et al. 2008). Once all pair-wise comparisons are obtained, the overall priority of each alternative is obtained by synthesizing the local and final preference weights (Tesfamariam and Sadiq 2006).

The discrete scale of comparisons in AHP is simple and easy to use, but it is not able to handle the uncertainty and ambiguity[2] present in assigning the ratings of different attributes (Chan and

[2] Vagueness is a property of a term or concept whose meaning is so broad that application of the term cannot distinguish legitimate from illegitimate uses of the term. Classic examples of vagueness include the concept of a

Kumar 2007). Environmental problems and issues are always containing lack of information, scarcity of data and vagueness (Tesfamariam and Sadiq 2006). It is often difficult to compare different criteria due to scarcity of information. Vagueness type uncertainty can be propagated using fuzzy set theory (Zadeh 1965).

2.4.2 Fuzzy-AHP Analysis

Fuzzy-Analytical Hierarchy Process (FAHP) is a compensatory approach for selecting an alternative and justifying the problem. This approach is able to account for data scarcity and vagueness in decision-making problems (Kahraman et al. 2003; Tesfamariam and Sadiq 2006). Due to the complexity of preferences and the fuzzy nature of the comparison process, using interval judgments is more pragmatically reliable than use of fixed value judgments (Kahraman et al. 2003). FAHP is also able to respond systematically to ambiguity, multiplicity of meanings, lack of essential data, and vagueness caused by linguistic content and subjectivity in judgment (Tesfamariam and Sadiq 2006).

2.4.3 FAHP Calculations

In order to achieve the goal of the evaluation, pair-wise comparisons are taken by the decision maker. Triangular fuzzy numbers (TFNs) ($\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$) are used to show the importance or priority of elements in pair-wise comparisons. By applying TFNs in pair-wise comparisons, fuzzy judgment matrixes $\tilde{A}$ (a_{ij}) are constructed. The fuzzy membership can be utilized by using the α-cut value. The decision maker's level of confidence in his preferences and judgments can be defined by the α-cut value. Interval sets of values for fuzzy numbers can be generated by α-cut value. If a_{ij} = (m1, m2, m3), then m2 is the mid value of a_{ij} and is one of the integers from 1 to 9 used in AHP method. Let us assume that m2 - m1= m3 - m2=δ is constant. If 0= δ, then values are crisp and fuzziness of comparisons is not incorporated in comparisons. If 0< δ<0.5, then TFNs do not have any crossover points and the cognitive fuzziness does not cast completely. If δ is greater than 1, then the degree of confidence decreases and fuzziness

'heap' of sand: the meaning of 'heap' is insufficiently determinate to provide application criteria enabling precise specification of the number of grains of sand required to constitute a "heap" as opposed to some other unit such as a "dune" or a "mountain".

increases. Zhu et al. (1999) suggested that 0.5<δ<1 is more applicable to cast the fuzziness since δ value is practically indicates the conflict of degree of confidence and fuzziness.

If the decision maker is not able to specify the pair-wise comparisons by using TFNs or evaluations are qualitative, linguistic variables shown in Figure 2-2 can be used. By assigning equal importance (EI), weak importance (WI), strong importance (SI), demonstrated importance (DI) and extreme importance (ExI) to TFNs, linguistic variables can easily converted into TFNs and accelerate the pair-wise comparison process.

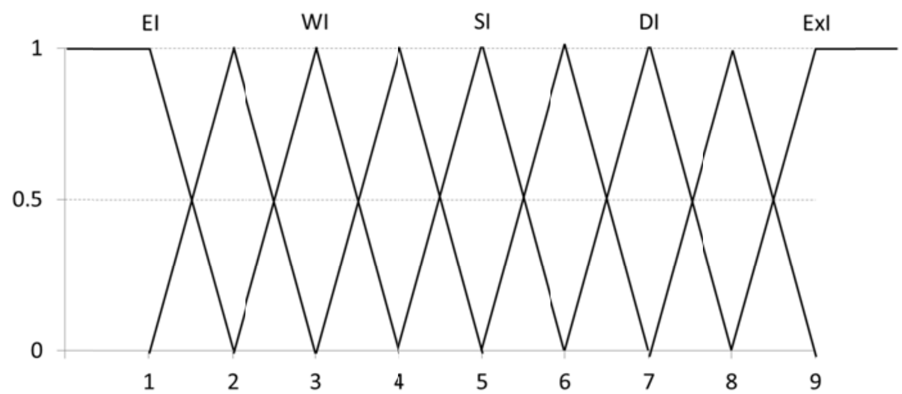

Figure 2-2: Linguistic definitions in FAHP

After the pair-wise comparisons are accomplished, pair-wise comparison matrices ($\tilde{A}_{ij}$) can be constructed. Since human judgments are subject to inconsistency, the consistency ratio of pair-wise comparison matrices should be calculated and be higher than 90%. The local preferences or fuzzy weights ($\widetilde{w}$) are computed using fuzzy arithmetic operations over ($\tilde{A}_{ij}$)s.

$$\tilde{A}_{ij} = (\tilde{a}_{i1} \otimes \ldots \otimes \tilde{a}_{in})^{1/n} \tag{1}$$

$$\tilde{w}_i = \tilde{A}_{ij} \otimes (\tilde{A}_{i1} \oplus \ldots \oplus \tilde{A}_{in})^{-1} \tag{2}$$

While the fuzzy weights are computed, the range of associated uncertainty and the most likely value of comparisons can be calculated. The mid value shows the most likely values of weights. The difference between the minimum and maximum values shows the range of uncertainty or fuzziness in the comparisons.

Final preferences of the alternatives are obtained by aggregating the local priorities at each level. This process is carried out from the alternative level to the goal level, therefore the final preferences can be computed as:

$$\tilde{G}_k = \tilde{w}_k . \tilde{G}_{k-1},$$
$$\tilde{G}_1 = \tilde{w}_1 \quad (3)$$

The final fuzzy score (F_{Ai}) of each alternative is the fuzzy arithmetic sum over each global preference for each alternative *Ai*.

$$F_{Ai} = \sum_{k=1}^{n} \tilde{G}_k \quad (4)$$

RSI can be calculated by defuzzifying the final fuzzy score of each alternative using Chen's ranking method (Chen 1985).

$$RSI_{Ai} = \frac{1}{2}\left[\frac{(c_1 - a_{\min})}{(c_{\max} - a_{\min}) - (b_1 - c_1)} + 1 + \frac{-(c_{\max} - a_1)}{(c_{\max} - a_{\min}) + (b_1 - a_1)}\right] \quad (5)$$

Using this method, a_{min} is the minimum of the smallest final fuzzy score among all alternatives' final fuzzy scores, and c_{max} is the maximum of the biggest final fuzzy score among all alternatives' final fuzzy scores.

The resulting *RSI* value gives a quantitative measure of the sustainability level of different green building technologies. The alternative with the highest *RSI* value is the most sustainable technology for implementation.

2.5 Sustainability Assessment Framework

In recent years, green building practices have been developed as a way to mitigate the long-term negative environmental impacts of buildings (Yoon and Lee 2003). Integrated design approaches and technologies have been implemented in green buildings to reduce the adverse impacts of buildings and urban development on the ambient environment and its occupants (Ali and Al Nsairat 2009).

Although there are various methods for assessing technologies implemented in green buildings, there is a lack of comprehensive and adequately precise framework for integrated evaluation of economic costs and benefits, environmental performance, and social aspects of these technologies (Nelms et al. 2007). Expensive mistakes may be made by overestimating the performance of green building technologies, and sustainable building practices may lose credibility.

Approaches to decision-making that seek to include environmental impact among reasons for action are challenged by the inherent complexity in the decision matrix, and the multi-disciplinary nature of the problem of inclusion of environmental impact (Gallopin et al. 2001). Moreover, such decision processes are prone to data scarcity and lack of knowledge (Harwell et al. 1986). Even where sufficient data are available, evaluation criteria often permit subjective judgments and contain ill-defined terms, which in turn give rise to uncertainty in the form of vagueness (Tesfamariam and Sadiq 2006). One major drawback of LCA is that the LCA ends up with categorized environmental impacts of the alternatives, which require a MCDM. In addition, linking the environmental impacts with socio-economic preferences of a process is challenging for many organizations as they would have to handle a complex dilemma with ambiguity and conflicting criteria (Chan and Wang 2013). Therefore, a simple and more cost effective framework is required. FAHP can be applied as a complement for LCA shortcomings. FAHP offers the advantages of AHP and most importantly, it is able to handle the uncertainty and ambiguity present in sustainability dilemma and system selection (Chan and Kumar 2007).

Few studies tried to integrate FAHP with LCA to evaluate and index green technologies (Kang and Li 2010; Zheng et al. 2011). Chan et al. (2013) employed an extended fuzzy-AHP to evaluate the greenness of a product design. They estimated a green index for a product based on an FAHP evaluation throughout every stage of products' life cycle. Alternative products were ranked over their lifecycle stages without performing a full LCA. However, performing a comprehensive LCA is essential to consider long-term sustainability performance of a product. Moreover, the evaluation was only based on environmental impacts of the products and socio-economic impacts were not considered in the evaluation.

2.6 Summary

In this chapter, the background information of the current research project is comprehensively reviewed. Green roofs are considered as LID practices. Green roof systems and their associated layers are defined. Green roof systems are roofs covered with a layer of vegetation. Green roof systems consist of a root barrier layer, drainage layer, filtration layer, growing medium and vegetation. Green roof systems are categorized into two main groups: extensive green roofs (with a growing medium< 15cm) and intensive green roofs (with a growing medium > 15 cm).

Although green roofs are generally developed for stormwater management, they can provide various environmental benefits including energy saving, urban heat island effect reduction, and air pollution reduction. However, green roofs' additional initial cost, operation and maintenance costs, and leak hazard may undermine their benefits.

LCA is a strong method for analyzing the environmental impacts of a product or a technology from cradle to grave. LCA is able to categorize the environmental impacts of a product into various environmental categories; as a result, LCA results in a multi-criteria problem that requires MCDM techniques to be solved.

MCDM techniques can be applied to a wide range of decision making problems with various conflicting criteria. MCDM techniques provide a range of non-dominant solutions for a decision-making problem. Applying different MCDM techniques may result in disparate solutions.

AHP is a popular MCDM technique that can be easily implemented by pair-wise comparisons of alternatives against each criterion. The final "best" solution is the alternative with the best score. Since AHP comparisons are based on human judgments, the evaluations may contain uncertainties, vagueness, and ambiguity. Fuzzy calculations can be used in AHP to handle these shortcomings.

The application of sustainability assessment frameworks for assessing the sustainability of the green built technologies is discussed. FAHP is a strong MCDM framework that can be used with LCA to mitigate the shortcomings and vagueness of LCA.

Chapter 3 : Experimental Investigation of Green Roofs Runoff Water Quality

The runoff quality of extensive green roofs was experimentally assessed in this chapter. The experiment consisted of conventional roofs, generic extensive green roofs, and extensive green roofs equipped with an additional pre-treatment layer. This chapter comprises extensive green roof runoff quality performance and enhances the performance of extensive green roofs by adding an additional pre-treatment layer to the green roof systems. The questions are whether green roofs can significantly change the runoff water quality, and if applying an additional pre-treatment layer can improve the runoff water quality. To answer these questions, runoff water quality from sixteen green roofs (with or without an additional pre-treatment layer) have been investigated and compared with four conventional roofs. The quality assessment is based on reclaimed water guidelines and fresh water guidelines for Canada. The experiment materials and method are explained in Section 3.1. The result of the experiment and analysis are shown in Section 3.1.4 followed by discussion and limitations in Section 3.3.

3.1 Materials and Method

This section discusses the study of the experiment site plan, experiment pilot design, rainfall sampling process, and chemical analysis of samples.

3.1.1 Study Site and Experiment Pilot Design

A green roof pilot experimental setup has been established near the EME building of the University of British Columbia–Okanagan campus (Kelowna, BC, Canada) under semi-arid weather conditions (Klock and Mullock 2001). The roof systems have been designed and built with 3 ft x 5 ft multi-plywood assemblies. The study sections are constructed with the same principles of full-scale roofs. All roof tops have been placed on a 3° slope to simulate common roof design. The pilot consists of eight green roofs, a gravel ballasted roof, and a control roof that was layered with EPDM (ethylene propylene diene monomer) (Figure 3-1).

The roofs runoffs were collected at the lower end of roof tops. Each roof was divided into two equal, discrete spaces with a median divider. There is a generic green roof with typical layers, which is considered as a control green roof; two generic green roofs with ten times additional simulated rain with local utility (tap) water (to examine the effect of aging on green roof's runoff water quality); and five green roofs enhanced with an additional pre-treatment layer.

Figure 3-1: Green roof pilot experimental setup at University of British Columbia (Okanagan campus)

The selection of an additional filtration layer was based on the ability of the filtration material to amplify the performance of green roofs by decreasing the nutrient leakage at a reasonable price. It was assumed that the additional filtration removes turbidity and suspended solids from runoff. Gravel and sand filters are the most efficient filter media for water treatment (USEPA 1999). Moreover, coconut fibre and crushed tile are other examples of common media for physical water treatment (Nkwonta and Ochieng 2009). As a result, a variety of filtration materials (i.e., washed sand, coconut fibre, wood bulk, crushed tile, and a combination of sand plus crushed tile) for pre-treatment of the stormwater treatment has been applied in the green roof layers between the growing medium and filter sheet. A complete list of green roof pilot tests has been summarized in Table 3-1.

The growing medium of the green roofs used in this experiment is a mixture of lightweight, mineral based materials. The soil is consist of porous aggregate and organic matter derived from composted plant materials, biosolids, and/or manure compost (Xeroflor America 2013). It is estimated that the mat thickness is 1 1/4" with 5.5 psf field weight and 8.5 psf saturated weight (Xeroflor America 2013). *Sedum* and *Delosperma* are used for the green roof vegetation medium, which has been used in most green roof experiments all over the world (Berndtsson

2010). The same pre-cultivated XF 301 vegetation mat provided by Xeroflor America was applied for all the green roof assemblies (Appendix B) (Xeroflor America 2013). Xeroflor pre-cultivated mats were planted with a mixture of drought-resistant green roof species such as *Sedum* and *Delosperma* (Xeroflor America 2013).

Table 3-1: Characteristics of different roof assemblies in the present study

Name	Insulation	Additional Filtration	Growing medium & Vegetation	Replication	Description
Accelerated Age GR	EPDM	-	Pre-vegetated Mats	4	Generic green roof with additional simulated rain water
GR	EPDM	-	Pre-vegetated Mats	2	Generic green roof
GR+S	EPDM	Sand	Pre-vegetated Mats	2	Generic green roof with an additional pre-treatment filtration layer
GR+CF	EPDM	Coconut Fiber	Pre-vegetated Mats	2	Generic green roof with an additional pre-treatment filtration layer
GR+WB	EPDM	Wood Bulk	Pre-vegetated Mats	2	Generic green roof with an additional pre-treatment filtration layer
GR+CT	EPDM	Crushed Tile	Pre-vegetated Mats	2	Generic green roof with additional pre-treatment filtration layer
GR+TSG	EPDM	Crushed Tile+ Sand	Pre-vegetated Mats	2	Generic green roof with an additional pre-treatment filtration layer
GB	EPDM	-	-	2	Generic gravel ballasted roof
EPDM	EPDM	-	-	2	Control roof

3.1.2 Rainfall Effect

Field experiments were conducted with natural rainfall events to evaluate the impact of green roofs and an additional filtering layer on runoff water quality. A preliminary study manifested that at least ~30 to 40 mm of rainfall was required for the soil to reach the saturation point and generate runoff water from green roofs. Hence, samples were collected once runoff started from all green roofs. A bulk sample of rain water and green roof runoff samples were collected in a pre-cleaned, 500 ml polyethylene container during each rainfall event and refrigerated (4^{0}C) until analysis (Figure 3-2)(USEPA 2007).

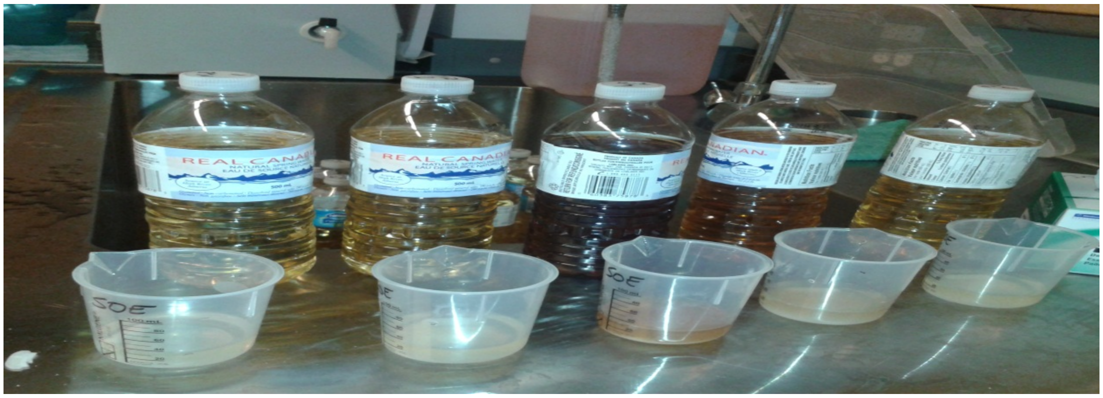

Figure 3-2: Runoff samples

3.1.3 Chemical Analysis

Rainwater and green roof runoff samples were collected to compare the amount of pollutants in a wet atmospheric deposition and green roof runoff. Rainwater samples were taken into the laboratory for water quality characterization and analysis. The characterization of NO_3-N, NH_4-N, ORP, EC, pH, color, and turbidity were performed using HACH instruments (Figure 3-3).

Figure 3-3: Hach sampling instruments

3.1.4 Design of Experiment (DOE)

The experiment is designed to answer which variable is most influential and whether other uncontrollable variables are impact on the experiment. The current experiment is a statically designed experiment based on Fisher's factorial concept. Fisher's factorial concept enables the experimenter to use all performed tests and investigate the main effects (Montgomery 2008). Analysis of Variance (ANOVA) is used for determining the significance of the relationship between different treatments. One-way ANOVA with blocking the intensity of the precipitation and post-ANOVA analysis with α level of 0.05 were performed to determine if any significant change was observed between enhanced green roofs, green roofs, control roofs, and precipitation. ANOVA has three assumptions: Normality, constant variance and independence (Montgomery 2008). If any of these assumptions violated, ANOVA is not applicable and other methods should be applied (Montgomery 2008).

3.2 Results

The current study considered the mixed effect of atmospheric deposition, green roof's materials, and fertilizers on runoff quality, as it was impossible to distinguish pollutants and emission load generated by each of those sources. Experiment sampling collection was started in September 2012 and continued until the end of December, however there was no runoff observed in September and precipitation changed to snow in early December. Therefore, the observation and analysis represents sampling from early October to the end of November 2012. Maximum and minimum precipitation that led to runoff was in late October and in the middle of October, respectively. The amount of rainfall event precipitation from September to December 2012 is shown in Figure 3-4. Sampled precipitation events ranged from 2.3 mm to 11.8 mm and included only rain.

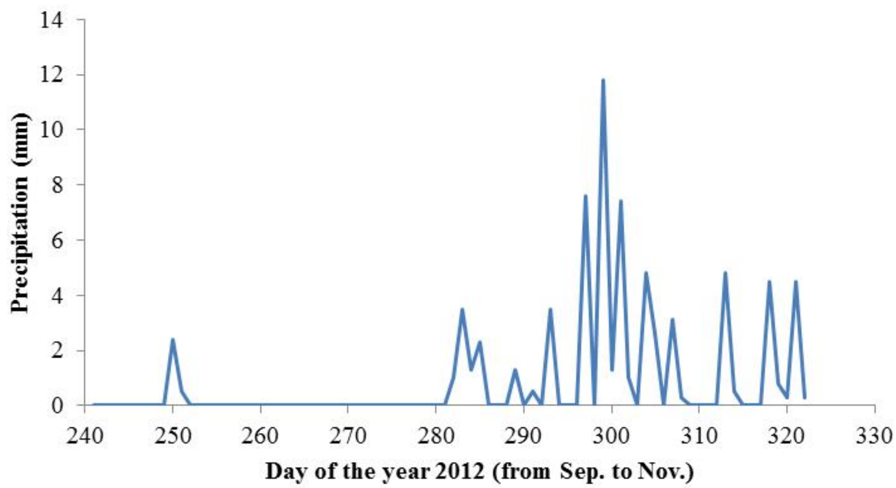

Figure 3-4 : Daily precipitation in Kelowna (Canada Climate 2013)

Results show that the green roof with an additional layer of coconut fibre and wood bulk produced the lowest quantity of runoff before saturation. The runoff retention or delay was due to the combined effect of additional retention capacity of coconut fibre/wood bulk and the possibility of water absorption in such a porous media. It is noticeable that the water retention capacity of the green roof with coconut fibre was about 40% higher than the generic green roof. Analysis showed that none of ANOVA assumptions are violated and ANOVA can be performed for statistical analysis of the current experiment (Appendix F). Overall, the retention capacity of green roof assemblies was strongly dependent on the weather conditions, which may accelerate evapotranspiration phenomena. The results of runoff water quality characterization and experimental analysis are described in the following sections.

3.2.1 pH

Green roofs ability to buffer acid rain and pH fluctuations is one of the benefits of green roofs (Berndtsson et al. 2006; USEPA 2009b). The results from the experimental analysis show that runoff from green roofs has a higher average pH level as compared to EPDM or a gravel ballasted roof. The higher level of pH in green roofs runoff is due to the buffering capacity of green roofs during rainwater passage through the green roof media. This is a considerable environmental advantage of green roofs as it can decrease the direct discharge of acidic runoff to natural water recipients (Berndtsson et al. 2009). Figure 3-5 shows the average and range of pH from generic green roofs and the conventional and gravel ballasted roofs.

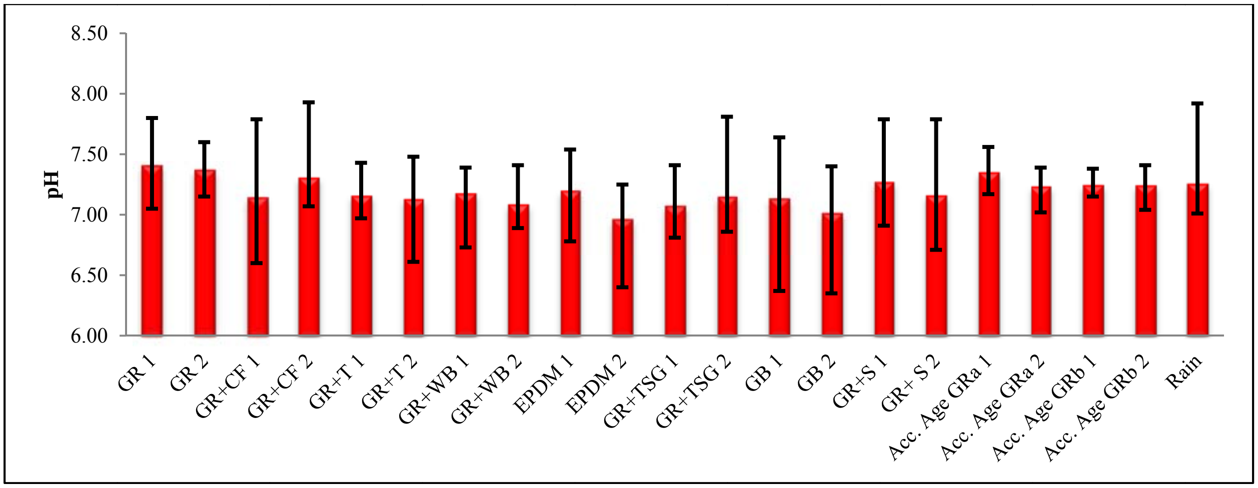

Figure 3-5: Average pH for the pilot scale events

The statistical analysis shows that the pH of the generic green roof with additional simulated rain water (accelerated age green roofs) was statistically lower than other green roof types and the same as the pH of rainwater. The runoff of GB and EPDM roof tops had a lower pH than rain water (*p-value* < 0.001). Similar to Berndtsson et al.'s (2009) findings, the generic green roof produced higher pH than rainwater. However, the additional filtering layer decreased green roof performance in buffering the pH fluctuations. For instance, the additional wood bulk layer in GR+WB had an unproductive effect on the buffering capacity of the green roof (*p-value* < 0.001). This aspect can be explained by the structure and buffering capacity of wood bulk. Although the additional coconut fiber layer in GR+CF did not improve the buffering capacity of the green roof, the pH of GR+CF runoff was higher than the other rooftops with the exception of the generic green roof.

3.2.2 Nitrate and Ammonia

The results show that all 16 green roofs produced higher amounts of NO_3-N and NH_4-N (Figure 3-6 and Figure 3-7) as compared to conventional roofs. The GB roof produced significantly higher level of nitrates as compared to other rooftops (*p-value* < 0.001). The generic green roof produced 90% less nitrates compared with the GB roof. The concentration in generic green roof runoff is the same as the ammonia concentration in gravel ballasted roof runoff, which is significantly lower than the ammonia concentration in EPDM roof runoff. In addition, the generic green roof produced significantly less nitrates and ammonia than the enhanced green roofs in this experiment (*p-value* < 0.001). In contrast, the GR+S generated the highest concentration of nitrogen nutrients among the other green roofs. The concentration of nitrate in the accelerated age green roofs is higher than in rainfall concentrations. Accelerated age green roofs resulted in the lowest concentration of ammonia (0.01 mg/l) in the runoff.

Berndtsson et al. (2006) reported that green roofs are a source of NO_3-N and NH_4-N, and their result was similar to the output of this study. An increase in NO_3-N and a decrease in NH_4-N concentration in the green roof runoff can be explained by the nitrification process that occurs in green roof soil media (Robertson and tiedje 1987). In this process, the ammonia is oxidized to nitrate during water passage from the soil medium. It is possible that by increasing in NO_3-N and NH_4-N, the amount of Tot-N decreases, which may result in a sink of Tot-N in green roofs (Berndtsson et al. 2006). Poor treatment of nitrate runoff from GR+T was similar to the findings of Mendez et al. (2011). Mendez et al. (2011) studied the effect of roofing material on runoff quality where the roof with tile surface resulted in a higher concentration of nitrate than conventional green roof.

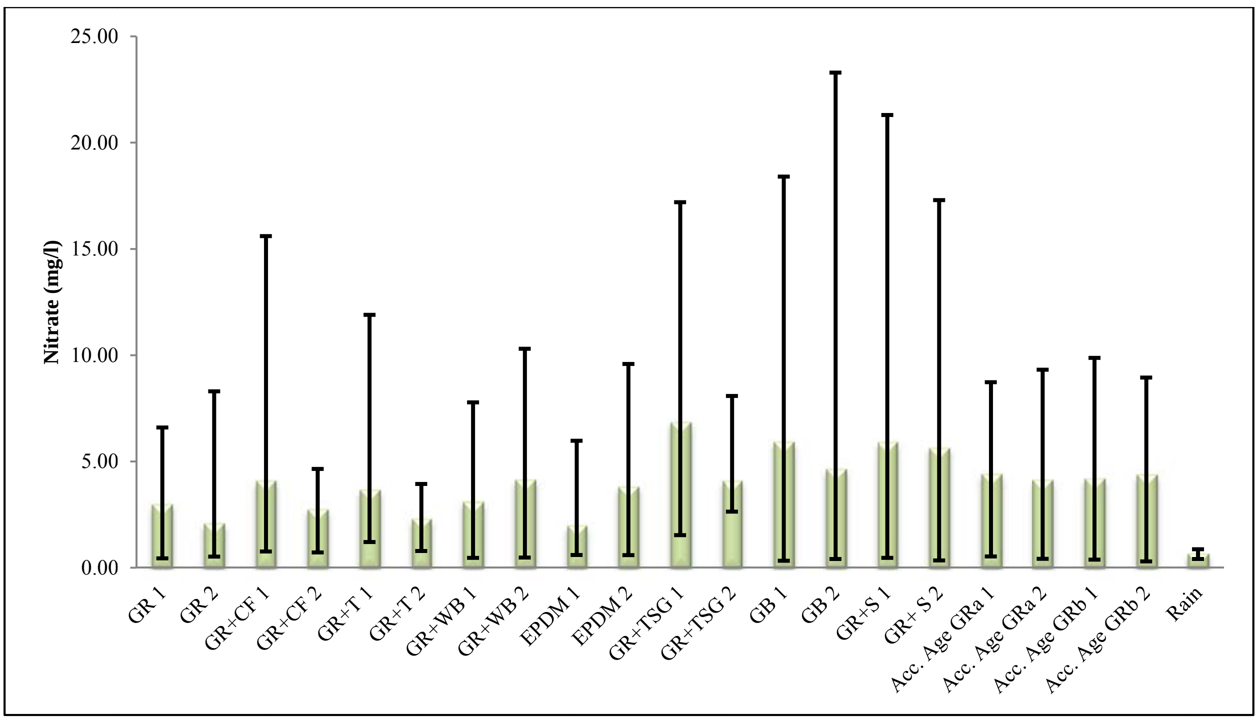

Figure 3-6: Average Nitrate for the pilot scale events

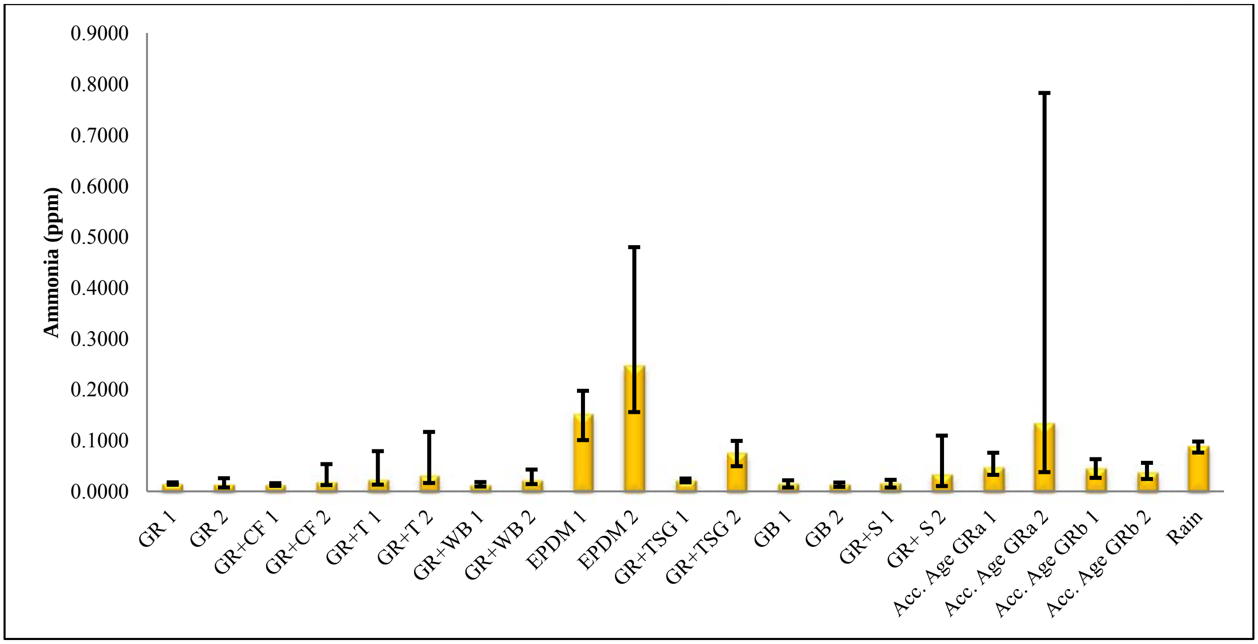

Figure 3-7: Average Ammonia for the pilot scale events

3.2.3 Color and Turbidity

The color of runoff is the most noticeable contrast between green roof runoff and other rooftops. The green roof runoff was very similar in colour to the leachate from wetlands. However, in most instances the green roof runoff was clear and without any turbidity.

Runoffs from GR+WB, GR+T, and GR+TSG were dark yellow or orange coloured. The runoffs from all green roofs except GR+CF were yellow to dark orange in colour. The GR+CF runoff was red. In general, the average colour of GR+CF was darker than the other rooftops' runoff. On the other side, the EPDM runoff was colourless and quite clear.

Since the thickness of the green roof mats in this experiment is just 1 inch, the nutrients in the growing medium washed out after huge rain events. By decreasing the concentration of nutrients in green roofs, the runoff colour changed to faded yellow in generic and accelerated age green roofs.

In contrast, the runoff from the green roof enhanced with coconut fiber was changed to dark red. The change in the green roof runoff colour was due to inorganic and organic substances in the green roof media (growing soil and additional layer if applicable). The intensity of runoff colour was dependent on the precipitation duration and intensity. During rainfall with higher intensive precipitation, the runoff was less coloured.

Figure 3-8 shows the turbidity measured from rooftop runoff. The turbidity of GR+TSG was the highest level among the green roofs, followed by gravel ballasted, conventional roofs, GR+WB, and GR+S. The average turbidity of GR+TSG was more than 200 NTU, which might be caused by fine components and materials in crushed tile and sand.

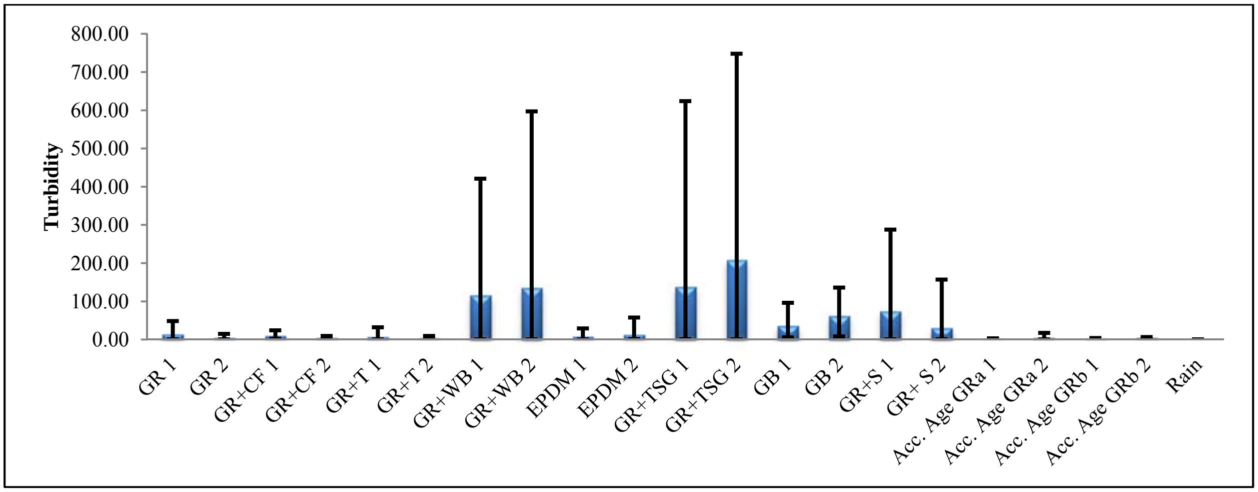

Figure 3-8: Average Turbidity

On the other hand, the turbidity level of accelerated age green roofs was about 2.32 NTU. The turbidity level of accelerated age green roofs was almost the same as the bulk rainwater turbidity level and lower than generic green roof. It is necessary to mention that the turbidity of GR+CF was marginally similar to the second accelerated age green roof and lower than generic green roof.

3.2.4 Oxidation Reduction Potential (ORP)

ORP measurements can be used to determine what biological reaction is taking place in the system (Gerardi 2007). Table 3-2 shows the ORP levels and the related reaction that is occurring in the system (Gerardi 2007).

Table 3-2: Oxidation-Reduction Potential (ORP) ranges for different activities

Range of ORP (mV)	Related Reaction	Description
+100 to +350	Nitrification	Oxidation of ammonia to nitrate
-50 to +50	Denitrification	Reduction of ammonia to Nitrate
-100 to -225	Biological Phosphorus release	-
+25 to +250	Biological Phosphorus removal	-

In general, a higher level of ORP is an indicator of a sample with higher water quality (Suslow 2007). For instance, values above 485 mV are detrimental to aquatic life and can be used as a disinfection procedure. Studied green roofs showed a substantial level of ORP (Suslow 2007). The result of ORP assessment of harvested rainwater is shown in Figure 3-9.

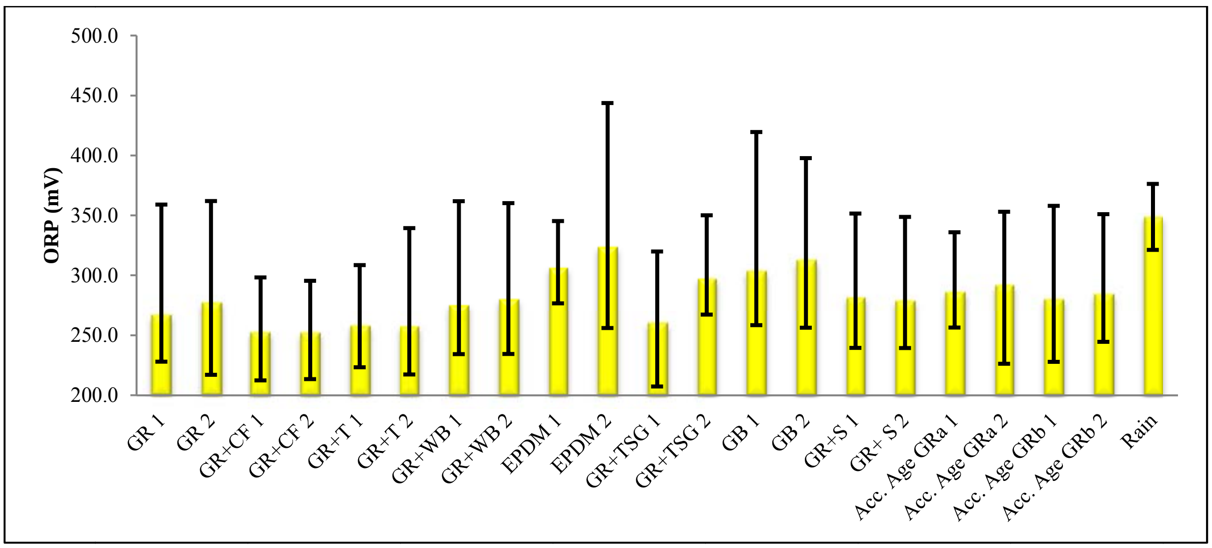

Figure 3-9: Average ORP for the pilot scale events

The rooftop covered with EPDM and the gravel ballasted rooftop had a higher ORP than the other green roofs. This outcome shows that the probability of chemical or microbial reactions in runoff from gravel ballasted roofs and EPDM is obviously lower than in green roofs. The GR+CF, GR+T, and GR+TSG runoff had a lower average of ORP among the other rooftops: 252, 255, and 260 mV, respectively. The two accelerated age green roofs had a better performance than the generic green roof with the ORP around 290 and 283 mV, respectively. The results show that EPDM and gravel ballasted roofs provide a higher level of ORP, which can be translated into a higher water quality (at least in this parameter) and lower probability of nitrification. It should be mentioned that by increasing the age of green roofs, the probability of nitrification decreases because a portion of nutrients and ammonia wash off or react with other chemicals in the growing medium.

3.2.5 Conductivity

The mean conductivity of rainfall bulk collected during the experiment was about 31 µS/cm and it is in the typical range of ambient rainwater (Yaziz et al. 1989; Lee et al. 2010). For the standard green roof, the conductivity of runoff was significantly higher than rainwater. The conductivity of the runoff from the other green roofs (Figure 3-10) enhanced with an additional layer was still higher than rainwater and runoff from EPDM and the gravel ballasted roof. Although the conductivity of runoff from accelerated age green roofs was more constant, the average conductivity was significantly higher than runoff from EPDM and gravel ballasted roofs. EPDM roofs had the lowest conductivity than the other roofs and they were near the rainfall conductivity average.

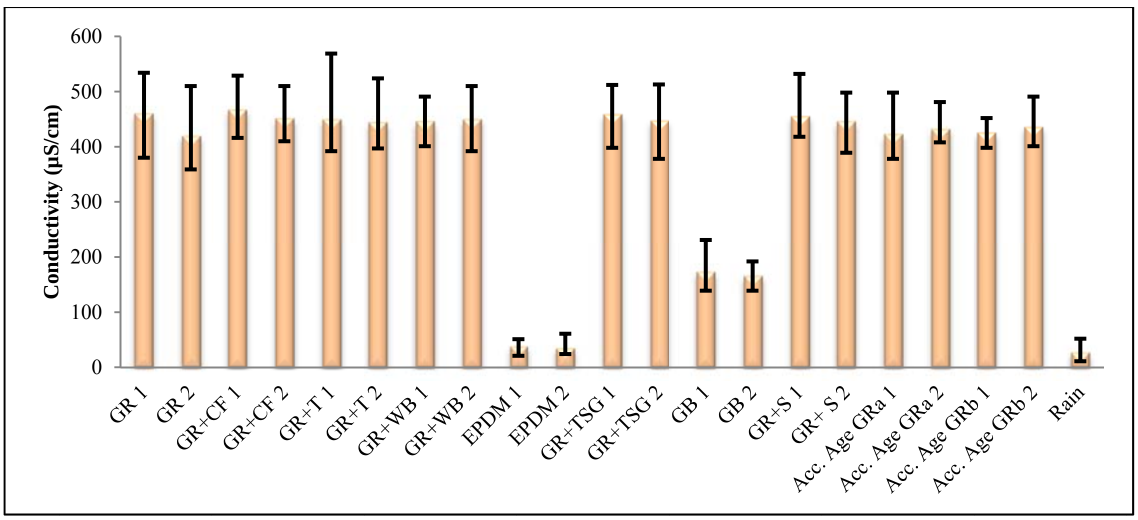

Figure 3-10: Average Conductivity for the pilot scale events

3.2.6 Appraisal of Green Roofs Runoff Quality

To express the results of experimental analysis of runoff water quality, the obtained results can be compared with Canadian guidelines for domestic reclaimed water, other water standards, or with other green roof runoff experiments. In this study, the overall quality of green roof runoffs from the experimental analysis were expressed with respect to guidelines and standards for treated wastewater, domestic reclaimed water, and the quality of urban runoff (available in literature).

Table 3-3 summarises the Canadian guidelines for domestic reclaimed water, the quality of runoff from previous green roof experiments, and fresh water quality. Table 3-4 summarises the average of current experiment roofs' runoff water quality.

Table 3-3: Required fresh water, domestic reclaimed water, and green roof runoff quality

Parameter	Unit	Fresh water[3]	Domestic[4] reclaimed water	Green roof runoff quality
pH		6.5 - 8.5	6.6 - 8.7	7.4[5]
Nitrate	mg/L	< 0.5	< 0.1–0.8	0.07[6]
Ammonia	mg/L	< 0.1	< 1.0–25.4	0.08[4]
Turbidity	NTU	<1	22-200	15[3]
ORP	mV	390[7]	-	-
Conductivity	mS/cm	-	325–1140	320[3]

Based on Health Canada (2010) standards, the pH of all runoffs was in an acceptable range. With the exception of accelerated age green roofs, the pH of green roofs runoff was higher than the average pH of rainfall, EPDM, and the gravel ballasted roof. The pH of accelerated age green roofs runoff was almost the same as the pH of rainfall. In general, the pH of runoff from all rooftops is in a neutral range (6.5-8.5) and acceptable. Since the acid rain event is not observed in the experiment during rainfall events, the ultimate capacity of green roofs to buffer the acid rain before the pH of the growing medium drops below the applicable level of plant growth or water quality guidelines should be investigated.

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[3] Guidelines for Canadian Drinking water quality, 2012.

[4] Canadian guidelines for domestic reclaimed water, 2010.

[5] Mendez et al. 2011.

[6] Brendtsson et al. 2009.

[7] Suslow, T.V., 2007.

Table 3-4: Average water quality parameters for each paired roof

Roof Type	GR	GR+CF	GR+CT	GR+WB	EPDM	GR+TS	GB	GR+S	Acc. Age GR	Rain
pH	7.39	7.23	7.15	7.13	7.09	7.11	7.08	7.22	7.28	7.26
Nitrate	3.97	3.44	3.00	3.64	2.92	5.48	5.29	11.59	4.29	0.69
Ammonia	0.016	0.017	0.028	0.018	0.200	0.050	0.016	0.026	0.066	0.090
Turbidity	19.10	15.70	7.22	135.37	13.74	238.66	120.74	117.47	3.21	0.31
ORP	272.64	252.77	258.20	278.30	315.53	279.45	308.86	280.95	275.64	348.92
Conductivity	440.85	459.90	447.85	448.65	37.70	453.90	170.05	451.35	428.05	28.70

According to the USEPA primary drinking water guidelines, turbidity of 95% of samples should be less or equal to 0.3 NTU (USEPA 2004). The turbidity of the runoff from all rooftop systems was higher than standards and needed to be treated for further utilization. According to Health Canada (2010), the median and maximum acceptable turbidity of reclaimed water is less than 2 and 5 NTU, respectively. The result showed that the turbidity of accelerated age green roof runoff is near to the acceptable range for domestic reclaimed water used in toilet and urinal flushing (Health Canada 2010).

The concentration of nitrate in all green roofs, EPDM, and the gravel ballasted roof was significantly higher than the concentration of nitrate in the rainfall. The concentration of nitrate was higher than the acceptable range for fresh water or even domestic reclaimed grey water. The average concentration of nitrate of green roof runoff in this experiment was significantly higher than previous studies on green roofs. The higher concentration of nitrate in green roof runoff can be accounted for by addition nutrients in fertilizers used in green roofs. But the source of nitrate in the EPDM and gravel ballasted roof is different and is due to dissolving nitrogen in the air during precipitation.

The ammonia concentration in green roof runoff was lower than the rainfall ammonia concentration. The decrease in ammonia concentration in green roof runoff is a result of the nitrification process that occurs during water passage from green roof media. During the nitrification process, a portion of ammonia is oxidized to nitrate. The concentration of all green roofs, except the accelerated age green roof and GR+S, is in the admissible range for fresh water. It is noticeable that as the green roof ages, the nitrification process in green roof soil decreases dramatically. The thin thickness of green roof soil medium in this experiment and accelerating the green roof usage showed that green roofs need maintenance after a period of operation.

The turbidity of runoff of generic and enhanced green roofs was higher than rainfall turbidity and was not in an acceptable range for fresh water. It can be noted that the additional GR+WB, GR+TSG, and GR+S decreased the performance of the green roof and increased significantly the turbidity of runoff. The average turbidity of the other green roofs was moderately higher than the EPDM roof's runoff. Although the accelerated age green roofs had the lowest turbidity among the roofs, the effluent turbidity was higher than the fresh water and average rainfall turbidity.

3.2.7 Scenario Analysis for Nitrate and Ammonia Removal

The existing results of the extensive green roof experiment can be applied to optimistic and pessimistic scenarios for estimating the nitrate and ammonia removal in a selected part of the Kelowna downtown (Figure 3-11). The first scenario is an optimistic scenario that assumes that 50% to 75% of all roofs are covered with XeroFlor extensive green roofs. The pessimistic scenario assumes that only 10% to 25% of buildings are retrofitted with extensive green roofs. The total surface area of roofs in the selected part of the Kelowna downtown was estimated to be 65 ha using Google Earth aerial maps. The total roof surface area is about 16-19.5 ha, which is about 25-30% of the total urban roof surface area.

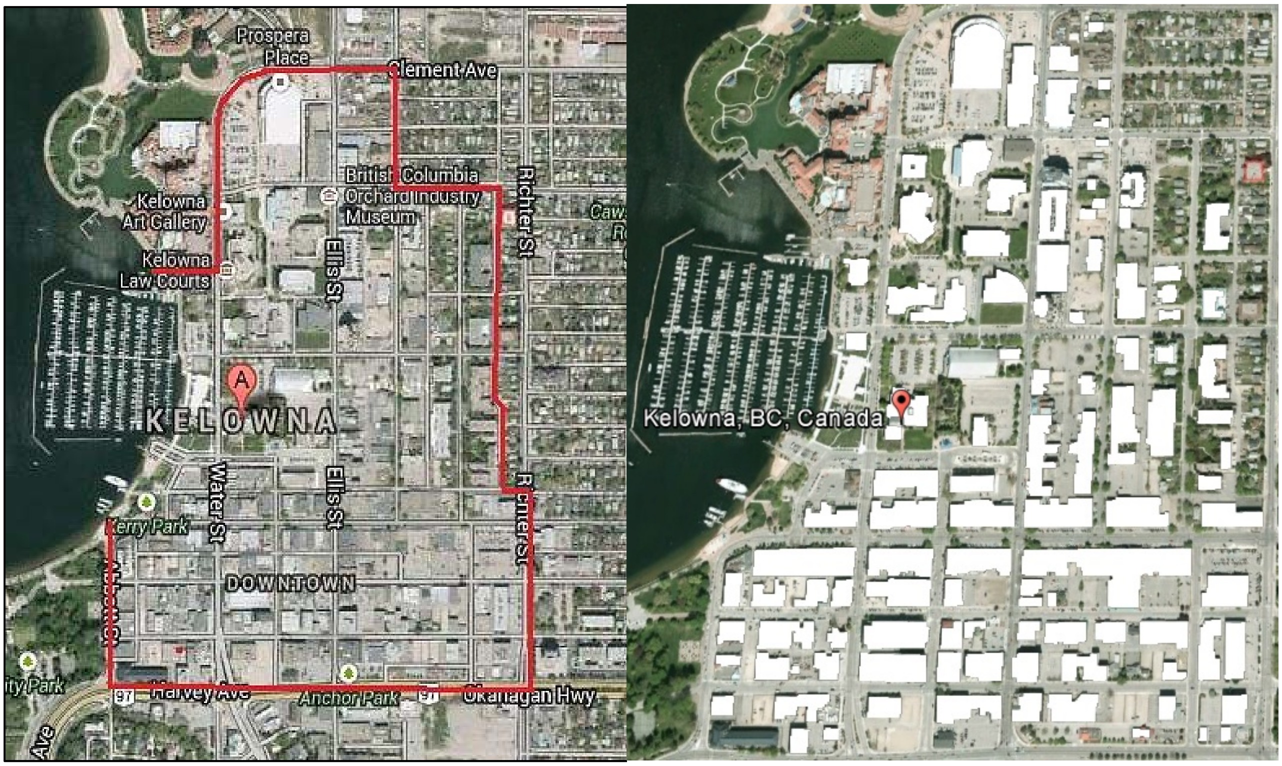

Figure 3-11: Selected area of the city of Kelowna (created by Google Map)

Based on the historical records from 1993 to 2012 collected by the Kelowna International Airport weather station, the average rainfall precipitation can be categorized into light rain (0.2 mm to 5 mm), moderate rain (5 mm to 10 mm) and thunderstorm (above 10 mm). The days with different types of rainfall and average monthly precipitation is shown in Figure 3-12 (The Weather Network 2013).

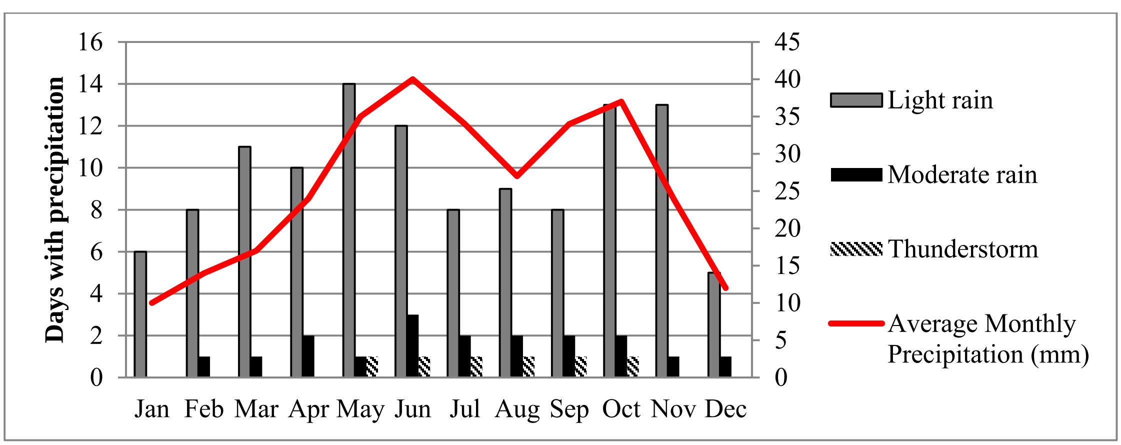

Figure 3-12: Days with light rain, moderate rain and thunderstorm in Kelowna (The Weather Network 2013)

The probability of each type of rain event and average precipitation in each day of every month is estimated based on the historical records and shown in Table 3-5.

Table 3-5: The probability of rain and average precipitation in each day based on historical records (The Weather Network 2013)

	Probability of rain %			Average precipitation (mm/day)		
Month	**Light rain**	**Moderate rain**	**Thunderstorm**	**Light rain**	**Moderate rain**	**Thunderstorm**
Apr	33	7	0	0.83	0.33	0
May	47	3	3	1.17	0.17	0.25
Jun	40	10	3	1	0.5	0.25
Jul	27	7	3	0.67	0.33	0.25
Aug	30	7	3	0.75	0.33	0.25
Sep	27	7	3	0.67	0.33	0.25
Oct	43	7	3	1.08	0.33	0.25
Nov	43	3	0	1.08	0.17	0

The average volume of runoff produced by 17 ha of roofs in downtown Kelowna is estimated and shown in Table 3-6**Error! Not a valid bookmark self-reference.**.

Table 3-6: The average estimated volume of runoff produced by 17 ha roofs

	Volume of precipitation (m^3)			
Month	**Light rain**	**Moderate rain**	**Thunderstorm**	**Total precipitation volume (m3)**
Apr	141.67	56.67	0	198.33
May	198.33	28.33	42.5	269.17
Jun	170	85	42.5	297.5
Jul	113.33	56.67	42.5	212.5
Aug	127.5	56.67	42.5	226.67
Sep	113.33	56.67	42.5	212.5
Oct	184.17	56.67	42.5	283.33
Nov	184.17	28.33	0	212.5

Previous studies on XeroFlor extensive green roofs estimated that the retaining capacity of these roofs is 6% to 10% (Taylor 2008). The warmer weather increases the evapotranspiration, which accelerates the removal of retained water in green roofs. The retaining capacity of extensive green roofs during warm seasons is considered to be 10%, and during the cold months (Oct., Nov., and Apr.) it is estimated to be 6%.

The amount of nitrate and ammonia that can be removed yearly can be estimated by multiplying the retaining capacity of green roofs with the average and probability of each type of rainfall events in each month. It is notable that the winter season (Dec., Jan., Feb., and Mar.) is excluded from the analysis since when green roofs are covered with snow, they are considered the same as conventional roofs. The amount of nitrate removal based on optimistic and pessimistic scenarios is shown in Table 3-7.

Table 3-7: The amount of nitrate removal using XeroFlor extensive green roofs

Nitrate Removal (g/month)				
	Optimistic scenario (50% to 75% is retrofitted)		**Pessimistic scenario (10% to 25% is retrofitted**	
Period	75%	50%	25%	10%
Apr	803	536	268	107
May	1817	1211	606	242
Jun	2008	1339	669	268
Jul	1434	956	478	191
Aug	1530	1020	510	204
Sep	1434	956	478	191
Oct	1148	765	383	153
Nov	861	574	287	115
Each year	11035	7357	3678	1471
Entire life (40 years	441405	294270	147135	58854

The ANOVA test on the result of ammonia in roof runoff showed that the ammonia concentration in green roof runoff is significantly lower ($\alpha<0.05$) than conventional roofs. The amount of ammonia removal can be estimated by a summation of runoff volume reduction and reduced ammonia concentration in green roof runoff. The amount of ammonia removal is shown in Table 3-8.

Table 3-8: The amount of ammonia removal using XeroFlor extensive green roofs

Ammonia Removal (g/month)								
	Ammonia removal by retaining the precipitation				**Ammonia removal by reducing the release concentration**			
	Optimistic scenario (50% to 75% is retrofitted)		**Pessimistic scenario (10% to 25% is retrofitted**		**Optimistic scenario (50% to 75% is retrofitted)**		**Pessimistic scenario (10% to 25% is retrofitted**	
Period	75%	50%	25%	10%	75%	50%	25%	10%
Apr	54	36	18	7	755	503	252	101
May	121	81	40	242	981	654	327	131
Jun	134	89	45	268	1084	723	361	145
Jul	96	64	32	191	775	516	258	103
Aug	102	68	34	204	826	551	275	110
Sep	96	64	32	191	775	516	258	103
Oct	77	51	26	153	1079	719	360	144
Nov	57	38	19	115	809	539	270	108
Each year	736	490	245	1371	7084	4722	2361	944
Entire life (40 years	29427	19618	9809	54856	283341	188894	94447	37779

Results show that XeroFlor extensive green roofs are able to reduce the non-point source pollution of nitrate and ammonia without changing the pH. Based on the different scenarios, the nitrate removal can be estimated to be 300-450kg in the optimistic scenario and 60-150kg in the pessimistic scenario during the extensive green roofs' lifespan. Moreover, extensive green roofs are able to remove 200-300kg of ammonia in the optimistic scenario and 40-100kg in the pessimistic scenario.

3.3 Discussion

The runoff quality performance of generic and enhanced green roofs with an additional filtering layer (e.g. sand, tile coconut fiber, and wood bulk) were compared with the runoff of conventional roofing systems including EPDM and gravel ballasted. Nitrate, pH, EC, ammonia, turbidity, ORP, and colour were measured in roof runoffs and harvested rainwater.

The results show that green roof runoff quality is lower than that of the other conventional roofs. Although some of the additional preliminary treatment layers improved the quality of runoff, the harvested rainwater from these roofs needs an additional primary and secondary treatment for further drinking water use. In particular, the harvested rainwater from green roofs needs treatment for turbidity, colour, and nitrate. However, with a small portion of dilution, green roof runoffs can be used as domestic, reclaimed grey water and meets the Canadian domestic reclaimed guidelines. The runoff quality of green roofs increases by aging.

The additional layer of coconut fiber and crushed tile improved the runoff quality in some directions but the overall quality of harvested rainwater was still poor. The EPDM runoff had a better quality than the other harvested rainwater in this experiment.

Bulk rainwater samples had a lower concentration of the contaminants than runoff from green roofs and conventional roofs. Green roofs can improve the quality of runoff with respect to specific water quality characteristics. The overall runoff quality with respect to the determined characteristics can be considered as acceptable for reclaimed water use. The concentrations of NO_3-N and ammonia in green roof's runoff were higher than runoff from conventional rooftops. The performance of green roofs increases by applying a coconut fiber layer. The coconut fiber layer improved the ORP level of runoff and provided more clear water. Moreover, coconut fiber media increased the retaining capacity of the green roof.

In addition, extensive green roofs are able to reduce the amount of nitrate and ammonia produced as non-point source pollution in urban areas. Optimistic and pessimistic scenarios for retrofitting extensive green roofs in downtown Kelowna show extensive green roofs are able to significantly reduce the amount of nitrate and ammonia without changing the pH. This amount reduction can benefit the Okanagan Lake environment as it is vulnerable to non-point source nitrate and ammonia emission.

Chapter 4 : Sustainability Assessment Framework for Green Roof Systems

A sustainability assessment framework for green roof systems is developed in this chapter. The framework is developed based on the FAHP decision support tool and LCA. The framework is able to calculate a relative sustainability index (RSI) score by using the LCA results, available literature, and interviews and discussions with experts in relevant fields. The sustainability assessment framework is described in Section 4.1. The LCA study of roofing systems including identifying goal, scope, system functional, and the system boundary, as well as inventory analysis are discussed in Section 4.2. Finally, results are presented and discussed in Sections 4.3 and 4.4, respectively.

4.1 Sustainability Assessment Framework

Recently various experimental studies and environmental assessment methods have been conducted to assess the environmental performance of green building technologies. Methods developed to date are, however, insufficient for accurate quantitative estimation and evaluation of triple-bottom-line (TBL) sustainability performance objectives (i.e. economic, environmental and social) in the context of green building technologies. The main objective of this chapter is to develop a green building sustainability evaluation framework to estimate the sustainability performance of new green building technologies under conditions of uncertainty and lack of sufficient knowledge. The framework provided here utilizes a fuzzy-analytical hierarchy process integrated with a cradle-to-grave life cycle assessment to address interactions and influence of various TBL criteria. The developed framework is implemented for evaluating and comparing sustainability performance of an extensive green roof and a gravel ballasted roof (both located at the Engineering, Management and Education building at UBC’s Okanagan campus) with an intensive green roof (located at the Centre for Interactive Research on Sustainability at UBC’s Vancouver campus).

FAHP is aggregated to LCA to help decision-makers to augment and in that way improve the reliability of LCA results. FAHP-LCA employs conventional LCA capabilities, including life cycle inventory (LCI) and life cycle impact assessment (LCIA).

The FAHP-LCA is applicable to multi-criteria decision-making problems. The FAHP-LCA can be used as a sustainability assessment framework for assessment of green building technologies, expressing a final score value of each alternative as the relative sustainability index (RSI) of that alternative. Easily comparable RSI scores can help decision makers to select the most sustainable green building technology and evaluate life cycle impacts of each alternative. Figure 4-1 shows the schematic FAHP-LCA for general green building technology evaluation.

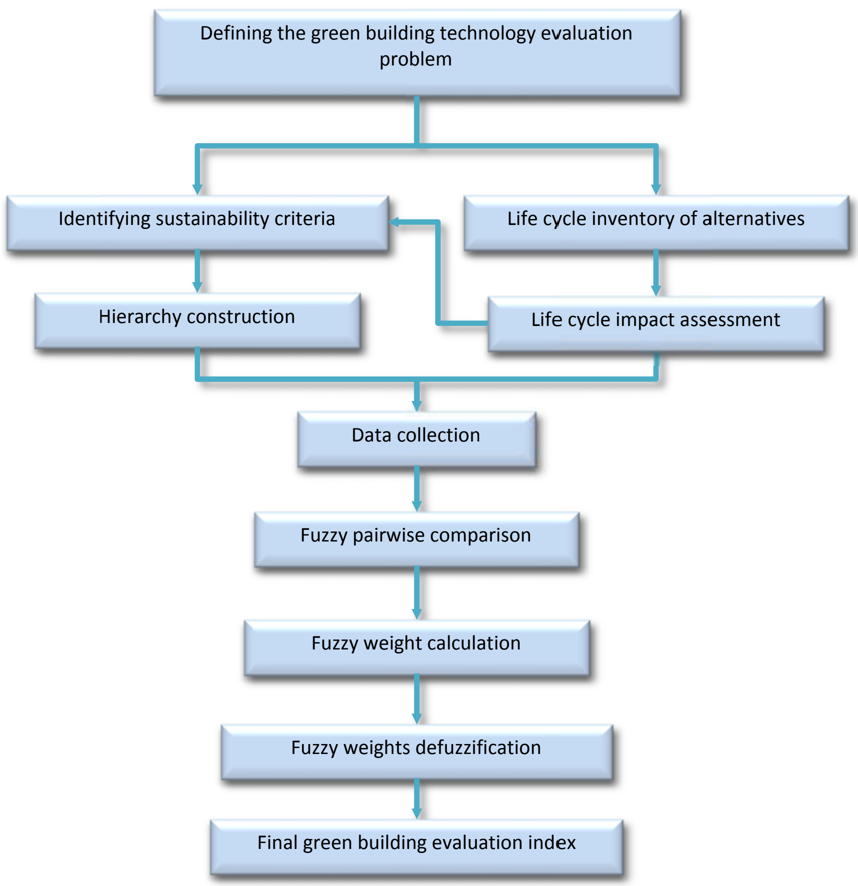

Figure 4-1: Sustainability Performance Assessment Diagram

4.2 LCA Study

In this section, the LCA for roofing systems is framed. The goal of the LCA, scope, boundary of the system, and the functional unit are discussed.

4.2.1 Identifying Goal, Scope

The goal of the current LCA is to analyze the environmental impacts of three different roofing systems. Based on CEN/TC 350 recommendations for sustainability assessment of construction works, three life stages were considered: the manufacturing and construction stage, the use stage, and the end-of-life stage. The transportation phase produces less impact (about 1.5%-2.4% of total emission) than the operation and manufacturing phases (Peuportier 2001). Since the transportation phase emission was less than 5% in the preliminary analysis and the roofing system alternatives were located in different cities, the transportation phase was ignored in the case study.

4.2.2 Functional Unit and System Boundary

Since the lifespan of green roofs is longer than other roofing systems, the functional unit for this analysis is defined based on the system that had a longer lifespan. Green roof systems' lifespan is reported between 40 and 60 years (Carter and Keeler 2008; Kohler et al. 2001). A conservative functional lifespan (40 years) was selected as the functional lifetime of roofing systems in this study. This selection reduces the uncertainties related to the estimation of environmental effects of the systems. During this period, both green roof types require maintenance every year and more thorough rehabilitation every 10 years. By contrast, gravel ballasted roofs require less maintenance than green roofs. The lifespan of a gravel ballasted roof is about 20 years. Thereafter, deterioration of roofing system components may negatively influence the roofing structure and decking components, at which time the gravel ballasted roof should be replaced (Kohler et al. 2001; Carter and Keeler 2008). In order to compare the two roof technologies over the same functional time, it was assumed that two gravel ballasted roofs would be constructed and used in sequence during the functional time.

4.2.3 Inventory Analysis

In this step, an inventory of materials inflow to the system and outflow back to the environment are analyzed. The inflow to the system is resources, raw materials, and energy used in the system. Outflow of the system is energy and emissions release to the environmental compartments including air, water, and soil media (Rebitzer et al. 2004).

The main inventory data of alternatives is performed by considering the life cycle phases of alternatives including manufacturing, transportation, operation and maintenance, and end-of-life phases. It should be noted that there is little reliable data available on the life span of building components (Kellenberger and Althaus 2009).

The LCI analysis was conducted for each life stage of each roofing system alternative. Information about components of green roof systems was collected based on FLL Guidelines (2002), ASTM E 2400-06, E2397 – 11, E2399 – 11 and E2398 − 11 (ASTM 2013a; ASTM 2013b; ASTM 2013c; ASTM 2013d) for green roof systems, and ASTM D7655/D7655M – 12 (ASTM 2013e) and roofing guidelines RCABC (2011) for gravel ballasted roofs. Different components of each roofing system are shown in Table 4-1. The information regarding materials manufacturing and fabrication, energy chains, and transportation was mainly extracted from the SimaPro software databases.

Scenarios for end-of-life of products were defined based on the available literature. It is noteworthy that while recycling processes prevent landfilling of recycled materials, the total cradle-to-grave-to-cradle manufacturing and transportation environmental impacts of recycled materials increase due to additional processes required for recycling.

Table 4-1: Material types for individual elements of roofing system for unit of area

	Intensive green roof	**Extensive green roof**	**Conventional roof**
	Material	Material	Material
Structural support/decking	Steel	Steel	Steel
Underlayment	Concrete	Concrete	Concrete
Root Barrier	Non-Rotting Polypropylene Fibers	Polypropylene	Polypropylene
Drainage Layer	Recycled Polyethylene,	Polystyrene Waffled Panels	Polystyrene Waffled Panels
Filter Fabric	Non-Rotting Thermal Consolidated Polypropylene	Micro-Perforated Polypropylene	Micro-Perforated Polypropylene
Top layer/ Growing Medium	Growing Medium For Semi-Intensive Green Roofs	Growing Medium For Extensive Green Roofs	Gravel

Plant Material	Drought Resistant Plants	Sedum	-

4.3 Results

To evaluate RSI, the FAHP analysis should be performed considering the TBL criteria as main criteria. FAHP comprises different steps including constructing a hierarchy structure, fuzzy pair-wise comparisons, fuzzy results defuzzification, and final ranking assessment.

4.3.1 Constructing a Hierarchy Structure

The hierarchy structure from top to bottom includes goal, main criteria, sub-criteria (if existing), and alternatives. The goal of the hierarchy is the evaluation of green building technologies. Alternatives are evaluated and weighted over the main TBL performance criteria including environmental and socio-economic performance. For a better evaluation, various sub-criteria were defined under the main criteria. The structured hierarchy for this study is shown in Figure 4-2.

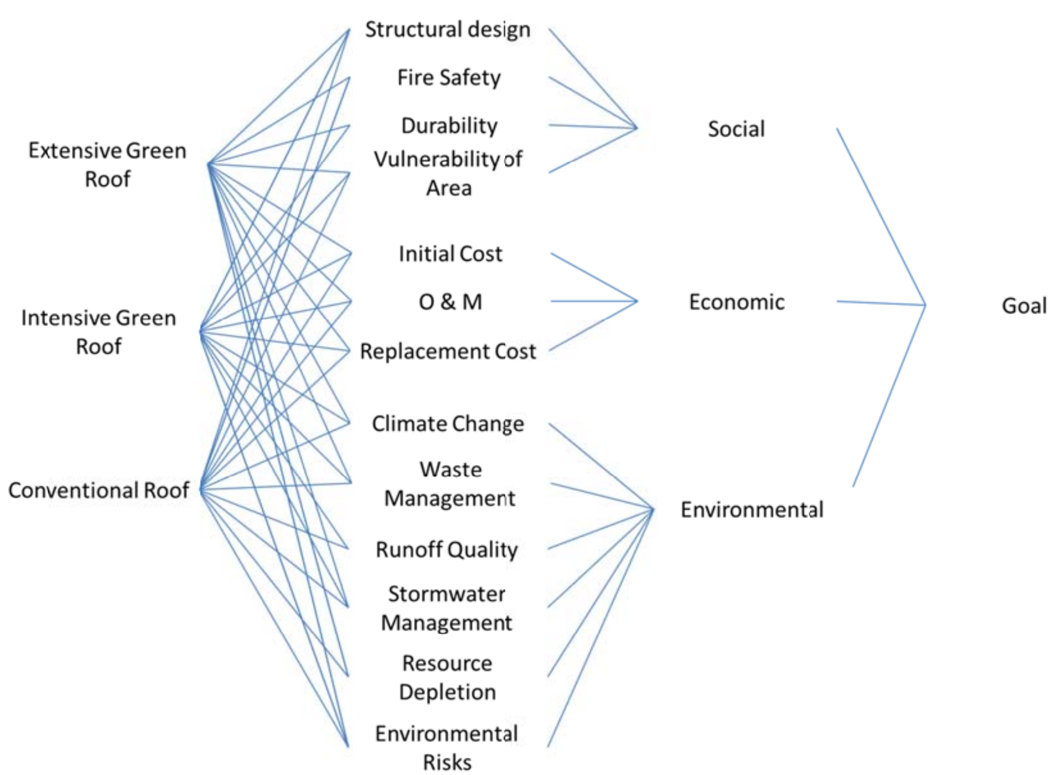

Figure 4-2: Hierarchical tree for comparison of roofing systems

4.3.2 Life Cycle Inventory Data

The analysis in this chapter is performed based on the RSI assessment framework. The LCI and lifecycle impact analysis are performed using SimaPro software. The TBL criteria are divided into sub-criteria for better comparison and assessment. The RSI assessment is conducted based on the fuzzy comparisons performed by groups of judgments.

4.3.3 Life Cycle Impact Analysis

Conduct of the LCI analysis enabled evaluation of the environmental impact of each alternative. The LCA results show the magnitude of impacts of each roofing system alternative in various mid-point impact categories. This analysis is conducted by SimaPro software based on the IMPACT 2002+ impact assessment method.

Figure 4-3 depicts the contribution of each life stage of the intensive green roof. It can be seen that the emission contribution of the manufacturing phase is higher than the other phases. The manufacturing phase in intensive green roofs is responsible for more than 95% of carcinogens and 60% of respiratory inorganics. Moreover, the manufacturing phase consumes more than 60% of non-renewable energy during the intensive green roof lifespan. The end-of-life stage is responsible for emission of more than 50% of global warming gases during the intensive green roof lifespan.

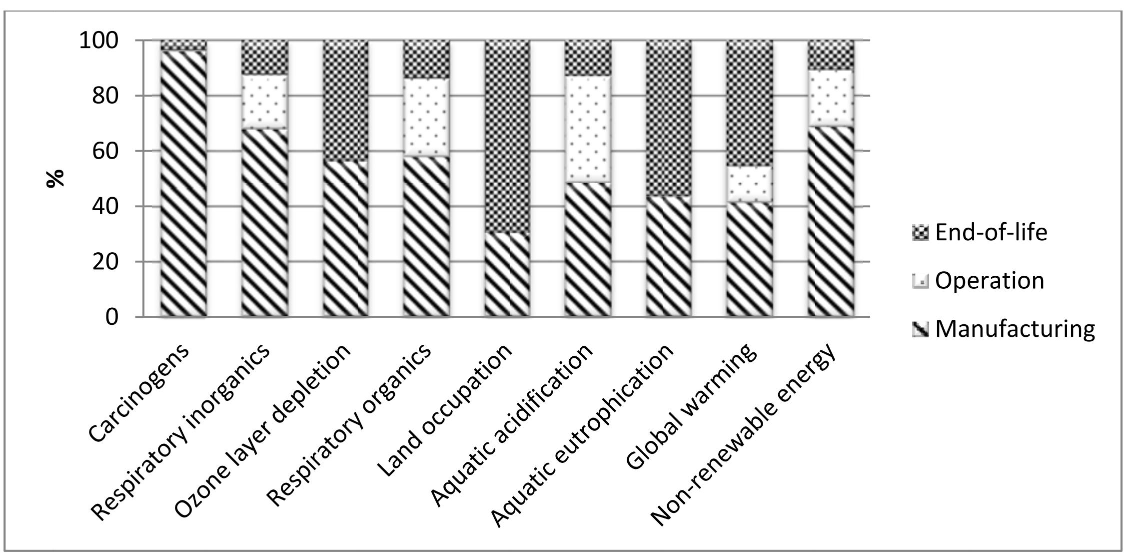

Figure 4-3: Intensive green roof life stages contribution

The contribution of an extensive green roof's life stages is shown in Figure 4-4. As with the intensive green roof, the manufacturing phase produces more than 95% of carcinogens. However, the contribution of the manufacturing phase in respiratory inorganics emission is almost 50%. The non-renewable energy consumption in the manufacturing phase is less than 60%, which is lower than that of the intensive green roof. This reduction can be seen in other impact categories and can be explained by the smaller amount of materials used in the extensive green roof. As with the intensive green roof, almost 50% of GHGs are emitted during the end-of-life stage of the extensive green roof.

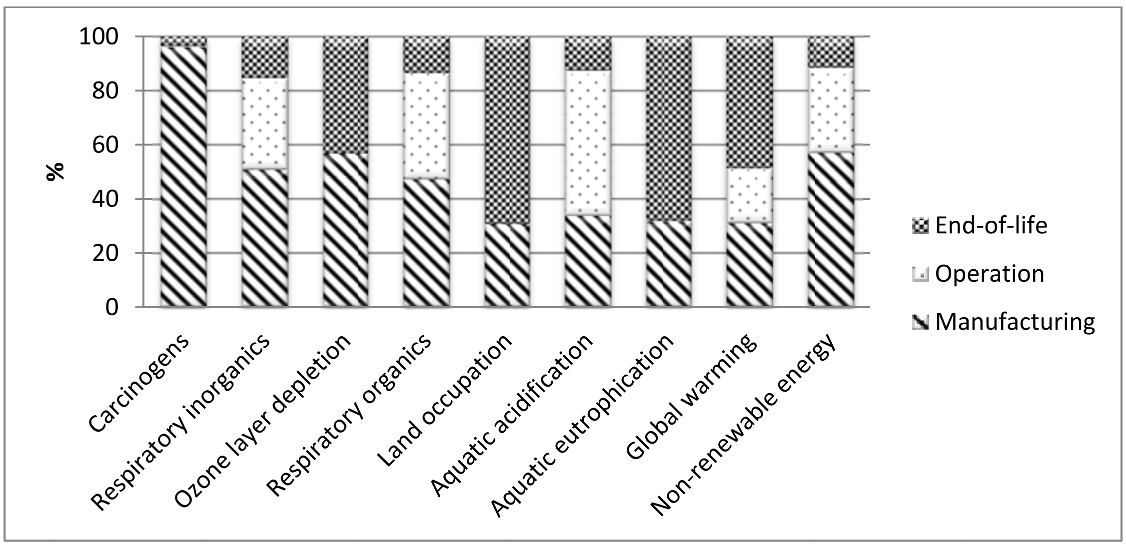

Figure 4-4: Extensive green roof life stages contribution

Figure 4-5 shows the contribution of life stages of the gravel ballasted roof. As with the other roofs the manufacturing phase produces the highest amount of environmental impacts. More than 95% of carcinogens are produced during the manufacturing phase. The end-of-life stage of the gravel ballasted roof is responsible for almost 80% of land occupation and aquatic eutrophication impacts. More than 60% of GHGs are emitted during the end-of-life stage.

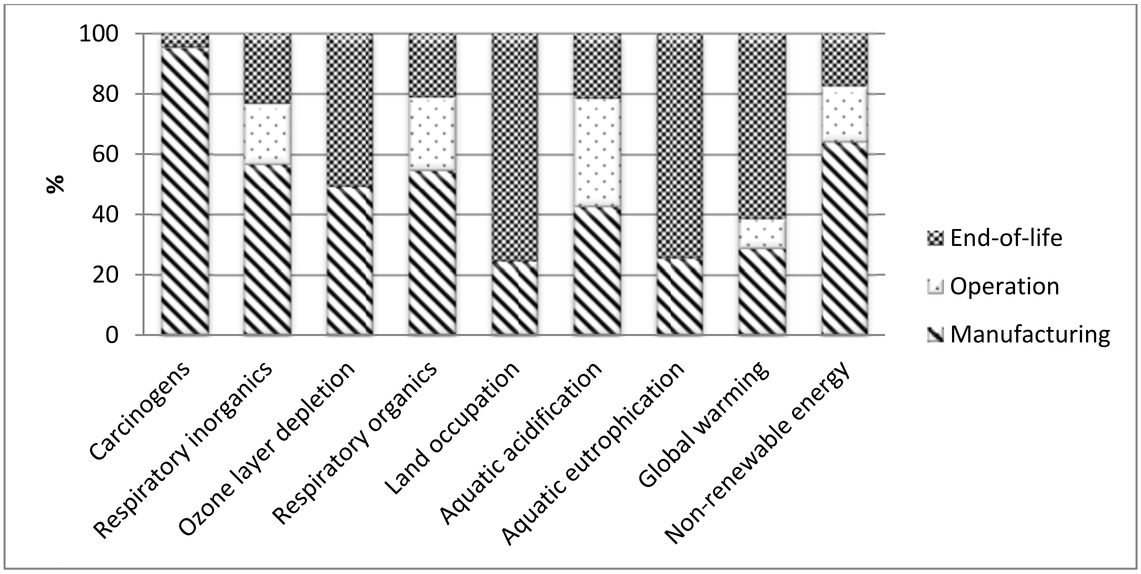

Figure 4-5: Gravel ballasted roof life stages contribution

Although the environmental impact contribution of each lifespan stage can show the importance of each stage, it is necessary to compare the environmental impacts of roofing systems with each other. The comparison between the non-renewable energy consumption of three different roofing alternatives is shown in Figure 4-6. As can be seen, most of the non-renewable energy consumption for all roof types occurs during the production phase. Due to better insulation, the operation phase energy consumption of both intensive and extensive green roofs is slightly lower than the gravel ballasted roof. The non-renewable energy consumption of the gravel ballasted roof in its end-of-life phase is higher than other roofs. In general, the extensive green roof consumes lower amounts of non-renewable energy during its lifespan.

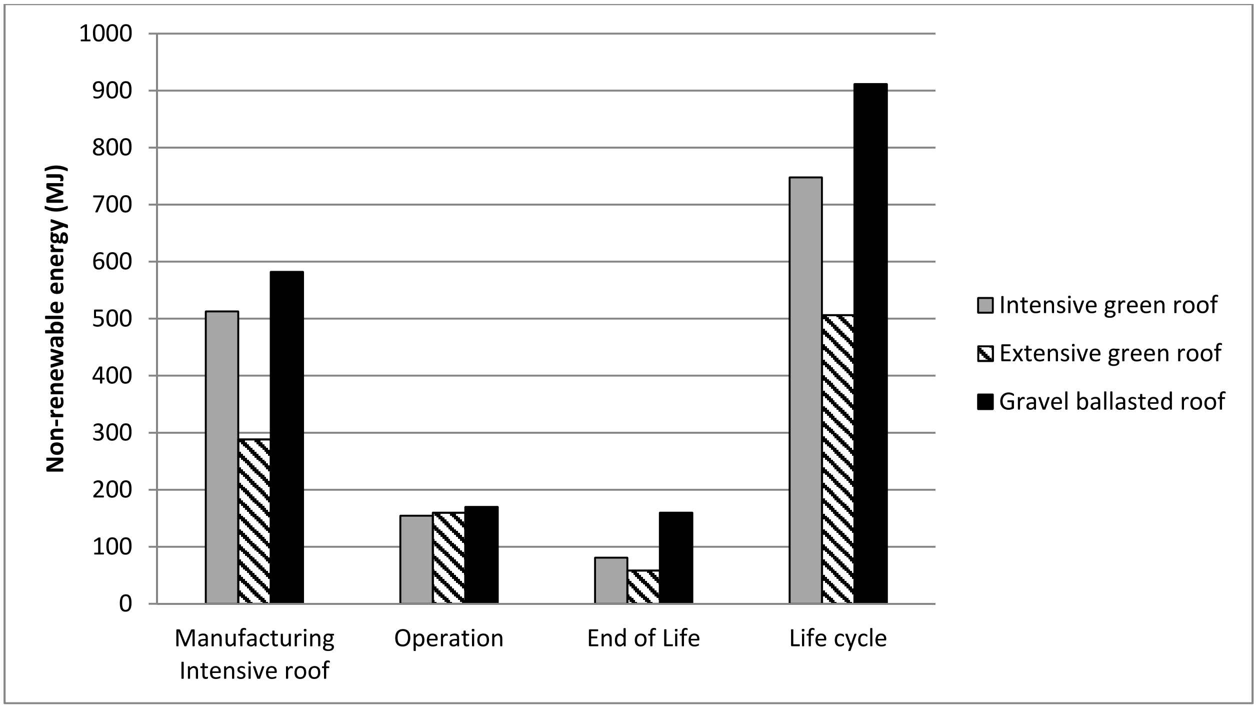

Figure 4-6: Non-renewable energy consumption of three different roofing alternatives

The global warming potential of all roofs is depicted in Figure 4-7. Based on the SimaPro software analysis, most of the CO_2 emission for all roofs occurs during the end-of-life phase. The gravel ballasted roof emits the highest amount of CO_2 equivalent. The extensive green roof is responsible for the lower amount of emission during its lifespan.

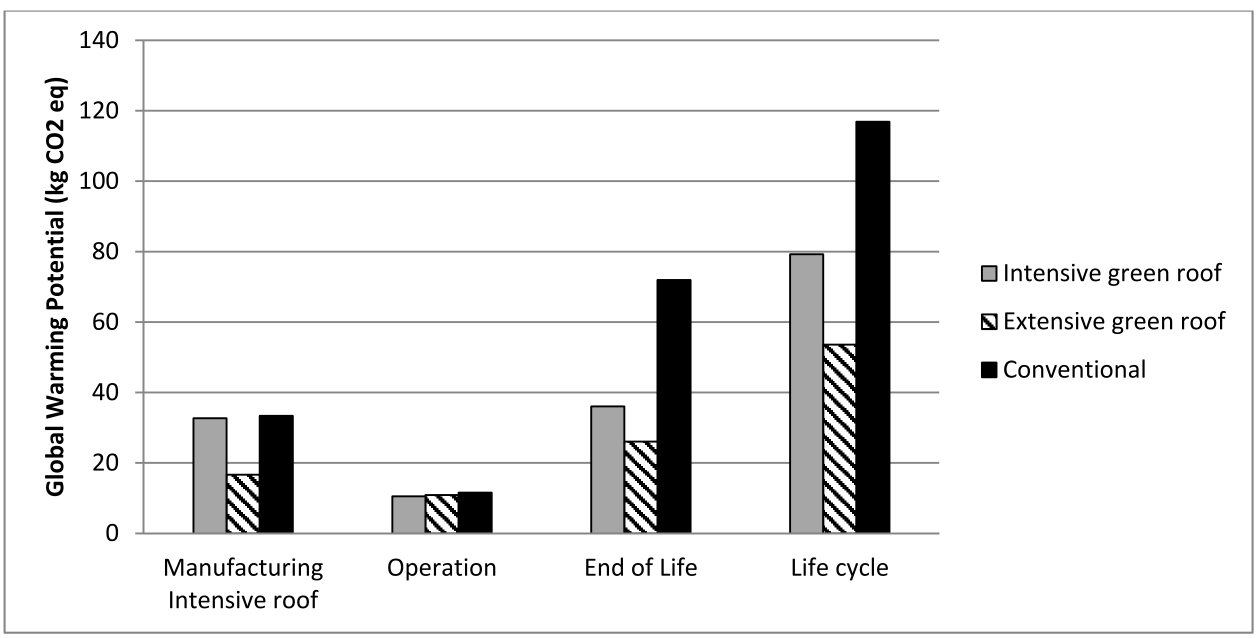

Figure 4-7: Global warming potential of three different roofing alternatives

The ozone layer depletion potential of all roofs is shown in Figure 4-8. As is illustrated, the CFC-11 equivalent emission of all roofs during the operation phase is negligible. The extensive green roof emits lower amount of CFC-11 equivalent than other roofs during the manufacturing and end-of-life phases.

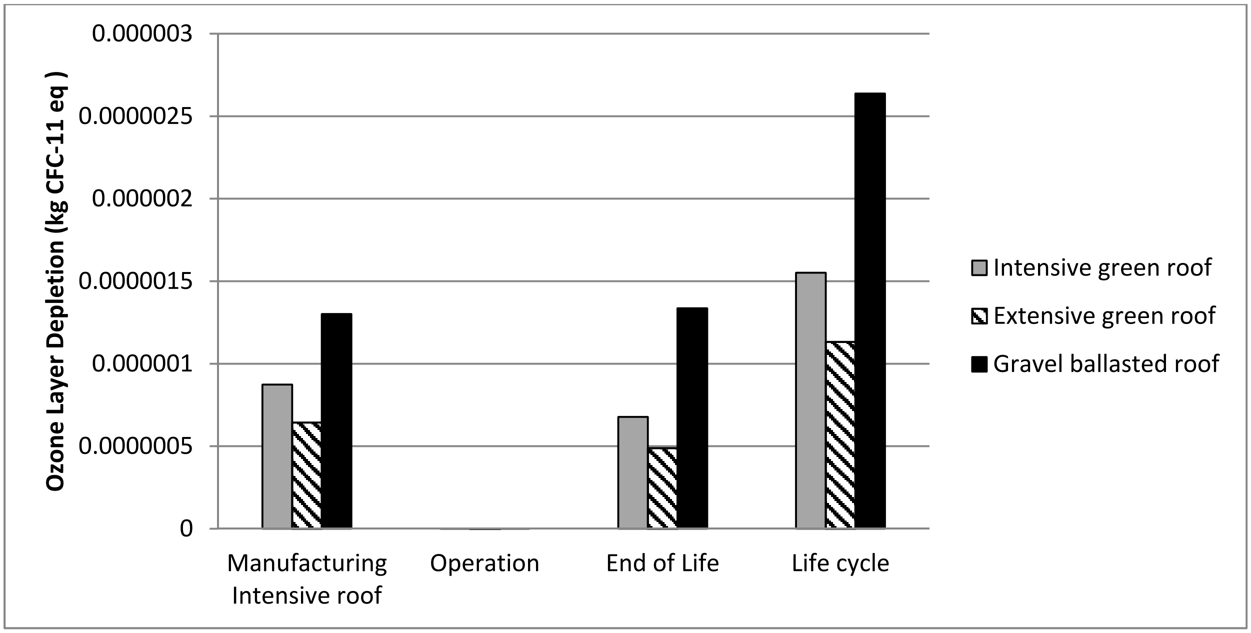

Figure 4-8: Ozone layer depletion of three different roofing alternatives

The acidification potential of all roofs is demonstrated in Figure 4-9. The SO_2 equivalent emission of the extensive green roof is lower than other roofs. Manufacturing and operation phases produce 90% of SO_2 equivalent emissions over the roof's lifespan. Although the operation phase emission of all three roofs is almost the same, the extensive green roof produces significantly lower amounts of SO_2 equivalent emission during the manufacturing phase.

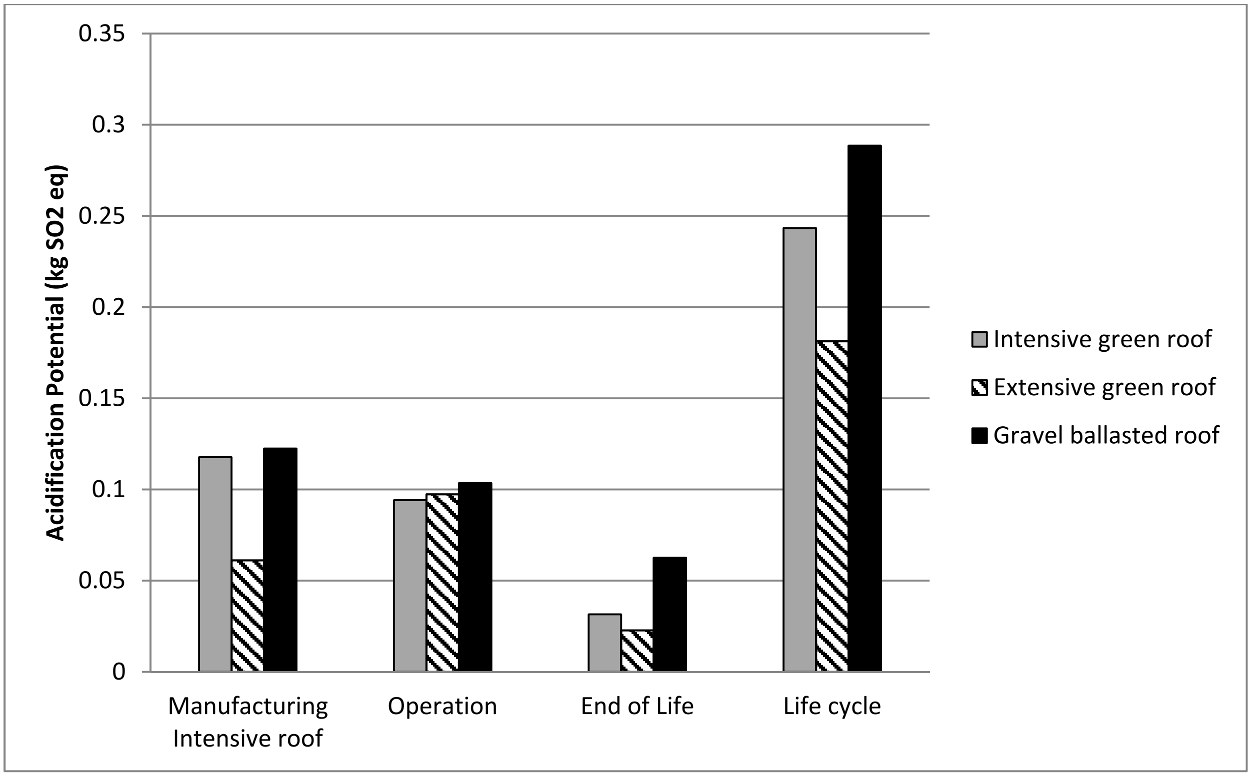

Figure 4-9: Acidification potential of three different roofing alternatives

The eutrophication potential of the three roofing alternatives is shown in Figure 4-10. The eutrophication potential is shown based on the kg PO_4 equivalent. As can be seen, the extensive green roof PO_4 equivalent emission is nearly half of the emission of the gravel ballasted roof. Most of the PO_4 equivalent emission occurs in the end-of-life stage. In contrast, the operation phase emission is negligible.

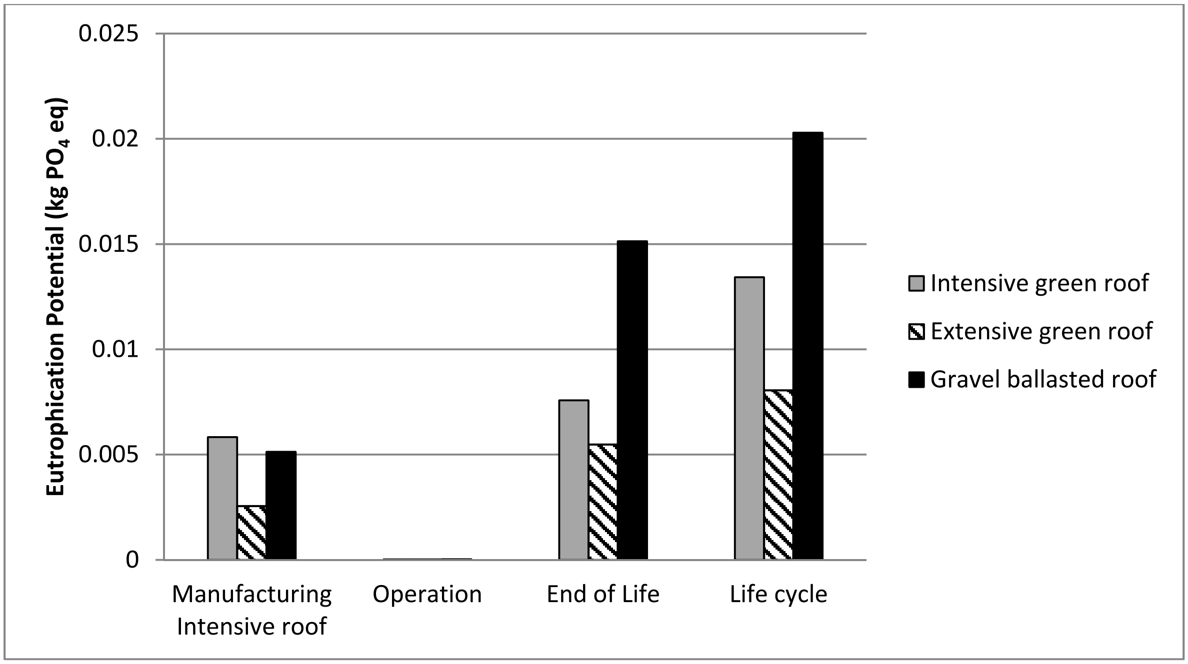

Figure 4-10: Eutrophication potential of three different roofing alternatives

The carcinogen emissions of three roofing systems based on kg C_2H_3Cl equivalent is shown in Figure 4-11. As it can be seen, the extensive green roof produces lower amount of carcinogenic emission in compare with the other roofing systems.

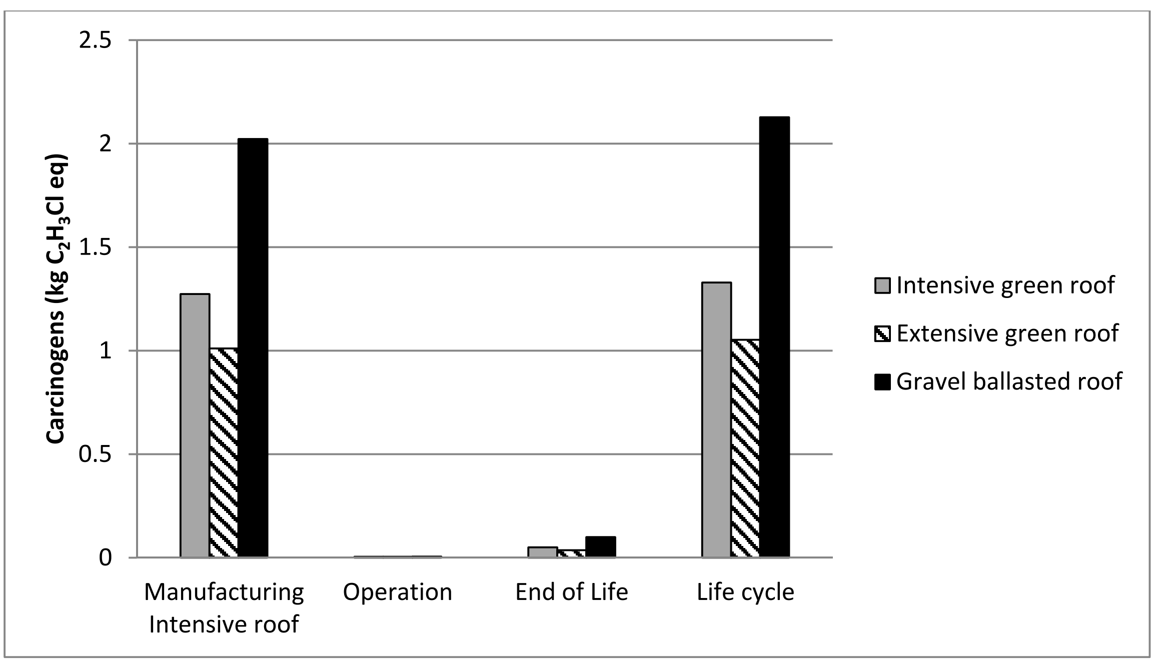

Figure 4-11: Carcinogens emission of three different roofing alternatives

The respiratory inorganic emissions of roofing systems is estimated based on kg $PM_{2.5}$ equivalent and shown in Figure 4-12. The extensive green roofs produces lower amount of respiratory inorganic particles over its lifecycle.

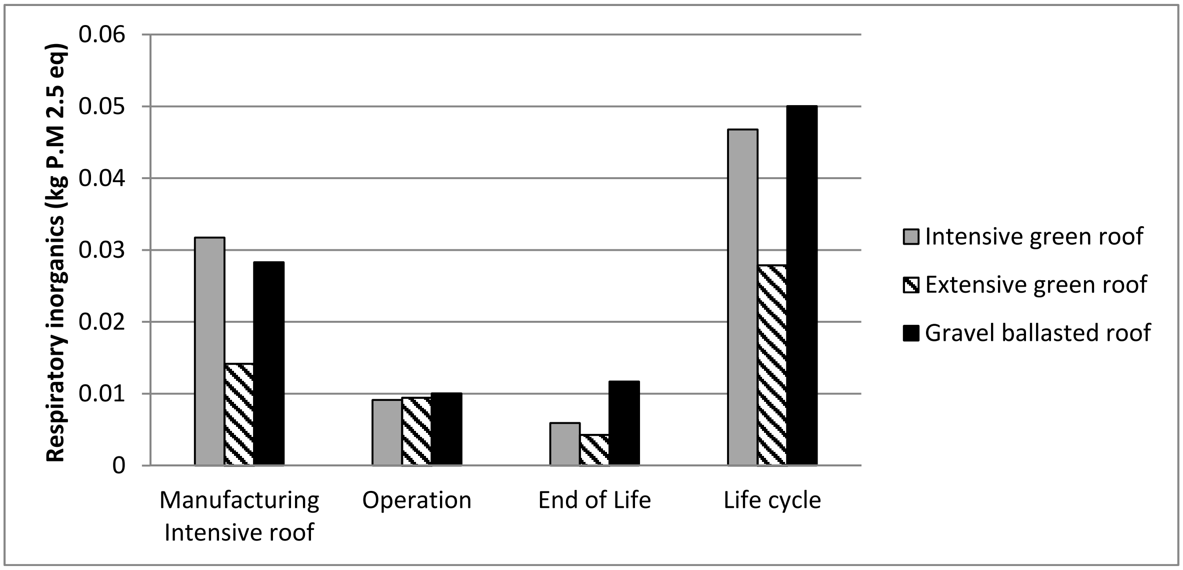

Figure 4-12: Respiratory inorganics emission of three different roofing alternatives

Figure 4-13 shows the respiratory organic emissions of roofing systems over their lifecycle and each life phase. The extensive green roof produces lower amount of organic emissions. The lifecycle emission of the extensive green roof is about 50% of the emission of the gravel ballasted roof.

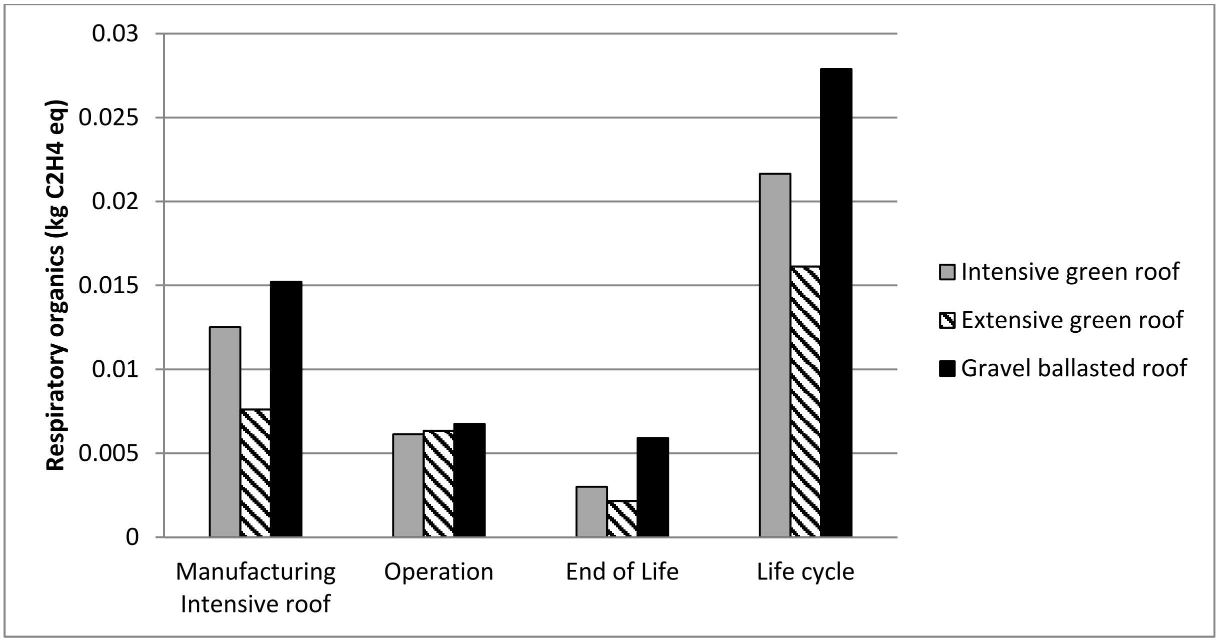

Figure 4-13: Respiratory organics emission of three different roofing alternatives

The detailed LCA confirms the outstanding environmental performance of the extensive green roof in this study, with the exception of energy savings and carcinogen chemical emissions. However, selecting a roofing system alternative is not a single-attribute decision-making process and depends on other factors. As a result, LCA needs to be supported by a multi-criteria decision making problem, which requires additional tools to be solved.

4.3.4 Selection of Sustainability Indicators for the Hierarchy

The indicators for the objective hierarchy were selected based on information collected from the peer-reviewed literature and public information. The criteria were selected to achieve the goal of the hierarchy, which is the selection of the most sustainable roofing system. TBL criteria are able to connect environment to the society and economy. Therefore, the second level consisted of sustainability TBL criteria (Reza et al. 2011; Lerario and Maiellaro 2001; Ostendorf et al. 2011; Waheed et al. 2009).

The sustainability TBL criteria were divided into sub-criteria to increase the clarity and specificity of the hierarchy. The selected sub-criteria should be independent, concise, and complete and satisfy the upper criterion objective. Moreover, sub-criteria should be relevant to the goal. For this purpose, thirteen sub-criteria were selected based on recommendations articulated in the relevant literature (Levett 1998; Lindholm et al. 2007; UNDPCSD 1995).

i- Environmental Impacts

Environmental impacts of roofing systems in the FAHP hierarchy were subdivided into six groups: climate change, stormwater management, runoff water quality, resource depletion, waste management, and environmental risks.

Climate change refers to the current studies of a wide range of indicators showing that climate change is occurring globally due to a gradual warning of the climate system (Canada climate change 2013; B.C. Air quality 2013). Global warming is the consequence of emission of CO_2 and a large number of trace gases such as CH_4 and NO_x (IPCC 2007). Pair-wise comparisons of different roofing alternatives with respect to climate change criterion have been done based on LCA impact assessment results.

Stormwater management is an important challenge in urban areas. High intensity thunderstorms increase runoff of precipitation. This runoff is carried by the sewer systems to streams and may result in floods downstream (Environment Canada 2003). Stormwater management goals include retaining a volume of precipitation and delaying the peak runoff. New approaches to urban planning include use of roofing systems to contribute to stormwater management. These approaches also consider the contribution of roof systems to runoff water quality control. Pair-wise comparisons of different roofing system scenarios with respect to stormwater management and runoff quality control were based on available literature on roofing systems such as Berndtsson (2010), Vijayaraghavan et al. (2012), Moran et al. (2004), Zimmerman et al. (2010), and other studies on green roof and conventional roof stormwater management impact and runoff water quality.

Resource depletion refers to the use of renewable and non-renewable resources, with particular concern for non-renewable resources and prolongation of their availability via reduced use and use of alternatives. Alternatives that consume less raw materials and energy in their lifespan are preferred. The comparisons of different alternatives with respect to resource depletion were based on LCA impact assessment results and available literature on the energy performance of green roofs and conventional roofs (Liu and Baskaran 2003; Jaffal et al. 2012; Desjarlais et al. 2008).

Waste management is an important criterion in environmental impact assessment. This criterion shows raw materials consumption. Pair-wise comparisons were conducted based on the results of the LCA in mineral extraction category.

ii- Economic Concerns

The economic concern criterion includes three sub-criteria: capital cost, maintenance cost, and renewal cost. The pair-wise comparisons were based on the available literature on green roof and gravel ballasted roof costs, together with direct contact with roofing system manufacturers, maintenance providers, and green roof owners like UBC Okanagan campus, Carter and Keeler (2008), and Bianchini and Hewage (2012) studies.

iii- Social Concerns

Social concerns criteria are selected based on the most common social concerns about implementing a roofing system, as documented in the literature. The third main TBL criteria were sub-divided into roofing weight, fire safety, durability, and vulnerability of area. Pair-wise comparisons are made based on the available literature such as the Green Roof Guide (2011), Bianchini and Hewage (2012), and a Sutton et al. (2012) study on prairie-based green roofs, guidelines, and expert judgment.

4.3.5 Weighting of Sustainability Indicators

Main assessment areas, main criteria, and associated sub-criteria are weighted with respect to their individual importance under the current case study. Data extracted in this paper was compiled through published literature, open ended interviews, and workshops. Data related to economic concerns under TBL performance criteria were collected based on available literature like journal papers and green roof cost reports, building owners, and informal interviews with consulting and manufacturing companies in North America. Other required information and appropriate pair-wise comparisons about roofing systems were collected based on available literature, and results of LCA and UBC-LCA group discussions. The FAHP weightings were calculated using an Excel spread sheet. Table 4-2, Table 4-3, Table 4-4, and Table 4-5 depict the relative pair-wise comparison of TBL criteria and associated sub-criteria in the current FAHP model. The consistency ratio of each judgment was checked to confirm that it is higher than 90%.

Table 4-2: The pair-wise comparison of TBL criteria for roofing system

	Social	Economic	Environmental
Social	1	1/4	1/3
Economic	4	1	2
Environmental	4	1/2	1

Table 4-3: The pair-wise comparison relevant to Social criterion

	Structural Design Force	Fire Safety	Durability	Vulnerability of Area
Structural Design Force	1	7	5	8
Fire Safety	1/7	1	1/3	3
Durability	1/5	3	1	5
Vulnerability of Area	1/8	1/3	1/5	1

Table 4-4: The pair-wise comparison relevant to Economic criterion

	Initial Cost	O&M	Replacement cost
Initial Cost	1	7	9
O&M	1/7	1	4
Replacement Cost	1/9	1/4	1

Table 4-5: The pair-wise comparison relevant to Environmental criterion

	Climate Change	Waste Management	Runoff Quality	Stormwater Management	Resource Depletion	Environmental Risks
Climate Change	1	5	4	5	3	4
Waste Management	1/5	1	1/3	1/4	1/6	2
Runoff Quality	1/4	3	1	1	1/2	3
Stormwater Management	1/5	4	1	1	1/3	3
Resource Depletion	1/3	6	2	3	1	4
Environmental Risks	1/4	1/2	1/3	1/3	1/4	1

In order to demonstrate the application of the proposed FAHP-LCA method, the results were compared under different α-cut levels. For α-cut levels, 0.5 and 1 values are considered and alternatives were scored. The alternatives' score under different α-cut levels can be considered as a decision support tool since it is able to show the level of confidence and uncertainty in choosing the most sustainable alternative.

Fuzzy pair-wise comparisons have been made among different impact categories and their sub-criteria based on available literature, LCA results, and experts' judgement. Then the local and final fuzzy weights of alternatives and criteria were calculated. Table 4-6 provides the results of fuzzy local weights of alternatives after pair-wise comparisons, and

Table 4-7 shows the final fuzzy weights of alternatives and criteria.

Table 4-6: Fuzzy local weights of ($\tilde{w}$) with δ=1

Level 2	**W_1**			**Level 3**	**W_2**			**Level 4**								
								W_{31} (Conv. roof)			**W_{32} (Extv. green roof)**			**W_{33} (Int. green roof)**		
Social concerns	0.08	0.12	0.20	Structural design	0.50	0.65	0.84	0.47	0.67	0.93	0.16	0.24	0.37	0.06	0.09	0.13
				Fire safety	0.07	0.10	0.14	0.06	0.07	0.10	0.20	0.28	0.40	0.46	0.65	0.89
				Durability	0.15	0.21	0.29	0.06	0.08	0.11	0.40	0.46	0.52	0.40	0.46	0.52
				Vulnerability of Area	0.04	0.05	0.07	0.07	0.10	0.17	0.09	0.17	0.26	0.55	0.73	0.99
Economic limitations	0.31	0.54	0.88	Initial cost	0.67	0.78	0.90	0.44	0.63	0.88	0.21	0.29	0.42	0.06	0.08	0.11
				O & M	0.13	0.16	0.20	0.46	0.65	0.89	0.20	0.28	0.40	0.06	0.07	0.10
				Replacement cost	0.05	0.06	0.07	0.48	0.66	0.90	0.20	0.27	0.39	0.05	0.07	0.09
Environmental impacts	0.21	0.34	0.61	Climate Change	0.27	0.46	0.78	0.10	0.13	0.18	0.63	0.78	0.95	0.06	0.08	0.12
				Waste Management	0.02	0.04	0.07	0.08	0.09	0.11	0.55	0.64	0.60	0.29	0.27	0.38
				Wastewater Quality	0.07	0.11	0.21	0.46	0.64	0.88	0.17	0.26	0.38	0.07	0.10	0.15
				Stormwater Management	0.07	0.11	0.18	0.06	0.08	0.10	0.17	0.23	0.32	0.53	0.70	0.91
				Resource Depletion	0.13	0.24	0.44	0.35	0.58	0.89	0.22	0.34	0.59	0.06	0.08	0.12
				Environmental risk	0.02	0.04	0.07	0.17	0.22	0.31	0.54	0.71	0.92	0.06	0.07	0.09

Table 4-7: Evaluation of final global preference weights (Gk) with δ=1

		Conventional roof			Extensive roof			Intensive roof		
Social concerns	**Structural design force**	0.0182	0.0512	0.1534	0.0063	0.0185	0.0609	0.0025	0.0067	0.0211
	Fire safety	0.0003	0.0008	0.0027	0.0011	0.0032	0.0111	0.0025	0.0075	0.0244
	Human health	0.0007	0.0019	0.0061	0.0047	0.0113	0.0292	0.0047	0.0113	0.0292
	Durability	0.0002	0.0006	0.0022	0.0002	0.0010	0.0034	0.0015	0.0041	0.0130
	Flexibility	0.0905	0.2674	0.6945	0.0420	0.1210	0.3299	0.0121	0.0328	0.0843
Economic limitation	**Initial cost**	0.0186	0.0570	0.1586	0.0081	0.0245	0.0721	0.0022	0.0063	0.0173
	O & M	0.0075	0.0212	0.0590	0.0031	0.0087	0.0258	0.0008	0.0021	0.0059
	Replacement cost	0.0057	0.0212	0.0860	0.0359	0.1232	0.4505	0.0034	0.0128	0.0817
Environmental issues	**Climate Change**	0.0004	0.0011	0.0049	0.0026	0.0087	0.0262	0.0014	0.0058	0.0165
	Waste Management	0.0065	0.0248	0.1123	0.0024	0.0101	0.0491	0.0010	0.0041	0.0195
	Wastewater quality	0.0008	0.0027	0.0112	0.0023	0.0083	0.0348	0.0072	0.0253	0.1004
	Storm water Management	0.0094	0.0476	0.2382	0.0061	0.0282	0.1569	0.0016	0.0067	0.0318
	Land use	0.0007	0.0027	0.0137	0.0024	0.0087	0.0411	0.0002	0.0009	0.0042
	Environmental risk	0.0182	0.0512	0.1534	0.0063	0.0185	0.0609	0.0025	0.0067	0.0211

As shown in Table 4-8, the extensive green roof system is the most sustainable alternative for both α-cut values. Since the extensive green roof has the highest RSI value, it can be considered the best solution. The intensive green roof is not a sustainable alternative in this area. However, it is noticeable that by decreasing the uncertainty and increasing the confidence, the RSI value of the extensive green roof decreases and the RSI value of the conventional roof increases.

Table 4-8: Ranking of roofing systems

Alternative	***δ=1***	**Rank**	***δ=0.5***	**Rank**
Conventional roof	0.40	2	0.47	2
Extensive green roof	0.58	1	0.54	1
Intensive green roof	0.16	3	0.13	3

4.4 Discussion

Developers, building consultants and other stakeholders are under increasing public pressure to take sustainability issues and green building technologies into consideration. Reliable, evidence-based tools are needed to help these and other decision-makers to choose the most sustainable options among competing green technology alternatives. The purpose of this study was to develop a decision-making framework that can aggregate the results of LCA with multi-criteria decision-making under uncertainty and lack of knowledge for green building technologies. A hierarchical structure was developed addressing concerns of decision makers during selection of the most sustainable technology linked with the implementation of sustainability TBL criteria.

This framework generates a sustainability score for different alternatives. Such a quantified sustainability score will be useful to evaluate the comparative sustainability level of alternatives and to guide decision makers in complex sustainability dilemmas. The results have been summarized and compared for both conventional LCA and proposed FAHP-LCA.

The developed sustainability index represents the overall sustainability level of a particular green technology. Environmental impacts are derived from LCA. The relative weights and quantified comparisons for other TBL criteria are analyzed through the fuzzy approach to identify the most sustainable green technology. The results could be implemented to support decision-making processes, for example in environmental consulting companies that plan to reduce environmental impacts with acceptable economic efficiency and consistency, with specified client or public values. Moreover, the outcomes can be useful for regulators seeking to adopt or advocate and demonstrate preferred green technologies and practices. This framework aids decision makers to analyze the sustainability of different alternatives in a particular problem. Although the model is developed based on roofing system alternatives, it can be extended to other green building technologies and other industries by tuning the model with the appropriate criteria and desired objectives for the new MCDM process.

Compared to existing LCA studies, the proposed approach in this paper is able to aggregate the results of LCA into a hierarchy process. The FAHP model is flexible enough to capture vagueness of uncertainty within LCA, as well as to incorporate subjective considerations, level of confidence, and preferences of decision makers. The proposed FAHP-LCA framework is able to reduce the possibility of selecting an inappropriate building technology/alternative among various current technologies. This framework thus provides a more robust and more reliable decision-making method for sustainability assessment problems.

Chapter 5 : Conclusions and Future Works

The summary and conclusions of the current research are provided in Section 5.1, followed by the limitations that arose during the research in Section 5.2. Finally, the research contribution and suggested future works are presented in Sections 5.3 and 5.4.

5.1 Summary and Conclusions

LID practices have been an appropriate response to non-point pollutant management in urban areas. Green roof systems are one of the LID practices that have been designed and implemented by architects, engineers, and building owners in recent years. This study investigated the performance of extensive green roofs in a semi-arid climate. The quality of extensive green roofs was assessed and the potential of improving green roof runoff quality was explored. Results show that the runoff quality of extensive green roofs examined in this thesis are statistically similar to the runoff quality of conventional roofs.

In addition, the current research developed a sustainability assessment framework to assess the sustainability of roofing systems. The important characteristics in sustainability assessments of roofing systems were identified. The results of the sustainability assessment framework showed that extensive green roofs are the most sustainable roofing system among conventional roofs and intensive green roof systems.

Results of Chapter 3 prove that extensive green roof impact on runoff quality is the same as conventional roofs. The runoff quality of sixteen different extensive green roofs was compared with four conventional roofs. Nitrate, ammonia, pH, colour, turbidity, ORP, and EC were measured to determine the performance of each roof. Results in Chapter 3 can be summarized as follows:

The results of the experiment showed that there was no significant difference between the pH of green roof runoff and conventional roofs. The average pH of green roofs was slightly higher than conventional roofs and rain. Moreover, the pH of generic green roofs decreases with age and additional rain events. The pH of green roofs was in an acceptable range for Canadian guidelines for both fresh water and domestic reclaimed water.

The generic green roof nitrate concentration was significantly lower than the concentration of nitrate in gravel ballasted roofs' runoff. However the nitrate concentration in generic green roof runoff was statistically the same as the nitrate concentration of EPDM roof runoff. The experiment showed that the concentration of nitrate in generic green roofs was higher than the nitrate concentration in rainwater. The nitrate concentration in green roofs was higher than the accepted concentration for Canadian guidelines for fresh water or domestic reclaimed water.

The ammonia concentration of generic green roofs was the same as the concentration of ammonia in gravel ballasted roof runoff and was significantly lower than the ammonia concentration in EPDM roof runoff. The sample analysis showed that the ammonia concentration in generic green roofs was about 90% lower than the ammonia concentration in EPDM roof runoff. Moreover, the concentration of ammonia in green roof runoff was lower than the ammonia concentration in rainwater and was in the accepted range for Canadian guidelines for fresh water.

The sample analysis showed that the green roof runoff was coloured. Although the green roof runoff was clear, the colour and turbidity of green roof runoff was not in an acceptable range for fresh water or reclaimed water.

Green roof runoff had a lower ORP level than EPDM roof runoff, which shows that the runoff from EPDM roofs had a higher water quality. The ORP of green roof runoff was around 220 to 290 mV and was not in an acceptable range for fresh water guidelines.

The conductivity of green roof runoff was significantly higher than conductivity of EPDM and gravel ballasted roof runoff and rainwater. The conductivity of aged green roof runoff was more constant than the conductivity of other green roof runoff.

Since Okanagan Lake is vulnerable to non-point source nitrate and ammonia release, two optimistic and conservative scenarios were defined for retrofitting part of downtown area of Kelowna with XeroFlor extensive green roofs. The results show that by retrofitting just 50% to 75% of that area, the nitrate removal can be estimated to be 300-450kg. In the conservative scenario and retrofitting just 10% to 25% of that area, the nitrate removal would be 60-150kg over the extensive green roof lifespan. Moreover, extensive green roofs were able to remove 200-300kg of ammonia in the optimistic scenario and 40-100kg in the conservative scenario.

In Chapter 4, a sustainability assessment framework was proposed and developed. Sustainability triple-bottom-line (TBL) criteria were considered for assessing the sustainability of the roofing system. TBL criteria consist of economic, environmental, and social criteria. Each TBL criterion was divided into sub-criteria for better assessment. The framework is developed based on the LCA and F-AHP methodology. Three different roofing systems, including an intensive green roof, an extensive green roof, and a gravel ballasted roof were compared. The analysis was based on the current roofing systems constructed on SOE and CIRS buildings at UBC campuses.

The environmental impacts of each roofing system were performed using LCA. The LCA results show that extensive green roof system located at SOE has a lower contribution to non-renewable energy consumption, global warming gas production, ozone layer depletion impact, and other environmental impacts. The environmental impact contribution of the intensive green roof was significantly higher than the extensive green roof. The intensive green roof's environmental impact contribution was lower than the gravel ballasted roof contribution in some categories but higher in other environmental categories. Green roof systems' initial cost, and operation and maintenance costs are much higher than other conventional roofing systems. This additional cost influences the sustainability of green roof systems.

The framework considered the uncertainty in decision making, LCA and cost analysis. The assessment was based on the LCA results, available literature and experts' judgments. The results show that the SOE's extensive green roof is the most sustainable roofing system among other roofing systems.

5.2 Limitations

There are a variety of physical and chemical water quality characteristics regulated by environmental agencies, but due to the scope of the experiment only primary water quality characteristics were considered. The effect of temperature drops in winter, heavy rainfall during the spring season, and drought situations during summer in this area was not examined. It is noticeable that the current limitation is correlated with the previous limitation and may change the green roof runoff quality. Since it was impossible to distinguish contaminants and emission loads from pollutants in the air or green roof fertilization, the mixed effect of green roofs on runoff quality were measured. Planting species need several years to be established in the new environment due to being under several extreme heat and cold temperatures, drought situations, and the performance of vegetation changes. Therefore, these experiments should be prepared over a long-term period e.g. 5 years or more.

Although the proposed framework has various advantages over existing methods, there are some limitations that need to be taken into consideration. The main challenge in this model is to provide a single index for sustainability to embody the overall sustainability level of implementing a green building technology. All criteria and associated sub criteria should be accounted and aggregated in the hierarchy model. Aggregating the results of LCA is the most complex part. Converting categorized LCA impacts into different sub-criteria requires a solid knowledge of environmental assessment. In addition, FAHP and LCA are both time consuming and may prolong the process of decision-making. Indeed developing a web-based FAHP tool can facilitate the application of the proposed framework.

5.3 Research Contributions

The current research is a significant contribution to assessing the sustainability of green building technologies based on TBL criteria. There is no other research using LCA and fuzzy assessment to develop a sustainability assessment framework for green buildings to date.

The results of the current research on the green roof runoff show that there is no significant difference between the quality of green roof runoff and conventional roof runoff. This result can be used for updating the building regulations and guidelines.

This study evaluated the runoff quality of green roof systems for re-use purposes. The results show that green roof runoff meets the Canadian reclaimed water guidelines.

5.4 Future Research

There is a need to run the experiment over longer periods (e.g. five years or more) and with different types (e.g. various soil depth). This result can provide better analysis of green roof runoff quality in a semi-arid environment. Running the experiment over longer periods of time provides more accurate results on green roof runoff quality considering the aging depreciation.

The experiment should be conducted with different plant species (e.g. local species). Performance of different plants can be assessed and provide a better understanding about the applicable plants for the green roof system.

A full life cycle cost analysis of green roofs should be performed considering social and environmental benefits as well. This will provide a better understanding about the range of green roofs benefits/cost and help the policy makers to update the regulation guidelines and possible incentives for green roof systems.

During the current research, developing an inventory of green roof materials was a challenge. It is necessary to develop a specific database for green roof systems with detailed information of layers, materials, vegetation, and physical and chemical properties. This database can be used for future simulations and building studies.

Bibliography

Ali, Hikmat H., and Saba F. Al Nsairat. 2009. "Developing a Green Building Assessment Tool for Developing Countries – Case of Jordan." *Building and Environment* 44 (5): 1053–1064. http://www.sciencedirect.com/science/article/pii/S0360132308001868.

ALwaer, H., and D.J. Clements-Croome. 2010. "Key Performance Indicators (KPIs) and Priority Setting in Using the Multi-Attribute Approach for Assessing Sustainable Intelligent Buildings." *Building and Environment* 45 (4): 799–807. http://www.sciencedirect.com/science/article/pii/S036013230900225X.

Aras, Haydar, Şenol Erdoğmuş, and Eylem Koç. 2004. "Multi-Criteria Selection for a Wind Observation Station Location Using Analytic Hierarchy Process." *Renewable Energy*. Vol. 29. http://www.sciencedirect.com/science/article/pii/S0960148103004051.

Arnold, Chester L., and C. James Gibbons. 1996. "Impervious Surface Coverage: The Emergence of a Key Environmental Indicator." *Journal of the American Planning Association* 62 (2) (June 30): 243–258. doi:10.1080/01944369608975688. http://dx.doi.org/10.1080/01944369608975688.

ASTM. 2013a. "Standard Guide for Selection, Installation, and Maintenance of Plants for Green Roof Systems."

ASTM. 2013b. "Standard practice for determination of dead loads and live loads associated with vegetative (green) roof systems."

ASTM. 2013c. "Standard test method for water capture and media retention of geocomposite drain layers for vegetative (green) roof systems."

ASTM. 2013d. "Standard test method for maximum media density for dead load analysis ofvegetative (green) roof systems."

ASTM. 2013e. "Standard classification for size of aggregate used as ballast for membrane roof systemsB.C. Air quality. 2013. "The Earth's Climate System." http://www.bcairquality.ca/climate-change/what-is-climate-change.html.

Bass, Brad, Scott Krayenhoff, Alberto Martilli, and Roland Stull. 2002. "Mitigating the Urban Heat Island with Green Roof Infrastructure." *Green Roofs Infrastructure Monitor* 4 (1). http://www.5dstudios.com/clients/gcca/wp-content/uploads/2012/04/finalpaper_bass.pdf.

Berndtsson, Justyna Czemiel. 2010. "Green Roof Performance towards Management of Runoff Water Quantity and Quality: A Review." *Ecological Engineering* 36 (4): 351–360. http://www.sciencedirect.com/science/article/pii/S0925857410000029.

Berndtsson, Justyna Czemiel, Lars Bengtsson, and Kenji Jinno. 2009. "Runoff Water Quality from Intensive and Extensive Vegetated Roofs." *Ecological Engineering* 35 (3): 369–380. http://www.sciencedirect.com/science/article/pii/S0925857408002024.

Berndtsson, Justyna Czemiel, Tobias Emilsson, and Lars Bengtsson. 2006. “The Influence of Extensive Vegetated Roofs on Runoff Water Quality.” *Science of The Total Environment* 355 (1): 48–63. http://www.sciencedirect.com/science/article/pii/S0048969705001713.

Bianchini, Fabricio, and Kasun Hewage. 2012a. “How ‘green’ Are the Green Roofs? Lifecycle Analysis of Green Roof Materials.” *Building and Environment* 48: 57–65. http://www.sciencedirect.com/science/article/pii/S0360132311002629.

Bianchini, F., & Hewage, K. 2012b. “Probabilistic social cost-benefit analysis for green roofs: a lifecycle approach.” *Building and Environment* 58: 152–162.

Blackhurst, Michael, Chris Hendrickson, and H. Scott Matthews. 2010. “Cost-Effectiveness of Green Roofs.” *Journal of Architectural Engineering* 16 (4) (December 5): 136–143. doi:10.1061/(ASCE)AE.1943-5568.0000022. http://ascelibrary.org/doi/abs/10.1061/(ASCE)AE.1943-5568.0000022.

Bottero, Marta, Elena Comino, and Vincenzo Riggio. 2011. “Application of the Analytic Hierarchy Process and the Analytic Network Process for the Assessment of Different Wastewater Treatment Systems.” *Environmental Modelling & Software* 26 (10): 1211–1224. http://www.sciencedirect.com/science/article/pii/S1364815211001009.

Boulanger, Bryan, and Nikolaos P. Nikolaidis. 2003. “Mobility and Aquatic Toxicity of Copper in an Urban Watershed.” *Journal of the American Water Resources Association* 39 (2) (April): 325–336. doi:10.1111/j.1752-1688.2003.tb04387.x. http://doi.wiley.com/10.1111/j.1752-1688.2003.tb04387.x.

Brezonik, Patrick L, and Teresa H Stadelmann. 2002. “Analysis and Predictive Models of Stormwater Runoff Volumes, Loads, and Pollutant Concentrations from Watersheds in the Twin Cities Metropolitan Area, Minnesota, USA.” *Water Research* 36 (7): 1743–1757. http://www.sciencedirect.com/science/article/pii/S004313540100375X.

Brunner, Norbert, and Markus Starkl. 2004. “Decision Aid Systems for Evaluating Sustainability: A Critical Survey.” *Environmental Impact Assessment Review* 24 (4): 441–469. http://www.sciencedirect.com/science/article/pii/S0195925503002063.

Canada Climate. 2013. “Daily Data Report for Kelowna, British Columbia, Canada.” http://climate.weather.gc.ca/climateData/dailydata_e.html?StationID=48369.

Canada climate change. 2013. “Information on climate change.” . http://www.climatechange.gc.ca/default.asp?lang=En&n=F2DB1FBE-1. (Accessed 12/09/2013).

Carter, T., and A. Keeler. 2008. “Life-Cycle Cost–benefit Analysis of Extensive Vegetated Roof Systems.” *Journal of Environmental Management* 87 (3): 350–363.

Castleton, H.F., V. Stovin, S.B.M. Beck, and J.B. Davison. 2010. “Green Roofs; Building Energy Savings and the Potential for Retrofit.” *Energy and Buildings* 42 (10): 1582–1591. http://www.sciencedirect.com/science/article/pii/S0378778810001453.

Chan, A.L.S., and T.T. Chow. 2013. “Energy and Economic Performance of Green Roof System under Future Climatic Conditions in Hong Kong.” *Energy and Buildings* 64: 182–198. http://www.sciencedirect.com/science/article/pii/S0378778813002910.

Chan, Felix, and Niraj Kumar. 2007. “Global Supplier Development Considering Risk Factors Using Fuzzy Extended AHP-Based Approach.” *Omega* 35 (4): 417–431. http://www.sciencedirect.com/science/article/pii/S030504830500112X.

Chan, Hing Kai, and Xiaojun Wang. 2013. *Fuzzy Hierarchical Model for Risk Assessment*. London: Springer London. doi:10.1007/978-1-4471-5043-5. http://link.springer.com/10.1007/978-1-4471-5043-5.

Chan, Hing Kai, Xiaojun Wang, Gareth Reginald Terence White, and Nick Yip. 2013. “An Extended Fuzzy-AHP Approach for the Evaluation of Green Product Designs.” *IEEE Transactions on Engineering Management* 60 (2) (May): 327–339. doi:10.1109/TEM.2012.2196704. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6204329.

Chatzimouratidis, Athanasios I., and Petros A. Pilavachi. 2009. “Technological, Economic and Sustainability Evaluation of Power Plants Using the Analytic Hierarchy Process.” *Energy Policy* 37 (3): 778–787. http://www.sciencedirect.com/science/article/pii/S0301421508005880.

Chen, Shan-Huo. 1985. “Ranking Fuzzy Numbers with Maximizing Set and Minimizing Set.” *Fuzzy Sets and Systems* 17 (2): 113–129. http://www.sciencedirect.com/science/article/pii/0165011485900508.

Chung, Eun Sung, and Kil Seong Lee. 2009. “Prioritization of Water Management for Sustainability Using Hydrologic Simulation Model and Multicriteria Decision Making Techniques.” *Journal of Environmental Management* 90 (3): 1502–1511. http://www.sciencedirect.com/science/article/pii/S0301479708003022.

City of Toronto. 2010. “Green Roofs - Zoning & Environmental Planning - City Planning | City of Toronto.” http://www1.toronto.ca/wps/portal/contentonly?vgnextoid=3a7a036318061410VgnVCM10000071d60f89RCRD.

Coffelt, Donald P., and Chris T. Hendrickson. 2010. “Life-Cycle Costs of Commercial Roof Systems.” *Journal of Architectural Engineering* 16 (1) (March 12): 29–36. doi:10.1061/(ASCE)1076-0431(2010)16:1(29). http://ascelibrary.org/doi/abs/10.1061/%28ASCE%291076-0431%282010%2916%3A1%2829%29.

Dabaghian, M. R., S. H. Hashemi, T. Ebadi, and R. Maknoon. 2008. “The Best Available Technology for Small Electroplating Plants Applying Analytical Hierarchy Process.” *International Journal of Environmental Science & Technology* 5 (4) (September 1): 479–484. doi:10.1007/BF03326044. http://link.springer.com/10.1007/BF03326044.

DeNardo, J., A. Jarrett, H. Manbeck, D. Beattie, and R. Berghage. 2003. “Stormwater Detention and Retention Abilities of Green Roofs.” In *World Water & Environmental Resources Congress*, 1–7. ASCE. doi:10.1061/40685(2003)310. http://ascelibrary.org/doi/abs/10.1061/40685(2003)310.

Desjarlais, A.O., T.W. Petrie, and J.A Atchley. 2008. “Evaluating the Energy Performance of Ballasted Roof Systems.” http://www.spri.org/pdf/Thermal Performance of Ballast Study Final Report 05 08 .pdf.

Dietz, Michael E. 2007. “Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions.” *Water, Air, and Soil Pollution* 186 (1-4) (September 5): 351–363. doi:10.1007/s11270-007-9484-z. http://link.springer.com/10.1007/s11270-007-9484-z.

Dolowitz, David, Melissa Keeley, and Dale Medearis. 2012. “Stormwater Management: Can We Learn from Others?” *Policy Studies* 33 (6) (November): 501–521. doi:10.1080/01442872.2012.722289. http://dx.doi.org/10.1080/01442872.2012.722289.

Dunnett, Nigel, and Noel Kingsbury. 2008. *Planting Green Roofs and Living Walls*. Timber Press. http://www.amazon.com/Planting-Green-Roofs-Living-Walls/dp/0881929115.

Dunnett, Nigel, Ayako Nagase, Rosemary Booth, and Philip Grime. 2005. “Vegetation Composition and Structure Significantly Influence Green Roof Performance.” In *Greening Rooftops for Sustainable Communities, Washington, DC, May 4-6, 2005*, 10.

Egodawatta, Prasanna, Evan Thomas, and Ashantha Goonetilleke. 2009. “Understanding the Physical Processes of Pollutant Build-up and Wash-off on Roof Surfaces.” *Science of The Total Environment* 407 (6): 1834–1841. http://www.sciencedirect.com/science/article/pii/S0048969708012916.

Ellis, J.B. 2013. “Sustainable Surface Water Management and Green Infrastructure in UK Urban Catchment Planning.” *Journal of Environmental Planning and Management* 56 (1) (January): 24–41. doi:10.1080/09640568.2011.648752. http://dx.doi.org/10.1080/09640568.2011.648752.

Environment Canada. 2003. “Understanding stormwatermanagement:an introduction to stormwater management planning and design.” www.ene.gov.on.ca/stdprodconsume/groups/lr/.../std01_079720.pdf. (Accessed 11/11/2013).

Eumorfopoilou, E., and D. Aravantinos. 1998. “The Contribution of a Planted Roof to the Thermal Protection of Buildings in Greece.” *Energy and Buildings* 27: 26–36.

Fioretti, R., A. Palla, L.G. Lanza, and P. Principi. 2010. “Green Roof Energy and Water Related Performance in the Mediterranean Climate.” *Building and Environment* 45 (8): 1890–1904. http://www.sciencedirect.com/science/article/pii/S0360132310000806.

FLL Guidelines. 2002. “Guideline for the Planning, Execution and Upkeep of Green Roof Sites”. Bonn, Germany. http://www.greenroofsouth.co.uk/FLL Guidelines.pdf.

Galal, H. S. 2013. “Integrating sustainability in municipal wastewater infrastructure decision-analysis using the analytic hierarchy process”. University of British Columbia. https://circle.ubc.ca/bitstream/handle/2429/44590/ubc_2013_fall_galal_hana.pdf?sequence=5. (Accessed 14/11/2013).

Gallopin, G. C., Funtowicz, S., O’Connor, M., & Ravetz, J. 2001. “Science for the twenty-first century: from social contract to the scientific core.” *International Social Science Journal* 53 (168): 219–229. doi:10.1111/1468-2451.00311.

Gerardi, M. H. 2007. "Oxidation reduction portential and wastewater treatment." http://www.neiwpcc.org/iwr/reductionpotential.asp. (Accessed 11/05/2012).

Getter, K. L., & Rowe, D.B. 2006. "The role of extensive green roofs in sustainable development." *HortScience* 41 (5): 1276–1285.

Gill, S.E., Handley, J.F,. Ennos, A.R., & Pauleit S. 2007. "Adapting cities for climate change: the role of the green infrastructure." *Built Environment* 33 (1): 115–133.

Graham, P., & Kim, M. 2003. "Evaluating the stormwater management benefits of green roofs through water balance modeling." In *Greening Rooftops for Sustainable Communities Conference*.

Green roof Guide. 2011. "Green Roof Guide". Sheffield. http://www.greenroofguide.co.uk/pdfs/.

Green roofs for healthy cities. 2013a. "Green roofs statistics." http://www.greenroofs.org/index.php/about/aboutgreenroofs. (Accesse 02/02/2013).

Green roofs for healthy cities. 2013b. "Green roofs for healthy cities." http://www.greenroofs.org/index.php/about/aboutgreenroofs. (Accesse 02/02/2013).

Gregoire, Bruce G., and John C. Clausen. 2011. "Effect of a Modular Extensive Green Roof on Stormwater Runoff and Water Quality." *Ecological Engineering* 37 (6): 963–969.

Haimes, Y. 1992. "Sustainable Development: A Holistic Approach to Natural Resource Management." *IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS,* 22 (3): 413–417.

Harwell, M., C. Harwell, and J. Kelly. 1986. "Regulatory Endpoints, Ecological Uncertainties, and Environmental Decision-Making." In *OCEANS '86*, 993–998. IEEE. doi:10.1109/OCEANS.1986.1160433.

Health Canada. 2010. "Canadian guidelines for domestic reclaimed water." http://www.hc-sc.gc.ca/ewh-semt/alt_formats/hecs-sesc/pdf/pubs/water-eau/reclaimed_water-eaux_recyclees/reclaimed_water-eaux_recyclees-eng.pdf. (Accessed 07/06/2012).

Hobbs, B. F., & Horn, G. T. 1997. "Building public confidence in energy planning: a multimethod MCDM approach to demand-side planning at BC gas." *Energy Policy* 25 (3): 357–375.

IPCC. 2007. "IPCC fourth assessment report: climate change 2007." http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10.html. (Accessed 10/10/2013).

ISO. 2006. "14044: 2006. Environmental management-life cycle assessment-requirements and guidelines." http://www.iso.org/iso/catalogue_detail?csnumber=38498. (Accessed 10/10/2012).

Jaber, J. O., & Mohsen, M. S. 2001. "Evaluation of Non-Conventional Water Resources Supply in Jordan." *Desalination* 136 (1): 83–92.

Jaffal, I., Ouldboukhitine, S., & Belarbi, R. 2012. "A comprehensive study of the impact of green roofs on building energy performance." *Renewable Energy* 43: 157–164.

Jolliet, O. et al. 2003. "IMPACT 2002+: a new life cycle impact assessment methodology." *The International Journal of Life Cycle Assessment* 8 (6): 324–330. doi:10.1007/BF02978505.

Kahraman, C., Cebeci, U., & Ulukan, Z. 2003. "Multi-criteria supplier selection using fuzzy AHP." *Logistics Information Management* 16 (6): 382–394. doi:10.1108/09576050310503367.

Kang, Y, & Li, J. 2010. "Green rationality evaluation of degradable packaging based on lca and fuzzy AHP." In *2010 IEEE 17Th International Conference on Industrial Engineering and Engineering Management*, 329–332. IEEE. doi:10.1109/ICIEEM.2010.5646599.

Kellenberger, D., & Althaus, H.J. 2009. "Relevance of simplifications in lca of building components." *Building and Environment* 44 (4): 818–825.

Kholghi, M. 2001. "Multi-Criterion Decision-Making Tools for Wastewater Planning Management" 3: 281–286.

lock, R., & Mullock, J. 2001. "The weather of british columbia." http://www.navcanada.ca/EN/media/Publications/Local Area Weather Manuals/LAWM-BC-EN.pdf. (Accessed 14/11/2013).

Klöpffer, Walter. 2005. "The Role of SETAC in the Development of LCA." *The International Journal of Life Cycle Assessment* 11 (S1) (December 6): 116–122. doi:10.1065/lca2006.04.019.

Köhler, M., & Schmidt, M. 2003. "Study of extensive 'green roofs' in Berlin. (S. Cacanindin, Trans.). Roofscapes, Inc.: Water Quality Benefits." Berlin. http://www.roofmeadow.com/water_quality.htm. (Accessed 15/08/2012).

Kohler, M., M. Schmidt, F. Grimme, M. Laar, and F. Gusmao. 2001. "Urban Water Retention by Greened Roofs in Temperate and Tropical Climate." In *The 38th IFLA World Congress*. Singapore.

Kosareo, Lisa, and Robert Ries. 2007. "Comparative Environmental Life Cycle Assessment of Green Roofs." *Building and Environment* 42 (7): 2606–2613.

Kruijf, J. de. 2007. "Problem Structuring in Interactive Decision-Making Processes : How Interaction, Problem Perceptions and Knowledge Contribute to a Joint Formulation of a Problem and Solutions." http://essay.utwente.nl/524/1/scriptie_de_Kruijf.pdf.

Lee, Ju Young, Jung-Seok Yang, Mooyoung Han, and Jaeyoung Choi. 2010. "Comparison of the Microbiological and Chemical Characterization of Harvested Rainwater and Reservoir Water as Alternative Water Resources." *The Science of the Total Environment* 408 (4) (January 15): 896–905. doi:10.1016/j.scitotenv.2009.11.001. http://www.ncbi.nlm.nih.gov/pubmed/19962177.

Lerario, A., and N Maiellaro. 2001. "Support Measures for Sustainable Building. Towards Sustainable Building." In *Towards Sustainable Building*, edited by N Maiellaro, 171–200. Kluwer Academic Publishers.

Levett, R. 1998. "Sustainability Indicators-Integrating Quality of Life and Environmental Protection." *Journal of the Royal Statistical Society: Series A (Statistics in Society)* 161 (3) (October): 291–302. doi:10.1111/1467-985X.00109. http://doi.wiley.com/10.1111/1467-985X.00109.

Lindholm, Oddvar, James M. Greatorex, and Adam M. Paruch. 2007. “Comparison of Methods for Calculation of Sustainability Indices for Alternative Sewerage systems—Theoretical and Practical Considerations.” *Ecological Indicators* 7 (1): 71–78. http://www.sciencedirect.com/science/article/pii/S1470160X05001111.

Liu, K., & Baskaran, B. 2003. “Thermal performance of green roofs through field evaluation.” In *First North American Green Roof Infrastructure Conference, Awards and Trade Show,*, 1–10. Chicago. http://archive.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc46412/nrcc46412.pdf. (Accessed 03/05/2012).

Lloyd, Shannon M., and Robert Ries. 2008. “Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches.” *Journal of Industrial Ecology* 11 (1) (October 9): 161–179. doi:10.1162/jiec.2007.1136. http://doi.wiley.com/10.1162/jiec.2007.1136.

Long, Brett, Shirley E. Clark, Katherine H. Baker, and Robert Berghage. 2006. “Green Roof Media Selection for the Minimization of Pollutant Loadings in Roof Runoff.” *Weftec*: 5528–5548.

McHarg, Ian L. 1995. *Design with Nature (Wiley Series in Sustainable Design)*. Wiley. http://www.amazon.com/Design-Nature-Wiley-Series-Sustainable/dp/047111460X.

Medineckiene, Milena, Zenonas Turskis, and Edmundas Kazimieras Zavadskas. 2010. “Sustainable Construction Taking into Account the Building Impact on the Environment.” *Journal of Environmental Engineering and Landscape Management* 18 (2) (June): 118–127. doi:10.3846/jeelm.2010.14.

Mendez, Carolina B., J. Brandon Klenzendorf, Brigit R. Afshar, Mark T. Simmons, Michael E. Barrett, Kerry A. Kinney, and Mary Jo Kirisits. 2011. “The Effect of Roofing Material on the Quality of Harvested Rainwater.” *Water Research* 45 (5): 2049–2059.

Mofarrah, Abdullah, Tahir Husain, and Kelly Hawboldt. 2013. “Decision Making for Produced Water Management: An Integrated Multi-Criteria Approach.” *International Journal of Environmental Technology and Management (IJETM)* 16 (1/2).

Montgomery, Douglas C. 2008. *Design and Analysis of Experiments*. John Wiley & Sons, Inc.

Moran, A., Hunt, B., & Jennings, G. 2004. “A north carolina field study to evaluate green roof runoff quantity, runoff quality, and plant growth.” http://www.bae.ncsu.edu/greenroofs/GRHC2004paper.pdf. (Accessed 07/05/2012).

Muga, Helen E., and James R. Mihelcic. 2008. “Sustainability of Wastewater Treatment Technologies.” *Journal of Environmental Management* 88 (3): 437–447.

Nelms, Cheryl E., Alan D. Russell, and Barbara J. Lence. 2007. “Assessing the Performance of Sustainable Technologies: A Framework and Its Application.” *Building Research & Information* 35 (3) (May): 237–251. doi:10.1080/09613210601058139.

Newsham, G.R., S. Mancini, and B. Birt. 2009. “Do LEED-Certified Buildings Save Energy? Yes, But...” *Energy and Buildings* 41 (8): 897–905.

Nkwonta, Onyeka, and George Ochieng. 2009. “Roughing Filter for Water Pre-Treatment Technology in Developing Countries: A Review.” *International Journal of Physical Sciences* 4 (9): 455–463.

OECD. 2001. “OECD environmental indicators towards sustainable development”. Paris, France. http://www.oecd.org/site/worldforum/33703867.pdf. (Accessed 16/09/2012).

Oke, TR. 1995. “The heat island of the urban boundary layer: characteristics, causes and effects.” http://www.citeulike.org/group/15109/article/9351714. (Accessed 03/02/2013).

Onmura, S, M Matsumoto, and S Hokoi. 2001. “Study on Evaporative Cooling Effect of Roof Lawn Gardens.” *Energy and Buildings* 33 (7): 653–666.

Osmundson, Theodore H. 1999. *Roof Gardens: History, Design, and Construction*. Ney York: W. W. Norton & Company.

Ostendorf, Bertram, Maria Luisa Paracchini, Cesare Pacini, M. Laurence M. Jones, and Marta Pérez-Soba. 2011. “An Aggregation Framework to Link Indicators Associated with Multifunctional Land Use to the Stakeholder Evaluation of Policy Options.” *Ecological Indicators* 11 (1): 71–80.

Palme, Ulrika, Margareta Lundin, Anne-Marie Tillman, and Sverker Molander. 2005. “Sustainable Development Indicators for Wastewater Systems – Researchers and Indicator Users in a Co-Operative Case Study.” *Resources, Conservation and Recycling* 43 (3): 293–311.

Peck, S., & Kuhn, M. 2001. “Design guidelines for green roof. Ontario association of architects.” http://www.cmhc.ca/en/inpr/bude/himu/coedar/loader.cfm?url=/commonspot/security/getfile.cfm&PageID=70146. (Accessed 02/04/2012).

Peri, Giorgia, Marzia Traverso, Matthias Finkbeiner, and Gianfranco Rizzo. 2012. “Embedding ‘substrate’ in Environmental Assessment of Green Roofs Life Cycle: Evidences from an Application to the Whole Chain in a Mediterranean Site.” *Journal of Cleaner Production* 35: 274–287.

Peuportier, B.L.P. 2001. “Life Cycle Assessment Applied to the Comparative Evaluation of Single Family Houses in the French Context.” *Energy and Buildings* 33 (5): 443–450.

Pilavachi, Petros A., Stilianos D. Stephanidis, Vasilios A. Pappas, and Naim H. Afgan. 2009. “Multi-Criteria Evaluation of Hydrogen and Natural Gas Fuelled Power Plant Technologies.” *Applied Thermal Engineering* 29 (11): 2228–2234.

Pompeii, W. C. 2010. “Assessing urban heat island mitigation using green roofs: a hardware scale modeling approach”. Shippensburg University. http://www.ship.edu/uploadedFiles/Ship/Geo-ESS/Graduate/Theses/pompeii_thesis_100419.pdf. (Accessed 24/02/2013).

Poulenard, Jérôme, Pascal Podwojewski, Jean-Louis Janeau, and Jean Collinet. 2001. “Runoff and Soil Erosion under Rainfall Simulation of Andisols from the Ecuadorian Páramo: Effect of Tillage and Burning.” *CATENA* 45 (3) (September): 185–207. doi:10.1016/S0341-8162(01)00148-5.

Rajendran, Sathyanarayanan, John A. Gambatese, and Michael G. Behm. 2009. “Impact of Green Building Design and Construction on Worker Safety and Health.” *Journal of Construction Engineering and Management* 135 (10): 1058–1066.

RCABC. 2011. “Consumer Guide to Roofing a Guide for the Selection of Roofing Services.”

Rebitzer, G., T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W.-P. Schmidt, S. Suh, B.P. Weidema, and D.W. Pennington. 2004. “Life Cycle Assessment.” *Environment International* 30 (5): 701–720. http://www.sciencedirect.com/science/article/pii/S0160412003002459.

Reza, Bahareh. 2013. “Emergy-Based Life Cycle Assessment (em-Lca) for Sustainability Appraisal of Built Environment.” University of British Columbia.

Reza, Bahareh, Rehan Sadiq, and Kasun Hewage. 2011. “Sustainability Assessment of Flooring Systems in the City of Tehran: An AHP-Based Life Cycle Analysis.” *Construction and Building Materials* 25 (4): 2053–2066. http://www.sciencedirect.com/science/article/pii/S0950061810005714.

Robertson, G.P., and J.M. tiedje. 1987. “Nitrous Oxide Sources in Aerobic Soils: Nitrification, Denitrification and Other Biological Processes.” *Soil Biology and Biochemistry* 19 (2) (January): 187–193. doi:10.1016/0038-0717(87)90080-0. http://www.sciencedirect.com/science/article/pii/0038071787900800.

Rosén, N. 2009. “Evaluation methods for procurement of business critical software systems”. Institutionen för kommunikation och information. http://www.diva-portal.org/smash/get/diva2:222953/FULLTEXT01.pdf. (Accessed 04/07/2012).

Rosenfeld, Arthur H., Hashem Akbari, Joseph J. Romm, and Melvin Pomerantz. 1998. “Cool Communities: Strategies for Heat Island Mitigation and Smog Reduction.” *Energy and Buildings* 28 (1): 51–62.

Rosenzweig, C., G. Stuart, and P Lily. 2006. “Green Roofs in the New York Metropolitan Region”. New York.

Rowe, D. Bradley. 2011. “Green Roofs as a Means of Pollution Abatement.” *Environmental Pollution* 159 (8): 2100–2110. http://www.sciencedirect.com/science/article/pii/S0269749110004859.

Ryan B. et al. 2008. “USEPA 2008. Reducing Urban Heat Islands: Compendium of Strategies.”

Saaty, TL. 1980. *The Analytic Hierarchy Process*. New York: McGraw-Hill.

Saiz, Susana, Christopher Kennedy, Brad Bass, and Kim Pressnail. 2006. “Comparative Life Cycle Assessment of Standard and Green Roofs.” *Environmental Science and Technology* 40 (13): 4312–4316. doi:DOI: 10.1021/es0517522.

Santamouris, M., C. Pavlou, P. Doukas, G. Mihalakakou, A. Synnefa, A. Hatzibiros, and P. Patargias. 2007. “Investigating and Analysing the Energy and Environmental Performance of an Experimental Green Roof System Installed in a Nursery School Building in Athens, Greece.” *Energy* 32 (9): 1781–1788.

Sarkis, Joseph, and Srinivas Talluri. 2002. “A Model for Strategic Supplier Selection.” *The Journal of Supply Chain Management* 38 (1) (December): 18–28. doi:10.1111/j.1745-493X.2002.tb00117.x.

Schilling, J. 2010. “Towards a greener green space planning.” http://www.lumes.lu.se/database/alumni/08.10/thesis/schilling_jasper_thesis_2010.pdf. (Accessed 08/07/2013).

Shaviv, Avi. 2001. “Advances in Controlled-Release Fertilizers.” *Advances in Agronomy* 71: 1–49.

Shepherd, M.F., S. Barzetti, and D.R. Hastie. 1991. “The Production of Atmospheric NOx and N2O from a Fertilized Agricultural Soil.” *Atmospheric Environment* 25a (9): 1961–1969.

Sonne, J. K. 2006. “Energy performance aspects of a florida green roof.” In *Fifteenth Symposium on Improving Building Systems in Hot and Humid Climates*. Orlando. http://www.fsec.ucf.edu/en/publications/html/FSEC-PF-412-06/. (Accessed 03/05/2012).

Steen, Bengt. 1997. “On Uncertainty and Sensitivity of LCA-Based Priority Setting.” *Journal of Cleaner Production* 5 (4): 255–262.

Suslow, T.V. 2007. “Oxidation-Reduction Potential (ORP) for Water Disinfection Monitoring, Control, and Documentation.” *ANR Publication*. Davis. http://anrcatalog.ucdavis.edu/pdf/8149.pdf.

Sutton, R. K. et al. 2012. “Prairie-based green roofs: literature, templates, and analogs.” *Journal of Green Building* 7 (1) (January 16): 143–172. doi:10.3992/jgb.7.1.143.

Taylor, Brian. L. 2008. “The Stormwater Control Potential of Green Roofs in Seattle.” In *International Low Impact Development Conference*. Seattle.

Teemusk, Alar, and Ülo Mander. 2007. “Rainwater Runoff Quantity and Quality Performance from a Greenroof: The Effects of Short-Term Events.” *Ecological Engineering* 30 (3): 271–277. http://www.sciencedirect.com/science/article/pii/S0925857407000134.

Tesfamariam, S., & Sadiq, R. 2006. “Risk-based environmental decision-making using fuzzy analytic hierarchy process (F-AHP).” *Stochastic Environmental Residents Risk Assessment* 21: 35–50. doi:10.1007/s00477-006-0042-9.

The Weather Network. 2013. “Kelowna precipitation statistics.” http://www.theweathernetwork.com/forecasts/statistics/precipitation/cl11239r0. (Accessed 22/09/2013).

Tupenaite et al. 2010. “Multiple criteria assessment of alternatives for built and human environment renovation.” *Journal of Civil Engineering and Management* 16 (2): 257–266. doi:10.3846/jcem.2010.30.

UNDPCSD. 1995. “Work programme on indicators for sustainable development.” UNI EN 832.

USEPA. 1999. “Storm water technology fact sheet sand filters.” http://water.epa.gov/scitech/wastetech/upload/2002_06_28_mtb_sandfltr.pdf.

USEPA. 2004. “Guidelines for water reuse. Washington, D.C. EPA/625/R-04/108”. Washington. http://water.epa.gov/aboutow/owm/upload/Water-Reuse-Guidelines-625r04108.pdf.

USEPA. 2007. “Methods for analyses and properties. Chapter 3.”

USEPA. 2009a. “National water quality inventory: 2004 Report. EPA-841-R-08-001.”

USEPA. 2009b. “Green roofs for stormwater runoff control.” www.epa.gov/ord.

Vijayaraghavan, K, U M Joshi, and R Balasubramanian. 2012. “A Field Study to Evaluate Runoff Quality from Green Roofs.” *Water Research* 46 (4) (March 15): 1337–45. doi:10.1016/j.watres.2011.12.050.

Waheed, Bushra, Faisal Khan, and Brian Veitch. 2009. “Linkage-Based Frameworks for Sustainability Assessment: Making a Case for Driving Force-Pressure-State-Exposure-Effect-Action (DPSEEA) Frameworks.” *Sustainability* 1 (3) (August 10): 441–463. doi:10.3390/su1030441.

Wang, Jiang-Jiang, You-Yin Jing, Chun-Fa Zhang, and Jun-Hong Zhao. 2009. “Review on Multi-Criteria Decision Analysis Aid in Sustainable Energy Decision-Making.” *Renewable and Sustainable Energy Reviews* 13 (9): 2263–2278.

Wang, Ranran, Matthew J. Eckelman, and Julie B. Zimmerman. 2013. “Consequential Environmental and Economic Life Cycle Assessment of Green and Gray Stormwater Infrastructures for Combined Sewer Systems.” *Environmnetal Science and Technology* 47: 11189–11198. doi:dx.doi.org/10.1021/es4026547.

Wedding, G. Christopher, and Douglas Crawford-Brown. 2007. “Measuring Site-Level Success in Brownfield Redevelopments: A Focus on Sustainability and Green Building.” *Journal of Environmental Management* 85 (2): 483–495.

Xeroflor America. 2013. “Xeroflor America.” http://www.xeroflora.com/specs-tech/technical-documents. (Accessed 05/08/2012).

Yaziz, M.I., H. Gunting, N. Sapari, and A.W. Ghazali. 1989. “Variations in Rainwater Quality from Roof Catchments.” *Water Research* 23 (6): 761–765. http://www.sciencedirect.com/science/article/pii/004313548990211X.

Yok, T.P., and A Sia. 2005. “A Pilot Green Roof Research Project in Singapore.” In *Green Roofs for Healthy Sustainable Cities Conference*. Washington.

Yoon, So Won, and Dong Kun Lee. 2003. “The Development of the Evaluation Model of Climate Changes and Air Pollution for Sustainability of Cities in Korea.” *Landscape and Urban Planning* 63 (3): 145–160.

Zadeh, L.A. 1965. “Fuzzy Sets.” *Information and Control* 8 (3): 338–353.

Zaman, M., M.L. Nguyen, J.D. Blennerhassett, and B.F. Quin. 2008. “Reducing NH3, N2O and NO3-N Losses from a Pasture Soil with Urease or Nitrification Inhibitors and Elemental S-Amended Nitrogenous Fertilizers.” *Biology and Fertility of Soils* 44: 693–705.

Zheng, Guozhong, Youyin Jing, Hongxia Huang, and Yuefen Gao. 2011. “Applying LCA and Fuzzy AHP to Evaluate Building Energy Conservation.” *Civil Engineering and Environmental Systems* 28 (2) (June): 123–141. doi:10.1080/10286608.2010.482655.

Zhu, Ke-Jun, Yu Jing, and Da-Yong Chang. 1999. “A Discussion on Extent Analysis Method and Applications of Fuzzy AHP.” *European Journal of Operational Research* 116 (2): 450–456.

Zimmerman, M.J., Waldron, M.C., Barbaro, J.R., & Sorenson, J.R. 2010. “Effects of low-impact-development (LID) practices on streamflow, runoff quantity, and runoff quality in the Ipswich River Basin, Massachusetts: a summary of field and modeling studies.” U.S. Department of the Interior and U.S. Geological Survey.

Appendices

Appendix A: Impact Category Description

IMPACT 2002+ method considers nine impact categories:

- Carcinogens
- Respiratory Inorganics
- Respiratory Organics
- Ozone Layer Depletion
- Land Occupation
- Aquatic Acidification
- Aquatic Eutrophication
- Global Warming Potential
- Non-Renewable Energy Consumption

These impacts are explained as follows:

Carcinogens (kg C_2H_3Cl eq)

Carcinogenic materials are materials that may cause adverse health effects on the human body. Carcinogenic materials are emitted during different chemical activities. Complex production processes may produce higher amounts of known carcinogenic materials. Carcinogenic materials are calculated based on the kg C_2H_3Cl equivalent.

Respiratory Inorganics (kg $P.M_{2.5}$ eq)

Respiratory inorganics have an adverse impact on human health. These materials may cause or amplify human respiratory diseases (e.g. asthma, bronchitis, acute pulmonary disease, etc.). Respiratory Inorganics are calculated based on the kg $P.M_{2.5}$ equivalent.

Respiratory Organics (kg C_2H_4 eq)

Respiratory organics have an adverse impact on human health. Respiratory organics are calculated based on the kg C_2H_4 equivalent.

Ozone Layer Depletion (kg CFC-11 eq)

Emission of ozone depleting substances causes the protective effect of the ozone layer within the stratosphere to diminish, which is called ozone layer depletion. CFCs, HFCs, and halons are ozone depleting substances. The ozone depletion potential is indicated based on kg of equivalent CFC-11.

Aquatic Acidification (kg SO_2 eq)

Aquatic acidification is a regional impact that influences human health. High concentrations of NO_x and SO_2 cause adverse human health issues. Aquatic acidification is calculated based on the kg SO_2 equivalent.

Aquatic Eutrophication (kg PO_4P-lim)

Aquatic eutrophication is a result of adding limited or rare nutrients to a water body. Due to the additional nutrients, aquatic plants grow rapidly and may consume the soluble oxygen. Aquatic eutrophication causes various environmental impacts ranging from odors to the death of fish. Aquatic eutrophication is calculated based on the equivalent kg PO_4P-lim.

Global Warming Potential (kg CO_2 eq)

Global warming potential (GWP) is a reference measure for expressing the global warming potential of an activity in CO_2 equivalent.

In this category, carbon dioxide is the reference standard for GWP and all other greenhouse gases (GHGs) are referred to as having a "CO_2 equivalence effect". Since the reactivity or stability of gases may change over time, GWP has a time horizon. Since GHG emissions are mostly by products of a combustion function, some materials emit GHGs during the processing of a raw material.

Non-Renewable Energy Consumption

Non-renewable energy consumption is an important indicator for environmental impacts. As non-renewable energy production takes millions of years, the consumption of these sources of energy should be controlled and managed. Processing raw materials consumes a large amount of non-renewable energy. In contrast, additional insulation saves energy for heating and cooling the building, which may reduce the non-renewable energy consumption.

Appendix B: Xero flor XF301 Vegetated mat green roof system specifications (Xeroflor America 2013)

Part I – General

1.1 Summary

It is intended as a guideline for materials function and assembly instruction. The green roof materials assembly is subject to modification as needed for each specific project.

1.2 Definitions

A. Root Barrier: A flexible, synthetic polymer layer installed below the green roof system that serves as protection against root encroachment into underlying roof components.

B. Drainage Mat: A composite geotextile that creates a free flowing space below the vegetated and retention fleece layers to permit unrestricted movement of excess water to roof drains.

C. Retention Fleece: A non-woven fabric layer to serve as filter fabric against particle erosion and to retain supplemental water for root uptake and plant use. A lightweight fleece is part of the pre-cultivated XF301 vegetation mat (see definition below). One or two additional fleece layer(s) may be used in the green roof system assembly for enhanced water holding capacity.

D. Pre-cultivated Vegetation Mat: An integrated unit of plant material, growing medium, and natural fiber or geotextile carrier. Pre-cultivated mats are harvested fully vegetated from the production field and delivered to the installation site as flat or rolled sheets.

E. Growing Medium: A low-organic / high-mineral composition growing mix composed of composted organic matter and lightweight porous aggregate.

1.3 Deliveries, Storage, and Handling of Material

Xero Flor plant materials shall be delivered in such a manner to preserve the quality of the plants. Truck delivery must protect the vegetation mats from temperature or wind damage during transport, such as use of plant-compatible tarp covers. Closed or open trailers may be used for transport times less than one day. For longer duration transport times, vegetation mats must be delivered in a climate controlled trailer. Upon arrival, the mats shall be immediately off-loaded, plastic wrap removed (if used), and installed within twelve hours. If timely installation is not achievable, then a holding area shall be reserved to unroll and store the mats until installation.

1.4 Vegetation Coverage Guarantee

A. Xero Flor mats shall be delivered with a minimum of 80% vegetation coverage at the time of installation and achieve a minimum of 90% coverage after the second full growing season.

PART II - PRODUCTS

2.1 XF112 Root Barrier

A. A flexible polymer sheet installed on top of the roof membrane and below the other green roof components. The standard Xero Flor XF112 root barrier is a water-impermeable sheet of 20mil low density polyethylene (LDPE), though may be increased to 30mil (XF113) or 40mil (XF114) thickness as specified by the membrane supplier and/or project designer.

2.2 XF108H Drain Mat

A layer of flexible, non-woven, entangled polymeric filaments with a perforated, geotextile filter-fabric bonded to one side.

2.3 XF157 Water-Retention Fleece

A fabric produced from a blend of recycled, synthetic fibers with a saturated weight of not more than 1.5 psf.

2.4 XF301 Pre-cultivated Vegetation Mat

XF301 is a textile-based vegetation carrier of lightweight fleece sown to PA/PP entanglements bonded to geotextile fabric filled with a thin-layer of growing medium and pre-cultivated with an even layer of low-profile, drought-tolerant vegetation. Mat thickness 1 1/4”, field weight 5.5 psf, saturated weight 8.5 psf.

2.5 XeroTerr Growing Medium

A proprietary mixture of lightweight, mineral based materials; including porous aggregate and organic matter derived from composted plant materials, biosolids, and/or manure compost.

2.6 Hose Bib / Water Supply

A. A spigot source or other means of supplying water to the roof with sufficient pressure is required. Irrigation must be applied during the plant recovery phase, e.g. first 1-2 weeks, after installation. In order to support mature establishment of the vegetated community, it is highly recommended that periodic irrigation be applied during the hottest months of the 1st and possibly 2nd growing seasons after installation. The method of supplying irrigation may vary with regard to removable or permanent piping, rotary heads, drip irrigation, or other approved irrigation technologies.

PART III - EXECUTION

3.1 General

All green roof system components, including irrigation if specified, are to be installed by certified contractors with demonstrated experience and project references. The various layers shall be installed in such a manner as to not damage or disturb any previously installed roofing components. Installing the system in any manner inconsistent with manufacturer guidelines voids all guarantees and warranties.

Appendix C: Sampling and analysis of waters, wastewaters, soils and wastes

Selection and preparing water samples, and test procedures should comply with this appendix based on the USEPA sampling guide AS/NZS 5667.1:1998, USEPA SW846[8]. The recommended volumes are for a single sample and volume of sampling may varied based on the analytical method. All containers should be clean and free from relevant contamination.

Table C.1: USEPA sampling process

Analytical parameter	Container	Typical volume (mL)	Sampling and transport	Preservation	Maximum holding time	Storage
Ammonia	Polyethylene, PTFE or glass	**500**	Transport under ice	Filter sample on site (0.45 µm cellulose acetate membrane filter). Acidify with sulfuric acid to pH < 2, or freeze upon receipt by laboratory	Analyse within 24 hours Up to 28 days acceptable	Refrigerate (< 6°C) Refrigerate (< 6°C) if acidifying, otherwise freeze (- 20 ºC)
Colour	Polyethylene, PTFE or glass	**500**	Transport under ice, in dark		48 hours	Refrigerate (< 6°C) in dark.
Electrical Conductivity	Polyethylene or glass	**500**	Fill container completely to exclude air. Transport under ice		24 hours 28 days if refrigerated	Refrigerate (< 6°C)

[8] www.epa.gov/epawaste/hazard/testmethods/sw846/online/index.htm#table

Table C.1: USEPA sampling process (continue)

Nitrate (NO^{3-})	Polyethylene, PTFE or glass	500	Transport under ice Filter on site (0.45 µm cellulose acetate membrane filter) and freeze sample immediately upon collection.	Acidify with HCl to pH <2	48 hours without Acidification 7 days with acidification 28 days if frozen	Refrigerate (< 6°C) Freeze (-20 oC)
Oxygen, dissolved (DO)	Glass BOD bottle with top	300	Exclude air from bottle and seal.		Analyse immediately on site (in situ)	
pH	Polyethylene, PTFE or borosilicate glass	**100**	Fill bottle to exclude air. Transport under ice		Determine *in situ* if possible, or upon arrival to laboratory.	Analyse immediately
Turbidity	Polyethylene, PTFE or glass	**100**	Transport under ice, in dark		Up to 48 hours	Refrigerate (< 6°C) in dark.

Appendix D: The experiments' results

Table D.1: GR1sample results

GR 1						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.29	2.52	37.8	243.3	0.0173	450
10/15/2012	7.05	6.6	48.7	253	0.0156	380
10/23/2012	7.8	4.27	121	232.5	0.0179	479
10/27/2012	7.53	5.52	1.93	228	0.0143	460
10/29/2012	7.63	5.74	28.8	245.6	0.0148	510
10/31/2012	7.5	2.03	1.26	233.9	0.0152	486
11/3/2012	7.31	0.83	0.69	237.8	0.0165	396
11/6/2012	7.22	0.44	3.24	359	0.0167	427
11/12/2012	7.34	1.34	2.96	332.2	0.0179	490
11/17/2012	7.45	0.89	1.49	310.1	0.0134	534

Table D.2: GR2 sample results

GR 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.15	1.78	10.5	254	0.0148	390
10/15/2012	7.31	1.44	5.59	362	0.0164	410
10/23/2012	7.6	32.3	89	234	0.0146	375
10/27/2012	7.49	11.9	1.79	217	0.0169	359
10/29/2012	7.54	8.3	15	241	0.0187	510
10/31/2012	7.44	1.62	3.24	244.2	0.0261	428
11/3/2012	7.31	0.83	0.8	236.4	7.88E-03	476
11/6/2012	7.24	0.52	4.7	340.3	9.80E-03	390
11/12/2012	7.37	1.46	1.39	320	0.0145	452
11/17/2012	7.29	1.01	2.1	328.4	0.0112	415

Table D.3: GR+CF1 sample results

GR + CF 1						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.21	2.56	17.3	232.4	0.0165	450
10/15/2012	7.27	1.85	5.58	276.5	0.0156	438
10/23/2012	7.45	4.53	112	224.3	0.0143	520
10/27/2012	7.51	15.6	24.4	212.3	0.0165	497
10/29/2012	7.79	9.76	20	219.2	0.0154	416
10/31/2012	6.6	2.28	5.32	269.9	0.0123	529
11/3/2012	6.67	0.92	3.9	262.3	0.011	480
11/6/2012	6.98	0.76	2.4	266.4	0.0121	420
11/12/2012	7.01	1.56	4.2	298.3	0.0149	478
11/17/2012	6.98	1.21	3.82	267.6	0.0156	450

Table D.4: GR+CF2 sample results

GR + CF 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.1	2.67	9.01	213.4	0.0179	437
10/15/2012	7.26	1.67	9.51	232.3	0.0145	457
10/23/2012	7.39	4.65	76.3	243	0.0139	429
10/27/2012	7.59	4.05	3.37	224.5	0.0156	490
10/29/2012	7.93	2.27	1.43	225.1	0.054	426
10/31/2012	7.16	2.41	3.16	287.2	0.0126	480
11/3/2012	7.07	0.72	2.06	253.5	0.0189	435
11/6/2012	7.08	2.03	4.5	262.4	0.0179	410
11/12/2012	7.12	3.2	2.54	295.4	0.0138	510
11/17/2012	7.39	4.1	3.2	289.3	0.0167	446

Table D.5: GR+T1 sample results

GR + T 1						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.03	1.48	13.2	232.3	0.0168	460
10/15/2012	7.14	1.83	6.94	223.3	0.0178	426
10/23/2012	7.43	4.12	35	254.3	0.0145	392
10/27/2012	7.32	3.59	3.45	231.6	0.0137	436
10/29/2012	7.21	11.9	32.3	255.4	0.0167	479
10/31/2012	7.12	5.43	1.66	289.7	0.0173	569
11/3/2012	7.07	1.21	0.88	234.8	0.0792	460
11/6/2012	6.97	1.55	3.2	308.5	0.0254	425
11/12/2012	7.01	2.45	1.4	278.2	0.0198	451
11/17/2012	7.29	3.21	2.15	276.9	0.0187	406

Table D.6: GR+T2 sample results

GR + T 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.11	2.45	9.66	245.3	0.0234	435
10/15/2012	7.17	2.24	1.65	217.3	0.0198	417
10/23/2012	7.35	2.32	18.3	229.4	0.0189	437
10/27/2012	7.37	2.28	2.09	225.4	0.0201	459
10/29/2012	7.48	2.86	0.95	231.2	0.0167	524
10/31/2012	6.99	3.94	3.77	235.6	0.117	478
11/3/2012	6.61	0.79	0.88	339.4	0.0384	453
11/6/2012	7.09	0.91	2.3	322.3	0.0287	397
11/12/2012	7.03	2.17	1.45	265.7	0.0211	417
11/17/2012	7.11	3.35	3.2	267.3	0.0196	436

Table D.7: GR+WB1 sample results

GR + WB 1						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.11	3.35	360	243.2	0.0187	401
10/15/2012	7.28	2.29	421	254.3	0.0165	453
10/23/2012	6.73	3.47	122	234.2	0.0134	426
10/27/2012	7.04	5.44	18	256.3	0.0156	478
10/29/2012	7.08	7.78	234	249.3	0.0143	423
10/31/2012	7.32	2.47	1.46	261.8	0.0138	491
11/3/2012	7.29	0.46	0.86	361.8	9.73E-03	423
11/6/2012	7.28	0.55	3.4	339.3	0.0112	486
11/12/2012	7.39	2.23	2.25	301.2	0.0132	418
11/17/2012	7.27	3.2	1.76	256.4	0.0123	469

Table D.8: GR+WB2 results

GR + WB 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	6.98	4.13	597	234.4	0.0237	432
10/15/2012	6.89	6.27	553	267.3	0.0176	478
10/23/2012	6.96	5.43	321	287.3	0.0167	457
10/27/2012	6.89	7.86	18.9	256.4	0.0145	510
10/29/2012	7.03	10.3	46.1	277	0.0198	453
10/31/2012	7.41	2.15	1.4	260.9	0.0219	428
11/3/2012	7.26	0.48	0.78	360.2	0.0432	392
11/6/2012	7.13	0.57	1.32	307.9	0.0324	459
11/12/2012	7.11	1.98	2.21	289.3	0.0201	481
11/17/2012	7.21	2.34	1.03	267.4	0.0176	415

Table D.9: EPDM1 results

EPDM 1						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	6.78	1.92	17.6	278.6	0.145	32
10/15/2012	7.09	1.69	7.57	287.4	0.198	46
10/23/2012	7.21	1.67	78.3	289.4	0.154	51
10/27/2012	7.28	2.86	3.38	298.4	0.143	35
10/29/2012	6.89	5.97	29.4	296.6	0.121	21
10/31/2012	7.44	2.07	0.99	276.6	0.101	38
11/3/2012	7.54	0.71	0.55	335	0.171	49
11/6/2012	7.32	0.6	3.23	341.9	0.165	42
11/12/2012	7.22	1.24	2.45	321.3	0.154	38
11/17/2012	7.24	1.45	7.56	345.3	0.176	41

Table D.10: EPDM2 results

EPDM 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	6.4	9.59	21.6	276.4	0.176	27
10/15/2012	7.08	1.4	5.91	289.4	0.189	51
10/23/2012	6.68	5.43	8.68	269.3	0.252	39
10/27/2012	6.68	5.43	8.68	298.3	0.179	37
10/29/2012	6.88	7.91	57.9	289.1	0.156	61
10/31/2012	7.24	2.79	10.2	256.1	0.196	31
11/3/2012	7.25	0.6	1.7	443.7	0.48	27
11/6/2012	7.16	0.59	3.45	390.4	0.346	29
11/12/2012	7.23	2.11	2.45	387.7	0.265	24
11/17/2012	7.11	2.32	3.24	339.7	0.238	35

Table D.11: GR+TSG1 results

GR + TSG 1						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	6.81	5.52	624	237.4	0.0256	410
10/15/2012	6.87	1.53	413	223.8	0.0239	398
10/23/2012	6.91	2.18	210	235.3	0.0231	453
10/27/2012	6.96	8.78	40.5	264.9	0.0256	476
10/29/2012	7.23	17.2	407	279.1	0.0245	481
10/31/2012	7.28	11.8	12.6	207.3	0.0251	497
11/3/2012	7.41	5.09	1.17	305.8	0.0219	512
11/6/2012	6.99	4.61	5.43	319.9	0.0189	462
11/12/2012	7.12	3.45	3.46	276.4	0.0216	431
11/17/2012	7.18	8.45	8.49	259.4	0.0179	478

Table D.12: GR+TSG2 results

GR + TSG 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	6.86	5.88	536	275.4	0.0823	436
10/15/2012	6.89	2.64	748	267.3	0.0694	474
10/23/2012	6.98	3.45	456	287.3	0.0498	483
10/27/2012	7.36	3.47	353	298.3	0.0985	513
10/29/2012	7.81	2.68	924	269.2	0.0768	451
10/31/2012	6.96	8.08	19.6	350.1	0.0996	438
11/3/2012	7.25	2.67	0.87	313.2	0.0808	419
11/6/2012	7.02	4.61	4.23	308	0.0876	378
11/12/2012	7.13	3.24	2.19	289.3	0.0675	425
11/17/2012	7.25	4.25	3.56	321.6	0.0587	463

Table D.13: GB1 results

GB 1						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	6.37	18.4	83.2	276.5	0.0148	156
10/15/2012	6.77	2.05	28.7	258.4	0.0174	183
10/23/2012	6.87	3.86	864	278.4	0.0165	167
10/27/2012	7.23	5.1	96.4	267.5	0.0157	139
10/29/2012	6.77	18.4	69.6	278.2	0.0138	187
10/31/2012	7.64	2.44	10.1	287	7.91E-03	231
11/3/2012	7.59	0.33	10.5	419.6	0.022	169
11/6/2012	7.39	0.66	9.87	342	0.0198	156
11/12/2012	7.32	3.76	5.64	295.4	0.0211	187
11/17/2012	7.42	4.32	8.74	342.4	0.0176	163

Table D.14: GB2 results

GB 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	6.35	23.3	114	256.3	0.0139	139
10/15/2012	6.72	2.07	94.7	276.6	0.0157	167
10/23/2012	6.83	2.52	674	256.3	0.0164	183
10/27/2012	7.09	4.6	118	256.4	0.0147	148
10/29/2012	6.98	5.39	136	267.9	0.0176	192
10/31/2012	7.4	1.95	38.4	347	9.21E-03	171
11/3/2012	7.35	0.41	18	397.8	0.0154	189
11/6/2012	7.1	0.6	14.3	378.8	0.0178	139
11/12/2012	7.12	3.27	12.3	365.3	0.0156	179
11/17/2012	7.28	2.45	8.43	329.3	0.0167	156

Table D.15: GR+S1 results

GR + S 1						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.12	6.3	145	278.4	0.0159	462
10/15/2012	6.91	3.03	288	265.3	0.0173	418
10/23/2012	7.32	21.3	347	248.6	0.0168	439
10/27/2012	7.36	13.3	144	239.5	0.0186	458
10/29/2012	7.79	63.9	504	257.8	0.0158	498
10/31/2012	7.33	2.25	2.61	263.3	7.93E-03	532
11/3/2012	7.2	0.46	0.92	340.5	0.0215	437
11/6/2012	7.1	0.63	6.54	351.6	0.0231	427
11/12/2012	7.17	3.48	4.72	299.3	0.0198	437
11/17/2012	7.43	2.51	3.58	278.4	0.0201	451

Table D.16: GR+S2 results

GR + S 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	6.71	8.64	157	256.3	0.0278	451
10/15/2012	7.03	2.11	62.7	276.6	0.0173	489
10/23/2012	6.98	17.3	154	267.3	0.0213	389
10/27/2012	6.9	13.1	11.8	239.4	0.0289	410
10/29/2012	7.79	63.9	504	257.8	0.0132	436
10/31/2012	7.16	2.36	1.4	241.7	0.0109	427
11/3/2012	7.2	0.34	1.19	348.7	0.11	419
11/6/2012	7.25	0.93	3.25	328.8	0.0764	498
11/12/2012	7.26	3.48	4.35	301.2	0.0219	482
11/17/2012	7.34	2.52	3.42	278.4	0.0208	467

Table D.17: Acc.Age GRa1 results

Acc. Age GRa 1						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.56	4.32	2.64	2.87	0.0426	410
10/15/2012	7.29	6.57	3.25	267.3	0.0328	405
10/23/2012	7.46	7.63	2.54	256.4	0.0635	378
10/27/2012	7.41	8.73	2.17	298.4	0.0763	429
10/29/2012	7.36	5.64	2.96	278.4	0.0328	439
10/31/2012	7.37	2.65	1.4	263.8	0.0514	418
11/3/2012	7.37	2.65	1.4	263.8	0.0514	498
11/6/2012	7.27	0.53	1.02	335.9	0.0432	421
11/12/2012	7.17	2.23	1.32	293.4	0.0379	426
11/17/2012	7.28	3.21	2.13	325.4	0.0521	411

Table D.18: Acc.Age GRa2 results

Acc. Age GRa 2						
Date	pH	Nitrate	Turbidity	ORP	Ammonia	Conductivity
10/13/2012	7.39	3.45	3.25	276.4	0.783	408
10/15/2012	7.27	5.41	4.53	258.4	0.0489	419
10/23/2012	7.31	9.32	3.68	279.7	0.0543	432
10/27/2012	7.27	6.59	2.48	289.1	0.0732	437
10/29/2012	7.23	7.64	3.48	269.5	0.0683	448
10/31/2012	7.02	2.47	17.6	226.3	0.115	436
11/3/2012	7.03	0.42	0.83	353	0.082	481
11/6/2012	7.31	0.44	1.23	329.5	0.0382	439
11/12/2012	7.21	2.39	3.75	325.8	0.0452	417
11/17/2012	7.32	3.27	2.54	319.4	0.0421	409

Table D.19: Acc.Age GRb1 results

Acc. Age GRb 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.34	5.38	2.62	251.9	0.0361	421
10/15/2012	7.24	6.31	3.19	287.7	0.0621	431
10/23/2012	7.28	9.87	3.29	276.4	0.0483	423
10/27/2012	7.38	6.49	4.27	239.4	0.0584	451
10/29/2012	7.17	6.37	2.28	257.6	0.0637	428
10/31/2012	7.26	2.47	1.3	227.8	0.0581	452
11/3/2012	7.17	0.38	0.84	358	0.0269	412
11/6/2012	7.32	0.63	1.49	325.3	0.0342	398
11/12/2012	7.15	2.21	2.21	301.4	0.0427	432
11/17/2012	7.16	1.93	2.69	284.3	0.0379	416

Table D.20: Acc.Age GRb2 results

Acc. Age GRb 2						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.41	5.49	4.39	256.3	0.0341	417
10/15/2012	7.32	6.29	4.28	245.7	0.0247	438
10/23/2012	7.22	8.95	3.17	298.4	0.0337	431
10/27/2012	7.31	6.94	3.79	279.4	0.038	491
10/29/2012	7.27	7.82	6.37	269.4	0.0278	418
10/31/2012	7.2	2.51	6.41	244.5	0.0475	452
11/3/2012	7.04	0.3	0.72	351	0.0437	463
11/6/2012	7.29	0.67	2.39	333.3	0.0453	431
11/12/2012	7.26	2.63	5.38	279.6	0.0564	423
11/17/2012	7.13	2.31	3.28	295.3	0.0348	401

Rain						
Date	**pH**	**Nitrate**	**Turbidity**	**ORP**	**Ammonia**	**Conductivity**
10/13/2012	7.11	0.74	0.28	337.9	0.0875	21
10/15/2012	7.04	0.71	0.31	321.2	0.0764	25
10/23/2012	7.17	0.68	0.35	365.4	0.0969	41
10/27/2012	7.21	0.79	0.27	347.5	0.0824	16
10/29/2012	7.01	0.87	0.32	343.8	0.0921	34
10/31/2012	7.92	0.72	0.29	331.6	0.0977	15
11/3/2012	7.38	0.41	0.36	346.2	0.0981	52
11/6/2012	7.3	0.56	0.25	345.2	0.0895	41
11/12/2012	7.18	0.76	0.32	376.3	0.0899	31
11/17/2012	7.28	0.65	0.38	374.1	0.0956	11

Appendix E: The current experiment’s pictures

Figure E.1: Snap shot of the experiment pilot

Appendix F: ANOVA assumptions validation

The ANOVA assumptions are evaluated for nitrate and ammonia. The results for other samples were identical.

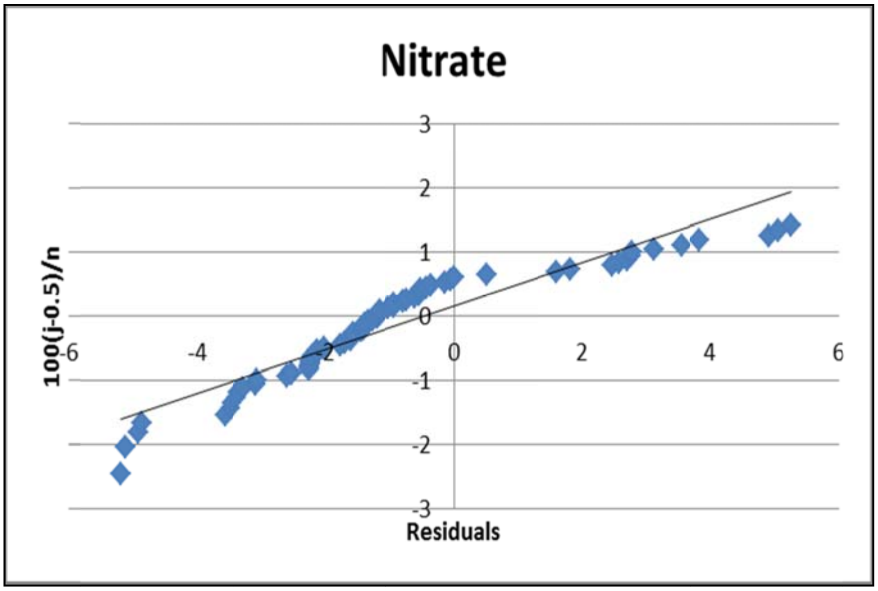

Figure F.1: Checking the normality assumption for nitrate

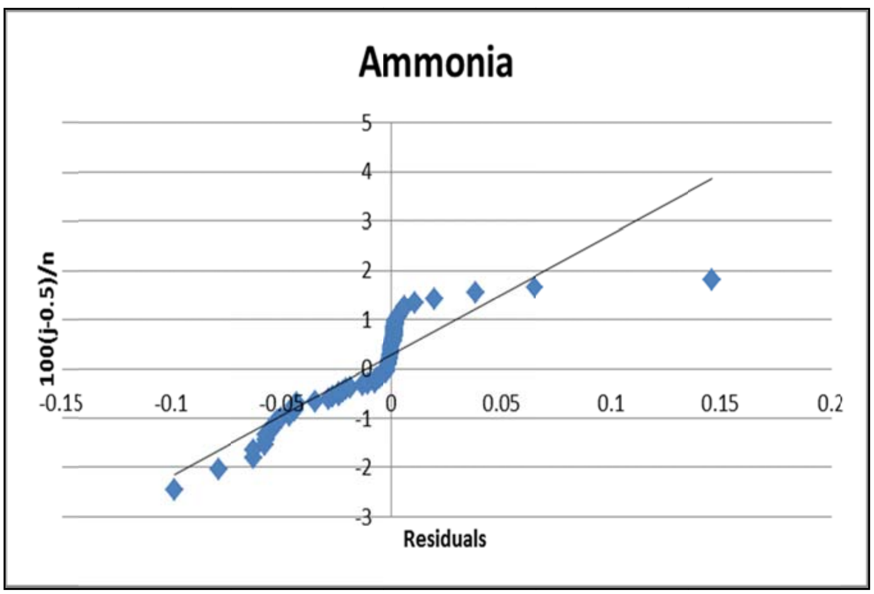

Figure F.2: Checking the normality assumption for ammonia

As it can be seen, the samples are almost linear. Therefore, the normality assumption is satisfied.

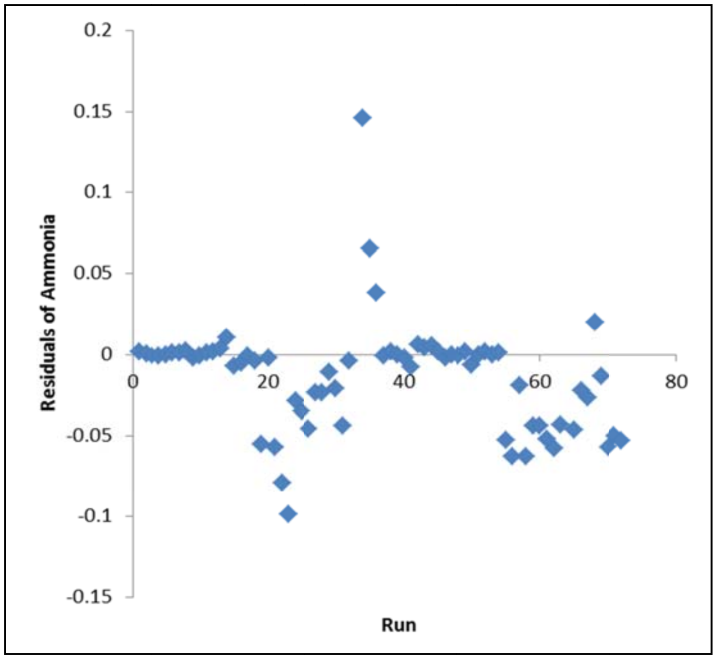

Figure F.3: Checking the independence residuals assumption for nitrate

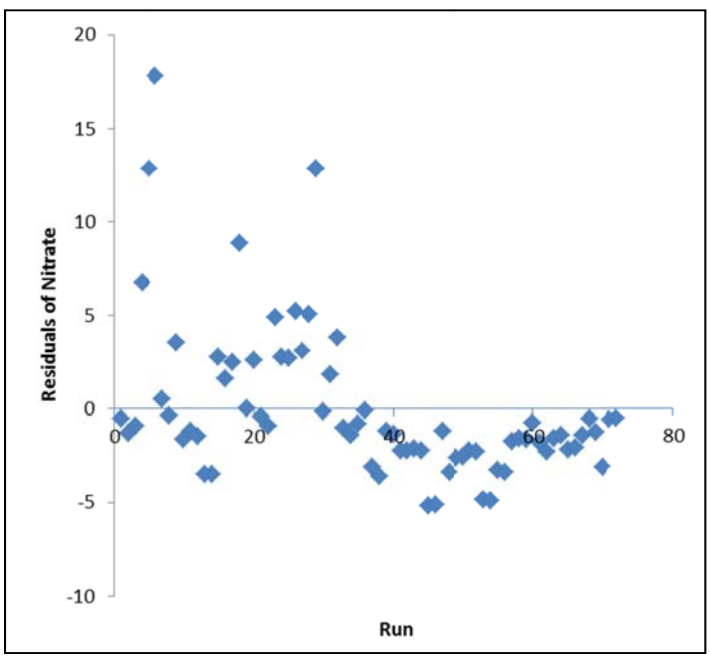

Figure F.4: Checking the independence residuals assumption for ammonia

The Figures F.3 and F.4 show that there is not any relation between the samples and the independency of sampling is satisfied. Figures F.5 and F.6 show that each series of sampling has almost the same variance.

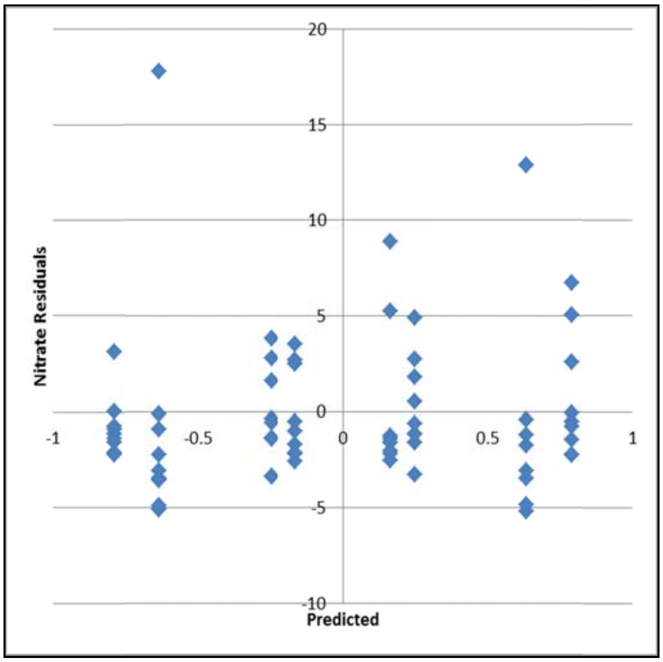

Figure F.5: Checking the constant variance assumption for nitrate

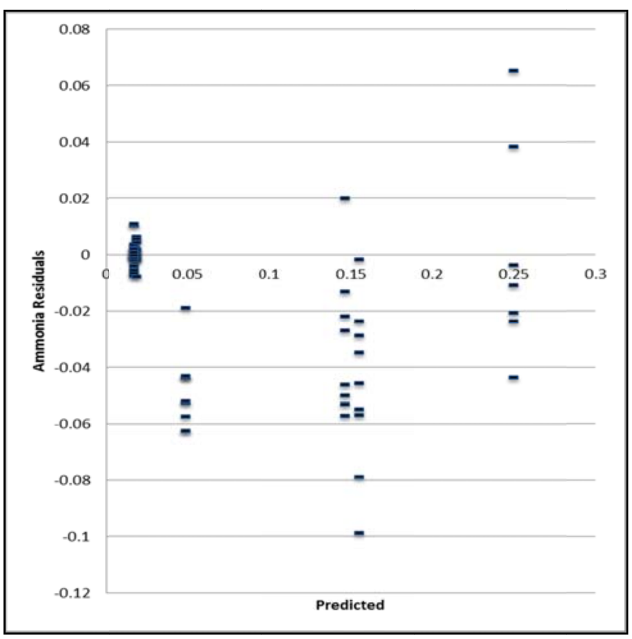

Figure F.6: Checking the constant variance assumption for ammonia