A Hydrologic Assessment of using Low Impact Development to Mitigate the Impacts of Climate Change in Victoria, BC, Canada

by

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B.Sc., University of Victoria, 2005

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Geography

Supervisory Committee

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Abstract

The purpose of this study is to determine if Low Impact Development (LID) can effectively mitigate flooding under projected climate scenarios. LID relies on runoff management measures that seek to control rainwater volume at the source by reducing imperviousness and retaining, infiltrating and reusing rainwater. An event-driven hydrologic/hydraulic model was developed to simulate how climate change, land use and LID scenarios may affect runoff response in the Bowker Creek watershed, a 10km^2 urbanized catchment located in the area of greater Victoria, British Columbia, Canada. The first part of the study examined flood impacts for the 2050s (2040-2069) following the A2 emissions scenario. For the 24-hour, 25-year local design storm, results show that projected changes in rainfall intensity may increase flood extents by 21% to 50%. When combined with continued urbanization flood extents may increase by 50% to 72%.

The second part of the study identified potential locations for three LID treatments (green roofs, rain gardens and top soil amendments) and simulated their effect on peak flow rates and flood volumes. Results indicate that full implementation of modeled LID treatments can alleviate the additional flooding that is associated with the median climate change projection for the 5-year, 10-year and 25-year rainfall events. For the projected 100-year event, the volume of overland flood flows is expected to increase by 1%. This compares favourably to the estimated 29% increase without LID. In terms of individual performance, rain gardens had the greatest hydrologic effect during more frequent rainfall events; green roofs had minimal effect on runoff for all modelled events; and top soil amendments had the greatest effect during the heaviest rainfall events.

The cumulative performance of LID practices depends on several variables including design specifications, level of implementation, location and site conditions. Antecedent soil moisture has a considerable influence on LID performance. The dynamic nature of soil moisture means that at times LID could meet the mitigation target and at other times it may only partially satisfy it. Future research should run continuous simulations using an appropriately long rainfall record to establish the probabilities of meeting performance requirements.

In general, simulations suggest that if future extreme rainfall events follow the median climate change projection, then LID can be used to maintain or reduce flood hazard for rainfall events up to the 25-year return period. This study demonstrates that in a smaller urban watershed, LID can play an important role in reducing the flood impacts associated with climate change.

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Acknowledgments

I would foremost like to thank my supervisors, Dr. Stanton Tuller and Dr. Daniel Peters, for their guidance and for providing me the opportunity to conduct this research. I would like to extend my appreciation to Taylor Davis of Terra Remote Sensing Inc. whose knowledge, ingenuity and enthusiasm were instrumental in completing this study. A special thanks to Jeff Howard, Craig Kipkie and staff from Kerr Wood Leidal Associates Ltd. and Jim Dumont of Morrison Hershfield Ltd. for their assistance with the hydrologic modeling. Trevor Murdock and Arelia Werner from the Pacific Climate Impacts Consortium provided valuable advice on climate change projections.

The basis and inspiration for this research lies in the efforts of all of those who are working to protect and improve watershed health. I am especially grateful to Ian Graeme and Rob Miller; Jody Watson of the Capital Regional District; and Kim Stephens of the Partnership for Water Sustainability in BC for sharing their passion, optimism and for their dedication to improving water stewardship. The Pacific Institute for Climate Solutions (PICS), the Water and Climate Impacts Research Centre and the Bowker Creek Initiative provided a supportive and enriching environment to conduct research. I appreciate the various measures taken by Dale Wall, Glen Brown, Liam Edwards and staff at the Ministry of Community, Sport and Cultural Development which enabled me to pursue this research. This work was made possible by the financial assistance provided by PICS, Natural Science and Engineering Research Council, Government of British Columbia and the University of Victoria.

Most importantly, thank you to my parents, daughter, family and friends for the endless support and finally to Roxanne Ahmed for her help, encouragement and contagious smile.

CHAPTER1: INTRODUCTION

1.1 Impact of Climate Change on Flood Hazard

There is broad consensus in the scientific community that atmospheric emissions from human activities are causing major changes in the earth's climate (IPCC, 2007). It is anticipated that climate change, as it is commonly referred to, will have many adverse affects across the planet (IPCC, 2008). In Canada the most severe and costly impacts are expected to be associated with flooding (Lemman *et al*., 2008). The potential for future flood impacts are closely linked to predictions of increasing precipitation (Salathe *et al*., 2007). Escalating flood hazard may be a widespread global issue because the intensity of extreme storm events is *very likely* going to increase over most areas during the 21st century (IPCC, 2008). Evidence indicates a trend of precipitation patterns already moving towards more intense storm events (Groisman *et al*., 2005; Madsen and Willcox, 2012). The anticipated changes in precipitation pose significant consequences for the risk of rain-generated floods and infrastructure failure (Walker and Sydneysmith, 2008). In order to prepare for climate change, it is critical that communities assess how future precipitation may affect flood flows and develop appropriate mitigation strategies (Ashley *et al*., 2005).

1.2 Urbanization and Watershed Hydrology

Climate change may have a significant impact on watershed hydrology, but how will it compare to the dramatic effect that urbanization has on hydrological processes? Across the globe human populations are becoming increasingly urban, with approximately 50% of the world’s population now living in urban areas (Cohen, 2003). It is expected that by 2030, this percentage will rise to more than 60% (UN Population Division, 2007). The increase in urban areas has important implications for flood risk because compared to all other land use changes affecting an area's hydrology, urbanization is by far the most forceful (Leopold, 1968).

Urbanization is the process where natural areas are largely cleared of vegetation and replaced with buildings and pavements (Horner and May, 1998). This process typically reduces infiltration and increases the magnitude of flood flows (Dunne and Leopold, 1978). While the broader term urbanization is often used to describe the source of these changes, the vast majority of the hydrologic impacts are caused by just one feature of the urban landscape: impervious surfaces (Booth and Jackson, 1997).

1.2.1 Impervious Surfaces

Impervious surfaces can be defined as "any human-produced material or activity that prevents infiltration of water into the soil" (Theobald *et al*., 2009, p.362). Schueler (1994) proposes that impervious surfaces are composed of two primary components: the *rooftops* under which we live, work and shop, and the *transport* systems (road, driveways and parking lots) that we use to get from one roof to another. These rooftop and transport systems commonly account for 80% of all the impervious surfaces in an urban watershed (Slonecker and Tilley, 2004). Therefore, any initiative that aims to reduce the flood impacts of climate change, or impervious areas in general, need to focus on these two major sources of surface water runoff.

There is extensive scientific literature that relates the amount of imperviousness to specific changes in the hydrology, geomorphology, water quality and health of aquatic ecosystems (e.g. Leopold, 1968; Thomas and Schneider, 1970; Weiss *et al*., 2005). This existing research, conducted in many geographic areas, concentrating on many different variables and employing widely different methods, has yielded a surprisingly similar conclusion: stream degradation occurs when approximately 10% or more of a watershed is converted to impervious surfaces (Schueler, 1994). Besides parks and agriculture, there are few urban land uses that create less than 10% imperviousness. Consequently, stream degradation is a predictable result of unmitigated urban development (National Research Council, 2008).

How can relatively low levels of imperviousness have such potent effects? The explanation can be attributed to three dominant hydrologic changes: 1) impervious surfaces restrict precipitation from infiltrating into the soil and re-charging groundwater; 2) they reduce surface roughness which increases the rate of surface runoff; and 3) they reduce evapotranspiration. These changes have a powerful effect on runoff response. For example, as a watershed changes from a forested state to 10–20% impervious surfaces, runoff increases twofold; 35–50% impervious cover increases runoff threefold; and 75–100% increases surface runoff more than fivefold over forested catchments (Arnold and Gibbons, 1996).

In terms of assessing climate impacts, impervious surfaces play a key role because they generate increased peak flows (Konrad and Booth, 2002; Leopold, 1968); higher discharge variability; and a greater occurrence of extreme flow events (O'Driscoll *et al*., 2010). In addition to impervious surfaces, conventional stormwater management approaches significantly alter watershed hydrology (Denault *et al*., 2006).

1.2.2 Conventional Stormwater Management

The conventional engineering approach for managing rainwater focuses on flood control for infrequent storm events (Maidment, 1993). The emphasis has been on managing storm events, instead of the full spectrum of rainfall events. This has lead to the term "stormwater" management. While each community has its own local priorities and criteria, in general the primary goal of stormwater management has been - and continues to be- the protection of public safety and property (Mailhot and Duchesne, 2010). The conventional approach used to achieve this goal is to design drainage infrastructure to concentrate runoff and dispose of it as quickly and efficiently as possible (Marek, 2011).

Conventional design criteria establishes a *minor drainage system* which serves as the surface drainage system, and a *major drainage system*, which is the flood control system (Maidment, 1993). The minor drainage system is generally designed to prevent nuisance flooding by conveying runoff from storm events that have a return period of 10-years or less. The major drainage system provides for the safe conveyance of large storm events such as the 100-year flood event (Maidment, 1993). In urban watersheds, the minor drainage system generally consists of gutters, catch basins and pipes that quickly convey rain water to the nearest waterbody. The major drainage system may manage storm runoff through the use of dykes, floodplain modifications and enlarged concrete- lined stream channels. This approach has generally been effective at protecting public safety and property from flood waters (Weiss *et al*., 2005).

Urban drainage systems have typically been designed based on the rational method for estimating peak flows, (National Research Council, 2008). The equation for the rational method is:

$$Q = CiA \qquad \text{(Eq. 1)}$$

where:
Q - peak flow (m^3/s)
C - dimensionless runoff coefficient
i - rainfall intensity (mm/hr)
A - catchment area (ha)

The rational method is appropriate for estimating peak discharges in smaller watersheds (up to 50 hectares), but it is subject to several limitations, assumptions and precautions (NZWERF, 2004; Chow *et al*., 1988). A key weakness of the rational method is that it severely limits the evaluation of design alternatives such as low impact development due to its inability to accommodate the presence of storage in the drainage area (Marek, 2011). Relying on the rational method, conventional stormwater management typically increases the volume, frequency, and velocity of runoff flows; reduces water quality and causes habitat degradation (EPA, 2000). Due to these adverse impacts, new approaches and goals are continuously being established which attempt to maintain natural hydrology as much as possible (NJDEP, 2004).

In North America, the evolution from conventional stormwater management to modern techniques has gone though four distinct stages: 1) starting in the early in the 1970's, on-site detention started to be used to reduce peak flows and flooding; 2) from the mid-1970's to mid-1980's, hydrologic and hydraulic models were used to develop comprehensive stormwater master plans; 3) in the late 1980's, the stormwater paradigm started to shift to address environmental problems; and 4) in the 1990's, modern 'watershed-based' approaches and 'low impact development' were being introduced (Stephens *et al*., 2002). From integrated stormwater management plans, to green infrastructure practices, there are now a wide range of techniques being employed to address a variety of watershed management objectives.

Terminology is also changing to reflect this broader context with the conventional "stormwater" management term being replaced or complimented by "rainwater" management. "Stormwater" management is the term often used to describe conventional engineering which uses materials such as cement and pipes to quickly convey the flows from storm-events (ELC, 2010). Modern science and engineering have evolved new ways to address rainfall events in a way that reflects natural watershed hydrology and the whole spectrum of rainfall events and management objectives. "Rainwater" management describes a more ecological and holistic approach which is being embraced by growing numbers of scientists, engineers, designers, planners, developers, environmentalists and governments (ELC, 2010). According to Stephens

(2009) rainwater management is about integration and an interdisciplinary approach that is landscape-based, and therefore goes well beyond the narrow engineering definition for conventional stormwater management.

1.2.3 Habitat & Biotic Community

An increase of impervious surface area is the most pervasive and consistent cause of damage to urban aquatic environments (Paul and Meyer, 2001). There is extensive and consistent scientific literature on the deleterious effects of impervious surfaces on aquatic ecosystem health (e.g. Scheuler, 1995; Arnold and Gibbons, 1996). According to Miltner (2004), due to the collective environmental stressors directly resulting from increased surface imperviousness, aquatic ecosystems become severely impaired when watershed imperviousness reaches 8-20%. Research shows that instream physical and biological measures generally change the most rapidly during the initial phase of watershed development, as total impervious area changed from 5% to 10% (Stephens *et al*., 2002). After 10%, habitat degradation and biological productivity continue to decline, but at a slower rate (Horner, 1998).

Maintaining a stream's natural hydrograph is fundamental for the protection of aquatic ecosystem health (Poff *et al*., 1997). Pomeroy *et al*. (2008) did an extensive review trying to determine precisely which hydrograph changes have the greatest influence on biological integrity. He found that no single measure was significantly responsible for degraded biological integrity and concluded that a range of attributes were responsible including flow variability and flashiness, flow volume, flow timing and flow duration. There is a large literature relating aquatic habitat and biological integrity to various hydrologic, geomorphic and water quality changes caused by urbanization. This body of research can be distilled down to one overarching conclusion: there is a direct relationship between levels of urban development and the degraded biological condition of downstream receiving waters. Schueler (1994, p. 11) states:

> *Research has revealed that imperviousness is a powerful and important indicator of future stream quality and that significant degradation occurs at relatively low levels of development. The strong relationship between imperviousness and stream quality presents a serious challenge for urban watershed managers. It underscores the difficulty in maintaining urban stream quality in the face of development.*

1.3 Reducing the Impacts of Urbanization on Watershed Hydrology

The shift from single objective "stormwater management" to the multi-objective "rainwater management" has resulted in a variety of new terms and vocabulary that all generally describe an approach to land development that tries to maintain or replicate pre-development flow regimes by mimicking natural hydrologic processes. This approach to rainwater management is commonly referred to as 'Sustainable Urban Drainage System' in the United Kingdom and 'Water Sensitive Urban Design' in Australia. In Canada and the United States, there does not yet appear to be a common set of definitions or vocabulary that matches the terms consistently used in other nations (Stephen *et al.*, 2002). In North America rainwater management has been characterized with terms such as 'Integrated Stormwater Management', 'Design with Nature', 'Green Infrastructure', 'On-Site Source Controls', 'Stormwater Best Management Practices' and of particular relevance, 'Low Impact Development' (LID). While each of these terms has their own definitions and unique nuances, in general, they are not mutually exclusive and at times are interchanged with each other to suit context and audience. The unsettled vocabulary underscores how community values for water and watersheds are evolving, resulting in a shift from engineered stormwater infrastructure to the systems based approach of rainwater management.

1.3.1 Low Impact Development

This study uses 'Low Impact Development' (LID) to describe a suite of on-site rainwater management measures. The definition of LID is often broad, encompassing a range of land use planning and design practices used to minimize the hydrologic impact of development. For example, LID can extend to considerations such as narrower street designs, compact cluster development, conservation of natural features, protection of important ground water recharge areas and site design criteria. Within the context of this study, LID refers to a limited selection of techniques used to manage rainwater at its source (also known as 'on-site source controls'). The term 'rainwater management' is used to describe a spectrum of potential activities used to preserve natural watershed hydrology including but not limited to: planning, engineering, financial incentives, policies, bylaws and design criteria. Rainwater management also includes considerations for precipitation that occasionally falls as snow in the study watershed.

Over the last two decades, LID has been developed to deliver improved environmental, economic, social and cultural outcomes for urban watersheds (NJDEP, 2004). The fundamental approach of LID is the antithesis of conventional stormwater management. Instead of concentrating surface runoff and quickly conveying it to a centralized location in the watershed, LID uses decentralized designs that seek to control rainwater runoff at the source. LID relies on runoff management measures that reduce imperviousness and retain, infiltrate and reuse rainwater. According to the Environmental Protection Agency's (EPA, 2000, p.1) Low Impact Development Center, LID is a "site design strategy with a goal of maintaining or replicating the pre-development hydrologic regime through the use of design techniques to create a functionally equivalent hydrologic landscape. Hydrologic functions of storage, infiltration, and ground water recharge, as well as the volume and frequency of discharges are maintained through the use of integrated and distributed micro-scale stormwater retention and detention areas, reduction of impervious surfaces, and the lengthening of flow paths and runoff time."

LID drainage systems have a broad and interconnected range of benefits including; flood management, water and air pollution removal, increased infiltration and base flows, lower surface and air temperatures, habitat creation and protection and increased community environmental awareness (Davis, 2009). The benefits LID offers have significant implications for urban watershed management, particularly as restoration efforts seek to re-establish lost hydrologic and ecosystem functions (O'Driscoll, 2010). LID is increasingly being used to reduce the adverse hydrologic and water quality effects of urbanization (NJDEP, 2004). Implementation, while often sparse, is becoming more widespread, especially in regions such as the Georgia Basin of Canada (Gulik, 2010). As the practice matures, LID techniques continue to evolve to suit a range of geographic areas, environments and climates. The progress LID has made in the last twenty years is evident in the many techniques and design guidelines that are now available (Elliot and Trowsdale, 2007).

LID does not present a "one size fits all approach". The suitability of LID techniques must be evaluated based on watershed objectives and the site's unique characteristics including landscape, urban and infrastructure context (De Greeff and Murdock, 2011). The level of effort required to achieve this site-by-site evaluation is not feasible for this study; therefore for a simplification of LID designs and sites was warranted. Out of the many possible LID practices, this study selected the following three as the focus for the hydrologic assessment: Green Roofs, Rain Gardens and Amended Topsoil.

1.3.2 Green Roofs

In context of their abundance, roof tops often represent one of greatest impacts on urban runoff (Connelly *et al*., 2006). On developed urban lots, the building footprint is typically the largest portion of impervious area (Metro Vancouver, 2009). Mitigating the hydrologic impact of roof tops is important for reducing peak flows and maintaining natural hydrologic regimes. Green roofs offer one solution to the rainwater runoff issues caused by impervious roof tops.

A modern green roof is a conventional roof structure with layers of drainage and vegetated growing medium installed on top of a waterproof membrane (Figure 1.1).

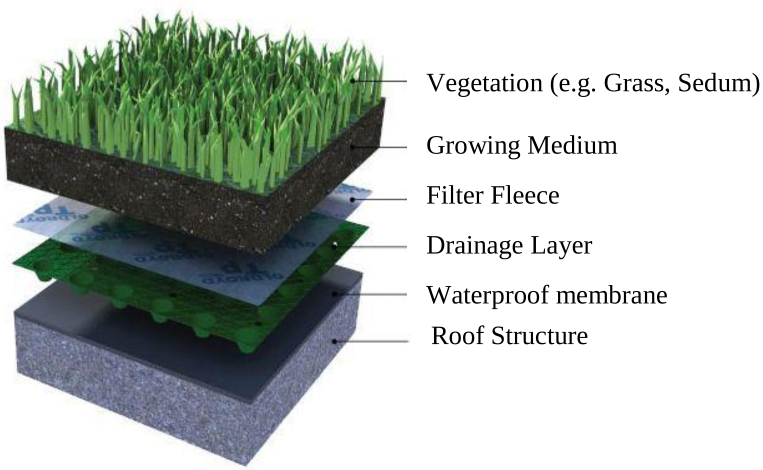

Figure 1.1: Structure of a modern Green roof (adapted from Oldroyd, 2010).

Green roofs are commonly defined as either extensive or intensive. Intended usage, plant selection and growing media depth are primarily used to classify green roof type though there are other characteristics that help distinguish the two types (Table 1.1). Both types of roofs are usually installed on low slope roofs (<3%) though occasionally they are installed on moderate slope roofs (up to 25%).

Table 1.1: Comparison of the typical characteristics of intensive and extensive green roofs (adapted from Martin, 2008).

Characteristic	Intensive Green Roof	Extensive Green Roof
Purpose	Public space, garden	Not accessible to public
Maintenance	Regular to high	Minimal to none
Irrigation	Regular	Only during plant establishment
Vegetation type	Wide variety of shrubs, trees and other herbaceous materials	Limited variety of hardy, low growing, drought tolerant plants
Growing media (soil) thickness	Greater than 150 mm	Between 20 and 150 mm
Saturated Weight	290 – 970 kg/m^2	70 – 170 kg/m^2
Building structural requirements	Additional structural support required	Load can be carried by most existing structures

Intensive green roofs are typically designed for public access and recreational functions. There are akin to roof top gardens or parks and can be covered with ornamental shrubbery, small trees, vegetables or lawns. Growing medium has a high organic content. Average growing medium depth is 350 mm and ranges from 150 mm to 1000 mm or more (Metro Vancouver, 2009). Deeper soil depths are required to accommodate the roots of large plants. Intensive green roofs often have less roof top coverage than extensive green roofs due to patios, pathways and other features associated with public access.

Intensive green roofs have two major drawbacks. First is a roof's structural load constraint. Due to the weight involved, intensive green roofs almost always have to be incorporated into the building's structural design. Intensive green roofs have limited opportunities for retro-fit applications because their installation could exceed a roof's structural capacity limits and required upgrades can be prohibitively expensive and impractical. The second drawback is that similar to regular gardens; intensive green roofs require ongoing maintenance including regular irrigation, weeding and fertilization (Metro Vancouver, 2009).

Another consideration is that for their additional cost and maintenance, intensive green roofs may only provide a marginal increase in rainwater management benefits (Martin, 2008).

Extensive green roofs help overcome some the challenges associated with intensive green roofs. Since extensive systems are not intended to provide public space, vegetation is selected not for visual appeal, but for their ability to regenerate and maintain themselves over long periods of time, as well as to withstand the harsh conditions on rooftops such as exposure to extreme cold, heat, drought and wind (Metro Vancouver, 2009). Vegetation is normally comprised of low maintenance mosses, succulents, herbaceous plants and grasses. Irrigation may be required to establish vegetation, but otherwise is not required because plants should be able to survive solely on the natural rainfall that reaches the roof (Neufeld *et al*., 2009). Extensive roofs are designed to be largely self-maintaining though, depending on the application, occasional weeding and replanting may be required. Growing medium is usually between 20 mm and 150 mm with a lower organic content than used on intensive roofs. To minimize weight and maintain acceptable water retention characteristics, the growing media are often a specialized lightweight mixture of organic and inorganic materials (Martin, 2008).

Because of the lighter weight growing medium and vegetation, extensive systems may not require structural upgrades and can, therefore, be less expensive and well suited for retrofit applications (Metro Vancouver, 2009). Due to their minimal requirement for additional roof structural capacity and low maintenance, it is believed that the wide spread use of green roofs in an urban area would most likely be accomplished with extensive green roof systems (Martin, 2008). An extensive green roof provides many of the benefits of an intensive system while being simpler, less expensive to install and easier to maintain (Martin, 2008).

According to Neufeld *et al*., (2009), green roofs provide several benefits including:

- lower frequency and magnitude of combined sewer overflows;
- reduced urban heat island effect;
- increased building insulation which reduces energy demand for air conditioning and heating;
- improved urban aesthetics and amenities;
- removal of pollution from water and air; and,
- reduced hydrologic changes caused by impervious surfaces.

Green roofs alter runoff response by promoting evapotranspiration of water back to the atmosphere and detaining and retaining water (Palla *et al*., 2010). These effects can delay and reduce peak flows (Martin, 2008). Research on the hydrologic performance of green roofs is in its infancy in North America (Johnson *et al*., 2004; EPA, 2000). Interest began to increase approximately 10 years ago with a substantial increase over the last 5 years. Industry, government and academic researchers are now all contributing to research efforts which are helping to improve green roof designs. Field studies have found that in coastal British Columbia, various green roof systems all reduce runoff volume and peak flow and delay the start of runoff and peak runoff (Connelly *et al*., 2006). Given these hydrologic effects, green roofs have potential to help mitigate future climate impacts.

1.3.3 Rain Gardens

Rain gardens are a depressed area of the ground planted with vegetation that allows runoff from impervious surfaces the opportunity to be collected and infiltrated or returned to the atmosphere (EPA, 2010). They are constructed with highly absorbent soils and are attractively landscaped with native plant species (Kipkie and Johnson, 2006). Rain gardens visually enhance the community and provide habitat and green space, both of which have positive impacts on human physical and mental health (Kaplan, 1995). Rain gardens reduce the hydrologic impact of urban development by mimicking natural hydrologic processes such as detention, infiltration and evapotranspiration. By delaying the time of concentration and reducing runoff volume and peak flows, rain gardens can significantly reduce the hydraulic pressures placed on drainage infrastructure and receiving streams. Research has demonstrated that under both dry and saturated soil conditions, rain gardens can capture 80% to 89% of the runoff from large storm events (Kipkie and Johnson, 2006). Another main function of rain gardens is to provide a high level of water quality treatment. Rain gardens reduce total suspended solids; reduce pollutant transport capacity and lower overall pollutant loading (EPA, 2000).

There is no general standard for rain garden design. Guidelines encourage certain common elements, but the form and function of rain gardens is typically unique to each application and reflect local objectives and site conditions (Dietz and Clausen, 2008). Rain garden designs range from simple runoff collection areas in residential backyards to specialized engineered facilities, which; depending on the specifics of location, expected performance, and municipal design standards; are connected to existing drainage infrastructure. Manuals and guidance documents recommend sizing rain gardens anywhere from 3% to 43% of their associated drainage areas (Palla *et al*, 2010). Figure 1.2 shows one example of a rain garden design and operation concept. As described by Kipkie and Johnson (2006), during rain events, runoff from impervious areas is directed to rain gardens and the engineered absorbent soils store or hold runoff until it's depleted by evapotranspiration. When the volume of runoff exceeds the saturation capacity of the soil, water drains into the subsurface rock pit from where it will infiltrate into the native soils. If the incoming flow rate exceeds the natural infiltration rate then the runoff will accumulate in the rock pit storage area; if the storage area capacity is exceeded, then a perforated pipe at the top of the rock pit will collect and convey excess water to the drainage system. During high intensity storms, the incoming flow rate may exceed the infiltration rate of the engineered soils or the inlet sizing on the perforated pipe. During these heavy events water is allowed to temporarily pond (up to 48 hours) at the surface. Water that exceeds the full capacity of the rain garden drains into the overflow pipe at the surface.

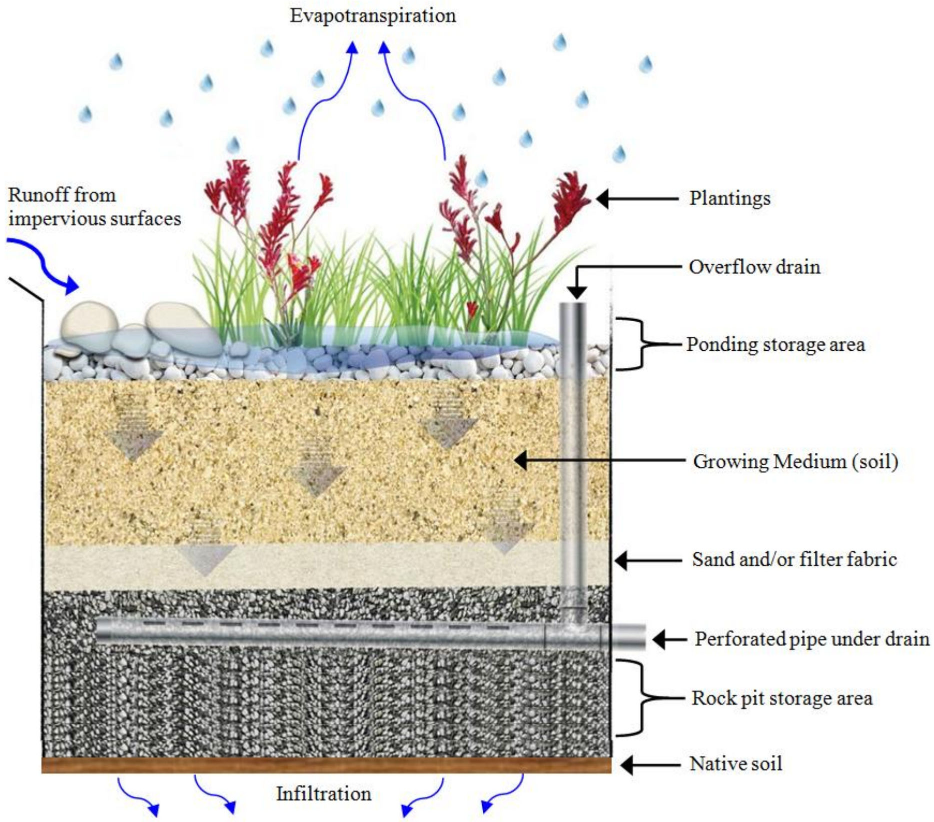

Figure 1.2: Rain Garden design with overflow drain, under drain and rock pit (adapted from Melbourne Water, 2010).

The scientific literature on the hydrologic performance of rain gardens is growing though, in general, more long-term field studies are required to accurately assess the effectiveness of rain gardens across a range of conditions and to determine long-term trends (EPA, 2000). The need for more research should not delay the wider implementation of rain gardens because the modelled and demonstrated benefits of rain gardens are clear (Palla *et al*., 2010). Rain gardens are now one of the most frequently cited and promising strategies for meeting watershed management objectives (Hilton *et al*, 2008; Martin, 2008). By reducing runoff from impervious surfaces, rain gardens can be used to help maintain natural watershed hydrology, protect downstream ecological health and decrease peak flows which contribute to flooding (Beuttell, 2008).

1.3.4 Topsoil Amendments

Naturally occurring (undisturbed) soil provide important rainwater management functions including: water infiltration; nutrient, sediment, and pollutant adsorption; water interflow storage and moderation of peak stream flows (Washington State DOE, 2005). These functions are largely lost when development compacts and strips away native soil, replacing it with minimal topsoil and sod. Amending topsoil improves detention/infiltration and reduces runoff from lawn and landscaped areas, especially on the clay and compacted glacial till soils common to this region (Beatty, 2008).

Re-establishing, maintaining and enhancing soil quality and depth has gained wide acceptance as an important and effective strategy for on-site management of rainwater (Stenn *et al.*, 2010). Part of the reason for its attractiveness as a source control is that improving or adding an amended topsoil layer to a site is one of the simplest and easiest source controls to implement. Furthermore, compared to other LID techniques, amending topsoil is forgiving in its design with failsafe performance if basic sizing guidelines are observed (Rutherford and Dubé, 2010). Amending soils with organic material and other soil textures provides the following benefits:

- restores soil water infiltration and storage capacities;
- decreases surface water runoff and erosion;
- traps sediments, heavy metals and excess nutrients;
- biodegrades chemical contaminants;
- improves plant health, with reduced need for additional water, fertilizers and pesticides; and,
- aids deep plant root growth and vigorous vegetative cover which increases evapotranspiration (Stenn *et al.*, 2010).

Because of its relative ease of application and dependable performance, topsoil standards are often one of the first non-conventional rainwater management measures adopted by governments (Beatty, 2008). The development specifications, design criteria and regulations for many local governments now stipulate post-construction topsoil requirements (e.g. British Columbia's City of Surrey and City of Courtenay; and Washington State's King County).

Due to its hydrologic effects and potential range of application, amended topsoil could play a valuable role in climate change adaptation strategies.

1.4 Adapting Drainage Infrastructure for Increased Precipitation

Urban drainage infrastructure is typically designed to convey runoff from a rainfall event that is based on a region's *historical* climate. The key assumption of this approach for designing infrastructure is that the past can be used to predict the future. More specifically, the conventional approach assumes stationarity, which is that the statistical parameters of the hydrological variables remain constant over time, without major fluctuations or long-term trends (Denault *et al*., 2006). Unfortunately, this assumption can no longer be met given the consensus of predictions and observed trends which indicate the global climate is rapidly changing (IPCC, 2008; Walker and Sydneysmith, 2008; Rodenhuis *et al*., 2007; Groisman *et al*., 2005). Water resource engineers, decision-makers and other professionals are therefore challenged with designing and assessing future performance of drainage infrastructure that will very likely be subject to higher discharges than those known today (IPCC, 2007; Denault *et al*., 2006).

A significant amount of research effort is being directed at providing insight into the potential range of precipitation changes. Using an emissions scenario where CO_2 concentrations double by the 2050s, it is predicted that for some regions, rainfall intensity will increase by 15% to 20% (Zwiers and Kharin, 1998). The significance of this is that such an increase results in a halving of the return period of many design storms. For example, using this projection a rainfall event with a magnitude that would be considered a 100-year return period event based on historic climate data would be considered a 50-year return period event in the 2050s.

The anticipated hydrologic impact of climate change necessitates a change in the approach to plan for and design drainage infrastructures (He *et a*l., 2006; Denault *et al*., 2002; Arisz and Burrell, 2006). Design criteria for drainage infrastructure should be revised to take into consideration the expected changes in the intensity and frequency of heavy rainfall events (Grum *et al*., 2006). Given the non-stationarity of rainfall statistics, using historical records for defining design parameters is no longer appropriate. If such practices continue, then it could result in grossly under-designed drainage infrastructure. The implications of catastrophic flood events are significant, especially in densely populated urban areas.

With the current state of knowledge and high level of uncertainty, it would be difficult to commit and justify the considerable cost of modifying existing drainage infrastructure. A pragmatic approach would be to develop adaptation options that could be implemented incrementally and include a sufficient degree of flexibility (Arisz and Burrell, 2006). LID may offer an appropriate solution. LID has considerable appeal over conventional infrastructure in that it can be constructed incrementally to match the actual observed rate of precipitation increase. Additionally, compared to a hard engineered approach, LID also provides significant secondary benefits for the environment and society. Therefore, this option offers a "no-regrets" solution to climate change. If predicted changes do not occur, then watershed and public benefits are still realized. Another potential benefit of LID is that it may save communities significant expenditures by eliminating the need to upgrade the capacity of existing drainage infrastructure.

To date, most LID has been implemented with the goal of maintaining or enhancing natural hydrological processes and environmental health (ELC, 2010). Implementation may accelerate if it can be demonstrated that LID can also be effectively used to mitigate the impacts of climate change.

Note that in reference to climate change research, the term *mitigation* typically refers to technologies and policies used to lower greenhouse gas (GHG) emissions and enhance sinks (IPCC, 2007). Within the context of this study, the term mitigation is not used to describe a GHG reduction initiative, but rather, it is used in specific reference to reducing (i.e. mitigating) flood impacts. This study falls within the broad category of climate change *adaption*, a term commonly used to describe initiatives to reduce the vulnerability of natural and human systems against actual or expected climate change effects (IPCC, 2007).

1.5 Research Need and Purpose

In current practice, LID is often designed, implemented and studied at specific development sites. This has resulted in a growing body of research on the hydrologic performance of individual LID sites or specific LID facilities such as green roofs (Palla *et al*., 2010). However, due to this site-by-site approach, there is a lack of peer-reviewed studies that quantifies the cumulative effect of LID on a watershed scale. This underlies a further knowledge gap regarding the effectiveness of using LID to reduce the hydrologic impacts of climate change.

The overarching purpose of this study is to contribute to the understanding of how LID can be used as a climate change adaptation strategy. Specifically the research uses the Bowker Creek watershed as a case study to address the following questions:

i) What changes in extreme rainfall and land-use are likely to occur in the 2050s (2040-2069?

ii) How will projected changes in extreme precipitation and land use affect watershed hydrology?

iii) Where are suitable locations for LID and how much can be implemented?

iv) Can LID effectively mitigate the flood impacts associated with projected changes in extreme rainfall?

1.6 Thesis Format

The thesis format is a hybrid between a traditional thesis and the structure of a journal-style manuscript. The overall organization is designed to reflect two stand-alone journal articles. However, to reduce redundancies and improve integration, information in the two papers and other chapters is linked and meant to be cumulative.

Chapter 1 provided the literature review, context and scientific background. Chapter 2 provides the climate change and land use analysis and quantifies the impacts for rain-generated runoff events. Chapter 3 identifies potentially suitable locations for three LID source controls and assesses hydrologic performance to determine if the selected LID measures can mitigate the projected changes in extreme precipitation. This thesis concludes with Chapter 4 which contains a summary of major findings and suggests future research directions in the application of LID for climate change adaptation.

CHAPTER 2: QUANTIFYING THE IMPACTS OF CLIMATE CHANGE ON EXTREME RAINFALL GENERATED RUNOFF EVENTS FOR VICTORIA, BC, CANADA

2.1 Introduction

Extreme weather, such as high intensity rainfall directly affects British Columbians more than any other climate risk (Harford, 2008). Global Circulation Models (GCMs) generally agree that climate change will bring wetter winters for coastal British Columba (PCIC, 2011). The predicted hydro-climatic regime of the future and associated flood flows are expected to increase the risks of infrastructure failure, property damage and potentially, loss of life (Lemmen *et al.*, 2008; Kije Sipi Ltd., 2001; Milly *et al.*, 2002).

For urban watersheds, a critical aspect of flood risk is the rainfall Intensity-Duration-Frequency (IDF) curves used to design drainage infrastructure. IDF curves allow calculation of the average rainfall intensity for a given return period over a range of durations (Maidment, 1993). A fundamental assumption of IDF curves and drainage design is the stationarity of rainfall statistical parameters (i.e. the future rainfall regime will be equivalent to the historic rainfall regime). This assumption may not be valid given the unequivocal evidence that the climate is changing (IPCC, 2007). Consequently, drainage infrastructure that was designed based on historic rainfall statistics may be unable to safely convey flows under future rainfall regimes.

Changes in extreme rainfall are posed to heighten flood hazard, but this risk may be magnified by continued urbanization as this process typically increases peak flows (Dunne and Leopold, 1978). The combination of higher intensity rainfall with additional runoff from impervious areas has the potential to significantly raise the frequency and magnitude of flood events. Understanding how changes in extreme rainfall and land use can affect watershed hydrology is a research area of critical importance (Rodenhuis *et al*., 2007).

2.2 Objectives

Using a case study area, three objectives have been identified for this chapter:

i) Examine projected changes in extreme rainfall for Victoria, BC, Canada;

ii) Assess how impervious areas may be affected by changes in land use; and

iii) Quantify the hydrologic impact of projected changes in extreme rainfall and land use.

2.3 Case Study Area

The Bowker Creek watershed, situated on the south-eastern tip of Vancouver Island, BC, Canada (centre at 48° 26' 55'' N, 123° 19' 57'' W) is used as a case study. The western edge of this urban watershed is 1.5 km from the downtown core of the City of Victoria (Figure 2.1). The watershed lies within the municipalities of the District of Oak Bay, District of Saanich and the City of Victoria.

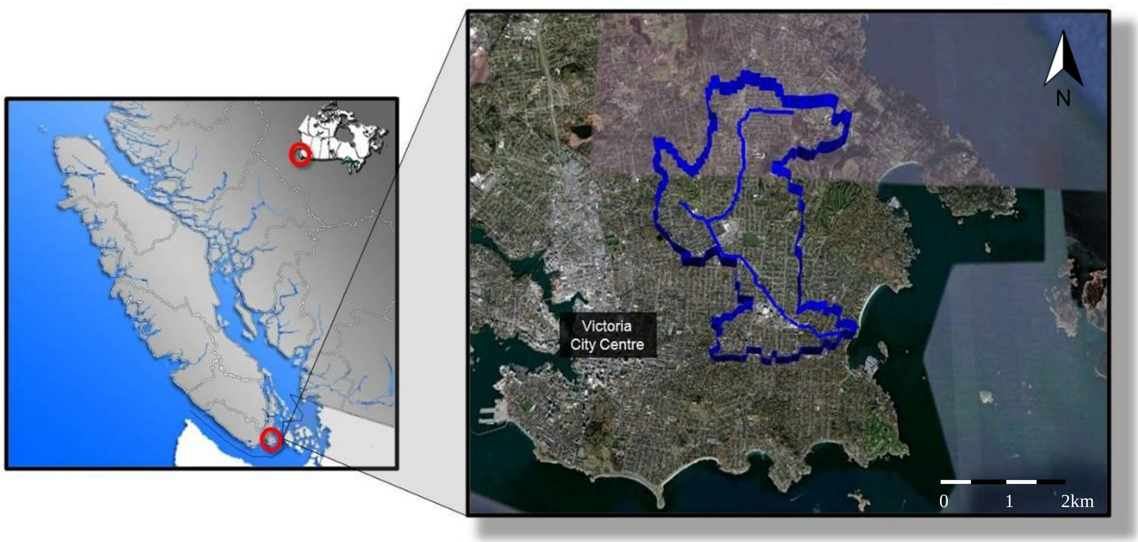

Figure 2.1: Case Study Location - Bowker Creek watershed.

2.3.1 Physical Characteristics

The Bowker Creek watershed is 1018 ha in area, of which approximately 50% is covered with impervious surfaces (KWL, 2007). With headwaters at the University of Victoria, the main channel flows for 7.9 km through storm drains, culverts and open channels to a marine discharge in Oak Bay (KWL, 2007). Thirty-seven percent of Bowker Creek is open channel, with the rest being enclosed within storm drains and culverts (BCI *et al.*, 2010). Most of the open channel sections have been straightened, native vegetation removed, and artificial banks constructed (Crowther, 2000). Fifteen sites of high erosion have been identified in areas without artificial banks (KWL, 2007). Open channels are often deeply incised with steep (1:2) bank slopes.

The case study area is a low gradient watershed with slopes generally less than 5% (BCI *et al.*, 2010). The main channel has an average gradient of 0.5% in the upper reaches which reduces to less than 0.4% in the lower reaches (Crowther, 2000). Mount Tolmie, at an elevation of 124m above sea level, is the highest point in the watershed. The majority of the underlying soil within the catchment is clay with some areas of sands/gravels, sands, and bedrock outcrops.

The watershed is highly developed with the majority of the area currently being used for single-family residential developments. Other land uses include multi-family residential, commercial, institutional, recreational, and very few undeveloped parcels (KWL, 2007). The unmitigated urbanization of the Bowker Creek watershed combined with a conventional stormwater infrastructure has resulted in the expected hydrologic changes and impaired aquatic ecosystem health (see Chapter 1 for details).

2.3.2 Regional Hydroclimatic Setting

The Bowker Creek Watershed has a northern Mediterranean climate, typified by distinct wet and dry seasons, and mild winters (Werner, 2007). The region is considered *Csb* by the Köppen climate classification criteria which indicate a temperate/mesothermal climate with dry and warm summers. This classification means the driest summer month has less than 30 mm average precipitation, the warmest month averages below 22 °C and the area has at least 4 months averaging above 10 °C (Koeppe and De Long, 1958).

The region's climate variability (i.e. the variations in the mean and other statistics of the climate on all temporal and spatial scales beyond that of individual weather events (Walker and Sydneysmith, 2008)) is influenced by three dominant "modes" of ocean-atmosphere variability: the El Niño-Southern Oscillation (ENSO), Pacific Decal Oscillation (PDO) and the Pacific North American Pattern (PNA). These three modes are associated with different effects on the region's climate and operate at different timescales, from year-to-year variability to phases that persist from 20 to 30 years (Rodenhuis *et al*., 2007). While this study does not directly assess the role of the three modes in generating extreme rainfall events, the association between the probability of occurrence and the state of the modes must be kept in mind because the risk of extreme rainfall changes as the modes shift phase.

The close proximity to the Pacific Ocean and mid-latitude location makes this region especially susceptible to the low-pressure systems that frequently occur in winter (Werner, 2007). The majority of precipitation falls between October and March and the two wettest months are November and December (Environment Canada, 2012). Pacific storms usually cross the region from the west and pass north of Victoria. The region is protected from the full intensity of most low pressure systems because it is situated in the rain shadow of the Olympic Mountains to the south and the Sooke Hills to the west.

The 1971- 2000 climate normal annual precipitation for the Gonzales Heights weather station, located approximately 2 km southwest of the watershed's outlet, is 608 mm (Environment Canada, 2012). This is considerably lower than surrounding regions. For comparison, the Sooke Lake watershed 30 km to the northwest receives 1650 mm; North Vancouver 100 km to the north receives 3427 mm; and while it was monitored the Henderson Lake weather station 140 km to the northwest received more than 10 times the annual precipitation at 6655 mm (Philips, 2010). Snow fall in the area of the watershed is rare accounting for only 4% of annual precipitation (Environment Canada, 2012). Unlike other regions in Canada, snow is rarely associated with flood events in the study watershed. Therefore all precipitation in this study is considered to be comprised of rainfall.

The relative difference in rainfall intensity is not equal to that of annual precipitation. For example, North Vancouver's average total annual precipitation is 564% higher than that of the case study area, whereas, rainfall intensity for the 25-year, 24-hour event is only 44% higher. This suggests that the case study area may be significantly drier on a total annual precipitation basis, but in terms of extreme rainfall events, the watershed experiences rainfall intensities of a comparable scale as other watersheds in the region. Therefore, while the hydroclimatic setting of the case study area is unique, other rain-dominated urban watersheds in the Georgia Basin may experience similar changes in rainfall and associated flood hazard.

2.4 Methods and Data

2.4.1 Data Sources

This study builds on the technical work completed for the Bowker Creek Master Drainage Plan (MDP) developed by Kerr Wood Leidal Associates Ltd. (2007). Table 2.1

summarizes data sources used for the MDP which were subsequently used in this study. Figure 2.2 shows stream flow monitoring sites and weather stations.

Table 2.1: Data Sources

Information	Source	Description
Legal Cadastral	Capital Regional District, Saanich, Victoria, Oak Bay	Lot, roadway and right of way legal boundaries
Storm Drains	Saanich, Victoria, Oak Bay	Locations of the municipal storm drains within the watershed
As-Constructed Drawings	Saanich, Victoria, Oak Bay	As-Constructed drawings of the storm drains which convey Bowker Creek
Flow Monitoring	Capital Regional District	Sensors located at Trent St. and Monterey Ave.
Precipitation Data	Capital Regional District	Rainfall record in 5-minute time steps
Intensity-Duration Frequency Values	Environment Canada (Historic IDF), Victoria (2050s adjusted IDF).	Rainfall values for short duration (<24-hours) events for select return periods.
Soils	Geological Survey of Canada	Surficial geology mapping
Open Channel Data	Kerr Wood Liedal Associates Ltd and field survey.	Defined reaches, Manning's 'n', section elevation, length and slope
Sub-catchment	Kerr Wood Liedal Associates Ltd.	Delineation of sub-catchments
Impervious Areas	Kerr Wood Liedal Associates Ltd.	Imperviousness for sub-catchments

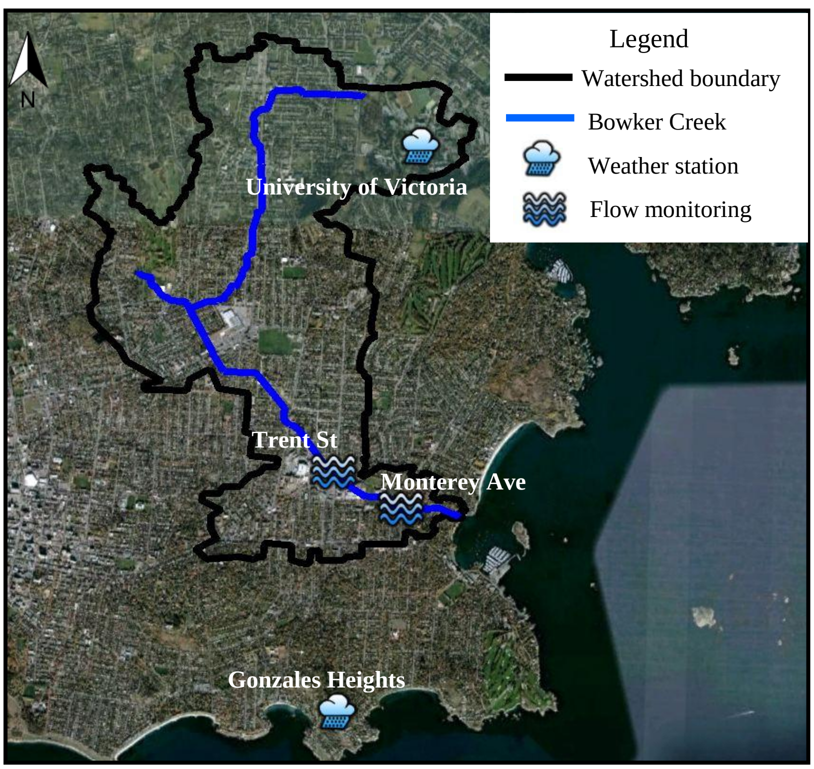

Figure 2.2: Locations of the Trent Street and Monterey Avenue flow monitoring stations and Gonzales Heights and University of Victoria weather stations.

In addition to the MDP, this study uses information contained in municipal plans and other relevant publications, including the following:

- The Bowker Creek Watershed Assessment (Crowther, 2000);
- The Bowker Creek Watershed Management Plan (Westland Resource Group, 2003); and
- The Bowker Creek Blueprint (BCI *et al*., 2010).

Terra Remote Sensing Inc. provided high-resolution LiDAR (Light Detection And Ranging) data and orthophotographs. These data were collected over the Bowker Creek Watershed from a fixed wing aircraft on March 28th, 2007 at 900m above ground altitude (Terra Remote Sensing Inc., 2007). Following data collection, calibration and automated classification routines, LiDAR data were manually edited to extract a total of approximately 7,000,000 ground points, yielding an overall average ground point density of $0.7/m^2$, increasing to approximately $2/m^2$ on hard surfaces. Ground points were used to generate a high-resolution Digital Elevation Model (DEM) for the watershed. Above ground points were used to create a Digital Surface Model (DSM). The DEM, showing ground topography, and the DSM, showing above ground features (e.g. buildings) were used in conjunction for different aspects of hydrologic/hydraulic modeling.

A field survey was required to measure channel cross-sections and verify information such as channel elevations, conduit size and other features affecting channel hydraulics. The survey was completed in September 2010 and included a total of 45 cross-sections. Channel reaches generally followed those used in the MDP. These were defined based on changes in channel shape, grade or alignment. The stream cross-sections used in the development of the hydraulic model were created for this study and may differ slightly from the cross-sections used in the MDP model.

Measured cross-sections were compared to cross-sections generated by the LiDAR derived DEM. The assessment showed a very high degree of consistency between field measurements and LiDAR data. Accuracy was approximately +/- 10cm. Differences in excess of this were often attributed to evident stream bank erosion that likely occurred between the 2007 LiDAR collection and the 2010 field survey. This comparison demonstrated the impressive vertical and horizontal accuracy of the LiDAR data and helped validate the DEM with field measurements.

2.4.2 Future Rainfall Scenarios

A key challenge of this study was to select an appropriate method for generating future rainfall scenarios. There is uncertainty in the literature regarding how projected increases in rainfall will affect the intensity of short duration extreme rainfall events. Research is trying to provide insight into whether the additional rainfall will occur primarily due to an increase in the frequency of rainfall days or an increase in rainfall intensity. Vincent and Mekis (2005) performed an analysis of precipitation indices from across Canada which revealed an increase in the annual total precipitation during the second half of the past century. This change was largely attributed to an increase in the number of days with precipitation. On the other hand, research also indicates that the intensity of infrequent storm events should also increase (Min *et al*., 2011).

To date, methods used to adjust future rainfall often do not explicitly account for intensity versus frequency changes. For example, a commonly used technique to generate future rainfall intensities is the Delta Change method (Olsson *et al*., 2009). This method adjusts rainfall intensities by increasing the values by the same percentage as is projected for monthly rainfall depth (e.g. monthly depth increases by 10%, then rainfall intensity increases by 10%). Under this method the frequency of rainfall days remains static while only storm intensity increases. As stated above, research indicates that the frequency of rainfall days is anticipated to increase and by not accounting for an increase in the number of rainfall days, this method may overestimate the intensity of future extreme rainfall events (Berggren, 2007). The Delta Change method was not selected for use in this study because it does not account for changes in the rainfall frequency.

Another method that could be employed is to follow a general guideline which states that the return period of storms will likely be halved by the 2080s (Arisz and Burrell, 2006; Grum *et al*, 2006; Mailhot *et al*, 2007; Bruce, 2002). Assessment of these studies reveals that their assumptions and local climate do not make this approach suitable for the case study area.

This study follows a method that uses regression equations to calculate future extreme rainfall values from changes in monthly rainfall amounts. The approach adjusts the local IDF curve which addresses both changes in rainfall frequency and magnitude. In order to extract a relationship between short duration precipitation and monthly precipitation, Jacob *et al*., (2009) used the following equation to fit power law curves to the data:

$$P_{short} = AP_{month}^{K} \qquad \text{(Eq. 2)}$$

where: P_{short} is the short duration precipitation intensity
P_{month} is the monthly precipitation total
A and K are parameters obtained by fitting Eq. 2 to the data

This relationship is manipulated to express fractional changes in the short-term precipitation as a function of fractional changes in monthly precipitation.

$$\frac{\Delta P_{short}}{P_{short}} = K\frac{\Delta P_{month}}{P_{month}} \qquad \text{(Eq. 3)}$$

Jacob *et al*. applied this statistical technique to 10 climate stations in Metro Vancouver, British Columbia, and found that "the fitted curves explained most of the variance, suggesting that there is a fairly robust relationship between monthly precipitation and short duration rainfall" (p.10). This conclusion is very important because it provides a technique to generate a higher temporal and spatial resolution than those currently provided by global and regional climate models. The correlation between monthly precipitation and short-duration rainfall is evident in the precipitation data for the case study watershed (Figure 2.3). As monthly precipitation amounts increase, so too do the extreme daily rainfall amounts.

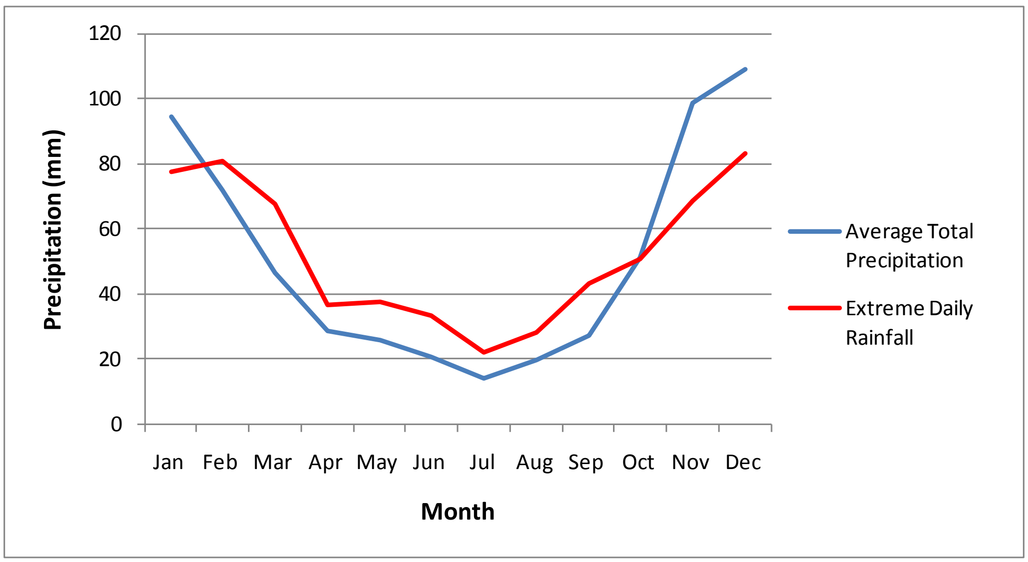

Figure 2.3: Average total monthly precipitation and extreme daily rainfall for 1971-2000 at Gonzales Heights, Victoria, BC, Canada (Environment Canada, 2012).

Holm and Weatherly (2010) used this relationship to adjust the IDF curve for Environment Canada's Gonzales Heights Climate Station (Lat 48°25' Long 123°19'). The researchers used the IPCC (2007) SRES A2 emission scenario in the Canadian Regional Climate Model to produce projections for fall and winter months for the 2050s (2040-2069). The climate model estimated an average precipitation increase of 10%. Regression equations were applied to this value to produce future changes for short duration rainfall. The resulting percentage changes to rainfall events were less than estimated changes to monthly rainfall (e.g. a 10% increase in monthly rainfall results in a 5.4% increase in rainfall depth for the 24-hour, 25-year rainfall event). This is consistent with research findings that indicate the percent increase in daily rainfall should be smaller than the percent increases in monthly rainfall (Sun *et al*., 2007).

This study also uses the A2 emission scenario because it is the most used in recent climate model studies (e.g. Zwiers *et al*., 2011; Kharin *et al*., 2007). The A2 scenario contains some of the highest CO_2 concentrations in all of the emission scenarios, however since production of the IPCC 2007 report, new knowledge has emerged which suggests that greenhouse gas emissions are exceeding the A2 “worst case” scenario (Holm and Weatherly, 2010). Therefore, given this information, A2 is a suitable emission scenario for this study.

The 2050s time frame is used because it is appropriate for long-term land use and infrastructure planning considerations; it limits the range of uncertainly regarding climate projections; and it is in line with the period used in other regional hydrologic impact studies (Rodenhuis *et al*., 2007).

The Pacific Climate Impacts Consortium’s (PCIC) Regional Analysis Tool was used to compare other GCMs to the CRCM that generated values for the Holm and Weatherly study. This online tool uses an ensemble of 15 GCMs to calculate future climate conditions for the Pacific and Yukon region (PCIC, 2011). The tool was used to produce the median and 75th percentile projections for the watershed’s three wettest months (Nov, Dec, Jan). Outputs indicate that the greatest percent increase in precipitation is expected to occur in November (Table 2.2).

Table 2.2: Percentage increase in precipitation for the median and 75th percentile projections for the 2050s (2040-2069) compared to baseline climate (1961–1990) simulated using an ensemble of 15 GCMs following the SRES A2 emission scenarios.

Month	median	75th
Nov	10	20
Dec	6	14
January	4	11

The 10% increase in monthly precipitation that Holm and Weatherly obtained from the CRCM is equal to the 10% median projection produced by PCIC's GCM ensemble for November. Given this agreement, this study elected to follow Holm and Weatherly's adjusted IDF curve. From here forth, the median 10% projection is defined as Scenario 1.

In addition to the median forecast, this study also explores a second scenario in which the potential effects of the 75th percentile projections are evaluated. Scenario 2 estimates that during the 2050s, precipitation for November will increase by 20%. This is twice the amount of change that is expected under Scenario 1. Therefore, the Scenario 1 values produced by Holm and Weatherly were doubled to provide Scenario 2 values (Table 2.3). The adjusted IDF data were used to identify future rainfall amounts for a range of durations and return periods which are necessary for assessing flood risk (Maidment, 1993).

Table 2.3: Change to return period rainfall amounts for the 2050s for the median (Scenario 1) and 75th percentile (Scenario 2) projections. Base rainfall amounts are from the Gonzales Heights (1925-1988) weather station (Holm and Weatherly, 2010).

		Return Period											
		5 year			10 year			25 year			100 year		
Duration	Unit		2050s Scenario			2050s Scenario			2050s Scenario			2050s Scenario	
		Historic	1	2	Historic	1	2	Historic	1	2	Historic	1	2
2-hour	mm	**15.0**	**15.8**	**16.6**	**17.4**	**18.4**	**19.4**	**20.4**	**22.3**	**24.3**	**25.0**	**26.4**	**27.8**
	% change		5.3%	10.7%		5.7%	11.5%		9.4%	18.9%		5.6%	11.2%
6-hour	mm	**28.2**	**30.0**	**31.4**	**33.0**	**35.4**	**37.8**	**39.0**	**42.7**	**46.4**	**47.4**	**51.0**	**54.6**
	% change		6.4%	11.3%		7.3%	14.5%		9.4%	18.9%		7.6%	15.2%
12-hour	mm	**42.0**	**45.6**	**49.2**	**49.2**	**52.8**	**56.4**	**58.8**	**62.4**	**66.0**	**72.0**	**76.8**	**81.6**
	% change		8.6%	17.1%		7.3%	14.6%		6.1%	12.2%		6.7%	13.3%
24-hour	mm	**64.8**	**67.2**	**69.6**	**74.4**	**79.2**	**84.0**	**88.8**	**93.6**	**98.4**	**108.0**	**115.2**	**122.4**
	% change		3.7%	7.4%		6.5%	12.9%		5.4%	10.8%		6.7%	13.3%

Together Scenario 1 and 2 represent changes to rainfall intensity that range from 3.7% to 18.9%. These values are generally inline with several studies including research by Onof and Arnbjerg-Nielsen (2009) that indicate increases of 2% to 15%; IPCC’s (1990) suggestion of a likely increase of 4 to 15%; and Kharin *et al.* (2007) predication of 7% to 12% increase in extreme precipitation. Interestingly, each of these studies uses unique methods and all resulted in relatively comparable projections.

2.4.3 Future Land Use

The watershed’s impervious area needed to be adjusted to account for future population growth and increased urban density. To create a future land use scenario, the watershed was divided into 21 sub-catchments and adjustments were made to the impervious area for each sub-catchment. Calculations made by KWL (2007) for the year 2032 were incorporated into the adjustments. KWL used municipal plans and staff input to predict that impervious area would increase from the existing 50% coverage to 56% for the year 2032. For the 2050s timeframe used in this study, the assessment determined that total average impervious area is anticipated to increase to 59%. The impervious areas of the 21 sub-catchments range from a low of 15% to a high of 74%.

2.4.4 Hydrologic/Hydraulic Model

A hydrotechnical assessment was completed using XPSoftware’s Stormwater and Wastewater Management Model (XPSWMM) version 2011. This software is widely used for predicting accurate flows for drainage systems which detain significant volumes of water (XPSWMM, 2011; KWL, 2007). XPSWMM is appropriate for use in the case study area because it is best suited for prediction of flow rates from smaller urban catchments (Elliot and Trowsdale, 2007). The current model generally follows the model structure developed by KWL.

New data was used in some instances (e.g. LIDAR) and parameters such as channel shape and conduit sizes were updated (Appendix C). See KWL (2007) for details on model construction.

Two modeling approaches are typically used with XPSWMM: single event and continuous simulation. This study uses a single event-based approach because this method is commonly used for modeling infrequent extreme storm events and it is suitable for purposes of assessing hydraulic capacity (Tan *et al.*, 2008). An event-based approach requires the values of several parameters to be defined and then assumes a rainfall event of a specific amount will always result in the same magnitude of runoff. The continuous simulation approach uses a historical rainfall record that can more accurately represent the spatial and temporal interaction of the physical aspects of the watershed which affect runoff (Stephens, 2011).

A major challenge of continuous simulation is the nature of obtaining rainfall records for infrequent events. Rainfall records available for the Bowker Creek watershed did not contain a sufficient sample of extreme rainfall events. Therefore, in order to perform the hydrologic/hydraulic assessment, a single event-based approach was used. Synthetic rainstorms were developed using the Soil Conservation Service (SCS) Type 1A hyetograph (Figure 2.4). This design storm accurately represents rainfall patterns for coastal BC and its suitability for use in the Bowker Creek watershed has been previously confirmed (KWL, 2007). Though the SCS Type 1A rain distribution may slightly overestimate peak flows, it is still appropriate given other uncertainties of climate change.

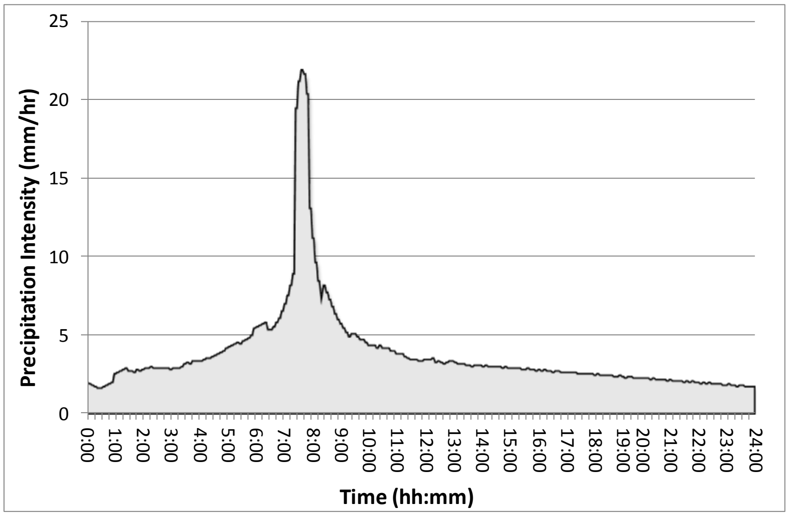

Figure 2.4: Soil Conservation Service Type 1A hyetograph for the historic 24-hour 25-year rainfall event.

2.4.5 Model Calibration and Validation

The model was calibrated using the rainfall record from December 14, 2006 to January 2, 2007 and validated using the records from January 3, 2006 to January 30, 2006. Modeled discharge with a 3 minute time step was compared to empirical discharge at the Trent Street and Monterey flow monitoring sites. Discharges at these sites were calculated from the stage-discharge equation (Table 2.4) used in the Bowker Creek Master Drainage Plan (KWL, 2007, KWL pers. comm., 2011).

Table 2.4: Stage-discharge equations for Trent St. and Monterey Ave. where y = discharge (m^3/s) and x = stage (m).

	Discharge m^3/s	Equation
Trent St.	0.0 to 0.32	$y = 7.6509x^2 + 0.3206x$
	>0.32	$y = 0.7183\ x^2 + 2.5299x$
Monterey Ave.	0.0 – 0.94	$y = 3.324\ x^2 + 1.3382x$
	>0.94	$y = -0.6752WLx^2 + 5.6352x - 0.5013$

Model calibration and validation was performed using in stream water level data that were collected by ultra-sonic level sensors. During flood events the sensors can become submerged causing a break in water level data. This typically occurs when discharge rates exceed the conduit capacities at Trent St. and Monterey Ave. Consequently, water level data were not available to calibrate and validate the model for large out of stream flood events. This introduces a level of uncertainty in the simulations for events that surcharge conduit capacity. In Appendix A, bold font indicates the discharge rates at which conduits were found to surcharge. Below these values, there is higher confidence in model accuracy and conversely, above these values there is lower confidence.

Model performance was evaluated using the Nash-Sutcliffe efficiency (NSE) coefficient. The NSE is a normalized measure (-∞ to 1.0) that compares the mean square error generated by a model simulation to the variance of the observed flows. A value of 1.0 indicates that the model perfectly simulates the observed flows. A value of 0 indicates that the model performance is equal to using the mean of the flows for predictions. A value <0.0 indicates questionable model performance because the discharge mean is more accurate for predictions than the simulation. The NSE represents a form of noise to signal ratio, comparing the average 'size' (variability) of model to the 'size' (variability) of the observed flows (Schaefli and Gupta, 2007). Though there are limitations with the NSE, it is commonly used by hydrologists when calibrating and reporting the results of catchment modeling. The NSE equation is as follows:

$$\text{NSE} = 1 - \frac{\sum_{t=1}^{T} \left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T} \left(Q_o^t - \overline{Q_o}\right)^2} \qquad \text{(Eq. 4)}$$

where:
Q_o is observed discharge
Q_m is modeled discharge
Q_o^t is observed discharge at time t
Q_m^t is modeled discharge at time t

Calibration efforts focused on peak in stream flows. A sensitivity analysis was used in conjunction with the NSE, resulting in minor adjustments to variables such as Manning's 'n' and soil properties. The calibration NSE coefficients for Trent St. and Monterey Ave. locations were 0.74 and 0.78 respectively (Figure 2.5). The corresponding validation values were 0.87 and 0.74 (Figure 2.6). The model can predict flow rates in Bowker Creek with a reasonable level of accuracy and is comparable to the model used in the KWL study. There is higher confidence in the model during major rainfall events compared to periods of lower flows (KWL, 2007).

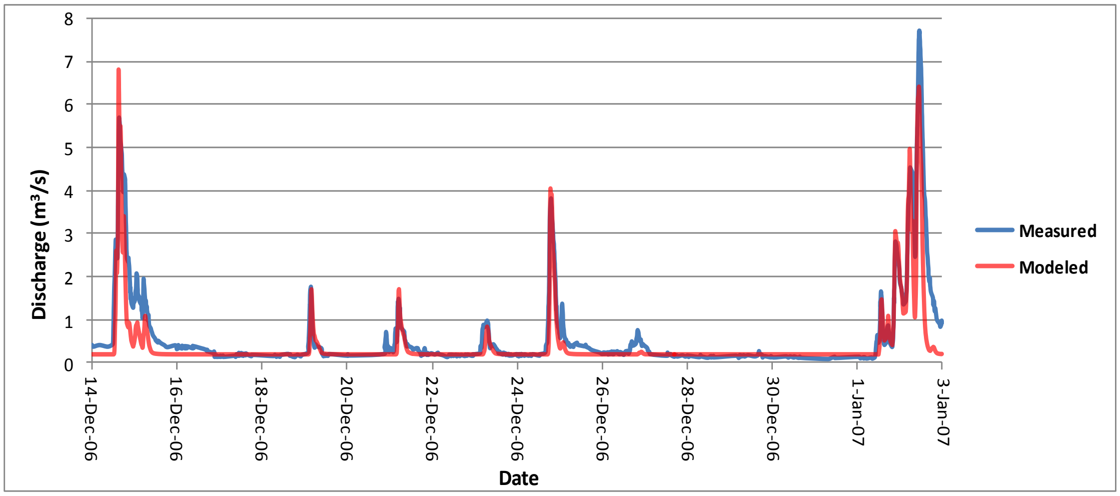

Figure 2.5: Measured and modeled discharge at Monterey Ave. for the calibration period (Dec 14, 2006 – Jan 2, 2007).

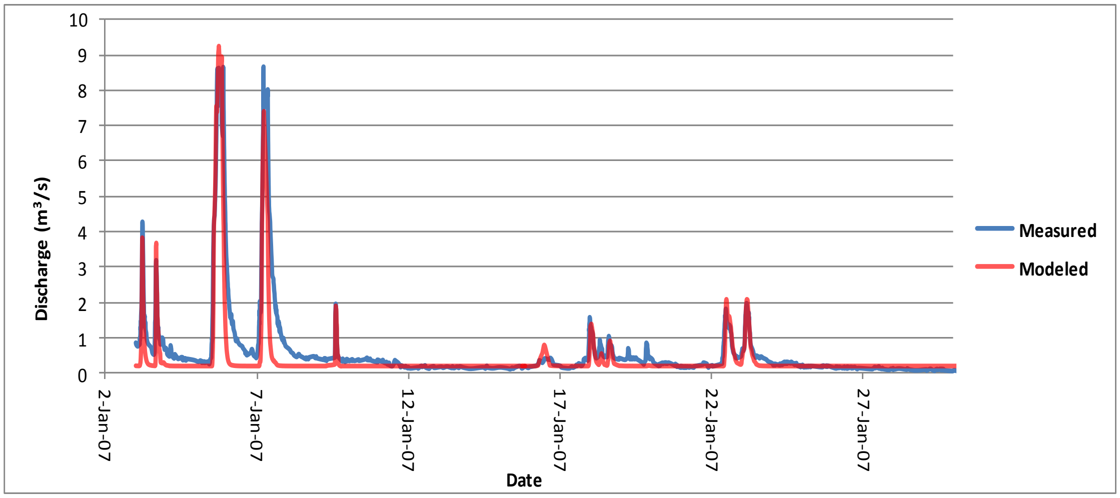

Figure 2.6: Measured and modeled discharge at Monterey Ave. for the validation period (Jan 3, 2007 – Jan 30, 2007).

Likely reasons for the imperfect NSE coefficient include errors in precipitation, inaccuracy in low flow measurements at the Trent and Monterey stations and errors in the stage-discharge rating curve (KWL, 2007). An assessment of the data indicates that the main sources for the variance are likely due to inaccuracies in measured and calculated flows at both high and low flows. For example, at high flows the modeled flows could be accurate; however, the data are compared against flows that were calculated using a stage-discharge equation that is beyond its established confidence limit. At high flows, equation accuracy is problematic because during major rainfall events the level sensors can be submerged producing inconsistent or no data. During low flows there are known issues with measurements due to a seasonal weir placement downstream of the Trent station (KWL, 2007). Inaccuracies in low flows and the recession period exist because the model was primarily developed to estimate peak flows. The combination of monitoring inaccuracies together with flows that the model was not targeted for has a negative effect on the NSE value.

2.4.6 Assumptions and Limitations

The analyses carried out in this study are based on the following assumptions and limitations:

1. The highest intensity rainfall events occur with synoptic weather patterns (i.e. not localized convective storms).
2. For the Trent and Monterey flow monitoring stations, the stage-discharge equations adequately represent the discharge flows at a given stage (i.e. no review was undertaken of the accuracy of the stage-discharge curves provided).
3. The IDF curve adequately represents the likelihood of a particular rainfall intensity and duration (i.e. no review was undertaken of the accuracy of the IDF curve).
4. The predicted change in precipitation is based on the outcomes for the A2 emission scenarios. Actual future emissions scenarios may follow alternate scenarios.

5. The Pacific Climate Impacts Consortium's Regional Analysis Tool can adequately project precipitation changes for the 2050s.
6. The statistical correlation between monthly precipitation depth and precipitation intensity remains reasonably constant over time (Holm and Weatherly, 2010).

2.5 Results and Discussion

2.5.1 Runoff modeling

The hydrologic/hydraulic model was used to assess how predicted changes in rainfall and land use may affect watershed hydrology. Changes to peak flows rates, flood extents and flood volume are examined in detail.

The local level of service for flood protection in the Bowker Creek watershed is to have no flooding of private property during the 24-hour 25-year storm event. To maintain consistency with the local standard, the assessment primarily focuses on impacts as they relate to this design storm. For additional information beyond the local design standard, the 5-year, 10-year and 100-year return periods for the 2-hour, 6-hour, 12-hour and 24-hour event durations are also modeled, but are generally not reviewed in detail. Unless otherwise specified, results described below refer to 24-hour events.

2.5.1.1 Peak Discharge

Conduit capacity (hydraulic grade line at conduit crown) has a limiting effect on peak flow rates during extreme rainfall events. The model shows that capacity is reached at peak flow rates of 13.6 m^3/s for Monterey Ave. and 18.4 m^3/s for Trent St. (Appendix A). These flow rates correspond to approximately a 3-year and 10-year return periods respectively. As discharge rates surpass these thresholds, these sections begin to surcharge which limits the downstream impact on conduit flow rates. Model results show that under existing land use conditions, discharge rates begin to be affected by conduit capacity when rainfall amounts reach 70 mm (Figure 2.7). Based on the historic IDF curve, this corresponds to a return period of approximately 8-years. Under future land use conditions, capacity begins to be reached at approximately 65 mm or a 5-year return period. This represents a 60% increase in the frequency that the system will begin to surcharge.

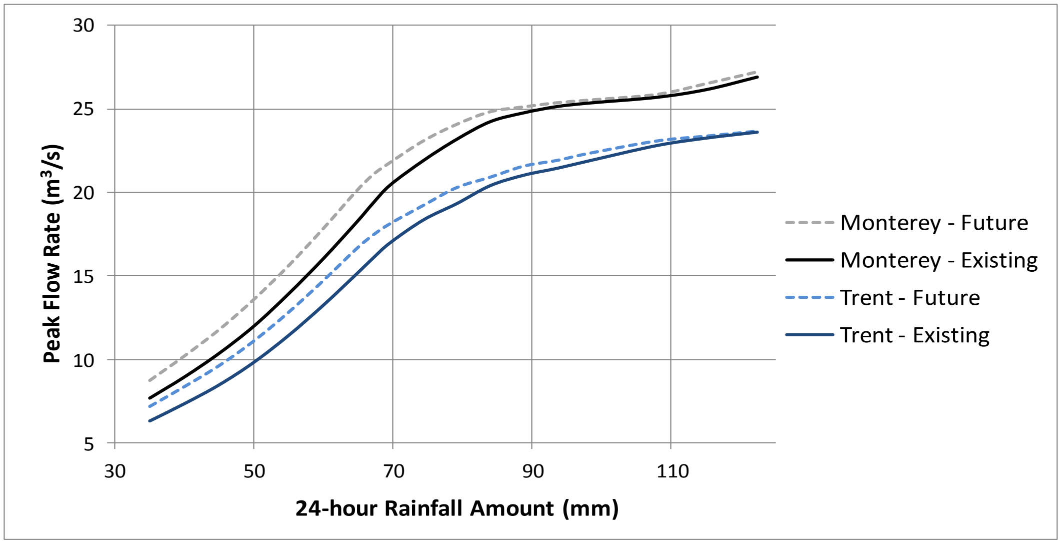

Figure 2.7: Peak flow rates at Monterey Ave. And Trent St. for future land use and existing land use.

As water levels rise above conduit capacity, some sections become pressurized and velocity rises resulting in continually smaller increases in discharge rates. This generally occurs between 70 and 100 mm storm events. After 100 mm there are minimal increases in peak flow rates indicating full hydraulic capacity in some sections. Consequently, additional runoff must be temporary stored within the system or discharged out of the system creating overland flow. If conduits had higher capacities, then during major storm events peak flow rates would raise significantly more than those reported. Figure 2.7 above can be used to identify peak flow rates for specific rainfall amounts (e.g. future rainfall events) and determine the impact of future land use. Figure 2.8 provides a closer illustration.

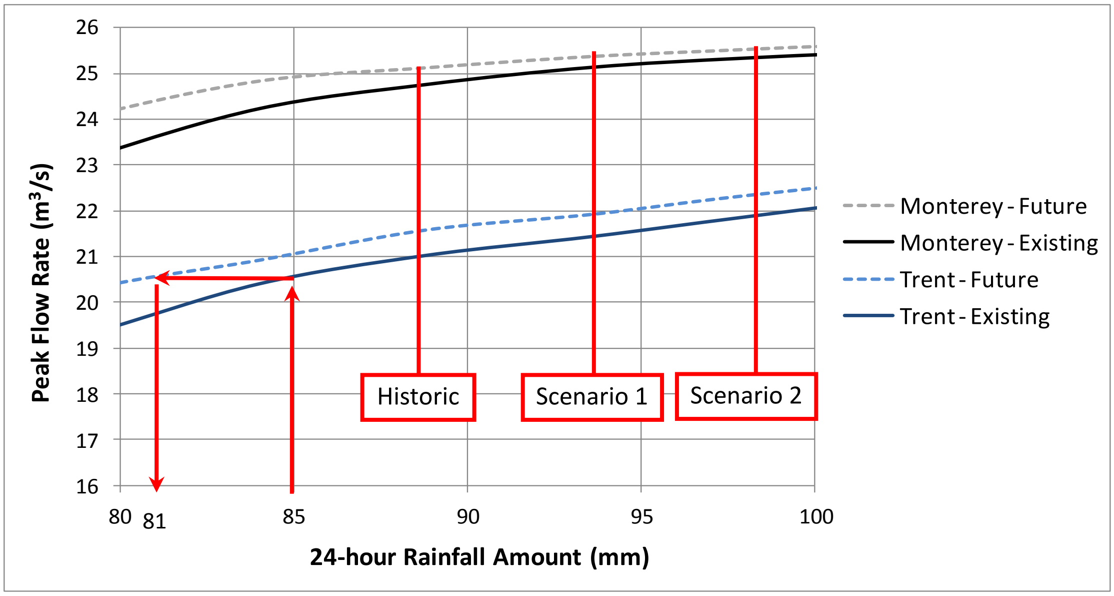

Figure 2.8: Peak flow rates for the 25-year rainfall event showing historic and two future climate scenarios. Arrows indicate rainfall amounts required to generate equal peak flows under current and future land use.

Model results indicate that predicted land use changes have a comparable impact on peak flow rates as climate scenario 1. Future land use has the largest effect on less frequent storm events (e.g.12% increase for the 5-year event) and the least effect the major storm events (e.g. 1% for the 100-year storm event). Part of this difference is attributed to capacity issues described above. Another important factor for the variation is that during large events, pervious areas become saturated and act like impervious areas (Mejia and Moglen, 2010). Therefore, land use changes have less effect because some pervious areas were already performing like impervious areas. During smaller storm events, this situation does not occur to the same degree.

Due to restricted hydraulic capacity, peak flow rates do not indicate the true magnitude of potential change for major storm events and thus, they are not an adequate metric for assessing the full extent of climate impacts for major storm events. Peak flow rates are most suitable for evaluating the magnitude of changes up to conduit capacity. Above this area, flood extent and flood loss volume are a more useful metric for quantifying climate impacts as they are not subject to the same underground hydraulic restrictions.

2.5.1.2 Flood Extents

Modeling results indicate that the historic 25-year 24-hour rainfall event floods an approximate area of 35,300m^2. This is anticipated to increase by 21% under scenario 1 and by 50% under scenario 2. With continued urbanization, flood extents are estimated to increase by 50% for 72% respectively (Figure 2.9 and Table 2.5).

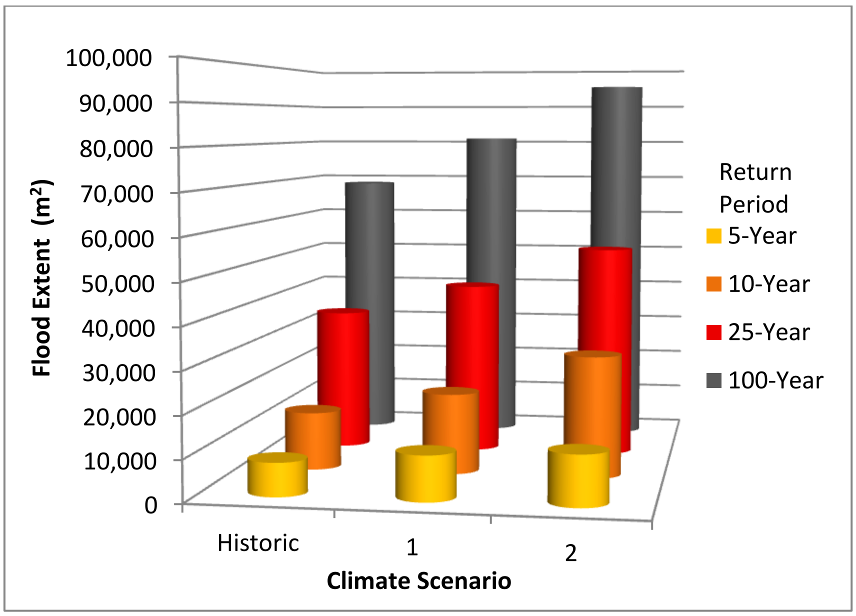

Figure 2.9: Flood extent simulated using existing land use for the historic and two projected climate scenarios.

Table 2.5: Total area flooded and percent change for present and future land use for the historical and two projected climate scenarios.

		Return Period											
		5-year			10-year			25-year			100-year		
		Historic Climate	2050s Scenario 1	2050s Scenario 2	Historic Climate	2050s Scenario 1	2050s Scenario 2	Historic Climate	2050s Scenario 1	2050s Scenario 2	Historic Climate	2050s Scenario 1	2050s Scenario 2
Existing Land Use	Flood Area (m^2)	8,000	10,800	12,100	14,000	19,500	29,400	35,300	42,800	52,800	68,500	81,000	95,200
	% change		35%	51%		39%	110%		21%	50%		18%	39%
Future Land Use	Flood Area (m^2)	11,300	12,800	13,700	18,800	28,000	35,300	43,200	52,800	60,900	77,600	90,800	102,100
	% change*	41%	61%	72%	34%	99%	151%	22%	50%	72%	13%	33%	49%

* % change calculated against the base scenario of historic climate and existing land use.

The increases in flood extents are a concern considering they were the result of comparatively small increases in rainfall intensity (5.4% and 10.8%). If other methods, such as the delta change method, were followed then future rainfall increases would be almost double the values used in this study. Consequently, estimated impacts on flood extents would be significantly greater than those reported. The difference in rainfall scenarios used in this study compared to other similar studies highlights the challenges of uncertainty when quantifying the effects of climate change. Other methods may overestimate future impacts, but given the high level of uncertainty, this level of caution may be warranted.

To help overcome the inherent limitation of defining specific scenarios, Figure 2.10 can be used to estimate the predicted flood extent for a range of rainfall amounts. Should alternative rainfall scenarios be desired, this figure can provide estimates for events that differ from the values used in this study.

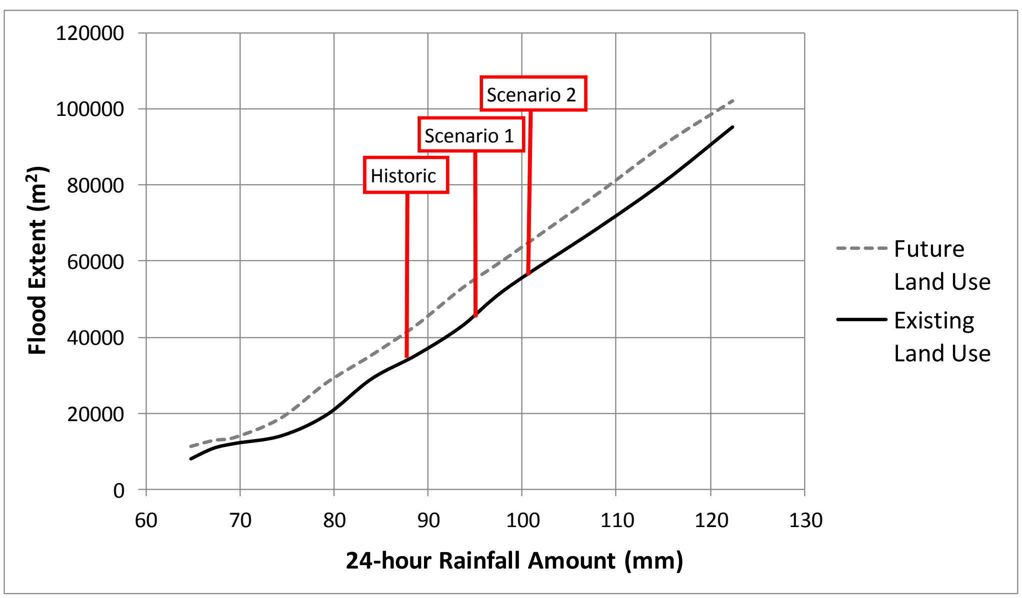

Figure 2.10: Modeled flood extent by rainfall amount for existing and future land use. Historic and future climate scenarios indicated for 25-year return period.

The increase in flood extent is a concern, particularly for 25-year and larger events where much of the expansion flows onto properties with buildings or houses. For more frequent storm events, the majority of the area that is expected to flood is green space and roads, though some buildings are also at risk. In general, results indicate that climate change is expected to increase the frequency and magnitude of flood events, however, impacts are not considered severe in terms of public safety (e.g. threat of drowning).

Results suggest that climate change and increases in impervious areas may cause additional buildings to fall below the 25-year flood protection standard. In particular, a community recreation centre, located near the centre of Figure 2.11 appears susceptible to projected flood flows. This location currently should not experience flooding during the historic 25-year design storm, but under climate scenario 1, this area is projected to flood. If the climate does not change, then this area is still expected to flood due to continued urbanization. The combination of future land use changes and climate scenario 2 results in the greatest potential flood impacts. Additional figures in Appendix B show flood extents for the 10-year and 100-year return period events. Note only downstream areas with largest areas of flooding are shown in the figures.

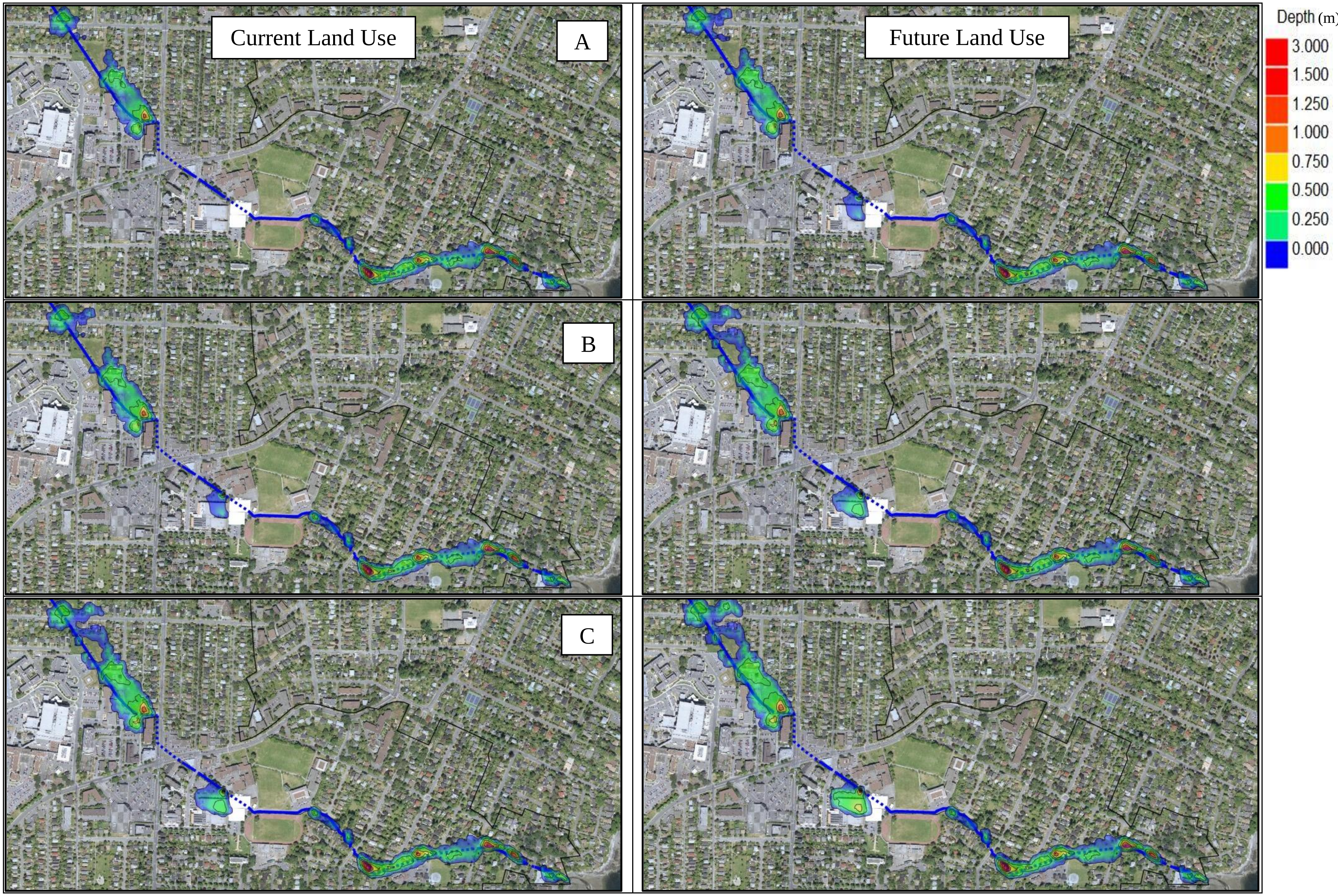

Figure 2.11: Areas of main flooding using present land use (left) and future land use (right) for the 24-hour 25-year rainfall event simulated using: (A) historical climate; (B) 2050s climate scenario 1 (median projection); and (C) 2050s climate scenario 2 (75^{th} percentile projection).

The largest percent change to flood extent occurs during the 10-year storm event. Under existing land use conditions, flood extent was shown to increase by 39% and 110% for climate scenarios 1 & 2 respectively. When assessed with future land use changes, values increase to 99% and 151% (Figure 2.12). While the area is relatively small compared to longer return period events, this change nonetheless indicates a considerable decrease in the level of flood protection. In practical terms, the compounding effect of climate change and urbanization means the total area that presently floods on average once every 10 years (14,000 m^2) may in the future, be similar to the total area that floods on average once every 5 years (13,700m^2 for scenario 2 and future land use). This represents a halving of the return period (or in other terms, a doubling in the frequency of that flood magnitude).

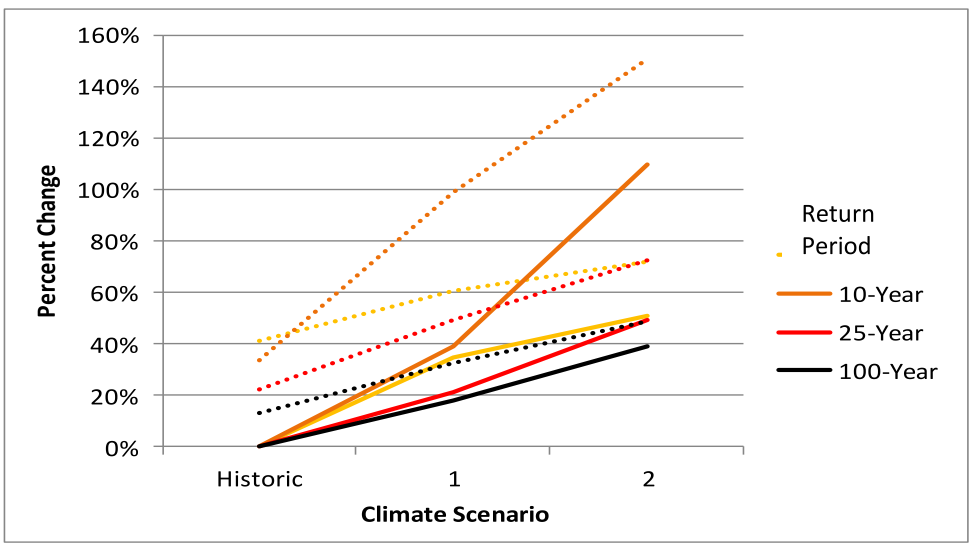

Figure 2.12: Total percent change in the extent of flooded area. Solid line shows current land use, dotted line shows future land use.

The data show that urbanization has the largest effect on smaller rainfall events. If the historic climate does not change, then the predicted changes in land use can increase flood extent by 41%, 34%, 22% and 13% for the 5, 10, 25 and 100-year return period events respectively. Given the sensitivity of smaller storm events to changes in imperviousness, it is important to minimize the creation of additional impervious surfaces and mitigate runoff from new impervious surfaces.

2.5.1.3 Flood Volume

The XPSWMM hydrologic/hydraulic model calculates flood loss volume by multiplying the flow rate of water spilling out of the channel at each node by time. The model indicates that the historic 25-year 24-hour rainfall generates overland flood flows with an approximate volume of 39,200 m^3. This is anticipated to increase by 39% under scenario 1 and by 86% under scenario 2. With continued urbanization, flood volume is estimated to increase by 73% and 123% respectively (Figure 2.13 and Table 2.6).

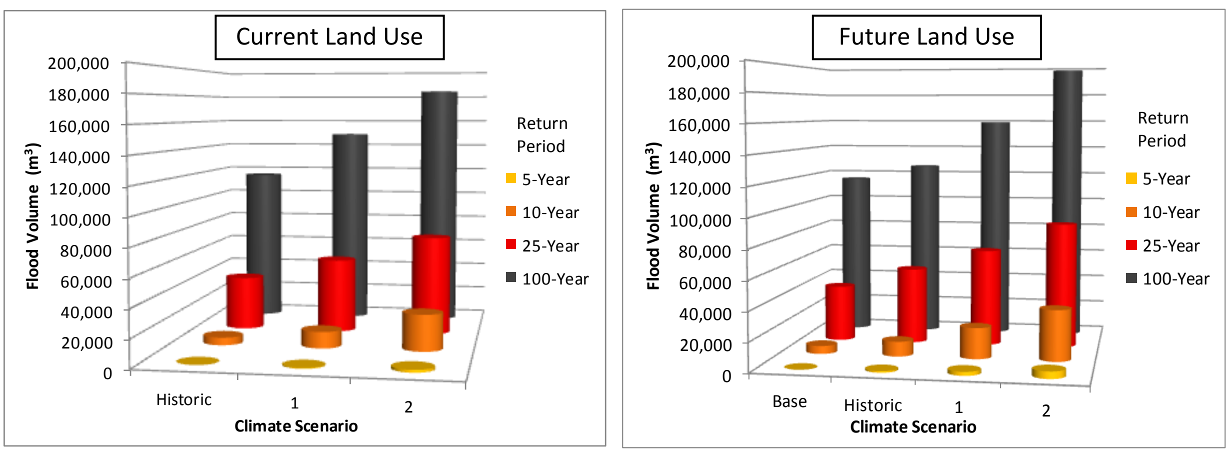

Figure 2.13: Changes in flood volume under historic and two future climate scenarios for current and future land use.

Table 2.6: Total flood loss volume and percent change for the 24-hour storm duration showing the effect of current and future land use with historic and two future climate scenarios.

		Return Period											
		5-year			10-year			25-year			100-year		
		Historic Climate	2050s Climate		Historic Climate	2050s Climate		Historic Climate	2050s Climate		Historic Climate	2050s Climate	
			1	2		1	2		1	2		1	2
Present Land Use	Volume (m^3)	0	500	1,900	5,500	11,900	26,300	39,200	54,400	72,900	115,600	149,100	184,000
	% change		∞	∞		114%	376%		39%	86%		29%	59%
Future Land Use	Volume (m^3)	1,000	2,600	4,800	10,200	21,300	35,100	53,200	67,700	87,500	125,600	159,100	197,800
	% change*	∞	∞	∞	84%	285%	535%	36%	73%	123%	9%	38%	71%

*% change calculated against the base scenario of present land use and historic climate

Changes to flood volume help indicate the possible magnitude of mitigation measures. To maintain current levels of flood protection, there is the potential that onsite rainwater management facilities could be used to mitigate the increase in flood volume (Semadeni-Davies *et al*., 2008). This strategy would attempt to temporarily store rainwater to prevent runoff which contributes to downstream flooding (Deitz, 2007). To be effective, facilities should be able to accept the volume of rainfall that occurs before and during the peak of the storm event. The combined volumes begin to reveal the extent of landscape-based sourced controls that would be required to help mitigate future impacts.

2.5.2 Implications for Drainage Infrastructure

Drainage infrastructure in the watershed does not currently meet the local flood protection level of service and it is anticipated that climate change will further reduce the level of service. Under future scenarios for land use and rainfall change, private property may flood under the 5-year storm event. This level of flood protection is significantly below the 25-year target and below the normal modern design standards for a major drainage facility (Crowther, 2000). Upgrading drainage infrastructure to the local standard will require significant infrastructure investments. KWL (2007) assessed required infrastructure upgrades, under both current and future climate/land use scenarios and determined the Class ‘D’ preliminary estimates for such upgrades are between $22 million and $46 million (2007 dollars). A main reason for the significant cost is that 63% of the watershed’s main drainage infrastructure is underground.

The need to initiate a culvert and storm drain replacement program is essentially determined by the magnitude of the expected damages that should, through a decision making process, be compared to the costs of implementing infrastructure upgrades (Mailhot and Duchesne, 2010; Auld and Maclver, 2005). A detailed assessment of potential damage costs due to flooding has not been completed for the case study watershed. A brief review of at-risk properties and their market value was conducted and it did not clearly indicate that potential damage costs would outweigh the costs for recommended infrastructure upgrades. This comparison does not include the range of socioeconomic and environmental impacts and costs that are also associated with flood events. At this time, given the significant investment required and uncertainty of projected climate change scenarios, local governments may prefer to accept a reduction in the level of service and defer infrastructure upgrades.

A potentially more cost effective long-term strategy to mitigate the hydrologic impacts of climate change and land use would be to develop an asset management program that focuses on the remaining service life of drainage infrastructure. As culverts and storms drains reach the end of their service life, they can be replaced with higher capacity conduits that are designed to convey future flows. Upgrading capacity at the time of replacement can be undertaken at relatively little additional cost (Denault *et al*., 2006). Deferring upgrades also provides the significant benefit of allowing additional time for climate science to improve model projections and rainfall design criteria. Given the range of uncertainties that currently exist, the additional time and knowledge gained could increase the confidence of implementing appropriately designed infrastructure upgrades.

Using an asset management approach for climate adaptation means that for many decades, communities may experience a continual reduction in the level of flood protection with the highest risk of flooding occurring as the asset nears the end of its useful life. This may not be publically acceptable and decision makers will have to determine the costs and benefits of such an approach. Furthermore, if rainfall intensities increase at a faster rate than projected, then an asset management approach may not be appropriate and communities may want to upgrade prior to the end of the asset's useful life.

Another key consideration is sequencing infrastructure upgrades. Ideally, infrastructure upgrades begin at the bottom of the watershed and move up to the headwaters (KWL, 2007). Increasing the capacity of conduits higher in the watershed may exasperate flooding in the lower portions. Prioritizing the schedule of upgrades will need to consider both the infrastructure life cycle and sequencing of upgrades.

Given the significant effect of urbanization on watershed hydrology, a flood management strategy should not only be limited to in-stream infrastructure upgrades. Consideration should also be given to landscape based approaches that aim to minimize the creation of new impervious areas and mitigate associated runoff. Compared to hard infrastructure such as underground culverts, a landscape-based approach can provide a range of additional social, environmental and economic benefits that may not be realized under conventional flood management techniques (EPA, 2000).

2.6 Summary

This study used hydrologic/hydraulic modeling to simulate how projected changes in extreme rainfall and urbanization may affect flooding in the Bowker Creek catchment, an urban watershed located near Victoria, British Columbia, Canada. The assessment focused on quantifying impacts for the 24-hour 25-year local design storm. The A2 emissions scenario was used in an ensemble of GCMs to generate the median and 75th percentile projections for the 2050s. The monthly rainfall changes generated by the GCMs were adjusted with regression equations to produce two scenarios for short-duration rainfall. This resulted in the design storm being increased by 5.4% and 10.8%. To account for future land use changes, the catchment's impervious area was increased from a total average of 50% to 59%. Based on these parameters, the principal findings are as follows:

- The drainage system currently does not have adequate capacity to meet the local flood protection standard. Projected changes in climate and land use are anticipated to magnify existing flood risks.
- The return period for a flood event of a given magnitude has the potential to be halved (e.g. a flood event with a 10-year return period may occur on average once every 5-years in the future).
- Predicted land use changes pose similar flood impacts as climate scenario 1.
- The two simulated climate scenarios increased flood extents by 21% and 50%. When combined with future land use, flood extents were shown to increase by 50% and 72%.

Due to the multiplicative nature of uncertainties and assumptions used in the research, study findings should be used with caution. Results should not be used as precise predictions as they are based on an underlying ensemble of GCMs which contains variation and assumptions regarding the statistical relationship between monthly rainfall volume and rainfall intensity. Results should be viewed as a general indication of the magnitude and direction of change that could occur over the next 30 to 60 years. This study offers some guidance as to whether predicted changes in climate and land use present critical areas of concern for the protection of public safety and the built environment. To-date reported flood episodes have been rare and limited to specific locations (Crowther, 2000), however the shift in the distribution of rainfall extremes and continued urbanization are set to increase the occurrence and magnitude of flood events. Mitigation measures will likely be necessary to maintain the current level of service for flood protection.

APPENDIX A – Peak Discharge

Table 2.7: Peak flow rates for Trent St and Monterey Ave for the 2050s following two climate projections representing the median (Scenario 1) and 75th percentile projections (Scenario 2) modeled using current (50%) impervious area coverage.

Trent St		Return Period											
		5-year			10-year			25-year			100-year		
Duration	Peak Flow Rate	Historic Climate	2050s Scenario 1	2050s Scenario 2	Historic Climate	2050s Scenario 1	2050s Scenario 2	Historic Climate	2050s Scenario 1	2050s Scenario 2	Historic Climate	2050s Scenario 1	2050s Scenario 2
2-hour	(m^3/s)	9.1	9.8	10.5	11.3	12.3	13.3	14.3	16.4	17.9	**18.4**	**19.1**	**20.5**
	% change		8%	16%		9%	17%		14%	25%		4%	11%
6-hour	(m^3/s)	12.2	13.3	14.2	15.2	16.7	17.7	18.3	**19.5**	**20.9**	**21.1**	**21.7**	**22.2**
	% change		9%	16%		10%	17%		7%	14%		3%	5%
12-hour	(m^3/s)	13.0	14.8	16.6	16.6	17.9	**19.0**	**19.7**	**20.8**	**21.3**	**22.1**	**22.6**	**23.2**
	% change		13%	27%		8%	15%		6%	8%		2%	5%
24-hour	(m^3/s)	15.1	16.1	17.0	**18.4**	**19.3**	**20.7**	**21.0**	**21.4**	**21.9**	**22.8**	**23.3**	**23.6**
	% change		6%	12%		5%	13%		2%	4%		2%	4%
Average % change			9%	18%		8%	15%		7%	13%		3%	6%

Monterey Ave		Return Period											
		5-year			10-year			25-year			100-year		
Duration	Peak Flow Rate	Historic Climate	2050s Scenario 1	2050s Scenario 2	Historic Climate	2050s Scenario 1	2050s Scenario 2	Historic Climate	2050s Scenario 1	2050s Scenario 2	Historic Climate	2050s Scenario 1	2050s Scenario 2
2-hour	(m^3/s)	11.1	12.0	12.9	**13.8**	**15.0**	**16.3**	**17.5**	**20.0**	**21.9**	**22.6**	**23.4**	**24.5**
	% change		8%	16%		9%	18%		14%	25%		4%	8%
6-hour	(m^3/s)	**14.9**	**16.2**	**17.2**	**18.4**	**20.2**	**21.5**	**22.2**	**23.5**	**24.7**	**24.9**	**25.3**	**25.6**
	% change		9%	16%		10%	17%		6%	11%		2%	3%
12-hour	(m^3/s)	**15.9**	**18.0**	**20.2**	**20.2**	**21.7**	**23.1**	**23.6**	**24.5**	**25.0**	**25.4**	**25.7**	**25.9**
	% change		13%	27%		8%	14%		4%	6%		1%	2%
24-hour	(m^3/s)	**18.2**	**19.4**	**20.5**	**21.9**	**23.2**	**24.3**	**24.8**	**25.2**	**25.4**	**25.7**	**26.2**	**26.9**
	% change		6%	12%		6%	11%		2%	2%		2%	5%
Average % change			9%	18%		8%	15%		6%	11%		2%	4%

BOLD: Peak flow rates limited because conduit at capacity (Hydraulic Grade Line at conduit crown). Beginning of surcharge. Flooding may occur.

Table 2.8: Peak flow rates for Trent St and Monterey Ave showing the effect of future (59%) impervious area against existing conditions (Base Scenario) using the historic climate and two future climate scenarios representing the median (Scenario 1) and 75th percentile projections (Scenario 2).

Trent St		Return Period															
		5-year				10-year				25-year				100-year			
Duration	Peak Flow Rate	Base Scenario	Climate Scenario			Base Scenario	Climate Scenario			Base Scenario	Climate Scenario			Base Scenario	Climate Scenario		
			Historic	1	2		Historic	1	2		Historic	1	2		Historic	1	2
2-hour	(m^3/s)	9.1	10.3	11.1	11.9	11.3	12.8	13.8	15.0	14.3	16.1	17.8	**19.2**	**18.4**	**19.6**	**20.6**	**21.1**
	% change		13%	22%	31%		13%	22%	33%		13%	24%	34%		6%	12%	14%
6-hour	(m^3/s)	12.2	13.9	15.0	16.0	15.2	17.0	18.2	**19.1**	18.3	**19.5**	**20.8**	**21.6**	**21.1**	**21.7**	**22.3**	**22.9**
	% change		13%	23%	31%		12%	20%	26%		6%	14%	18%		3%	6%	9%
12-hour	(m^3/s)	13.0	14.7	16.5	18.0	16.6	18.0	**19.2**	**20.6**	**19.7**	**20.9**	**21.4**	**21.8**	**22.1**	**22.5**	**23.1**	**23.4**
	% change		13%	27%	38%		8%	16%	24%		6%	8%	10%		2%	5%	6%
24-hour	(m^3/s)	15.1	16.7	17.5	18.1	**18.4**	**19.2**	**20.5**	**20.9**	**21.0**	**21.6**	**21.9**	**22.4**	**22.8**	**23.1**	**23.4**	**23.7**
	% change		10%	15%	20%		5%	11%	14%		3%	4%	6%		1%	3%	4%
Average % change			12%	22%	30%		10%	17%	24%		7%	13%	17%		3%	6%	8%

Monterey Ave		Return Period															
		5-year				10-year				25-year				100-year			
Duration	Peak Flow Rate	Base Scenario	Climate Scenario			Base Scenario	Climate Scenario			Base Scenario	Climate Scenario			Base Scenario	Climate Scenario		
			Historic	1	2		Historic	1	2		Historic	1	2		Historic	1	2
2-hour	(m^3/s)	11.1	12.5	13.5	**15.5**	**13.8**	**15.6**	**16.9**	**18.3**	**17.5**	**19.7**	**21.8**	**23.3**	**22.6**	**23.6**	**24.7**	**25.0**
	% change		13%	22%	40%		13%	22%	32%		12%	24%	33%		4%	9%	11%
6-hour	(m^3/s)	**14.9**	**16.9**	**18.3**	**19.4**	**18.4**	**20.6**	**22.0**	**23.2**	**22.2**	**23.5**	**24.7**	**25.2**	**24.9**	**25.3**	**25.5**	**25.8**
	% change		13%	22%	30%		12%	19%	26%		6%	11%	13%		1%	2%	4%
12-hour	(m^3/s)	**15.9**	**17.9**	**20.1**	**21.8**	**20.2**	**21.8**	**23.1**	**24.1**	**23.6**	**24.6**	**25.0**	**25.3**	**25.4**	**25.6**	**25.9**	**26.4**
	% change		13%	26%	37%		8%	15%	20%		5%	6%	8%		1%	2%	4%
24-hour	(m^3/s)	**18.2**	**20.1**	**21.1**	**21.8**	**21.9**	**23.1**	**24.1**	**24.8**	**24.8**	**25.1**	**25.4**	**25.5**	**25.7**	**25.9**	**26.5**	**27.2**
	% change		10%	16%	20%		5%	10%	13%		1%	2%	3%		1%	3%	6%
Average % change			12%	22%	32%		10%	17%	23%		6%	11%	14%		2%	4%	6%

BOLD: Peak flow rates limited because conduit at capacity (Hydraulic Grade Line at conduit crown). Beginning of surcharge. Flooding may occur.

APPENDIX B – Flood Extents

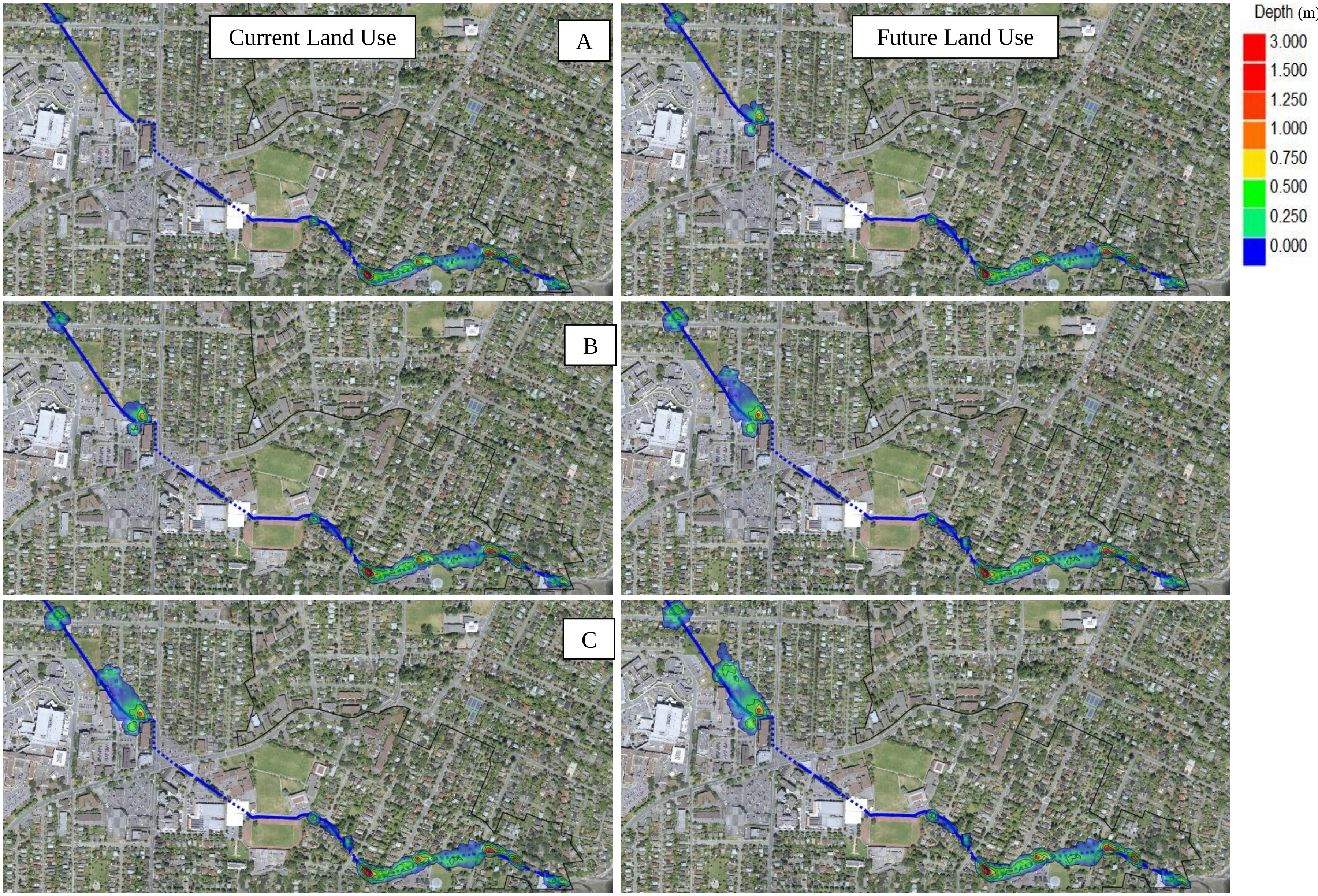

Figure 2.14: Areas of main flooding using present land use (left) and future land use (right) for the 24-hour 10-year rainfall event simulated using: (A) historical climate; (B) 2050s climate scenario 1 (median projection); and (C) 2050s climate scenario 2 (75th percentile projection).

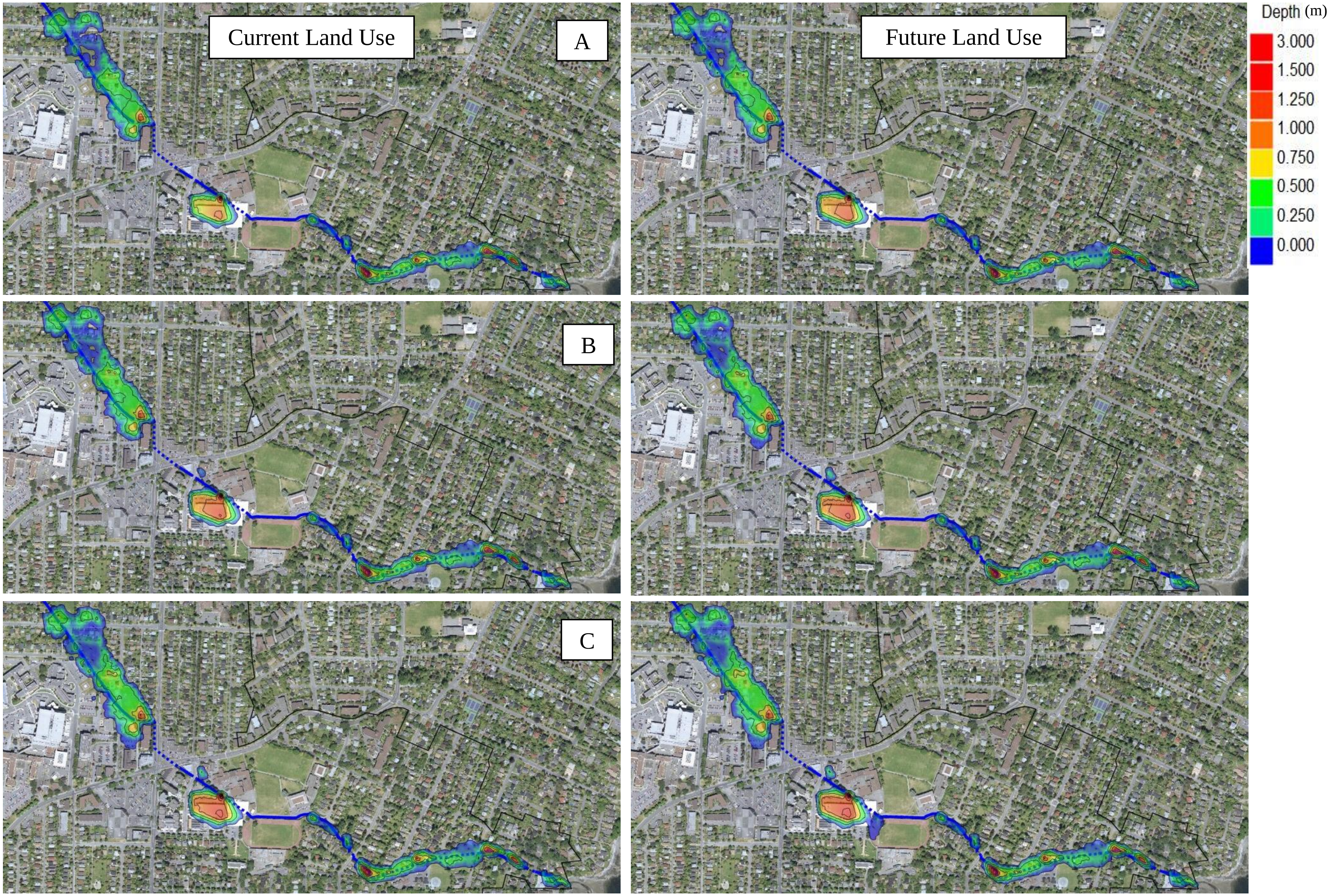

Figure 2.15: Areas of main flooding using present land use (left) and future land use (right) for the 24-hour 100-year rainfall event simulated using: (A) historical climate; (B) 2050s climate scenario 1 (median projection); and (C) 2050s climate scenario 2 (75th percentile projection).

APPENDIX C –Differences between Study and KWL Study

The hydrologic/hydraulic model developed for this study was based on the model used for the Bowker Creek Master Drainage Plan, developed by Kerr Wood Ledeil (2007). The two studies use much of the same data; however, updates and different values have been used in some instances (Table 2.9). The table highlights key differences between the studies. The list is not exhaustive. The difference in model values help to explain variance between model results. The model is sensitive to many parameters; therefore assumptions regarding these values can have considerable effect on model results. Any future research should revisit the assumptions and variables listed below.

Table 2.9: Key data difference between current study and the KWL study.

Variable	Description	Current Study		KWL Study	
Soil Saturated Hydraulic Conductivity	Clay	0.8 mm/hr		1.5 mm/hr	
Soil Wilting Point	Clay	0.26		0.1	
	Sand/Gravel	0.07		0.1	
Soil Field Capacity	Clay	0.36		0.14	
	Sand/Gravel	0.17		0.14	
Conduits	Oak Bay Tennis Bubble	CSP Ellipse 4.2 m x 2.7 m		CSP Ellipse 3.8 m x 2.7 m	
	Fort St and Foul Bay Rd	Arch 3.0 m x 2.7 m		Arch 3.0 m x 3.6 m	
Open Channel Shape		Developed from Sept 2010 survey and LiDAR data		Developed from Nov 2006 survey	
Elevations		DEM and DSM developed from LiDAR		Topographic maps with contours at 0.5 m or 1.0 m.	
24-Hour Rainfall	Return Period	Existing	Future	Existing	Future
	5-year	64.8	See Table 2.3 for details	64.8	77.0
	10-year	74.4		75.6	87.7
	25-year	88.8		85.2	102.0
	100-year	108.0		112.8	123.6
Future Impervious Area	Timeframe	2050s		2032	
	% impervious	59%		56%	
Peak Flow		3-Minute peak flow		15-Minute peak flow	
Modeling Software		XPSWMM 2011 with 2D (TUFLOW) extension		XPSWMM 9.5	

CHAPTER 3: HYDROLOGIC ASSESSMENT OF USING LOW IMPACT DEVELOPMENT TO MITIGATE PROJECTED FLOOD FLOWS IN VICTORIA, BC, CANADA

3.1 Introduction

The majority of climate change research has been focused on developing the data, methods and systems for predicting future climates. This research has been at the forefront of the significant scientific, public and political debate about whether the climate is changing, or will change in the future, and the drivers of this change. The debate may be subsiding now that the evidence for climate change is unequivocal (IPCC, 2007). As consensus solidifies, governments are responding by increasing calls for adaptation measures (BC MOE, 2010). For example, upon her retirement, the Auditor General of Canada, Sheila Fraser, stated that a “national long-term strategy and action plan are needed to plan for adaptation” (Fraser, 2011, p.5). This is one of only four matters of special importance that she outlined to the Government of Canada which underscores the acuteness and urgency of the challenge.

Such recommendations address the relative lack of research, tools and progress for climate change adaptation. There is extensive literature on potential climate impacts but comparatively little on viable mitigation measures. The unbalance is understandable given the necessary sequencing of research; however, a contributing factor is that adaptation efforts are hindered by the uncertainties and complexities of climate projections (Barnett *et al*., 2006; Auld and Maclever, 2005). A lack of confidence in the accuracy of climate projections makes it challenging to develop specific ‘actions plans’ and commit funding for implementation. While general impact studies can explore and report on a range of potential scenarios, implementing adaptation measures typically require more narrowly defined parameters. This is particularly true for designing urban drainage infrastructure (Mailhot *et al.*, 2007; Kije Sipi Ltd., 2001). A priority for many regions is to mitigate anticipated flood impacts; however, the ability to translate global climate science to local rainfall design criteria has been an obstacle for many (Mailhot and Duchesne, 2010; Arisz and Burrell, 2006; Metro, 2008).

New research is beginning to provide the techniques needed to move forwards with developing design targets for extreme rainfall events (Jacob *et al.*, 2009; Holm and Weatherly, 2010). Reducing the ambiguity of design parameters enables research to proceed to the next step in the evolution of climate adaptation: developing and evaluating pragmatic options for adapting to the expected changes in precipitation.

Conventional engineering approaches have been used to identify infrastructure upgrades required to mitigate anticipated flooding (Arisz and Burrell, 2005; Watt *et al*., 2003; KWL, 2007). However, due to the significant capital costs involved and uncertainties, governments have been reluctant to commit funding for recommended upgrades. An alternative potential solution is to use a decentralized approach that employs Low Impact Development (LID) techniques to manage the additional rainfall where it falls, before it enters drainage infrastructure. LID relies on runoff management measures that seek to control rainwater volume at the source by limiting imperviousness and retaining, infiltrating and reusing rainwater (Graham *et al*., 2004). By reducing the volume and rate of rainfall runoff, LID has the potential to maintain current flow rates under future rainfall regimes, thereby eliminating the need to increase the capacity of existing drainage infrastructure. LID has generally been implemented with the goal of maintaining or enhancing natural hydrological processes and environmental health (Graham *et al*., 2004). Suggestions to use it for the purpose of climate adaptation are relatively new (Semadeni-Davies *et al*., 2008; Bizikova *et al*., 2008). While research on site specific LID practices show that reduced flow volumes and reduced peak flow rates can occur (US EPA, 2000), there is still a lack of peer-reviewed studies demonstrating the effectiveness of LID on a watershed scale (Deitz and Clausen, 2008). Research is needed to determine if watershed scale application of LID can be used to mitigate the flooding that is anticipated to occur with climate change.

3.2 Objectives

Two objectives have been identified for this chapter:

i) Select three LID techniques and identify suitable locations for implementation in the Bowker Creek watershed.

ii) Evaluate the effectiveness of the three LID treatments in mitigating flood flows associated with projected changes in extreme 24-hour rainfall.

3.3 Case Study Area

The Bowker Creek Watershed located in Victoria, BC, Canada us used as a case study. See Chapter 2 for information.

3.4 Methods

3.4.1 Runoff Model

The same XPSWMM model described in Chapter 2 was used for this LID assessment.

3.4.2 Selection of LID Treatments

The first step in developing a manageable number of LID scenarios was to select a total of three LID treatments. There is a wide range of LID techniques that could potentially be used to reduce flood flows (Chapter 1). LID treatments used in this study were selected based on the primary criteria of:

- hydrologic profile

- potential for widespread application
- re-establishes or mimics natural conditions and processes

Secondary considerations include:

- aesthetics
- opportunities for public education and engagement
- asset replacement liability
- additional environmental and/or social benefits provided (e.g. water quality benefits, public amenity)

Based on these criteria the three treatments selected are:

- green roofs
- rain gardens
- top soil enhancements

Other options such as underground storage tanks, which can provide significant peak flow reductions, were not selected for this study largely due to the secondary considerations.

From here forth this study uses the term LID to refer to the three selected options, however, it must be recognized that these represent a subset of all possible LID treatments and scenarios. LID based developments typically have a diversity of "design with nature" approaches which are needed in order to satisfy the overall objective of maintaining a site's natural hydrology. Thus, the modeled scenarios do not represent the maximum or optimum combination of all possible LID treatments. Inclusion of additional LID treatments would likely further reduce peak flows and flood volume. Modeling a subset was required in order to minimize the complex multiplicative effect of combining various LID scenarios, future rainfall scenarios and return periods.

3.4.3 LID Suitability Assessment

Following the selection of three LID treatments, the next process was to determine the extent of potential application for each treatment. Because urban areas are extensive and multifaceted environments, demarcating possible LID sites presents a challenging aspect of implementation. Availability of remotely sensed LiDAR (Light Detection And Ranging) data and orthophotographs made it possible to complete a desktop analysis of potential suitable LID sites for green roofs, rain gardens and top soil enhancement. Remote sensing was ideal for this task because of its efficiency, detail, and total coverage of private and public lands. The following sections describe the methods used to identify potential LID sites.

3.4.3.1 Green Roof Assessment

In order to model the hydrologic effect of the green roofs, an estimate was needed of the total suitable roof top area and specific areas within the watershed that could over time, be redeveloped to include a green roof. The assessment is not meant to suggest that these existing buildings are appropriate for a green roof retrofit application.

This section describes how a Digital Surface Model (DSM, see Chapter 2 for details) and a GIS layer of building rooftops were used to identify potentially suitable roof areas. Impervious surfaces cover approximately 50% (509 ha) of the watershed's area (KWL, 2007). The GIS layer of buildings rooftops shows that roofs occupy 14.4% (147 ha) of the watershed's total area. Roof tops therefore represent almost 30% of all impervious surfaces.

While roofs occupy a large percentage of the watershed's impervious area, only a portion of this may be appropriate for the installation of a green roof. Identifying appropriate roofs was accomplished by selecting roofs that met the following two primary criteria: roofs need to be large ($\geq 300m^2$) and low slope (0% - 3%). Only large roof tops were selected because green roofs are often applied to sizeable buildings such as those commonly found on institutional, commercial, industrial and multi-family buildings (Metro Vancouver, 2009). A GIS assessment reveals that 340 buildings had a roof area of at least 300 m^2. The identified sites were validated through high resolution orthophotographs. Four buildings were considered inappropriate for a potential green roof application due to uses such as rooftop parking. These buildings were subsequently removed. The remaining 336 buildings occupy a total of 4.1% (42 ha) of the watershed and represent approximately 29% of all roof areas.

The next process used ArcGIS Surface Analyst tool to identify low slope roof areas. Low slope roofs were used in the assessment because research indicates that low slopes provide the greatest peak flow rate reductions (Getter *et al.*, 2007) and to-date, most applications of green roofs have been on low slope roofs (Metro Vancouver, 2009). The first step in identifying low slope roofs was to generate a slope raster layer from the DSM layer. Grid cell size was set to $1m^2$. A building rooftop layer with polygons of the large ($\geq 300m^2$) rooftops was used to clip the slope raster layer resulting in a layer showing slopes for large roof tops. This layer was used to identify appropriately sloped roof tops which, for the purposes of this study, are considered to be slopes up to 3%. A classification procedure was run to identify all slopes between 0% and 3%. The analysis showed that 62% of the total rooftop area of large buildings is low slope (Figure 3.1**Error! Reference source not found.**). The final result shows that 2.6% (26 ha) of the total watershed area meets the criteria for green roof suitability. This value is used as the maximum limit of green roof application based on the current population density, zoning and land uses.

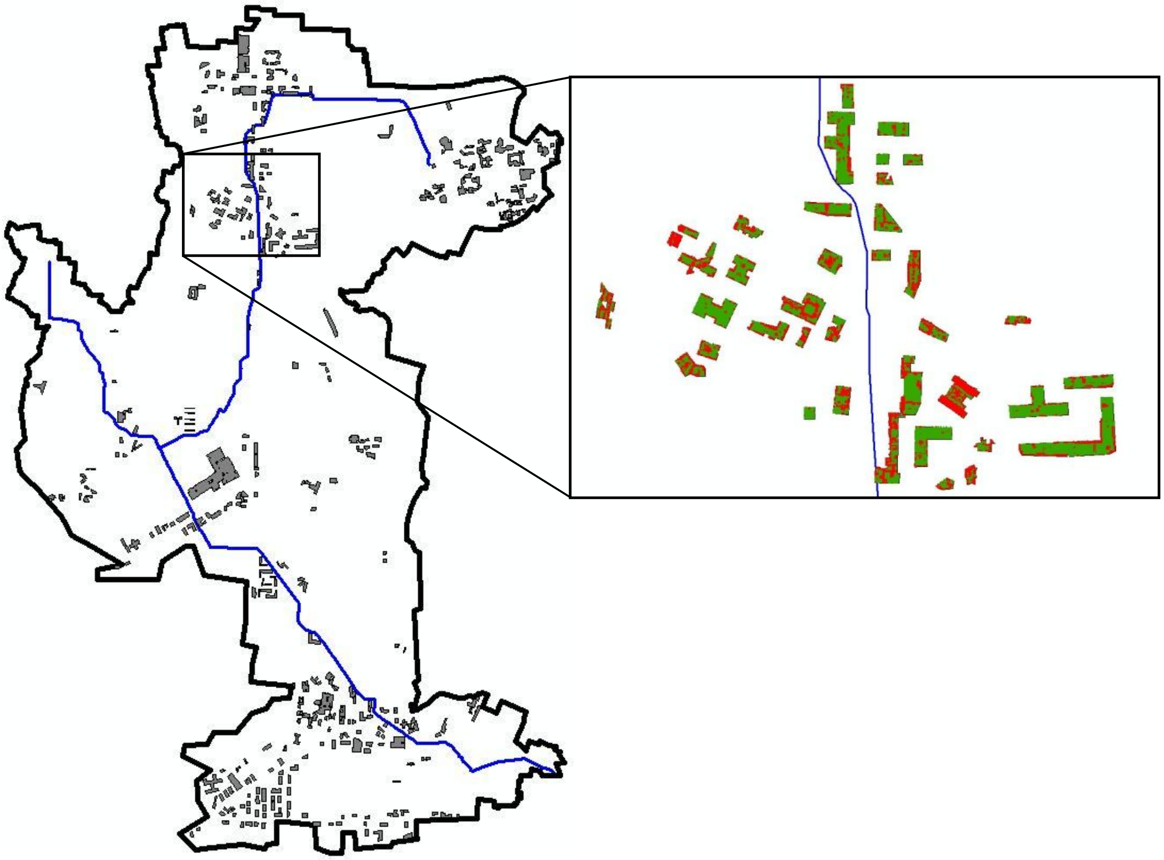

Figure 3.1: Roofs tops larger than 300m^2 within the watershed. Expanded area shows classification of roof top slope where green areas indicate potentially suitable locations for green roofs (slope ≤ 3%) and red areas indicate steeper roof top slopes (slope >3%).

Approximately 38% of large roof areas are considered unsuitable for green roofs. It is estimated that half of this area is due to sloped roofs that exceed 3% slope (19% of total area). The other half (19% of total area) is attributed to equipment such as heating, ventilation and air conditioning systems and other features such as sky lights.

3.4.3.2 Rain Garden Site Selection

This section describes the processes used to identify potential areas for rain garden installation. The purpose of rain gardens in this study is to mitigate flows from ground level impervious surfaces. This study does not consider directing runoff from roofs to rain gardens (i.e. downspout disconnection to rain garden).

The rain garden site selection process was performed to identify impervious areas where runoff could be directed to a rain garden. The first step in the analysis used a GIS roads layer to calculate the total area covered by roads and sidewalks. The assessment showed that roads cover 16.1% (164 ha) of the watershed (Table 3.1). There was no comprehensive and up-to-date GIS layer that could be used to accurately quantify the remaining impervious areas (i.e. not roofs, roads or sidewalks). A visual assessment of orthophotographs was used to estimate the land uses for the unclassified impervious area. This showed that approximately 90% of the remaining impervious area is covered by parking surfaces and driveways. Miscellaneous features such as patios and trails accounted for the remaining 10%.

Table 3.1: Summary of the impervious areas in the Bowker Creek Watershed

	Area (ha)	Percent of Watershed
Roofs	148	14.5%
Roads and Sidewalks	164	16.1%
Other (e.g., parking)	191	18.8%
Total	509	50%

The next procedure involved using LiDAR data and Terrasolid's TModel LiDAR modeling software to delineate small-scale drainage paths and runoff collection points for grid sizes of 1, 5, and 25m². (Figure 3.2).

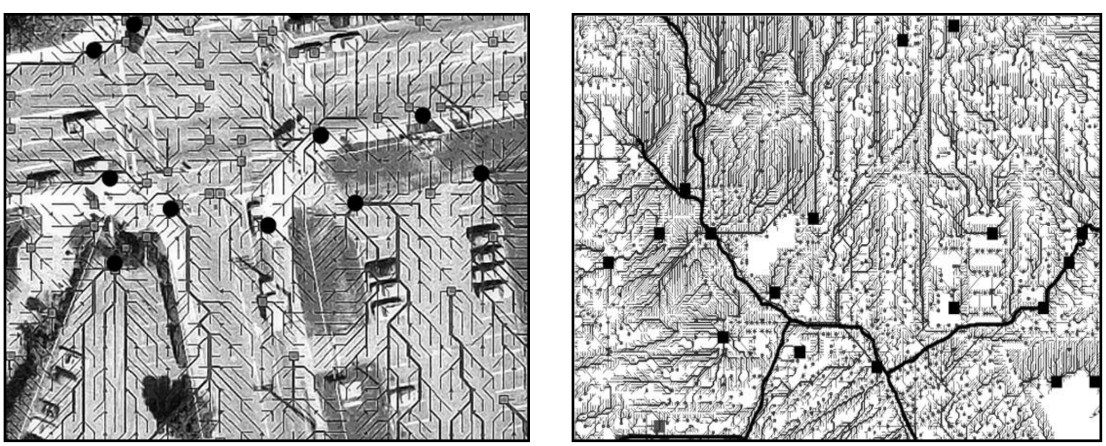

Figure 3.2: Small-scale drainage paths and runoff collection points were generated from high resolution LiDAR data. These were used to locate potential sites for rain gardens.

The drainage vectors and collection points were validated by overlaying them on orthophotographs and local municipal GIS data showing stormwater catch-basin locations. Examination of the drainage patterns and municipal catch-basin locations showed a high correlation between the LiDAR generated drainage vectors, collection points, and stormwater inflow locations. This demonstrates the excellent vertical and horizontal accuracy of the LiDAR data.

The runoff collection points generated by the 25m² grid cells were the most appropriate size for identifying potential locations for rain gardens. The 25m² grid cell was found to be dense enough to isolate suitable areas and not as overwhelming as the collection points shown on the 1 m² and 5m² grid cells. The higher resolution cells were used in complex areas to establish and confirm flow paths and runoff collection points.

The drainage vector and collection point layers were used in conjunction with the roads layer and other GIS layers to remove all areas that were not considered appropriate for installation of a rain garden. The primary processes used to remove unsuitable areas are as follows: rainwater drainage paths that were entirely located within natural or permeable sites were deleted; isolated impervious areas that are not considered hydraulically linked to the drainage system (i.e. not part of the Effective Impervious Area) were removed; a GIS water feature layer was used to remove collection points that existed on water features such as ponds or creeks; a raster slope layer was used to remove areas on slopes steeper than 7 degrees; and runoff collection points were manually examined to remove sites that were not well suited for rain gardens (e.g. dense road intersections).

The results of the procedure showed that rain gardens could be used to manage runoff from 12.9% (131 ha) of the watershed. If all of the identified areas were implemented, then runoff from approximately 26% of the watershed's impervious areas would be directed to rain gardens. This value is considered the maximum area based on the selection criteria. No adjustments were made for future land use changes. The assessment also revealed that 2/3 of the watershed's impervious area is used to support transportation. Consequently, a high priority for climate change adaptation should be to mitigate runoff from land uses associated with transportation.

It is important to note that quantifying suitable rain garden area is more uncertain and subjective than the process used to identify suitable green roof areas. Compared to green roofs, rain gardens can be installed in a much wider variety of site conditions. While the above estimate is considered the upper boundary for practical application, more aggressive development standards and policies could result in higher implementation rates.

3.4.3.3 Top soil Amendments

GIS layers and orthophotographs were used to assess potential areas for topsoil amendments. Areas receiving top soil amendments should be gently sloping <2% (GIP, 2010). To identify low slope areas, the LiDAR data were used in the same manner as the processes described in the above sections. All surfaces with slopes greater than 2% were removed. Orthophotographs were used in conjunction with other GIS layers to remove impervious areas and sites that would be unsuitable for top soil amendment (e.g. playground areas, forest and bedrock outcroppings). The focus for top soil amendment was lawn areas, particularly single family residential areas.

There is a relatively large potential area that is suitable for top soil amendments; however the assessment recognized that opportunities to amend top soil are limited. Green roofs and rain gardens can be implemented during the necessary renewal and redevelopment of built assets, but the same opportunities are unlikely to exist for amending top soil. Unlike building and road infrastructure which often needs to be replaced within 100 years (PSAB, 2007), soil does not have an estimated useful life after which time it must be replaced. Therefore, a primary consideration for quantifying the area that could receive top soil amendment was the rate of implementation. The combination of site suitability and rate of implementation identified that 5.4% (54.8ha) of the watershed could potentially receive topsoil amendments within the timeframe of this study (2040-2069).

3.4.4 LID Design Parameters

For modeling purposes, generalizations were made regarding LID design parameters (Table 3.2). Site-specific factors such as slope, connectivity to drainage conveyance systems, surface material, and land use govern how much a site contributes to rainwater runoff and ultimately dictates the design and performance of LID treatments for each location. However, determining unique designs for each site is beyond the scope of this study. Standard designs were therefore used to model LID treatments. While this approach may affect model accuracy, it is appropriate given other uncertainties in the research (e.g. climate change projections). Furthermore, because the evolution of LID techniques is relatively young, a number of practical questions remain unanswered regarding optimum design (Palla *et al*., 2010; Stander *et al*., 2010). In light of these considerations, the use of standard design specifications is appropriate for this modeling application. The LID treatments were assumed to function independently. No assessment was made to determine performance of treatments run in a series (e.g. runoff from a green roof is directed to a rain garden).

Table 3.2: Design specifications for LID treatments.

	Green Roofs	Rain Gardens	Topsoil Amendments
Maximum Applicable Area of Watershed (%)	2.6	1.26*	5.4
LID Soil Depth (mm)	150	500	400
Available Water Storage Capacity of Soil (%)	30	20	20
Top Soil Infiltration Rate (mm/hr)	50	40	20
Native Soil Infiltration Rate (mm/hr)	N/A	0.8	0.8
Ponding/Depression Storage (mm)	0	150	6
Rock Pit Depth (mm)	N/A	800	N/A
Rock Pit Storage Capacity (%)	N/A	35	N/A
Maximum Available Water Storage Capacity (mm)	45	380**	80
Overflow/under drain connected directly to drainage system	Yes	Yes	No
Ratio of impervious area to LID area	1:1	10:1*	N/A

* At a 10:1 ratio, rain gardens would collect runoff from 13.9% of the total watershed area.
** Max volume adjusted to account for losses due to construction of side slopes.

3.4.4.1 Rain Garden Design Storm

Compared to green roofs and top soil amendments, rain gardens have the advantages of greater water storage capacity and larger potential collection area. This combination suggests that rain gardens could play a major role in mitigating the impacts of future extreme rainfall events. A critical parameter for determining a rain garden's hydrologic profile is the design storm used for sizing (Atchison *et al*., 2006). A common design storm used for sizing rain gardens is the 6-month 24-hour storm (e.g. Kipkie and Johnson, 2006; Metro Vancouver, 2005). The Department of Fisheries and Ocean's draft *Urban Stormwater Guidelines and Best Management Practices for Protection of Fish and Fish Habitat* recommends using this design storm to satisfy volume control objectives (Chilibeck and Sterling, 2001). The same design storm is required in the *Stormwater Management Manual for Western Washington* (2005) for water quality objectives. However, there is no standard design storm for flood control because LID is not typically used for managing runoff from major storms (Manwaring, 2009). Therefore, the 6-month 24-hour event recommended for volume control and water quality objectives is used for the base design storm.

The 6-month rainfall event can be estimated as 72% of the 2-year storm event (WDOE, 2005). Based on the historic climate, the calculated rainfall capture target is 34.6 mm in 24-hours. It is important to note that research shows that increasing the design storm to a 2-year event can further reduce peak discharges and provide additional flood protection across a range of flood events including the 100-year storm event (Clar, 2001). For this reason, this study also investigates the hydrologic response of using the 2-year storm event to design rain gardens (48 mm in 24-hours).

3.5 Results and Discussion

3.5.1 Mitigating climate impact with Low Impact Development

Peak flow rate and flood loss volume were used as the two metrics for assessing the performance of LID in reducing the effects of climate change. Flood extent is not included because flood loss volume can adequately represent the out-of-channel changes against the mitigation target. Furthermore, including the visual representation of flood extents suffers from the multiplicative effect of combining scenarios for climate, LID and return periods.

Results indicate that under the 25-year design storm, full LID implementation can completely mitigate the additional rainfall and associated runoff of scenario 1. Under scenario 2, simulations suggest that LID can reduce the majority of the hydrologic impacts; however, small increases in flood flows may still occur. It is estimated that full LID implementation can alleviate a maximum 9% increase in rainfall for the local design storm (from 88.8 to 97 mm). In general, the mitigation benefits of rain gardens and green roofs are greatest for smaller rainfall events (e.g. 5-year event) and the least for major storm events (e.g. 100-year event). Conversely, top soil amendments had greatest effect during major storm events and the least during smaller rainfall events (Figure 3.3 & Table 3.3).

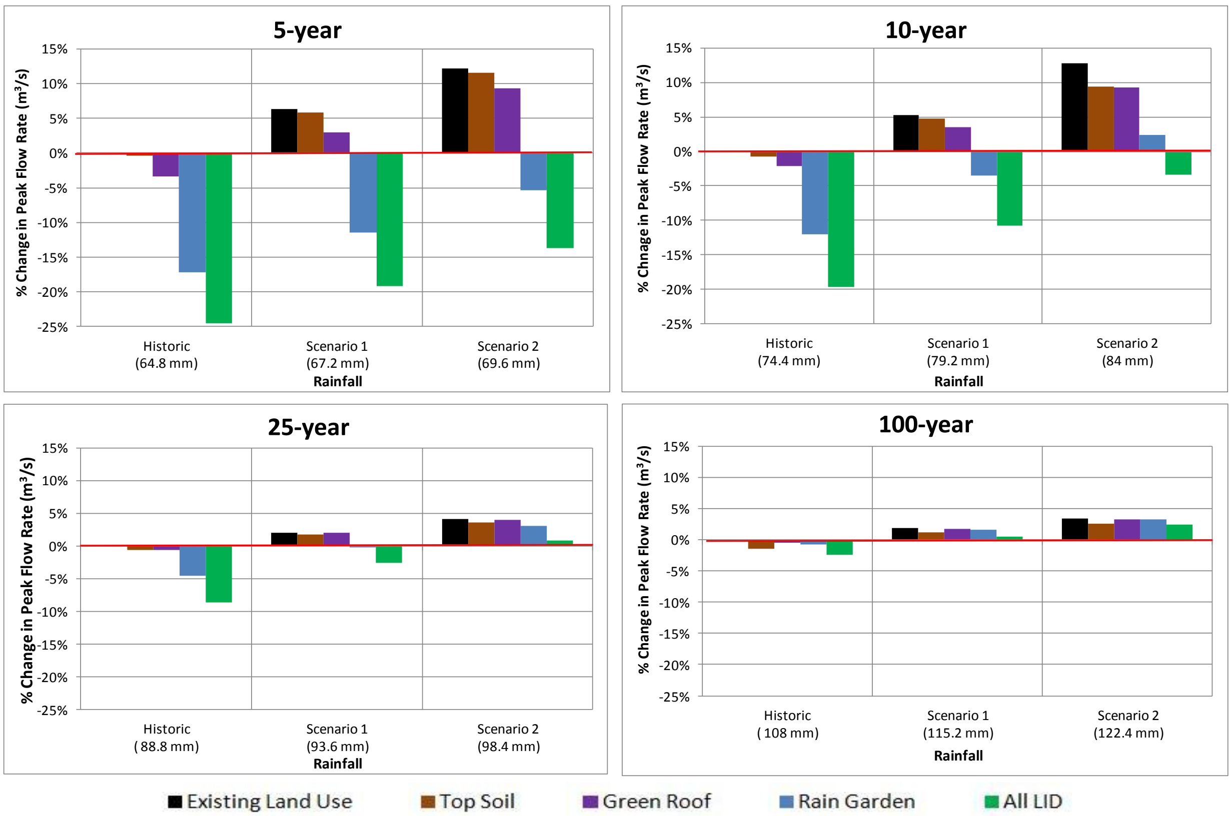

Figure 3.3: Effect of three Low Impact Development techniques on peak flow rates for the 24-hour, 5, 10, 25 and 100-year return periods for the historic and two future climate scenarios.

Table 3.3: Flood loss volume for the 24-hour duration, 5, 10, 25, 100-year return period events under historic and two future climate scenarios with existing land use and three Low Impact Development techniques.

		Return Period											
		5-year			10-year			25-year			100-year		
		Historic	1	2	With LID	1	2	With LID	1	2	With LID	1	2
Rain Garden	(m^3/s)	0	0	0	142	3124	9136	20224	39390	60910	102926	139121	181013
	% change	∞	∞	∞	-97.4%	-43.5%	65.2%	-48.5%	0.4%	55.2%	-10.9%	20.4%	56.6%
Green Roof	(m^3/s)	0	0	837	4236	9639	18952	35548	53251	71170	110784	145094	182020
	% change	∞	∞	∞	-23.4%	74.3%	242.8%	-9.4%	35.7%	81.4%	-4.2%	25.5%	57.5%
Top Soil	(m^3/s)	0	254	1429	5076	10553	19261	35054	49512	66208	99372	130223	163517
	% change	∞	∞	∞	-8.2%	90.9%	248.4%	-10.7%	26.2%	68.7%	-14.0%	12.7%	41.5%
All LID	(m^3/s)	0	0	0	0	428	4509	10982	26857	43843	84031	116911	150671
	% change	∞	∞	∞	-100.0%	-92.3%	-18.4%	-72.0%	-31.6%	11.7%	-27.3%	1.1%	30.4%
No Lid	(m^3/s)	0	520	1919	5529	11851	26290	39242	54434	72918	115582	149095	183975
	% change		∞	∞		114%	376%		39%	86%		29%	59%

LID treatments were shown to create hydrologic responses that, taken as a composite, could be considered effective in managing a broad range of projected increases in extreme precipitation. Simulations reveal that hydrologic benefits varied considerably by return period and specific LID treatment. This complexity necessitates an examination of LID performance for a range of return periods and therefore, discussed below are also findings for the 5-year, 10-year 25-year and 100-year events.

3.5.1.1 5-Year Return Period

During the historic 5-year event, full LID implementation would lower peak flow rates by approximately 25%. Rain gardens account for the majority of this reduction. If only rain gardens were installed, then peak flows are estimated to decrease by approximately 17%. Green roofs provide an estimated 3.5% reduction and top soil amendments have minimal effect with only a 0.5% decrease. Simulations indicate that under climate scenario 1 and 2, rain gardens alone can achieve and surpass the mitigation targets. Green roofs and top soil amendments were unable to alleviate the additional runoff from projected rainfall scenarios. Given these results, rain gardens are considered the most effective method for mitigating the predicted increase in rainfall for the 5-year return period event.

3.5.1.2 10-Year Return Period

Under historic conditions, LID is estimated to eliminate flooding by reducing the volume of overland flood waters from approximately 5,500m^3 to 0 m^3. Results indicate that LID will also decrease peak flows by approximately 20%. Rain gardens continue to account for the majority of reductions. If only rain gardens were installed, it is estimated that there would be a 12% decrease in peak flow rates and existing overland flood volumes would be decrease by over 97% which would virtually eliminate the existing flood hazard. Findings for green roofs suggest that as a standalone measure, this approach would reduce peak flow rates by 2% and flood volume by 23%. Finally, the respective results for top soil amendments are 0.6% and 8%.

In terms of the adaptation objective, full LID implementation can alleviate the additional runoff simulated under the two future rainfall events. For scenario 1, LID was shown to reduce peak flow rates by 11% and flood volume by 92%. For scenario 2, the respective results are approximately 3% and 18%. On its own, rain gardens were shown to fully mitigate climate scenario 1 and continued to improve the level of flood protection by reducing peak flows by 4% and overland flood volume by 44%. However, the additional rainfall simulated under scenario 2 surpassed rain garden capacities resulting in increases of 3% for peak flows and 65% for flood volume. While not completely achieving the more challenging target, the result compares favourably against the respective 12% and 376% increases that are estimated to occur if no mitigation measures were implemented.

Neither green roofs nor top soil amendments could mitigate the hydrologic impacts of scenario 1 or 2. Under scenario 1, green roofs provided greater hydrologic benefits than top soil amendments; however under scenario 2, the two treatments generated almost identical responses. Compared to the status quo land use, the installation of green roofs was shown to reduce both peak flows and volumes by approximately 33% for scenario 1. For top soil amendments these values are 10% and 20% respectively. Simulations suggest that during the larger scenario 2 rainfall event, green roof performance declines and top soil amendments improves resulting in nearly equivalent responses. When evaluated against the runoff from existing land uses, each were shown to reduce peak flow rates by approximately 26% and flood volume by 33%. Evidently, these two treatments can help reduce climate impacts, but as standalone measures they are not sufficient to alleviate predicted changes in the 10-year return period event.

3.5.1.3 25-Year Return Period

During large storm events, peak flow rates are limited due to conduit capacity (Chapter 2). For the 25-year and 100-year events, flood volume is a more suitable metric for assessing the magnitude of potential impacts and will therefore be the focus of discussion.

If there is no change in the rainfall regime, then results indicate that LID can lower flood volume from an estimated 39,000m^3 to 11,000 m^3; a 72% reduction. This demonstrates that LID can provide important flood protection benefits. However, LID is generally known to perform best during smaller storm event and studies report that it has minimal effect during large storm events (Williams and Wise, 2006; Holmann-Dodds *et al*., 2003). A key goal of this study is to evaluate whether this ‘minimal effect’ is sufficient to mitigate flood flows associated with projected changes for the 25-year return period event. This study found that LID can alleviate the flood impacts of climate scenario 1. LID was shown to not only accommodate a 5.4% increase in rainfall, but at the same time it also improved the level of service for flood protection by reducing flood volume by 32%.

Simulations suggest that the scenario 2 target (10.8% increase in rainfall) cannot be completely mitigated with LID. It is estimated that flood volume would increase by 12%. While LID cannot fully alleviate scenario 2 impacts, reductions are considerable compared to the 86% increase that may occur if no mitigation measures were implemented. Therefore, while LID does not completely achieve the scenario 2 mitigation target, it still provides important flood protection benefits.

Scenario 1 was found to be the maximum amount of additional rainfall that rain gardens can accommodate. This suggests that when rain gardens have full available capacity at the on-set of the storm, they can effectively eliminate the flood impacts of climate scenario 1. Green roofs were found to have a minor influence on discharge as values increased at almost same rate as from existing land uses. With green roofs flood volumes increased by 36% compared to a 39% without green roofs. This demonstrates that green roofs can reduce overland flooding; however, the hydrologic performance of this option is far from providing adequate protection against the rainfall increase simulated under scenario 1.

As storm size increases, top soil amendments begin to have an increasing influence on discharge whereas the effect of rain gardens and green roofs declines sharply. This transition occurs near the 25-year event and is discussed in detail later in this chapter. In general, during smaller storm events green roofs were found to provide more hydrologic benefits than top soil amendments, but for the larger design storm, this order switches and top soil amendments were shown to provide greater reductions. Top soil amendments could not achieve the scenario 1 mitigation target as flood volume was shown to increase by 26%. While this is a considerable gain, it still represents a 1/3 reduction compared to runoff from existing soil conditions.

Under scenario 2, flood volumes increased as follows: rain gardens 55%; top soil amendments 69% and green roofs 81%. When evaluated against status quo land use, these values represent reductions of 36%, 20% and 6% respectively. As standalone options, none of the three tested LID treatments can provide a sufficient degree of protection again scenario 2 rainfall increases.

3.5.1.4 100-Year Return Period

During the historic 100-year rainfall event, results suggest that LID has the potential to reduce flood volumes by 27%. In term of climate adaptation, simulations indicate that full LID implementation can reduce the majority of the flood impacts associated with scenario 1. Flood volumes were found to increase by a negligible 1%. This is significant when measured against the 29% increase that is estimated to occur if no adaptation measures are taken. For scenario 2, the combined suite of LID treatments reduced flood volumes by approximately ½ compared to a non-LID landscape (30% increase with LID versus a 59% increase without LID).

For 100-year and larger rainfall events, top soil amendments had the greatest hydrologic influence of the three modelled LID treatments. During storms of this size, rain gardens and green roofs provide relatively minimal benefit because they have typically reached capacity before peak rainfall intensity. Top soil amendments however, may have available capacity to continue to infiltrate and store rainwater during the most intense period of the event. Of the flooding associated with climate change, this study found that the respective reductions for scenario 1 and 2 were 54% and 30% for top soil amendments; 30% and 4% for rain gardens; and 12% and 3% for green roofs. When looking at the three options, it appears that amending top soil is the most effective method for reducing the flood impacts of the 100-year return period event. This finding suggests for the most extreme rainfall events, it may be valuable to incorporate top soil amendments into the planning processes for climate adaptation.

3.5.2 Implementation Considerations

Study results were generated by an event-driven hydrologic/hydraulic model. This approach is appropriate for assessing extreme rainfall events (Maidment, 1993); however, findings are based on assumptions regarding that state of variables at the on-set of a rainfall event. The values selected for the model represent specific conditions and therefore do not indicate a range of potential conditions and their effect on runoff. For example, antecedent soil moisture plays an important role in watershed response and LID performance. In the model, initial moisture content was set to 86% of the soil's field capacity (field capacity being the moisture content when saturated soil first drains until the remaining water held by surface tension on the soil particles is in equilibrium with the gravitational forces causing drainage

(Maidment, 1993)). This value represents the relatively moist soil conditions that typically occur in the months prone to flooding. During extreme rainfall events soils could also be saturated or conversely could be at their wilting point (i.e. drier). These alternative scenarios would alter the watershed's runoff response by respectively decreasing and increasing the soil's available water storage capacity. Consequently, when soils are drier LID has a higher probability of meeting the mitigation target and when soils are wetter, LID may only partially satisfy it. Initial values and the potential range of values for parameters such as soil moisture can greatly affect the efficacy of infiltration practices (Davis, 2008) and should be taken into account during planning and implementation.

3.5.2.1 Rain Gardens and Top Soil Amendments

Model results help establish the relative influence of rain gardens and top soil amendments across a spectrum of storm sizes. In general, during small storms rain garden provide significant mitigation benefits and top soil amendments produce virtually none. Conversely, during large storm events, rain gardens have a minimal effect whereas top soil amendments provide considerable reductions. Data indicate that the transition in the dominant effect changes from rain gardens to top soil at a 101.5 mm rainfall event (Figure 3.4). This represents an approximate return period of 60-years based on historic records, 40-years under scenario 1 and 30-years under scenario 2.

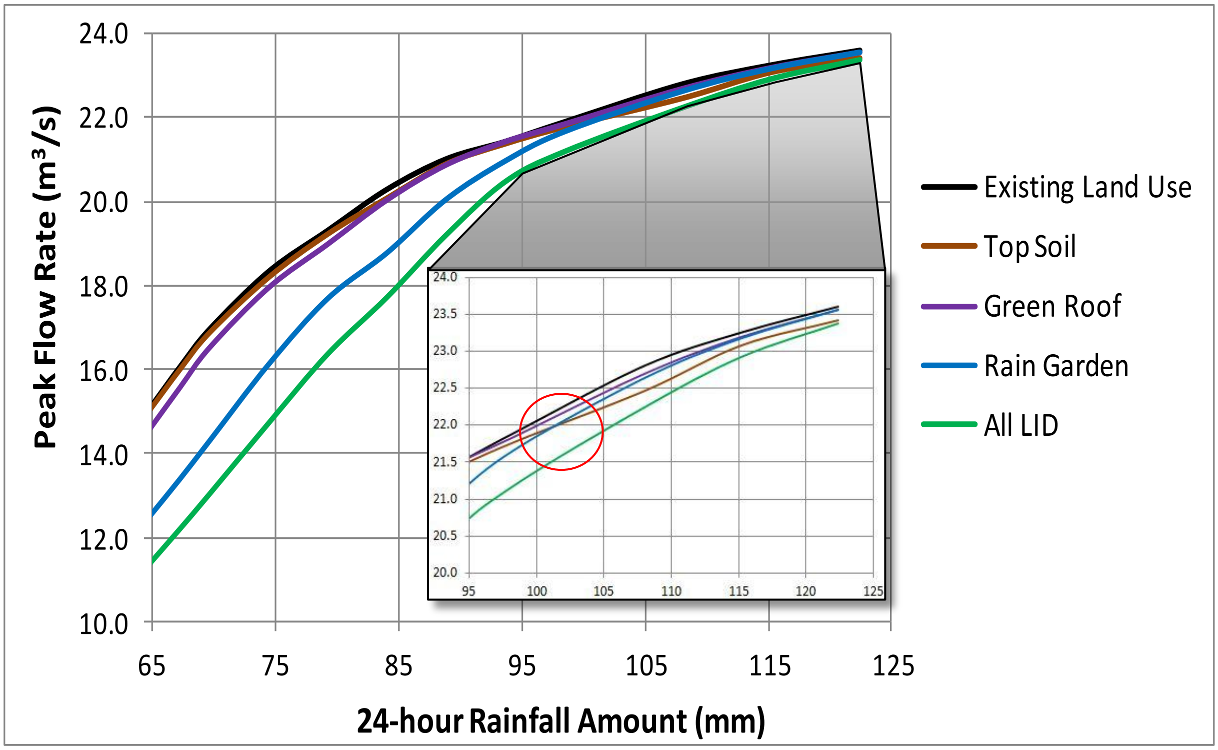

Figure 3.4: Peak flow rates and rainfall amounts for the 24-hour duration event for three Low Impact Development techniques. Circle highlights the transition point where top soil amendments surpass rain gardens as the dominant influence on peak flow rates.

This suggests a possible complementary approach for climate adaptation where rain gardens are used to mitigate runoff from impervious areas for smaller storm events and top soil amendments are used to reduce runoff from pervious areas during the very large storm events. Both techniques may need to be considered when attempting to reduce flood risk for a range of storm sizes.

3.5.2.2 Rain Garden Design

Rain gardens that are sized based on the 6-month rainfall event have the capacity to accept runoff until shortly after the peak storm intensity of the SCS Type 1A synthetic rainfall distribution. As rainfall amounts increase above the historic 25-year event, rain garden capacity begins to be exceeded prior to peak rainfall intensity. Once saturated conditions are reached, rain gardens provide practically no additional mitigation benefits at the site. However, the volume of rainfall that was captured prior to saturated conditions still results in some downstream flow reductions.

Rain garden efficacy is significantly improved if there is available storage during peak rainfall intensity (Williams and Wise, 2006). This occurs under the historic design storm, but as rainfall amounts increase from scenario 1 to scenario 2, capacity begins to be reached prior to peak storm intensity. This makes the facility unavailable during the critical period of rainfall (Figure 3.5). The increase in rainfall from the historic rainfall through to scenario 2 crosses over a key performance threshold for rain gardens.

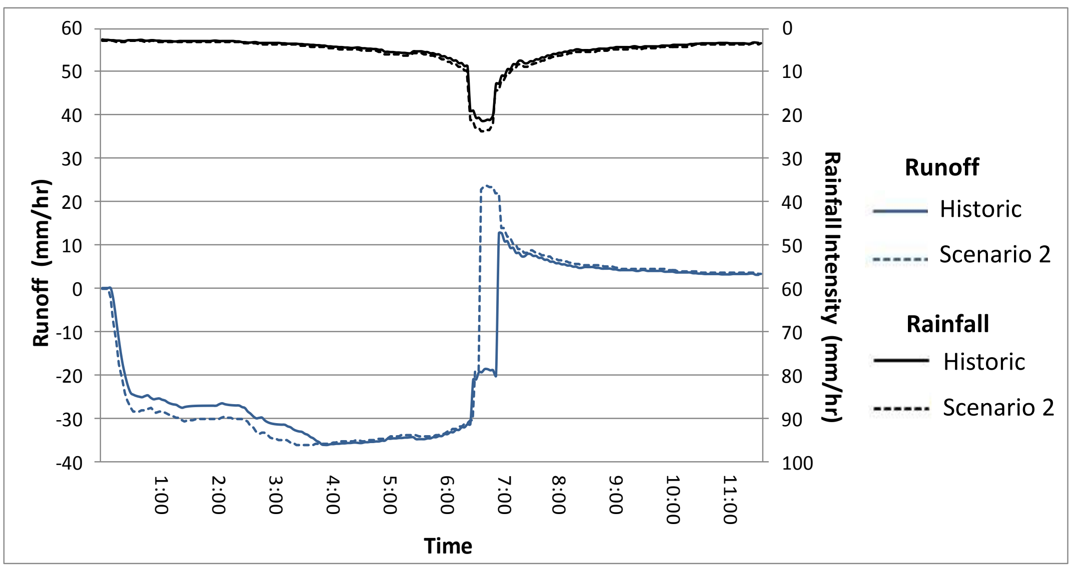

Figure 3.5: Rain garden runoff for the 25-year return period event under the historic climate and future climate scenario 2.

Simulations suggest that increasing the design storm from the commonly recommended 6-month rainfall event to the 2-year event can provide available storage capacity during peak storm intensity (Figure 3.6). This is the critical period where rain gardens can have the most effect on discharge rates and flooding. If rain gardens are to be incorporated into a flood management strategy, then the costs and benefits of using the 6-month versus 2-year or larger design event should be assessed in detail.

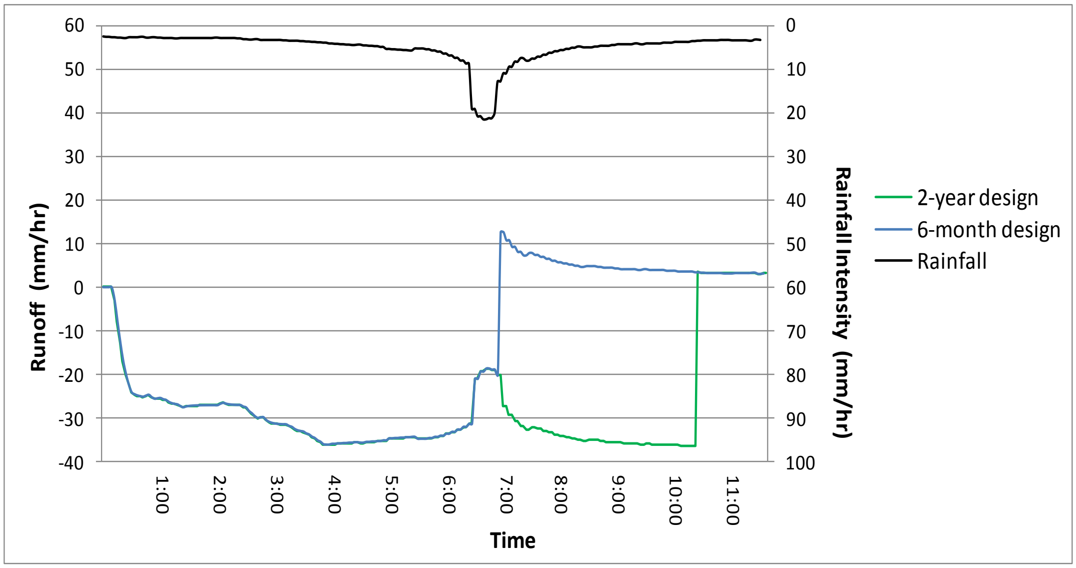

Figure 3.6: Runoff for the historic 25-year return period event for rain gardens based on the 2-year and 6-month design storm.

Infiltration rate is another important parameter in rain garden performance. Bioengineered soils with high infiltration rates are recommended for rain gardens (Hinman, 2009; PGCM, 2009). Soils with high permeability such as 120 mm/hr are being used in rain gardens (Trowsdale and Simcock, 2008). This allows for full infiltration of higher rainfall intensities and/or higher ratio of collection area to rain garden area. The Master Municipal Specifications used by many local governments in British Columbia require a minimum saturated hydraulic conductivity of 20 mm/hr for applications such as rain gardens (MMCD, 2009). This study assumed a minimum infiltration rate of 40 mm/hr. If rain gardens are to be considered part of a flood management strategy, then it is vital to ensure that the growing medium has a sufficiently high infiltration rate.

3.5.2.3 Costs and Maintenance

Research suggests that when selecting rainwater management measures such as LID, cost is one of the most important factors influencing decisions (Atchison *et al*., 2006). As such, a preliminary capital costs estimate is provided in Table 3.4.

Table 3.4: Preliminary capital costs for full implementation of green roofs, rain gardens and top soil enhancement.

	Estimate		
	Low	Med	High
Green Roof			
incremental cost per m^2	$100	$200	$300
	$26,468,000	$52,936,000	$79,404,000
Rain Garden			
cost per m^2	$150	$300	$450
	$19,392,900	$38,785,800	$58,178,700
Top Soil			
cost per m^3	$10	$25	$40
	$2,198,880	$5,497,200	$8,795,520

Table 3.4 provides an indication of the order of magnitude of potential costs. The range of costs depends on many factors including size, complexity, land availability, location and specific design required for residential, commercial or institutional applications. Capital costs may be reduced if equipment is already onsite as in new construction or infrastructure renewal projects (Chrisholm, 2008).

Based on the preliminary estimate, green roofs are the highest cost option, followed by rain gardens and top soil amendments. In terms of satisfying the adaptation objective, study findings show that green roofs provide the least amount of protection against changes in extreme rainfall. When combined with their high cost, they appear to be the lowest ranked option. Rain gardens are recommended as the preferred option for limiting the flood risk for more frequent storm events. The high capital costs related to this option may be prohibitive in terms of the single objective of flood mitigation, however, when additional benefits such as water quality improvements are consider, then this level of investment may be warranted. Top soil amendments are the lowest cost option and this treatment provided the highest level of flood protection for the largest storm events. Given the relatively low capital cost and hydrologic benefits, top soil amendments should be considered a practical and viable solution that can assist in reducing the adverse impacts of future extreme rainfall.

Maintenance costs are fundamental to life cycle cost analysis and decision making (Malano *et al*., 1999). As LID practices are relatively new, there is a wide range of reported maintenance costs. For rain gardens, Weiss et al. (2005) reported between 0.7% and 10.2% annual maintenance cost as percentage of capital costs. Maintenance costs for green roofs largely depend on whether they are extensive or intensive systems. Annual maintenance costs for extensive systems range from $0.8 to $ 2.25 per m^2 and for intensive systems costs range from $6.50 to $44 per m^2 (Townshend and Duggie, 2007). Top soil amendments require no significant maintenance cost above existing maintenance routines for top soil (e.g. periodic aeration for lawn areas). Proper maintenance is required to ensure the ongoing performance of LID facilities and therefore associated costs are an important consideration in the evaluation and prioritization of options (PGCM, 2009).

3.5.2.4 Scale of Applications

Land use in smaller catchments results in more prominent flow changes than if similar changes were made in large watersheds (Figure 3.7). Consequently, altering land use practices in smaller catchments, such as the Bowker Creek watershed, will have greater effect on runoff response than in larger catchments. In terms of climate impacts, this means that smaller catchment have a higher probability of successfully using landscape based solution for mitigation.

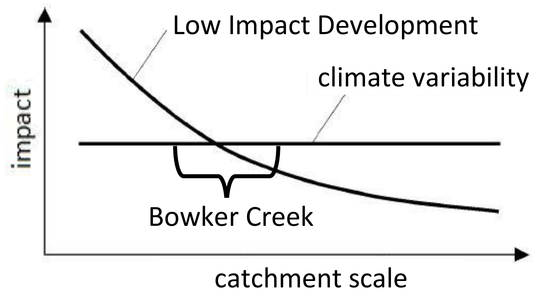

Figure 3.7: Relative impact of LID and climate variability on hydrological response as a function of scale (adapted from Bloschl *et al*., 2007).

This study investigated the effects of LID in a 1018 ha urban watershed with land uses that are typical of a fully developed urban watershed dominated by residential development with a supporting mix of institutional and commercial land uses. For a watershed of this size and geography, this study shows that full use of three LID treatments is near the threshold of being able to effectively mitigate future impacts for the 25-year local design storm. If the case study watershed area was smaller, then LID would have greater probability to alleviate future impacts. Conversely, if the watershed was larger, then LID would very likely be less effective. Watershed scale is therefore an important factor when considering the use of LID in other similar urban catchments.

3.6 Summary

This study has investigated the effectiveness of using LID techniques to mitigate future flood impacts for a relatively small urban watershed located in Victoria, British Columbia. Three LID treatments were selected for analysis: rain gardens, green roofs and top soil amendments. A site assessment was conducted to identify potentially suitable locations for the implementation. The assessment estimated that up to 1.26% of the watershed could be used for rain gardens; 2.6% for green roofs; and 5.4% for top soil amendments. Two scenarios representing the median (scenario 1) and 75th percentile (scenario 2) projections from an ensemble of Global Climate

Models were used to simulate extreme 24-hour rainfall for the 2050s (2040-2069). The LID and climate scenarios were run in an event-driven hydrologic/hydraulic model for the 5-year, 10-year, 25-year and 100-year return period events. Results suggest that the cumulative effect of all three LID treatments can mitigate the hydrologic impacts of climate scenario 1 and 2 for the 5-year and 10-year events. For the 25-year event, full LID implementation was shown to alleviate scenario 1 impacts. The scenario 2 mitigation goal could not be fully achieved resulting in relatively small increases in peak flow rate and overland flood volume. Results indicate that full LID implementation can mitigate a maximum 9% increase in rainfall for the 25-year event. LID could not sufficiently attenuate the additional flood flows resulting from scenario 1 or 2 for the 100-year event. In general, for all return periods and climate scenarios, the simulated LID treatments reduced the level of flood risk compared to existing land use conditions.

Green roofs were found to be the most costly and least effective technique for mitigating runoff from projected changes in extreme rainfall. As a standalone measure this treatment resulted in minimal reductions in discharge for any of the modelled return periods. For the 25-year local design storm, green roofs fulfilled approximately 5% to 8% of the performance target for flood volume. This is a significant shortfall from the mitigation goal and in terms of extreme rainfall; green roofs may be the least effective option for adapting to climate change.

In contrast, rain gardens were shown to more than alleviate the additional runoff that was simulated for the 5-year and 10-year return periods. Results indicate that the performance threshold of rain gardens is near the 25-year event: flood impacts from climate scenario 1 were virtually eliminated; however, scenario 2 resulted in 55% increase in overland flood volume. During the 100-year event rain gardens provided minimal protection against projected increases in rainfall. Given these findings rain gardens may be best suited for mitigating climate impacts for smaller more frequent rainfall events.

It was discovered that top soil amendments had the opposite effect of rain gardens: they provided minimal benefits for smaller storms, but had a considerable influence during large storm events. For the most severe rainfall event modeled (100-year, scenario 2), top soil amendments reduced the overland flooding associated with climate change by approximately 50% whereas the respective results for green roofs and rain gardens are 3% and 4%. These findings suggest a possible strategic combination where rain gardens are used to target runoff from more frequent rainfall events and top soil amendments are used to reduce flood impacts from larger, more intense and rarer events (e.g. greater than 100 mm of rainfall in 24-hours). Out of the three assessed LID treatments, top soil amendments offer the key advantages of simplicity, low installation cost, effectively no maintenance costs, greatest potential area for application and is the only option that was shown to substantially reduce flood impacts for the most extreme and highest risk storm events. With such benefits, climate adaptation initiatives should examine how land use policies and bylaws can be used to promote the development of an absorbent layer of top soil.

Rain garden design plays a critical role in their ability to mitigate runoff. As such, this study evaluated the hydrological benefits of using the 6-month and 2-year return period events for design criteria. Simulations reveal that facilities designed to capture and temporarily store runoff from the 6-month rainfall event became saturated near peak storm intensity, the period at which they could provide the greatest mitigation benefits. However, rain gardens designed based on the 2-year event had available storage capacity for more than 3 hours after peak storm intensity resulting in significantly greater reductions in flood flows. The costs and benefits of altering the design storm from the commonly used 6-month event to the 2-year event will need to be assessed in detail to determine whether the added flood protection warrants additional investment.

Landscape-based measures such as LID have the greatest effect on smaller-scale watersheds while climate variability has the greatest effect on larger-scale watersheds (Bloschl *et al.*, 2007). The scale at which the dominant influence changes is not well represented in the literature, but this research suggests that the 10km^2 Bowker Creek watershed may be near the size threshold for the ability of LID to offset projected increases in rainfall for the 25-year and larger events. It is plausible that LID techniques could be more effective in smaller watersheds and conversely, larger watershed may have a lower likelihood of successfully using LID for flood control.

APPENDIX A – Peak Flow Rates

Table 3.5: Effect of Low Impact Development on peak flow rates for Trent St and Monterey Ave for the 2050s following two climate projections representing the median (Scenario 1) and 75th percentile projections (Scenario 2) modeled using current (50%) impervious area coverage.

Trent St		Return Period											
		5-year			10-year			25-year			100-year		
Scenario	Peak Flow Rate	Historic	1	2	Historic	1	2	Historic	1	2	Historic	1	2
Rain Garden	(m^3/s)	12.5	13.4	14.3	16.1	17.7	**18.8**	**20.1**	**21.0**	**21.7**	**22.6**	**23.2**	**23.6**
	% change*	-17.2%	-11.4%	-5.4%	-12.1%	-3.6%	2.4%	-4.6%	-0.2%	3.1%	-0.7%	1.7%	3.4%
Green Roof	(m^3/s)	14.6	15.6	16.5	18.0	**19.0**	**20.1**	**20.9**	**21.4**	**21.9**	**22.7**	**23.2**	**23.6**
	% change*	-3.4%	3.0%	9.3%	-2.1%	3.5%	9.3%	-0.6%	2.0%	4.0%	-0.4%	1.8%	3.4%
Top Soil	(m^3/s)	15.1	16.0	16.9	**18.2**	**19.2**	**20.1**	**20.9**	**21.4**	**21.8**	**22.5**	**23.1**	**23.4**
	% change*	-0.4%	5.9%	11.6%	-0.8%	4.8%	9.5%	-0.6%	1.7%	3.6%	-1.5%	1.2%	2.7%
Full LID	(m^3/s)	11.4	12.2	13.0	14.7	16.4	17.7	**19.2**	**20.5**	**21.2**	**22.2**	**22.9**	**23.4**
	% change*	-24.6%	-19.3%	-13.8%	-19.7%	-10.7%	-3.4%	-8.6%	-2.6%	0.8%	-2.4%	0.6%	2.5%
No LID	(m^3/s)	15.1	16.1	17.0	**18.4**	**19.3**	**20.7**	**21.0**	**21.4**	**21.9**	**22.8**	**23.3**	**23.6**
	% change*		6.4%	12.3%		5.3%	12.8%		2.0%	4.2%		2.0%	3.5%

Monterey Ave		Return Period											
		5-year			10-year			25-year			100-year		
Scenario	Peak Flow Rate	Historic	1	2	Historic	1	2	Historic	1	2	Historic	1	2
Rain Garden	(m^3/s)	**15.1**	**16.1**	**17.1**	**19.3**	**21.1**	**22.6**	**23.8**	**24.8**	**25.2**	**25.7**	**25.9**	**26.8**
	% change*	-17.5%	-11.8%	-6.0%	-12.2%	-3.9%	3.3%	-4.0%	0.1%	1.8%	-0.2%	0.8%	4.3%
Green Roof	(m^3/s)	**17.6**	**18.8**	**19.9**	**21.5**	**22.9**	**23.7**	**24.7**	**25.1**	**25.4**	**25.7**	**26.0**	**26.9**
	% change*	-3.5%	2.8%	8.9%	-1.9%	4.4%	8.3%	-0.3%	1.3%	2.3%	-0.1%	1.2%	4.5%
Top Soil	(m^3/s)	**18.1**	**19.3**	**20.3**	**21.8**	**23.1**	**23.8**	**24.7**	**25.0**	**25.3**	**25.6**	**25.9**	**26.5**
	% change*	-0.6%	5.8%	11.3%	-0.5%	5.3%	8.5%	-0.3%	1.1%	2.0%	-0.3%	0.7%	3.2%
Full LID	(m^3/s)	13.7	14.7	**15.7**	**17.6**	**19.5**	**21.3**	**23.0**	**24.2**	**24.9**	**25.5**	**25.7**	**26.2**
	% change*	-24.8%	-19.6%	-14.2%	-19.7%	-11.0%	-2.9%	-7.3%	-2.2%	0.4%	-0.9%	0.0%	1.9%
No LID	(m^3/s)	**18.2**	**19.4**	**20.5**	**21.9**	**23.2**	**24.3**	**24.8**	**25.2**	**25.4**	**25.7**	**26.2**	**26.9**
	% change*		6.4%	12.1%		5.8%	10.6%		1.5%	2.4%		1.8%	4.7%

BOLD: Peak flow rates limited because conduit at capacity (Hydraulic Grade Line above crown elevation). Flooding and overland flow may occur.

* % change calculated against the base condition of existing land use (No LID) and historic rainfall

Table 3.6: Effect of Low Impact Development on peak flow rates for Trent St and Monterey Ave for the 2050s following two climate projections representing the median (Scenario 1) and 75th percentile projections (Scenario 2) modeled using future (59%) impervious area coverage.

Trent St		Return Period											
		5-year			10-year			25-year			100-year		
Scenario	Peak Flow Rate	Historic	1	2	Historic	1	2	Historic	1	2	Historic	1	2
Rain Garden	(m^3/s)	14.2	15.1	16.0	17.6	**18.8**	**19.7**	**20.9**	**21.6**	**22.1**	**23.1**	**23.5**	**23.7**
	% change*	-6%	0%	6%	-4%	3%	7%	0%	3%	5%	1%	3%	4%
Green Roof	(m^3/s)	16.1	17.0	17.8	**18.9**	**19.9**	**20.8**	**21.3**	**21.6**	**22.1**	**23.0**	**23.4**	**23.6**
	% change*	6%	12%	17%	3%	8%	13%	1%	3%	5%	1%	3%	4%
Top Soil	(m^3/s)	16.5	17.4	**18.0**	**19.2**	**20.0**	**20.9**	**21.2**	**21.7**	**22.1**	**22.9**	**23.3**	**23.5**
	% change*	9%	15%	19%	4%	9%	14%	1%	3%	5%	0%	2%	3%
Full LID	(m^3/s)	13.7	14.5	15.4	17.0	**18.1**	**19.0**	**20.2**	**21.2**	**21.7**	**22.5**	**23.2**	**23.5**
	% change*	-10%	-4%	2%	-8%	-1%	3%	-4%	1%	3%	-1%	2%	3%
No LID	(m^3/s)	**16.7**	**17.5**	**18.1**	**19.2**	**20.5**	**20.9**	**21.6**	**21.9**	**22.4**	**23.1**	**23.4**	**23.7**
	% change*	10%	15%	20%	5%	11%	14%	3%	4%	6%	1%	3%	4%

Monterey Ave		Return Period											
		5-year			10-year			25-year			100-year		
Scenario	Peak Flow Rate	Historic	1	2	Historic	1	2	Historic	1	2	Historic	1	2
Rain Garden	(m^3/s)	**17.0**	**18.1**	**19.2**	**21.0**	**22.5**	**23.5**	**24.7**	**25.2**	**25.4**	**25.8**	**26.3**	**27.1**
	% change*	-7%	-1%	5%	-4%	3%	7%	0%	2%	3%	0%	2%	5%
Green Roof	(m^3/s)	**19.4**	**20.5**	**21.3**	**22.8**	**23.6**	**24.5**	**25.0**	**25.3**	**25.5**	**25.8**	**26.4**	**27.1**
	% change*	7%	12%	17%	4%	8%	12%	1%	2%	3%	0%	3%	6%
Top Soil	(m^3/s)	**20.0**	**20.9**	**21.6**	**23.0**	**23.8**	**24.6**	**25.0**	**25.3**	**25.4**	**25.8**	**26.2**	**26.9**
	% change*	10%	15%	18%	5%	8%	12%	1%	2%	3%	0%	2%	4%
Full LID	(m^3/s)	**16.3**	**17.3**	**18.3**	**20.1**	**21.4**	**22.9**	**23.9**	**24.8**	**25.2**	**25.6**	**25.9**	**26.6**
	% change*	-10%	-5%	0%	-8%	-2%	4%	-3%	0%	2%	0%	1%	3%
No LID	(m^3/s)	**20.1**	**21.1**	**21.8**	**23.1**	**24.1**	**24.8**	**25.1**	**25.4**	**25.5**	**25.9**	**26.5**	**27.2**
	% change*	10%	16%	20%	5%	10%	13%	1%	2%	3%	1%	3%	6%

BOLD: Peak flow rates limited because conduit at capacity (Hydraulic Grade Line at conduit crown). Beginning of surcharge. Flooding may occur.

* % change calculated against the base condition of existing land use (No LID) and historic rainfall

Table 3.7: Flood loss volume for the 24-hour duration, 5, 10, 25, 100-year return period events under historic and two future climate scenarios with future land use and three Low Impact Development techniques.

		Return Period											
		5-year			10-year			25-year			100-year		
		Historic	1	2	Historic	1	2	Historic	1	2	Historic	1	2
Rain Garden	(m^3/s)	0	0	92	2355	6484	16003	33472	52992	71629	117509	153656	190399
	% change*	∞	∞	∞	-57.4%	17.3%	189.4%	-14.7%	35.0%	82.5%	1.7%	32.9%	64.7%
Green Roof	(m^3/s)	0	610	1666	8126	15633	28977	44892	59511	79039	121125	154983	191534
	% change*	∞	∞	∞	47.0%	182.8%	424.1%	14.4%	51.7%	101.4%	4.8%	34.1%	65.7%
Top Soil	(m^3/s)	941	2405	4375	9244	17311	33273	43628	59261	75020	112079	142306	175440
	% change*	∞	∞	∞	67.2%	213.1%	501.8%	11.2%	51.0%	91.2%	-3.0%	23.1%	51.8%
All LID	(m^3/s)	0	0	0	1053	3796	10066	20983	41117	58536	95950	129780	164778
	% change*	∞	∞	∞	-80.9%	-31.3%	82.1%	-46.5%	4.8%	49.2%	-17.0%	12.3%	42.6%
No Lid	(m^3/s)	1016	2568	4788	10210	21321	35085	53178	67650	87493	125578	159108	197803
	% change*	∞	∞	∞	85%	286%	535%	36%	72%	123%	9%	38%	71%

* percent change calculated against base conditions of existing land use and historic climate

CHAPTER 4: CONCLUSION

4.1 Conclusion

The first half of this study investigated how the Bowker Creek watershed may be affected by projected changes in extreme rainfall and urbanization. An event-driven hydrologic/hydraulic model was used to simulate historic and two climate scenarios for the 2050s. The assessment primarily focused on effects for the 24-hour, 25-year local design storm, though the 5-year, 10-year and 100-year return period scenarios were also reviewed. Based on the median projection from an ensemble of Global Climate Models (GCM), model results suggest that climate change may increase flood volume by 39% and flood extent by 21% for the 25-year event. These are the minimum changes identified for the local design standard. Flood impacts increase as urban expansion and more pessimistic climate scenarios are simulated. Study findings show that the predicted increase in imperious surfaces may have a similar impact on flood flows as the median climate change projection. The compounding effect of changes in land use and climate may result in a maximum 123% increase in flood volume and a 72% increase in flood extent for the 25-year event. These are not trivial changes in flood flows, especially considering they were the result of comparatively small increases in rainfall intensity.

To generate future rainfall values, this study followed a method that uses regression equations to calculate short duration rainfall from GCM projections. This relatively new method helps overcome the challenge of producing future short-duration rainfall statistics which are critical for flood impact studies. This method typically results in smaller changes than other commonly used methods such as the delta change method. For the local design storm, the change in future rainfall values applied in this study represent approximately ¼ and ½ of the value used in a similar study (KWL, 2007). Had alternate methods been followed, then projected flood impacts could be significantly greater than those identified. Given the magnitude of flood impacts that were revealed in this study and the potential greater impacts under alternate methods, it appears that climate change may very likely pose a considerable flood risk. In order to maintain the current level of flood protection, mitigation measures may be necessary.

The second portion of this study evaluated the effectiveness of using rain gardens, green roofs and top soil amendments to mitigate future flood impacts. Identifying suitable locations for implementation of the three green infrastructure practices was achieved primarily through the use of LiDAR and GIS data. Identified areas and standard design criteria were applied to the model to simulate the effect of implementing these measures.

Results indicate that rain gardens can potentially mitigate the impacts of climate change for rainfall events up to the 10-year return period. The beneficial mitigation effect of rain gardens is approached as storm magnitude increases to the 25-year event. The ability of rain gardens to alleviate climate impacts for this event depends on several factors including the distribution of rainfall intensity over the duration of the event, preceding rainfall events and rainfall increase attributed to climate change. During the 25-year event, rain garden efficacy should be viewed in a probability distribution: under certain conditions it may achieve the mitigation objective; however, under certain conditions rain gardens may not provide complete protection against climate impacts. Rain gardens did not achieve the performance objective for the 100-year event; however, flood flows were reduced compared to the existing land use condition. Understanding and taking into account the dynamic response of rain gardens and their effectiveness over the spectrum of rainfall events should be considered in climate adaptation planning and watershed management in general.

This study suggests that green roofs may not be a feasible solution as far as climate adaptation is concerned. At the locations and scale of implementation used in the modeling, green roofs had a negligible impact on runoff and were far from achieving the performance target. The minor effect on hydrologic response combined with their relatively high cost, means that green roofs are significantly less cost effective than the other two LID measures. It would be difficult to justify the use of green roofs for their mitigation benefit alone. Therefore, when considering the construction of a green roof, the rational for implementing this feature should be based on the other benefits they provide.

The mitigation function of top soil amendments generally begins when existing soil becomes saturated and produces runoff. Consequently, top soil amendments had minimal effect for smaller storm events because both existing soil and amended top soil produce no or modest surface runoff under these events. However, during large storm events this technique had a substantial hydrologic influence. This is primarily attributed to the ability of amended top soil to infiltrate and store rainfall during peak storm intensity whereas existing soils generated run off.

Study findings suggest that both rain gardens and top soil amendments may be required to adapt to the full spectrum of rainfall changes. To realize their cumulative benefit, relatively extensive use of these two techniques would be necessary. The desired degree of implementation would depend largely on the mitigation target. Results show the greatest reduction in the level of flood protection may occur near the 10-year return period (e.g. flood extent more than doubled in 3 out of the 4 modeled scenarios). Therefore, if the mitigation target was based on the 10-year return period, then less than full implementation may be required. Conversely, if the target was based on the 100-year event then the scale of implementation established in this study would be insufficient to completely achieve the adaptation objective. For the most extreme rainfall events, these measures may need to be used in conjunction with alternative or conventional engineering approaches to fully mitigate flood impacts.

Although rain gardens, green roofs and top soil amendment do not appear to be a panacea for eliminating all flood risk associated with climate change, results indicate that the green infrastructure practices can assist in reducing the adverse effects of a changing climate.

4.2 Assumptions and Limitations

The hydrologic assessment carried out in this research is based on the following general assumptions and limitations:

- The hydrologic/hydraulic model can predict flow rates in Bowker Creek with a reasonable level of accuracy.
- GHG emissions follow the SRES “A2” scenario.
- The Pacific Climate Impacts Consortium’s Regional Analysis Tool and the GCMs it is based on adequately represent rainfall changes for the 2050s.
- The statistical correlation between monthly rainfall volume and short-duration rainfall intensity remains reasonably constant into the 2050s (Holm and Weatherly, 2010).
- The site suitability estimates adequately represents the practical maximum application of LID.
- The site suitability assessment and standard design specifications used in the model do not account for site specific conditions and unique designs that may be required.
- The single event-driven simulations assume full available storage capacity of LID facilities. The dynamic response generated by a series of rainfall events was not investigated.

4.3 Further Research

The Bowker Creek Blueprint – A 100-year action plan to restore the Bowker Creek Watershed, provides recommendations from short- to long-term and from watershed to site-level scales. The actions outlined in the Blueprint are precisely those which are required to advance the implementation of LID. Please refer to the Blueprint for a comprehensive list of recommendations. To gain a better understanding of employing LID for adaptation purposes, the following research is suggested:

- Continuous simulation: To provide information on the full range of hydrologic benefits of LID, continuous simulation should be run in a hydrologic/hydraulic model. The rainfall record should be an adequate length (e.g. 30-years) and preferably in short-time steps (e.g. 15-minutes).
- Additional benefits: Evaluate how LID can provide additional benefits such as water quality improvements, enhanced ecosystem health, public amenities etc.
- Other LID techniques: Evaluate LID techniques that were not assessed in this study such as pervious pavements and expanded tree canopy.
- Implementation: Investigate mechanisms to promote LID implementation such as municipal Official Communities Plans, development policies, bylaws, creation of a drainage utility and financial incentives.
- Costs: Complete a detailed assessment of LID life cycle costs.
- Site restrictions: Examine potential site restrictions such as high winter groundwater levels and underground utilities.

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