Report on the
Environmental Benefits and Costs of
Green Roof Technology for the City of Toronto

Prepared For

*City of Toronto and
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Executive Summary
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Toronto has been at the forefront of organized green roof activity over the last several years. In early 1990's volunteers under the Rooftop Garden Resource Group (RGRG) started to promote green roof development in the city. This has been taken over by Toronto-based Green Roofs for Healthy Cities, a not for profit organization, which carries out world-wide education on green roofs.

The City of Toronto has been an active participant in studying wider use of green roofs as a sustainable alternative to meet many of the urban environmental challenges. In the past few years the City has shown leadership in promoting green roofs. In order to inform its actions, the City in partnership with OCE-ETech and the Federation of Canadian Municipalities, engaged a team of Ryerson researchers to develop further understanding of: the types of available green roof technology, the measurable benefits of green roofs to the city's environment, potential monetary savings to the municipality through use of green roofs, and minimum thresholds of green roofs that could be used for part of any incentives or programs.

This report presents the findings on the municipal level benefits of implementing green roof technology in the City of Toronto. Beyond this report, which addresses the immediate needs of the City of Toronto in assisting them to formulate appropriate programs and policies, the Ryerson team has been charged by OCE-ETech to develop a generic technological solution that can be used to predict the costs and benefits related to green roofs. This work is ongoing and is not reported here.

For this report, the Ryerson team conducted an extensive literature review to determine the benefits related to green roofs and, in particular, the quantification of these benefits. It also collected information on the types of buildings in Toronto and their geographic distribution. The information collected was modeled as a GIS database and used for aggregating the benefits on a city-wide basis. The Ryerson team also developed a method to compute the monetary value of the benefits. A survey of the existing green roof technologies and standards was carried out to inform the development of minimum requirements for green roofs.

The findings of the work are presented in the following sections of the report: Section 1, about the study, provides historical background related to this work; Section 2, survey of research related to green roofs, provides the findings of the literature review on benefits of green roofs; Section 3, survey of types of green roofs and their standards, provides information on the different green roof technologies currently available and the performance standards pertaining to green roofs; Section 4, green roof benefits and costs for the City of Toronto, provides the details of the quantification of benefits of city-wide implementation of
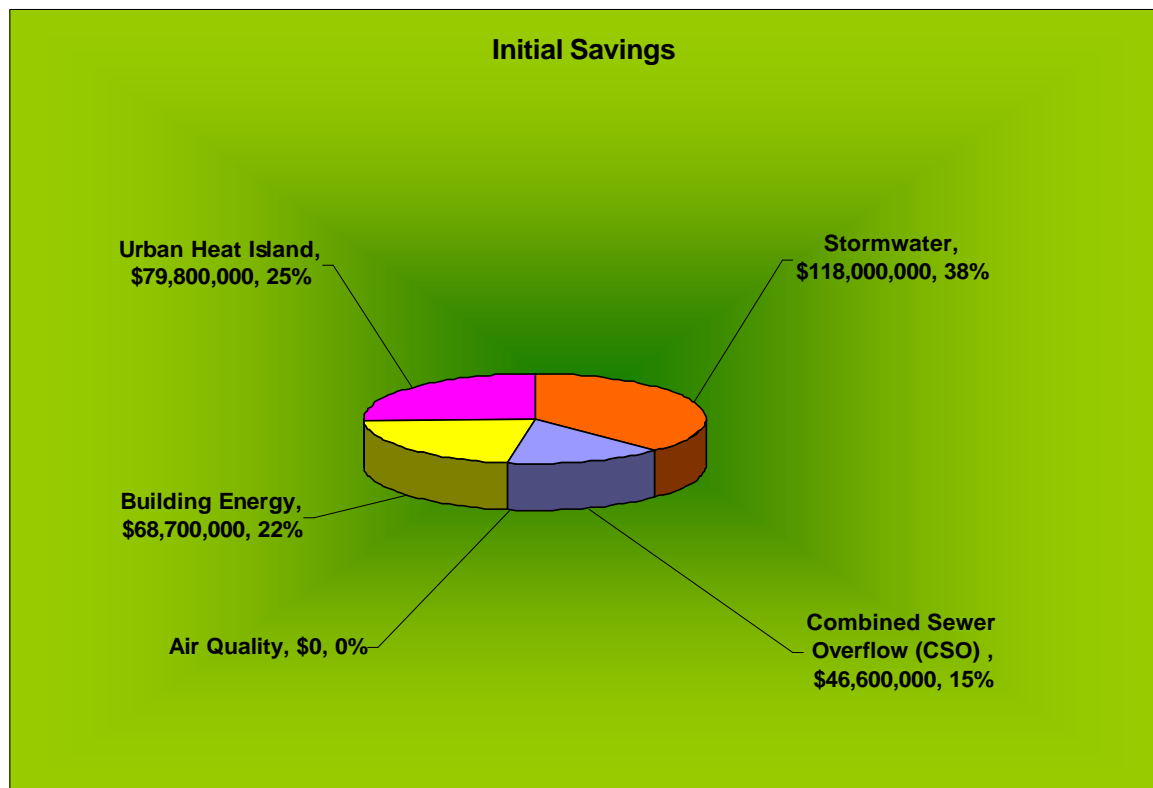
green roofs. The report ends with a summary and recommendation, in Section 5, which provides the recommendations, the minimum thresholds and guidance for further work.
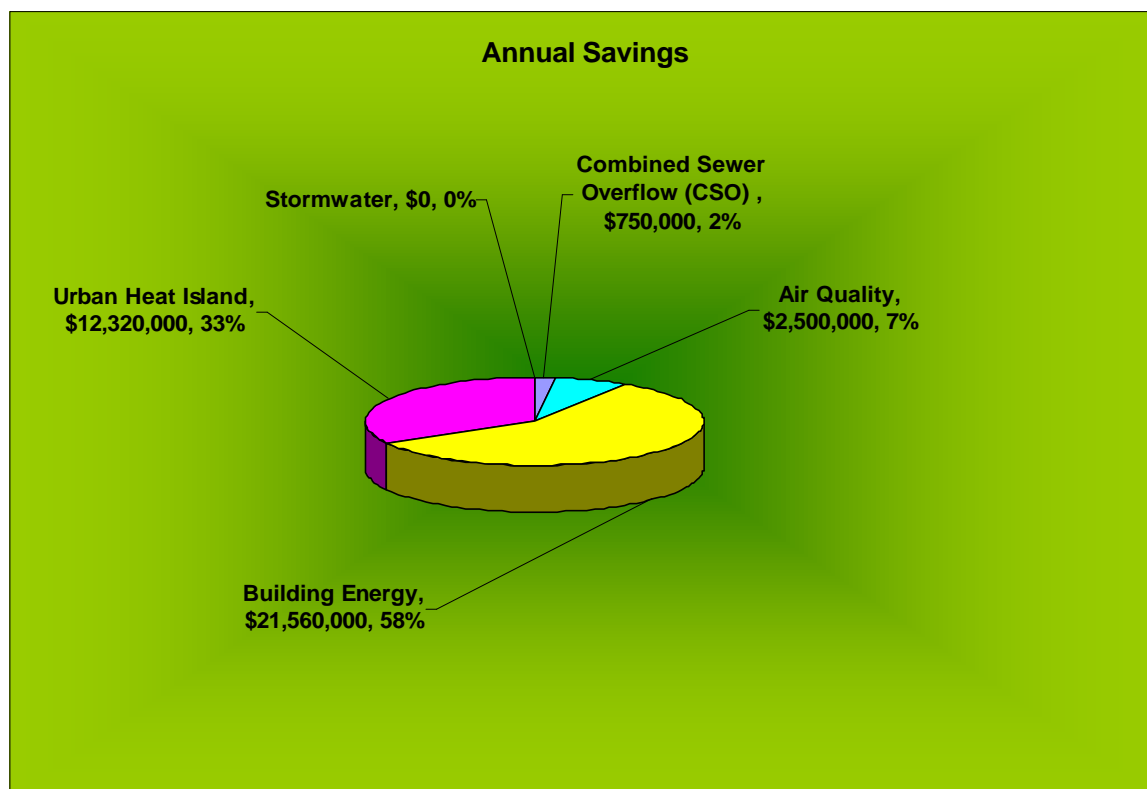
Of the many benefits of green roofs reported in the study, the ones that had the most quantifiable monetary value based on currently available research data are: benefit from stormwater flow reduction including impact on combined sewer overflow (CSO), improvement in air quality, reduction in direct energy use, and reduction in urban heat island effect.

The literature review indicated other benefits that could not be quantified in this report. These benefits included: aesthetic improvement of urban landscape, increase in property values, benefits resulting from green roofs used as amenity spaces, use of green roof for food production, and increased biodiversity. Further work is needed to quantify these benefits.

The benefits on a city-wide basis were calculated based on the assumption that 100% of available green roof area be used. The available green roof area included flat roofs on buildings with more than 350 sq. m. of roof area, and assuming at least 75% of the roof area would be greened. The total available green roof area city-wide was determined to be 5,000 hectares (50 million sq. m.).

The benefits were determined as initial cost saving related to capital costs or an amount of annually recurring cost saving. These are shown in the following charts and table.

Initial Savings

Urban Heat Island, $79,800,000, 25%

Stormwater, $118,000,000, 38%

Building Energy, $68,700,000, 22%

Air Quality, $0, 0%

Combined Sewer Overflow (CSO) , $46,600,000, 15%

Annual Savings

Stormwater, $0, 0%

Combined Sewer Overflow (CSO) , $750,000, 2%

Urban Heat Island, $12,320,000, 33%

Air Quality, $2,500,000, 7%

Building Energy, $21,560,000, 58%

Category of benefit	Initial cost saving	Annual cost saving
Stormwater	$118,000,000	
Combined Sewer Overflow (CSO)	$46,600,000	$750,000
Air Quality		$2,500,000
Building Energy	$68,700,000	$21,560,000
Urban Heat Island	$79,800,000	$12,320,000
Total	**$313,100,000**	**$37,130,000**

The report also presents the minimum considerations for the type of green roof to achieve the stated benefits. The key considerations include that: the roof system be of the type known as an extensive roof system, that it cover a significant portion of the roof, have a maximum runoff coefficient of 50%, and have at least a 150 mm. depth where structural loads permit. Green roofs with less depth could be used on roofs where structural loading does not permit the 150 mm. depth.

The benefits quantified in this report show that there is a case for development of public programs and the promotion of green roofs. The City of Toronto may wish to use this information to embark on consideration of programs that will give further impetus to the construction of green roofs.

Green roof technology is an emerging technology and many questions need further exploration. Although this study has made several advances in predicting benefits of green roofs, and it has provided information for the City of Toronto to move further on programs and policies pertaining to green roofs, there are several areas that will require further work. Questions remain to be answered regarding the uncertainty of the benefits, impact of less than 100% green roof coverage, impact of building specific constraints, the quantification of program costs leading to a complete cost benefit analysis, quantification of other social benefits and consideration of the effect of alternative technologies that may be able to perform one or more of the functions of a green roof. These questions are important and will need to be considered in further studies. Some of these will be explored in the continuing work by the Ryerson team. In the meantime, policy decisions regarding green roofs will need to consider the potential impact of these questions.

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1.0 About the study

1.1   Study objectives

This study is part of a project undertaken by Ryerson University through funding provided by the Ontario Centres of Excellence-Earth and Environmental Technologies (OCE-ETech) and matched by the City of Toronto as the major partner. Other partners include Trow Associates and 401 Richmond. This document reports on the first part of the project and deals with the municipal level benefits of Green Roof Technology.

Individual building owners are driving construction of green roofs; the City of Toronto is investigating the development of programs to promote green roofs and the required standards for their implementation.

In order to develop appropriate actions, the City of Toronto identified a need to determine the social and environmental benefits of green roofs on a city-wide level. The City of Toronto needs to have an understanding of:

- the types of green roof technology;
- the measureable benefits of green roofs to the city's environment;
- potential monetary savings to the municipality;
- minimum threshold points for the City of Toronto to provide incentives to make significant cost savings.

This study conducted by Ryerson University and as reported here will be used to inform the City of Toronto in developing programs to promote the use of green roof technology. The social and environmental benefits of this technology are of primary importance. It is expected that the information in this report will assist the City of Toronto to formulate the appropriate types of government programs or incentives to encourage private investment in green roofs and thus reap the social benefits. The public costs of these programs or incentives are as yet to be determined and not part of this project.

Beyond this study for the City of Toronto, the overall objective of the project is to build on the knowledge gained in order to formulate a model and useable technology that will allow individual building owners and other municipalities to measure the benefits of green roof technology.

1.2   Context and background of green roof related activity in Toronto

Green roof activities have been ongoing in Toronto for almost a decade. Promotion of green roofs in Toronto can be traced back to a small number of dedicated volunteers under the umbrella of the Rooftop Garden Resource Group. Their activity was enhanced with the involvement of an association that is today known as Green Roofs for Healthy Cities (GRHC).

The City of Toronto's formal involvement in green roofs is rooted in the recommendations of the Environmental Plan (2001). The Plan was the first to formally identify the need for a strategy to encourage green roofs and rooftop gardens. The Natural Environment policy within the City's new Official Plan further supports green roofs calling for "the development of innovative green spaces such as green roofs, and designs that will reduce the urban heat island effect."

Another place where green roofs have found a potential is in the Wet Weather Flow Management Master Plan for the City of Toronto completed in 2000. It examined ways to improve the water quality of local rivers and Lake Ontario by strengthening mechanisms to prevent and reduce stormwater runoff. Green roofs may appear in future stormwater planning policies that discuss best management practices; however, the policies have not been drafted at this point.

The following subsections deal with specific activities that have been undertaken to promote green roofs in the City of Toronto.

1.2.1   Green Roof Demonstration Project

In Fall 2000, Green Roofs for Healthy Cities, the Toronto Atmospheric Fund, the Federal Government and the City of Toronto partnered to initiate a Green Roof Demonstration Project.

Two demonstration green roofs were constructed as part of the project:
- eight plots covering more than 300 square metres on the podium roof of Toronto's City Hall building;
- a 465 square metre green roof on the Eastview Neighbourhood Community Centre.

For the first two years, the City of Toronto and Green Roofs for Healthy Cities managed the demonstration roofs jointly. After that period, the City assumed the management of the project.

The objectives of this million dollar, three-year project, were to find solutions to overcome technical, financial and information barriers to the widespread adoption of green roof infrastructure in the marketplace by:

- generating reliable technical data on green roof performance in areas such as energy efficiency, stormwater retention, the extension of roof membrane life span and plant survival in the Toronto climatic context;

- conducting research on city-wide cooling benefits of green roofs in the summer and the potential spin-off from greenhouse gas reduction, smog reduction and energy efficiency gains from reducing cooling loads in buildings;

- evaluating the costs and benefits of future public-private investments in green roofs;

- increasing awareness of the benefits of green roof technology by giving professionals the opportunity to visit a working demonstration site with multiple applications.

The City Hall podium green roof has been used to study the different plants that can be used for green roofs in Toronto.

The Eastview Neighbourhood Community Centre green roof is an extensive green roof built beside a regular membrane finished flat roof. It has been extensively instrumented, and results from the measurements have been published. The results to date have been encouraging.

1.2.2 Sustainable Technologies Consortium – York University Roof Monitoring Program

The Sustainable Technologies Consortium was formed in order to address the growing need for research to support the implementation of technologies promoting sustainable development. The Consortium is a public partnership between the Toronto and Region Conservation Authority (TRCA), Seneca College, the University of Guelph and Ryerson University. The multi-disciplinary nature of the Consortium's members was intended to reflect the nature of sustainable technology research, which integrates various disciplines and research interests. The mandate of the consortium is two-fold:

- to pursue scientifically defensible research in sustainable development;

- to quantify the potential benefits of technologies relating to stormwater management, water and energy conservation, and air pollution.

The impetus for the Sustainable Technologies Consortium can be traced to the International Joint Commission, which in 1987 identified Toronto as one of 42 regions of concern bordering the shorelines of the Great Lakes. It developed a Remedial Action Plan to restore polluted drainage networks and water bodies located in the city or along the shorelines of Lake Ontario. Some of the goals and actions recommended by the Remedial Action Plan can be achieved using green roof technology.

In 2003, a research site was established on the York University Computer Science Building. A green roof was designed during building construction and has been monitored by the TRCA. Unlike the Eastview Neighbourhood Community Centre building which was a retrofit the York University green roof was installed over a new building.

Measurements of climate, soil and runoff have been taken to quantify the stormwater quality and quantity benefit of the green roof. The monitoring devices have been linked to a single logger and network server that statistically calculates and communicates measured data via the internet. The internet connection also provides real-time measurements of activities (e.g. rainfall) that can be accessed from anywhere in the world.

Initial results from the monitoring of the effects of green roof technology on stormwater runoff control have been positive.

In addition to the monitoring, a hydrological modeling analysis of Highland Creek was undertaken using the monitored data. This data has been used in this study.

1.2.3 City of Toronto, FCM and OCE-ETech partnership

The encouraging results from the green roofs on the Eastview Neighbourhood Community Centre, Toronto City Hall and the York University Computer Science Building have provided positive impetus for ongoing promotion of green roofs. City planners started to examine the possibility of developing programs to promote green roofs. City of Toronto staff explored the possibility of seeking funding from Federation of Canadian Municipalities (FCM) to carry out research that would inform the development of programs and policies to promote green roofs.

The City of Toronto was successful in procuring funds from FCM for further studies to examine the municipal level social and environmental costs and benefits of green roofs. FCM has been the national voice of municipal government since 1901 and is dedicated to improving the quality of life in all communities by promoting strong, effective, and accountable municipal government. Recently, the Government of Canada endowed the FCM with $250 million to establish the Green Municipal Funds and support municipal government action to cut pollution, reduce greenhouse gas emissions, and improve quality of life.

The City of Toronto approached OCE-ETech, who organized a green roof think tank in November, 2003. OCE-ETech is a division of the Ontario Centres of Excellence and helps Ontario organizations grow by finding solutions for their innovation challenges. It engages clients and academic partners in various market driven strategic clusters of activities, including sustainable infrastructure and energy solutions. Research into the municipal level costs and benefits of green roofs was identified as an area of research.

Based on the City of Toronto's interest and FCM support, OCE-ETech put out an expression of interest (EOI) in the winter 2004. Teams from Ryerson and other universities participated in the EOI. In spring, 2004 a team from Ryerson and two teams from other universities were shortlisted to submit a detailed proposal. Ryerson submitted a proposal with the City of Toronto as the major partner. In Fall, 2004 Ryerson was selected to carry out the project related to the costs and benefits of green roofs.

As indicated earlier the project has multiple parts. The first part, which resulted in this report, was to examine the social and environmental benefits of green roofs at the municipal level for the City of Toronto.

1.3   Other FCM sponsored studies of GRT

In the past, FCM has supported work specific to green roof technology at two other municipalities: the City of Waterloo and the City of Winnipeg. The following sections provide a brief description of these studies.

1.3.1   City of Winnipeg study

Funded by the FCM grant, the City of Winnipeg explored the feasibility of developing a green roof strategy for flat-topped buildings in its downtown area. Such a strategy could help alleviate stormwater management problems in Winnipeg's downtown. The City felt that a green roof strategy could be incorporated into the Combined Sewer Overflow (CSO) control model to reduce runoff effects and provide other environmental benefits.

The Assiniboine district was the focus of this study due to its high concentration of flat-topped buildings. The area is also the most prone to overflows from the combined sewer system. Recent aerial photographs and visual inspections indicated that an area of 218,773 square metres (almost 20% of the total area of the district) could be used for green roof development.

Control-system models were created to simulate rainfall and runoff during a typical year. Various scenarios were examined to determine whether a green roof strategy could reduce not only the number of overflows in a year, but also their volume and the volume of wastewater going to the water pollution control centre.

In this study plant species were also evaluated for their carbon-fixation and sequestering potential.

Data collected during the stormwater modelling process indicated that the number of overflows could be reduced by 16%, if 100% of the potential roof space in the district were used. The volume of the overflow could also be reduced by approximately 48%, which in turn would cut the volume of flow to the water pollution control centres.

In terms of the carbon fixation it was found that if 100% of the potential green roof space were developed, 24.5 tonnes of carbon would be fixed (removed) annually.

1.3.2   City of Waterloo study

As part of its Environment First Policy, the City of Waterloo developed an Environmental Strategic Plan, which was adopted by Council in 2002. Green roofs fit into the Environmental Strategic Plan in all important areas.

In 2003, the City of Waterloo received a grant of $25,000 from FCM for a "Green Roofs Feasibility Study." As a condition of the grant, a green roof demonstration site was to be constructed on a city-owned building.

A multidisciplinary steering committee was formed to guide the study. It included 12 professionals from various agencies, levels of government and community interests. Totten Sims Hubicki, Enermodal Engineering and Elevated Landscape Technologies were retained to complete the above study on behalf of the City of Waterloo.

The purpose of the Green Roofs Feasibility Study was to identify a city-wide green roofs implementation plan for municipally owned buildings in the City of Waterloo, including identification of potential costs and associated maintenance. It would also, through the selection process, identify a preferred location for a green roof demonstration site in the City of Waterloo. The function of the demonstration site would be to raise public and industry awareness and to provide an educational forum to display the benefits of green roofs. A business plan for the green roof demonstration site, including an analysis of performance, benefits, and costs, was to be generated as part of the feasibility study.

The study, which was completed in February, 2005, identified a mechanism for selecting a site for implementing green roof technology. The green roof has recently been constructed on the City Hall building.

2.0 Survey of research related to green roofs

Municipal programs and policy development related to green roofs need to be informed by supporting research on the costs and benefits of green roofs. The green roofing industry in North America is not as mature as in some European jurisdictions, where a number of social and environmental benefits have been attributed to green roofs.

The purpose of this section is to document the results of a review of published literature pertaining to the social and environmental costs and benefits of green roof technology. The immediate objective of the review is to clarify the issues of green roof costs and benefits for a municipality, so that the methodology can be refined to reflect the most current state of knowledge about the performance of green roofs.

To begin this section we list the benefits that have been attributed to green roofs. In subsequent sections these are explored in terms of the evidence from reported research in the public domain. The derivation of actual economic benefit is then addressed and the implications summarized.

2.1   Potential green roof benefits

Municipalities considering policies for green roofs will need to examine the tangible and intangible benefits and costs associated with green roofs on a community-wide basis. What is needed is an approach that is comprehensive and realistic in determining the costs and benefits across the spectrum of circumstances and potential opportunities that may arise from installing green roofs.

Impacts of green roof that have been commonly cited are as follows:

- effects on energy budgets of individual buildings;
- effects on the urban heat island;
- effects on stormwater management strategies;
- effects on urban air quality;
- repercussions for urban amenities, such as food production, aesthetics, recreation; urban agriculture, noise reduction, real estate, therapeutics, open space;
- effects on waste management from increase in roof material "life cycle";
- promotion of horticulture/landscaping,
- promotion of biodiversity and wild life protection;
- promotion of health and well-being

The following review provides an exhaustive profile of existing publications from the scientific literature and also addresses the findings of agencies currently managing green roofs and jurisdictions in which green roof-advocacy policies are currently in place. It should be recognized that the highest priority is reserved for research presented in peer-reviewed

research publications. A great deal of green roof research has been undertaken in Germany; the results of many of these studies were originally published in German. Therefore, in some instances, citations identify reviews by others who have examined the results of the original German studies.

2.2   Energy budgets of individual buildings

Green roofs have been investigated for their effects on building energy costs. The insulating effects of added materials seem likely to reduce the penetration of summer heat and the escape of interior heat in winter and there is some scientific evidence to support these notions. There is possibly an even greater benefit in the summer due to the cooling created by the evapotranspiration effect from plants and the evaporation of retained moisture from the soil. Since different climatic conditions and architectural standards present distinctive energy transfer opportunities, research results should be interpreted in terms of where the study was undertaken and how relevant it is to the Canadian environment. Similarly, the conversion of energy savings into cost savings must recognize Canadian market conditions.

In some of the earliest reported research, measurements in Berlin conducted in 1984 revealed not only reduction in maximum surface temperature but also temperature amplitudes reduced by half due to green roof installation (Kohler et al., 2002).

Akbari et al. (1999, 2001) investigated means of reducing building energy in mid-latitude cities as one of several means for reducing the urban heat island (UHI) effect and documented the enhanced air conditioning demands (up to 10%) brought about by the UHI. This elevated load generally occurs in the late afternoon hours, corresponding to the peak summer electric utility load. Akbari also demonstrated that the afternoon electric utility load for southern California increases by more than 2% per degree Celsius increase in air temperature. Also noteworthy, was the determination that ozone concentration in the Los Angeles basin was positively correlated with air temperature, increasing at a rate of 5% per degree Celsius (Akbari et al., 1990; Sailor, 1995). By making roofs cooler, designers can reduce the amount of absorbed solar energy, and consequently reduce the amount of heat conduction into buildings. This reduces daytime net energy inputs (Akbari and Konopacki, 2004[1]; Akbari et al., 2001; Konopacki et al., 1997) and the demand for air conditioning.

Del Barrio (1998) explored the thermal behaviour of green roofs through mathematical analysis. The main conclusion of this study is that green roofs effectively act as thermal insulators. Eumorfopoulu (1998) also carried out calculations to examine the thermal behaviour of a planted roof and concluded that green roofs can contribute to the thermal performance of buildings. This study further showed that of the total solar radiation absorbed by the planted roof, 27% is reflected, while the plants and the soil absorb 60%, and 13% is transmitted into the soils. Evidently, with a green roof the insulation value is in both the plants and the layer of substrates (Eumorfopoulu, 1998). Patterson (1998) also showed that

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[1] This study will be referred to as the LBL study

green roofs prevented temperature extremes and the insulation value of the soil on the structure lowered the cooling energy costs.

Figure 2.1
Methodology to analyze the impact of cool roofs
and cool pavements on energy use. [After: Akbari et al. (2001)]
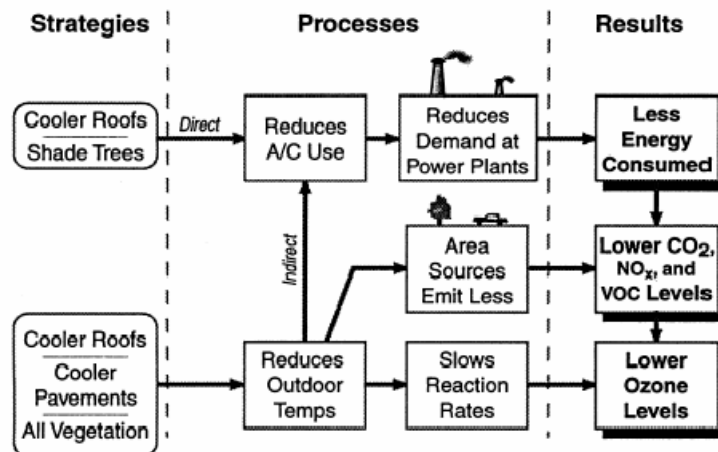
Recently, some quantitative data were obtained through field measurements, experimental and computational methods. Onmura et al. (2001) conducted a field measurement on a planted roof in Japan. The evaporative cooling effect of a rooftop lawn garden showed a 50% reduction in heat flux in the rooms below the garden. This research also revealed a reduction in surface temperature from 60 to 30°C during the day. The importance of evaporation in reducing the heat flux was quantitatively simulated in a series of wind tunnel experiments.

Niachou et al. 2001 conducted a measurement of surface and air temperature on a planted roof. The work was further complemented by a mathematical approach through which thermal properties of green roofs and energy savings were determined. Reviews by Wong et al. (2003) and Kohler et al. (2002), have shown that under a green roof, indoor temperatures were found to be at least 3 to 4°C lower than outside temperatures of 25 to 30°C.

In the only Canadian study, Liu and Baskaran (2003) report that field research in Ottawa has revealed that the energy required for space conditioning due to the heat flow through the green roof was reduced by more than 75%. The study focussed on controlled conditions featuring a reference roof and a green roof of equal dimensions; the experimental roof surface area was 72 m^2 (800 ft^2) with the green roof on one half and the reference roof on the other half. An energy reduction from 6.0 to 7.5 kWh/day for cooling was demonstrated (Liu and Baskaran, 2003; Bass and Baskaran, 2003).

Alcazar and Bass, (2005) have very recently reported that the installation of a green roof in Madrid reduced total energy consumption by 1% with 0.5% reduction in the heating season and a 6% reduction in the cooling season.

Table 2.1 – Summary of key findings from literature review related to heat transfer, energy use and green roofs

Study	Location	Monitoring	Qualitative/Quantitative Changes due to green roof	Study recommendations	Conversion to costs or benefits
Kohler et al. (2002)	Berlin, Germany	As early as 1984 surface temperatures of a green roof were monitored. The surface temp; shadowed surface temp of gravel; shadowed surface temp of green roof; temp of substrate; ambient air temp. were all measured	Green roof reduced surface temp. but also more importantly reduced the max. temp. amplitude by half.	The complex composition of green roofs represents a decisive additional buffer zone; the lowering roof temp. and added insulation effect are undeniably positive for indoor climate; the durability of flat roof is increased significantly	
Sailor (1995)	Los Angeles	Three-dimensional meteorological simulation of urban surface characteristics i.e. increasing albedo and or vegetative cover.	Increasing the albedo over the downtown L.A. area by 0.14 decreased summer time temperatures by 1.5^{o}C. Increasing the vegetative cover by using green roofs showed similar results.	Preliminary evidence suggests that albedo and vegetation increases would benefit cities by reducing air temp. and energy demand. A thorough cost-benefit analysis for modifying urban surfaces for other geographical locations is needed; feasibility issues for large scale implementation must be resolved	A reduction of 1°C in summer time afternoon air temp for L.A. corresponds to a 2% energy savings
Del Barrio (1998)	Mediterranean region	Mathematical model	Green roofs do not act as cooling devices but as insulation, reducing the heat flux through the roof	Soil density, thickness and moisture content are identified as relevant for green roof design parameters.	
Eumorfopoulu (1998)	Athens, Greece	Mathematical model to determine the thermal behaviour of planted roofs and the thermal protection	Of the total solar radiation absorbed by the planted roof, 27% is reflected, 60% is absorbed by the plants and the soil through evaporation and 13% is transmitted into the soils; Evidently, the insulation value is in both the plants and the layer of substrates.	Green roofs block solar radiation, reduce daily temp. variations and thermal ranges between winter and summer; planted roofs contribute to the thermal protection of a building, but do not replace the insulation layer.	

Table 2.1 – Summary of key findings from literature review related to heat transfer, energy use and green roofs (continued)

Study	Location	Monitoring	Qualitative/Quantitative Changes due to green roof	Study recommendations	Conversion to costs or benefits
Onmura et al..(2001)	Japan	Field measurements; wind tunnel experiment; numerical calculations.	The evaporative cooling effect of a roof lawn garden showed a 50% reduction in heat flux in the rooms below the garden. A reduction in surface temperature from 60 to $30^{\circ}C$ during day time led to the conclusion that evaporative component is an important role in reducing the heat flux.	Evaporation was dependent on the moisture content in the lawn	
Liu and Baskaran (2003); Bass and Baskaran (2003)	Ottawa, Canada	A green roof and a reference bituminous roof were instrumented to allow direct comparison of thermal performance	The green roof was more effective at reducing heat gain than heat loss. The green roof reduced temperature fluctuations and also modified heat flow through the roofing system by more than 75%	During the observation period, the green roof reduced 95% of the heat gain and 26% of the heat loss as compared to the reference roof. Then it is expected that its effectiveness will be more significant in warmer regions	A reduction from 6.0-7.5 kWh/day to less than 1.5kWh/day which corresponds to a 75% reduction and the potential for savings.
Alcazar and Bass, (2005)	Madrid, Spain	The energy performance of three roofing systems is compared. Thermal and optical characteristics are monitored ESP-r energy simulation software is used to compare annual energy consumption	The study show that the installation of a green roof in the building provides savings in annual and peak energy consumption; The green roof resulted in a total annual energy consumption reduction of 1% with a 0.5 % reduction in the heating season and a 6 % reduction in the cooling season.	This reduction was not homogeneous throughout the building. Below the third storey, under the roof, no savings were achieved. .	A total annual energy reduction of 1%
Bass et al. (2002)	Toronto, Canada	A mathematical model (MC2) was used to quantify the mitigation of the urban heat Island	Low level air temperatures were simulated for 48 hours in June 2001. With a 50% green roof coverage a $1^{\circ}C$ reduction in low level air temperatures was observed. Irrigation of the green roofs produced a cooling of $2^{\circ}C$	Further research is needed in this area. The model operated well, however, unexpectedly low reductions in air temperature may have been caused by unknown underlying assumptions.	

2.3   Urban heat island

The air in urban areas is typically warmer than that in surrounding undeveloped areas. This concept has been recognized in publications since early in the Industrial Revolution (Howard, 1818, cited in Landsberg, 1981). Over the years, concern for the catastrophic effects on human health has prompted the development of strategies for reducing the urban heat island effect. These strategies have included reducing heat radiation and other emissions, expanding vegetated spaces, and most recently the implementation of cool roofs (Akbari *et al.,* 1999; 2001; 2003) and green roofs (Kohler *et al.,* 2002; Wong *et al.,* 2003a, 2003b; Bass *et al.,* 2002).

The most frequently observed and documented climatic effect of urbanization is the increase in surface and air temperatures over the urban area, as compared to the rural surroundings. Oke (1995) simply defines an urban heat island (UHI) as the 'characteristic warmth' of a town or city. This warmth is a consequence of human modification of the surface and atmospheric properties that accompany urban development. This phenomenon is given its 'island' designation due to the isotherm patterns of near-surface air temperature which resemble the contours of an island rising above the cooler conditions that surround it. This analogy is further illustrated in Figure 2, which shows a schematic representation of near-surface temperature for a large city, traversing from countryside to the city centre. A typical 'cliff' rises steeply near the rural/suburban boundary, followed by a 'plateau' over much of the suburban area, and then a 'peak' over the city centre (Oke, 1987, 1995). The maximum difference in the urban peak temperature and the background rural temperature defines the urban heat island intensity. Over large metropolitan areas, there may be several plateaus and peaks in the surface temperature. Cooler patches coincide with open areas where vegetation or water are found.

Figure 2.2
Generalized cross-section of a typical urban heat island [After Oke (1987)]
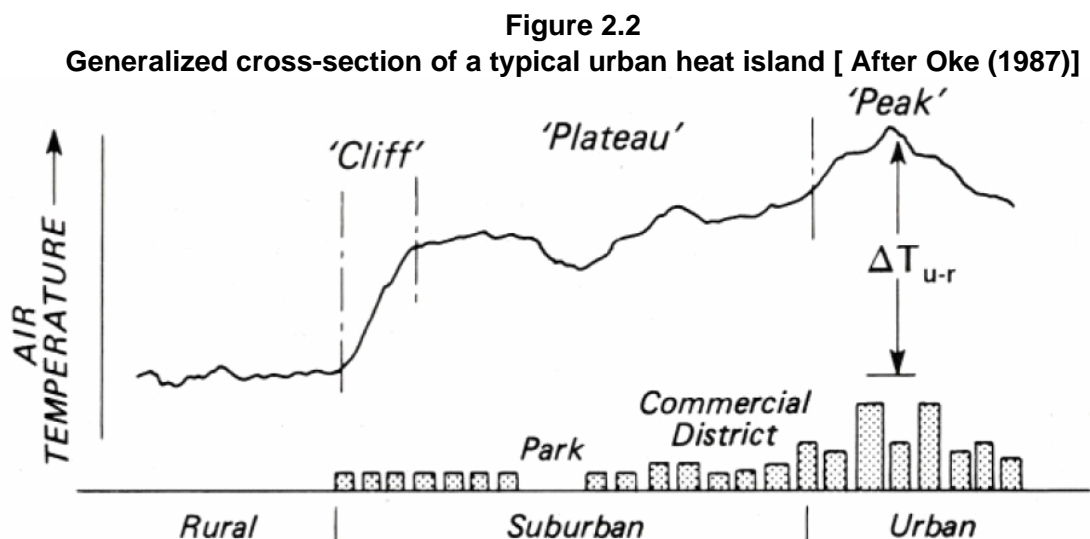
Many observations of the urban heat island over small and large cities have been reviewed by Landsberg (1981) and Oke (1987, 1995). The intensity of an urban heat island depends on many factors, such as the size of city and its energy consumption, geographical location, absence of green space, month or season, time of day, and synoptic weather conditions.

Oke (1987) recognized that the urban heat island is especially related to the high urban densities and configurations of buildings in downtown areas. He demonstrated that buildings can create 'canyons,' which substantially reduce the amount of sky view available for long wave radiation heat loss at night. Other factors contributing to the intensity of the heat island effect include: containment of heat by pollutants in the urban atmosphere, daytime heat storage due to the thermal properties of urban surface materials, emission of heat (from buildings, transportation, and industrial operations), decreased evaporation due to the removal of vegetation and the hard surface cover in the city which prevent rainwater percolation into the soil. The absence of vegetation and the nature of this hard surface cover can be addressed by green roof treatments. It is impermeable urban surfaces (buildings, roadways, sidewalks, patios, parking lots etc), and an absence of soil and vegetation that results in rapid shedding of water from rainfall and snowmelt. In the presence of stored moisture, energy is naturally used to evaporate water (as in rural and open areas). This sensible heat used to evaporate water creates a cooling effect, thereby reducing the temperature of the surroundings. In cities, the absence of such stored moisture, due to the increase of impervious surfaces, results in an elevation of surface temperature, which in turn increases the air temperature due to radiative heat transfer.

Through better understanding of the general causes and associated problems of the urban heat island, specific strategies for reversing the effect have been gaining acceptance by municipalities. These include designs to exploit natural sources of cooler air from the surrounding countryside and adjacent water bodies, parks within the city, air circulation created by urban structures themselves, and evaporative cooling from vegetation or other sources of water in the city (Landsberg, 1981; Chandler, 1976). Designs to reduce the heating of surfaces are also seen as especially useful in overcoming the urban heat island effect. The benefits of tree planting programs in metropolitan areas have been significant in cooling the air, as well as adding to the aesthetics, and reducing greenhouse gas (CO_2) contributions (Parker, 1982; Landsberg, 1981; Oke, 1987). However, the demand for space in cities inhibits expansion of forested areas.

Green roofs present the opportunity to expand the presence of vegetated surfaces by replacing impermeable surfaces in urban areas, providing for a reduction in peak summer urban heat island temperatures.

Rosenfeld et al. (1998) addressed strategies to cool urban areas by reducing the heat island effect and smog in Los Angeles. By focusing on the energy demand of buildings, they developed a model that showed Los Angeles could be cooled up to 3°C by reroofing and repaving using "cool" (high reflectance) materials, and by planting shade trees around buildings. However, Sailor (1995) had argued that in the urban environment, the lack of vegetation, which controls evapotranspiration, is the most significant factor contributing to

the urban heat island. Therefore green roof technology offers the possibility of much greater impact on the urban heat island effect than reflective roofs alone.

Quantifying the mitigation of the UHI has proved to be difficult (Kohler, 2003). Bass *et al.* (2002) attempted to mathematically model the effect of green roofs on the UHI in Toronto. Using a mesoscale model and the natural and urban surface parameters, low level air temperatures were simulated for a 48 hour period in June, 2001. The simulation assumed 50% green roof coverage and showed a reduction of 1°C in low level urban temperatures. The simulation was repeated with the addition of irrigated green roofs. Irrigated green roofs produced a cooling of 2°C and extended the 1°C over a larger geographic area. However, as successfully as the model operated, model assumptions, case study choices and input data of unknown quality created unexpectedly low reductions (Bass et al. 2002). It should be noted that UHI is of major concern in summer months. It is not deemed to be of much concern in the winter months in northern climates.

2.4   Stormwater management implications

Rainfall and snowmelt in urban areas are typically more problematic than in rural environments. Under natural conditions, precipitation is impeded from running off by vegetation, ground-surface retention and subsurface storage. The retained rainwater will contribute to the soil moisture and ground water replenishment. Urban landscapes are dominated by impervious surfaces, such as concrete sidewalks, building walls and roofs, and paved parking lots and roads. These collect the flow and direct it into storm gutters, sewers and engineered channels (collectively called the urban drainage system). Urban runoff eventually reaches receiving waters as sudden uncontrolled surges. Many surface contaminants are picked up in the passage of this runoff and are carried with this torrent of stormwater. Common contaminants include suspended solids, heavy metals, chlorides, oils and grease, and other pollutants that arise from the use of roadways and from other surfaces the water has passed over.

There are two basic categories of interrelated problems concerning urban runoff and wastewater from areas served by drainage systems: quantity management and quality management. Quantity management problems arise from upstream and downstream flooding, associated with overloaded sewer systems, and from erosion of conveyance channels downstream in the drainage basin. Untreated overflows to receiving waters from combined storm and sanitary sewer systems result in water quality management problems. Sanitary overflows usually contain high concentrations of organic compounds, bacteria and nutrients, which cause short and long-term quality problems to receiving waters. On the other hand, storm overflows often contain a considerable amount of trace metals and a high concentration of suspended solids, which may have long-term impacts on receiving waters as pollutants slowly release from deposited sediments. The following sections describe quantity and quality problems associated with each type of drainage system.

2.4.1   Combined sewer systems

Currently, the principal problems residual to existing combined sewer systems are deterioration of receiving water quality associated with combined sewer overflows during high runoff conditions, sewer backup, and downstream flooding.

Combined sewer overflows result from the limited capacity of interceptors to carry the large volumes of intermittent storm runoff for treatment. Since the design capacities of interceptors are usually limited to 2.5 to 3.5 times dry-weather flow, it is likely that excess combined sewer discharges will be spilled to receiving waters even during moderate rainfalls. For instance, with a customary interceptor capacity of 2.5 times dry-weather flow in Toronto, an average of 12 overflows per month has been observed (Hogarth, 1977).

Pollutant characteristics of combined sewer overflows are comparable to those of raw sewage with high concentrations of biochemical oxygen demand (BOD), suspended solids and coliform organisms. The high concentrations of pollutants in combined sewer overflows arise primarily from two sources. The first is associated with a process commonly called the ``first flush effect,'' in which solids deposited during dry-weather periods of low flow wash out by scouring during the initial stages of storm runoff. According to studies (Camp, 1963), as much as 30% of dry-weather solids may be contained in the overflows, even though only 3 to 6% of dry-weather flow volume may be lost in overflows. The second is related to the pollutant characteristics of stormwater runoff, which often contains a variety of pollutants such as nutrients and trace metals.

Localized upstream flooding problems associated with combined sewer systems are worse than the roadways flooding associated with storm sewer systems because of the backup of combined sanitary and storm flow to building drains. Sewer backup is due to obstructed flow or inadequate capacity at the downstream end of the system, and sometimes to hydraulic instability inside the sewer which causes pressurized flow to move upstream in the system. In contrast, downstream flooding in drainage basins is usually due to the limited capacity of receiving channels.

Increased erosion due to high runoff flow rates at downstream receiving channels, occurs frequently after urban development. Land development alters the hydrologic characteristics of catchments, resulting in increased runoff volumes, runoff velocities, and peak discharge rates. All these changes cause a greater rate of channel erosion downstream in the development.

2.4.2   Sanitary sewers

Quantity problems of sanitary sewer systems are primarily due to extraneous flows and infiltration/inflow during and after storm events, resulting in hydraulic overloading of both collection systems and treatment plants. Water enters sanitary sewers as infiltration through cracked pipes and defective joints, and as inflow through cross connections, faulty manholes, and submerged manhole covers. Extraneous flows due to improper house connections and illegal drains are also responsible for excess flow in sanitary sewers.

Quality problems associated with sanitary sewer systems are usually related to overflows. Although all sanitary flows are designed to be treated at treatment plants, overflow points are often built into the sewer systems to prevent overloading the plants. The overflow may be diverted to storm sewers or directly into receiving waters. As a result, the water quality of the receiving waters may be seriously impaired similar to the overflow situation in combined sewers.

2.4.3   Wastewater treatment systems

There are approximately 400 wastewater treatment plants in Ontario. They are mostly secondary treatment plants with phosphorus removal. Generally, organic and solids removal at these plants is about 85-90% under normal operation conditions. Problems of wastewater treatment systems are primarily associated with shock loadings, bypasses, and overloading due to wet weather. Other associated problems are related to odour and sludge management.

2.4.4   Storm sewer systems

Separated storm sewers are usually designed for storms with return periods of two to five years. As a result, sewer capacities are exceeded quite frequently. In addition to inadequate sewer capacity, the gradually-varied nature of storm flow and/or hydraulic instability in sewers (such as localized hydraulic jumps or waves) can also induce upstream and downstream flooding. As in combined sewer systems, increased runoff after urban development can cause greater rates of channel degradation downstream in drainage basins.

Over the past two decades at least, it has been realized that direct discharge of storm flows to receiving waters can cause significant deterioration of the receiving water quality (Lightfoot, 1989); in contrast, point sources such as treatment plant discharges are usually adequately regulated. As a result, the attention to storm sewer problems has been focused on their water quality impact. Although the main sources of pollution of stormwater runoff are from atmospheric deposition and washoff of accumulated pollutants on the land surface, it is common for illegal connections of sanitary sewers and/or industrial waste flows to be partly responsible for the contamination of storm water.

2.4.5   Control measures for sanitary sewer systems

Sanitary sewers are sized to convey peak and minimum wastewater flows without the deposition of suspended solids. These sewers are designed to flow by gravity between one-half and full depth. Collecting sewers gather flows from individual buildings and transport them to an interceptor or main sewers. Maintenance holes (previously called manholes) and other transition structures are usually built at every change in pipe size, grade and alignment. Grades should be designed so that the criteria for maximum and minimum flow velocities are satisfied. Pumping stations are used to equalize loadings and raise the hydraulic head so wastewater can flow through wastewater treatment systems by gravity. Theoretically, wastewater treatment plants should be able to handle the designed wastewater flows and no sanitary bypasses or overflows are permitted. In practice, sanitary overflow points are built to

spill excess wastewater to receiving water to prevent overloading of wastewater treatment plants. However, wastewater treatment operators must inform local public health units if there is a sanitary sewer overflow.

Control measures for sanitary sewer system are usually aimed at reducing extraneous flows and rainfall-derived infiltration/inflow into the sewers. Regulations should be enforced to prevent runoff from entering sanitary sewers and the direct connection of foundation drains to sanitary systems. To reduce infiltration to sanitary sewers, inspection and repair of faulty joints and leaks are required, as is good quality control during sewer construction. For overloaded sanitary sewer systems, construction of relief sewers or tunnels parallel to the existing lines may be needed to divert flows to alternative outlets.

2.4.5   Control measures for stormwater

Stormwater best management practices (BMPs) have provided a number of tools to decrease the quantity and improve the quality of stormwater runoff at the source, along the drainage system and at the outlet. These include such devices as downspout disconnection, stormwater gardens, rain barrels, infiltration trenches, stormwater exfiltration/filtration systems, sand filters, bio-retention areas, wet and dry detention ponds, and constructed wetlands. However most "Downstream Outlet" best management practices require a significant amount of land to host them, which is not generally available in downtown urban environments. The opportunity for green roofs to act as source level viable stormwater management devices is logical, since flat rooftops recreate the open space, previously at ground level, that has otherwise been eliminated for vegetation (Jennings et al. 2003).

Unlike some other BMPs, green roofs may be able to offer controls and improvements in both the quantity and quality of stormwater runoff. Graham and Kim (2003) conducted a study in Vancouver, BC which showed that suitably designed green roofs have great potential benefit in terms of protecting stream health and reducing flood risk to urban areas. The modeling results for a 50-year watershed retrofit scenario also show that green roof re-development on existing buildings could help to restore watershed health over time. Not only are green roofs able to filter contaminants out of rainwater that has flowed across the roof surface (Dramstad et al., 1996), but they can also degrade contaminants, either by direct plant uptake, or by binding them within the growing medium itself (Johnston and Newton, 1996).

Numerous studies have demonstrated quantitatively that a properly installed and maintained green roof will absorb water and release it slowly over a period of time, as opposed to a conventional roof where stormwater is immediately discharged. Typical extensive green roofs, depending on the substrate depth, can retain 60 to 100% of the stormwater they receive (Thompson, 1998). In addition, according to the ZinCo planning guide (1998), living roofs are normally able to retain 70 to 90% of the stormwater that falls on them during the summer months, depending on the frequency of rain and drying rates. In winter months, green roofs are predicted to retain 40 - 50% of the stormwater. These data are subject to variation based on variations in climatic conditions. The amount retained also depends on numerous factors

such as the volume and intensity of rainfall, the amount of time since the previous rainfall event, and the depth and saturation level of the existing substrate (Monterusso, 2003).

Several studies conducted in Germany have shown that a green roof with a substrate depth of 2 to 4 cm with a vegetation mix of mosses and sedum can retain 40 to 45% of the annual rainfall that falls on it (Liesecke, 1998). By increasing the depth of the substrate to 10 to 15 cm and changing the vegetation to a mixture of sedum, grasses, and herbs, green roofs can retain up to 60% of stormwater on an annual basis (Liesecke, 1993). Liesecke also indicated that there were noticeable differences between retention in warm weather and in cool weather. In warm weather, shallow substrate depth can retain 11% more stormwater than it can during cold weather (Liesecke, 1993). For deeper substrates, the effect was even more pronounced (20% more in warmer weather).

Liptan et al, (2003) demonstrated similar findings. Within a 15-month monitoring period, they found that precipitation retention was approximately 69% of the total. However, between December and March the rainfall retention was 59%, while from April to November, rainfall retention was 92%.

Research conducted by Jennings et al. (2003) in North Carolina showed that a green roof can retain up to 100% of the precipitation that falls on it in warm weather. However, the percentage retained for each storm decreased when there had not been an adequate amount of time between each storm event. As shown in Table 1, the percentage retained for each storm decreased with each respective rain event. The percentage of the stormwater retained dropped from 75% to 32%. According to the experimental results, Jennings et al. concluded that the capability of green roof retention is highly dependent on the volume and intensity of rainfall.

Table 2.2
April 2003 hydrologic retention for the WCC green roof in Goldsboro, NC [after Jennings et al. (2003)]

Storm Event	Rainfall (in)	Green roof Runoff (in)	Retained (in)	% Retained
7 April 2003	0.89	0.22	0.67	75
8-9 April 2003	1.02	0.57	0.45	44
9-11 April 2003	1.63	1.11	0.52	32

Rowe et al. (2003) found a similar result during their experiments. Their results showed that on average green roofs can retain 61% of total rainfall. During light rain events (<2mm daily), their green roof retained up to approximately 98% of rainfall, whereas the same green roof was capable of retaining only 50% of the heavy rain events (when rainfall >6mm).

As Jennings et al. (2003) concluded, the water holding capacity of the substrate was found to depend on the volume and intensity of the rainfall. Further, both Jennings et al. (2003) and Rowe et al. (2003) found that their green roof was able to reduce the peak flow and the time to peak (by 2 to 4.5 hours) when compared to a standard conventional roof (Figure 2.3). Liu

(2003) also found a stormwater runoff delay on green roofs. During a light rain (19mm in 6.5 hours), the green roof delayed the discharge of stormwater for 95 minutes.

Figure 2.3
Relationship between the peak flow and runoff
on green roof [after Jennings et al. (2003)]
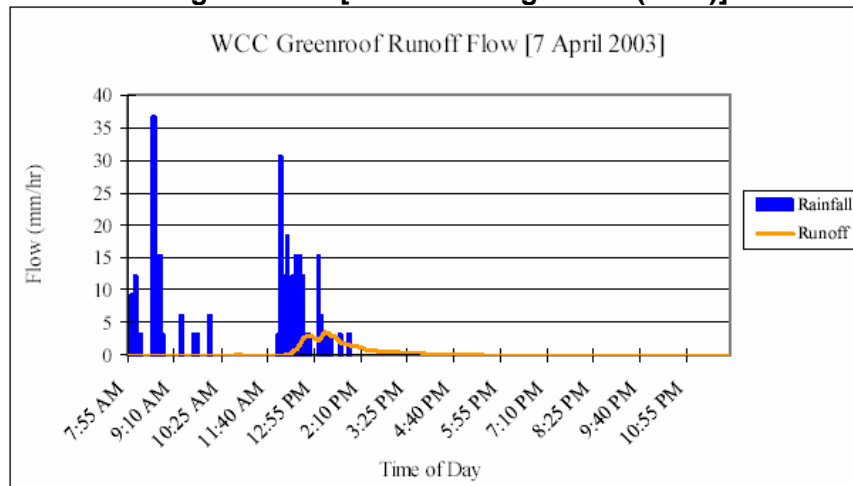
Several studies have shown that, in most cases, increasing roof slope does not necessarily increase runoff volume. Liesecke (1999) conducted studies on a green roof with 8.7% slope and found that the annual retention rates ranged from 55% to 65%, and were considered comparable to 2% slope roofs. Research that was done by Rowe et al. (2003) also indicated that retention percentages were unaffected by green roof slope. Schade (2000) had also reported similar findings that on green roofs with slopes ranging from 2% to 58% there were constant water retention rates.

Green roofs not only reduce the quantity of runoff from roofs but can also filter contaminants from rainwater. According to the United States Environmental Protection Agency (USEPA) (2003), "the most recent National Water Quality Inventory reports that runoff from urbanized areas is the leading source of water quality impairments to surveyed estuaries and the third-largest source of impairments to surveyed lakes". Most of the stormwater runoff enters water bodies directly without any treatment. Other problems are also associated with regular surface runoff, such as higher surface water temperatures due to the water travelling across hot, impervious surfaces like roofs, roads and parking lots (USEPA, 2003).

The substrate on green roofs has the ability to retain particulate matter in the stormwater and to reduce the quantity of runoff and, as a result the total mass of pollutants that flow off the roof. Thus, the stormwater runoff quality as well as the receiving surface water quality can be improved. Large numbers of studies have been conducted in Germany and Switzerland regarding green roof runoff quality. Dramstad et al. (1996) demonstrated that the physical and chemical properties of the growing substrate, as well as the green vegetative cover help to control the nitrogen, phosphorus, and contaminants generated by industrial activities, which

exit the roof surface. In some cases these substances can be taken up and broken down by the plants themselves (Johnston, 1996), but most of the time heavy metals and nutrients that exist in stormwater are bound in the green roof growing substrate instead of being discharged in the runoff. Johnston and Newton (1993) also concluded that over 95% of cadmium, copper and lead and 16% of zinc can be removed from the stormwater runoff through binding and uptake in the growing substrate.

The Toronto and Region Conservation Authority is monitoring stormwater performance of a green roof at York University (TRCA 2005). The objective of the study is to evaluate the effectiveness of green roof in reducing the quantity and improving the quality of stormwater runoff in Toronto's Remedial Action Plan (RA) Area of Concern (AOC). The research site is located on the Computer Science and Engineering building on the campus of York University in the North West part of Toronto. The project consists of two roofs: one with a Sopranature green roof by Soprema and another non green roof with shingles. Both roof surfaces have a 10% slope. The shingled roof is 131 sq. m. while the Soprema Green Roof (SGF) is 241 sq. m. The SGF consists of a 140 m substrate and is vegetated with wildflowers. The substrate is composed of crushed volcanic rock, compost, blonde peat, cooked clay and washed sand. It is designed to be light weight, retain rainwater, and reduce compaction. An irrigation system is installed on the roof and is operated automatically by soil moisture sensors.

Rainfall volume, water runoff quantity and quality from both surfaces, ambient air temperature, relative humidity, soil temperature, and soil moisture, have been monitored continuously since April 2003. Tables 2.3 and 2.4 summarize the effect of the green roof on the runoff volume and peak flow reductions in 2003 and 2004. It is noted that the green roof provided significant reductions in runoff volume and peak flows. On average, the runoff volume could be reduced by almost 65% while peak flow could be reduced by almost 98% of most of the rainfall less than 30 mm. Water quality analysis was conducted for 23 events and it was found that the green roof could improve water quality benefits such as suspended solids, copper and Polycyclic Aromatic Hydrocarbons (PAHs). Table 2.5 summarizes the results on water quality

Table 2.3
Green roof runoff volume reduction for 2003 and 2004 monitoring seasons
(TRCA 2005)

Year	Total rainfall (mm)	Measured outflow per unit area (L/m2)		Difference of inflow vs outflow volume in %
		Garden	**Control**	**Garden**
2003	663.8	304.8	675.8	54.1
2004	443.1	108.1	388.7	75.6

Table 2.4
Peak flow reductions for a range of event sizes (TRCA 2005)

Rainfall event category	Average difference in peak flow control vs garden in %
20-29 mm	85.1
30-39 mm	68.2
? 40 mm	50.3

Table 2.5
Comparison of concentrations for selected parameters
from the control roof and the garden (TRCA 2005)

Parameter	Flow-weighted mean concentrations			Loading difference control vs garden in %
	Guideline	**Control**	**Garden**	
Suspended solids (mg/L)	-	6.34	2.33	82.0
Total phosphorus (mg/L)	0.03	0.078	0.577	-276.0
Total Kjeldahl Nitrogen (mg/L)	3.2	0.711	1.61	-15.6
Copper (μ g/L)	5	111	42.9	79.8
Zinc (μ g/L)	20	10.8	8.2	60.5
Escherichia Coli (#/100 mL)	100	549	662	34.3
PAH; Phenanthrene (ng/L)	30	191.3	31.6	89.8
PAH: Fluoranthene (ng/L)	0.8	275.7	30.7	93.1
Note: Guidelines listed are Provincial Water Quality Objectives (PWQO) where available.				
For parameters with no PWQO, the Canadian Water Quality Guideline is used.				

Table 2.6 – Summary of key findings from a literature review related to stormwater and green roofs

Study	Location	Monitoring System and Duration	Water Quality Sampling	Flow Interval	Events	Qualitative Changes	Quantitative Changes	Costs/ Benefits	Recommendations
Jennings, et al, 2002	North Carolina	Runoff quantity and quality; Sigma 900Max TM automatic samplers; 5 months	Tritest, Inc. Lab	5 min.	6	yes	yes		Plant species
Hutchinson, et al, 2002, 2003	Portland, Oregon	Runoff quantity and quality analysis; Sigma model 950 bubbler-type flow meter; 15 months	Bureau of Environmental Sevices			yes	yes		Strategic selection of soils/growing media
Rowe, et al, 2002, 2003	Michigan	Slope and substrate depth influence on runoff quantity; Model TE525WS tipping bucket rain gauges; 2 months		5 min.	24		yes		
Graham and Kim, 2003	Vancouver	Evaluating the stormwater management benefits; water balance Modmel					yes		Retrofit to counteract climate change and land use densification, to restore watershed
Cunning, 2001	Winnipeg	Runoff quantity analysis; Kulching's Rational Formula; 5-, 20- and 50- yr storms					yes	yes	Durability of green roofing needs research; plant list needed
Monterusso, 2003	Michigan	Species selection and stormwater runoff quantity analysis; autoregressive type 1(AR1) error structure	Michigan State University Soil Testing Lab		4	yes	yes		Research fertilizer needs
VanWoert, 2002, 2003	Michigan	Runoff quantity analysis; Model TE525WS tipping bucket rain gauges; 430 days		5 min.	162 days		yes		Sedum
Liu, 2002, 2003	Eastview	Runoff quantity; Campbell Scientific CR23X data acquisition system; 13 months		15 min.			yes	yes	Research thermal efficiency in winter
Liu, 2000, 2002	Ottawa	Runoff quantity; tipping bucket mechanism; HP VXI data acquisition system; 1 year		15 min.			yes		
TRCA 2005	Toronto	Rainfall; runoff volume and water quality, soil	TRCA	15	23	Yes	Yes		Seed green roof

2.5 Air quality impacts

Declining air quality is an ongoing problem in cities globally, and solutions are being proposed. Some have been acted upon, ranging from local initiatives to global accords. Among these are both restriction of point-source emissions and restoration of biological systems that reduce airborne contaminants. In cities there is strong interest in measuring and dealing with air pollution levels since air contaminants are intensified due to the density of human activity, including use of fossil fuels, the presence of the urban heat island and the absence of natural biological controls. Inter-regional transport and global warming concerns serve only to heighten the issue, as the magnitude and frequency of smog alerts and summer heat waves increase (MacIver and Urquizo 1999). Evidence suggests that green roofs provide one opportunity to reduce local air pollution levels by lowering extreme summer temperatures, trapping particulates and capturing gases.

Akbari et al. (2001) and Kats (2003) discuss cool roofs and green roofs in terms of their potential indirect effect of reducing CO_2 emissions from power plants due to a reduction in the demand for summertime peak-period cooling.

It is well known that smog forms when nitrogen oxides (NO_x) react with volatile organic compounds, a process that is accelerated by higher ambient temperatures. In the report by Rosenfeld, et al. (1998), which looked at strategies to cool urban areas and reduce the heat island effect and smog in Los Angeles, it was noted that on a typical summer day in Los Angeles, 1350 tons of NO_x and 1500 tons of volatile organic compounds (VOCs) react to form ground level ozone. By calculating the small NO_x savings from avoiding air conditioning electricity use and combining it with the NO_x avoided by cooling Los Angeles up to 3 degrees, these researchers estimated that a 10% reduction in smog is equivalent to reducing precursors by about 25%, that is, reducing NO_x releases by 350 tons per day. Los Angeles has a smog offset trading mark that trades NO_x at $US3,000 per ton. To convert this to c/kWh of peak power they multiplied it by 0.5kg/MWH to get .15c/kWh. Hence, the 350 tons/day of avoided "equivalent" NO_x is then worth about $US1,000,000 per day to Los Angeles. The researchers then converted this saving to a yearly value, to find, on average, the 100 smog days experienced might provide a $US100 million per year saving to a city as large as Los Angeles.

Yok and Sia (2005), in their report on a pilot green roof project in Singapore, noted air quality improvements due to reduction of sulphur dioxide by 37% and nitrous acid by 21%. However, nitric acid increased by 48% and particulates (PM 2.5 and 10) also increased, possibly from re-suspended chips related to gravel ballast and bare spots on the green roof, though the particle number concentration decreased by 6% on the green roof.

Johnson and Newton (1996) estimate in urban forestry studies that 2,000 m^2 of unmowed grass on a roof could remove as much as 4,000 kg of particulates from the surrounding air by trapping it on its foliage.

Several researchers report that vegetation benefits air quality by trapping particulates and dissolving or sequestering gaseous pollutants, particularly carbon dioxide, through the stomata of their leaves (Nowak and Crane, 1998). Their research has predicted rates of entrapment and mitigation, given seasonality, daylight hours, and species, etc., and their model is currently being studied in Toronto (Currie, 2005).

2.6   Green amenity space

Some researchers believe that the need for meaningful contact with nature may be as important as people's need for interpersonal relationships (Kaplan, 1993). Moreover, impediments to meaningful contact with nature can be seen "as a contributing factor to rising levels of stress and general dissatisfaction within our modern society" (Zubevich, 2004).

Many urban buildings are positioned along busy streets and transportation routes where access to green space is negligible. Green roofs provide a measurable psychological benefit to urbanites by adding tangible, accessible natural viewing space for social interaction, recreation, and relaxation. A green roof offers building occupants proximity to common spaces where they can relax, dine, meditate, do yoga, interact with friends or business colleagues, and enjoy proximity to green plants. A study of tenants at 401 Richmond Ltd, Toronto, revealed that building occupants greatly value access to their green roof and refer to it as "an oasis in the city" (Cohnstaedt, Shields, & MacDonald, 2003). Similarly, research on graduate students at 30 Charles Street, Toronto, suggested that a view of their green roof "provides sanity and relief" from the pressures associated with dense urban living (Bass et al. 2004). Research on human behaviour suggests that a view of gardens and green plants serves to restore calm and reduce stress in humans - particularly those that drive a vehicle (Cackowski & Nasar, 2003). Other studies suggest that humans generally prefer a view of natural settings rather than congested or cluttered built environments and that accessibility to nature, specifically by way of a window or a walk, improves worker concentration and job satisfaction, and buffers negative job stress (Hertzog, Maguire & Nebel, 2003, Laumann, Garling & Morten Stormark (2003) and Leather, Pygras, Beale, & Lawrence (1998). A study by Tayor et al. (2001) determined that children with Attention Deficit Disorder (ADD) were noticeably more relaxed and better behaved after playtime in green settings compared with children who did not have access to green space.

There is significant evidence springing from multiple research projects to support the theory that people's exposure to natural elements increases their ability to focus, cope with stress, generate creative ideas, reduce volatility and promote the perception of self as part of a meaningful greater whole. In short, exposure to natural elements enhances an individual's mental well being.

2.7   Habitat preservation

Many authors report that adding green space in the form of green roofs to densely populated urban environments provides eco-restorative habitats for displaced creatures. Green roofs provide food, habitat, shelter, nesting opportunities and a safe resting place for spiders,

beetles, butterflies, birds and other invertebrates (Brenneisen, 2003; Gedge, 2003). In Europe and Chicago, green roofs are being studied for their unique ability to provide undisturbed, viable sanctuaries for rare and nearly extinct species. Studies report that this elevated urban ecosystem affords unique protection from grade level predators, traffic noise and human intervention (Federal Technology Alert, 2004). Studies reveal that butterflies can access green space on the 20th floor of a building (Johnston & Newton, 1992).

Table 2.7 – Summary of key findings from literature review related to air quality and green roofs

Study	Location	Monitoring	Qualitative / Quantitative changes	Costs / Benefits	Recommendations
Kats. 2003	California				
Yok and Sia, 2005	Singapore	Temperature of surface, substrate, air; HOBO data loggers, infrared radiometer (Thermo tracer TH7102WX, NEC Japan); HOBO Weather Station for humidity, solar radiation, wind speed and rainfall; air quality measured with annular denuder system (URG, Chapel Hill, NC, USA), particle counter (TSI, St. Paul, MN, USA) and air quality with an aerosol sampler (Airmetrics, Eugene, OR) and to measure black cargon mass Aethalometer (Magee Scientific	Reduction of surface temperatures by 15-20 degrees C; visible light (glare) from green roofs lowered by 12-56%; air quality improvements noted in sulphur dioxide by 37%; nitrous acid by 21%; but nitric acid increased by 48%; PM 2.5 and PM 10 increased (possibly from re-suspended chips related to gravel ballast and bare spots on green roof) and particle number concentration decreased by 6% on green roofs.	Benefits to building owner, building occupants, building neighbours, community and country regarding energy savings, improved air quality and subsequent health improvements	Application of green roofs in urban areas for reasons such as: reduced ambient air temperature, improved air quality and reduced glare from buildings
Currie, 2005	Toronto	UFORE – Urban Forest Effects Model from Northeaster Forest Service, Research Station, Syracuse, New York–quantified vegetation effects on air contaminants based on one year of data from Environment Canada's 3 local weather stations in Toronto	Air contaminant reductions between varying levels of vegetation in one neighbourhood in Toronto over a one year period	Externality values ($) by UFORE model $43,106.00 worth of contaminants removed when grass was added on typical flat roofs; in addition to $46,740.00 from shrubs at grade and $103, 176.00 from tress at grade (within the same neighbourhood).	Recommends the application of urban vegetation at grade and/or elevated surfaces to mitigate air pollution with resulting population health benefits.

2.8   Property values

Interviews with social and environmental coordinators at Toronto's Mountain Equipment Co-op (MEC) and Uurbanspace Property Group's 401 Richmond Ltd. report that green roofs have improved their building's aesthetic value (Robinson, 2005; Currie, 2005). Visitors to Toronto's annual Doors Open event - a public celebration of built form and historic building stock - flock to both MEC and 401 Richmond Ltd to experience a green roof. Attendance at MEC's Doors Open rose from 500 in 2003 to 880 in 2004, and the first requests were to see the green roof. Tenants at Urbanspace Property Group, located at both 401 Richmond Street West and 215 Spadina Avenue, report that interior and exterior green elements add to an overall perception of health and well-being in the urban work space. Toronto property owners like Margaret Zeidler of Urbanspace Property Group suggest that green roofs are the "right thing to do" and that more building owners should "just do it." Zeidler reports that word of mouth is all she requires to keep the Urbanspace Property Group buildings fully tenanted; there have been no expenditures on marketing to date for either building.

2.9   Derivation of economic benefit from green roofs

2.9.1   Methodology

Despite being a widely used method for decision-making, the cost benefit analysis (CBA) method has had limited comprehensive application to green roof projects. Several life-cycle analyses have been completed, largely ignoring many of the important benefits of green roofs. Instead, these analyses have focused on the private costs of green roofs relative to standard roofing materials. Nonetheless, these studies are of direct relevance to our investigation, as they consider the costs of construction, and maintenance, and the energy savings that would be part of both the private and social costs and benefits in CBA.

The underlying premise of CBA is that all costs and benefits, both present and future, can be standardized in monetary terms and consequently compared at a specific point in time (usually the present). Future costs and benefits, even if measured in real (or constant-dollar) terms, are considered not directly comparable to present costs and benefits for a number of reasons, including time preference (impatience), risk, and positive rates of return on investment (opportunity costs).[2] Future values are discounted at the appropriate rate to remove this incompatibility (and probabilities are occasionally assigned to future benefits and

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[2] The appropriate reasons for discounting generally depend on whether the discount rate is used by an individual decision-maker (the private discount rate) or for the government or society as a whole (the social discount rate). For example, private discount rates primarily reflect the opportunity cost of capital, while the social discount rate is widely considered to reflect the pure rate of time preference and factors concerning the future consumption (the elasticity of the marginal utility of consumption and the expected growth rate of average consumption per capita). The latter concerns the substitutability of manufactured capital for natural capital, with lower rates indicating less substitutability (Arrow et al., 1996). For more information, see Pearce and Ulph (1998). As society is more willing to delay benefits than private investors, the private discount rate is generally higher than the social rate.

costs to determine expected future values). The few cost benefits analyses and life cycle studies on green roof projects follow this approach. As each building needs some type of roof, the appropriate choice is not absolute costs and benefits, but incremental costs and benefits (for example, the costs of a green roof above the costs of a standard roof). However, discount factors differ across past studies, and so make direct comparison difficult.[3] Further, each study to date examines different costs and benefits of green roofs, particularly those related to society as a whole. A summary of these individual costs and benefits follows.

2.9.2   Time period

The appropriate time horizon for analysis is crucial to cost benefit analysis, as it affects the number of recurring periods of benefits as well as impacting on the replacement cost of the alternate standard roof. A longer green roof life implies that standard roof materials may have to be replaced (possibly more than once) during the life of the green roof, which would offset some of the higher costs of green roofs. For the most part, the consensus appears to be that green roofs do last longer than standards roofs. A common assumption, such as that made for New York City in Acks (2003), is that a green roof will have a service life of 40 years, while a standard roof will last 20 years. However, variations in the green roof service life are often found, including 20 years (identical service life) and 60 years in the Acks study.

2.9.3   Discount rate

As important as the service life, the discount rate applied to future costs and benefits has significant effects on net benefit calculation for both private and social cases. A higher discount rate implies lower present values of future costs and benefits. Private discount rates vary by industry, depending on factors such as industry-specific rates of return. Acks (2003) used a private real discount rate of 8% for New York City buildings, while the Treasury Board of Canada (1998) suggested a general rate of 10%. Wong et al. (2004), in a life cycle analysis of the private costs of green roofs in Singapore, used a rate equal to the average prime rate over 10 years in that country, or 5.15%. Social rates are present only in cost benefit analysis studies, such as the 5% rate used in Acks (2003). Most environmental studies, including Cline (1992), Arrow et al. (1996), Pearce and Ulph (1998), and Bateman et al. (2004), tend to use lower discount rates due to the irreversibility of many environmental activities. For example, both Cline and Arrow et al. used a range of 0-2% for climate change, while Bateman et al. used values of 1.5% and 3% for conversion of agricultural land to woodland.

2.9.4   Installation and maintenance costs

There is considerable confusion across studies relating to the initial cost of construction of green roofs relative to standard roofs. Difficulties arise between intensive and extensive

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[3] As green roof projects typically involve significant costs of construction in the present and benefits that accrue over the life of the roof, higher discount rates make these projects look less attractive than cases with identical costs and benefits but lower discount rates.

roofs, between different materials and plants used, and between new buildings and retrofit installations. In three scenarios, reflecting low, medium and high green roof performance, Acks (2003) used costs of $12, $18 and $24 per square foot for a green roof, and $9 per square foot for a standard roof. Wong et al. (2004) used $49.25 per square metre ($4.57 per square foot) for a standard roof, $89.86 per square metre ($8.35 per square foot) for an extensive roof, and $96.58 per square metre ($8.97 per square foot) for an intensive roof. In that study, accessible rooftops would cost considerably more (up to $197.16 per square metre or $18.31 per square foot). The approximate doubling of standard roof costs is also consistent with the life cycle analysis in England et al. (2004). Structural costs in most studies are ignored, in effect limiting the analysis to extensive green roofs. Acks (2003) assumed structural costs for all green roofs to be 0.2% of initial costs.

The type of green roof under consideration is crucial in the comparison of annual maintenance costs. For extensive roofs, previous studies indicate little difference between green roof and standard roof maintenance costs. For example, Acks (2003) assumed $0.60 per square foot for green roofs and $0.10 per square foot for standard roofs, and Wong et al. (2004) assumed identical costs for standard and inaccessible green rooftops (except for more frequent replacement for standard roofs). Intensive roofs presumably require more maintenance, depending on the type of plants chosen (Wong et al.).

2.9.5   Economies of scale

Acks (2003) includes an assumption of how the costs of green roofing would decrease if widely adopted, due to larger production volumes. Current costs are assumed to be for the production of a single green roof, and 144,000 roofs would be needed for their New York City study area target. On the basis of a past study, they suggest that each doubling of production will decrease green roof costs by a factor of 0.7 to 0.9. For 18 such doublings (from 1 to 144,000), costs are purported to fall to $3.60 per square foot, which is clearly unreasonable. As a result, an ad hoc value of $15 per square foot is chosen. Including returns to scale is an unusual practice in cost benefit analysis, particularly as it is unclear how competitive each sector of green roof production and installation will be (more competitive would imply fewer economies of scale).

2.9.6   Administration costs

Within social costs, municipal support for a green roof program can be included as an annual administration cost. For instance, Acks (2003) assumes initial program administration and setup costs to be approximately $30 million for New York City, or 0.1% to 0.3% of installation costs. This assumption is not made in other studies, and it is unclear how green roof administration would be different from standard roof policy practices.

2.9.7   Energy cost savings

As a private benefit, energy cost changes have been employed in previous cost-benefit and life-cycle cost analyses. Green roofs potentially also reduce urban air temperatures, which

would yield the benefit of lower cooling costs in summer months. Although cooling effects are clearly site specific, there have been attempts to generalize the energy cost savings from a green roof. The private cooling cost in Acks (2003) for a standard roof was estimated at $0.16 per square foot through five independent calculations, and a green roof was assumed to reduce cooling costs by approximately 15%. In Wong et al. (2004) energy costs were estimated using the energy model based on the Power DOE program, yielding annual energy savings of between 5,000 and 29,000 kWh. An extensive green roof under these conditions would result in cost savings of $4,773.40 each year, and these energy cost savings could significantly decreased costs of installing both extensive and intensive green roofs.[4] England et al. (2004) estimated green roof annual energy savings at a value between $2,500 and $12,500.

2.9.8   Urban heat island

Public benefits from a reduction in the urban heat island effect have previously been estimated by Acks (2003) as well, assuming air temperature is lowered by between 0.1 to 1.5 degrees Fahrenheit with the addition of 50% green roof infrastructure. Cooling was assumed to be necessary for temperatures above 65 degrees, and green roofs play a role in lowering temperatures by 0.1, 0.8 or 1.5 degrees thus reducing energy demand in summer by 0.7%, 5%, and 10%, respectively.

2.9.9   Stormwater flow reduction

Capital expenditures and operating costs for wastewater treatment in combined sewer areas and stormwater treatment in separated sewer areas are typically assumed to be lessened by the rainfall captured by green roofs. Acks (2003) assumed that a green roof would capture 20%, 50% or 80% of the rainwater that fell on it, which was multiplied by the land area of New York City greened in his scenario (4%) and a scale factor (90%) to generate a percentage reduction in water entering the sewer system. In this way, capital expenditures were reduced by between 0.6% and 3.4% in stormwater treatment.

2.9.10   Air pollution and greenhouse gas effects

Green roofs are expected to have positive benefits for air quality and from greenhouse gas reductions. Airborne particulate, nitrogen oxide, ozone, sulfur dioxide, and carbon monoxide levels have been assumed to decrease in the presence of green roofs. Based on a Toronto study (GRHC, 2003), Acks (2003) assumed that greenhouse gas reductions would be proportional to population and used a value of $20 per ton, or $0.18 per square foot. Airborne particulate matter was assumed to be reduced by 0.04 pounds per square foot of green roof, with a value of $2.20 per pound or $1.43 per square foot, and reductions of other air pollutants were valued at 10% to 30% of particulate matter reductions.

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[4] For example, an inaccessible extensive roof was 2.4% more expensive without energy considerations, yet 8.5% less expensive after energy costs were taken into account.

2.9.11   Food production

Several studies have indicated that particular green roofs have been used to grow agricultural items. This production may result in private cost savings to the owner if these products would otherwise have been purchased at a higher cost elsewhere. Acks (2003) accordingly assumes that the value of food production is $0.10 per square foot, partially based on the experience of the Fairmont Hotel in Vancouver. This is deemed to provide benefits to the owner or the local economy. Yet it is arguable whether these gains can be considered social benefits, as the products are likely substituting for production elsewhere in the economy. Local food production will however have an impact on energy use related to the transportation of food and the availability of locally produced fresh food. The social impacts of these have not been reported.

2.9.12   Aesthetic benefits

The presence of a green roof can confer an amenity value to both the private owner (through potentially higher property values) and society as a whole (through public enjoyment of the green space). Aesthetics, however, are a public good, such that values of this type are not easily captured through market transactions. For example, an owner may be able to charge higher property rents on the building itself, but cannot limit outside individuals (possibly in neighbouring buildings) from enjoying the benefits as well. No study to date has specifically examined the impacts of green roofs on property values, although related values have been estimated. The latter have not been used in past green roof cost-benefit analyses, although *ad hoc* benefits have been included by Acks (2003). In that study, a green roof benefits 6 people, who collectively pay the private building owner $170. For public benefits, it was assumed that between 0.85 million and 3.4 million residents of New York City would enjoy the benefits of having half of that city's viable roofs greened, with each resident willing to pay $10, $25 or $50 towards the cost.

2.9.13   Job creation

Several authors have suggested that there are job-creation benefits from green roof expansion. For example, Peck et al. (1999) allude to job creation and enhancement in several different markets related to green roof production, installation and maintenance. However, to date there is no indication that green roof projects will lead to reduction in unemployment. In another way, it is likely that job creation in green roof sectors will be offset by job losses in other markets, most notably standard roof material production, installation and maintenance. The Treasury Board of Canada Guidelines (1998), citing an earlier version, recommend CBA adopt the assumption that resources used would otherwise be fully employed.

2.9.14   Cost-benefit ratios and life-cycle cost assessments

Overall, there is considerable variation in the estimated benefit cost ratios and life-cycle costs between green roofs and standard roofs. Wong et al. (2004) provide three estimates, with only the inaccessible extensive green roof being less costly over the study period than a

standard roof. Intensive green roofs are estimated to cost 22.4% (accessible intensive with shrubs) or 42.6% (accessible intensive with trees) more than a standard roof. Despite significantly higher initial costs, England et al. (2004) suggest a green roof has a life cycle cost of 17% to 50% of a standard roof. The private benefit-cost ratio found by Acks (2003) for the moderate case is 0.54 (low 0.38 and high 1.85), while the social benefit-cost ratio for a 50% green roof infrastructure scenario is 1.02 (low 0.66 and high 3.87). Further study is required to determine whether private benefits of green roofs do exceed private costs, and whether social benefits exceed social costs.

2.10   Summary of green roof research on costs and benefits

Several benefits have been attributed to the use of green roofs and research has quantified some of these benefits. The quantification of the benefits has either been through experiments or through analytical and numerical models. The determination of social and environmental costs and benefits of green roofs in subsequent sections uses this information.

Reliable information based on experimental research, and which can be safely approximated for Toronto conditions is available for the following (the experimental results are generally conducted at a building level):

- quantity of average annual retention of stormwater including the impact of various thicknesses of green roofs on quantity of water retention. Results form these studies;

- reduction in surface temperature of the roof including the roof membrane, which has direct impact on energy benefits;

- reduction in energy use because of green roofs.

Analytical and numerical models have also been used in quantification of benefits from green roofs as follows:

- impact of urban heat island through regional temperature reductions. One study has modeled the temperature reduction from green roof implementation in the City of Toronto and has been used in this report;

- improvement in the air quality through mitigation of gases and particulate matters. One study specifically modeled a part of the City of Toronto. These results form the basis for calculations in this report;

- impact on energy consumption on a city-wide basis. One study was specifically conducted to study energy consumption impact on a city-wide basis for certain building types for some greening options. These results have been adapted in this study.

- reduction in stormwater runoff on a regional basis. One study has applied experimental results of stormwater runoff reduction to a portion of the City of Toronto. These results form the basis for calculation of stormwater benefit in this report

Current research appears to be lacking in terms of quantifying other benefits of green roofs. Researchers have provided empirical evidence of benefits relating to the use of green roofs for food production, or as amenity spaces. However, many of these benefits are very dependent on the specific green roof designs implemented on buildings. Such results cannot be easily extended to typical green roof installations without having an impact on other benefits. These benefits have not been quantified in this report.

The results from this section are used in Section 4 for the calculation of benefits.

3.0 Survey of types of green roofs and their standards

This section will provide a generic description of green roofs then it will provide and describe a few of the existing available systems. Then it will provide information on green roof standards, and finally the green roof performance requirements that have been adopted by some European municipalities as part of their green roof policies.

3.1 Green roofs described

The term "green roof" is generally used to represent an innovative yet established approach to urban design that uses living materials to make the urban environment more livable, efficient, and sustainable. Other common terms used to describe this approach are eco roofs, and vegetated roofs. Green Roof Technology (GRT) is the system that is used to implement green roofs on a building

Green roofs are constructed using components that

- have the strength to bear the added weight;
- seal the roof against penetration by water, water vapour, and roots;
- retain enough moisture for the plants to survive periods of low precipitation, yet are capable of draining excess moisture when required
- provide soil-like substrate material to support the plants;
- maintain a sustainable plant cover, appropriate for the climatic region;
- offer a number of hydrologic, atmospheric, thermal and social benefits for the building, people and the environment;
- protect the underlying components against ultraviolet and thermal degradation.

In describing Green Roof Technology of the last 10 to 15 years, Dunnett and Kingsbury (2004) find two approaches: extensive and intensive.

Intensive green roofs generally require more effort for the tending of plants, whereas the term extensive roofs call for a more passive approach. Intensive green roofs also emphasize the use of space and therefore raise higher aesthetic expectations than more functional extensive green roofs. Intensive green roofs generally need deeper substrate, more diverse plants including trees and shrubs, and proper watering schedules. Thus they involve higher costs (Dunnett and Kingsbury 2004; Peck et al. 1999). As in many design classifications, however, there are actually degrees of intensiveness in the approach to rooftop greening.

3.2 Currently available green roof technology

Green roof systems can be categorized as follows:
- complete systems where all different components including roof membrane are an integral part of the whole system;

- modular systems that are positioned above the existing roofing system;
- precultivated vegetation blankets that consist of a growing medium and plants that are rolled onto the existing roofing system with drainage mats and root barriers as required.

Variations between systems are generally found in the manner in which growing medium and drainage layers are treated.

The following are the common green roofing systems used in recent years in North America:

1. Sopranature by Soprema
2. Garden Roof by Hydrotech developed in conjunction with ZinCo GmbH
3. Easy Green by Elevated Landscape Technologies
4. Pre-cultivated vegetation blankets by Xero Flor Canada
5. Roofmeadow assembly by Roofscapes Inc. adapted from Optigreen of Germany
6. GreenGrid System by Weston Solutions Inc. and ABC Supply Co. Inc.
7. Green Roof Blocks by St. Louis Metalworks Company

In addition there are several green roof technologies available in Europe. Suppliers of these green roof technologies include: GDT Systems International in Germany, APP's Roof Garden Sets in Germany, Bauder's Green Roof System in the UK, and Kalzip's Nature Roof in UK.

3.2.1   Complete systems

Complete systems provide the most flexibility in terms of the type and nature of growing medium and drainage, and protection layers that can be used. These have direct impact in terms of the type of vegetation that the green roof can support. They also generally contribute the greatest amount the structural design load. Sopranature by Soprema, Garden Roof by Hydrotech, and Roofmeadow by Roofscapes fall into this category. Figure 3.1 shows a Sopranature system on a conventional roof assembly

Figure 3.1
A typical Sopranature green roof assembly on conventional roof
(Adapted from Soprema Inc.)

1) Vegetation
2) Sopraflor growing medium
(type X, I or L)
3) **Aquamat Jardin**
4) Sopradrain 10-G
5) Concrete, wood
or steel curb
6) Gravel or paver
7) Cap sheet membrane
8) Base sheet membrane
9) Primer
12) Vapour barrier
13) Support panel
14) Insulation
15) Microfab
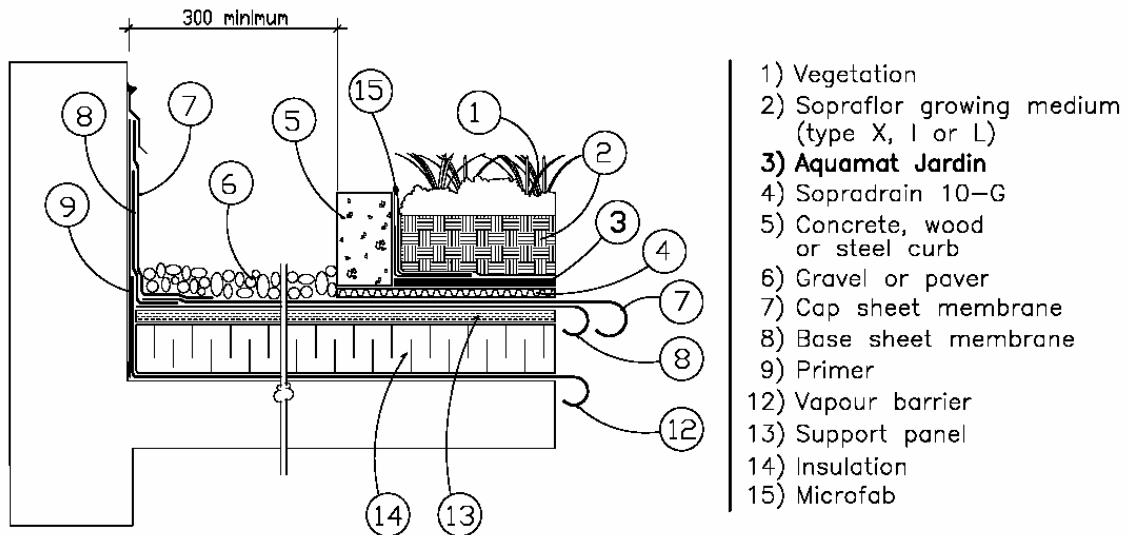
The Soprema system is typically used with its proprietary waterproofing membrane. The Hydrotech system is essentially similar in concept to the Soprema system, but also uses its own proprietary roofing membrane.

The Roofmeadow system by Roofscapes offers several options of varying thicknesses and weights from as low as 50mm to 75mm (2 to 3 inches) and 60 to 90 kg per sq. m, (12 to 18 lbs per sq. ft.). Roofmeadow systems can be installed with a variety of waterproofing membrane types, Roofmeadow will, however, take a single source responsibility for the performance of the whole roofing system. Their low thickness system is similar to the precultivated vegetation blanket system.

3.2.2   Modular systems

Modular systems are essentially trays of vegetation in a growing medium that are grown off site and simply placed on the roof to achieve complete coverage. They are available in different depths of growing medium typically ranging from 75mm to 300mm (3 to 12 inches). GreenGrid and Green Roof Block systems are examples of modular systems shown in Figures 3.2 and 3.3.

Figure 3.2
Photograph showing Green Roof Block System
(Adapted from St. Louis Metalworks Company)

Figure 3.3
Photograph showing GreenGrid System
(Adapted from Western Solutions Inc.)

3.2.3   Precultivated vegetation blankets

Xero Flor Canada and Elevated Landscape Technologies (ELT) offer precultivated vegetation blankets. Figure 3.4 shows photographs of the system offered by ELT. It is a pregrown interlocking green roof tile and in that respect it could be viewed as similar to the modular system. But its thickness categorizes it as a blanket system. It is available in one thickness of about 45mm (1.75 inches)

Figure 3.4
Photograph showing ELT system
(Adapted from Elevated Landscape Technologies)
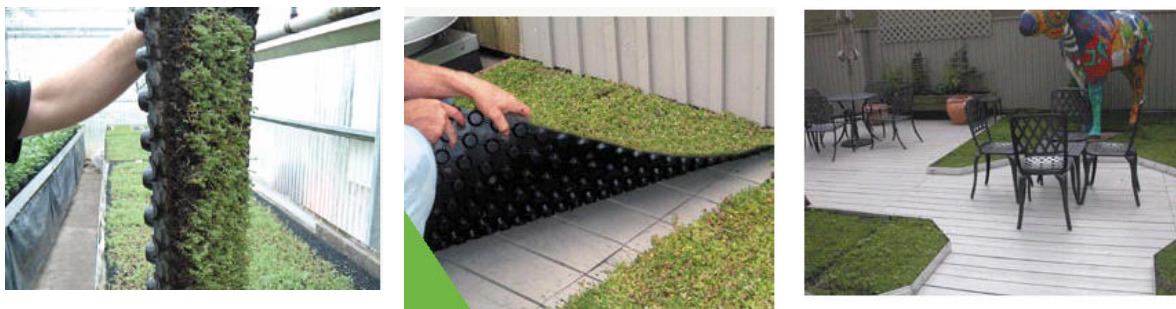
Xero Flor primarily offers extensive green roof systems. A variety of system designs are available, but perhaps the most versatile system contains 25 mm (1 inch) of planting substrate. The result is a lightweight system ranging in weight from 40 to 60 kg per sq. metre. The majority of the vegetation is made up of several varieties of sedum – a succulent plant (8.0 to 13.0lbs per sq. ft.) that is tolerant of extremes in temperature and that survives with little or no irrigation while requiring very little maintenance. Most Xero Flor systems are cultivated at ground level, then rolled-up and transported as a complete system on pallets or by crane.

Figure 3.5
Photograph showing Xero Flor System installation and cross section
(Adapted from Xero Flor Canada)
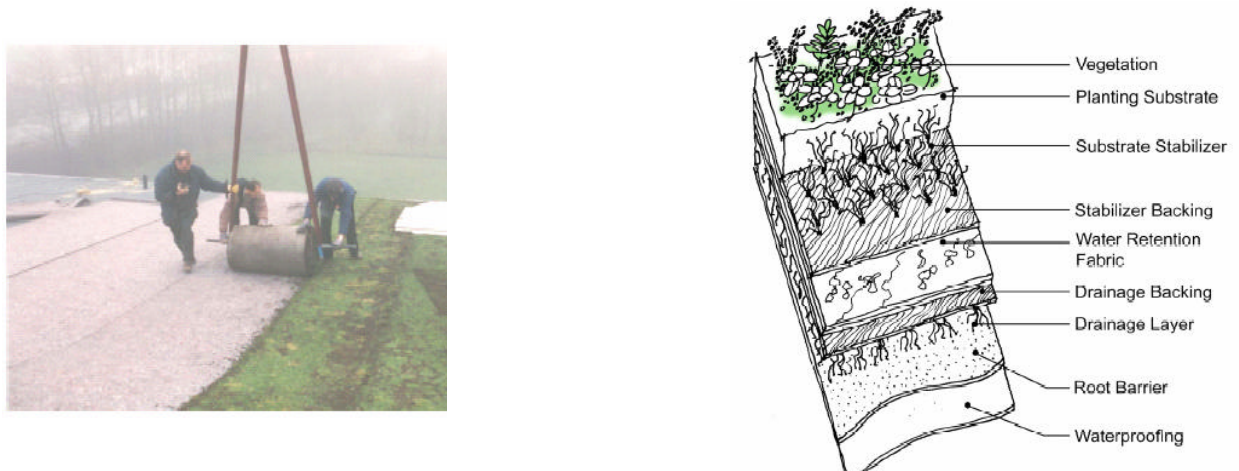
3.3 Survey of green roof system standards and performance requirements

The only comprehensive green roof guidelines in existence today are produced by Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) a landscape industry organization in Germany. An English version entitled "Guideline for the Planning, Execution and Upkeep of Green Roof Sites" was issued in 2002. The document covers design, construction and maintenance of green roofs, with detailed sections on stormwater considerations, planting medium requirements, and drainage and layer requirements. It also provides information on testing of some of the green roof components.

In North America, ASTM, a standards development organization has struck a committee to formulate standards. Some standards relating to the performance of components of green roof system components and determination of structural loads from green roofs will be published in Fall, 2005.

In addition to green roof standards, many European jurisdictions have established green roof performance requirements. These performance requirements are different from standards. They build on and rely on standards for green roof specifications to meet specific policy or incentive requirements in a municipal jurisdiction.

3.3.1 FLL guidelines

The FLL 2002 Guidelines in English contain very detailed information pertaining to the planning, execution and upkeep of green roofs. The following paragraphs describe some of the key elements of the document

The first section of the document deals with applicability and relationship to other standards. It is important to note that the same standard applies to greening of roofs, roof terraces, and underground parking garages.

The second section of the document describes the types of green roofs: intensive, simple intensive and extensive. It further provides guidelines on the type of vegetation that each of type of green roof may be able to support and the factors that contribute to the successful growth of the vegetation.

The third section provides general information on the benefits of green roofs. This is followed, in Section 4, by a discussion of the nature of building and roof construction on the design of green roofs. In identifies the slope of the roof as a key factor in the success of a green roof. Roofs with slopes less than 2% (which would include many flat roofs in the Toronto area) will need special precautions with respect to drainage and preventing water from clogging the roots. Other issues that are discussed in this section include: roof designs and their suitability to accept green roofs, consideration of structural roof loads, compatibility of materials, watering, drainage from roof areas, fall protection, and ensuring that green roofs do not accidentally contribute negatively to the environment

Section 5 provides technical construction requirements for green roofs. Details are provided for protection from: root penetration, mechanical damage, corrosion, emissions and effluents, and slipping and shearing. Details are also provided for drainage facilities, construction of joints, borders and parapets, wind load considerations, fire prevention, provision of furnishings and trafficable areas.

Section 6 introduces the various components of the vegetation area such as the growing medium, filter course, drainage course, protective layer, root-penetration layer, separation layer and the anti-bonding layer. It provides general construction guidelines for these components. Detailed requirements for some of these components are provided elsewhere. This section also provides general guidelines relating to water retention and watering requirements. Of particular interest is the chart titled "Standard course depths for different types of roof-greening" and the chart that provides reference values relating depths of growing medium and annual average water retention. Tables 3.1 and 3.2 below summarize this information.

Sections 7, 8 and 9 provide detailed information about the materials, their requirements and construction of the drainage course, filter course, and the vegetation support course (growing medium). Sections 10 and 11 provide detailed information pertaining to the planting of vegetation, its cultivation and maintenance. The guidelines also include requirements for quality control and assurance. Section 12 provides details of the tests that should be conducted to ensure components meet the requirements set out in the guidelines. Finally, Section 13 provides useful reference data related to weight of materials that can be used to determine structural loads.

The FLL guidelines in general would be applicable to green roofs in the City of Toronto as long as the plant requirements are replaced by those of local plant species.

Table 3.1
Growing medium depth required for various types of vegetation
on different types of green roofs and
Annual average water retention as percentage of rainfall
for selected types of green roofs

Type of green roofs and vegetation	Depth required for growing medium (cm)	Water retention – annual average (% of total rainfall)
Extensive green roofs		
Moss-sedum	2 to 6	40 to 45 %
Sedum-moss-herbaceous plants	6 to 10	50 %
Sedum-herbaceous-grass plants	10 to 15	55 %
Grass-herbaceous plants	15 to 20	60 %
Simple (semi) intensive green roofs		
Grass-herbaceous plants	12 to 35	See note below
Wild shrubs, coppices	12 to 50	
Coppices and shrubs	15 to 50	
Coppices	20 to 100	
Intensive green roofs		
Lawn	15 to 35	See note below
Low-lying shrubs and coppices	15 to 40	
Medium height shrubs and coppices	20 to 50	
Tall shrubs and coppices	35 to 70	
Large bushes and small trees	60 to 125	
Medium-size trees	100 to 200	
Large trees	150 to 200	

Notes to Table 3.1: Water retention for semi-intensive and intensive green roofs will depend on area coverage. For individual areas of greening retention will be greater than that for extensive roofs and as high as 90% or more. The retention percentages are based on an average rainfall of between 650-800 mm. The City of Toronto average annual rainfall falls into this category. In drier regions the retention percentage will be higher and in wetter regions the retention percentage will be lower.

3.3.2   Green roof requirements[5]

In Europe performance rating systems have been developed for green roof technology. The rating systems help municipalities stipulate requirements that are tied to various programs related to green roofs on specific projects. They help ensure that the performance goals, which form the basis of municipal support programs, are met and continue to be met.

An example of such a system is the one developed by the FLL in 1998, specifically for the rating of green roofs in land-use planning, building permit approvals, and construction acceptance. Ten base points are assigned for each cm. of depth of green roof available for plant root penetration per sq. m. of green roof coverage. So, a 10 cm design will earn a building 100 (10 points x 10 cm) points per sq. m. coverage of green roof. In order to qualify for these points, the roof construction should meet certain minimum requirements in the following categories:

- water retention capacity of the growing medium;
- water retention capacity of the drainage layer;
- number of plant species for extensive green roofs; and
- plant biomass or volume for intensive green roofs.

In addition to these above quantitative elements, the FLL system identifies qualitative characteristics according to type of roof construction. These are typically used to judge whether a project is suitable for ecological compensation according to the local conservation requirements. Each natural function parameter is deemed "possible to fulfill completely", "possible to fulfill partially", or "slightly or not possible to fulfill." The qualitative parameters are

- quality of soil;
- improvement in surface water quality;
- reduction in load of the sewer system;
- improvement in groundwater recharge;
- purification of stormwater;
- filtering of air;
- contribution to oxygen production;
- contribution to urban temperature levelling;
- contribution to establishment of flora and fauna habitat;
- contribution to landscape and urban scenery; and
- contribution to amenity for people / leisure / healing.

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[5] The discussion on green roof performance requirements is adapted from "Green Roof Policy: Tools for Encouraging Sustainable Design" by Goya Ngan, 2004 last accessed at http://www.gnla.ca/library.htm.

Another example of performance rating is the Karlsruhe Performance Rating System for green roofs. It rates green roofs according to five natural functions. Each of these functions, or categories is assigned a weight based on its importance. The five functions with their weights are as follows:

1. Type and depth of soil used (Soil) – 15%
2. Impact on climate due to evapotranspiration (Climate) – 15%
3. Type and variety of vegetation (Flora) – 30%
4. Impact on zoological biodiversity (Fauna) – 30%
5. Average annual stormwater retention (Water Balance) – 10%

Each type of green roof is assigned a rating in percentage for each of the above five functions. The sum of the weighted rating for each of the five functions is used to compare different green roofing systems and stipulate minimum requirements. In one example an extensive roof with 3-5 cm growing medium is rated at 0.14 on a numerical scale compared to 0.48 for a roof with a 15 cm growing medium.

In addition to these examples of specific requirements for green roofs to meet program requirements in specified jurisdictions are provided in Table 3.2:

Table 3.2 Green roof requirements in selected European jurisdictions

Name of jurisdiction	Requirements specific to green roofs
North Rhine Westphalia, Germany	Runoff coefficient as tested for specific green roof systems to be less than 0.3 or have a minimum depth penetrable by roots of 15cm.
City of Cologne, Germany	No specific requirements for runoff coefficient or minimum depth. However a stormwater fee discount is applied on a sliding scale, with 90% discount for roofs with a runoff coefficient of 0.1 or less decreasing to a discount of 30% for a runoff coefficient of 0.7. In addition each applicant is required to submit a stormwater infiltration data form providing details of the runoff characteristics of the green roof and the drainage management of the building and the site.
City of Berlin, Germany	Green roofs should meet industry standards such as FLL guidelines
City of Linz, Germany	For underground parking garages, green roofs are to have a root penetrable growing medium of at least 50 cm. with plant coverage of 80% of the designated green roof area. Other parts of new and existing buildings with an area more than 300 sq. m. and slopes of 20° or less are required to have green roofs with a root penetrable growing medium of 12 cm.

4.0 Green roof benefits and costs for the City of Toronto

4.1 Description of approach

The purpose of this study was to determine the environmental costs and benefits of green roofs at the municipal level. Such an exercise requires the compilation of very specific information from many diverse sources. The approach involved the following:

- Identifying the environmental benefits at municipal level;
- quantifying the impact of green roofs for each of the benefits;
- valuing the benefit in monetary terms;
- applying the benefits on a city-wide basis, based on actual distribution of buildings.

4.1.1 Identification of benefits

A literature review on this subject assisted in narrowing down the quantifiable benefits of green roofs at the municipal level. These were related to reduction in water flowing into the stormwater system, the CSO system, to improvements in air quality, mitigation of the urban heat island effect, and reduction in energy consumption due to reduced space heating and cooling needs.

4.1.2 Quantification of impacts

Once the benefits were identified it was necessary to quantify the impacts of green roofs on each of these benefits. For the purpose of this study the impacts were quantified based on research reported to date. As much as possible we relied on local research. For instance, the impact of green roofs on stormwater has been modeled for the Markham branch of Highland Creek. We relied on the results of this work to quantify the impact of stormwater for the rest of the City of Toronto. Another example is the impact of green roofs on air quality. For this we used the work done on the impact of air quality in downtown Toronto. Each is explained in the subsequent sections.

4.1.3 Monetary valuation of benefits

Once the impacts were quantified in terms of their respective benefits (for example, stormwater benefits were measured as reduction in water flow), an economic value needed to be developed for each of the benefits. Some of the work cited earlier had built into it the monetary considerations for each of the benefits. For others we had to develop functions to translate the benefits into monetary terms. Again for this information we relied on local data, such as data from the recently completed study on green roofs by the City of Waterloo.

4.1.4   City of Toronto specific determination of benefits – use of building inventory data

Finally, one goal of this study was to determine benefits taking into account the specific land use in Toronto. This was achieved using a GIS database. This study was based on aggregation of results based on building distribution and land use within each watershed, explained below. Initial consideration was given to determine the impact of different levels of green roofing (for instance, 30%, 60%, and 100% green roofing). However, the models used for stormwater and combined sewer overflow calculations did not readily permit the use of these different scenarios, and therefore the calculations were based only on 100% greening of eligible roofs. It is expected that as this project continues on to its next phase, a method can be developed to allow different scenarios to be constructed.

We have assumed the following about the eligible buildings for green roof applications for the purpose of this report[6]:

- Green roofs are considered on roofs with relatively low slope i.e. "flat" roofs with slopes less than 2%. It is possible to install green roofs on roofs with slopes greater than 2%; Many low-rise residential buildings, which constitute a large percentage of total available roof area, have sloped roofs. However, application of green roofs on sloped surfaces is not very common and the benefits that apply to applications on "flat" roofs do not necessarily apply to sloped surfaces. The reported research on the benefits of green roofing is relevant for construction practices used for flat roofs and cannot easily be extrapolated to green roofs over sloped surfaces. For this reason at this time only low sloped or flat roofs are considered as eligible roofs for greening.

- Green roofs will be installed on buildings that have a roof area of at least 350 sq. m. On buildings with low sloped roofs the roof surfaces are often used for positioning equipment for heating, cooling, and ventilation purposes. Based on empirical evidence, it was determined that on average the roof would have to be at least 350 sq. m. before any significant free area would be available for greening.

- Greenery over underground parking garages or similarly non-conditioned enclosed spaces at grade level is excluded from consideration as green roofs in calculating the benefits in this study. There are three reasons for this assumption. Firstly there was no easy way to identify and measure the number of such spaces in the GIS database. It was not possible to distinguish green areas over underground structures from green areas over regular earth. Secondly the greening of such spaces at grade level is often covered by requirements related to site plan and development or from the need of the

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[6] The nature and thickness of the growing medium and components of a green roof affects the amount of stormwater runoff, and the amount of energy transfer through the roof, and the variety of vegetation that can successfully survive on the roof. The models used in the calculation of benefits in this report are based on a minimum performance of green roofs. It is expected that, for stormwater runoff and energy transfer, green roofs with a thickness of 75 mm (3 inches) or more will provide measurable benefits. The minimum threshold for the thickness may however be dictated by the need to be able to use a variety of plants and have them survive for a long term. For this purpose a minimum thickness of 150 mm (6 inches) may be appropriate at the present time. However, the relationship between thickness of green roofs and its performance will become less important with the use of products in the green roof systems that will allow them to perform better at lesser thicknesses.

owners to maintain a certain aesthetic appeal for their property. This situation would not require a separate incentive or policy for more widespread use.

- When installed on a building, green roofs will occupy an area of at least 75% of the roof footprint. The benefits in this study are estimated based on the use of extensive green roof systems with a certain minimum amount of coverage. Use of intensive green roofs, or greening on roofs using planters or greenhouses, will result in benefits that are highly dependent on the nature of design and layout of such systems. The benefits of using these systems in terms of stormwater control and energy usage will be lower than those for a typical extensive roof. This assumption will therefore provide an upper limit for the social and environmental benefit at the municipal level.

Since this report relies very much on existing research it is important for an understanding of this section to also understand the findings reported in the literature review section.

4.2   Methodology and results

4.2.1   Use of geographic information system (GIS)

Working in a GIS environment made it possible to produce a methodology that examined the characteristics and distributions of actual rooftops across Toronto. GIS is a technology that represents landscape features, such as buildings, streets, stormwater infrastructure, and watersheds in terms of their geographic positions. This enables digital representations of features and their attributes to be related to one another as they are on the ground. This project therefore was able to exploit GIS modelling functions for data management, for numerical analysis (in conjunction with spreadsheets) and for developing presentation materials regarding stormwater and combined sewer systems, air quality, the urban heat island, building-energy use and monetization of benefits.

The City of Toronto's Works and Emergency Services Department provided GIS data. Their records represented the buildings, sewer networks (stormwater and combined sewer overflow) with recent aerial photographs, as well as data sets submitted by consultants as part of the Toronto Wet Weather Flow Management Master Plan Study (TWWFMMP, 2003). Data sets were compiled in a format consistent with City records (MTM NAD 27 projection), but standardized in ArcMap 9.0 format for ease in processing. Quality assurance entailed detailed positional accuracy checks, using digital orthophotographs supplied by the City, and monitoring of feature counts.

Records for the actual rooftops of interest across the city were derived from the buildings data. The City provided geographic records for all buildings whose roof areas were over 350 square metres, and included age, height, and building-use attributes. Many of the buildings' roofs were very intricately represented and had to be simplified so that a single flat roof area was defined for each building. The GIS then linked these with their encompassing subwatershed and watershed, for stormwater and other evaluations.

The Unit-Response Functions (URF) used to assess the ability of green roofs to divert stormwater from sewers were based on calculations in the TWWFMMP. In this report, each consulting team determined the amount of stormwater runoff from measurements of the extent of identified land uses and from permeable and impermeable areas per subwatershed. Aquafor Beech Ltd (2003) calibrated their model for runoff under current and projected green roof scenarios in the Highland Creek Watershed. The calibration values from their model were applied across the city in this study, by using the GIS to assign predicted runoff, based on records of usable roof areas, for each land use in each subwatershed. GIS then enabled aggregation of the stormwater diversions for watersheds and for the whole City of Toronto to demonstrate the reduced hydrological demands on the stormwater drainage network. These were then mapped using the GIS.

Air quality, urban-heat-island reduction and building energy assessments were addressed in a like manner. The work by Currie (2005) used the UFORE model to link vegetated areas to expected ambient air pollutant reductions and economic benefits. By mapping the extent of vegetation added by green roofs across the City, these results were extrapolated to show where air contaminant abatement could be expected and by how much. The distribution of air-quality, urban-heat-island reduction and building-energy benefits, as well as their sum for the City, were also mapped using the GIS.

The total area available for installation of green roofs was calculated as shown in Table 4.1

Table 4.1
Available areas for green roof implementation

Category	Area in hectares (percentage in paranthesis is of the total land area)
Total estimated land area of Toronto	63,175
Total building roof area	13, 478 (21%)
Total building roof area available for greening - flat roofs greater than 350 sq. m. and 75% green roof coverage	4,984 (8%)

4.2.2 Costs of GRT

The previous sections have discussed the benefits of green roof technology. In this study we also considered the costs of green roof technology. The costs associated with green roof implementation are primarily borne by private building owners. These costs can be stated as incremental costs of constructing and maintaining green roofs compared to those of a traditional roofing system. Based on recent work on specific projects completed by the City of Waterloo, the incremental cost of reroofing a building, with an extensive green roofing system are of the order of $75 to $90 per square metre of roofing (that is, over and above the cost of traditional roof).

Costs at the municipal level will include costs of programs to promote green roofs. These costs for the City of Toronto can be determined once the exact nature of the programs is known. At the present time there are no other costs at the municipal level to be considered related to green roof implementation.

4.2.3   Stormwater

Modelling of stormwater benefits requires a consistent approach to all watersheds in the City of Toronto. In 2004, the Toronto and Regions Conservation Authority (TRCA) commissioned Marshall Macklin and Monaghan Ltd. and Aquafor Beech Ltd. to analyze runoff reduction due to green roofs in the Highland Creek watershed. The modeling of runoff using the HSPF model was based on a unit response function (URF) approach, previously used in the Toronto Wet Weather Study in 2003. The URF of a certain land use category is the annual runoff from one hectare of drainage area. Assuming the runoff process is linear, total runoff can be calculated by multiplying the area by its corresponding unit response function. As unit response functions for other watersheds in Toronto must be determined separately using HSPF, it is assumed in this study that the Highland Creek's unit response function can be used to represent the whole city. Table C1 in appendix C shows the land use categories used in the current study and the annual runoff with and without green roofs. These unit response functions are estimated by

- adopting the unit response function generated in the Highland Creek case study if there is a corresponding land use category; or
- averaging the unit response functions generated in the Highland Creek case study if there are a few similar land use categories.

Using Table C1, annual runoff volumes from different land use categories in a watershed are estimated and aggregated. The percentage change of annual runoff due to green roofs is then calculated.

Three types of the stormwater benefits are estimated

- stormwater best management practice savings due to the application of green roofs;
- pollutant reduction;
- reduction of receiving stream erosion.

After reviewing the best management practice bundles used in the Toronto Wet Weather Study, we find three types of best management practices, which have high cost, may be replaced by green roofs in a generic manner. They are pervious pavements in residential highrise and commercial areas and underground storage in commercial areas. Table C2 in appendix C shows the unit costs of best management practices, which may be replaced by green roofs. This table was derived from the unit costs of best management practices including maintenance in the Toronto Wet Weather Study, while the cost saving is the difference in unit cost between green roofs and other best management practices. The total

area of green roofs and the unit cost savings of best management practices in Table C2 determine the best management practice benefit of green roofs.

The City of Waterloo's green roof study allows the pollutant reduction benefit (P) and erosion benefit (E) to be estimated as follows:

$$P = 0.5 * \$5,460 / ha\_of\_greenroof$$
$$E = \$5,055 * ha\_of\_greenroof$$

Based on a 4,984 ha of potential green roof implementation, the following stormwater benefits are estimated:

- A BMP infrastructure saving from $2.8 to $79 million.
- A pollutant reduction benefit of $14 million
- Savings from erosion control measures of $25 million

The total stormwater benefit is estimated to range from $41.8 to $118 million.

4.2.4   Combined sewers

The combined sewer overflow (CSO) benefit is obtained by estimating the reduction of storage required for the control of CSO in Toronto. The City of Toronto has developed a comprehensive model (the QQS model) to simulate the CSO conditions. Using the QQS model, it was predicted that the total annual CSO volume to Black Creek, Humber River, West Don River, Massey Creek, Lower Don River, Western Beaches, Inner Harbour, Eastern Beaches, and Scarborough Lake would be 10,187,056 m^3. The total CSO drainage area is 9100 ha. The Toronto Wet Weather Study recommends that underground storage of 258,955 m^3 will be required for the whole CSO area.

The QQS is a detailed continuous model which simulates the combined sewer network for the whole city. For planning level analysis of the effect of green roofs on CSO, a simplified approach is used in this study. It is based on analytical probabilistic models, SUDS, which transform the probability density functions of rainfall event characteristics (e.g. volume, duration, and inter-event time) into probability density function of overflow characteristics (Adams and Fabion 2000). These models have been applied to simulate the stormwater and CSO conditions at the 17 Canadian RAP areas (CH2M 1993). SUDS provides continuous analysis of rainfall, runoff, and overflows in urban drainage systems and has been found to provide results in good agreement with continuous simulation models such as STORM and SWMM. SUDS was calibrated with QQS's result and used to estimate the reduction of underground storage.

The method to estimate the reduction of underground storage after the implementation of green roofs is based on the following assumptions:

- The whole CSO area is considered to be one sewershed for modelling purposes.

- The green roof can replace a minimum 5% and a maximum 15% of the total impervious area in the combined sewer area.

With the assistance of the city's modellers, the QQS model was re-run for the 5% and 15% scenarios.

The SUDS model was first calibrated (Table 4.2) to produce a total annual CSO volume of 10,187,056 m^3 (predicted by QQS). Table 4.2 summarizes the input and calibrated data for the SUDS model.

The SUDS model was then used to simulate the following scenarios:

1. Existing CSO condition without green roof;

2. Existing CSO condition with 5% green roof;

3. Existing CSO condition with 15% green roof;

4. Future CSO condition with the Toronto Wet Weather Study's recommended underground storage;

5. Future CSO condition with the Toronto Wet Weather Study's recommended underground storage and 5% green roof;

6. Future CSO condition with the Toronto Wet Weather Study's recommended underground storage and 15% green roof;

The CSO benefit of green roofs is estimated by the reduction of underground storage for the same level of CSO control and a unit cost of $1,340/m^3 for underground storage (Toronto Wet Weather Study).

Table 4.2
Input and calibrated data for the SUDS model

Input and calibrated data	Value	Details
Total CSO area	9,106 ha.	QQS model input
Depression storage	4 mm.	Assumed parameter
Pervious runoff coefficient	25%	Assumed parameter
% Imperviousness	51%	Calibrated parameter
Effective interceptor capacity	0.152 mm/hr.	Estimated parameter
Existing CSO storage	0.135 mm.	Calibrated parameter
Proposed CSO storage	2.84 mm.	Toronto Wet Weather Study
Unit cost of CSO storage	$1,340/m^3	Toronto Wet Weather Study

Based on the SUDS model simulation, the existing and future CSO volumetric controls are 17.4% and 59.7% respectively (Table 4.3). With 5% and 15% of potential green roofs, the existing CSO volumetric control can be improved to 17.8% and 18.8%. To achieve the future 59.7% volumetric control, the reduction of underground storage due to 5% and 15% of potential green roofs is estimated to be 11,712 m^3 and 34,752 m^3. The total infrastructure savings for 5% and 15% of potential green roofs are $15.7 million and $46.6 million respectively. If the proposed underground storage is to be built in Toronto, the average annual number of CSOs and the average annual percent of runoff controlled can be improved by 1.3 CSO reductions and 2.3% volumetric reduction respectively. These reductions of CSO can result in additional benefits, such as reduction of beach closures and/or other environmental benefits. The beach closure benefit is based on the number of overflow reductions. In Toronto one CSO/year reduction is expected to result in 3 less days of beach closure during the season when swimming would be possible. The economic impact of extra beach openings is valued at $750,000.

It should be noted that a separate model was used to study the impacts of green roofs on CSO. The 15% potential green roof is close to the 100% green roofing assumption made for the other benefits.

Table 4.3
Analysis of CSO scenarios using the SUDS model

Analysis Scenarios	Average annual number of CSOs (#/year)	Average annual percent of runoff volume controlled (%)
a) Existing conditions without the recommended underground storage	34.1	17.4

b) with 5 % green roofs	34.0	17.8
c) with 15% green roofs	33.5	18.8
d) Future conditions with the recommended underground storage	16.6	59.7
e) with 5% green roofs	16.2	60.8
f) with 15% green roofs	15.3	63.0
Note: "Existing conditions" refers to the current CSO situation without the Toronto Wet Weather Study's recommended underground storage. "Future conditions" refers to the future CSO situation with the Toronto Wet Weather Study's recommended underground storage.		

4.2.5   Air quality

The method for determining air quality benefits due to green roofs was an extension of the research results of Currie (2005a, 2005b), which used the UFORE-D model from the USDA Forest Service (Nowak and Crane, 1998) in determining reductions in atmospheric pollutants (0_3, $S0_2$, $N0_2$, $C0$, PM_{10}) due to the distribution of urban vegetation habitats. The model predicts annual contaminant-deposition rates in response to pollutant concentrations in the air, and parameters reflecting the abundance of various classes of vegetation. Currie assembled the necessary data for developing these parameters in midtown Toronto. For each of 72 monitored plots (of 400 m^2 each), the model's parameters were derived from observations of land cover and land use, assembled from GIS data: tree, shrub and ground vegetation abundance, buildings, low, medium and high residential, commercial, industrial, institutional and open areas (DMTI Spatial 2000; Kenney, 2001). Hourly meteorological and air pollutant concentration measurements (Environment Canada, 1998) for nearby stations (Pearson Buttonville, and Toronto Island Airports) were also collected.

The UFORE-D model develops measures of expected annual contaminant removals and their dollar value. This economic measure is based on work by Murray (1994) in New York State, and represent "the perceived cost to society of pollution emissions based on predicted air pollution consequences to health and the environment" (Currie, 2005a).

To use Currie's results in the current study, these atmospheric-contaminant reductions and their dollar values were related to the surface area taken up by buildings' rooftops. Currie used a study area of 1215.4 ha. Of which 9% of this area was capable of taking a green roof

(109.386ha). Her application of the UFORE-D model predicted reductions associated with "grass roofs" as shown in Table 4.4

Table 4.4
Impact on air quality from grass roofs
Reductions in contaminants and monetary impact as shown

	CO	NO$_2$	O$_3$	PM$_{10}$	SO$_2$	US$
mg per 109.386 ha of green roof area per year	0.35	1.6	3.14	2.17	0.61	43,106

These results were extrapolated over the city as a measure of the air quality improvement expected by green roof adoption, and were calculated first by prorating the available green roof areas per watershed, then summing these for a Toronto-wide total.

The economic value of the air quality benefits related to green roofs resulting from reduction in CO, NO$_2$, O$_3$, PM$_{10}$, SO$_2$ for 100% green roof implementation in the City of Toronto would be $394.07 per hectare of green roof x 4984 hectares = US$1,970,000. The equivalent in Canadian dollars based on 2004 exchange rates adjusted for purchasing power parity would be approximately $2,500,000 per year (OECD 2005).

4.2.6   Building energy and the urban heat island

The method used to determine of the impact of the urban heat island and building energy was essentially similar. Building energy has been included here as a community-wide benefit, although it might be argued that it accrues directly to the building owner. The reason for including it was that to some extent energy efficiency in buildings has been considered a societal benefit. Some impacts of energy use, such as carbon dioxide production from coal-fired plants that supply electricity for cooling buildings, accrue at community level and can be separately quantified. However, there are other impacts, such as the use depletion of resources, that benefit the society but which are not readily quantifiable. Therefore, we have used the monetary savings in the use of energy at the building level to provide a measure of the societal benefit.

We have determined the savings in annual energy and also the reduction in peak demand. Examining the avoidance cost of building power generating plants of the same capacity can value the reduction in peak demand.

The energy savings will also have an impact on the operation of power generating plants. Assuming that these power-generating plants use fossil fuels, there will be a further benefit of reducing energy in the reduction of carbon dioxide. We use the value of 0.27224 kg of carbon dioxide reduction for every kWh of energy saved.

4.2.6.1 Building energy

In order to quantify the benefits of green roofs with respect to the building energy this report relied on the modelling done at the Lawrence Berkeley Laboratory (LBL) study (Akbari et al. 2004). The LBL study determined the energy savings from applications of various heat island reduction strategies. This study reported the savings from direct measures and indirect measures.

The direct measures impact the heat flow characteristics through the building envelope by implementation of the appropriate measures. For the purpose of this study, energy savings reported in LBL's study related to cool roofing were used. Other studies have indicated that green roofing can provide as much or more energy benefit than cool roofing. Green roofs have the added advantage of benefiting from evapotranspiration during the summer months. So, use of this data should provide conservative estimates of energy savings from implementing green roofs. LBL's data identified significant savings resulting from summertime cooling. LBL data was also broken down by building types.

Data from monitoring on Eastview and the City of Toronto's City Hall roof were also taken into account. These data overestimated the energy reduction by a factor of 4 to 5 compared to the results from LBL's study. However, these data, which provided annual energy savings, showed a fair contribution of energy savings from reduction in wintertime heating demand.

In addition, results of modelling of a typical building done by Enermodal in the FCM sponsored green roof feasibility study of the City of Waterloo were also taken into account. The Enermodal study simulated the energy savings in a one storey building from the use of green roofs. It integrated data from work done by the National Research Council of Canada on green roofs in Ottawa. The results from this study related to cooling load were about 4 times lower than the LBL study.

Table 4.5 summarizes the potential savings in energy use in buildings resulting from the implementation of green roofs.

Table 4.5
Direct Energy savings from green roof implementation

Savings category	Amount of saving per sq. m. of green roof area
Direct energy savings	4.15 kWh/ sq. m./year
Demand Load reduction from direct energy reduction	0.0023kW/ sq. m. peak

Before the economic benefits from building energy savings can be determined it is necessary to establish the cost of energy. We have calculated the cost of electricity, which is predominantly used to run equipment that cools buildings, to be $0.1017 per kWh. Based on annual energy savings of 4.15 kWh per sq. m., the city-wide implementation of green roofs would result in savings of $21 million per year.

The demand reduction, based on peak demand reduction of 0.0023 kW per sq. m. for city-wide green roof implementation would be 114.6 MW[7]. Based on the cost of bringing in new generation capacity at $0.6 million per MW (based on a cost of bringing in 2,500 MW of new power plant estimated at $1.5 billion), the cost avoided from reduction in peak demand would be $68.7 million

The carbon dioxide mitigation from reduction in fossil fuel use at power generating stations would be 56,300 metric tonnes per year. Assuming the cost of carbon permits to be $10 per metric tonne, the cost savings from carbon dioxide mitigation would be $563,000 per year.

4.2.6.2 Urban heat island

Reduction of the urban heat island effect requires a fairly wide spread implementation of green roofs. Localized and sporadic implementation of green roofs will not result in reduction.

For the purpose of quantifying the urban heat island effect two studies were examined: the study done by the Ministry of the Environment Climate Adaptation Group and the study done by LBL.

Widespread implementation of green roofs would reduce the local ambient temperature. Such reduction in local temperature in turn would have an impact on heat flow through the buildings' walls and roofs. This impact can be determined in the same way as done for direct energy savings in section 4.2.6.1.

Based on the studies we have determined that the wide spread implementation of green roof would reduce the local ambient air temperatures in Toronto between 0.5 and 2 degrees C, depending on the time of the year.

These changes in temperature will have an impact on energy balance through the buildings' walls and roofs. Table 4.6 summarizes the energy savings from reduction in temperature due to the impact of green roofs on the urban heat island effect.

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[7] Please see the next footnote

Table 4.6
Indirect energy savings from green roof implementation
(Impact of reduction in urban heat island effect in Toronto)

Savings category	Amount of saving per sq. m. of green roof area
Direct energy savings	2.37 kWh/ sq. m./year
Demand load reduction from direct energy reduction	0.00267kW/ sq. m. peak

The economic benefits from the reduction in the urban heat island effect are calculated in the same manner as the building energy benefits. Based on the annual energy savings of 2.37 kWh per sq. m., the city-wide implementation of green roofs would result in a savings of $12 million.

The demand reduction based on peak demand reduction of 0.00267 kW per sq. m. for city-wide green roof implementation would be 133 MW[8]. Based on the cost of bringing in new generation capacity at $0.6 million per MW (based on a cost of bringing in 2,500 MW of new power plant estimated at $1.5 billion) the cost avoided from reduction in peak demand would be $79.8 million.

Finally the carbon dioxide mitigation from reduction in fossil fuel use at power generating stations would be 32,200 metric tonne per year. Assuming the cost of carbon permits to be $10 per metric tonne, the cost savings from carbon dioxide mitigation would be $322,000 per year.

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[8] The peak demand savings of approximately 248 MW (direct and urban heat island) resulting from 100% green roofs coverage may be considered high given the total peak demand attributed to cooling in Toronto of approximately 2.5 GW peak (as provided by Toronto Hydro during personal communications). Please refer to Section 5.4 regarding uncertainty in predicted values and sensitivity analysis.

5.   Summary and recommendations

This report is the first significant milestone in a bigger project undertaken by Ryerson University and funded by OCE-ETech through partnerships with the City of Toronto, Trow Associates and 401 Richmond. The objective of this report is to estimate the municipal level environmental benefits and costs of implementing green roofs in the City of Toronto.

A geographical information systems (GIS) based approach has been undertaken to identify buildings suitable for green roof application. Appropriate assumptions had to be made in the use of such data. It is expected that the methodology will continue to be refined and more refined data will become available to be used in the second part of this project.

Based on the work undertaken to date, Table 5.1 summarizes the economic benefits of green roofs in the City of Toronto. The benefits are based on greening 100% of the available flat roofs larger than 350 sq. m. on buildings. The identification of benefits, the process of quantification and the monetary valuation of the benefits have primarily been based on existing primary research available in the public domain.

Table 5.1
Summary of municipal level environmental benefits of green roof implementation in the City of Toronto (Assuming green roof coverage of approximately 5,000 hectares

Category of benefit	Initial cost saving	Annual cost saving
Stormwater		
Alternate best management practice cost avoidance	$79,000,000	
Pollutant control cost avoidance	$14,000,000	
Erosion control cost avoidance	$25,000,000	
Combined Sewer Overflow (CSO)		
Storage cost avoidance	$46,600,000	
Reduced beach closures		$750,000
Air Quality		
Impacts of reduction in CO, NO_2, O_3, PM_{10}, SO_2		$2,500,000
Building Energy		
Savings in annual energy use		$21,000,000
Cost avoidance due to peak demand reduction	$68,700,000	
Savings from CO_2 reduction		$563,000
Urban Heat Island		
Savings in annual energy use		$12,000,000
Cost avoidance due to peak demand reduction	$79,800,000	
Savings from CO_2 reduction		$322,000

5.1   Other benefits

Several benefits, particularly relating to the use of green roofs as an amenity space, could not be quantified, as too little research has been completed in this area. In some instances benefits have been documented, but apply to very specific types of greening options, which compete with other benefits. For instance, the benefits of green roofs as a medium for local food production are documented. However in a situation where such benefits have been quantified in terms of the amount of production per sq. m. of roof, the food is grown in a greenhouse on the roof. Greenhouses lend themselves well to plant growing on roofs but take away from other social and environmental benefits.

At the municipal level the greatest social and environmental benefits appear to be a result of the use of extensive green roof systems. Use of intensive roofs, with uneven green coverage, use of planters for greening, and use of greenhouses have their own individual benefits. These benefits are highly dependent on the actual design implementation or plan for greening. They are likely to have a very high value with respect to amenity space, aesthetics, direct health benefits and real estate values depending on the design. However, it is unclear as to whether such approaches and systems will provide a significant direct benefit at the municipal level.

There are several other social and environmental benefits of a green roof such as its impact on biodiversity, water quality and the quality of life. This can bring significant benefits, which would need additional research beyond the scope of this project to quantify.

5.2   Green roofs on sloped surfaces

It is inevitable that consideration may be given to green roofs on sloped surfaces such as those on wood frame houses. These types of buildings constitute a large portion of roof area in the City of Toronto and provide a tremendous opportunity for greening. We have, however, not found enough basis in the research to quantify the benefits of green roofs on such surfaces. There may also be some questions about the feasibility of constructing and maintaining such roofs. Until further research shows quantifiable benefits and feasible solutions for implementation, we are unable to recommend the use of green roofs on sloped surfaces.

5.3   Recommendation for types of green roofs

The major municipal level environmental benefits of green roofs identified in this study for Toronto are improvements in stormwater management, CSO control, air quality and reduction of energy use and its impact on carbon dioxide reduction. The characteristics of green roof technology that will impact the performance in the noted areas are as follows:

- depth and nature of growing and drainage medium;
- percent of roof greened; and
- plant coverage on greened area.

As each of these increases in quantity, the performance of the green roof will increase with respect to the environmental benefits. However the cost of green roof increases with the increase in the depth and area coverage. Also, for existing buildings structural load limitations impose a restriction on the nature of the green roof that can be implemented. Since the economic impacts of the benefits of green roof technology in this study have been calculated for existing buildings, structural load limitations are an important criterion and therefore will prevent green roofs with deeper growing medium.

Based on this study we recommend the following as minimum considerations for the type of green roof system to be used to obtain the benefits listed in this study:

- Extensive green roofs with a continuous coverage of growing media over at least 75% of the roof footprint of the building.

- Green roofs to be installed over "flat roofs". Many of these roofs are nominally sloped by about 2%. Where roofs have zero slope, green roof systems will need to be designed to drain water away from the root.

- The green roof system should have a maximum runoff coefficient of 50%, based on annual average rainfall retention of 50% for Toronto conditions. There are many systems on the market with varying depths of growing medium that will meet these performance requirements.

- On existing buildings a structural analysis should be conducted to determine the thickness of growing media that can be accommodated. Where permitted by the structure of the existing buildings and on new buildings where there is flexibility at design stage with regard to the structural design, a green roof with a depth of at least 150 mm (6 inches) should be considered. This depth will permit greater flexibility in terms of the type and variety of vegetation that can be incorporated. It will ensure greater survival of plants.

- Green roofs with a growing medium thickness as low as 75 mm (3 inches) are available and can provide the benefits stated in this study. Such systems should be considered acceptable where structural loads on existing building do not permit green roofs of greater thickness. Manufacturers of such systems should be required to submit test data indicating the performance of these systems with respect to water runoff.

- This study is based on green roofs installed over air-conditioned spaces that are heated and cooled. Green roofs that are installed over unheated and unconditioned spaces, for example over underground parking garages, will not provide energy related benefits. In general green roofs where public and or vehicular access is possible from the grade level have been built without specific green roof incentives and policies. Although they will provide many of the benefits of green roofs, we are not recommending them to be included in the category of green roofs described in this study.

- Several of the systems described in Section 3 are available for green roofs in Toronto. It is recommended that green roofs systems be designed and installed according to manufacturers' recommendations.

5.4 Next steps

This study has enumerated the social and environmental benefits of green roofs on a city-wide basis. Not all benefits of green roofs can be quantified at this time. Given the quantifiable benefits and the potential benefits that cannot easily be quantified we believe that there is a case for public programs to promote green roofs. We recommend that the City of Toronto embark on consideration of such programs that will give further impetus to green roofs. The City of Toronto may wish to consult the users of such programs and determine the level of logistical, technical and financial support that may be appropriate to promote green roof construction in the city. Once determined the costs of such programs can be used to complete the cost benefit analysis of green roofs at the municipal level.

Although this study has made several advances in predicting benefits of green roofs and it has provided information for the City of Toronto to move further on programs and policies pertaining to green roofs, there are several areas that will require further work. Questions remain to be answered regarding the uncertainty of the benefits, impact of less than 100% green roof coverage, impact of building specific constraints, the quantification of costs leading to a complete cost benefit analysis, quantification of other social benefits and consideration of the effect of alternative technologies that may be able to perform one or more of the functions of a green roof. These questions are important and will need to be considered in further studies. Policy decisions regarding green roofs will need to consider the impact of these questions.

Uncertainty of benefits arises because of various factors. Some of the factors that contribute to the uncertainty in this study include the sources of building inventory data and the models used to predict benefits (stormwater, energy and air quality). Although not explicitly evident in the analysis, in this report we examine boundary conditions with respect to framing uncertainty of the information presented. However sensitivity analysis can better frame the predictions presented in this report.

In this report we examined 100% green roof coverage on available green roof area. This has provided a good starting point on the envelope of potential benefits. Knowing the impact of a range of green roof coverage would also be useful. The continuing part of this study will examine the possibility of developing models to predict such impacts.

Building specific constraints will dictate the feasibility of implementing green roofs and also impact the benefits that will accrue for any particular building. Many constraints will impact the costs and benefits related to green roofs such as: the structural load carrying capacity, the heating and cooling plants and distribution systems, and the building dimensions. Our research has indicated that the currently available green roof technology can cater to wide variations in building needs and overcome some of the obstacles such as structural loading.

Further studies may be considered to take into account building level constraints. Such studies can be helpful in predicting building level impacts and also in refining the municipal level impacts.

Another area that needs further development is the quantification of social and environmental benefits of green roofs beyond those that are available from current research. For that it may be necessary to draw on research done on similar benefits in other areas.

This report only examines green roof technology. Green roofs are unique because they can provide multiple benefits using one type of sustainable technology. While it is difficult to find any one technology that can provide the range of benefits of a green roof, there are technologies available that either singly or in combination can provide either some or all of the benefits of green roofs. Traditional models of comparing green roofs with other technologies are not suitable in this regard. Further work needs to be carried out to determine how decisions can be made in comparing green roof technologies to other technologies, either in combination or singly.

The intent of our continuing work remains to produce a model that will allow the benefits and costs to be analyzed. As this work continues we expect to develop models to predict costs that will enable a complete cost benefit analysis.

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Prepared by Ryerson University *Page 63*

Appendix A
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Appendix B
List of GIS Data and Sources

Buildings: footprint coordinates; Attributes database fields (age (year built),area, elevations at foundation and rooftop, use/description)

Stormwater Management Infrastructure: geographic extent for drains, CSO and sewer lines, subwatersheds, watersheds

Land Use: geographic extent; attribute codes for:
        Commercial; Bigbox; Downtown; Strip Mall
        Educational/Institutional
        Golf Courses
        Government-Institutional
        Waterbodies
        Highway Corridors
        Industrial; Prestige Industrial
        Open Space/Park
        Residential
        Residential Low Density
        Residential Medium Density
        Residential High Density
        Resource-Industrial
        Roadways

Digital Orthophotographs

Sources:

City of Toronto Works and Emergency Services and Toronto Wet-Weather Master Plan Consultants: CH2M Hill (old City of Toronto), Totten Sims-Hubicki (Mimico and Etobicoke Creeks Watersheds), XCG (Humber River Watershed), Marshall Macklin Monaghan (Don River Watershed), and Aquifor-Beech (Rouge River Watershed).

Appendix C
Data for Stormwater Calculations

Table C1
Unit response functions for runoff calculations

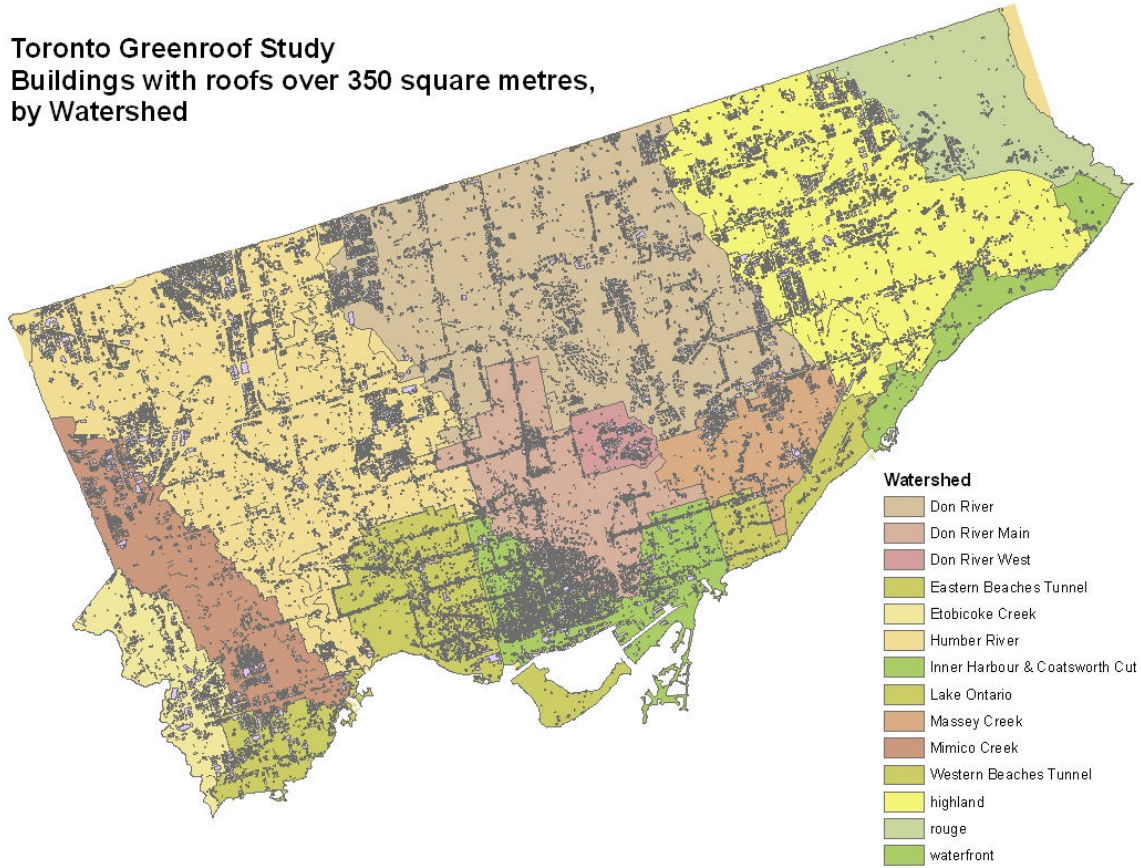| LANDUSE CODE	DESCRIPTION	RUNOFF-NO GREENROOF m^3/ha	RUNOFF-WITH GREENROOF m^3/ha
C	Commercial	6019	4913
CBB	Commercial Bigbox	6223	5067
CDT	Commercial Downtown	6019	4913
CI	Commercial-industrial	5742	4912
CR	Commercial-residential	4054	3480
CSM	Commercial Strip Mall	6210	5063
EIS	Educational/Institutional	2222	1827
GC	Golf Course	653	534
GS	Greenspace: parks	875	729
I	Industrial	5260	4757
IBB	Industrial Bigbox	5260	4757
IN	Resource-Industrial	4571	4070
IPR	Prestige Industrial	4571	4070
IR	Resource-Industrial	2723	2400
MIX		2222	1827
OGC	Open Space -golf	653	534
OHC	Open hydro corridor	875	729
OPL	Open Space/Park Land	875	729
OPL	Open TRCA land	430	339
OVL	Open Valley Lands	430	339
PK	Park	875	729
R	Residential	1897	1897
RES	Residential, open area	1254	1254
RHD	Residential High Density	2415	2415
RHR	Residential High Rise	3305	3060
RLD	Residential Low Density	1254	1254
RMD	Residential Medium Density	1897	1897
RS	Residential, open area	1254	1254
RT	Commercial	6019	4913
SC	Government-Institutional,	1254	1254
SPC	STP, Park, commercial-industrial	2501	2205
TA	Government-Institutional,	1254	1254
TAP	Downsview airport	1386	1313
THC	Highway Corridors	1078	1078
UNK	Roadways	1078	1078
W	Water	0	0

Table C2
Comparison of unit costs of best management practices and
estimation of cost saving of green roofs

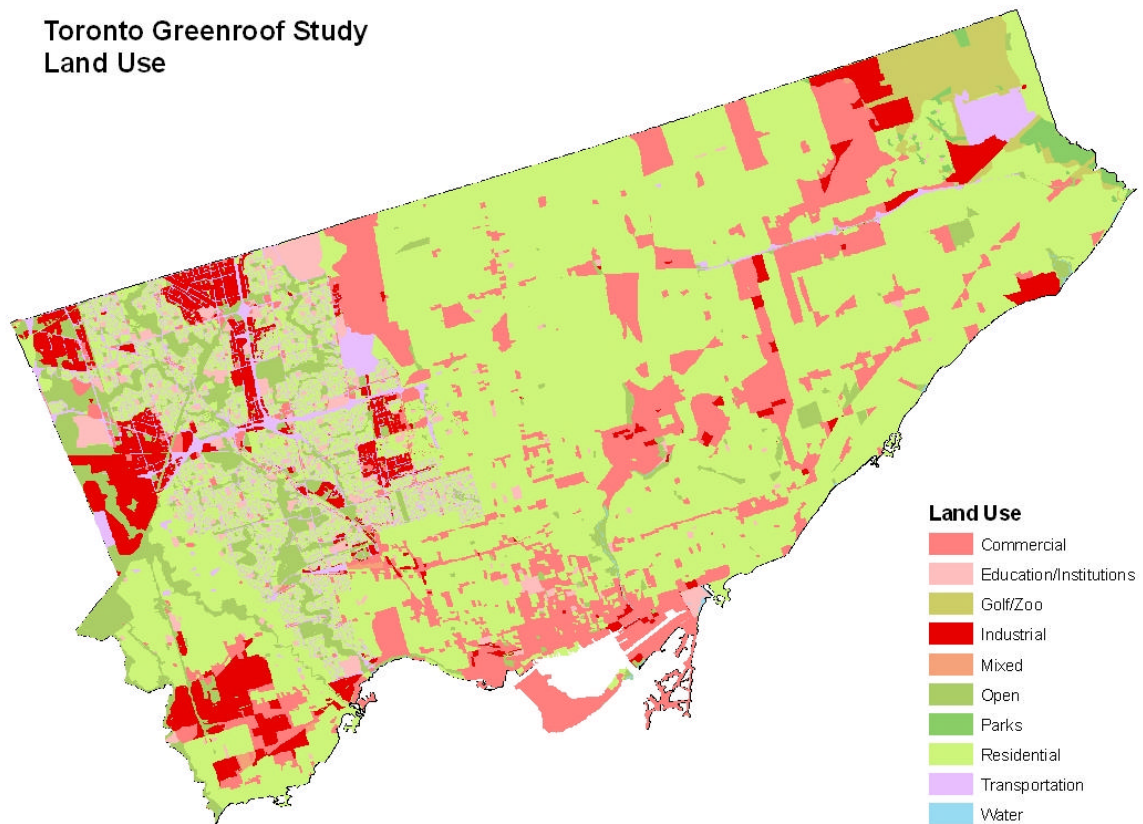| Type of BMPs	Total cost ($/ha)*
Rooftop gardens for strip mall	65801
Rooftop gardens for big box	104801
Rooftop gardens for downtown	183782
Residential high density foundation drain disconnection	265005**
Residential highrise and institution pervious pavement/parking	398722**
Commerical underground storage	144041
Commercial pervious pavement in parking	151026**
Note: The above unit costs were used in the Toronto Wet Weather Study	
Note: *total cost includes capital and O&M over 50 years; **based on 80% imperviousness	
GRT for mall and big box	85301
GRT for downtown	183782
Average GRT	134542

BMP with higher costs than GRT	Unit cost
Residential highrise and institution pervious pavement/parking	398722
Commerical underground storage	144041
Commercial pervious pavement in parking	151026
Green roofs	134542
BMP substitution	**Unit cost saving ($/ total ha)**
Low estimate of BMP saving (Commerical underground storage)	9500
High estimate of BMP saving (Residential highrise pervious pavement)	264181
BMP substitution	**Unit cost saving ($/ha of GRT)**
Low estimate of BMP saving (Commerical underground storage)	570***
High estimate of BMP saving (Residential highrise pervious pavement)	15851***
Note: *Total cost includes capital and O&M over 50 years per ha of drainage area; **Based on 80% imperviousness ***Assuming 6% of the total area is green roof.	

Appendix D
GIS Maps

Toronto Greenroof Study
Buildings with roofs over 350 square metres,
by Watershed

Watershed

	Don River
	Don River Main
	Don River West
	Eastern Beaches Tunnel
	Etobicoke Creek
	Humber River
	Inner Harbour & Coatsworth Cut
	Lake Ontario
	Massey Creek
	Mimico Creek
	Western Beaches Tunnel
	highland
	rouge
	waterfront

Toronto Greenroof Study
Land Use

Land Use
- Commercial
- Education/Institutions
- Golf/Zoo
- Industrial
- Mixed
- Open
- Parks
- Residential
- Transportation
- Water

**Toronto Greenroof Study
CSO Sewersheds**
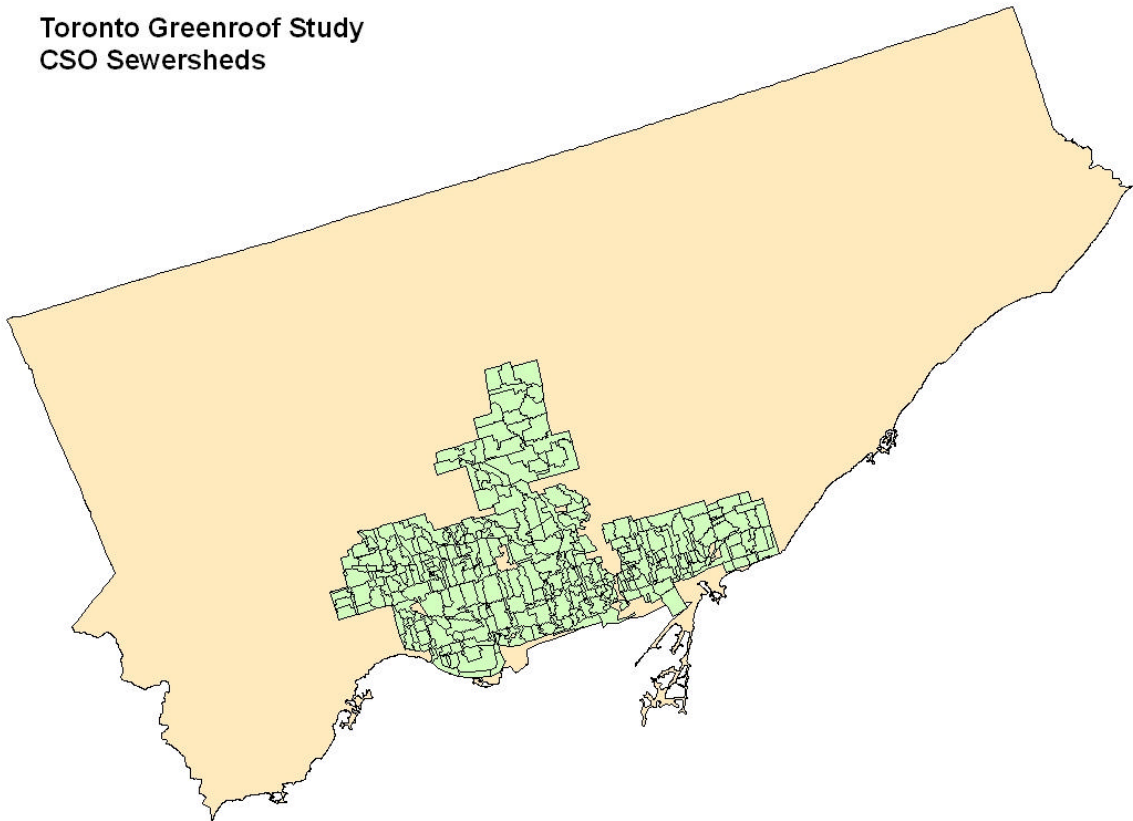
Toronto Greenroof Study
Runoff Reduction due to
Greenroof Implementation,
by Watershed

9.7

7.6

6.8

4.1

8.1

11.4

7.2

9.0

5.5

4.4

9.1

8.4

12.3

9.7

9.0

9.0

Watershed Runoff Reductions

under 5.0%

5.0 - 7.0%

7.0 - 9.0%

9.0- 11.0%

11.0 - 13.0%

Overall Runoff Reduction 12 680 769m3/yr,
8.0 % of Total Stormwater Runoff