

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).

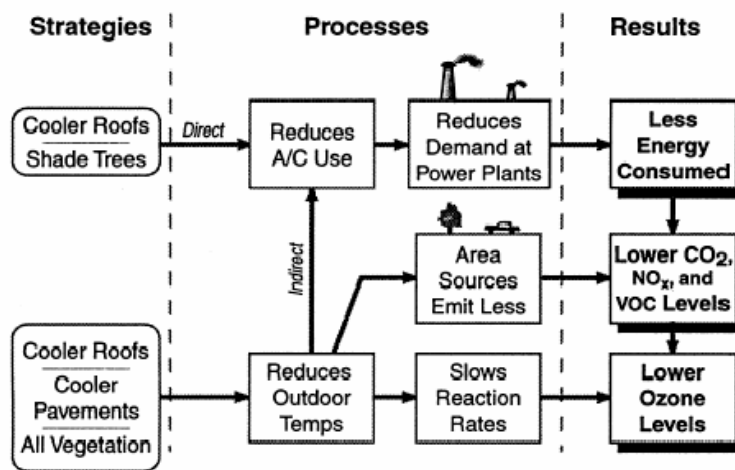
Akbari et al. (1999, 2001) investigated means of reducing building energy in mid-latitude cities as one of several means for reducing the urban heat island (UHI) effect and documented the enhanced air conditioning demands (up to 10%) brought about by the UHI. This elevated load generally occurs in the 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, 2004¹; 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. Eumorfopoulou (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 (Eumorfopoulou, 1998). Patterson (1998) also showed that

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 m² (800 ft²) 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°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.	
Eumorfopoulou (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.	

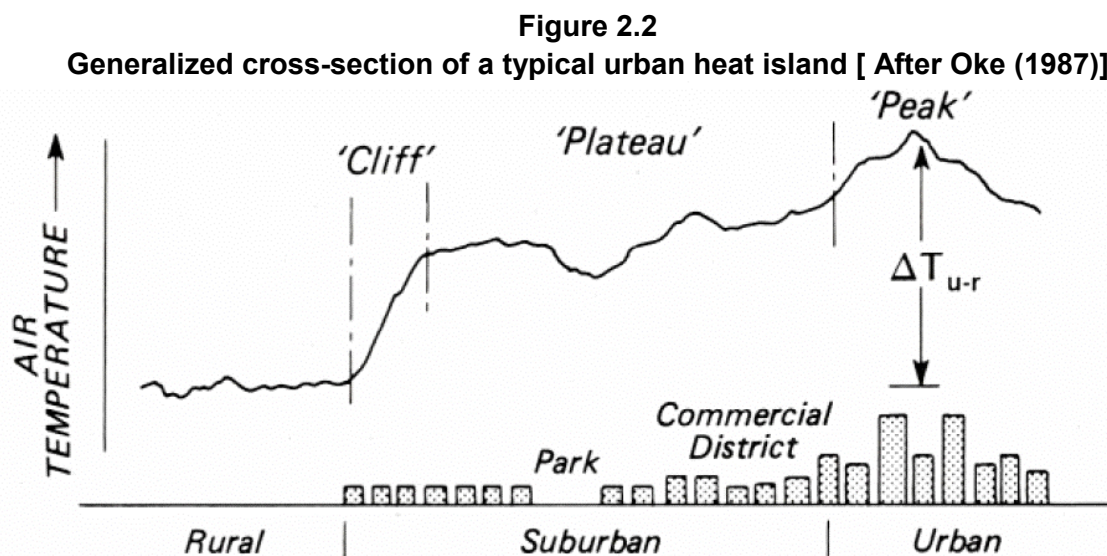
Table 2.1 – Summary of key findings from literature review related to heat transfer, energy use and green roofs (continued)

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°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°C reduction in low level air temperatures was observed. Irrigation of the green roofs produced a cooling of 2°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.



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 (CO₂) 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)]

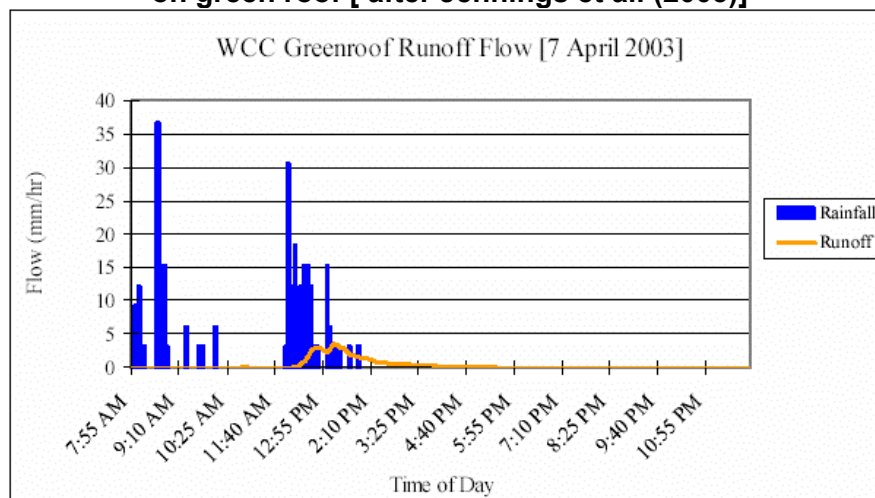
Storm Event	Rainfall (in)	Green roof Runoff (in)	Retained (in)	% Retained
7 April 2003	0.89	0.22	0.67	75
8-9 April 2003	1.02	0.57	0.45	44
9-11 April 2003	1.63	1.11	0.52	32

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/m ²)		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 (µg/L)	5	111	42.9	79.8
Zinc (µg/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 Sampling	Quality	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 Services				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 CO₂ 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 m² 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 Taylor 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 carbon 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 Northeast 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 trees 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 Urbanspace 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

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 standard 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

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.

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 from 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.