Evaluating Green and Blue Roof Opportunities in Canadian Cities

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Flat roof surfaces represent a significant proportion of urban areas and perform a variety of functions for buildings, with a corresponding variety of impacts on the urban environment and its infrastructure. One of the most important flat roof functions is the collection and discharge of rainwater, which especially during storms has a substantial impact on municipal sewer systems and the water bodies into which they discharge. The use of vegetated, or 'green', roofs has become a prevalent strategy for mitigating the impacts of stormwater runoff from flat roof surfaces in urban areas, including in Canadian cities, and has received a significant amount of research attention. There is also a variety of 'blue' roof strategies that involve detention or retention of rainwater, either on roof surfaces or in cisterns. These approaches have received considerably less research attention, particularly for large buildings.

This study compares the performance of green and blue roof systems, based on their effectiveness as stormwater management strategies, as well as their life cycle energy, carbon dioxide, and economic impacts. The more qualitative attributes of green and blue roofs are also explored, as well as their compatibility with other rooftop technologies including solar photovoltaic panels, solar thermal hot water heating systems, and high albedo membranes. In this context, the apparently under-appreciated opportunities for rainwater harvesting and reuse inside buildings are examined for a variety of large building types in three Canadian cities with different climatic conditions: Calgary, Alberta, London, Ontario, and Halifax, Nova Scotia.

From this investigation, recommended decision criteria are developed for the selection of the most appropriate green or blue roof strategies depending on the characteristics of a particular building project, including its size, occupancy, geographic location, and urban context. Limitations of this study's methods, as well as issues in need of further research, are also discussed.

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Dedication

for Charlotte Amelia Hammond

and her fellow inhabitants of the next century

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1. Introduction

1.1 Scope of Study

Flat roof surfaces represent a significant proportion of urban areas, with similarly significant impacts over the life of a building that spans many decades. One of the most important impacts for the urban environment is stormwater runoff, because conventionally designed flat roofs rapidly discharge rainwater into municipal storm sewer systems. During large storm events, this rapid discharge can exceed the capacity of the infrastructure: causing local flooding, erosion, and siltation of downstream bodies of water. The impacts are particularly significant in older sections of cities, many of which still have 'combined' storm and sanitary sewers. In these areas, excess stormwater can cause treatment plants to overflow and release raw sewage into rivers and lakes (Kloss, 2008).

The use of vegetated (or 'green') roofs has emerged as a preferred strategy for attenuating stormwater runoff in urban areas. Green roof advocates also point out other benefits of vegetated roofing, including reducing the urban heat island effect and lowering building energy consumption, as well as their aesthetic attributes compared to conventional flat roofs (Kosareo & Ries, 2007). For these reasons, many municipalities across North America have made vegetated roofs mandatory for new buildings while others are offering incentives, primarily based on anticipated savings from reduced stormwater infrastructure construction and maintenance (Clark, 2008). However, predicting the actual performance of green roofs has proven to be difficult because this depends on many highly variable factors, including local environmental conditions, the saturation of the growing media, and the health of the plants themselves.

There is a variety of other strategies for mitigation of stormwater runoff through either detention or retention of rain. These systems can be designed to release rainwater gradually into storm sewers, or to facilitate its infiltration into the ground. Alternatively, rainwater can be 'harvested' for reuse in irrigation, toilet flushing, or other uses in building systems where potable water is not necessary. These approaches to managing rainwater have come to be referred to as 'blue' roofs, a term that will be employed in this study to distinguish them from vegetated 'green' roofs. These blue roof strategies can be combined to have a number of advantages over green roofs, particularly because their performance is more predictable.

Green and blue roofs can be used in combination with a variety of other strategies to enhance the performance of buildings and minimize their environmental impacts. This study will compare green and blue roofs based on their compatibility with these other strategies, including increased roof insulation, high albedo membranes, as well as photovoltaic and solar thermal panel applications.

Canadian cities also present some unique challenges for flat roofs due to extreme environmental conditions, both seasonally and diurnally. These effects introduce important distinctions in the application of findings from international studies of the impacts of alternative flat roof systems, the majority of which are based on findings from more southerly climates.

The primary questions that this study proposes to answer are:

> ***What are the most important benefits of using green or blue roofs on large buildings in Canadian cities and how are these benefits influenced by building size, occupancy, and location?***
> ***What barriers exist to enabling wider use of green or blue roofs?***
> ***What criteria can be identified to assist with appropriate decision-making in applying these systems?***

As a result of exploring these questions, recommendations are developed for how green and blue roof systems can be most effectively implemented on a particular project, by identifying a set of key decision criteria for application in choosing among roof options. Because the focus of this study is on mitigating stormwater runoff, it will also address the importance of this factor in comparison with the other impacts of flat roofs on buildings and the urban environment.

The scope of the investigation deals with flat roof surfaces on large buildings in Canadian cities. Flat roofs have a slope of less than 1:10 vertical to horizontal and are the predominant form on larger buildings (CRCA, 2011). While sloped roofs actually make up a slightly larger proportion of the total roof area of North American buildings (NRCA, 2012), these tend to be located on houses and other smaller structures. The purpose of the focus on the Canadian context is based on access to information for a number of completed buildings across the country, as well as to limit the climate data inputs to a manageable number of representative locations.

The primary product of this study is a decision support tool that will assist building designers and approval authorities in determining whether green or blue roof systems, or a combination, are appropriate on large projects by quantifying their benefits based their long term effectiveness for managing stormwater as well as a variety of other attributes.

1.2 Flat Roofs as Multifunctional Surfaces

Flat roofs provide a variety of functions that result in a variety of impacts. As illustrated in Figure 1.1, these functions include the conventional architectural services associated with the need for roofs on buildings: protection from the sun (shading), protection from rain and snow (waterproofing), and protection from temperature fluctuation (insulation).

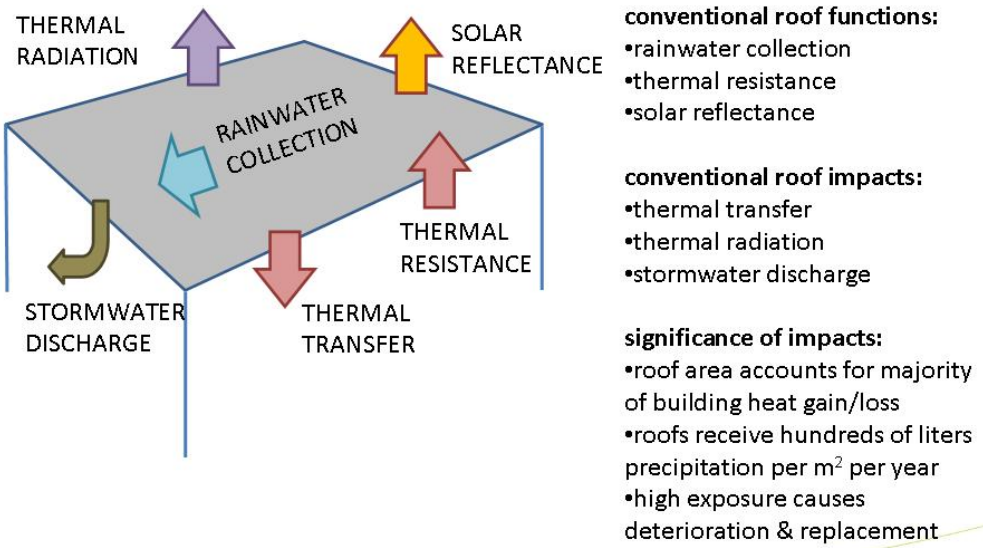


Figure 1.1 Flat Roof Functions and Impacts (the author)

Also as illustrated, these conventional functions produce corresponding impacts, including reflection of sunlight as both light and heat, transfer of thermal energy to and from the building interior, and discharge of stormwater. As Carter & Keeler (2008) have observed, flat roofs are ‘multifunctional surfaces’ that intercept and process sunlight and precipitation, and that interact with the building and its urban context in complex ways.

1.3 Challenges for Flat Roofs in the Canadian Climate

The Canadian climate is among the harshest on earth when it comes to impacts on building envelopes and on roofs in particular. With most Canadian cities clustered along the southern boundary of the country, buildings experience an enormous range of temperatures, both annually and diurnally. These temperature fluctuations can wreak havoc on roof materials, causing membranes to stretch and crack, insulation to deteriorate rapidly, and drainage systems to come apart. Ultimately this reduces the life span of a roof system, something that greatly increases its environmental impact. The replacement of a roof generates a significant amount of waste, in addition to the material and energy impacts associated with the new roof. For these reasons, flat roofs tend to be constructed to last for as long as possible, with a typical usable lifespan of 20-25 years (CRCA 2011).

When a roof fails and begins to leak, repairs are generally urgent to limit water damage to the building and its contents. Again due to Canada's climate variability, this means that repairs are often performed under less than ideal conditions, increasing the likelihood of subsequent repairs being necessary in the future. The roofing industry has responded to these challenges by developing new products that better withstand temperature fluctuations, by emphasizing proper detailing of critical elements that are prone to failure, and by introducing 'protected membrane' assemblies that cover the primary waterproofing element with other layers of materials.

1.4 Significance of Flat Roof Impacts for Buildings and Cities

According to a study based on detailed analysis of satellite imagery, Jacobsen & Ten Hoeve (2012) have shown that the average North American city is made up of:

- 52.2% vegetation
- 27.8% rooftops
- 18.5% pavements
- 1.57% bare soil

Of course, there is great variability within the urban boundary of any city, particularly between its higher density core and its suburban periphery. Nevertheless, this indicates that, somewhat surprisingly, roofs comprise 50% more surface area than roads and parking combined. The large proportion of the surface area of cities that is represented by roof surfaces means that their impacts, including thermal radiation and stormwater discharge illustrated in Figure 1.1, can be very significant for the urban environment. The extent of these impacts is evaluated in Section 2, based on criteria from contemporary green building rating systems. Conclusions are drawn in Section 8 about the most effective use of green and blue systems in mitigating the impacts of flat roofs, as well as optimizing their potential benefits.

1.5 Flat Roofs as an Untapped Urban Resource

When considering how best to utilize flat roofs on buildings, it is important to appreciate more than their conventional roles in keeping occupants shaded, dry, and comfortably separated from the outdoors. It is also important to recognize the negative impacts of conventional flat roofs, including their tendency to heat up buildings and their urban contexts in warm weather, as well as their rapid production of runoff following storms.

Beyond these conventional functions, flat roofs can deliver many other positive services. These include the conversion of energy from sunlight, either into electricity using photovoltaic materials or into hot water by using solar thermal collectors, and the collection of rainwater for use in irrigation or within the building to offset potable water consumption.

Conventional flat roofs tend to be overlooked once a building is completed. Even as part of the design of buildings, the only use that is normally made of flat roof surfaces is as a convenient location for packaged mechanical equipment. With the rise of sustainable building design over that last twenty years promoted by organizations like the United States Green Building Council (USGBC) and its counterpart in Canada (CaGBC), greater attention has been paid to the role of roofs and their potential to both mitigate environmentally harmful effects and optimize desirable ones. The tremendous growth of the vegetated roof industry over this period is perhaps the most visible testament to this increasing awareness.

Given the large proportion of flat roof surfaces for most urban areas, they represent an enormous potential resource that has gone largely untapped, particularly for water conservation. Providing a tool that identifies relevant criteria for implementing alternative roof system according to the characteristics of a particular project would enable designers to make more effective decisions based on authoritative sources. This would also enable approval authorities to identify the most effective opportunities for stormwater mitigation and drinking water conservation in their cities.

1.6 Methods and Reference Standards Used

This study began with a review of the literature on the subjects of green roofs, blue roofs, cool roofs, rainwater harvesting, low impact development, and life cycle assessment (LCA). For industry references, the National Roofing Contractors Association's 'SmartBrief' service was utilized. Search results were generally limited to after 2000 and were reviewed for their relevance based on their abstracts. The most relevant were reviewed in detail and form the collection of references cited.

Initially, an emphasis was placed on the life cycle energy and carbon dioxide impacts of flat roofs, comparing a variety of conventional and green assemblies using energy modeling and LCA software. Early results indicated that the energy savings and reduced carbon dioxide emissions attributed to flat roofs are determined largely by the type and thickness of insulation, and are less dependent on whether green or blue systems are employed. As well, while energy and carbon dioxide impacts are well characterized in the literature, water impacts are less so, particularly with respect to performance metrics. This realization has led to a focus on the primary function of flat roofs in collecting rain, and how the use of green or blue roof systems affects the resulting impacts of runoff from roofs on the urban environment.

The following discussion outlines the general methods and references used in this study. As well, each section beings with an introduction to the subject with an explanation of the methods applied in exploring this.

1.6.1 Example Building Types

To provide a broad assessment of roof impacts in different situations, 15 building types were analyzed under five occupancy classifications representing common examples, as summarized in Table 1.1. Data on the average sizes and occupancy rates for each type have been taken from the US Department of Energy's Energy Star Portfolio Manager Data Trends benchmarking databases.

Table 1.1 Representative Building Types

Categories	Assembly	Education	Institutional	Residential	Commercial
Building Types	Community Centre	Elementary School	Hospital	Apartment	Office
	Library	Secondary School	Long Term Care	Student Residence	Retail
	Theatre	College/ University	Retirement Home	Hotel	Warehouse

1.6.2 Construction and Performance Standards

Typical construction details for green roofs were taken from technical standards developed by Green Roofs for Healthy Cities for the City of Toronto (Toronto, 2012). Details for typical large scale rainwater harvesting systems were taken from course materials developed by HeatSpring for Net Zero Water for Buildings and Sites (Bruce, 2010), completed by the author in 2015. Current best practices for other low impact development measures were taken from standards assembled by the Toronto Regional Conservation Authority (TRCA, 2010).

Criteria for the performance of green and blue roofs were drawn primarily from LEED Canada NC-2009 green building rating system, as were the parameters for plumbing fixture utilization inside buildings to determine water demand for each building type.

1.6.3 Precipitation Data

Because of the author's involvement in a separate study of green roofs lead by Dr. Denis O'Carroll at Western University, hourly precipitation data were made available for Calgary, AB, London, ON, and Halifax, NS. For this reason, this study uses these locations to evaluate opportunities for rainwater harvesting across the range of representative building types in each of these cities. Hourly data are compared to Environment and Climate Change Canada's annual and monthly precipitation normals for these locations (EnviroCan, 2016) to highlight the importance of individual storm events.

The three locations provide a diverse range of climate conditions, considered to be reasonably representative of the range of climate zones across southern Canada and the northern United States. The applicability of the results for other similar locations is discussed in Section 7.

London ON represents a humid continental zone typical of Eastern North America, having moderate winters with significant snowfall and warm summers. Calgary AB represents a climate zone typical of northwestern North America, having cold winters with limited snowfall as well as cool dry summers. Halifax NS represents a northeastern coastal climate zone with moderate winter and summer temperatures as well as significant precipitation throughout the year.

1.6.4 Generation of Results

Data on rainfall, building size, occupancy, and demand for water were input into a series of Excel spreadsheets to generate results upon which the findings of this study are based. These results are illustrated graphically to compare the differences between building types, as well as the implications of varying height or combining multiple occupancies.

From these detailed results, a set of criteria is identified for the selection of the most appropriate measures, or combination of measures, according to the characteristics of a particular project.

1.7 Organization of the Study

This study begins in Section 2 with an identification of the key criteria that influence the design of flat roofs based on optimizing their environmental performance. These criteria, including energy consumption, carbon dioxide emissions, and water conservation, are taken from the prevailing green building design standards in North America. The importance of capital and operating costs are also considered, as well as other subjective factors influencing decisions about green building design.

Section 3 reviews green roof systems in light of their growing use and the large volume of research attention that they have attracted. Their associated energy and carbon dioxide impacts are discussed based on authoritative sources, as well as their role in water conservation, and their other attributes.

Section 4 reviews blue roof systems, which have received considerably less research attention, particularly for large buildings. The components of a typical rainwater harvesting system for large buildings are reviewed, based on industry references. Capital cost data are taken from seven projects with large rainwater harvesting systems with which the author has been involved.

Section 5 discusses issues of compatibility for green and blue roof systems with other opportunities to enhance the performance of flat roofs, including increased insulation, high albedo membranes, photovoltaic and solar thermal panels, as well as making roofs accessible to building occupants by creating terraces. Issues with combining both green and blue roofs are also identified.

Section 6 presents the evaluation of opportunities for rainwater harvesting in large buildings, based on comparing 15 different building types in three different locations: Calgary, AB, London, ON, and Halifax, NS. Results are presented graphically to illustrate the relative performance of the various buildings in each location based on their ability to retain stormwater and to offset potable water use.

Section 7 discusses the limitations of the study's methods, including the use of aggregated rainfall data and the use of average building occupancy rates. The general applicability of the results based on the building types and locations is also discussed. Effects of climate variability and accuracy of economic data are identified as significant issues.

Conclusions are drawn in Section 8, identifying key criteria for deciding whether to employ green or blue roof systems as opposed to other low impact measures, based on the findings of this study.

An Appendix provides detailed information on the sources of data used to determine parameters (occupancy, water demand, and rainfall collected according to building size, type and location) that have been used to generate the results presented in Section 6.

2. Key Criteria from Green Building Design Standards

2.1 Green Building Standards and their Application in this Study

The field of green building design has evolved from its origins in the early 1990s as a general notion derived from the principles of sustainable development, to become a significant part of the North American construction industry. Because the actual number of projects that have been formally ‘certified’ under the various rating systems still represents a very small proportion of annual construction activity, the real influence of these systems has sometimes been questioned. However, considering that every major building product manufacturer now offers ‘green’ material options, and few design or construction firms are without some form of green building credentials, it is apparent that there has been a huge influence on the market over the past two decades. Likewise, the emergence of numerous green building design standards and rating systems is evidence of increasing interest in the construction sector, both in North America and internationally. There have also been numerous studies of green building trends over this period, including comprehensive reviews that evaluate the effectiveness of various standards and rating systems such as those by New et al. (2016) and Rahman & Sadeghpour (2010).

Much of the credit for initiating and supporting this interest in sustainable building design is due to the USGBC and its Leadership in Energy and Environmental Design (LEED) rating systems. Organized in 1993, the USGBC introduced the first version of its LEED for New Construction rating system in 1998 (IEE, 2012). From this starting point, both the organization and its collection of resources have grown substantially, offering specialized rating systems for a variety of building types such as schools and hospitals, for existing buildings and interiors, as well as for neighbourhood development (IEE, 2012). The creation of these rating systems uses a consensus-based approach with draft versions open to review, comment, and voting by all members of the organization. The LEED rating systems have critics, however, particularly with respect to the equivalency of ‘credits’ across vastly different categories of building impacts (Rahman & Sadeghpour, 2010). Other criticisms centre on the increasingly onerous submission requirements, which involve what amounts to auditing services by specialist consultants who can add a substantial premium to the project cost in beyond the premiums for the green building measures they are documenting (Todd et al., 2013).

Several alternative rating systems have emerged in response to the limitations of the LEED series, most notably the Green Globes system provided by the Green Buildings Institute (GBI, 2016). In contrast to the LEED system, this relies on a web-based interface, which is adapted to the process of building design, by moving from more general principles to more detailed requirements as the design takes shape. The first stage of certification is based on a review of the construction documents, followed by an on-site visit at the completion of the project, with final certification completed after submission of a full year of utility consumption data. These features offer a number of advantages over the LEED system while avoiding the need for specialized consulting services and therefore reducing the cost of certification. These advantages have led to a growing adoption of the Green Globes system, particularly in the US (GSA, 2016). Critics point out that the Green Globes system is prone to abuse because the construction documents submitted for certification can be altered during the actual construction of the building, in ways that may be difficult to ascertain during a single on-site inspection after work is completed. Only those changes that affect energy performance would be apparent in the utility consumption data submitted for final certification.

A new, more comprehensive rating system has emerged, called the Living Building Challenge. Developed by the International Living Future Institute, it sets ambitious criteria for green buildings under seven 'petal' categories: place, water, energy, health & happiness, materials, equity, and beauty (ILFI, 2014). Its criteria include 'net positive' energy and water impacts, requiring buildings to offset more energy and water production than they consume. While this may become an influential approach, it has not yet had a significant impact on current practice, with less than 200 certified projects internationally, predominantly in the US.

Notwithstanding their differences, the LEED and Green Globes systems are remarkably similar in their overall organization. As illustrated in Tables 2.1 and 2.2, they both categorize the impacts of buildings under similar headings. Likewise, the overall proportion of credits is similarly distributed among these categories. Furthermore, both systems use the same reference standards produced by independent organizations such as ASHRAE and the EPA as the basis for calculating compliance with particular credits. This study will rely on the emphasis placed by these rating systems for the purpose of identifying the key impacts associated with flat roofs.

Table 2.1 LEED and Green Globes Credit Allocation (CaGBC, 2009; ECD, 2004)

<table>
<tr><th colspan="3">LEED Canada NC (2009)</th><th colspan="3">Green Globes Canada (2004)</th></tr>
<tr><th rowspan="2">CATEGORY</th><th colspan="2">POINTS AVAILABLE</th><th rowspan="2">CATEGORY</th><th colspan="2">POINTS AVAILABLE</th></tr>
<tr><th>NUMBER</th><th>PERCENT</th><th>NUMBER</th><th>PERCENT</th></tr>
<tr><td>Sites</td><td>26</td><td>23.6%</td><td>Sites</td><td>115</td><td>11.5%</td></tr>
<tr><td>Water</td><td>10</td><td>9.1%</td><td>Water</td><td>85</td><td>8.5%</td></tr>
<tr><td rowspan="2">Energy and Atmosphere</td><td rowspan="2">35</td><td rowspan="2">31.8%</td><td>Energy</td><td>380</td><td>38%</td></tr>
<tr><td>Emissions</td><td>70</td><td>7%</td></tr>
<tr><td>Resources</td><td>14</td><td>12.7%</td><td>Resources</td><td>100</td><td>10%</td></tr>
<tr><td>Indoor EQ</td><td>15</td><td>13.7%</td><td>Indoor EQ</td><td>200</td><td>20%</td></tr>
<tr><td>Innovation</td><td>6</td><td>5.5%</td><td rowspan="2">Design Process</td><td rowspan="2">50</td><td rowspan="2">5%</td></tr>
<tr><td>Local Priority</td><td>4</td><td>3.6%</td></tr>
<tr><td>TOTALS</td><td>110</td><td>100%</td><td>TOTALS</td><td>1000</td><td>100%</td></tr>
</table>

Table 2.2 LEED and Green Globes Certification Levels (CaGBC, 2009; ECD, 2004)

<table>
<tr><th colspan="3">LEED Canada NC (2009)
Certification Levels</th><th colspan="3">Green Globes Canada (2004)
Certification Levels</th></tr>
<tr><th rowspan="2">LEVEL</th><th colspan="2">THRESHOLD</th><th rowspan="2">LEVEL</th><th colspan="2">THRESHOLD</th></tr>
<tr><th>POINTS</th><th>PERCENT</th><th>POINTS</th><th>PERCENT</th></tr>
<tr><td rowspan="2">BASIC</td><td rowspan="2">40</td><td rowspan="2">36%</td><td>1 GLOBE</td><td>150</td><td>15%</td></tr>
<tr><td>2 GLOBES</td><td>350</td><td>35%</td></tr>
<tr><td>SILVER</td><td>50</td><td>45%</td><td>3 GLOBES</td><td>550</td><td>55%</td></tr>
<tr><td>GOLD</td><td>60</td><td>55%</td><td>4 GLOBES</td><td>700</td><td>70%</td></tr>
<tr><td>PLATINUM</td><td>80+</td><td>73%</td><td>5 GLOBES</td><td>850+</td><td>85%</td></tr>
</table>

2.2 Energy Consumption

The largest proportion of credits in both the LEED and Green Globes rating systems pertain to energy performance. In the case of LEED, the most current versions for new construction in both the US and Canada have increased the emphasis on reducing building energy consumption. This is likely due in part to criticisms of earlier versions' tendency to equate relatively easy-to-achieve credits under other categories with the normally more difficult and expensive credits associated with improving the energy performance of buildings. At the same time, the efficiency levels for achieving energy credits were also increased, based on exceeding baseline performance requirements of either the National Energy Code for Buildings or ASHRAE 90.1 Energy Standard for Buildings.

An important aspect of the energy performance ratings is that they are based on a theoretical model that compares the predicted energy consumption of a proposed design to a similar 'reference' building meeting the mandatory requirements of the applicable standard (in Canada, either NECB-2010 or ASHRAE 90.1-2007). Critics have pointed out that this rewards computer modeling as opposed to actual building performance. In fact, there have been a number of high profile examples of LEED certified buildings not performing up to their predicted energy modeling results, including a number of new 'green' schools built by the Toronto District School Board, which actually performed worse than ordinary schools built at the same time (OAA, 2006).

In response to these criticisms, the green building rating agencies have tightened their requirements for energy modeling. A document released by the Canada Green Building Council sets out their expectations for building energy models used in support of submissions for certification (CaGBC, 2013). While this permits a variety of software platforms to be employed including EE-4, eQuest, and DOE-2, the model itself must be prepared by a consultant independent of the project design team.

In 1999, the US Environmental Protection Agency extended its Energy Star rating system for consumer products to apply to whole buildings, based on their 'source' energy consumption (EPA, 2013). The system uses a straightforward online assessment tool to establish a rating for both new and existing buildings on a scale of 1-100 relative to average performance based on similar size, type, and age from the quadrennial Commercial Buildings Energy Consumption Survey. This system is based on inputting actual utility consumption data over 12 consecutive months of operation, and hence eliminates the issues associated with predictive modeling. A score of 75 and above entitles a building to receive an Energy Star label. With over 200,000 buildings rated in this system, the EPA claims to have influenced the US construction market, although it is difficult to differentiate its impact from that of the LEED or Green Globes standards. The Energy Star website includes a link to the ORNL 'Roof Savings Calculator' tool, which allows users to input basic data comparing two roof options and estimates annual energy cost savings (ORNL, 2015).

Clearly, energy consumption is an important criterion, which influences a wide range of decisions affecting green building design. To the extent that roof surfaces represent a large proportion of the building envelope for all but very tall structures, the performance of the roof assembly in limiting energy transfer and managing solar gains is critical to improving overall energy performance.

Of course, buildings are also able to generate energy, not merely consume it, with roofs being a primary location for photovoltaic electricity production or solar thermal water heating systems. Both LEED and Green Globes building rating systems include credits associated with on-site energy generation, based on the installed capacity and rated output of proposed systems

Finally, an aspect of energy consumption (or production) that tends to make it a focal issue is its ease of measurement and valuation. Virtually every building includes utility meters for each type of energy source, whether electrical or from fuels. This makes the consumption of energy by buildings convenient to track on monthly or annual time scales according to utility invoices. Likewise, the cost per unit of energy by source is also easily determined by published rates for any local jurisdiction. Although prone to fluctuation, the general trend of increasing cost across all sources introduces a strong incentive for energy savings and a means of evaluating alternative measures based on their present value.

2.3 Carbon Dioxide Emissions

Although neither the LEED nor Green Globes rating system has a specific category for reducing carbon dioxide emissions, this is implicit in many of the individual credits. Those associated with energy savings are directly correlated with CO_2 emission reductions, based on the local 'grid mix' of electrical energy and the type of fuel used for building space or hot water heating. Likewise, material credits that emphasize local, reused, or recycled content do so partly because of the reduced energy consumption and therefore lower CO_2 emissions associated with transportation or processing raw resources.

The general importance of reducing anthropogenic CO_2 emissions has become widely accepted since its association with climate change was first documented by the Intergovernmental Panel on Climate Change (IPCC 1990). While various jurisdictions have moved to adopt economic incentives in the form of 'carbon tax' or 'cap and trade' policies, these have been slow to achieve international acceptance, particularly in North America. Consequently the question of the 'value' of a tonne of CO_2 is debatable, and highly dependent on the local regime in which a particular project is developed. As well, none of the existing tax or trade schemes accounts for the full social costs of these emissions. Nevertheless, to the extent that public awareness of climate change is growing, studies of commercial buildings have pointed to some value associated with the differentiation between 'green' and 'standard' buildings leading to higher occupancy and leasing rates (Fuerst & McAllister, 2011).

2.4 Water Conservation

A primary function of buildings is to provide safe, potable water supply to their users, normally through a municipally operated distribution system. As cities grow, their demand for drinking-quality water also increases while their ability to access increased supplies can be limited. In many jurisdictions across North America, access to water resources is becoming a critical impediment to urban growth (Sedlack, 2014). Therefore, there has been a significant increase in regulations associated with water conservation, particularly those associated with plumbing fixtures. In 2006, the EPA introduced its WaterSense rating system to promote improved performance of fixtures and appliances (EPA, 2015).

Most of the water entering a building needs to be discharged to a sanitary sewer system, again usually operated by a local municipality. Like the demand for drinking water, the volume of sanitary sewage increases with urban population growth, while the capacity of a municipal system to manage greater volumes safely is limited, especially in light of increasing regulatory control over discharges into surface waters. There is also an energy cost associated with collecting, treating, and pumping water in municipal systems, estimated by the US Department of Energy as consuming an average of 1 kWh of energy per cubic metre of water delivered (DOE, 2014),

Finally, most buildings have a separate system in addition to water supply and sanitary sewage disposal, for the collection and discharge of rainwater. Because buildings represent a large impervious surface area, they tend to create a significant increase in flows to municipal storm sewers, especially during (and after) storms. This has led to the introduction of 'stormwater management' regulations where the capacity of the infrastructure is limited. These regulations require the initial outflow from a building and its site to be controlled through temporary storage (normally using surface ponding) followed by gradual release and/or infiltration into the ground where soil conditions permit.

In dealing with water, both the LEED and Green Globes standards place all three aspects of drinking water, sanitary wastewater, and stormwater under a single category of water conservation. Clearly, roofs have the most significant impact on stormwater impacts, and the rating systems have separate credits for reducing rainwater discharge from roof surfaces. Roofs can also play a role in reducing potable water use by offsetting its consumption with collected rainwater. This is typically used either for irrigation or for toilet flushing. Both green building rating systems recognize this opportunity by making specific credits available for rainwater collection and reuse.

Unlike energy consumption, not all aspects of water use in buildings can be easily measured and translated into an economic value. Traditionally, only municipally delivered drinking water has been metered, enabling building owners or tenants to be billed based on consumption. There has been a recent trend by municipalities to introduce separate charges for sanitary sewer use, based on an assumption that its volume is equal to the metered volume of drinking water delivered in the same period. Because of the difficulty of metering stormwater, municipalities do not have a direct means of billing for use of their stormwater systems based on volume. Some do, however, have fees based on the calculated volume that a building and its site generate according the amount of impervious area and any stormwater management measures employed.

2.5 Capital and Operating Costs

The question of the economic value of green buildings has been debated from the earliest introduction of green rating systems. Advocates of green buildings have claimed that their benefits outweigh any incremental costs, presuming the environmental and human health improvements are accounted for in addition to any direct cost savings from reduced energy consumption (Rahman & Sadeghpour, 2010). As discussed above, evaluating energy savings is relatively straightforward thanks to energy consumption meters and associated rates, as is establishing associated CO_2 reductions based on its intensity in fuels and the local electrical grid, although pricing the gains from GHG mitigation remains challenging. The value of reducing potable water use can be determined using metered consumption, but the reduction of rainwater discharge is more difficult to evaluate because this is impractical to measure directly.

Going beyond the biophysical parameters of energy, CO_2, and water, some studies have attributed a very significant economic value to the human health benefits of green buildings. In the case of schools, a study by Katz (2006) reviewed the incremental cost associated with LEED certified facilities and compares this to their benefits under a number of categories. As summarized in Table 2.3, the results show a total benefit of $74/ft^2 of school area. By comparison, the study indicates an average cost of the green building measures required to achieve these benefits of only $3/ft^2. Over a 20-year lifespan, this produces a 17% annual rate of return on the incremental capital cost investment. However, because most of this benefit is associated with human health and productivity improvements, the future economic returns are not easily measured or attributable to specific building improvements.

Table 2.3 Financial Benefits of Green Schools ($/ft²) (from Katz, 2006)

Benefit	Environmental	Human Health	Productivity
Energy Savings	$9		
Reduced Emissions	$1		
Asthma Reduction		$3	
Cold and Flu Reduction		$5	
Teacher Retention			$4
Employment Impact			$2
Increased Future Earnings			$49
TOTALS	**$10**	**$8**	**$55**

In response to this study and others claiming significant financial benefits associated with 'greening' school buildings, the National Academies of Science commissioned a review of the literature on this subject by an expert panel drawn from across major academic and professional institutions in the US. In the final report, the panelists acknowledge a lack of adequately designed studies that sufficiently isolate the complex variables associated with human health and economics, and conclude that 'the effects of the built environment will necessarily appear to be small, given the number of variables.' (NRC, 2007). The authors continue, however, by observing that even though the economic value of health and economic benefits is difficult to quantify, there is good evidence that these health and economic benefits do exist:

> *However, the committee believes that empirical measures do not necessarily capture all relevant considerations that should be applied when evaluating research results. Qualitative aspects of the environment are also important. Thus, in the committee's collective judgment, there is value in attempting to identify design features and building processes and practices for green schools that may lead to improvements in learning, health, and productivity for students, teachers, and support staff, even if the empirical results are less than robust.* (NRC, 2007 p.38)

Because of the difficultly in applying a cost to qualitative factors like human health, most studies of the economic value of green buildings have focused on the more readily identified benefits arising from reduced energy consumption, calculating either the simple payback period or the net present value of investing in energy savings measures. A study of 221 buildings across the US by Davis Langdon (2007) provides a comparison of the cost of green buildings to those without such measures. This demonstrates that although there is a premium associated with LEED certified buildings, this is small in comparison to the range in total cost per square foot for buildings of a similar type. Figure 2.1 illustrates the results for academic buildings.

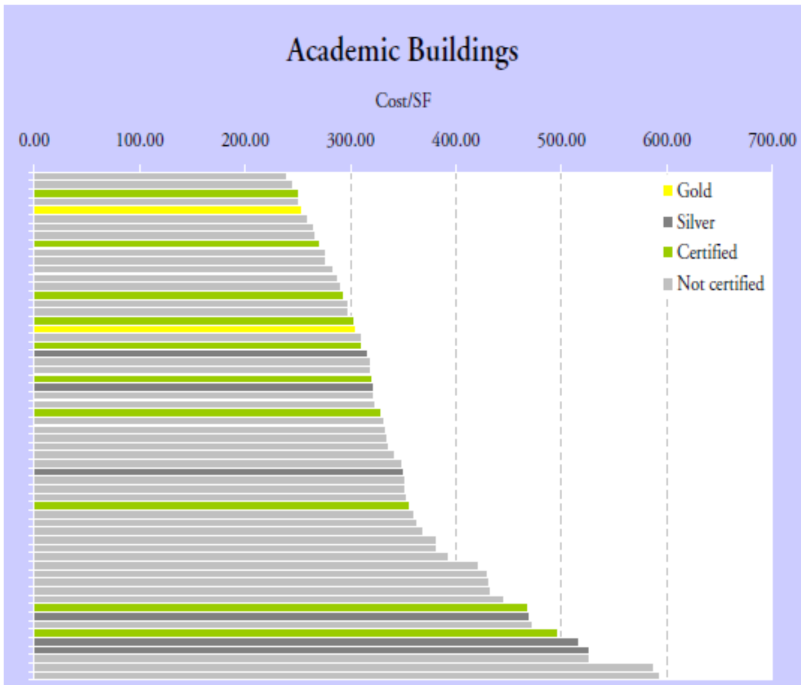


Figure 2.1 Cost of Academic Buildings ($/ft²) (Davis Langdon, 2007)

2.6 Other Factors

As evidenced by the green building rating systems discussed above, there are many other factors and associated measures that affect the environmental performance of buildings, such as minimizing waste, limiting resource depletion, and improving thermal comfort. Also as indicated by these rating systems, the weighting of these other factors is significantly less, indicating that they are considered to have a lower relative importance compared with the more significant criteria, particularly those pertaining to energy consumption. There are, however, two other factors not part of any rating system but that have great importance in the decision to embark on a green building project in the first place: ethics and aesthetics.

Proponents of green buildings have been effective in presenting their approach as the 'right' thing to do from an ethical point of view. They have conveyed a notion that by committing to a green building, an individual or organization is demonstrating an awareness of anthropogenic climate change and taking meaningful action to help with its mitigation. The value placed on certification under the various rating systems reinforces the importance of this ethical motivation, because a tangible independent endorsement 'label' supports owners' claims about the environmental benefits of their green buildings. The language of the rating systems includes terms such as 'leadership', 'initiative', and 'innovation' that reinforce the sense of being progressive and setting an example for society at large. The rating systems also attempt to define what 'green building' actually means, implying that projects not certified according to their procedures cannot claim the associated environmental performance benefits. The following excerpt from the CaGBC's introduction to each of its LEED rating systems explains the organization's view of the extensive scope and authoritative content of its materials:

> *The LEED Green Building Rating Systems are voluntary, consensus-based, and market-driven. Based on existing and proven technology, they evaluate environmental performance from a whole building perspective over a building's life cycle, providing a definitive standard for what constitutes a green building in design, construction, and operation. (CaGBC, 2009 p.xiv)*

Aesthetic considerations are an inherent part of building design, and much has been written about the 'art of architecture'. One of the earliest commentaries on the issue came from Vitruvius, the architect of Imperial Rome for Caesar Augustus, who defined architecture as 'firmness, commodity, and delight' (Vitruvius, ca.100). Of these three aspects of buildings, their aesthetic qualities – delight – tend to be the most noticeable. Certainly, those buildings with the most striking visual design tend to be the ones published in professional journals and featured in the media. Contemporary construction material technology has enabled designers to create ever more sculptural building forms that break the normal rules of conventional construction practice, and apparently even the laws of physics. The emergence of the green building movement has also influenced the aesthetics of buildings. Many green buildings make very obvious gestures to convey their environmental features. Because vegetated roofs are among the most visible of all green building measures they have come to symbolize the project's 'greenness'. For many designers of green buildings, not having a vegetated roof on a project is akin to not having icing on a cake. A further motivation for creating vegetated roof surfaces is that these are a quintessential feature of many influential early modernist buildings, particularly projects by Le Corbusier (Figure 2.2), who advocated the idea of roof gardens as one of the five elements of his 'New Architecture' (Le Corbusier, 1927).

Figure 2.2 Roof Terraces, Le Corbusier's Villa Savoye, Poissy, France (the author)

The influence of ethical and aesthetic motivations in the design of green buildings is undeniable, and something that this study embraces as part of the complex set of issues associated with this subject. As important as these issues may be, the difficulty of objectively evaluating them means that the focus of this study will be on those issues that are more readily accessible to measurement and evaluation of their associated value. The resulting decision tool attempts to enable both objective and subjective criteria to be considered, assisting the proponents of a particular project with determining the relative importance of these factors in their case.

2.7 Summary

While there are a variety of green building standards, each with its own intricacies, the prevailing LEED and Green Globes rating systems, as well as the emerging Living Building Challenge, share a similar overall categorization of measures.

Measures associated with energy conservation are associated with the highest proportion of credits under each system. To the extent that energy savings reduce fossil fuel consumption, these result in reduced atmospheric emissions, including carbon dioxide. Other measures associated with material and resource conservation also contribute to reducing a building's 'carbon footprint' as an important overall outcome of green building design.

Each rating system also identifies water conservation as an important objective, albeit secondary to energy savings and carbon dioxide reductions. Separate credits are associated with reducing irrigation, using less potable water indoors, as well as minimizing storm and sanitary outflows.

Because of the multi-functional role of flat roofs, they have a significant influence on a building's energy consumption, carbon dioxide emissions, and water conservation. Other building systems, such as mechanical equipment or exterior fenestration, may have large impacts on individual factors, but none has the comprehensive impact on numerous factors that the roof assembly does.

Although green building measures are becoming more commonplace and there is increasing availability of materials and systems that comply with the rating systems, there is nevertheless a cost premium associated with their implementation, especially for large buildings. This introduces an inevitable discussion of trade-offs depending on the goals and financial resources of a particular project. While measures associated with saving energy have offsetting cost savings, and new carbon tax or trade systems may incentivize associated mitigation measures, the relatively low cost of municipal services makes water conservation measures difficult to justify on strictly economic grounds.

3. Green Roof Systems

3.1 What is a Green Roof?

A green roof is a collection of materials overlaid on the upper surface of a building structure, supporting the growth of plants. Historical precedents for green roofs include traditional buildings using live sod as a covering, as well as ancient stepped 'ziggurat' structures with planted horizontal surfaces and classical villas with 'hanging gardens' built over a lower level of interior spaces. The advent of green roofs in contemporary buildings has generated a large volume of research attention, ranging from broad life cycle analyses to detailed assessments of specific attributes such as energy conservation or water savings.

This section relies on recent literature and systematic reviews to identify the most important criteria that influence the performance of green roofs. Technical information on best construction practices is drawn from industry standards, in order to establish representative characteristics that will be used as a basis of comparison with blue roof systems and other measures evaluated in this study.

3.2 Green Roof Types

Having originated in Europe with the development of the *Forschungsgesesellschaft Landschaftsentwicklung Landschaftsbau* (FLL) standard in Germany in 1975, commercial green roof systems based on the 2002 version of the FLL standard have become widely available in North America (GRT, 2016). The FLL standard categorizes green roofs as either 'intensive' or 'extensive', with intensive green roofs providing a soil depth greater that 150mm to support the growth of more substantial plants. Conversely, extensive green roof systems provide a soil depth of 150mm or less, which limits the type of plant material that they can support: typically sedums, mosses, or grasses (Berndtsson, 2010). Because extensive roofs involve less material, they are less costly than intensive systems and also impose lower structural loads. For these reasons, as illustrated in Figure 3.1, most installed green roof systems in North America are of the extensive type.

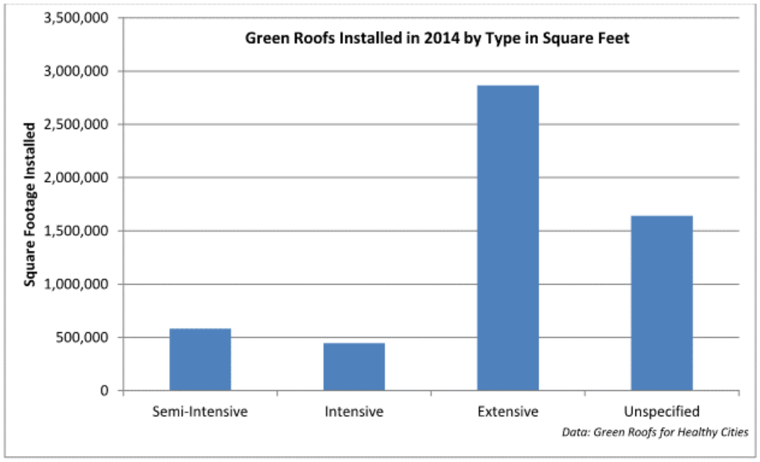


Figure 3.1 Green Roof Installation, 2014 (GRHC, 2015)

The typical configuration for an extensive green roof used as the basis of this study is illustrated in Figure 3.2. This is installed on top of a flat roof assembly, and consists of a root barrier to protect the roof membrane, a drainage layer, filter fabric, growing media, and plants. Insulation can be located below the roof membrane as part of a 'conventional' flat roof assembly, or on top of the roof membrane as part of an 'inverted' flat roof assembly. In either configuration, the insulation is considered part of the roof assembly, not the green roof system.

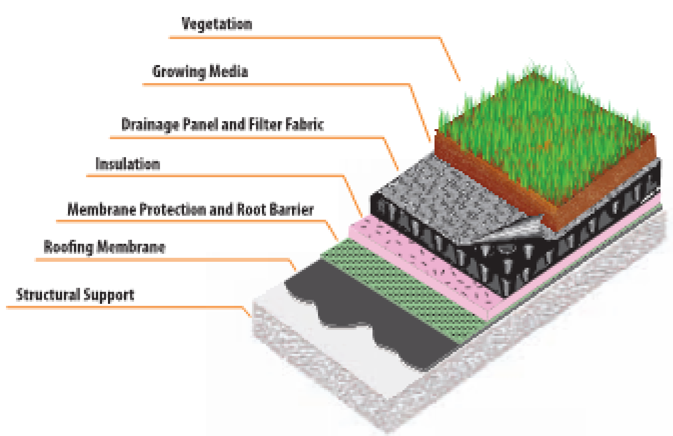


Figure 3.2 Typical Green Roof Configuration (Toronto, 2012)

3.3 Energy and Carbon Dioxide Impacts

As discussed in Section 2, energy savings and carbon dioxide reductions are important drivers of decision-making in green building design. Advocates of green roofs claim that they can significantly reduce building energy consumption, and therefore reduce carbon dioxide emissions depending on the energy source. However, typical studies including those by Kosario & Ries (2007), Saiz et al. (2006), and Sproul et al. (2012) compare the performance of green roofs with that of conventional flat roofs with dark membranes and minimal insulation, as opposed to roofs with increased insulation and reflective membranes. Energy savings are attributed primarily to the thermal resistance and high albedo properties of green roofs. Some of these authors cite more subtle effects from evapotranspiration of plants or micro-shade from their tiny members, which are the subject of further research.

Lstiburek (2011) eloquently explains that the energy savings benefit of green roofs is not significant when compared with simply increasing roof insulation beyond the minimum levels required by local building codes. Similarly, Hosseini & Akbari (2016) demonstrate the effectiveness of light coloured roof membranes in reducing building energy consumption, even in locations as far north as Edmonton, AB or Anchorage, AK. Touchaej et al. (2016) demonstrated similar benefits for buildings in Montreal, PQ.

Because the focus of this study is on water, the impacts of green roofs on a building's energy use are not a primary consideration. While green roofs produce energy savings, these savings can be realized more effectively through the use of increased insulation thickness and widely available reflective roof membranes. Hence, energy efficiency gains are not dependent on green roofs. Note that these building-level energy impacts are distinct from the urban-level impacts, as well as the many other positive attributes of green roofs discussed below.

3.4 Water Conservation

The primary benefit of green roofs is the retention of stormwater, reducing impacts on downstream bodies of water. Mentens et al. (2006) prepared a summary of 18 studies evaluating the performance of installed extensive green roof systems in Germany, and found that their retention of annual rainfall varied between 27% and 81%. The authors explain that the wide variation in retention rates is due to a number of variables including depth of media, plant type and condition, as well as the timing and duration of each study. Note that green roofs are considered to retain rainwater by permanently diverting it from entering the municipal storm system, up to a point of saturation of the growing media. Even if the media is saturated, green roofs still serve to detain excess water by slowing its rate of flow into the storm system.

A study by O'Carroll (2016) used consistent media depth and plant types to enable a more direct comparison of green roof performance to be made between three different locations in Canada: London, ON, Calgary, AB, and Halifax, NS. The results of the study are summarized in Table 3.1, showing that the performance of green roofs in retaining rainwater is significant, and varies according to the intensity of rainfall events and the local climate conditions.

Table 3.1 Summary of Rainfall Events 2013-2014 (O'Carroll, 2016)

London, ON		
Event Size	Events	Retention (%)
Small (<3mm)	51	93.8
Medium (3-15mm)	81	77.2
Large (>15mm)	28	42.8
All Events	**160**	**76.5**
Calgary, AB		
Small (<3mm)	38	94.5
Medium (3-15mm)	39	91.7
Large (>15mm)	9	58.5
All Events	**86**	**89.6**
Halifax, NS		
Small (<3mm)	32	89.6
Medium (3-15mm)	36	52.2
Large (>15mm)	30	36.4
All Events	**98**	**59.6**

Bruce (2010) explains that that the ability of a green roof to retain water depends on two primary factors: the saturation of the growing medium and the health of the plants. A drier growing medium has more capacity to absorb rainfall, and healthier plants increase the rate of transpiration. As illustrated in Figure 3.3, there is a moisture range within which a green roof is effective. Once the medium is saturated, any further precipitation is discharged as runoff. As the medium dries, it reaches a threshold below which the plants are unable to extract water and ultimately begin to wilt with further drying.

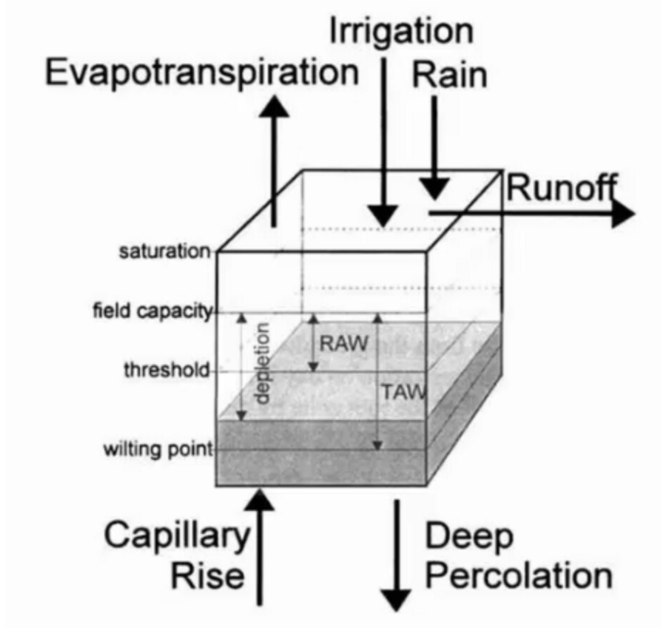


Figure 3.3 Green Roof Moisture Properties (Bruce, 2010)
(RAW=root available water, TAW=total available water)

3.5 Capital, Operating, and Replacement Costs

With the increasing prevalence of green roofs in North America over the past two decades, a large number of commercial green roof providers have emerged. As well, an industry association called Green Roofs for Health Cities (GRHC), founded by Stephen Peck and colleagues in 2004, has become the leading source for advocacy, research, and training of practitioners through their Green Roof Professional certification program (GRHC, 2016). This organization recently surveyed the industry to establish criteria for capital, operating, and replacement costs of green roofs in Toronto, ON. Table 3.2 summarizes their findings and provides a valuable reference for economic impacts based on practical experience.

Table 3.2 Life Cycle Costs of Green Roofs (Peck & Lilauwala, 2016)

Variable	Value		
	Conventional Roofs	Cool Roofs	Green Roofs
Study Period	50 Years		
Installation Cost Premium (over Conventional)	N/A	$2.625/m²$	$182/m²$
Maintenance Cost Premium (over Conventional)	N/A	$0.21/m²$	$2.90/m²$
Lifespan	17 Years	17 Years	40 Years
Replacement Cost (% of Installation Cost)	100	100	33.3 (Plants and growing medium are salvaged)
Disposal Cost	$3.97/m²$	$3.97/m²$	$1.29/m²$
Design Characteristics	N/A	Aged Solar Reflectance of 0.55	11.45 cm (4.5 in) growing medium, Leaf Area Index of 2, irrigated
Discount Rate	3.75% (Residential), 7% (Commercial and Industrial)		
Inflation Rate	1.64%		
Energy Price Inflation Rate	2.4%		
Average Energy Cost	$0.165/kWh (Residential), $0.205 kWh (Commercial)		
Average Natural Gas Cost	$0.26/m³		

While this survey was comprehensive, including both scholarly papers and industry sources, there is no indication that the cost of increased structural capacity was accounted for as part of the capital cost, likely due to the difficulty of quantifying this over a wide variety of building types and structural systems. Typical extensive green roofs weigh 175-200 kg/m² when saturated (LiveRoof, 2016), compared to 10-15 kg/m² for a conventional roof assembly (CRCA, 2011). This represents a substantial increase compared to the roof loads from snow or rain, which range from 230 kg/m² in London ON, to 215 kg/m² in Halifax NS, and 95 kg/ m² in Calgary, AB (NBC, 2010). In spite of the difficulty of determining a precise premium, there is an impact on the structural loading that designers must account for when a green roof system is employed, along with a corresponding capital cost impact.

3.6 Qualitative Factors

3.6.1 Urban Heat Island Mitigation

A number of studies have explored attributes of green roofs other than their energy and water impacts. First among these is the contribution green roofs make to reducing the urban heat island effect associated with dark, low-albedo surfaces. These surfaces, including dark conventional roof membranes, absorb energy from solar radiation during the day that is emitted as heat an night, contributing to elevated urban temperatures in the summer. In hot weather, the inability of the urban environment to cool down in the evening has been associated with a series of negative human health impacts (EPA, 2016) as well as increased energy and emissions from building air conditioning. Wang et al. (2016) simulated the impact on urban heating by increasing surface vegetation by 10% in three 9.0 ha areas of Toronto, representative of low-rise, mid-rise, and high-rise intensity of development. Their results, illustrated in Figure 3.4, show a reduction in summer nighttime temperatures, particularly for the mid-rise and high-rise areas.

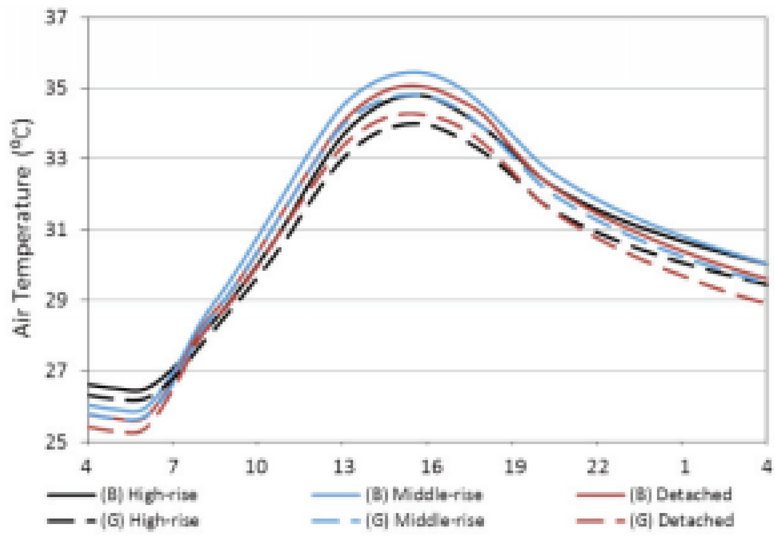


Figure 3.4 Urban Heat Island Reduction from Increased Vegetation (Wang et al., 2016)
B = Baseline, G = Green

Sproul et al. (2012) compared the urban heating impacts of white and green roofs with those of conventional dark roofs based on 22 case studies in 7 different climate zones and concluded:

> *If global climate change is a major concern, white roofs--which are three times more effective at cooling the globe than green roofs--will be a better choice. But if stormwater management costs or urban "natural" landscapes are preferred, a green roof will serve the purpose better at a negligible annualized cost. Nonetheless, for warm climates the paper strongly recommends that dark-colored roofs be phased out because they heat buildings, cities, and the globe.* Sproul et al. (2012) p. 26

Therefore, although a benefit of green roofs, the reduction of urban heating can also be accomplished at lower cost by employing light high-albedo roof membranes or coatings.

3.6.2 Increased Biodiversity

A green roof on a large building can provide a significant surface area of vegetation, which may be the largest green space on an intensively developed site. Depending on the plant type, green roofs can attract insects, including pollinators when wildflowers are included as illustrated in Figure 3.5. Numerous studies including those by Dimoudi & Nikolopoulou (2003), Carter & Keeler (2008), and Doshi (2015) cite the importance of green roofs for provision of natural habitat, particularly in dense urban areas where natural open space is limited or non-existent. A review by Lundholm et al. (2010) examined the importance of plant species selection in optimizing the ecosystem benefits of green roofs according to local environmental conditions.

Figure 3.5 Green Roof with Wildflowers, New York (greenroofs.com, 2016)

Because green roofs create a degree of natural habitat where this may be limited in urban areas, they also attract nesting wildfowl, as illustrated in Figure 3.6. A review of this issue by Fernandez-Carnero & Gonzalez-Redondo (2015) identified risks to nestlings that may not be able to escape, or have sufficient access to water or food. They explain that consideration of the likelihood of birds using green roofs should be part of their design, in which case accommodation for urban wildfowl could be made.

Figure 3.6 Geese Nesting on Green Roof, Dearborn (MSU, 2016)

3.6.3 Aesthetic Benefits

When they are visible, green roofs provide a more attractive appearance than a conventional roof surface. A few studies such as those by Dimoudi & Nikolopoulou (2003) and Muga et al. (2007) have attempted to evaluate these visual benefits in term of their effects on human health. Fedrizzi (2015) makes a case for ascribing increased real estate values for buildings with green roofs, and for neighbouring buildings that overlook them. Figure 3.7 is a particularly visually striking example of a green roof at the California Academy of Sciences in San Francisco.

Figure 3.7 California Academy of Sciences (SFR&P, 2016)

Of course, for the aesthetic benefits of green roofs to be appreciated, they must be visible, and in good condition. Visibility is a consideration for building designers, and condition a factor for building operators. There are many examples, particularly on high-rise buildings or warehouses, of green roofs being located where their visual qualities cannot be appreciated by either building occupants or neighbours. Likewise, there are also examples of neglected green roofs that have lost their plant material. Dead plant material on green roofs becomes highly combustible and has been identified as a fire safety issue in many jurisdictions, including Toronto (Toronto, 2012). These factors are inter-related in that a roof that is not visible is less likely to be well maintained, an example of which is the Stork Family YMCA in Waterloo ON, as illustrated in Figure 3.8.

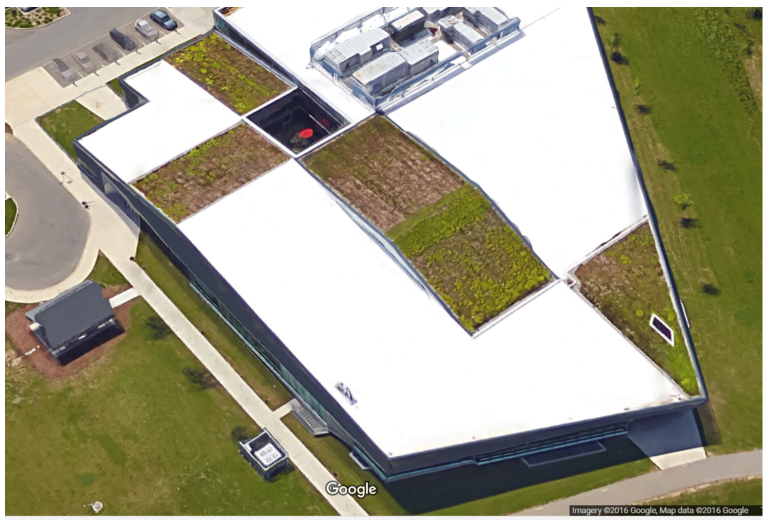


Figure 3.8 Stork Family YMCA, Waterloo ON (Google Maps, 2016)

Although aesthetic considerations are inherently subjective, and developing appropriate metrics is difficult, they are nevertheless very important to the human experience of the visual environment. In this sense, the improvements provided by green roofs to the appearance of urban roofscapes can be seen in the context of the growing interest in creating beautiful urban environments, including the integration of natural elements. These issues are inherent in the philosophy of 'New Urbanism' (CNU, 2016), in the LEED Neighbourhood Design rating system (USGBC, 2016), as well as in generally accepted urban design principles that are now part of official planning policy for virtually every North American city.

3.7 Summary

Based on this review, extensive green roof systems, because of their prevalence, will be used in this study as the basis of comparison with blue roof systems. While there are energy consumption and carbon dioxide emissions reductions associated with green roofs, these are not considered significant when compared to the utilization of more direct measures, including increased insulation and high albedo membranes. This emphasizes the primary role of green roofs in mitigating the impacts of stormwater runoff. Other qualitative benefits are, however, also important. These include reducing the urban heat island effect, increasing biodiversity, as well as providing aesthetic benefits when the roofs are visible.

4. Blue Roof Systems

4.1 What is a Blue Roof?

The term blue roof has emerged relatively recently as a way to distinguish a collection of stormwater mitigation techniques from those associated with green roofs. In essence, a blue roof is a system that captures rainwater and either holds it for a period of time or reuses it for other purposes, such as outdoor irrigation or offsetting potable water use indoors. Like green roofs, there are historical precedents for the collection of rain that falls on the roofs of buildings, including many houses in North American cities that had cisterns prior to the advent of municipal water distribution systems early in the 20th century.

Compared to the volume of literature on green roofs, blue roof systems have received considerably less attention, particularly for large buildings that are the subjects of this investigation. Most studies are focused on rainwater harvesting in arid parts of the world, particularly Australia, or where there are concerns with the quality of other water sources, such as in India. This section uses the literature that does exist to characterise the performance of blue roof systems so that they can be compared with green roofs and other measures discussed in the following sections. Information on the technical details of rainwater harvesting systems is taken from industry sources as well as a number of completed projects with which the author has been involved.

4.2 Rainwater Detention

The simplest example of a blue roof system is one that is designed to detain stormwater temporarily on the surface of the roof and gradually release it over an extended period of time, typically up to 24 hours. This is accomplished using a 'flow control' roof drain, consisting of a conical weir with an open top 100-150mm above the roof surface, as illustrated in Figure 4.1. The weir has one or more slits that restrict the flow of rainwater into the roof drain. The open top allows extreme rain events to bypass the slits, and to avoid flooding if the slits become blocked.

Figure 4.1 Flow Control Roof Drain with Weir (Watts, 2016)

Flow control roof drains are a widely recognized part of Best Management Practices (BMPs) for municipal stormwater management, and are commonly used where the capacity of the municipal storm system serving a particular building is limited (ASPE, 2014). These devices are low cost, have no moving parts, and do not require any more maintenance than an ordinary roof drain, involving periodic removal of leaves and other debris that accumulate around the protective screen.

Although these devices allow water to pond on the roof for only a short period of time, this nevertheless imposes a substantial load on the roof structure. Examples of roof failures due to water ponding have led to formal declarations being required from building designers as part of permit applications across Canada, confirming whether roof control drains are proposed and that appropriate measures (including structural capacity, number of drains, and overflows) have been taken (EABO, 2016). Because all roofs in Canada must be designed to support peak snow loads, this provides capacity for supporting an equivalent weight of ponded water. Building codes permit designers to assume that snow and water loads are not cumulative, up to a maximum depth of 150mm of water, if precautions are taken to prevent flooding by providing a sufficient number of roof drains with overflows. It is therefore uncommon for roof water detention systems to be designed to permit more than 150mm of water to accumulate. This also means that these systems can be incorporated into existing roof structures that have been designed to support conventional snow loads.

Because the use of flow control roof drains is such a common, reliable, and low cost strategy for rainwater detention, it is proposed to consider this practice as the basis of comparison with the performance of both green roofs and rainwater harvesting systems.

4.3 Rainwater Harvesting

Many existing resources provide assistance on the design of rainwater harvesting systems, focused on small-scale domestic applications. An extensive guide for larger systems has been developed by Bruce (2010) that covers the details of system sizing, selection of pumps and other components, and options for water treatment. North American studies such as those by Despins et al. (2009) and Devkota et al. (2015) tend to focus on water quality issues and the effectiveness of treatment methods. Lee et al. (2012) evaluated the effects of the roof surface materials on water quality. While rainwater harvesting systems are widely used in arid regions of the world, they are relatively uncommon in North American cities. To promote their wider adoption by municipalities, a study was commissioned by the US EPA with guidance on policy and regulation (Koss, 2008).

As such, while information on design and treatment is readily available, experience with implementation of these systems both by designers and installers is limited, especially at a large scale. Where municipal water supply is available, these systems tend to be incorporated only as part of advanced green buildings, where credits for rainwater harvesting are included in both the LEED (CaGBC, 2009) and Green Globes (ECD, 2004) rating systems. Rainwater harvesting is also an essential part of the water 'petal' in the Living Building Challenge (ILFI, 2014).

This study deals with rainwater harvesting systems serving large buildings, as opposed to smaller scale residential systems. The typical components of a large rainwater harvesting system are illustrated in Figure 4.2. While there are numerous variations, these systems tend to consist of an underground cistern (5) located near the building, connected to a filtration system (11) and holding tank (12) inside the building. A non-potable supply piping system (15) draws water from the holding tank through a treatment system (13) before being distributed to interior fixtures by a circulating pump (14). During periods of low precipitation, the cistern is maintained at a minimum level from the building's internal water supply, through a backflow device (8) to prevent potential contamination of the potable system.

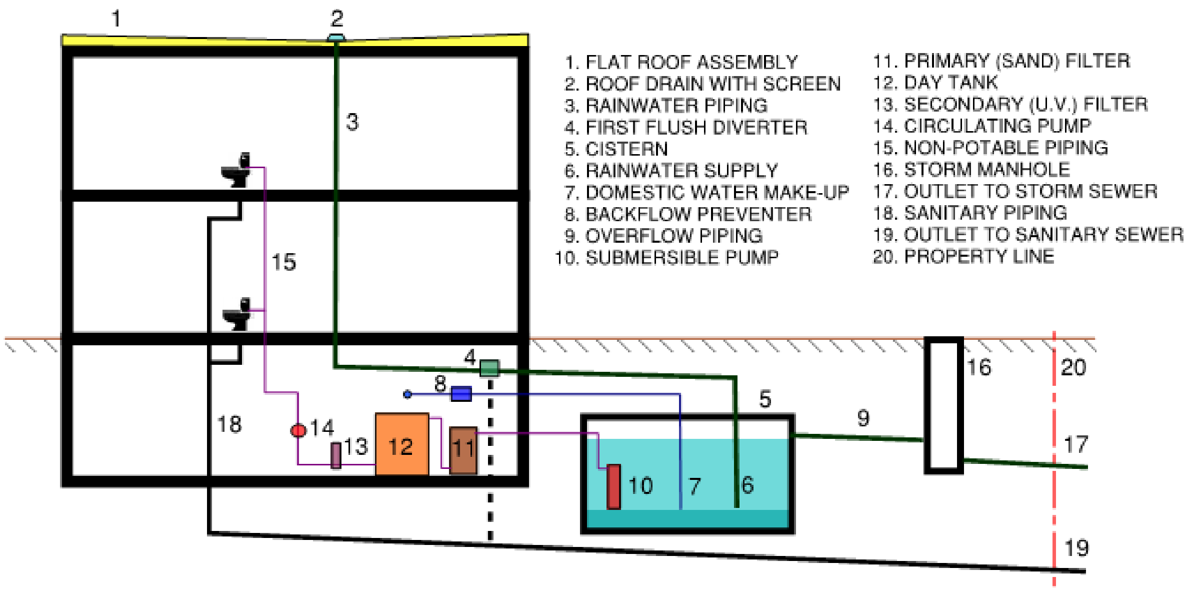


Figure 4.2 Large Rainwater Harvesting System Components (the author)

Cisterns serving large commercial harvesting systems are typically located underground, as opposed to inside buildings or on roofs, for a variety of reasons, including accessibility for maintenance or replacement, avoiding risk of interior flooding from a failure of the vessel, as well as reducing space and structural impacts from their considerable size and weight.

Cisterns are sized based on historical rainfall patterns and projected demand for water. Of course, actual rainfall can vary significantly from historical averages and the harvesting system must also be designed to account for this variation. Similarly, demand for water varies considerably by building type and the uses of the harvested water. These factors will be explored as part of evaluating rainwater harvesting opportunities for different building types and locations in Section 6.

4.4 Energy and Carbon Dioxide Impacts

To the extent that the use of rainwater offsets the consumption of water from a municipal water supply system, this also offsets the energy associated with collecting, treating, and distributing this water. Of course, there are numerous variables affecting energy consumed by a municipal water system, particularly the density of the urban area that it serves. Similarly, the associated carbon dioxide emissions also vary considerably depending on the source of the energy, particularly for the local electrical grid that provides energy for pumping.

A systematic review by Vieira et al. (2014) evaluated the energy intensity of rainwater harvesting systems (that they abbreviate as RHS) for a number of locations across the globe. Their results are summarized in Figure 4.3. The consensus of the empirical studies reviewed is that the median energy intensity of rainwater harvesting systems is 1.40 kWh/m³, compared with conventional municipal water systems that have intensities between 0.22 kWh/m³ and 0.80 kWh/m³. Where centralized systems rely on recycled water using reverse osmosis (RO) treatment, their energy intensity approaches that of rainwater harvesting. Desalination systems generally have much higher energy intensity compared to rainwater harvesting, particularly those using high temperature treatment as opposed to forward osmosis (FO).

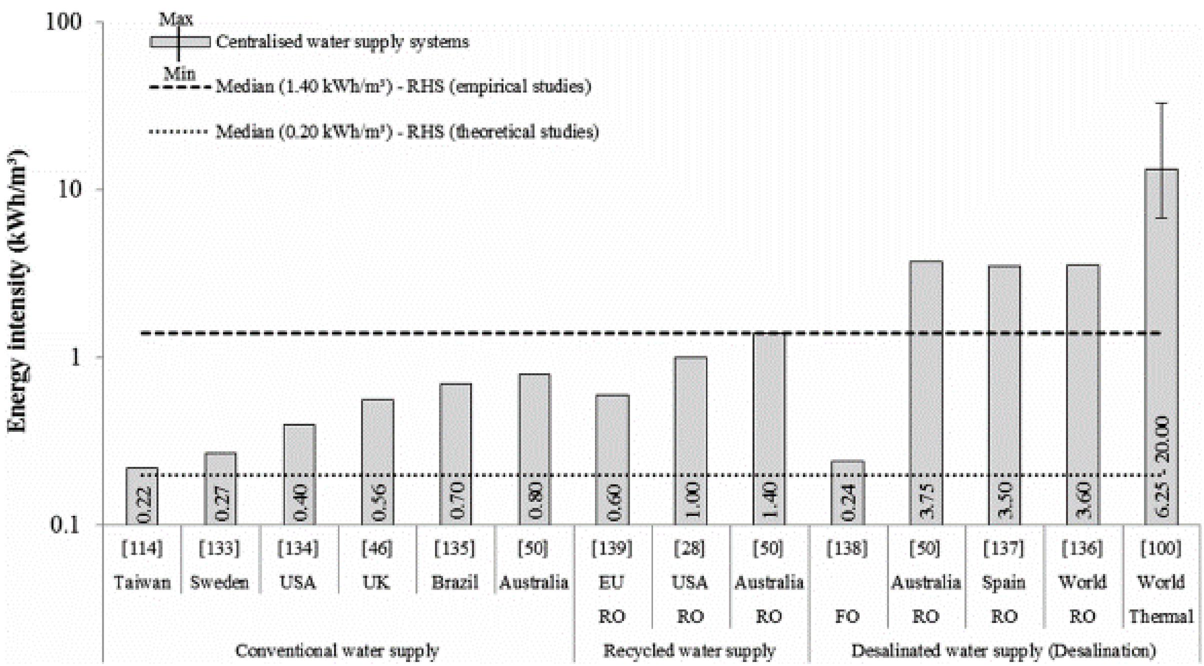


Figure 4.3 Energy Intensity of Centralized and Rainwater Harvesting Systems (Vieira et al., 2014)
[] brackets indicate source citations

4.5 Water Conservation

The consumption of water varies by building size and type, with higher use rates in buildings that involve accommodations, such as apartments, hotels, and institutional occupancies. Table 4.1 summarizes the ratio of water consumption by use for typical office and hotel occupancies, differentiating uses that require potable water (EPA, 2008).

Table 4.1 Daily Water Use for Office Buildings and Hotels (EPA, 2008)

	Office Buildings	Hotels
Potable Uses	**14%**	**57%**
Bathing	0%	27%
Faucets	1%	1%
Cooking	3%	10%
Other	10%	19%
Non-Potable Uses	**48%**	**33%**
Toilets	25%	9%
Laundry	0%	14%
Cooling	23%	10%
Outdoor Uses	**38%**	**10%**

Although there are jurisdictions such as Bermuda that for decades have relied almost exclusively on harvested rainwater for potable uses (Rowe, 2011), this is uncommon in North American cities, where municipal water is normally available to all properties within an urban service area. Ensuring that harvested rainwater meets drinking water standards involves significantly more sophisticated treatment technology and testing regimens than are necessary for non-potable indoor uses or for outdoor irrigation.

Many rainwater harvesting systems are used exclusively for outdoor irrigation, as this can simplify their design and operation as well as limit the degree of treatment required (EPA, 2008). It also avoids the extensive distribution piping required for using non-potable water inside buildings. A common example of this application is a rain barrel that is connected to the downspout from the roof of a house and used to collect rain during storms for reuse during periods of low precipitation. Sites for large buildings frequently include irrigation systems, particularly when substantial areas of grass are included in the landscape design. However, particularly in Canada, there is little justification for utilizing outdoor irrigation considering the increasing availability of indigenous plant material, including drought-tolerant grasses that are able to survive prolonged periods of low precipitation without supplementary irrigation (CaGBC, 2009).

Setting aside uses requiring potable-quality water and uses for outdoor irrigation, this study focuses on indoor non-potable uses that can be served by harvested rainwater without elaborate treatment. These consist primarily of water for flushing toilets and urinals, with a predicable demand in every building.

Water consumption is highly dependent on the efficiency of fixtures, where significant improvements have been realized over the past two decades through both technology and regulation. Table 4.2 compares flow rates for toilets and urinals based on Traditional, International Plumbing Code (ICC, 2009), and EPA WaterSense standards (EPA, 2015). Most contemporary building codes are based on IPC Standards, and these are used in this study to determine demand, with comparisons to EPA standards. Although buildings using traditional fixtures would have a greatly increased demand for harvested rainwater, these fixtures are no longer available and will gradually disappear as they fail and are replaced with IPC- and EPA-compliant units.

Table 4.2 Fixture Flow Rates (EPA, 2015)

	Toilets litres/flush	Urinals litres/flush
Traditional Fixtures	15-30	10-15
IPC Standard	6.0	3.8
EPA WaterSense	4.8	1.9

The quality of harvested rainwater is a consideration even if it is intended for non-potable uses, because there remains a risk to humans from coming into accidental contact with it, particularly in open fixtures such as toilets or urinals. Surprisingly, there are currently no regulations in Canada dealing with this issue, as most building codes simply require that non-potable piping systems be clearly labelled, and any connections to back-up municipal water supplies be protected with suitable backflow prevention devices (Ontario, 2012). Recommendations from the U.S. EPA are that UV disinfection should be provided for non-potable systems to maintain fecal coliform levels less than 100 colony forming units (cfu) per 100ml and total coliform levels less than 500 cfu per 100 ml (EPA, 2008).

Feitelson (2012) argues that conventional attitudes to water must change, to understand it not as an undifferentiated substance with more or less contamination, but as many types of 'waters' with different physical and 'normative' properties based on their source, purpose, and importance for human and environmental health. It is suggested that these types of waters be categorized under either 'blue' water (surface and ground water), 'green' water (clouds, precipitation, and soil moisture), or 'grey' water (altered by humans). The 'normative' aspects of these waters depend on their importance to human and environmental well-being, with 'meritorious' waters essential to maintaining society and natural systems. Other human purposes that treat water as a commodity should be priced to reflect its full social and environmental costs. Such considerations would support the use of harvested rainwater for any applications where potable water is not essential and becomes more expensive as consumption increases.

4.6 Capital, Operating, and Replacement Costs

A rainwater harvesting system is a completely redundant set of components for a building that has access to a municipal water supply. With the exception of roof drains and the associated rainwater piping that any building with a flat roof requires, the rest of the components illustrated in Figure 4.2 above represent additional capital expenditure for both design and installation. Table 4.3 summarizes the cost of a number of installed systems with which the author has been involved, normalized on a cost per square metre of gross building area, and as a percentage of the total cost of the building.

Table 4.3 Rainwater Harvesting System Costs (2016 dollars, see Appendix)

Category Building Type	**RWH System Cost**	**Total Building Cost**	**Building Area m^2**	**RWH System Cost per m^2**	**RWH System % Total Cost**
#1 Assembly Community Centre	$86,000	$24,087,000	6,748	$12.77	0.36%
#2 Education College/ University	$60,000	$21,522,000	4,478	$13.34	0.28%
#3 Education College/ University	$221,000	$121,449,000	25,455	$8.67	0.18%
#4 Education College/ University	$89,000	$33,171,000	9,606	$9.27	0..49%
#5 Institution Long Term Care	$180,000	$18,597,000	8,350	$21.61	0.97%
#6 Institution Long Term Care*	$53,000	$26,784,000	14,288	$3.71	0.20%
#7 Institution Retirement Home	$219,000	$26,442.000	13,156	$16.68	0.83%

* Project #6 rainwater harvesting system used for outdoor irrigation only

Details of each project are provided in the Appendix. The systems were installed between 2006 and 2016, with a number of differences, particularly regarding the degree of water treatment, with earlier systems providing little or no treatment. Note that the system for Project #6 is designed and used only for outdoor irrigation with no water treatment. Its much lower relative cost compared to the other systems indicates the impact of adding water treatment and non-potable distribution piping as part of using harvested rainwater inside buildings. The relative costs of the systems serving Assembly and Educational building types (Projects #1 - #4) are significantly lower than the costs of the systems serving Institutional building types (Projects #5 & #7). This is likely a reflection of the increased extent of non-potable distribution piping, which has to serve ensuite washrooms in each unit of an Institutional building, as opposed to central washroom facilities in the other types.

While this is a small sample of building types, it indicates that the cost of a rainwater harvesting system represents less than 1% of the total capital cost in each case. However, given limited funding for most building projects, the developer is faced with a decision about whether to invest resources into a rainwater harvesting system versus other options, such as improving the building envelope, increasing mechanical system performance, or myriad aesthetic enhancements.

Of course, reduced consumption of municipal water will result in a reduction of monthly water charges. Most cities in Canada use monthly water consumption volume as the monthly sanitary sewer volume, on the assumption that virtually all potable water enters the sewer system. Figure 4.4 summarizes the water and sewer rates in each province from 2009 data, excluding Newfoundland and Labrador for which there were too few data (EnviroCan, 2011). This shows a national average rate of approximately \$55 per $25m^3$, or \$2.20 per m^3.

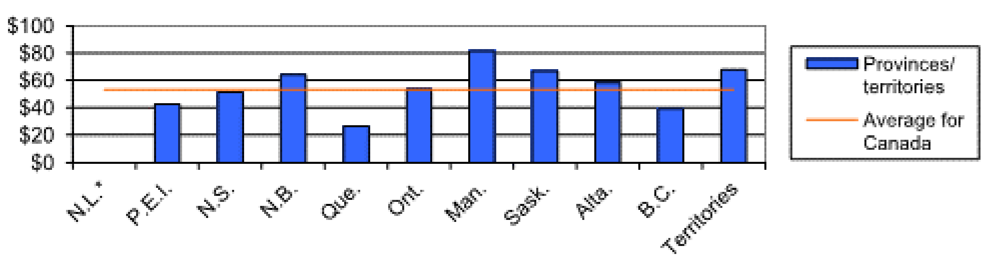


Figure 4.4 Canadian Water and Sewer Rates per $25m^3$ (EnviroCan, 2011)

In the same way that rainwater harvesting systems represent a redundant series of components that are not required in a typical building connected to a municipal water supply system, these systems also involve redundant efforts to keep them operating and properly maintained. While much of the operation of rainwater harvesting systems is automated, there is manual effort involved in cleaning and replacing filters. Properly designed first-flush diversion systems can help to reduce the volume of debris that enters the system, but primary filtration is necessary to prevent coarse organic matter from accumulating in the cistern. Similarly, secondary filtration is necessary to prevent fine suspended materials from entering the pump, distribution piping, and the plumbing fixtures. All of these filters require regular cleaning and replacement, which is not typically possible to automate. Other operating costs include the energy costs for pumps and treatment systems, discussed in 4.2 above, as well as periodic (at least monthly) testing and inspection.

Finally, because rainwater harvesting systems consist of mechanical and electrical components, there will be inevitable failures. Distribution pumps are the most critical part of the system, and operate on a continuous basis to keep fixtures supplied with water. This consequently reduces their service life and increases the need for regular preventative maintenance. Similarly, floats and sensors are in constant contact with water and their performance deteriorates over time. Treatment systems also fail, particularly ultraviolet units, whose lamps have an average service life of 15,000-20,000 hours, or approximately 2 years of continuous operation (Trojan, 2016).

While very little data exist documenting actual operating, maintenance, and replacement costs for rainwater harvesting systems, the components are analogous to those of small municipal well water systems. The major difference is the cistern itself, which tends to require little attention once it is buried in the ground. Statistics Canada conducted a survey of the operation and maintenance costs of well water treatment plants and concluded that in 2007, the average cost for a for a small-scale municipal system was $0.43/m^3 of water (StatsCan, 2011). Applying average annual escalation of 2%, this makes the cost in 2016 dollars $0.47/m^3. Considering that even a small municipal-scale system is much larger than a building-scale system, it is suggested that in order to provide a conservative estimate for the purposes of this study, this cost is doubled to $0.94/m^3 of water for building-scale systems.

Taking the same approach as that of Table 3.2 in Section 3.4 that summarizes the capital, operating, and replacement costs for green roofs, the data discussed above for blue roofs are summarized in Table 4.4 for the capital, operating, and replacement costs for blue roof systems.

Table 4.4 Blue Roof Life Cycle Costs (compiled from preceding sources)

Variable	Flow Control Drains	Rainwater Harvesting
Life Cycle Period	50 years	
Installation Cost Premium	negligible	$9-22/m^2$ of building area
Maintenance Cost Premium	negligible	$0.94/m^3$ of water collected
Life Span of Components	20 years	2 years - UV lamps 10 years - filters 20 years - pumps 50 years - cistern
Replacement Cost	negligible	100% of installation cost per component
Disposal Cost	negligible	negligible

Of the seven systems listed in Table 4.3 with which the author has been involved, three have been shut down, with the supply from the cistern bypassed to use municipal water for all toilet flushing. The consistent reason given by the building managers is that they had not anticipated the associated operating and maintenance costs to be so significant. Unfortunately, none of these organizations has retained records of what these costs actually are. Although disappointing, it demonstrates the importance of understanding the implications of operating and maintaining a rainwater harvesting system as part of the decision whether to include this in a building project, as well as taking steps in the design to make the system simple and reliable to use by incorporating durable components and accessible maintenance points.

4.7 Qualitative Factors

Unlike the numerous attributes of green roofs discussed in Section 3.5, blue roofs have few other factors associated with their use that are apparent to building occupants or inhabitants of the surrounding urban context. In a sense, this is actually their primary attribute: they are innocuous strategies that are not readily apparent to someone who is not otherwise aware of their incorporation into a building design, except when something goes wrong.

In the case of flow control roof drains, these allow rainwater to pond on the roof surface for a period of hours. This activity would not be noticeable for building occupants, and only neighbours overlooking the roof surface would be aware of this happening. If there is a failure of the overflow mechanism, this could lead to water infiltrating into the building through flashings or mechanical openings, when building occupants would be very aware that the system is not working properly. In an extreme case, accumulation of excess water on the roof could overload the capacity of the structure and lead to a collapse. As discussed in Section 4.1, contemporary building regulations require precautions to be incorporated into the building design that make this unlikely.

In the case of rainwater harvesting systems that provide water to flush toilets and urinals, these also normally operate without being apparent to people using the fixtures. In periods of low precipitation, the systems automatically provide water from the municipal supply system, maintaining the collection cistern at a minimum level to continue operation. If the filter systems fail, water to the fixtures will become discoloured or will acquire a stagnant odour, which is apparent to building users. Failure of pumps will cut off supply of non-potable water to the fixtures, again an occurrence obvious to occupants.

To maintain fixture operation when the harvesting system is not working, either due to pump failure or regular maintenance, manual bypass valves are necessary to allow the supply to be switched over to the municipal system. As discussed in the example systems above, the provision of these manual bypass valves, while necessary, also allows building managers to easily avoid having to look after rainwater harvesting systems by leaving the non-potable distribution piping permanently connected to the municipal water supply.

4.8 Summary

Because flow control roof drains are such a well-established approach to stormwater management, these will be used as the basis of comparison with the performance of green roofs as well as will rainwater harvesting systems. The performance of rainwater harvesting systems is a function of local precipitation, roof area, and demand for the harvested water that can be reliably predicted from data for building occupancy rates. Unlike green roofs, blue roofs have few additional attributes, other than that they operate without building users necessarily being aware of them, until something in the system fails.

5. Compatibility of Green and Blue Roofs Systems

5.1 Sources of Compatibility Issues

As discussed in Section 1.1, flat roofs perform a variety of functions, including thermal resistance and protection from solar radiation, as well as offering a platform for other rooftop systems including building mechanical equipment and photovoltaic or solar thermal arrays. The introduction of these other systems creates issues of compatibility with both green and blue roofs.

5.2 Increased Roof Insulation

The most direct method of improving the energy performance of flat roofs is increasing the thickness of roof insulation. Recognizing this, building codes and energy standards across North America have evolved to require increased thermal resistance of roof assemblies. In Canada, the 2011 National Energy Code for Buildings requires minimum levels of performance depending on the type and location of the building, resulting in a substantial increase in the overall energy performance of the building compared with earlier standards (Figure 5.1) (NRCan, 2012). These improvements are due in large part to increased thermal resistance of the building envelope, particularly roof assemblies.

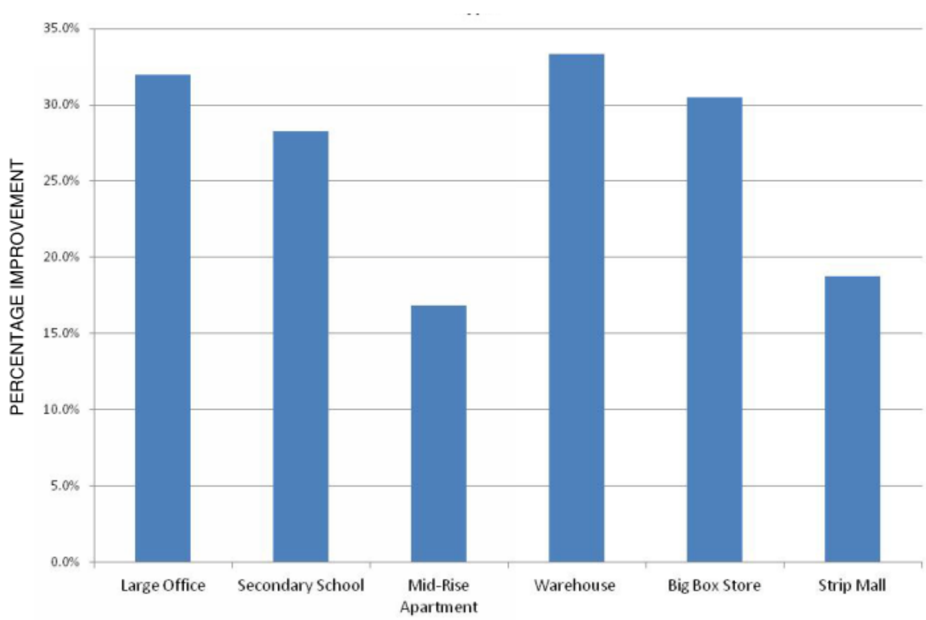


Figure 5.1 Percentage Improvement by Building Type for NECB 2011 vs. 1997 (NRCan, 2012)

The minimum thermal resistance values can be adjusted by modeling the energy performance of the building as a whole to demonstrate a minimum overall level of efficiency. Increased roof insulation above the minimum values is an effective way to improve energy performance of buildings with flat roofs, because these surfaces represent a large proportion of the building envelope and are not interrupted by window openings. By doing so, designers are often able to offset reduced performance of other parts of the building envelope, such as from increased window area, to accomplish other benefits or design objectives.

The thickness of flat roof insulation is typically limited to 150-200mm as thicker insulation complicates construction detailing. The increased thickness does not provide a linear energy performance benefit, making the extra insulation less cost-effective and increasing the payback period on both an economic and life-cycle energy basis.

The thickness of roof insulation has relatively little impact on whether a green or blue roof system is installed on top of the roof assembly. Increasing the thickness of insulation does add weight, however, and therefore on a roof with restricted weight bearing capacity, adding more insulation could be limited by the weight of either a green roof system or a rooftop rainwater retention system that allows water to pond and be gradually released. Because growing media (in the case of green roofs) and water (in the case of rainwater retention) are both much denser than insulation, every centimeter of these materials would require the reduction of many centimeters of insulation, to keep within the capacity of the roof structure. Table 5.1 compares the weight of common types of insulation with that of saturated growing media and water, based on 100mm of thickness and a 1m^2 surface area.

Table 5.1 Weights of Roof Materials (Wilson, 2013)

Material	Density g/cm^3	Weight per m^2 100mm thick
Polyisocyanurate	0.02	2 kg
Extruded Polystyrene	0.03	3 kg
Rigid Fibreglass	0.06	6 kg
Green Roof Media (wet)	0.50	50 kg
Water	1.00	100 kg

In practice, because the weight of insulation is not substantial, accommodating increased thickness in the design of a new building's roof structure is not difficult. This factor is more significant for existing buildings, where upgrading the capacity of the roof structure is often impractical. Therefore, compared with other measures such as vegetated roofing or photovoltaic panels that involve substantially increased structural loads, increased roof insulation is a viable way to improve the energy performance of existing buildings with flat roofs.

5.3 High Albedo Membranes

The common measure of the reflectance (or albedo) of roof membranes is the Solar Reflective Index (SRI), which is defined so that a standard black surface (reflectance 0.05, emittance 0.90) is 0 and a standard white surface (reflectance 0.80, emittance 0.90) is 100 (CaGBC, 2009). As discussed in Section 1.2, many studies have demonstrated the negative impacts of dark roof surfaces (with an SRI less than 30) on the energy performance of buildings, as well as the impact these roofs have on increasing the urban heat island effect. These effects are obviously more severe in southern latitudes, and most studies such as Sproule et al. (2013) are focused on the benefits of using light coloured roof surfaces (with an SRI greater than 60) in these locations.

A study by Hosseini & Akbari (2016) looked at the impacts of high albedo roof surfaces in cool climate zones where the effect of the 'heating penalty' from reflecting solar radiation in winter offsets the summer benefits. This study modeled a range of building types in four locations (Anchorage, AK, Milwaukee, IL, Montreal, PQ, and Toronto, ON) comparing annual energy performance of low albedo (dark) roofs with that of high albedo (light) roofs. The results show that in spite of the heat lost from reflectance in winter, high albedo roofs have a net benefit for annual energy savings for the majority of building types, even in an extremely cold location like Anchorage. A unique consideration in this study was the effect of snow cover. The authors found that this tends to minimize the difference in albedo between dark and light roofs in winter, when both are under a layer of snow. Figure 5.2 summarizes the results for new buildings based on energy savings in dollars per 100m^2 of roof area.

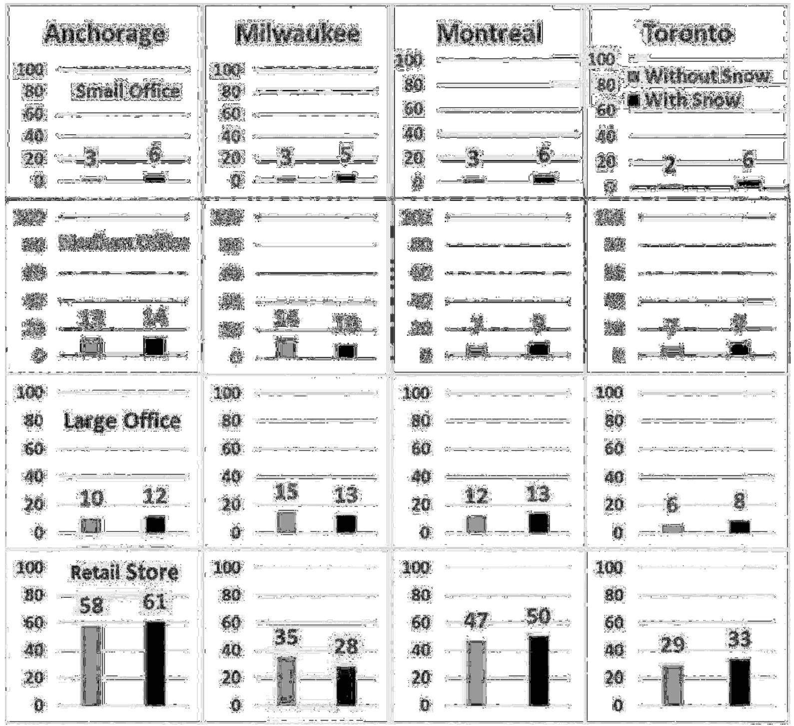


Figure 5.2 Energy Savings ($/100m²) from Reflective Roofs (Hosseini & Akbari, 2016)

The authors summarize their conclusions as follows, providing an important and counter-intuitive insight into the energy performance of flat roof surfaces in cold climates.

> *In cold climates, during the winter the sun angle is lower, days are shorter, sky is cloudy, and most heating occurs during early morning or evening hours when the solar intensity is low. In addition, the roof may be covered with snow for most of the heating season. All these lead to a negligible winter time heating penalties for cool roofs. For most building types and in most climates, our simulations show that a cool roof saves in annual overall energy expenditure even without the effect of snow.* (Hosseini & Akbari 2016, p. 154)

Because high albedo roof membranes must be exposed to the sky to be effective, they are incompatible with green roof systems. However, green roofs are normally considered a 'cool' roofing strategy because the provide cooling though evapotranspiration (when enough water is present) and because they have a higher albedo than conventional dark roofing, with a typical SRI of 40 (Sproule et al.. 2013).

5.4 Photovoltaic and Solar Thermal Systems

Since 2000, there has been a significant increase in the use of both photovoltaic and solar thermal panels across the US and in some Canadian provinces, particularly Ontario. According to data collected by IRENA (2016) illustrated in Figure 5.3, this trend is primarily due to the combination of rising electricity prices and reduced hardware costs, as well as growing public interest in the adoption of green building measures.

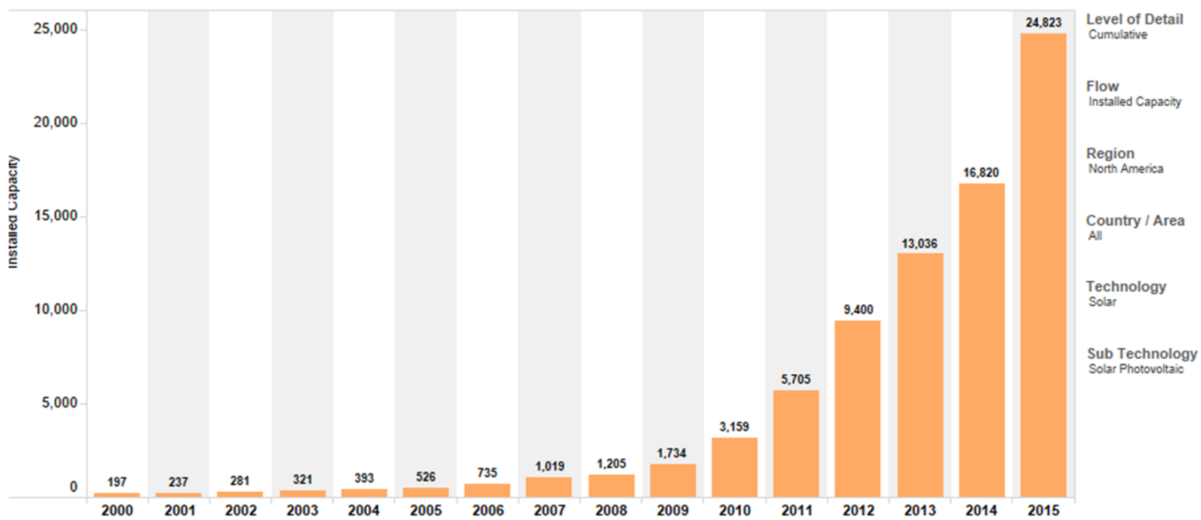


Figure 5.3 Installed North American PV Capacity (MW) 2000-2015 (IRENA, 2016)

Many studies have evaluated conventional crystalline silicon photovoltaic panels based on their life cycle impacts as well as their energy inputs and volume of waste generated in their manufacture (Baharwani, 2014, Soppato, 2008, Yao, 2014). While the manufacturing impacts are significant, the reliability of these systems over their typical 25 year service life results in a net positive life cycle energy impact. While the vast majority of installed photovoltaic systems are based on crystalline silicon, many new materials and manufacturing techniques are being explored, with the objective of decreasing the cost of electricity generated per installed unit of panel area. A study by the National Renewable Energy Lab surveyed the numerous new module technologies under development in 2014, as summarized in Figure 5.4. Note that a full-sized version of this figure is included in the Appendix.

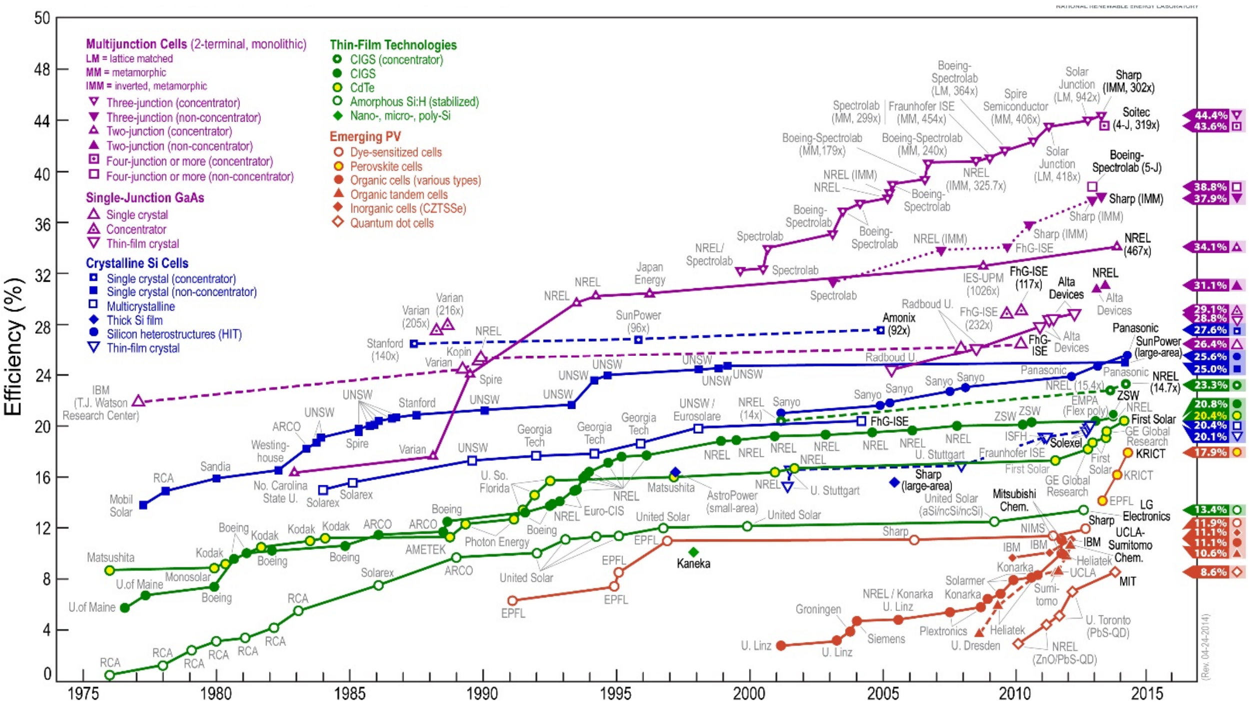


Figure 5.4 Summary of Photovoltaic Module Efficiencies, 1975-2015 (NREL, 2014)

Solar thermal hot water systems, which use sunlight for heating water, have also become more prevalent since 2000 for reasons similar to those driving increased adoption of photovoltaic systems. A study by Lamnatou & Chemisana (2015) examined the life cycle impacts of these systems, concluding that they produce positive results in most applications, thanks to their relatively simple components and the reliability of established commercial systems.

With respect to their compatibility with green and blue roofs, photovoltaic and solar thermal systems are treated in an equivalent manner, based on their similar mounting configuration above the flat roof surface. There are two common methods for installing these systems on buildings: either ballasted or suspended. Ballasted systems are the most cost effective because they do not require any physical connection to the building structure, relying on the weight of concrete blocks or paving stones producing friction with the roof surface to resist being moved or damaged by wind loads. Figure 5.5 illustrates a typical ballasted system.

Figure 5.5 Ballasted PV System (Arcadian, 2016)

Because they produce friction with the roof surface, ballasted systems can cause the roof membrane to deteriorate prematurely. For this reason, most roofing manufacturers recommend the addition of a wear layer between the panel base and the primary roof membrane. Ballasted systems also pose a significant impediment for roof maintenance, including finding and repairing roof leaks.

As an alternative to ballasted systems, panels can be suspended above the roof surface, supported by posts connected to the roof structure as illustrated in Figure 5.6. This avoids the issues associated with ballasted systems by maintaining clear access to the roof surface. Suspended systems are, however, more complicated to coordinate as they require greater integration of the structural design of the building and the installation of a photovoltaic or solar thermal panel system.

Figure 5.6 Suspended Panel System (SolarForm, 2016)

The weight of a roof mounted photovoltaic or solar thermal array has an impact on the ability of the roof structure to allow water to pond as part of a rainwater detention system, resulting in a trade-off between the number of panels and the depth of water that can be detained. On the other hand, no such impact exists for a rainwater harvesting system as it does not impede drainage from the roof and would continue to operate independently of the panels mounted on it.

The weight of green roofs, particularly intensive systems, also introduces a trade-off with the weight of roof-mounted panels. As well, the application of a green roof under these panels raises a number of issues for roof access and maintenance. Studies such as Lamnatou (2014) have examined the combination of photovoltaic and green roofs as 'hybrid' systems and identify some potential benefits, particularly the ability of the vegetation to dissipate excess heat generated by the panels. Of course, depending on the panel spacing, shading and excess heat can have a negative effect on the health of the plants. These studies tend to ignore the impact on the building structure of the combined weight of both green roof and panel systems. Also overlooked are the long term consequences of combining ballasted panels in particular on the ability of building managers to maintain and repair the roof membrane. As discussed in Section 3.4, advocates of green roofs claim an increase in the longevity of the roof membrane by protecting it from exposure to the sun and the atmosphere. However, industry experience shows that unless leak detection systems have been installed, finding and repairing roof leaks can be so difficult that the entire green roof has to be removed and the whole membrane replaced much sooner that would normally be expected (Liu, 2012). This situation is further exacerbated by the installation of a ballasted panel system over the green roof.

There has also been recent development of innovative thin-film photovoltaic materials, including some of the products in Figure 5.4 above, which have the potential to be manufactured into the roof membrane itself. These have the potential of combining the benefits of high albedo membranes discussed in Section 5.2 with the energy generating benefits discussed in this section. These would be truly 'building integrated' products, as they would simply replace the roof membrane, including on existing buildings where little additional weight would be added. If widely adopted, these integrated membranes could drastically reduce the demand for green roof systems because they would cover areas of the roof available for power generation.

5.5 Roof Mounted Mechanical Systems

Also as discussed in Section 1.1, a common function of flat roofs is the support for roof mounted mechanical systems. Flat roofs are an expedient location for heating, ventilating, and air conditioning components because they are reasonably secure from vandalism, less visible from ground level, and provided with ample outdoor air for their operation. Mounting this equipment on the roof also avoids the cost of constructing enclosed mechanical rooms inside the building or penthouses above the roof level.

The presence of either green or blue roof systems has little impact on the use of the roof for mechanical equipment. The weight and footprint of the equipment is localized and accounted for in the structural capacity of the roof. Safe access to the equipment for maintenance personnel must be maintained irrespective of the type of roof surface, and is normally provided by conventional patio stones.

5.6 Accessible Roof Terraces

Many urban buildings with limited site area take advantage of opportunities to use flat roofs as accessible outdoor spaces. Doing so requires designers to consider roof terraces as equivalent to occupied rooms in the building, including increasing structural capacity to accommodate occupants, provision of emergency egress, and adding perimeter guardrails.

Providing regular access to the roof for building occupants has significant implications for green roof systems due to the substantially increased weight involved. Similarly, occupied roof areas limit the extent to which they can serve for rainwater retention as part of a blue roof strategy. Conversely, roof terraces would not impact rainwater harvesting systems presuming the materials used are porous and permit rainwater to enter the drainage system normally without adding detritus to the water.

5.7 Combining Green and Blue Roof Systems

A final consideration is the combination of green and blue roof systems together. As discussed in Section 3, an inherent feature of both extensive and intensive green roofs is their ability to retain stormwater. It is also possible to permit green roofs to flood under extreme storm conditions and temporarily detain additional rain, similar to a flow control roof. These attributes are limited by the capacity of the structure to support the combined weight of both the green roof systems and the rainwater, again resulting in a trade-off for designers.

The combination of green roofs with rainwater harvesting systems has resulted in serious failures of distribution equipment due to silt accumulation (Bruce, 2015). Filters become rapidly clogged, material accumulates in fittings, and pump components are damaged by suspended grit. Where buildings incorporate both green roofs and rainwater harvesting systems, it is important that they are served by separate drainage piping to prevent this type of equipment failure.

5.8 Summary of Compatibility

Table 5.2 summarizes the compatibility considerations discussed above for green and blue roofs. This illustrates that green roofs tend to have limited compatibility with other rooftop systems while blue roofs tend to be compatible with most other rooftop systems. Of course, a given building can comprise a combination of roof areas that may be appropriate for different purposes and applications. Green roofs are particularly appropriate where roofs offer accessible outdoor space for building occupants.

Table 5.2 Compatibility Matrix for Green and Blue Roof Systems

Compatibility Matrix for Green and Blue Roof Systems	GREEN ROOF – INTENSIVE	GREEN ROOF - EXTENSIVE	BLUE ROOF – DETENTION	BLUE ROOF – HARVESTING
Increased Roof Insulation	Limited Compatibility	Limited Compatibility	Limited Compatibility	Compatible
High Albedo Membrane	Incompatible	Incompatible	Compatible	Compatible
Integrated PV Membrane	Incompatible	Incompatible	Compatible	Compatible
Ballasted PV or Thermal Array	Incompatible	Limited Compatibility	Limited Compatibility	Compatible
Suspended PV or Thermal Array	Limited Compatibility	Limited Compatibility	Compatible	Compatible
Roof Mounted Mechanical Systems	Limited Compatibility	Limited Compatibility	Limited Compatibility	Compatible
Accessible Roof Terraces	Compatible	Compatible	Limited Compatibility	Limited Compatibility

Compatible (green)

Limited Compatibility (yellow)

Incompatible (red)

6. Evaluating Rainwater Harvesting Opportunities

6.1 Evaluation Methods and Data Sources

To evaluate the opportunities for using rainwater harvesting systems in a broad range of building types, this section uses a variety of common buildings encompassing a range of occupancies classified under assembly, education, institutional, residential, and commercial categories. Typical parameters for size, height, and occupancy rates are taken from databases assembled by the US Department of Energy as part of the Energy Star standards. This information generates the number of female and male occupants who normally occupy each type of building, including how these numbers vary depending on the occupancy schedule. The frequency of use of plumbing fixtures by these individuals is based on standards used in the LEED NC-2009 green building rating system. Water consumption by toilets and urinals is based on International Plumbing Code standards, which form the basis of the plumbing components of most Building Codes in North America. Collectively, this information generates a total demand for non-potable water to flush toilets and urinals in each type of building.

This range of building types is analyzed in three Canadian cities with differing climatic conditions based on Environment and Climate Change Canada's annual and monthly weather normals. The availability of rainwater for collection is compared with the demand for non-potable water. The results are normalized per square metre of total floor area so that the potential for rainwater harvesting can be compared between different building types. The sensitivity of the results is also analyzed based on variations in building height and multiple occupancy combinations.

6.2 Building Type and Occupancy Parameters

A range of representative buildings has been developed, consisting of 15 types of use organized under five categories as summarized in Table 6.1. Each of these building types has its own characteristics in terms of physical configuration and occupancy patterns, which are also summarized in the table.

Table 6.1 Occupancy Parameters by Building Type (see Appendix)

CATEGORY	Roof Area	Storeys	Area/Person	Occupancy	Gender Mix
Building Type	**m^2**	**number**	**m^2/p**	**percent**	**percent f/m**
ASSEMBLY					
Community Centre	5000	2	15	50%	50%/50%
Library	2500	1	20	25%	50%/50%
Theatre	2500	1	5	75%	50%/50%
EDUCATION					
Elementary	5000	2	11	90%	50%/50%
Secondary	10000	2	13	90%	50%/50%
College/University	10000	4	16	75%	50%/50%
INSTITUTIONAL					
Hospital	10000	4	120	90%	50%/50%
Long Term Care	5000	3	60	90%	75%/25%
Retirement Home	5000	2	42	90%	65%/35%
RESIDENTIAL					
Apartment	5000	6	200	90%	50%/50%
Student Residence	5000	5	44	90%	50%/50%
Hotel	5000	3	44	75%	50%/50%
COMMERCIAL					
Office	5000	2	40	75%	50%/50%
Retail	10000	1	232	25%	50%/50%
Warehouse	10000	1	155	50%	50%/50%

The data for roof area and number of storeys are drawn from representative examples for each building type. Although these are somewhat arbitrary values, the results are normalized per square meter as discussed in Sections 6.5 and 6.6. Implications of variations in building height are discussed in Section 6.7.

Data for area per occupant in Table 6.1 are taken from the US Environmental Protection Agency Energy Star Portfolio Manager Data Trends database (EPA, 2015a), with the exception of buildings in the Education category that are excluded from this source. Data for education buildings are taken from the NREL Technical Support Document for Development of the Advanced Energy Design Guide for K-12 Schools (NREL, 2007). These sources provide an average area per person for each building type based on its gross floor area, from a survey of a large number of buildings across the US. These data are considered in this study to be applicable to similar building types in Canada.

Also as indicated in Table 6.1, buildings are not occupied at their maximum possible rate at all times with a few exceptions in the Institutional category. Therefore, for the purposes of this study the area per person is increased by an occupancy factor representative of the type of building. Increasing the area per person has the effect of reducing the number of occupants to levels representing actual utilization. As discussed by Zavala (2012) there are remarkably few data dealing with the actual average occupancy of buildings, as most codes and standards are based on based maximum occupancy rates (or minimum areas per person) in determining such things as the capacity of mechanical systems. To the extent that this leads to an overcapacity of these systems under normal circumstances, it would seem to be a valuable area for further investigation.

Finally, utilization of toilets and urinals varies by gender according to reasonably well-identified patterns on which a number of standards are based, including the LEED rating system (CaGBG, 2009). These standards presume an equal mix of genders except where specific circumstances dictate otherwise. As indicated in Table 6.1, most building types in this study are presumed to have an equal mix of genders, with the exception of those catering to elderly persons where demographics show a higher proportion of females.

See the Appendix for detailed information on how the data from these sources have been incorporated into the Excel spreadsheets used to generate the results discussed in the following sections.

6.3 Fixture Utilization and Consumption Parameters

In contrast to the variability of occupancy parameters depending on the type of building, utilization of toilets and urinals tends to be relatively consistent. As such, it represents predictable demand for the reuse of collected rainwater.

The LEED NC-2009 standard has developed consensus-based data for fixture utilization rates, which differ for males and females as summarized in Table 6.2 below (CaGBC, 2009). Because utilization of fixtures differs for employees, visitors, customers, students, and residents, the groups have been differentiated as indicated in the table.

Table 6.2 Fixture Utilization Rates (from LEED NC-2009)

Users gender	Uses per day	Hours per day	Uses per hour
Employees			
t-female	3	8	0.38
t-male	1	8	0.13
u-male	2	8	0.25
Visitors			
t-female	0.5	8	0.06
t-male	0.1	8	0.01
u-male	0.4	8	0.05
Customers			
t-female	0.2	8	0.03
t-male	0.1	8	0.01
u-male	0.1	8	0.01
Students			
t-female	3	6	0.50
t-male	1	6	0.17
u-male	2	6	0.33
Residents			
t-female	5	24	0.21
t-male	5	24	0.21
u-male	0	24	0.00

t= toilets u=urinals

Like the absence of data for overall building occupancy discussed in Section 6.2 above, there is limited information about the actual mix of occupants for most building types. In the absence of such data, numbers of employees have been determined based on the proportion per building user as indicated in Table 6.3 below. While these ratios may vary from building to building, there are relatively few employees per gross building area for most building types. The exceptions to this are the buildings in the Commercial category that tend to be dominated by employee occupancy with relatively few visitors or customers per gross building area.

The other important parameter in predicting the utilization of water for flushing toilets and urinals is the amount of water they consume per flush. The efficiency of plumbing fixtures has improved dramatically in recent years, particularly for toilets that use only one half to one fifth of the amount of water of the previous generation of fixtures. Most codes in North America, including the National Building Code of Canada, reference the International Plumbing Code for minimum fixture performance (NRCan, 2010).

Table 6.3 Occupant Mix by Building Type (see Appendix)

CATEGORY Building Type	Employees %	Visitors %	Customers %	Students %	Residents %
ASSEMBLY					
Community Centre	2%	98%			
Library	3%	97%			
Theatre	10%	90%			
EDUCATION					
Elementary	5%			95%	
Secondary	3%			97%	
College/University	1%			99%	
INSTITUTIONAL					
Hospital	10%				90%
Long Term Care	5%				95%
Retirement Home	2%				98%
RESIDENTIAL					
Apartment		10%			90%
Student Residence	2%				98%
Hotel	1%				99%
COMMERCIAL					
Office	90%	10%			
Retail	96%		4%		
Warehouse	100%				

Although there are products on the market that have lower rated volumes per flush, in practice their performance has been problematic especially when first introduced. These include dual-flush toilets, pressure-assist toilets, and 'waterless' urinals. There have been numerous complaints of maintenance, odour, and overflow issues particularly for new products (SavingWater, 2011). While these innovative products may perform acceptably in private houses, their application in large buildings that are the subject of this study introduces the risk of significant (and unpleasant) failures where maintenance resources are limited and fixtures are expected to last for decades. This means that the development of reliable fixtures takes time, and is normally initiated in countries with water shortages like Australia.

This is not to say that further improvements in efficiency with reliability are not possible. To this end, the EPA has developed a WaterSense standard, which goes beyond the performance of the IPC standard. Table 6.4 provides a comparison of the two standards (ICC 2009, EPA 2015), as well as typical flow rates for the previous generation of fixtures. It is obvious that most of the progress has already been made, leaving some relatively small gains once the EPA fixtures become more widely accepted, likely thanks in part to the bugs being worked out by brave homeowners willing to give them a try.

Table 6.4 Comparative Fixture Performance (ICC 2009, EPA 2015)

Generation	Toilet litres/flush	Urinal litres/flush
Traditional Fixtures	13-26	13-19
IPC Standard	6.0	3.8
EPA WaterSense	4.8	1.9

6.4 Basis of Calculations

The following sections use the preceding parameters for building size and occupancy, fixture utilization rates, occupancy mix, and fixture performance to estimate the expected water demand for the 15 building types evaluated, based on the following formulae:

$F = (R \times S) / A \times P \times O_F$

$M = (R \times S) / A \times P \times O_M$

$D_F = F \times U_T \times OM \times C_T$ (for each class of occupant)

$D_M = M \times U_T \times OM \times C_T + M \times U_U \times OM \times C_U$ (for each class of occupant)

Where:
- F = number of female occupants
- M = number of male occupants
- D_F = water demand from female occupants (liters/hour)
- D_M = water demand from male occupants (liters/hour)
- R = roof area (from Table 6.1) (m^2)
- S = number of storeys (from Table 6.1)
- A = area per person (from Table 6.1) (m^2)
- P = occupancy percent (from Table 6.1) (%)
- O_F = mix of female occupants (from Table 6.1) (%)
- O_M = mix of male occupants (from Table 6.1) (%)
- U_T = toilet flushes per hour (from Table 6.2)
- U_U = urinal flushes per hour (from Table 6.2)
- OM = occupant mix (from Table 6.3) (%)
- C_T = toilet consumption (from Table 6.4) (litres/flush)
- C_U = urinal consumption (from Table 6.4) (litres/flush)

The estimated monthly water demand for each building type is compared with the supply of rainwater based on the area of the roof and precipitation data for each of the three locations taken from Environment Canada monthly averages for 1981-2010. Refer to the Appendix for the detailed spreadsheets.

6.5 Rainwater Harvesting Results for London ON

Figure 6.1 compares total fixture demand versus rainwater collected for the 15 representative building types. These results are calculated using IPC rated fixtures based on average annual occupancy and average annual precipitation.

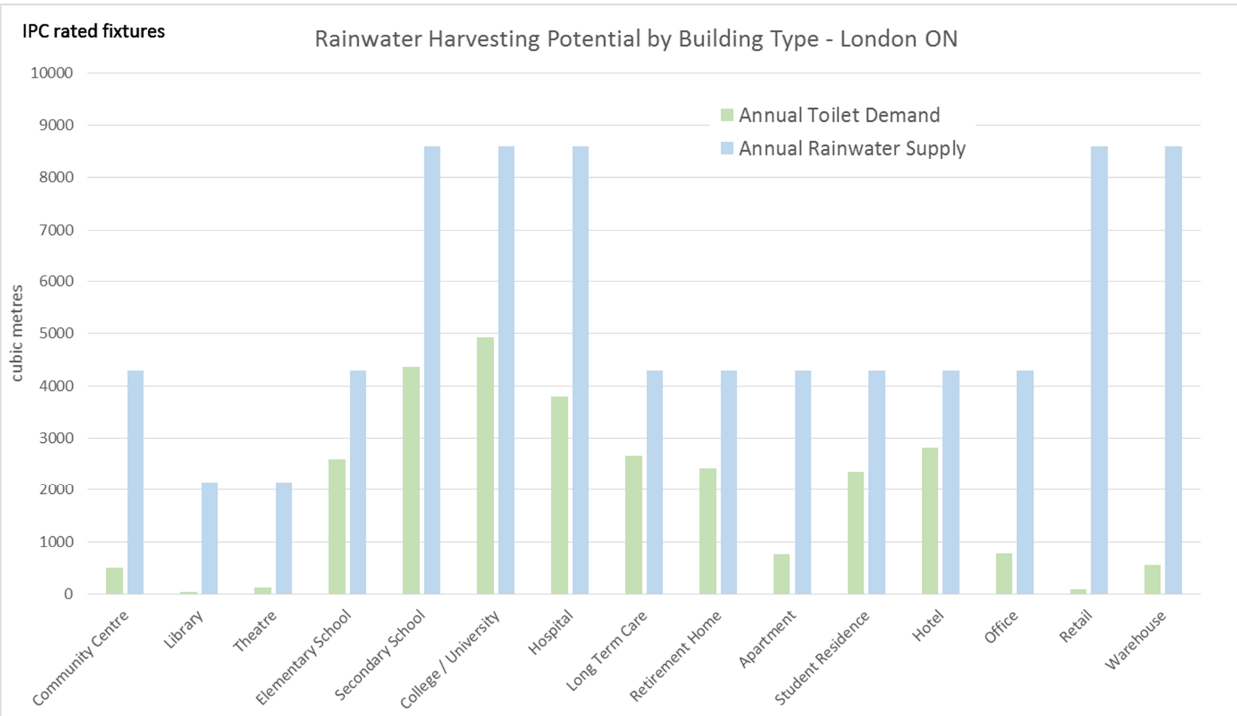


Figure 6.1 Annual Toilet Demand and Rainwater Supply by Building Type

It is important to note that these are highly aggregated results, showing the gross volume of precipitation available and the gross volume of water needed for toilet/urinal flushing according to average building occupancy levels. This is the conventional approach used in assessing rainwater harvesting potential in contemporary green building rating systems such as LEED and Green Globes, whose default parameters are based on annual precipitation and demand statistics.

Because the 15 building types vary in area and number of storeys, in order to compare their relative potential, it is useful to normalize the results per square metre of floor area, as illustrated in Figure 6.2. This figure also indicates the percentage of precipitation that is collected and used for toilet and urinal flushing. Like Figure 6.1, it is important to note that the data are aggregated based on average annual precipitation and fixture demand. Collection percent is the supply divided by the demand.

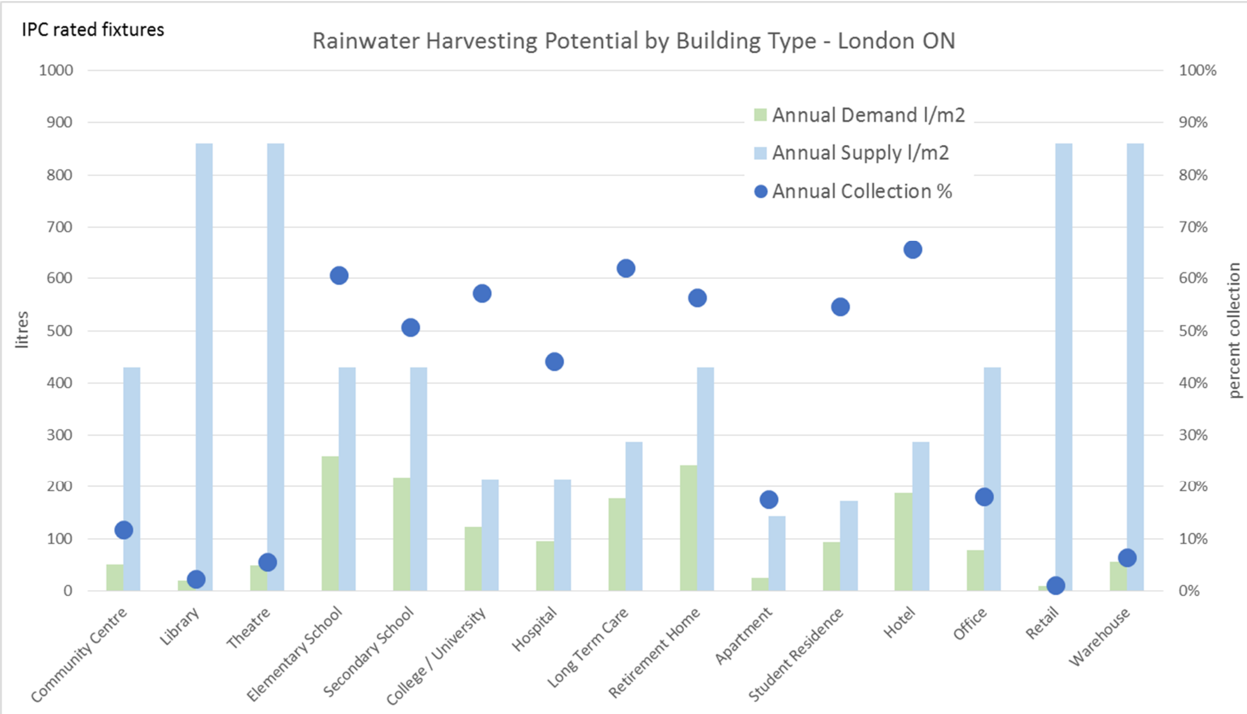


Figure 6.2 Normalized Annual Toilet Demand and Rainwater Supply by Building Type

It is evident from this illustration that all of the example building types in London, ON receive sufficient annual precipitation to offset all potable water needed for toilet flushing. On the other hand, as indicated by the range of values for the percent of precipitation collected, there is a large variation between building types in terms of their potential to divert a significant proportion of the stormwater flows. Most of the Public Assembly buildings divert little stormwater per m^2 of floor area, due to their relatively large footprints (that receive a significant amount of precipitation) and relatively low numbers of people per square metre of floor area (that limits the demand for toilet flushing). Conversely, most of the Institutional buildings have the potential to divert a large proportion of stormwater, in the order of 60-70%, due to their generally more compact footprints and higher occupancy rates, as well as the fact they are in use at all times throughout the year.

Based on Environment Canada data from 1981 through 2010, London ON receives an average of 1011mm of precipitation, predominantly as rain. As illustrated in Figure 6.3 below, this varies over the year with peaks in the spring and fall. London receives a substantial amount of snow from December through February, which is converted into equivalent precipitation in mm. The winters are relatively mild and therefore melting of snow normally occurs during the daytime, particularly on flat roof surfaces, making the water available for collection. For the purposes of this study, it is presumed that all snow received in a month melts at some point during that month.

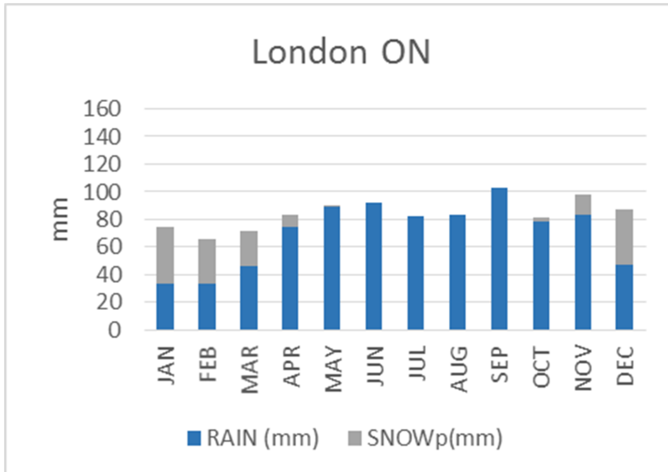


Figure 6.3 London ON Monthly Average Precipitation (EnviroCan, 2016)

Not unlike the way annual precipitation varies monthly over the year, building occupancy also varies considerably on a monthly basis. Figure 6.4 below summarizes typical monthly occupancy rates for the 15 representative building types.

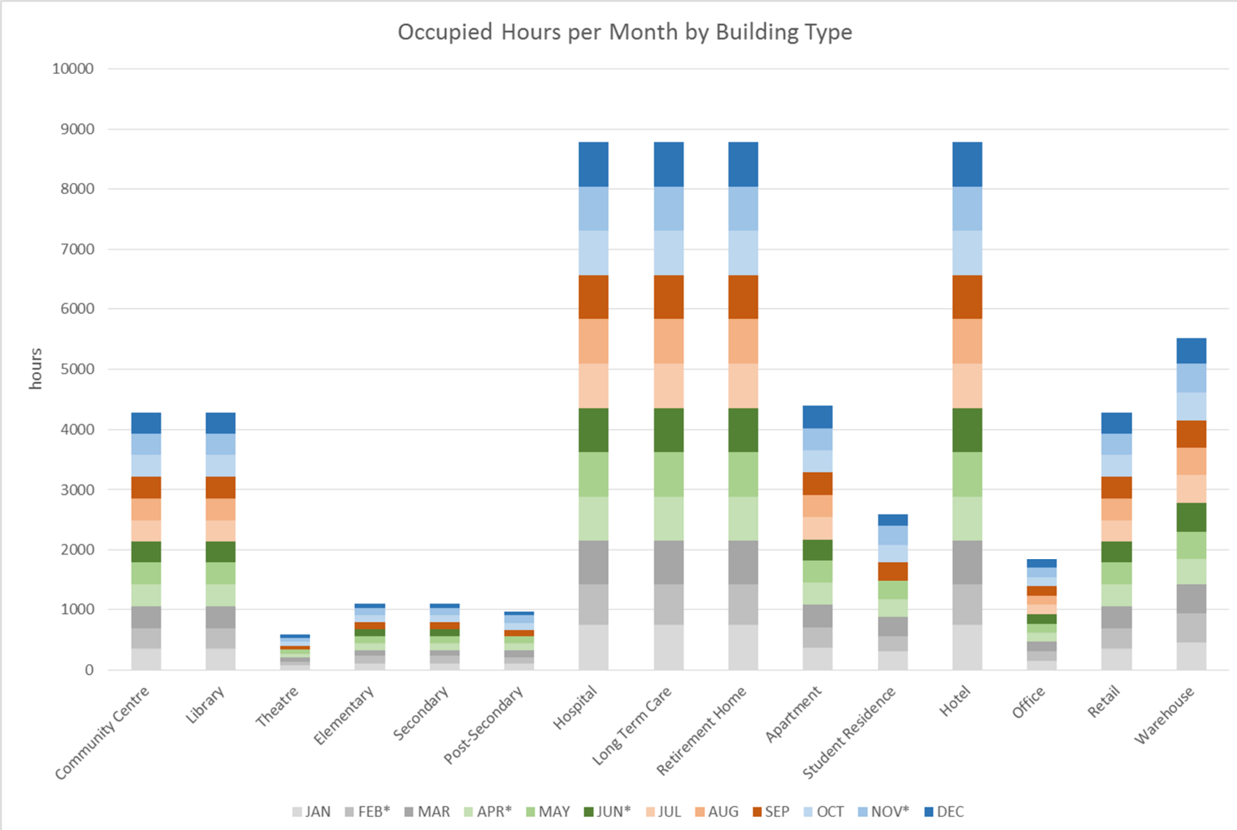


Figure 6.4 Monthly Occupancy by Building Type (see Appendix)

By combining monthly precipitation data with monthly occupancy data, it is possible to provide a more fine-grained evaluation of rainwater harvesting potential. Taking a monthly approach to rainwater harvesting also permits the use of a cistern to be characterized, which is difficult to do using annual data alone. Figure 6.5 illustrates the integration of these data, including a cistern sized at twice the maximum monthly demand volume (providing one month of drought protection). The horizontal line shows the comparable average percent retention for green roofs from O'Carroll (2016).

Contrasting these results with those illustrated in Figure 6.2 for annual data produces some significantly different conclusions for rainwater harvesting potential. While this still confirms that all building types receive sufficient precipitation to offset all of the potable water needed for toilet and urinal flushing, the proportion of stormwater that is diverted is lower in some cases and higher in others.

Retail and Warehouse buildings divert the lowest proportion of precipitation, at less than 10%. Community Centres, Libraries, and Theatres also have low rainwater retention rates. All of these buildings have common characteristics of large roof area, low height, and low occupant density or hours of use. The proportion of rainwater diverted based on monthly data is higher for a number of other building types, including Apartments, Student Residences, and Hotels. The performance of Hospitals, Long Term Care Homes, and Retirement Homes is similar to the results based on annual data, because these are operated on a continuous basis throughout the year.

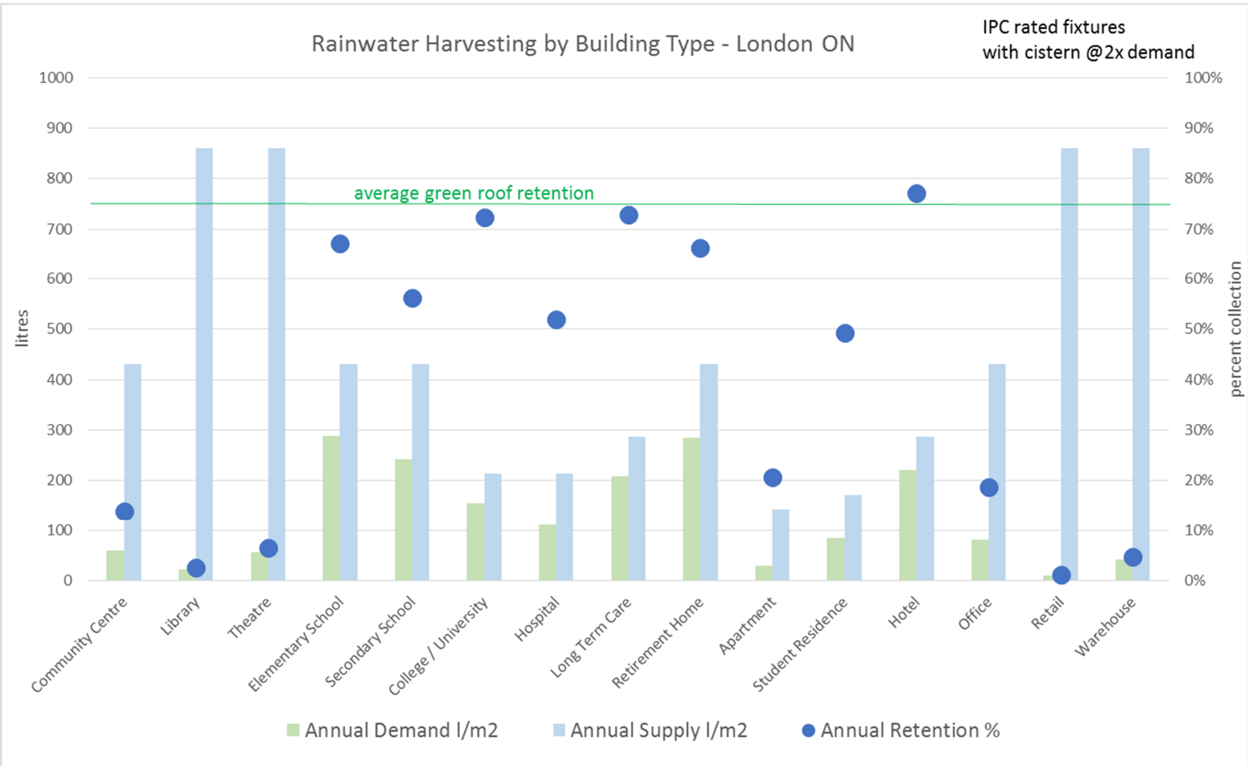
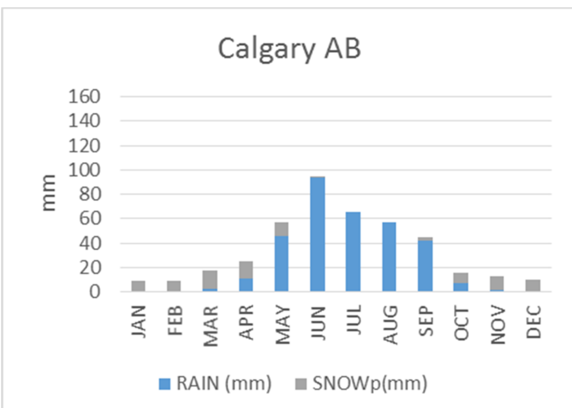


Figure 6.5 Annual Toilet Demand and Rainwater Supply Using Monthly Data for London ON

To the extent that part of the rationale for implementation of rainwater harvesting systems is the diversion of stormwater, this raises some important considerations for their predicted performance. The results demonstrate that the performance varies considerably by building type and is limited by the practical consideration of cistern size. This also raises some opportunities for better optimizing these systems to improve their ability to retain rainfall, which is discussed in Section 6.7.

6.6 Comparative Results for Calgary AB and Halifax NS

To examine how rainwater harvesting opportunities for various building types are affected by different climate conditions, this section provides results for buildings located in Calgary AB and Halifax NS. As illustrated in Figure 6.6, the amount of precipitation these cities receive is significantly different than London (1011mm annual precipitation), with Calgary being much drier (419mm annual precipitation) and Halifax being much wetter (1468mm annual precipitation). The precipitation pattern for Halifax is similar to London, with peaks in the spring and fall. Calgary's pattern is much different, with a peak in the summer and very little precipitation from October through April. Like London, Halifax receives a substantial amount of snow from December through March. Also like London, for the purposes of this study it is presumed that the snow received during a month will melt at some point during that month due to intermittent mild temperatures.



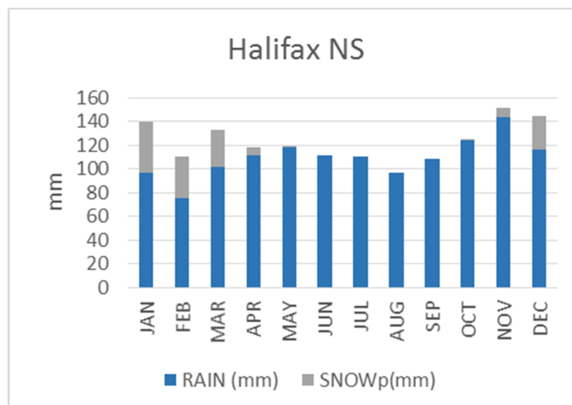


Figure 6.6 Precipitation for Calgary AB & Halifax NS (EnviroCan, 2016)

Figure 6.7 illustrates the normalized results for Calgary. In comparing these to the results for London in Figure 6.5 in the previous section, a different profile is apparent in the relative opportunities for rainwater harvesting in the various building types.

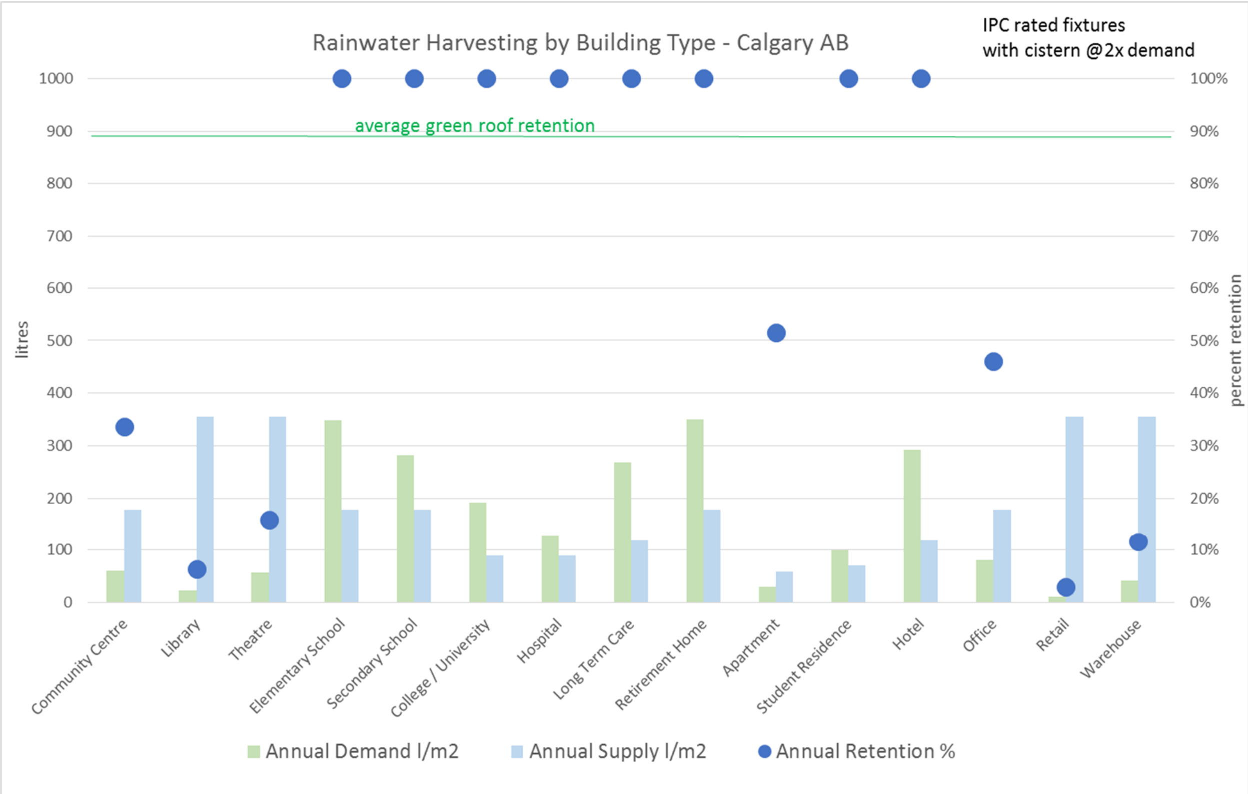


Figure 6.7 Annual Toilet Demand and Rainwater Supply Using Monthly Data for Calgary AB

Unlike London, many building types in Calgary receive an insufficient amount of precipitation on a monthly basis to offset all potable water used for toilet flushing, particularly those with high occupancy rates or continuous operation in the Education and Institutional categories.

Compared to London, all building types in Calgary divert a substantially higher percentage of the total annual precipitation they receive. This means that rainwater harvesting systems represent a much more important stormwater management opportunity here. As in London, Education and Institutional building types represent the best opportunities for diverting stormwater with a 100% potential retention rate. Student Residences and Hotels also have the potential to retain all the rainwater they receive.

Figure 6.8 illustrates the normalized monthly results for Halifax. Comparing the results with those for London in Figure 6.5 shows a similar profile in the relative opportunities for rainwater harvesting across the various building types.

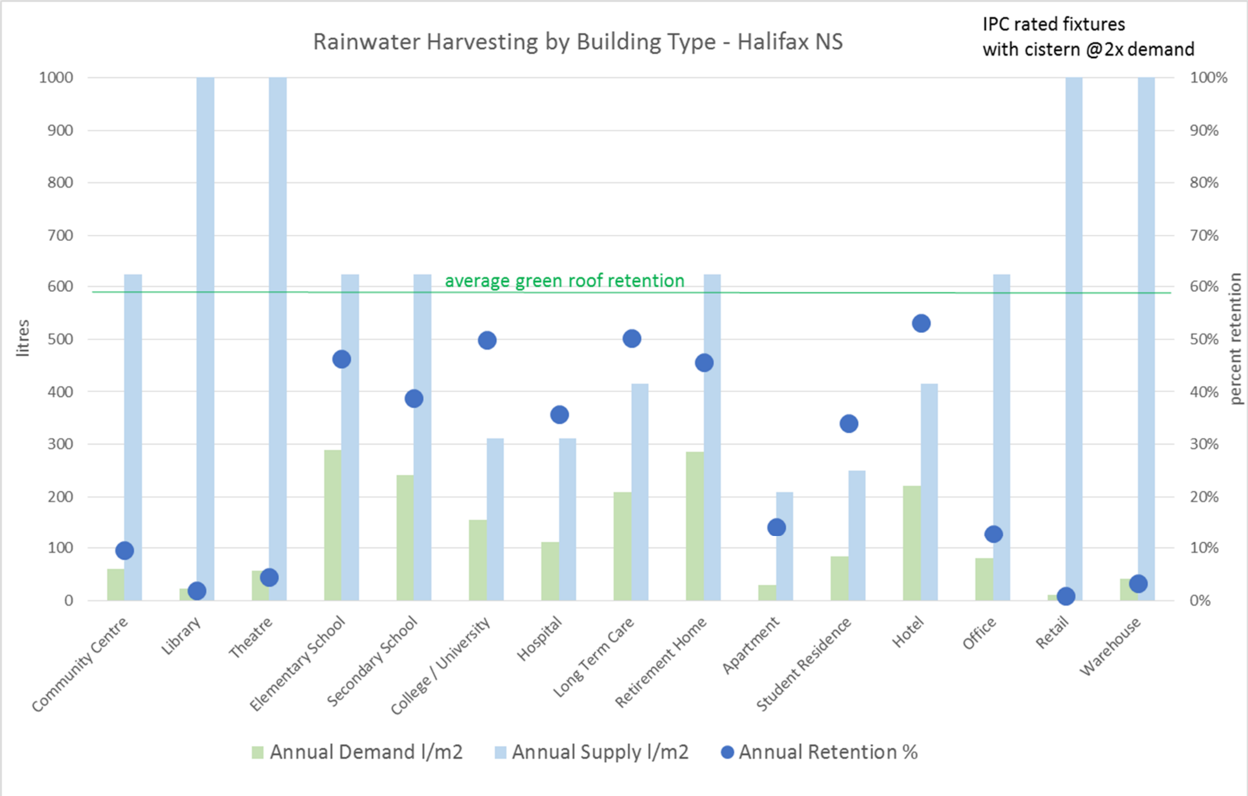


Figure 6.8 Annual Toilet Demand and Rainwater Supply Using Monthly Data for Halifax NS

To an even greater degree than London and Calgary, with the amount of rainfall that Halifax receives, all building types are able to offset all potable water used for toilet flushing.

Compared to London and Calgary, the proportion of precipitation diverted from the municipal stormwater system is generally lower. This means that for most building types, rainwater harvesting systems are a much less important stormwater management strategy here.

In all locations, the potential for stormwater diversion could be improved by increasing the number of storeys. Many of the building types, particularly in the Assembly and Education categories, tend to be in lower-rise buildings, so increasing their height would be atypical. However, many of the other building types, particularly Residential and Office, can be configured in multi-storey structures. As well, a common configuration in urban areas is a high-rise multi-use building combining a variety of occupancies under the same roof. These building types represent perhaps the best opportunities for diversion of a substantial proportion of the stormwater they receive, while also offsetting all of the potable water required for toilet flushing.

6.7 Opportunities for Optimizing Rainwater Harvesting Systems

Based on the results discussed above for the range of building types, it is apparent that the performance of rainwater harvesting systems is a function of the number of occupants and the area of the roof surface available for collection. When considering the single-use low-rise buildings analyzed, the results indicate that the proportion of rainwater collected is significant for many building types, typically retaining over 50% of the precipitation that the roof receives, but much lower for other types. This raises the question of how to optimize the performance of these systems, so that they not only meet the needs for toilet flushing but also make a more significant difference in the retention of stormwater and reduction of peak flows.

6.7.1 Rainwater Versus Stormwater

The terms ‘rainwater’ and ‘stormwater’ tend to be used interchangeably, but making a distinction between them is useful in understanding the performance of rainwater harvesting systems and their impacts on municipal stormwater infrastructure. Although all stormwater comes from rain, to the extent that large storm events have the most significant impacts, the term ‘stormwater’ tends to refer to the surge of water associated with storms over periods of less than one hour, as opposed to general rainfall distributed over many hours.

O’Carroll (2016) characterizes storm events as ‘small’ if they produce less than 3mm of precipitation, ‘medium’ if they produce between 3mm and 15mm of precipitation, and ‘large’ if they produce more than 15mm of precipitation, over one hour. Table 6.5 summarizes the number of events in each category observed during 2013 and 2014 for London, Calgary, and Halifax.

Table 6.5 Storm Events, 2013-2014 (O’Carroll, 2016)

Location	Small Events (<3mm)		Medium Events (3-15mm)		Large Events (>15mm)	
	number	percent	number	percent	number	percent
London ON	51	32%	81	51%	28	17%
Calgary AB	38	44%	39	46%	9	10%
Halifax NS	32	33%	36	37%	30	31%

Although in each location large events represent the smallest proportion, they nevertheless represent a substantial volume of precipitation because each event is many times the size of the small and medium ones. The large events also generate the peak flows that are frequently beyond the capacity of the local municipal infrastructure, resulting in overflows into sanitary treatment system in older areas with combined storm and sanitary sewers.

6.7.2 'Smart' Cisterns

Because of the importance of larger storm events, improving the ability of harvesting system to deal with these would significantly increase the benefits to a municipality. It is conceivable that a cistern could be designed to collect only large events, helping to reduce peak flows that overtax municipal storm infrastructure.

The effect of such a system would be to maintain the cistern at a minimal level so that most of its capacity is available when a large storm event occurs. One method of doing so would be to increase the scale of 'first flush' diversion systems discussed in Section 4 that are normally used to divert the first millimeter of rain that tends to contain large volumes of debris. A first flush system could be designed to divert all small and medium sized events while maintaining a minimum level of water in the system to meet toilet flushing requirements over a predetermined period of time, typically seven days. When a large event occurs, the cistern would fill, and the water would be gradually used by toilet flushing until the cistern volume reaches a minimum level again.

A method of further optimizing cistern performance would be to link the management of water level to both historical and predicted rainfall data. Historical data would be useful in determining the likelihood of large storm events occurring at a particular time of the year. If the likelihood is low, collection of more water from small and medium events would be permitted, as maintaining reserve capacity would be less important. For those periods of the year when large storm events are more likely, the system could keep the water level at a minimum level more often.

Such a system could also be fined-tuned based on short-term weather predictions providing more accurate rainfall information. This could inform the system about the timing of the largest event expected over a period of days, allowing it to avoid using its capacity prematurely for a smaller storm when a large one is expected to follow.

Of course, optimizing the performance of a harvesting system to retain only the largest events by maintaining minimum water levels most of the time risks the level falling below minimum during unexpected periods of drought. Such a situation occurred in Halifax, traditionally one of the wettest locations in Canada, during the summer of 2016. To maintain a supply of water for toilet flushing, harvesting systems require back-up supply from a potable water source, normally the municipal main. A well designed system would minimize this risk, and would 'learn' by adapting its performance with current data on both historical trends and local predictions.

6.7.3 Increasing Building Height

To the extent that the volume of stormwater that a harvesting system is able to retain is limited by the number of persons accommodated under the roof of the building, an obvious way to improve stormwater retention is to increase building height. This has the effect of putting more floors occupied by people under the same roof.

While some building types occur over a range of heights, others tend to be exclusively low-rise, including most buildings in the Assembly and Education categories, as well as Retail and Warehouse types. This leaves a large group of buildings in the Institutional and Residential categories as well as Office types that can occur in high-rise configurations. Planning trends from cars and sprawl to transit and density are likely to add incentives for increased building height, at least along transit corridors. Figure 6.9 uses rainfall data for London and summarizes the number of storeys for each of these types at which 100% of the rainwater is retained, making a significant impact on stormwater mitigation.

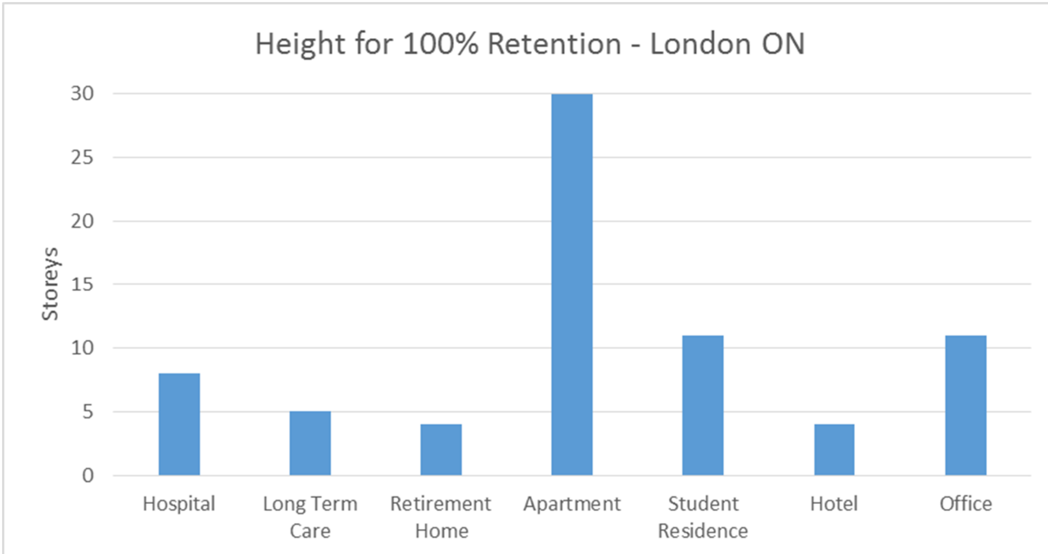


Figure 6.9 Building Heights to Achieve 100% Rainwater Retention in London ON

6.7.4 Multiple Occupancy Combinations

A further strategy for optimizing the performance of rainwater harvesting systems to reduce peak storm flows is to combine multiple types of occupancy that have complementary patterns of use. The most obvious example would be to combine office and residential uses, which tend to have complementary occupancy patterns, with offices normally occupied during the weekday and residences occupied on evenings and weekends. Combining these types of uses on multiple floors in the same building results in a more constant demand for toilet flushing, making continuous use of the cistern capacity. Such multi-use buildings are becoming common in large urban centres because the complementary nature of the uses has other benefits, including reducing transportation and parking demand and balancing energy utilization.

Combining Assembly building types with residential uses can also dramatically improve the ability of rainwater harvesting systems to significantly reduce peak stormwater flows. These types of combinations tend to produce 'tower and podium' building configurations, with the larger common spaces accessible at grade and residential space stacked on smaller floor plates above.

Figure 6.10 illustrates the performance of rainwater harvesting systems in buildings with a variety of occupancy combinations, based on rainfall data for London, ON.

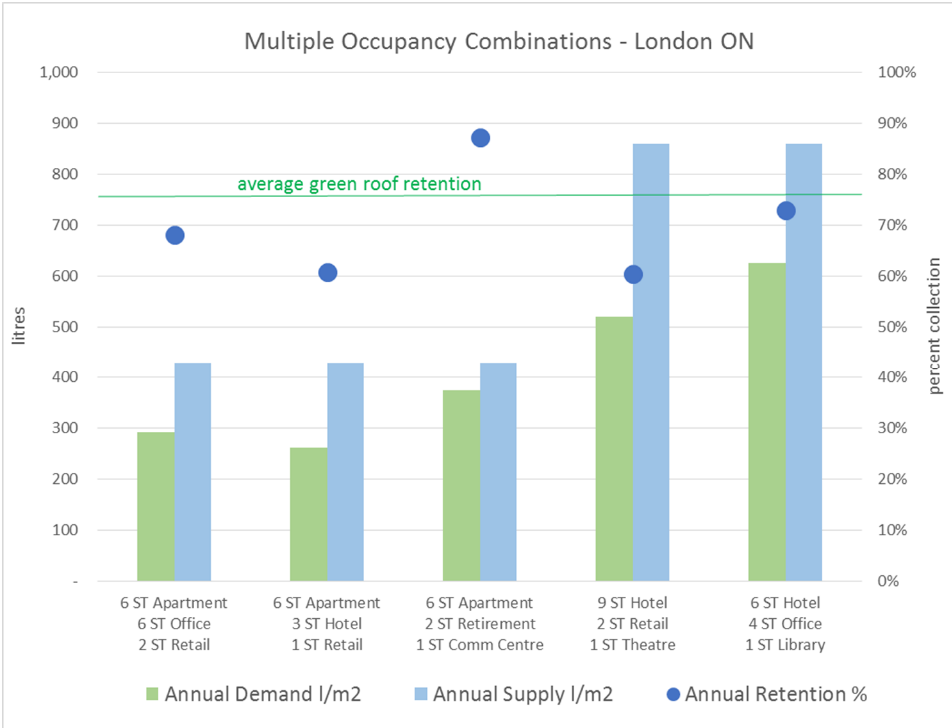


Figure 6.10 Multiple Occupancy Combinations – London ON

6.8 Summary

These results show that all building types in London and Halifax receive sufficient rainwater to offset completely the water required for flushing toilets and urinals, as do most types in Calgary. The results also show that, based on using a cistern sized to store twice the maximum monthly demand for water, the proportion of stormwater retained is also significant for most building types, particularly in Calgary where there is less total rain compared to London and Halifax. There are a variety of ways to increase the proportion of stormwater collected, including linking cistern operation with weather data to anticipate storm events, increasing building height to have more people under the roof surface, and combining multiple uses with complementary occupancy schedules to make demand more continuous.

7. Limitations of the Evaluation Methods

7.1 Areas of Uncertainty

This section discusses the limitations of the study's methods, identifying the primary areas of uncertainty and the reasons for these, particularly with respect to the aggregation of data on building occupancy and the use of historical rainfall averages. The general applicability of the results based on the building types and locations is also discussed. Effects of future climate variability and extrapolation of economic data are identified as significant issues.

7.2 Use of Aggregated Monthly Precipitation Data

As indicated in Section 6.3, precipitation data for this study are based on average monthly statistics collected by Environment Canada for London, ON, Calgary, AB and Halifax, NS from 1981 through 2010. Also as discussed in Section 6.3, monthly data provide a more accurate way to compare supply with demand compared to using only annual data, as well as allowing cistern volume to be characterized. This results in a much lower proportion of stormwater being collected compared with what is predicted using annual data without the effect of a cistern being considered. The latter approach based on annual data is the basis of most rainwater harvesting calculators available online (RHL, 2016) as well as the method used by the current LEED green building rating system (CaGBC 2009). Based on the results from this study, these calculators therefore should be using monthly precipitation data, particularly if they are intending to evaluate the performance of a collection system for the retention of stormwater.

While monthly precipitation data provide more useful results than annual data, because the monthly information has been aggregated over 30 years, the actual precipitation for a particular month can be considerably different. This means that for a given month or year, the actual performance of a rainwater harvesting system will vary from the predicted performance. It is for this reason that cisterns are commonly sized to provide twice the capacity required to meet the maximum predicted monthly demand, so that the system is able to cope with up to one month of drought conditions.

For example, the summer of 2016 was unusually dry in Halifax, normally one of the wettest locations in Canada. Halifax received only 290mm of rain from May through August (EnviroCan, 2016) compared to the 437mm it has received on average since 1981 (see Table 6.7). In this case a rainwater harvesting system with one month of spare capacity may not have met the demand for toilet flushing at certain times depending on the pattern and volume of storms. Conversely, because a cistern would have been at a constantly low level, the performance of the system for detention of stormwater would have been improved. The reverse would be true in a year of unusually high rainfall, where a cistern would have been maintained at close to its capacity. There would be plentiful water available for toilet flushing but the system would not have much effect on detention of the huge volume of stormwater.

A further limitation of aggregated monthly data is that they do not identify individual storm events, which are the most important issue affecting municipal stormwater infrastructure. A monthly approach effectively characterizes precipitation as a continuous flow every day, as opposed to the intermittent nature of rainfall over the course of a month, with many days without rain, some rainy days, and a few large storms. Apart from a few studies such as O'Carroll (2016) where detailed hourly precipitation information has been collected, there seem to be very few data sets available on the actual pattern of rainfall events. Collecting and publishing this kind of refined data would be an onerous task for Environment and Climate Change Canada, but may become possible with the advent of more advanced automated data collection, analysis and reporting systems. Such refined data showing the actual pattern of rainfall (and snowfall) events on an hourly basis for major jurisdictions across the country would be very valuable, not only for the design of rainwater harvesting systems discussed in this study, but also for design and management of municipal infrastructure including storm sewer networks and flood control systems.

7.3 Variations in Building Occupancy Patterns

As discussed in Section 6.1, there is a limited amount of information available about the average occupancy of most building types. Building codes and design standards tend to be establish the maximum occupancy (or minimum area per person) according to the intended purpose of the building. These parameters are used to determine requirements for a wide range of building components including structural capacity, life safety systems, space conditioning, and numbers of plumbing fixtures. To infer typical occupancy, this study takes the maximum occupancy parameters set out in the National Building Code of Canada and applies an 'occupancy factor' for each type of use derived from information collected from a number of market sources, summarized in the Appendix.

The average occupancy of some building types varies much more than others, as do the patterns of occupancy. For example, Assembly types including Community Centres, Libraries, and Theaters have highly variable occupancy rates with intermittent peaks based on organized events. Educational and Institutional types, in contrast, tend to have much more consistent patterns of occupancy. Contemporary Educational buildings tend to be highly programmed in order to optimize space utilization, operating at close to their maximum capacity during the school year, with systems such as lighting and space conditioning set back during summer months when occupancy is typically at a minimum level. Institutional building types, including Hospitals, Long Term Care Facilities, and Retirement Homes, tend to be managed to maintain close to their full capacity at all times. The occupancy for the large Residential building types that are the subject of this study is relatively high. These include multi-storey Apartments, Student Residences, and Hotels, all of which tend to be developed according to objective market assessments and hence closely follow demand based on demographics. Commercial types, including Office, Retail, and Warehouse buildings, tend to have highly variable occupancy rates that are closely related to local economic conditions.

What this means for this study is that the predicted performance of rainwater harvesting systems is expected to be reasonably accurate for most building types, as it accounts for seasonal variability in monthly occupancy. For some building types, in particular Commercial occupancies, the predicted performance is expected to vary considerably depending on the actual occupancy of the building.

7.4 Selected Locations and General Applicability

As discussed in section 1.6.3, the three locations were selected to provide a diverse range of climate conditions that represent typical conditions across much of southern Canada and the northern United States, including coastal cities like Halifax. arid ones like Calgary, and humid ones like London.

Therefore, the method used in this study to evaluate the potential of rainwater harvesting systems by building type is considered reasonably indicative for the majority of Canadian municipalities, which tend to be clustered along the US border. Similarly, the method is also expected to be applicable to US municipalities that fall within a similar range of climate characteristics. As illustrated in Figure 7.1, the locations selected share similar traits of relatively moderate temperatures, moderate relative humidity, and moderate rainfall compared to the extremes of these conditions elsewhere on the continent. To the extent that there are many other large municipalities in this group, including Toronto, Montreal, Chicago, Pittsburg, and Washington, the method used in this study should be applicable to a large number of buildings in these locations.

Figure 7.1 North American Hygro-Thermal Regions (Lstiburek, 2011a)
C = Calgary, L = London, H = Halifax

In locations further north, such as Edmonton AB, results are not expected to be representative, particularly because of the lack of water from melting snow over the winter months. The accumulation of snow until it melts in the spring would limit the effectiveness of rainwater harvesting systems for most building types, particularly Education buildings with high occupancy during the winter and low occupancy during the summer.

In more southerly locations, the effect of evaporative losses from rain falling on very hot roofs would be a significant factor not accounted for by the method used in this study. Humid southeastern jurisdictions tend to have much higher rainfall throughout the year, generating ample water for toilet flushing but reducing the portion of stormwater detained especially considering the frequency of large storms. In southwesterly locations with more arid conditions, cistern sizes would need to be increased to account for longer dry periods. This would also increase their capacity to detain large storm events, making rainwater harvesting systems a very important strategy there.

7.5 Future Climate Variability

Many studies emerging from the Intergovernmental Panel on Climate Change reports on the global climate have documented increasing climate variability as strongly associated with increasing surface temperature (IPCC 2015). Most authorities agree that surface temperature is anticipated to continue to increase throughout the 21st century, with considerable debate over the degree of increase versus the effect of mitigation efforts. There are some proponents including Allenby (2005) and Morton (2015) of controversial although potentially effective near-term climate engineering strategies that could halt further increases in temperature. However, presuming that such short term measures require a degree of multi-national cooperation that is unlikely to occur, increasing climate variability is expected to continue.

Increased variability of precipitation will affect the accuracy of the method used in this study. Such variability will make the use of aggregated (historical) monthly data less representative of actual rainfall and snowfall patterns, including very large events that will further tax the ability of municipal infrastructure to cope with them. These circumstances would make 'smart' cistern systems discussed in Section 6.5.2 more important as they could adapt to changing conditions and anticipate large events based on short term weather forecasting.

With increased climate variability comes increased difficulty of prediction. However, if the sophistication of climate models also continues to improve, these will become even more important tools for planning infrastructure and designing more resilient systems. As discussed in Section 7.1, more refined data that track actual rainfall events and more robust analytical systems that can identify trends will also be important in optimizing the design of rainwater harvesting systems and improving their performance in stormwater detention.

7.6 Limited Economic Data for Rainwater Harvesting Systems

As discussed in Section 4.4, there is a very limited amount of information available about the capital, operating, and replacement costs for rainwater harvesting systems serving large buildings. In the absence of these data, information on seven projects with which the author has been involved is used to provide an indication of the range of costs for these systems in comparison to the total cost of the buildings they serve. Even for these example projects, however, there is no information on the actual maintenance cost of the systems because this is not tracked separately from that of the whole building. Finally, because these systems have yet to be replaced, the associated costs are untknown and have to be estimated based on the life cycle of the conventional mechanical components of which these systems are comprised.

7.7 Summary

Based on the limitations identified, it is important to acknowledge that the results of this study indicate the *potential* opportunities for rainwater harvesting systems based on the building types and locations examined, not the *actual* performance for specific projects. The findings provide assistance to projects considering green and blue roof alternatives for mitigating stormwater impacts, so that decisions on which systems to pursue can be made based on relevant criteria. A suggested approach to applying these criteria is discussed in the Conclusions.

8. Conclusions

8.1 Developing a Framework for Decision-Making

As discussed in Section 1, flat roofs on large buildings perform a variety of functions, which have a corresponding variety of impacts on the buildings themselves, as well as on their urban context and its infrastructure. Among these numerous factors, mitigating the impacts of stormwater runoff has been identified as a priority for flat roofs based on the criteria established in the prevailing green building rating systems discussed in Section 2. The potential benefits of green and blue roof systems are significant, not only in mitigating stormwater impacts, but also because of their other attributes identified in Sections 3 and 4. These benefits vary considerably depending on the characteristics of a particular building type and the location of its site, and introduce issues of compatibility with other techniques, as summarized in Section 5.

Based on modeling rainwater harvesting systems for a range of building types and locations in Section 6, their performance characteristics have been identified. This enables a comparison to the stormwater mitigation performance of green roofs, which in spite of the extensive research attention green roofs have received, remains difficult to determine with precision. While more predictable, there are some areas of uncertainty with the performance and operating cost of rainwater harvesting systems, due to limited research attention and the constrained scope of this particular study, discussed in Section 7.

Recognizing the complexity of combining these factors, this concluding section develops an approach to the application of those criteria that have been identified as critical in differentiating between green and blue roof opportunities, and offers a framework for applying these systems in large buildings where stormwater impacts are an important issue.

8.2 Green and Blue Roofs as 'Enhanced' Low Impact Development Strategies

Green and blue roofs can be considered as part of a collection of techniques whose primary purpose is to reduce the impact of stormwater runoff on municipal stormwater infrastructure. These techniques serve Low Impact Development Stormwater Management (LID SWM), and most of them encourage rainwater discharged from roofs and other impervious surfaces to infiltrate into the ground instead of entering the municipal storm sewer system. Table 8.1 summarizes the most common strategies, which can be used individually or in combination on any particular project (TRCA, 2010).

Table 8.1 Summary of LID SWM Strategies (TRCA, 2010)

LID Stormwater Management Practice	Depth to high water table or bedrock[1] (m)	Typical Ratio of Impervious Drainage Area to Treatment Facility Area	Native Soil Infiltration Rate (mm/hr)[3]	Head[4] (m)	Space[5] %	Slope[6] %	Pollution Hot Spots[7]	Set backs[8]
Rain barrel	Not applicable	[5 to 50 m^2][2]	Not applicable	1	0	NA	Yes	None
Cistern	1	[50 to 3000 m^2][2]	Not applicable	1 to 2	0 to 1	NA	Yes	U, T
Green roof	Not applicable	1:1	Not applicable	0	0	0	Yes	None
Roof downspout disconnection	Not applicable	[5 to 100 m^2][2]	Amend if < 15 mm/hr[9]	0.5	5 to 20	1 to 5	Yes	B
Soakaway, infiltration trench or chamber	1	5:1 to 20:1	Not a constraint	1 to 2	0 to 1	< 15%	No	B, U, T, W
Bioretention	1	5:1 to 15:1	Underdrain required if < 15 mm/hr	1 to 2	5 to 10	0 to 2	No	B, U, W
Biofilter (filtration only Bioretention design)	Not applicable	5:1	Not applicable	1 to 2	2 to 5	0 to 2	Yes	B, T
Vegetated filter strip	1	5:1	Amend if < 15 mm/hr[9]	0 to 1	15 to 20	1 to 5	No	None
Permeable pavement	1	1:1 to 1.2:1	Underdrain required if < 15 mm/hr	0.5 to 1	0	1 to 5	No	U, W
Enhanced grass swale	1	5:1 to 10:1	Not applicable	1 to 3	5 to 15	0.5 to 6	No	B, U
Dry swale	1	5:1 to 15:1	Underdrain required if < 15 mm/hr	1 to 3	5 to 10	0.5 to 6	No	B, U, W
Perforated pipe system	1	5:1 to 10:1	Not a constraint	1 to 3	0	< 15%	No	B, U, T, W

Notes:
1. Minimum depth between the base of the facility and the elevation of the seasonally high water table or top of bedrock.
2 Values for rain barrels, cisterns and roof downspout disconnection represent typical ranges for impervious drainage area treated.
3. Infiltration rate estimates based on measurements of hydraulic conductivity under field saturated conditions at the proposed location and depth of the practice.
4. Vertical distance between the inlet and outlet of the LID practice.
5. Percent of open pervious land on the site that is required for the LID practice.
6. Slope at the LID practice location.
7. Suitable in pollution hot spots or runoff source areas where land uses or activities have the potential to generate highly contaminated runoff (*e.g.*, vehicle fueling, servicing or demolition areas, outdoor storage or handling areas for hazardous materials and some heavy industry sites).
8. Setback codes: B = Building foundation; U = Underground utilities; T = Trees; W = drinking water wellhead protection areas.
9. Native soils should be tilled and amended with compost to improve infiltration rate, moisture retention capacity and fertility.

These strategies are widely endorsed by municipal development approval authorities as alternatives to stormwater detention ponds, and have gradually been adopted, particularly by building projects seeking certification under the LEED or Green Globes rating systems where a number of credits are associated with them (CaGBG,, 2009; ECD, 2012). The Living Building Challenge rating system also requires that projects incorporate these measures as part of minimizing impacts from growth and achieving ‘net positive water’ (ILFI 2014). With the exception of green or blue roof systems, the effectiveness of these measures depends on infiltration of water into the ground. Therefore, the composition of the local subsoil is critical, as infiltration-based systems are more difficult to implement in soils with low permeability or locations with high water tables. The infiltration-based systems also work only when water is in liquid form, and therefore they must be carefully designed with sub-drains and overflows into the municipal storm system to operate in cold weather when the ground may be partially frozen but rain or melting snow is still generating runoff.

A systematic review by Dietz (2007) found that while numerous studies confirm the general effectiveness of infiltration strategies and consensus on best practices, there are limited data on their actual performance in the field. There is some evidence that infiltration systems do continue to perform in poor soils or under freezing conditions, although the degree of performance reduction is uncertain. In Canadian settings, it is therefore difficult for designers to rely on these strategies being functional under all conditions, which means that an on-site stormwater system must be designed to receive all the water in the worse-case scenario. Therefore, there tend to be few savings from reduced traditional infrastructure to offset the cost of the LID SWM measures. This conservative 'belt and suspenders' approach to implementing these measures will presumably relax as they become more widely used and their attributes better understood.

Both green and blue roofs are distinct from infiltration-based strategies in that they detain rainwater on the roof, or in a cistern in the case of rainwater harvesting, before it enters an on-site stormwater management system. As discussed in Sections 3 and 4, both green and blue roofs have more predicable performance characteristics compared with the less certain characteristics of infiltration-based LID SWM techniques. In the case of green roofs, the substantial amount of data on installed systems, particularly from Green Roofs for Healthy Cities (Peck & Liauwala, 2010), provides designers with some confidence in their actual performance. The performance of blue roofs is even more predictable, especially for flow control roof drains, which have become such a common measure that they are often overlooked as an LID SWM strategy (and are not listed with the other measures in Table 8.1). While rainwater harvesting systems are less common, as explained in Section 4, their performance is nevertheless a function of relatively few variables associated with roof area, rainfall patterns, cistern capacity, and water demand.

Because both green and blue roof systems offer benefits beyond their primary purpose of stormwater detention, they can be considered 'enhanced' LID SWM strategies. As discussed in Section 3, green roofs have a number of other attributes, primarily mitigating the urban heat island effect, contributing to local biodiversity, and enhancing the aesthetic appearance of roof surfaces when these are visible. As discussed in Section 5, blue roofs tend to be more compatible with other strategies for utilizing roof surfaces to offset building impacts, including increased insulation thickness, high albedo roof membranes, and roof-mounted solar thermal or photovoltaic arrays. In Section 6, it was shown that rainwater harvesting systems for the wide range of building types evaluated in three Canadian cities are capable of offsetting all the potable water that would normally be used for flushing toilets or urinals in virtually every building type across a wide range of occupancy categories.

8.3 Importance of Reducing Stormwater Impacts for Selected Locations

Reducing the impacts of stormwater on municipal sewer systems is important for those jurisdictions with combined storm and sanitary mains. For these systems, excess stormwater overwhelms the system and causes untreated sewage to bypass treatment plants and be discharged directly into surface waters. For two of the locations selected in this study, London, ON and Halifax, NS, this is a serious issue. Across Canada, 15 of the 22 largest municipalities surveyed in 2004 had combined sewer systems, which in some cases represented over 50% of the total sewer capacity (Sierra, 2004).

In the case of London, ON, a 2013 Ecojustice study ranked the municipality as second worst of the twelve largest cities in Ontario in terms of sewage treatment quality and frequency of untreated discharges, largely due to combined sewer systems. Table 8.2 summarizes the results, showing London with an overall grade of C- (Ecojustice, 2013).

Table 8.2 Ontario Cities Ranked by Sewage Treatment Quality (Ecojustice, 2013)

City	Rank	Grade
Peel Region	1st	A-
York & Durham	2nd	B+
Collingwood	3rd	B+
Kitchener-Waterloo	4th	B+
Midland	5th	B
Brockville	6th	B
Sarnia	7th	C+
Sudbury	8th	C
St. Catharines	9th	C
Toronto	10th	C
London	11th	C-
Windsor	12th	C-

In the case of Halifax, NS, a study in 2004 by the Sierra Legal Defence Fund found that the metropolitan area discharged over 65 billion litres of raw sewage annually, resulting an overall grade of D that placed it among the worst of the 22 municipalities studied across Canada. This poor performance was associated in part with the fact that approximately 30% of the storm and sanitary sewers are combined. A summary of these results is provided in Table 8.3 (Sierra, 2004).

Of course, both these municipalities are aware of this issue and are working to gradually replace their combined sewer systems, a process that will take many decades and involve major disruptions to the established urban areas where this older infrastructure tends to be located.

Table 8.3 Canadian Sewage Treatment Improvements, 1999-2004 (Sierra, 2004)

City	Summary	1999 Grade	+/-	2004 Grade
Brandon	Implemented 100% secondary treatment and UV disinfection. Combined overflow of up to 2.8 million litres per year.	D	+	B-
Calgary	UV disinfection added to 100% tertiary treatment. Additional upgrades in the works ($250 million).	A	+	A+
Charlottetown	Primary treatment only. Volume of discharges not monitored. Plans to upgrade to secondary by 2006.	E	+	E+
Dawson City	Still discharging one billion litres of raw sewage per year. Await funding for upgrade to secondary treatment.	F-	+	E
Edmonton	Upgraded to 100% tertiary treatment and UV disinfection	B+	+	A-
Fredericton	Secondary treatment with UV disinfection. No major improvements since 1999. Low percentage of CSOs.	B	NC	B
Halifax	More than 65 billion litres of raw sewage discharged each year. Regional plants provide secondary or tertiary treatment.	E-/C	+	D
Hamilton	Upgrades to secondary and tertiary treatment. Discharges 5.9 billion litres of raw sewage each year. Only 88% of population served.	C-	+	C+
Montreal	Primary treatment only. No discernible progress made.	F+	-	F
Ottawa	Secondary treatment. Seasonal chlorine disinfection, no dechlorination. Overflow system controls installed.	C	+	B-
Quebec City	Secondary treatment with seasonal UV disinfection. Combined sewer overflow events reduced.	C	+	B
Regina	Enhanced secondary treatment with expanded UV disinfection. Extensive upgrades planned.	B	+	B+
Saint John	Reduction in combined sewers. Primary and secondary treatment. Almost 40% of population still do not receive treatment.	E	+	D
Saskatoon	100 % secondary treatment. Minimal changes since 1999.	C+	NC	C+
St. John's	More than 33 billion litres of raw sewage discharged.Primary sewage treatment plant under construction.	F-	+	E
Toronto	Toughest Sewer-Use Bylaw in country. Secondary treatment. Still discharge 9.9 billion litres of untreated sewage and run-off.	C/B	+	B-
Vancouver	Up to 22 billion litres of combined overflows each year. Upgrades to 100% secondary treatment won't be completed until 2030.	C-	-	D
Victoria	Preliminary screening, no treatment. More than 34 billion litres of raw sewage still discharged each year.	F-	-	Suspended
Whitehorse	Secondary Treatment. Minimal progress since 1999. Efforts under way to reduce volumes of sewage. No raw sewage discharges.	B-	NC	B-
Winnipeg	100% secondary treatment. Reduced number of combined sewers, still one billion litres of combined sewer overflow per year.	C	+	B-
Whistler	100% tertiary treatment.	-		A
Yellowknife	100% secondary treatment with natural UV disinfection. Only minor changes since 1999.	B+	NC	B+

In the case of Calgary, Table 8.3 shows that the Sierra study ranked the municipality's sewage treatment system as among the best in Canada, with no combined sewers and an overall grade of A+. While this means that Calgary avoids the negative effects of overflows from combined systems, its storm sewer infrastructure nevertheless discharges rain directly (untreated) into the Bow River. Although it contains no sewage, this water does collect any debris and chemical residues from hard surfaces and conveys them to the river. As observed by Sedlack (2014):

> *Although a properly functioning combined sewer will burp out a mixture of stormwater runoff and household waste a few times a year, a separate [storm] sewer conveys whatever is on the impervious surfaces of the city to urban waterways during every storm.* Sedlack (2014) p.128.

This reality provides grounds for reducing stormwater volumes in any municipality, not only those like London and Halifax with combined sewer systems, to mitigate the impacts on natural water courses and their associated ecosystems. Because green and blue roof systems offer the most predicable level of performance, these should take precedence over other infiltration-based techniques whose performance in Canadian climates is much less predictable.

8.4 Decision Criteria for Green and Blue Roof Systems

As discussed in Section 4, the simplest type of blue roof system consists of flow control roof drains, which detain rainwater and gradually release it over a period of time. The fact that this is a commonly used and low cost technique makes it useful as a basis for comparison with the attributes of both extensive green roofs and rainwater harvesting systems that are the primary subjects of this study.

Both roofs with flow control drains and green roofs are capable of detaining rainwater, including heavy storms. As noted in Section 3, the modest thermal resistance provided by a green roof can be accomplished with a small increase in the roof insulation itself, at an insignificant cost and weight of material compared to the growing medium required to support plants. Likewise, the contributions made by a green roof to reducing urban heating can also be accomplished by incorporating a high albedo roof membrane as part of a conventional roof with flow control drains.

In light of these considerations, combined with the substantial capital, operating, and maintenance costs associated with green roofs, it is remarkable that they have continued to increase in prevalence. While some of this increase could be attributed to effective marketing by green roof system manufacturers or over-enthusiastic endorsement by building designers, the increasing implementation of green roofs belies other powerful motivations that go beyond either hyperbole or the quantifiable biophysical factors discussed above. As discussed in Section 3, these motivations are primarily the contributions green roofs make to biodiversity where this is otherwise limited in an urban setting, as well as their aesthetic value when they are visible or accessible either to building occupants or their neighbours. Although difficult to quantify, neither of these motivations is trivial, considering the increasing importance society is placing on both the environmental health and the visual quality of the urban environment.

A similar comparison can be made between flow control roof drains and rainwater harvesting systems. From the point of view of stormwater management, both approaches offer predicable results. In the absence of data on the performance of rainwater harvesting systems for large buildings, Section 6 explored opportunities for their application using a number of variables for building size, occupancy type, and local climate characteristics for three Canadian municipalities. This showed that the significance of rainwater harvesting systems in detaining stormwater largely depends on the degree of utilization of the harvested water, particularly for flushing toilets and urinals. The demand for harvested water is therefore a function of the number of people under the roof, and favours building types with higher concentrations of people, longer hours of use, and more storeys. Hence, ideal candidates for rainwater harvesting systems are higher buildings that contain a mix of uses whose occupancy patterns complement each other, generating a large and consistent demand for the harvested water.

Beyond their contribution to stormwater management, rainwater harvesting systems can significantly offset the normal demand for potable water. Although these systems are often used for outdoor irrigation, this tends not to be necessary given the availability of indigenous plant material suited to local precipitation patterns. When used inside buildings, harvested rainwater can offset all of the potable water normally used for flushing toilets and urinals for the wide range of building types examined in Section 6. Because municipally supplied water is metered, offsetting its use results in a corresponding savings in municipal water charges.

Data are provided in Section 4 for a number of projects the author has been involved with, summarized in Table 4.3. Rates for water and sewer charges across Canada are shown in Figure 4.4, with an average cost of $2.20/m^3 of water delivered. Typical operating and maintenance costs were conservatively estimated in Section 4 at $0.94/m^3. Therefore the net savings are $2.20 – $0.94 = $1.26/m^3. Using these figures, Table 8.4 summarizes the simple cost payback period for each of the example systems listed in Table 4.3.

Table 8.4 Payback Calculations for Example Rainwater Harvesting Systems (from Section 4)

Category Building Type	**RWH System Cost**	**Annual Water Savings m^3**	**Net Savings $/m^3**	**Annual Savings $**	**Simple Payback (yrs)**
#1 Assembly Community Centre	$86,000	674	$1.26	$850	101
#2 Education College/ University	$60,000	672	$1.26	$846	71
#3 Education College/ University	$221,000	3,818	$1.26	$4,811	58
#4 Education College/ University	$89,000	1,441	$1.26	$1,816	92
#5 Institution Long Term Care	$180,000	1,670	$1.26	$2,104	86
#6 Institution Long Term Care*	$53,000	n/a	n/a	n/a	n/a
#7 Institution Retirement Home	$219,000	3,947	$1.26	$4,973	44

* Project #6 rainwater harvesting system used for outdoor irrigation only

As discussed in Section 4, there are numerous differences among the example systems, particularly in the sophistication of their water filtration and treatment components. The lengthy payback periods indicate that a case cannot be made for these systems as simple economic investments, at least when based on current water and sewer rates which may not account for the system costs of water delivery and sewage disposal including their environmental impacts. However, if funds can be allocated separately for the initial capital cost, which while substantial is less than 1% of the total building cost in the examples cited, the annual savings would more than offset expected maintenance costs.

Based on the findings of this study, some key decision criteria can be identified to assist the proponents of a particular project with making an informed selection among alternative approaches to handing the rain that inevitably will fall on the roofs of their buildings. These are illustrated in Figure 8.1, showing the suggested relationship between the variables discussed and the alternative systems.

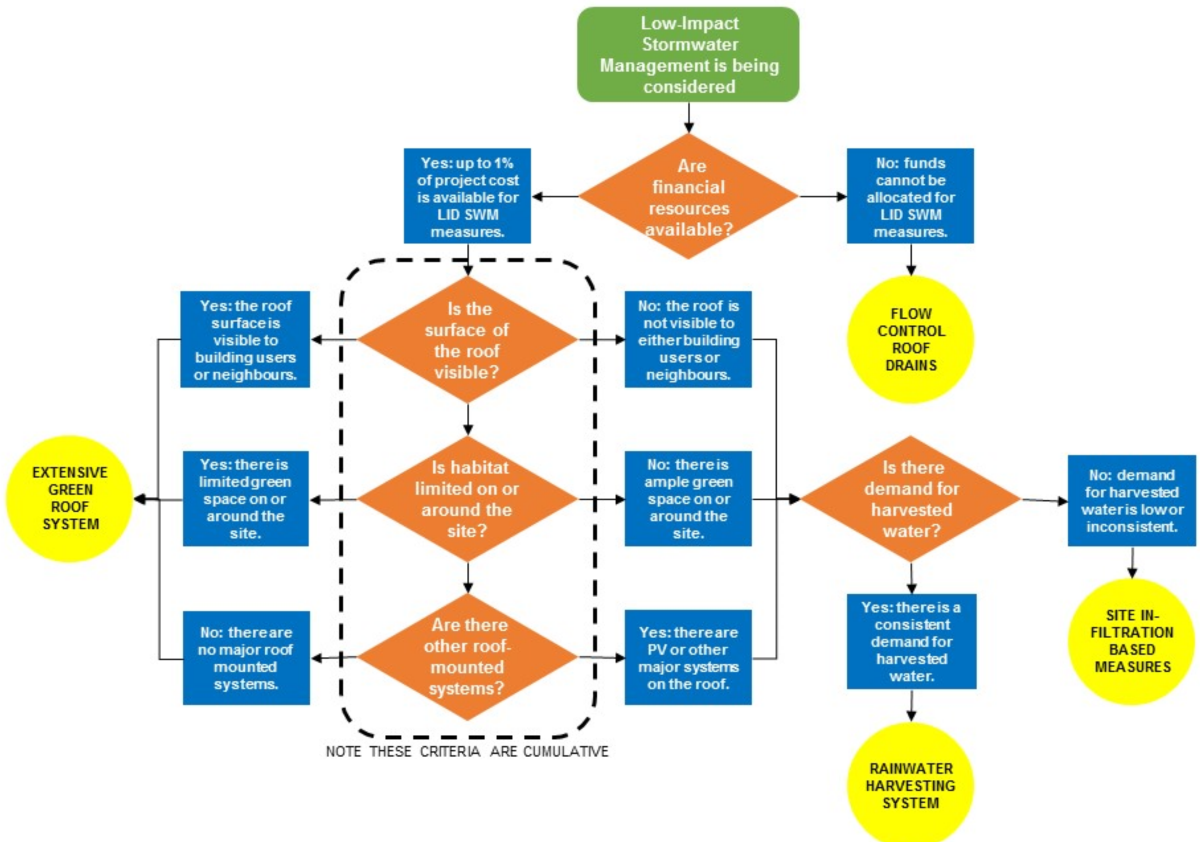


Figure 8.1 Green and Blue Roof Decision Criteria Flowchart

This flowchart has been developed as a result of the exploration in this study into the attributes of green and blue roofs, based on both the literature and the empirical examples available. It offers a suggested approach to deliberations leading to the decision whether to utilize either an extensive green roof or a rainwater harvesting system in lieu of conventional flow-control roof drains or other infiltration-based measures. As indicated above, the initial decision depends on whether the proponents are willing commit financial resources to consider alternative approaches. From that point, much depends on the characteristics of the particular project and the value the proponents place on the less tangible but important attributes of green roofs on one hand, and their openness to managing the relatively complex and redundant components of a rainwater harvesting system on the other. The key factors identified in this study in selecting green versus blue roofs (visibility of the roof surface, importance of habitat creation, and presence of other rooftop systems) are noted as cumulative because a decision should be made in light of the combination of these considerations.

So far, the prevalence of green roofs shows that their merits have been considered very important, although the findings of this study show that blue roof attributes can have greater benefits for stormwater mitigation and potable water conservation at a similar magnitude of capital and operating cost. While economics may not be a primary motivation, it is very likely that the cost of municipally supplied services, including water, will continue to increase. As Sedlack (2014) again observes:

> *But the knowledge that a more expensive future is coming can also be the wakeup call we need to not just patch over our aging water infrastructure, but to reinvent urban water systems in a way that ensures that they provide a more reliable source of water that will simultaneously protect our health and the environment.* Sedlack (2014) p.186

For the large buildings that are the subject of this study, rainwater harvesting systems have the potential to make a substantial difference in reducing stormwater impacts on downstream infrastructure while also reducing demand from upstream municipal water supply systems. As more of such buildings employ these systems, the cumulative benefits for cities will become more significant. Like the development of green roofs, greater awareness of appropriate applications for rainwater harvesting systems and less uncertainty over their design and operation will hopefully lead to their wider acceptance across the country.

8.5 Other Issues and Considerations for Additional Research

8.5.1 Water as an Undifferentiated and Undervalued Commodity

Especially in Canada with its access to extensive rivers, lakes, and aquifers, water is perceived as a virtually unlimited commodity. Hamlin (2000) discusses the issues with this contemporary attitude to water as an 'essentialist' notion of it as a single substance with various impurities, leading to the commonly asked first question about a new water source being, 'Is it safe?' This is contrasted with historical attitudes that understood water more empirically as possessing many different qualities with equally many purposes, to the extent that these 'waters' were considered different substances. It is argued that the implications for water policy have been significant, leading to all publicly supplied water expected to be 'maximally pure' in spite of its end use. Feidelson (2010) advocates for a change in policy based on this alternative notion of many types of waters, along with better definition of each type according to its physical properties as well as its importance to both human and environmental health. It is suggested that beyond a level of consumption essential for human wellbeing (estimated at 50-60m^3 per person per year), publically supplied water should be priced as a commodity to include its full social and environmental costs.

Compared to current water policy in Canada that prices water based on limited economic inputs and discounts this already low rate as consumption increases for large volume users, the differentiation of numerous waters by source and application would be an opposite approach. Sedlack (2014) argues for just such a change in policy, and along with it a more decentralized water system connecting sources and uses more closely. If such predictions are bourne out, this would provide a strong economic incentive for the rebirth of rainwater harvesting systems in Canada, which were common before the advent of municipal water mains in the early 20th century.

8.5.2 Inadequacy of Canadian Standards for Rainwater Harvesting Systems

As discussed in Section 4, in the absence of established standards for the design of rainwater harvesting systems for large buildings, individual designers are responsible for determining the appropriate measures to use, particularly for water filtration and treatment. Likewise, municipal approval authorities must determine the acceptability of these systems based on limited information about their risks and benefits.

This situation tends to lead to excessively conservative measures being adopted to manage uncertain risks, as the cost of incorporation of these systems has no direct impact on either the designer of the system or the municipal authority approving it. While there is a CSA standard for non-potable water systems, it fails to identify appropriate quality standards or treatment procedures, making it virtually useless (CSA, 2006). A standard is needed for rainwater harvesting systems that establishes reasonable parameters for system design and water quality, likely dependent on the occupancy of the building in which the harvested rainwater is used.

8.5.3 Lack of Performance Data for Rainwater Harvesting Systems

As discussed in Sections 4 and 6, there are limited data available on the actual performance of rainwater harvesting systems, including their initial cost, annual water savings, and annual operating cost (including maintenance). Collection of these data may be difficult considering that much of the information pertains to private buildings and may be sensitive, particularly when substantial costs are involved.

A further difficulty is that there are no requirements for metering water collected by cisterns. In the absence of a separate meter, the amount of water saved can be approximated by comparing actual water use to what would normally be expected based on the building occupancy and types of fixtures.

In light of the common concerns over the cost of operating and maintaining rainwater harvesting systems, the absence of objective information is frustrating. As indicated for the example projects discussed above, a conservative estimate of the operating cost is less than the typical cost of the water saved, even at today's prices which are expected to increase dramatically.

8.5.4 Development of Detailed Modeling for Rainwater Harvesting System Design

With the availability of detailed weather data including hourly precipitation patterns for any location, it is possible to construct detailed models that match the capacity of a rainwater harvesting system to the supply, reducing the need to significantly oversize the cistern and other components. This would also help to identify the types of projects that are best suited to rainwater harvesting in a particular location.

8.5.5 Development of Appropriate Municipal Incentive Programs

Because municipalities have an interest in the demand on both their water supply and stormwater discharge systems, incentives for implementation of rainwater harvesting could be justified based on cost/benefit analysis. To avoid introducing a separate mechanism for this purpose, municipalities could take advantage of systems already in place, particularly water consumption fees and development charges.

In the case of potable water fees, these use monthly water consumption to determine to the volume of both water delivered and sewage received by the municipal infrastructure. Using harvested rainwater for flushing toilets and urinals reduces the demand for potable water, but does not reduce the volume of sewage discharged. In spite of this, municipalities could allow the full amount of the water and sewer charges to be refunded based on the metered water savings instead of refunding only the water consumption portion.

Development charges are normally based on the area of new floor space being constructed, and are intended to account for the impact on existing municipal infrastructure, including roads, schools, and emergency services, as well as water, sewage, and stormwater systems. These charges are substantial and are normally paid at the commencement of construction as a pre-condition for obtaining a building permit. Considering that the availability of capital funds is a key criterion in determining whether a rainwater harvesting system can be considered, a reduction in development charges, in proportion to reduced impacts on municipal water and storm systems, could be an extremely effective incentive.

8.5.6 Development of 'Smart' Cisterns

As part of the discussion in Section 6 regarding possible ways to optimize performance, the opportunity to link the operation of rainwater harvesting systems to real-time weather data was identified. This would enable the system to predict storm patterns and conserve capacity in the cistern to receive them. Such a system could significantly improve the effectiveness of the cistern in detaining rain from a higher proportion of the largest storms that are the cause of the worst downstream impacts. Without such 'intelligent' capabilities, the impact on stormwater retention is limited by the random nature of large storm events.

8.5.7 Development of Packaged 'Plug and Play' Installations

All of the rainwater harvesting systems serving the large buildings discussed in this study were designed and constructed as unique installations, with many variations between individual systems. Similarly, each system has unique operating and maintenance requirements. In the case of three of the seven examples cited difficulties with operating and maintenance have led the building managers to bypass the systems.

At the same time, the installation of rainwater harvesting systems has increased internationally, particularly in Australia and India. It is conceivable that as these systems become mass produced, widely available, and automated, they will identify a market in North America, not only in the arid southwest of the United States but also in Canada as the value of water conservation increases. The availability of rainwater harvesting systems that are supplied as a complete package along with a reliable operating system requiring minimal oversight would transform their acceptance by the broad ICI building sector. For example, the incorporation of sensors that monitor filters and that automatically activate disinfection systems would greatly reduce the time and cost associated with manual inspections and testing. This is not unlike the progress made with packaging and automation for other complex systems, from compact GPS navigation aids to massive internet data centres.

8.6 A Hidden Urban Resource

Flat roofs are normally invisible, both to building occupants and to pedestrians. Nonetheless, they are a major feature of the urban landscape. Roof surfaces also have significant impacts on the urban environment, particularly in the rapid discharge of rainwater during storms. Out of the collection of low impact development techniques available to manage stormwater impacts, green and blue roofs offer significant benefits beyond the control of excess rainfall, most importantly habitat creation and water conservation. Green and blue roof systems, appropriately applied and combined with other strategies that conserve energy, reduce emissions, and mitigate urban heating, enable the roofs of large buildings to be transformed from a hidden opportunity to become an important urban resource for Canadian cities.

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Appendix

A.1 Supporting Material for Section 4

Project details for example rainwater harvesting systems have been collected from proprietary technical drawings and specifications, with the exception of those for Project #3 that were sourced online. Cost data are taken from project budget reports. These data and sources are summarized in Table A.1

Table A.1 Project Details for Example Rainwater Harvesting Systems

Rainwater Harvesting Example Project Data — Current Date: Dec-16 — Escalation Rate: 2%

Project Number	7	2	1	3	5	6	4
Project Name	Sisters Residence	Lassonde Pavilion	Stoney Creek Community Centre	Ivey School of Business	Earls Court Nursing Home	University Gates Nursing Home	New Engineering Building
Location	London ON	London ON	London ON	London ON	London ON	Waterloo ON	London ON
Owner	Sisters of St Joseph	Western Univeristy	City of London	Western University	Sharon Village Care Homes	Schlegel Villages	Western University
Category	Instiution	Education	Assembly	Education	Institution	Institution	Education
Type	Retirement Home	College/ Unversity	Community Centre	College/ Unversity	Long Term Care Home	Long Term Care Home	College/ University
Tender Date	Oct-06	Nov-07	Jun-09	Aug-11	Feb-13	Aug-13	16-Sep
Escalation	1.22	1.20	1.15	1.10	1.06	1.06	1.00
RWH System Cost							
Original	$ 180,000	$ 50,000	$ 75,000	$ 252,000	$ 170,000	$ 50,000	$ 166,499
Current	$ 219,419	$ 59,755	$ 86,151	$ 278,228	$ 180,405	$ 53,060	$ 166,499
Building Cost							
Original	$ 21,692,000	$ 18,009,000	$ 20,969,000	$ 110,000,000	$ 17,524,000	$ 25,239,000	$ 34,286,000
Current	$ 26,442,427	$ 21,522,422	$ 24,086,790	$ 121,448,888	$ 18,596,609	$ 26,783,829	$ 34,286,000
Building Area							
sq feet	141,612	48,204	72,635	274,000	89,882	153,800	141,612
sq metres	13,156	4,478	6,748	25,455	8,350	14,288	13,156
RWH $/m^2	$ 16.68	$ 13.34	$ 12.77	$ 10.93	$ 21.61	$ 3.71	$ 12.66
RWH/Bldg %	0.83%	0.28%	0.36%	0.23%	0.97%	0.20%	0.49%
RWH Features							
Cistern vol m^3	30	10	6	73	15	5	30
Filtration	cartridge	cartridge	dual inline	unknown	cartridge	cartridge	sand
Treatment	none	none	none	none	ultraviolet	none	ultraviolet
Outdoor Use	no	no	no	no	no	irrigation	no
Indoor Use	toilets & urinals	toilets & urinals	toilets & urinals	toilets, urinals & cooling tower	toilets & urinals	no	toilets & urinals
In Operation?	yes	no	yes	no	no	yes	under construction
Sources of Project Details	Cornerstone Construction Docs 17SEP2006	Shore Tilbe Irwin Construction Docs 30OCT2007	Perkins+Will Construction Docs 5MAY2009	Ivey Business School www.ivey.uwo.ca/ new-building/ publication.pdf 17NOV2016	Cornerstone Construction Docs 10JAN2013	Cornerstone Construction Docs 17JUN2016	Perkins+Will Construction Docs 15SEP2016
Sources of Cost Data	McKay Cocker Project Budget 27OCT2006	CM2R Cost Report 23NOV2007	McKay Cocker Project Budget 10JUN2009	Western University email 12DEC2016	Bronnenco Cost Report 22FEB2013	Van Del Budget Report 6AUG2013	Norlon Contract Breakdown 12DEC2016

A.2 Supporting Material for Section 6

Occupancy data for each building type, except education, are taken from the U.S. Environmental Protection Agency EnergyStar Portfolio Manager Data Trends, available at: https://www.energystar.gov/sites/default/files/tools/DataTrends_All_20150129_508.compressed.pdf.

Occupancy data for education building types are taken from the US Department of Energy Technical Support Document: Development of the Advanced Energy Design Guide for K-12 Schools, available at http://www.nrel.gov/docs/fy07osti/42114.pdf.

Data for occupancy schedules for each building type are taken from the U.S. Department of Energy Commercial Reference Building Models of the National Building Stock available from: http://www.nrel.gov/docs/fy11osti/46861.pdf.

The numbers of toilets and urinals required per person by occupancy type are taken from the 2010 National Building Code of Canada available at: http://www.nrc-cnrc.gc.ca/eng/publications/codes_centre/2010_national_building_code.html.

Utilization rates per person by occupancy type for toilets and urinals are taken from the LEED v2009 Water Use Reduction Calculator available at: http://www.usgbc.org/resources/2009-water-use-reduction-calculator.

Fixture performance data are based on International Plumbing Code standards available at: https://law.resouce.org/pub/us/code/ibr/icc.ipc.2009.pdf.

Monthly precipitation data are taken from Environment Canada's Canadian Climate Normals 1981-2010 for each location, as follows.

Calgary, AB:
http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=2205&autofwd=1

London, ON:
http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=4789&autofwd=1

Halifax, NS:
http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=6357&autofwd=1

The data above are compiled for each building category and type in Table A.2 for Calgary, Table A.3 for London, and Table A.4 for Halifax. References sources and formulae are listed in column 'R' of each table.

Table A.2 Compiled Data for Calgary, AB

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
3	**CRITERIA**	**UNITS**	**ASSEMBLY OCCUPANCIES**			**EDUCATIONAL OCCUPANCIES**			**INSTITUTIONAL OCCUPANCIES**			**RESIDENTIAL OCCUPANCIES**			**COMMERCIAL OCCUPANCIES**			**DATA SOURCES**
4	**BUILDING TYPE**		Community Centre	Library	Theatre	Elementary	Secondary	Post-Secondary	Hospital	Long Term Care	Retirement Home	Apartment	Student Residence	Hotel	Office	Retail	Warehouse	
5	**AREA DATA**																	
6	Roof Area	m2	5,000	2,500	2,500	5,000	10,000	10,000	10,000	5,000	5,000	5,000	5,000	5,000	5,000	10,000	10,000	INPUT VARIABLE
7	Storeys	#	2	1	1	2	2	6	8	3	6	6	5	5	2	1	1	INPUT VARIABLE
8	Occupied Area	m2	10,000	2,500	2,500	10,000	20,000	60,000	80,000	15,000	30,000	30,000	25,000	25,000	10,000	10,000	10,000	= LINES 6x7
9																		
10	**OCCUPANT DATA**																	
11	Area/Occupant	m2/p	15	20	5	11	13	16	30	60	42	200	44	44	40	232	155	EnergyStar datatrends
12	Occupancy Factor	%	50%	25%	75%	90%	90%	75%	90%	90%	90%	90%	90%	75%	75%	25%	50%	EnergyStar datatrends
13	Total Occupants	p	333	31	363	794	1,346	2,901	2,403	225	639	135	509	424	186	11	32	= LINES 8/11*12
14	Ratio F/Total	%	50%	50%	50%	50%	50%	50%	50%	75%	65%	50%	50%	50%	50%	50%	50%	EnergyStar datatrends
15	Females	p	167	16	182	397	673	1,450	1,201	169	416	68	254	212	93	5	16	= LINES 13x14
16	Males	p	167	16	182	397	673	1,450	1,201	56	224	68	254	212	93	5	16	= LINES 13-15
17																		
18	**OCCUPANCY DATA**																	
19	Hours per day	hr	12	12	4	6	6	6	24	24	24	12	16	24	8	12	24	EnergyStar datatrends
20	Days per week	d	7	7	4	5	5	5	7	7	7	7	7	7	5	7	7	EnergyStar datatrends
21	Weeks per year	wk	50	50	40	40	40	32	52	52	52	52	32	52	52	52	52	EnergyStar datatrends
22	Hours per year	hr/p	4,200	4,200	640	1,200	1,200	960	8,736	8,736	8,736	4,368	3,584	8,736	2,080	4,368	8,736	= LINES 19x20x21
23																		
24	**FIXTURE DATA**																	
25	Females per toilet	p	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	NBC (2010) Part 3.7
26	Males per toilet	p	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	NBC (2010) Part 3.7
27	Toilet Number	#	15	1	16	36	61	131	108	10	28	6	23	19	8	0	1	= LINES 15/25
28	Toilet Flow	l/f	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	= LINES 16/26
29	Males per urinal	p	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	NBC (2010) Part 3.7
30	Urinal Number	#	17	2	18	40	67	145	120	17	42	7	25	21	9	1	2	LINES 16/29
31	Urinal Flow	l/f	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	ICC (2009)
32																		
33	**UTILIZATION DATA**																	
34	Toilets - Female	f/hr	0.070	0.072	0.100	0.519	0.513	0.504	0.246	0.227	0.218	0.215	0.216	0.212	0.381	0.376	0.375	LEED NC-2009
35	Toilets - Male	f/hr	0.015	0.016	0.025	0.173	0.171	0.168	0.221	0.215	0.211	0.210	0.211	0.210	0.126	0.126	0.125	LEED NC-2009
36	Urinals - Male	f/hr	0.055	0.056	0.075	0.346	0.342	0.336	0.025	0.013	0.006	0.005	0.005	0.003	0.255	0.251	0.250	LEED NC-2009
37																		
38	**DAILY DEMAND**																	
39	Female fixtures	l/d	840	81	436	7,415	12,413	26,301	42,526	5,518	13,029	1,043	5,269	6,472	1,699	146	872	= LINES 15x19x28x34
40	Male fixtures	l/d	598	58	316	5,602	9,378	19,872	40,940	1,802	6,942	1,034	5,224	6,444	1,282	110	659	= LINES 16x19(28x35+31x36)
41	**Total Demand**	**l/d**	**1,438**	**139**	**752**	**13,017**	**21,791**	**46,172**	**83,466**	**7,320**	**19,971**	**2,077**	**10,494**	**12,916**	**2,981**	**256**	**1,531**	= LINES 39+40
42																		
43	**ANNUAL DEMAND**																	
44	Female fixtures	l/yr	294,000	28,301	69,752	1,482,954	2,482,508	4,208,118	15,479,364	2,008,598	4,742,671	379,607	1,180,304	2,355,837	441,741	53,037	317,374	= LINES 15x22x28x34
45	Male fixtures	l/yr	209,300	20,180	50,571	1,120,454	1,875,673	3,179,467	14,902,168	656,019	2,526,864	376,363	1,170,278	2,345,655	333,406	40,081	239,793	= LINES 16x22(28x35+31x36)
46	**Total Demand**	**l/yr**	**503,300**	**48,480**	**120,323**	**2,603,408**	**4,358,181**	**7,387,584**	**30,381,532**	**2,664,617**	**7,269,536**	**755,970**	**2,350,582**	**4,701,492**	**775,147**	**93,117**	**557,167**	= LINES 44+45
47																		
48	**ANNUAL SUPPLY**																	
49	Annual Precip	mm	418.8	418.8	418.8	418.8	418.8	418.8	418.8	418.8	418.8	418.8	418.8	418.8	418.8	418.8	418.8	EnviroCan (2016)
50	Roof Area	m2	5,000	2,500	2,500	5,000	10,000	10,000	10,000	5,000	5,000	5,000	5,000	5,000	5,000	10,000	10,000	= LINE 6
51	Gross Volume	l	2,094,000	1,047,000	1,047,000	2,094,000	4,188,000	4,188,000	4,188,000	2,094,000	2,094,000	2,094,000	2,094,000	2,094,000	2,094,000	4,188,000	4,188,000	= LINES 49*50
52	Evaporative Losses	10%	- 209,400	- 104,700	- 104,700	- 209,400	- 418,800	- 418,800	- 418,800	- 209,400	- 209,400	- 209,400	- 209,400	- 209,400	- 209,400	- 418,800	- 418,800	Bruce (2010)
53	System Losses	5%	- 104,700	- 52,350	- 52,350	- 104,700	- 209,400	- 209,400	- 209,400	- 104,700	- 104,700	- 104,700	- 104,700	- 104,700	- 104,700	- 209,400	- 209,400	Bruce (2010)
54	**Total Supply**	**l**	**1,779,900**	**889,950**	**889,950**	**1,779,900**	**3,559,800**	**3,559,800**	**3,559,800**	**1,779,900**	**1,779,900**	**1,779,900**	**1,779,900**	**1,779,900**	**1,779,900**	**3,559,800**	**3,559,800**	= LINES 51-52-53
55	**Demand/Supply**		**28.3%**	**5.4%**	**13.5%**	**146.3%**	**122.4%**	**207.5%**	**853.5%**	**149.7%**	**408.4%**	**42.5%**	**132.1%**	**264.1%**	**43.6%**	**2.6%**	**15.7%**	= LINES 46/54
56	Per Storey		14.1%	5.4%	13.5%	73.1%	61.2%	34.6%	106.7%	49.9%	68.1%	7.1%	26.4%	52.8%	21.8%	2.6%	15.7%	= LINES 55/7
57	Storeys for 100%		7	18	7	1	2	3	1	2	1	14	4	2	5	38	6	= 1/LINE 56
58	Demand per GSM		50	19	48	260	218	123	380	178	242	25	94	188	78	9	56	= LINES 46/8
59	Supply per GSM		178	356	356	178	178	59	44	119	59	59	71	71	178	356	356	= LINES 54/8

Table A.3 Compiled Data for London, ON

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	**Rainwater Harvesting Assessment Tool**			backup locally as RWH Assessment Tool - backup YYYY-MM-DD					toilet lpf	6.0	IPC	4.8	EPA					
2	21-Dec-16 v3.6L		London						urinal lpf	3.8	IPC	1.9	EPA					
3	**CRITERIA**	**UNITS**	**ASSEMBLY OCCUPANCIES**			**EDUCATIONAL OCCUPANCIES**			**INSTITUTIONAL OCCUPANCIES**			**RESIDENTIAL OCCUPANCIES**			**COMMERCIAL OCCUPANCIES**			**DATA SOURCES**
4	**BUILDING TYPE**		Community Centre	Library	Theatre	Elementary	Secondary	Post-Secondary	Hospital	Long Term Care	Retirement Home	Apartment	Student Residence	Hotel	Office	Retail	Warehouse	
5	**AREA DATA**																	
6	Roof Area	m2	5,000	2,500	2,500	5,000	10,000	10,000	10,000	5,000	5,000	5,000	5,000	5,000	5,000	10,000	10,000	INPUT VARIABLE
7	Storeys	#	2	1	1	2	2	6	8	3	6	6	5	5	2	1	1	INPUT VARIABLE
8	Occupied Area	m2	10,000	2,500	2,500	10,000	20,000	60,000	80,000	15,000	30,000	30,000	25,000	25,000	10,000	10,000	10,000	= LINES 6x7
9																		
10	**OCCUPANT DATA**																	
11	Area/Occupant	m2/p	15	20	5	11	13	16	30	60	42	200	44	44	40	232	155	EnergyStar datatrends
12	Occupancy Factor	%	50%	25%	75%	90%	90%	75%	90%	90%	90%	90%	90%	75%	75%	25%	50%	EnergyStar datatrends
13	Total Occupants	p	333	31	363	794	1,346	2,901	2,403	225	639	135	509	424	186	11	32	= LINES 8/11*12
14	Ratio F/Total	%	50%	50%	50%	50%	50%	50%	50%	75%	65%	50%	50%	50%	50%	50%	50%	EnergyStar datatrends
15	Females	p	167	16	182	397	673	1,450	1,201	169	416	68	254	212	93	5	16	= LINES 13x14
16	Males	p	167	16	182	397	673	1,450	1,201	56	224	68	254	212	93	5	16	= LINES 13-15
17																		
18	**OCCUPANCY DATA**																	
19	Hours per day	hr	12	12	4	6	6	6	24	24	24	12	16	24	8	12	24	EnergyStar datatrends
20	Days per week	d	7	7	4	5	5	5	7	7	7	7	7	7	5	7	7	EnergyStar datatrends
21	Weeks per year	wk	50	50	40	40	40	32	52	52	52	52	32	52	52	52	52	EnergyStar datatrends
22	Hours per year	hr/p	4,200	4,200	640	1,200	1,200	960	8,736	8,736	8,736	4,368	3,584	8,736	2,080	4,368	8,736	= LINES 19x20x21
23																		
24	**FIXTURE DATA**																	
25	Females per toilet	p	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	NBC (2010) Part 3.7
26	Males per toilet	p	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	NBC (2010) Part 3.7
27	Toilet Number	#	15	1	16	36	61	131	108	10	28	6	23	19	8	0	1	= LINES 15/25
28	Toilet Flow	l/f	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	= LINES 16/26
29	Males per urinal	p	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	NBC (2010) Part 3.7
30	Urinal Number	#	17	2	18	40	67	145	120	17	42	7	25	21	9	1	2	LINES 16/29
31	Urinal Flow	l/f	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	ICC (2009)
32																		
33	**UTILIZATION DATA**																	
34	Toilets - Female	f/hr	0.070	0.072	0.100	0.519	0.513	0.504	0.246	0.227	0.218	0.215	0.216	0.212	0.381	0.376	0.375	LEED NC-2009
35	Toilets - Male	f/hr	0.015	0.016	0.025	0.173	0.171	0.168	0.221	0.215	0.211	0.210	0.211	0.210	0.126	0.126	0.125	LEED NC-2009
36	Urinals - Male	f/hr	0.055	0.056	0.075	0.346	0.342	0.336	0.025	0.013	0.006	0.005	0.005	0.003	0.255	0.251	0.250	LEED NC-2009
37																		
38	**DAILY DEMAND**																	
39	Female fixtures	l/d	840	81	436	7,415	12,413	26,301	42,526	5,518	13,029	1,043	5,269	6,472	1,699	146	872	= LINES 15x19x28x34
40	Male fixtures	l/d	598	58	316	5,602	9,378	19,872	40,940	1,802	6,942	1,034	5,224	6,444	1,282	110	659	= LINES 16x19(28x35+31x36)
41	**Total Demand**	**l/d**	**1,438**	**139**	**752**	**13,017**	**21,791**	**46,172**	**83,466**	**7,320**	**19,971**	**2,077**	**10,494**	**12,916**	**2,981**	**256**	**1,531**	= LINES 39+40
42																		
43	**ANNUAL DEMAND**																	
44	Female fixtures	l/yr	294,000	28,301	69,752	1,482,954	2,482,508	4,208,118	15,479,364	2,008,598	4,742,671	379,607	1,180,304	2,355,837	441,741	53,037	317,374	= LINES 15x22x28x34
45	Male fixtures	l/yr	209,300	20,180	50,571	1,120,454	1,875,673	3,179,467	14,902,168	656,019	2,526,864	376,363	1,170,278	2,345,655	333,406	40,081	239,793	= LINES 16x22(28x35+31x36)
46	**Total Demand**	**l/yr**	**503,300**	**48,480**	**120,323**	**2,603,408**	**4,358,181**	**7,387,584**	**30,381,532**	**2,664,617**	**7,269,536**	**755,970**	**2,350,582**	**4,701,492**	**775,147**	**93,117**	**557,167**	= LINES 44+45
47																		
48	**ANNUAL SUPPLY**																	
49	Annual Precip	mm	1,012	1,012	1,012	1,012	1,012	1,012	1,012	1,012	1,012	1,012	1,012	1,012	1,012	1,012	1,012	EnviroCan (2016)
50	Roof Area	m2	5,000	2,500	2,500	5,000	10,000	10,000	10,000	5,000	5,000	5,000	5,000	5,000	5,000	10,000	10,000	= LINE 6
51	Gross Volume	l	5,057,500	2,528,750	2,528,750	5,057,500	10,115,000	10,115,000	10,115,000	5,057,500	5,057,500	5,057,500	5,057,500	5,057,500	5,057,500	10,115,000	10,115,000	= LINES 49*50
52	Evaporative Losses	10%	- 505,750	- 252,875	- 252,875	- 505,750	- 1,011,500	- 1,011,500	- 1,011,500	- 505,750	- 505,750	- 505,750	- 505,750	- 505,750	- 505,750	- 1,011,500	- 1,011,500	Bruce (2010)
53	System Losses	5%	- 252,875	- 126,438	- 126,438	- 252,875	- 505,750	- 505,750	- 505,750	- 252,875	- 252,875	- 252,875	- 252,875	- 252,875	- 252,875	- 505,750	- 505,750	Bruce (2010)
54	**Total Supply**	**l**	**4,298,875**	**2,149,438**	**2,149,438**	**4,298,875**	**8,597,750**	**8,597,750**	**8,597,750**	**4,298,875**	**4,298,875**	**4,298,875**	**4,298,875**	**4,298,875**	**4,298,875**	**8,597,750**	**8,597,750**	= LINES 51-52-53
55	**Demand/Supply**		**11.7%**	**2.3%**	**5.6%**	**60.6%**	**50.7%**	**85.9%**	**353.4%**	**62.0%**	**169.1%**	**17.6%**	**54.7%**	**109.4%**	**18.0%**	**1.1%**	**6.5%**	= LINES 46/54
56	Per Storey		5.9%	2.3%	5.6%	30.3%	25.3%	14.3%	44.2%	20.7%	28.2%	2.9%	10.9%	21.9%	9.0%	1.1%	6.5%	= LINES 55/7
57	Storeys for 100%		17	44	18	3	4	7	2	5	4	34	9	5	11	92	15	= 1/LINE 56
58	Demand per GSM		50	19	48	260	218	123	380	178	242	25	94	188	78	9	56	= LINES 46/8
59	Supply per GSM		430	860	860	430	430	143	107	287	143	143	172	172	430	860	860	= LINES 54/8

Table A.4 Compiled Data for Halifax, NS

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	**Rainwater Harvesting Assessment Tool**			backup locally as RWH Assessment Tool - backup YYYY-MM-DD					toilet lpf	6.0	IPC	4.8	EPA					
2	21-Dec-16 v3.6H	Halifax							urinal lpf	3.8	IPC	1.9	EPA					
3	**CRITERIA**	**UNITS**	**ASSEMBLY OCCUPANCIES**			**EDUCATIONAL OCCUPANCIES**			**INSTITUTIONAL OCCUPANCIES**			**RESIDENTIAL OCCUPANCIES**			**COMMERCIAL OCCUPANCIES**			**DATA SOURCES**
4	**BUILDING TYPE**		Community Centre	Library	Theatre	Elementary	Secondary	Post-Secondary	Hospital	Long Term Care	Retirement Home	Apartment	Student Residence	Hotel	Office	Retail	Warehouse	
5	**AREA DATA**																	
6	Roof Area	m2	5,000	2,500	2,500	5,000	10,000	10,000	10,000	5,000	5,000	5,000	5,000	5,000	5,000	10,000	10,000	INPUT VARIABLE
7	Storeys	#	2	1	1	2	2	6	8	3	6	6	5	5	2	1	1	INPUT VARIABLE
8	Occupied Area	m2	10,000	2,500	2,500	10,000	20,000	60,000	80,000	15,000	30,000	30,000	25,000	25,000	10,000	10,000	10,000	= LINES 6x7
9																		
10	**OCCUPANT DATA**																	
11	Area/Occupant	m2/p	15	20	5	11	13	16	30	60	42	200	44	44	40	232	155	EnergyStar datatrends
12	Occupancy Factor	%	50%	25%	75%	90%	90%	75%	90%	90%	90%	90%	90%	75%	75%	25%	50%	EnergyStar datatrends
13	Total Occupants	p	333	31	363	794	1,346	2,901	2,403	225	639	135	509	424	186	11	32	= LINES 8/11*12
14	Ratio F/Total	%	50%	50%	50%	50%	50%	50%	50%	75%	65%	50%	50%	50%	50%	50%	50%	EnergyStar datatrends
15	Females	p	167	16	182	397	673	1,450	1,201	169	416	68	254	212	93	5	16	= LINES 13x14
16	Males	p	167	16	182	397	673	1,450	1,201	56	224	68	254	212	93	5	16	= LINES 13-15
17																		
18	**OCCUPANCY DATA**																	
19	Hours per day	hr	12	12	4	6	6	6	24	24	24	12	16	24	8	12	24	EnergyStar datatrends
20	Days per week	d	7	7	4	5	5	5	7	7	7	7	7	7	5	7	7	EnergyStar datatrends
21	Weeks per year	wk	50	50	40	40	40	32	52	52	52	52	32	52	52	52	52	EnergyStar datatrends
22	Hours per year	hr/p	4,200	4,200	640	1,200	1,200	960	8,736	8,736	8,736	4,368	3,584	8,736	2,080	4,368	8,736	= LINES 19x20x21
23																		
24	**FIXTURE DATA**																	
25	Females per toilet	p	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	NBC (2010) Part 3.7
26	Males per toilet	p	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	NBC (2010) Part 3.7
27	Toilet Number	#	15	1	16	36	61	131	108	10	28	6	23	19	8	0	1	= LINES 15/25
28	Toilet Flow	l/f	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	= LINES 16/26
29	Males per urinal	p	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	NBC (2010) Part 3.7
30	Urinal Number	#	17	2	18	40	67	145	120	17	42	7	25	21	9	1	2	LINES 16/29
31	Urinal Flow	l/f	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	ICC (2009)
32																		
33	**UTILIZATION DATA**																	
34	Toilets - Female	f/hr	0.070	0.072	0.100	0.519	0.513	0.504	0.246	0.227	0.218	0.215	0.216	0.212	0.381	0.376	0.375	LEED NC-2009
35	Toilets - Male	f/hr	0.015	0.016	0.025	0.173	0.171	0.168	0.221	0.215	0.211	0.210	0.211	0.210	0.126	0.126	0.125	LEED NC-2009
36	Urinals - Male	f/hr	0.055	0.056	0.075	0.346	0.342	0.336	0.025	0.013	0.006	0.005	0.005	0.003	0.255	0.251	0.250	LEED NC-2009
37																		
38	**DAILY DEMAND**																	
39	Female fixtures	l/d	840	81	436	7,415	12,413	26,301	42,526	5,518	13,029	1,043	5,269	6,472	1,699	146	872	= LINES 15x19x28x34
40	Male fixtures	l/d	598	58	316	5,602	9,378	19,872	40,940	1,802	6,942	1,034	5,224	6,444	1,282	110	659	= LINES 16x19(28x35+31x36)
41	**Total Demand**	**l/d**	**1,438**	**139**	**752**	**13,017**	**21,791**	**46,172**	**83,466**	**7,320**	**19,971**	**2,077**	**10,494**	**12,916**	**2,981**	**256**	**1,531**	= LINES 39+40
42																		
43	**ANNUAL DEMAND**																	
44	Female fixtures	l/yr	294,000	28,301	69,752	1,482,954	2,482,508	4,208,118	15,479,364	2,008,598	4,742,671	379,607	1,180,304	2,355,837	441,741	53,037	317,374	= LINES 15x22x28x34
45	Male fixtures	l/yr	209,300	20,180	50,571	1,120,454	1,875,673	3,179,467	14,902,168	656,019	2,526,864	376,363	1,170,278	2,345,655	333,406	40,081	239,793	= LINES 16x22(28x35+31x36)
46	**Total Demand**	**l/yr**	**503,300**	**48,480**	**120,323**	**2,603,408**	**4,358,181**	**7,387,584**	**30,381,532**	**2,664,617**	**7,269,536**	**755,970**	**2,350,582**	**4,701,492**	**775,147**	**93,117**	**557,167**	= LINES 44+45
47																		
48	**ANNUAL SUPPLY**																	
49	Annual Precip	mm	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	1468.1	EnviroCan (2016)
50	Roof Area	m2	5,000	2,500	2,500	5,000	10,000	10,000	10,000	5,000	5,000	5,000	5,000	5,000	5,000	10,000	10,000	= LINE 6
51	Gross Volume	l	7,340,500	3,670,250	3,670,250	7,340,500	14,681,000	14,681,000	14,681,000	7,340,500	7,340,500	7,340,500	7,340,500	7,340,500	7,340,500	14,681,000	14,681,000	= LINES 49*50
52	Evaporative Losses	10%	- 734,050	- 367,025	- 367,025	- 734,050	- 1,468,100	- 1,468,100	- 1,468,100	- 734,050	- 734,050	- 734,050	- 734,050	- 734,050	- 734,050	- 1,468,100	- 1,468,100	Bruce (2010)
53	System Losses	5%	- 367,025	- 183,513	- 183,513	- 367,025	- 734,050	- 734,050	- 734,050	- 367,025	- 367,025	- 367,025	- 367,025	- 367,025	- 367,025	- 734,050	- 734,050	Bruce (2010)
54	**Total Supply**	**l**	**6,239,425**	**3,119,713**	**3,119,713**	**6,239,425**	**12,478,850**	**12,478,850**	**12,478,850**	**6,239,425**	**6,239,425**	**6,239,425**	**6,239,425**	**6,239,425**	**6,239,425**	**12,478,850**	**12,478,850**	= LINES 51-52-53
55	**Demand/Supply**		**8.1%**	**1.6%**	**3.9%**	**41.7%**	**34.9%**	**59.2%**	**243.5%**	**42.7%**	**116.5%**	**12.1%**	**37.7%**	**75.4%**	**12.4%**	**0.7%**	**4.5%**	= LINES 46/54
56	Per Storey		4.0%	1.6%	3.9%	20.9%	17.5%	9.9%	30.4%	14.2%	19.4%	2.0%	7.5%	15.1%	6.2%	0.7%	4.5%	= LINES 55/7
57	Storeys for 100%		25	64	26	5	6	10	3	7	5	50	13	7	16	134	22	= 1/LINE 56
58	Demand per GSM		50	19	48	260	218	123	380	178	242	25	94	188	78	9	56	= LINES 46/8
59	Supply per GSM		624	1,248	1,248	624	624	208	156	416	208	208	250	250	624	1,248	1,248	= LINES 54/8

Figure A.1 Enlarged Version of Figure 5.4