THE DYNAMIC STORMWATER RESPONSE OF A GREEN ROOF

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ABSTRACT

THE DYNAMIC STORMWATER RESPONSE OF A GREEN ROOF

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University of Guelph, 2008  Professor R. Corry

Impervious surfaces negatively affect urban hydrology by altering the depth, frequency and seasonal distribution of stormwater runoff. To assess the imperviousness of green roofs, a mathematical model was developed to simulate the stormwater response of a hypothetical green roof. The model is based on the physical processes that affect the green roof stormwater response and uses historic climate data. The results show that green roof imperviousness fluctuated according to climate conditions and precipitation sequence. Only 29% of the total precipitation received by the green roof resulted in runoff, however, the response varied substantially when evaluated at a daily interval. Runoff was eliminated during 82% of days with rain and a higher proportion of runoff disturbances were eliminated during the spring and summer compared to the fall. In comparison to an impervious surface, the green roof showed a reduction in the depth and frequency of runoff thereby improving urban hydrology.
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1 INTRODUCTION

1.1 OVERVIEW AND INCENTIVE

Research implies that the stormwater response of a green roof is the most important environmental benefit they provide (Monterusso et al., 2004; DeNardo et al., 2005; Schmidt, 2006). However, the connection between the environmental benefit and green roof runoff has not been explicitly examined nor has this impact been studied in relation to other environmental impacts of green roofs. This thesis examines the first part of the uncertainty by assessing how green roof stormwater response impacts stream health, by simulating the variable response of a hypothetical green roof in Waterloo, Ontario.

Green roof stormwater responses impact stream health through a complex relationship. Research has shown that the impact of urban development on stream health potential is a function of the impervious surface area contributed by urban development (Schueler, 1995; CWP, 2003). Specifically, as impervious surface area increases, potential stream health decreases. Examining green roof contribution to impervious area is one way of assessing the potential environmental impact of green roofs in terms of stream health.

As urban development expands, taking over “green fields”, filling in remnant open space in cities, removing vegetation, compacting soils and sealing of surfaces, a significant shift in the natural hydrologic cycle occurs. Impervious surface cover created by urban development increases stormwater runoff while decreasing evapotranspiration and infiltration, thereby adversely affecting water quality, stream hydrology, habitat, and biotic community (Schueler, 1995; Arnold and Gibbons, 1996; Walsh, 2000; Paul and Meyer, 2001; Wang, 2001; CWP, 2003; Roy et al., 2005, Walsh et al., 2005). The hydrologic cycle in a developed area is characterized
by larger and more frequent flow disturbances to streams. Traditional urban development expedited the collection and conveyance of stormwater providing for the short-term needs of human health and well-being, but neglected the long-term effect of the urbanized hydrologic regime on ecological systems and processes, and overall health of the environment.

Increased runoff alters stream hydrology and water quality resulting in reduced habitat quality and degraded biotic communities. A number of studies show that the amount of impervious cover within a stream catchment has measurable adverse consequences on the potential health of the stream (Schueler, 1995; CWP, 2003). As impervious cover increases beyond ten percent of the catchment area, stream health is impacted. Once impervious cover exceeds 25% stream health is considered degraded (Schueler, 1995; CWP, 2003). This suggests that impervious cover is one simple metric that can be used to estimate and measure the environmental impact of urban development.

Urban planners set impervious area targets for new developments as a means of maintaining a hydrologic regime that can help sustain stream health. In response to these targets professionals involved in land development are integrating more efficient site designs to reduce impervious surface area and implementing stormwater management devices to offset the increase in impervious cover due to development. Detention ponds are a commonly used device incorporated into stormwater management plans. Although such devices assist in reducing local flood concerns, they do little to prevent downstream flooding and have shown little benefit to mitigating the negative environmental impact of an urbanized hydrologic regime (Ferguson, 1994; Harbor, 1994; Booth and Jackson, 1997). Although detention ponds slow down the rate at which water is delivered to streams, what is really needed is a significant reduction in the volume and frequency that stormwater is delivered to streams. Infiltration
devices such as rain gardens, infiltration basins, vegetated swales and porous paving materials aid in this regard by reducing runoff and increasing infiltration into groundwater supplies. Unfortunately, the potential to integrate infiltration devices into existing urban development are limited as ground level space is at a premium. In addition, infiltration devices contribute little to evapotranspiration which is also reduced by urban development. A green roof is another stormwater management device that can be used to mitigate the negative hydrologic impacts of urban development.

Green roofs are quickly gaining popularity for their aesthetic and environmental qualities. Many studies suggest that green roofs can reduce stormwater runoff in comparison to conventional roofs (Köhler et al., 2001; Hutchinson et al., 2003; Lui, 2003; Moran, 2004; Bengtsson et al., 2005; VanWoert et al., 2005a). The average reduction in stormwater runoff would appear to provide an indication of the impervious contribution of a green roof; however, the response of a green roof to precipitation events is highly variable. This variability is a result of the dynamic stormwater response of a green roof to a particular set of climate conditions and changes with green roof design.

One way of determining the stormwater response of a green roof in a particular context is to install a demonstration green roof and monitor precipitation and runoff from its surface. Such an approach provides limited value as climate variables impacting green roof retention can change dramatically from one year to the next. Therefore short-term monitoring may not provide sufficient information regarding the range of responses that can be expected over the life of a green roof.

An alternative approach is to simulate the stormwater response of a green roof within a specific climate context using a model that accurately represents the physical processes
occurring within the green roof. The output of such a model should allow for the prediction of
the extreme stormwater response as well as the contribution of green roofs to runoff,
infiltration and evapotranspiration.

A pervious surface is viewed as one that reduces stormwater runoff. It is often presumed that
this is accomplished by infiltrating precipitation into ground water supplies, however rarely is it
noted that this is not the case with green roofs. Green roofs reduce runoff by temporarily
retaining and then returning water back to the atmosphere through evapotranspiration.

In an effort to improve stream health, organizations often concentrate on rehabilitating in-
stream and near-stream conditions. Re-vegetating riparian zones and rebuilding in-stream
habitat are common approaches in this regard. Immediate results are seen but may not be
sustained if urban development has degraded the natural hydrologic cycle to too great an
extent. If excessive impervious area due to development is the underlying cause of
degradation, in-stream and near-stream efforts may not have a lasting effect on stream health.

Landscape architects, with allied disciplines in land development and management, hydrology,
and ecology need to address the way in which urban development will impact remote natural
processes and systems. The strong correlation between the impervious cover within a stream
catchment and the resulting health potential of the stream should be used to guide urban
development. The ability to simulate green roof stormwater performance in a specific context
is important as it provides a means of examining the range of impervious response likely to be
exhibited by the green roof. This provides valuable information to professionals involved in
land development as they can ascertain the contribution that green roofs can make to the
development.
1.2 STUDY GOAL
The goal of this research is to understand and elaborate the environmental impact of a green roof by assessing the variability of its stormwater response to a long-term series of precipitation events.

1.3 STUDY OBJECTIVES
a. Develop and apply a mathematical model that simulates the green roof stormwater response; is based on the physical processes impacting runoff from a green roof; and is adaptable to different green roof designs, and different climate and location contexts.

b. Assess the dynamic response of a simulated green roof to a series of historic precipitation and climate conditions in Waterloo, Ontario.

c. Apply this response to the relationship between impervious surface area and potential stream health to assess how green roofs applied at a broad scale may contribute to potential stream health.

1.4 ORGANIZATION
This paper is organized into five parts: Introduction, Literature Review, Methods, Results and Discussion, and Conclusion. The literature review examines the relationship between urban development and potential stream health followed by a review of green roofs and how they respond to precipitation events. The methods section, provides details as to the framework used to simulate green roof stormwater response to a series of past precipitation events. The various attributes assigned in the mathematical model are based on the location and climate context of Waterloo, Ontario and a hypothetical extensive green roof that should remain viable in such an environment. Using the framework and methods outlined it would be possible to replicate this work to investigate alternative green roof designs or additional location and climate contexts. The output from the simulation is reported in the results and discussion.
section where the connection to impervious response and water balance is identified. Finally, the conclusion examines how the data gathered can aid in understanding the potential environmental impact resulting from the widespread application of green roofs.
There are three main topics covered in the literature review. The first starts by exploring the affect of urbanization on the hydrologic cycle and the corresponding effect on aquatic environments and ends by examining how the degrading effect of urbanization can be reduced through improved site design and the application of innovative stormwater management devices. The next portion of the literature review examines the stormwater management device of particular interest in this study, the extensive green roof. The characteristics, performance and processes relating to green roof stormwater response are then covered, setting the stage for the final topic related to the modeling of the green roof stormwater response, which involves a significant review of evapotranspiration, a key process affecting the stormwater response of a green roof.

2.1 HYDROLOGIC CYCLE

Hydrology is the study of the movement and storage of water over and under the surface of the earth. The movement of water from one phase and location to another is a continuous process known as the hydrologic cycle. Dunne and Leopold (1978) extend the definition of the hydrologic cycle to include the movement of both water and its constituents.

Solar energy drives the cycle by evaporating water from the surface of the earth and storing it as vapour in the atmosphere. As atmospheric conditions change, water vapour can condense and fall back to the ground as precipitation. Precipitation that lands on vegetation is slowed down reducing its erosive power. A portion of the water that lands on vegetation will be intercepted, returning to the atmosphere through evaporation without ever having reached the ground. Xiao et al. (2000) report interception losses of approximately 20% of the total
annual precipitation that falls in forested areas, while Dunne and Leopold (1978) found that the median reported interception loss from forests in North America is 27%. The remaining 70 – 80% of the precipitation drips off leaves and runs along branches slowly moving through the layers of vegetation until it reaches the ground. Vegetation can increase the rate at which water infiltrates the soil. It also draws moisture from the soil using it in biological processes, which subsequently return the water to the atmosphere through transpiration. Soil moisture also returns to the atmosphere through evaporation. Together the two processes are referred to as evapotranspiration.

Soil moisture can be displaced by additional water infiltrating the soil pushing it deeper into groundwater reserves or it can flow horizontally as subsurface flow, where at some point it may breech the surface. Water can enter a waterway by either surface or subsurface routes. Precipitation that infiltrates and percolates deeper into the ground can take weeks or months to reach streams, as opposed to minutes and hours as it does through overland runoff. This subsurface flow helps to even out the inconsistent flow originating from precipitation events. Precipitation replenishes groundwater and supplies baseflow to streams.

The route taken by precipitation that falls over land can follow one of three principal paths: it can return to the atmosphere through evapotranspiration; infiltrate the ground; or, travel across the surface as runoff. The mixture of each path taken is known as the water balance. Arnold and Gibbons (1996) generalize that in a forested area 40% of precipitation returns to the atmosphere through evapotranspiration, 50% infiltrates the ground and only 10% runs off continuing its path back to the ocean. The Ontario Ministry of Natural Resources (MNR, 2008) estimates that 60% of precipitation evaporates or transpires while 30% infiltrates and 10% runs off from natural watersheds. A more dramatic shift can be seen when examining the water
balance of a particular watershed. For example, in the Spree and Havel watersheds in Germany it is estimated that 80% of precipitation is returned to the atmosphere through evapotranspiration (Schmidt, 2006).

The hydrologic cycle is closely tied to many other natural processes that have evolved in response to the movement of water. The formation of landscapes and recycling of geologic material is significantly affected by the movement of water. As water moves across the surface of other materials it is able to pick up and move sediment, chemicals, heat, nutrients, flora and fauna (Dunne and Leopold, 1978).

2.2 THE IMPACT OF URBANIZATION

Urban development imparts significant change on the hydrologic cycle by altering the path that water takes.

... the hydrologic cycle is an appropriate framework for analyzing human modification of land and water resources. ... people are major agents in the hydrologic cycle. They alter the land surface, manipulate the quantities of water in storage in various parts of the cycle, and radically change the concentrations of sediment, solutes, heat and biota. A great many problems that confront a planner therefore, can be analyzed by considering the paths that water takes, what the water is doing at various stages along each path, and how the quantity, pressure, chemistry, or any other characteristic of the water is altered by human action.

(Dunne and Leopold, 1978, p.6)

Urban development is marked by the removal of vegetation, compaction of soil and sealing of surfaces which reduces the proportion of water that returns to the atmosphere and infiltrates the ground, causing an increase in the volume of water that remains on the surface of the land.
Smooth, developed topography reduces the opportunity for surface depression storage and increases the rate at which water travels across the land.

Surface water is treated as an undesirable by-product of traditional urban development. Infrastructure has been developed that in a reactionary way to collect excess water and drain it rapidly to receiving waterways. While eliminating the problem of surface water, it negatively impacts the natural hydrologic cycle.

Removing vegetation takes with it the contribution of interception, transpiration and increased infiltration. Bare soil is more likely to be eroded in the absence of vegetation. Vegetation binds the soil together and provides a protective cover, shielding soil from the erosive power of falling rain.

Urbanization is characterized by the presence of extensive amounts of impervious surfaces such as roads, parking areas, sidewalks, patios, rooftops, and compacted soils. These impervious surfaces are some of the most impactful features of land development on the environment (Dunne and Leopold, 1978; Ferguson, 1994; Arnold and Gibbons, 1996). Ferguson (1994) defines an impervious surface as one that alters the hydrologic cycle, preventing water from following natural paths and processes, degrading pre-development storage and flow regimes. The increase in impervious surface coverage reduces the amount of water that infiltrates the ground. Subsequently, this alters the processes of groundwater recharge and stream baseflow (Ferguson, 1994). Most definitions of impervious surfaces suggest that they reduce infiltration and increase surface runoff while they neglect to mention the impact on evapotranspiration. By replacing natural vegetated areas with impervious surfaces, evapotranspiration is reduced. This reduction is due to the loss of vegetation which contributes to transpiration and the sealing of the surface which prevents water from
percolating and storing near the surface reducing its availability to return to the atmosphere through evaporation.

The impervious cover of different land uses varies considerably (Table 1), with residential lots contributing 20% of their area to impervious cover, while industrial and commercial development contains on average more than 75% impervious surface area.

Table 1 - Imperviousness and land use

<table>
<thead>
<tr>
<th>Land Use Type</th>
<th>Impervious Surface Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential lot, 1 acre</td>
<td>20</td>
</tr>
<tr>
<td>Residential lot, 1/2 acre</td>
<td>25</td>
</tr>
<tr>
<td>Residential lot, 1/3 acre</td>
<td>30</td>
</tr>
<tr>
<td>Residential lot, 1/4 acre</td>
<td>38</td>
</tr>
<tr>
<td>Residential lot, 1/8 acre</td>
<td>65</td>
</tr>
<tr>
<td>Industrial</td>
<td>75</td>
</tr>
<tr>
<td>Commercial</td>
<td>85</td>
</tr>
<tr>
<td>Shopping Center</td>
<td>95</td>
</tr>
</tbody>
</table>

Data from: Arnold and Gibbons (1996)

Two common measurements used to estimate the imperviousness of urban development are total impervious area (TIA) and effective impervious area (EIA).

2.2.1 TOTAL IMPERVIOUS AREA (TIA)

TIA is a measure that assumes a surface is either impervious or it is not. Typically, surfaces are identified through remote sensing such as the interpretation of aerial photos. Those areas that appear to be sealed surfaces such as building roofs and transportation surfaces are assumed to contribute all precipitation that land on them to runoff. TIA can also be determined by estimating the total area occupied by each land use type and then multiplying those values by standard rates of imperviousness for each land use. Research such as Meyer et al. (2005) used
standard land use impervious values published by Arnold and Gibbons (1996) to estimate the total impervious area of study catchments.

TIA assumes that all impervious surfaces are directly connected to the storm sewer system, discharging runoff directly to a receiving body of water. It is easily observed however that some impervious areas drain to adjacent pervious surfaces and not directly to the storm sewer system. TIA also assumes that pervious surfaces can infiltrate all the precipitation that lands on them. However, some pervious surfaces such as bare and compacted soils contribute significant amounts of runoff, acting more like impervious surfaces (Schueler, 1995; Brabec et al., 2002). Even though there is variation in the impervious performance of different surfaces, TIA has been shown to provide good correlation to other environmental qualities, making it a valuable metric of the potential ecological impact of a particular urban development (Schueler, 1995).

Schueler (1995) recommends that total impervious area be used as a metric to guide urban watershed protection as it is quite easy to measure, monitor and control.

2.2.2 EFFECTIVE IMPERVIOUS AREA (EIA)

A more accurate representation of urban development’s contribution to runoff considers whether an impervious surface is connected to or disconnected from the storm drainage system. Effective impervious area (EIA) is comprised solely of impervious surfaces that are directly connected to a storm drainage system and discharge runoff into a waterway (Schueler, 1995; Arnold and Gibbons, 1996; Brabec et al., 2002; Walsh et al., 2005a). Almost all of the precipitation that lands within a directly connected impervious area becomes runoff (Schueler, 1995). Even with this refined definition of imperviousness the performance of different
surfaces still show variation. Schueler (1995) notes that disconnected impervious areas still produce runoff. Although much reduced, they can contribute 25 to 50% of the runoff of connected impervious surfaces.

EIA requires a more detailed examination of the catchment area, and as such can be more costly and time consuming to develop versus total impervious area. EIA can be estimated by examining the layout of urban drainage in conjunction with the location of impervious surfaces. This process is made easier through the use of digital data sources and the use of geographical information system (GIS) analysis tools (Brabec et al., 2002).

Recent research has shown improved correlation between EIA and certain stream health measures (Walsh et al., 2005a), but the simpler measure of TIA still holds strong value in identifying the impact of development on stream ecosystem health.

### 2.2.3 WATER BALANCE

The hydrologic cycle can be described as water balance which is comprised of runoff, infiltration and evapotranspiration. Every natural and urban catchment has a unique mixture of flows contributing to the water balance. The comparison of the urban landscape and pre-development landscape water balances provides a simple measure as to the likelihood that natural processes can continue to be supported by the altered landscape.

Research focusing on urban stormwater response tend to evaluate impervious versus pervious surface ratios and suggests that water either runs off the surface of the land or infiltrates into the ground (Harbor, 1994; Schueler, 1995; Brander et al., 2004; DeNardo et al., 2005). It is important to understand the relative contribution of each surface type to the water balance. To understand the net result from land development it is important to consider the type of
surface being replaced as well as the characteristics of the new surface. Replacing vegetation with an impervious surface such as a parking area reduces infiltration and evapotranspiration, while increasing rates and volumes of runoff.

The impact of urbanization on the water balance is expressed as a change in evapotranspiration, runoff and infiltration resulting from different values of impervious surface cover. Such a relationship has only been established for the pre-development condition of a forested area as defined by Arnold and Gibbons (1996). As the amount of impervious area increases, runoff increases while infiltration and evapotranspiration decrease (Figure 1).

![Figure 1 - Changes to the water balance as a result of different levels of imperviousness. The grey horizontal arrows provide a reference to 10% runoff typical of the natural ground cover condition. The actual runoff is shown by the black arrows.](image)

Data from: Arnold and Gibbons (1996)

While Figure 1 shows a decrease from 50% infiltration in a forested area to only 15% infiltration in a highly impervious area, conflicting opinions remain concerning the impact of urban development on groundwater recharge and stream baseflow. Studies comparing the low flow condition of streams in highly urban areas to those of rural areas have found little evidence that this occurs (Schueler, 1995). Dunne and Leopold (1978), Harbor (1994), Paul and Meyer (2001), and Wang (2001) suggest that an increase in impervious cover results in increased
runoff and reduced groundwater recharge. This in turn reduces water supplies and groundwater baseflow to streams. Such reductions in baseflow could impact streams during low flow periods, occasionally causing stream beds to become dry counter to pre-development conditions (Dunne and Leopold, 1978; Harbor 1994). However, the net impact to groundwater recharge and stream baseflow has not been confirmed by research (Arnold and Gibbons, 1996). Paul and Meyer (2001) and Roy et al. (2005) indicate that irrigation, septic drainage, wastewater discharge and leaks from potable water supplies can increase groundwater recharge. Stream flow is further complicated by other potential influences on ground water supply such as topography, climate and geology (Brabec et al., 2002; Roy et al., 2005).

Evapotranspiration from a forested area accounts for the path taken by approximately 40% of the annual precipitation. Extensive urban development resulting in high levels of imperviousness reduces this value to 30% of the annual precipitation (Figure 1). The reduction of vegetation in urban areas reduces the amount of water returned to the atmosphere through evapotranspiration by up to 25% as compared to a forested area (Figure 1). Dunne and Leopold (1978) and Brabec et al. (2002) note that urban areas are likely to support higher potential evapotranspiration rates than rural or forested areas due to the freer horizontal air movement and increased surface temperatures. Higher potential evapotranspiration rates in combination with adequate soil moisture and vegetation might contribute to higher amounts of evapotranspiration from urban areas.

Arnold and Gibbons (1996) indicate that as a stream catchment changes from a natural forested condition to low levels of impervious cover (10-20%) runoff volumes can double. Increasing imperviousness to higher levels (75-100%) can increase runoff by a factor of five compared to the forest condition (Figure 1).
2.3 THE IMPACT OF IMPERVIOUSNESS ON POTENTIAL STREAM HEALTH

Until recently, few researchers had generalized that land development in the form of urbanization has a significant degrading effect on stream ecosystems (Walsh, 2000). Research now shows that the dominant influence on stream quality is the amount of impervious surface within its catchment (Brabec et al., 2002).

Imperviousness is a simple environmental indicator that corresponds well to the quality of many environmental systems that interact with the urban environment (Arnold and Gibbons, 1996). As urban development occupies a higher percentage of a stream catchment area, impervious surface cover increases resulting in a more pronounced impact on aquatic ecosystem health (Arnold and Gibbons, 1996; Brabec et al., 2002; Roy et al., 2005). Paul and Meyer (2001) indicate that in the United States, 130,000 km of streams and rivers are impaired due to urban development. The negative degree of impact of urban development is second only to that of agriculture (Paul and Meyer, 2001).

Increases in impervious cover alter the water balance, increasing runoff while reducing infiltration and evapotranspiration. This leads to an altered hydrologic regime and changes in water quality delivered to waterways. In turn, this degrades a number of stream health measures (Figure 2). To understand the relationship between urbanization and stream health, a number of researchers have examined the relationship between impervious measures and a wide variety of stream health indicators. Walsh et al. (2005a) compared the effective impervious area of a catchment to a number of environmental indicators such as “water chemistry, algal biomass and assemblage composition of diatoms and invertebrates” (p.690).
Stream health measures can be grouped as either abiotic or biotic variables of the stream ecosystem (Brabec et al., 2002). Each stream health measure responds to different levels of imperviousness and is typically assigned a value from good/natural to poor/degraded (Walsh, 2000). Abiotic variables characterize the quality of the stream environment focusing on parameters such as stream hydrology, stream geomorphology, habitat, water composition and water temperature. Biotic variables include species diversity and abundance. Biotic measures may be a better indicator as they reflect the cumulative and long term effects of the stream on the aquatic life (Brabec et al., 2002). Some research combines a number of abiotic and biotic measurements into a single stream health indicator.
The value of these variables can change significantly with changes in imperviousness. Studies typically note the point at which imperviousness causes a particular stream health measure to move to a degraded level. These threshold values change with each variable, making it difficult to determine a single point at which imperviousness moves overall stream health to the degraded state (Brabec et al., 2002). The impervious threshold is set at the point when all stream health variables move to the degraded state (Brabec et al., 2002).

2.3.1 STREAM HYDROLOGY

When urbanization alters the water balance of a watershed increasing the amount of runoff (Schueler, 1995; Arnold and Gibbons 1996; Paul and Meyer, 2001) and altering the flow regime of water supply, the result is stress to streams (Booth, 2005). Due to increased runoff and more efficient conveyance structures the pattern of stormwater runoff delivered to streams changes dramatically from pre-development to post-development conditions. Meyer et al. (2005), Roy et al. (2005), and Walsh et al. (2005b) describe the urban stormwater runoff hydrograph as ‘flashy’. It is characterized by an accelerated rise and fall of stormwater discharge (Roy et al., 2005) or a burst of peak flow (Arnold and Gibbons, 1996) (Figure 3).

![Figure 3 - Changes to the storm hydrograph due to urbanization. Adapted from: Harbor, 1994](image-url)
Schueler (1995) indicates that low levels of imperviousness (between 5 to 10%) can increase peak discharge rates by 5 to 10 times pre-development rates for small storms (storms with a one-year return period or less). This results in significant change to stream morphology (Walsh, 2000; Paul and Meyer, 2001; Meyer et al., 2005; Roy et al., 2005; Walsh et al., 2005b) such as straighter stream channels with uniform banks (Arnold and Gibbons, 1996). In response to higher flows, stream cross-sectional area increases as banks widen and/or the stream bed is downcut (Schueler, 1995; Arnold and Gibbons, 1996; Walsh, 2000). These changes lead to channel instability (Schueler, 1995; Meyer et al., 2005) characterized by increased stream bank erosion and habitat loss (Schueler, 1995).

The impact of imperviousness on the stream hydrograph is greater during small storm events (Schueler, 1995; Roy et al., 2005). Small storm events result in frequent high flow disturbances that reduce channel stability (Schueler, 1995). Such disturbances do occur in natural watersheds but far less often. The change in the frequency of disturbance results in significant damage to the stream ecosystem (Booth and Jackson, 1997).

These increases are less pronounced with larger storm events (storms with a return period greater than one year). In such cases the baseline forested catchment acts more like an impervious surface with increased surface runoff as soil becomes saturated (Paul and Meyer, 2001). Catchments with high (24%) and low (5%) impervious surface coverage exhibit similar flow heights during the largest storm events (Roy et al., 2005).

The distribution of rain events throughout the year can result in seasonal changes in the frequency and degree of disturbance caused by urbanization as compared to natural catchments. During spring when precipitation is often greatest, natural landscapes can experience high flow rates. At these times, overland flow increases due to saturation of soil
and lower evapotranspiration rates. As a result, urbanized catchments with high levels of imperviousness may provide a similar level of disruption as do forested landscapes during the spring season (Roy et al., 2005). The frequency of disturbance caused by impervious areas is greater during the summer and fall compared to a natural catchment. Typically, precipitation values are lower during the summer and fall and the natural landscape is able to infiltrate the majority of stormwater, minimizing runoff. This contrasts the large amounts of runoff occurring from urbanized catchments during the same small storm events (Roy et al., 2005).

### 2.3.2 HABITAT

The urbanized hydrologic regime results in changes that cascade down through the aquatic ecosystem, altering stream morphology, stream channel stability and reducing the quality and quantity of in-stream habitat structures (Booth, 2005). Pool and riffle frequency is altered and increased rates of erosion strip away riparian zone vegetation eliminating habitat and overhead cover (Schueler, 1995; Arnold and Gibbons, 1996). There is good correlation between increases in catchment impervious cover and the loss of in-stream habitat (Schueler, 1995; Paul and Meyer, 2001).

### 2.3.3 BIOTIC COMMUNITY

Urbanization, evaluated as a measure of the total impervious area has been compared against the index of biotic integrity a commonly used index that quantifies the composition and richness of stream aquatic species (Brabec et al., 2002; Booth, 2005). Increased catchment urbanization degrades biotic community quality (Walsh, 2000; Paul and Meyer, 2001; Booth et al. 2003; 2004).
The result of altered stream hydrology has a negative impact on many variables critical to supporting healthy and diverse aquatic species. These variables include increased sedimentation, loss of habitat, degrading water level fluctuations, and disturbances to high flow and low flow conditions (Schueler, 1995; Brabec et al., 2002; Paul and Meyer, 2001; Roy et al., 2005; Walsh et al., 2005b).

As well as influencing high flow disturbances, Roy et al. (2005) observed that imperviousness has a seasonal impact on low flow conditions which increased in duration during the fall. Roy et al. (2005) found that this increased duration was accompanied by an increased richness of species tolerant of still water. The timing of such events in relation to the lifecycle of different species can play an important role in the biotic health of a stream ecosystem. The degree of impact may be related to the coordination of when storm flow is altered and the life cycle of the specific fish species (Roy et al., 2005).

### 2.3.4 POLLUTANTS

Increase in impervious cover results in increased loading of pollutants (Walsh, 2000; Paul and Meyer, 2001). Impervious surfaces do not generate pollutants however they do collect, concentrate and deliver pollutants into waterways. Pollution results in impaired water quality and increased toxicity (Booth, 2005). Not only do pollutants impact aquatic organisms, they can also result in possible health hazards to people using a waterway for recreational purposes (Arnold and Gibbons, 1996).

Impervious surfaces collect non-point source pollutants including: nutrients, toxins, pesticides, pathogens, organic contaminants, and debris (Walsh, 2000; Paul and Meyer, 2001). Runoff from urban areas is one of the most significant sources of pollutants to rivers (Arnold and
Gibbons, 1996). The proportion of impervious area in a stream catchment is effective at predicting cumulative impacts of pollution to stream environments, simplifying the complex interactions involving nonpoint source pollution (Arnold and Gibbons, 1996).

As drainage efficiency and runoff rates increase so too does pollutant delivery, resulting in greater degradation to the receiving stream (Walsh, 2000). Higher runoff rates allow water to carry more sediment increasing pollution delivery. Pollutants tend to bond to the surface of sediments that are washed into streams. Excessive amounts of runoff can also result in combined sanitary sewer overflows. These can cause sudden and significant amounts of pollution to be delivered to the stream environment (Walsh et al., 2005b).

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Source Surface</th>
<th>Source Land Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathogens</td>
<td>Roads</td>
<td>Residential</td>
</tr>
<tr>
<td>Sediment</td>
<td>Roads</td>
<td>Industrial</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>Lawns (a pervious surface)</td>
<td>Residential</td>
</tr>
<tr>
<td>Zinc</td>
<td>Roofs</td>
<td>Industrial</td>
</tr>
<tr>
<td>Copper</td>
<td>Roads</td>
<td>Industrial</td>
</tr>
</tbody>
</table>

*Table 2 - Most significant sources of common pollutants from residential, commercial and industrial land uses in urban areas*

Data from: Bannerman et al. (1993)

Pollution is not equally contributed by different urban elements and land uses (Table 2). Bannerman et al. (1993) investigated the pollution contribution from various surface types across three different land uses (commercial, industrial and residential) in urban areas. Impervious surfaces related to transportation provide the majority of pollutants, with the exception of zinc which is found in higher concentrations from industrial rooftop runoff (Bannerman et al., 1993). Bannerman et al. (1993) noted that pervious surfaces also contribute pollutants transported in runoff that flows from pervious to impervious surfaces. Chemical lawn treatments such as fertilizers and pesticides as well as pet/animal excrement, can run off
onto the impervious surfaces contributing to non-point source pollutants that enter urban streams. Arnold and Gibbons (1996) noted that in urban areas runoff from residential lawns is the most significant source of phosphorous in streams.

### 2.3.5 STREAM TEMPERATURE

Stream water temperature is critical to the survival of many aquatic organisms (LeBlanc, 1997). Changes in stream temperature affect the life cycle, metabolic rates, and the sensitivity (to disease, parasites and pollutants) of aquatic organisms (LeBlanc et al., 1997; CWP, 2003). Water temperature also influences stream processes such as the rate of leaf decomposition (Paul and Meyer, 2001). Urban stream temperatures are higher during the summer and lower during the winter in comparison to streams draining forested regions (Paul and Meyer, 2001). The change in temperature is often attributed to the loss of riparian cover above the stream surface (Arnold and Gibbons, 1996; LeBlanc et al., 1997; Paul and Meyer, 2001; Herb, 2008). However, Schueler (1995) states that the primary factor contributing to the difference in water temperature between an urban stream and one draining a forested catchment is the level of catchment impervious cover. The addition of impervious surface cover causes stream banks to widen and increases stream bank erosion resulting in the loss of riparian vegetation. This increases stream surface area and reduces the portion of the waterway that is shaded. Stream temperature changes as a result of the increase in the exposure of the stream surface. In addition, runoff from impervious surfaces such as pavement may contribute thermal pollution to the waterway which can be conveyed through stormwater piped directly to the stream (Herb et al., 2008).
2.4 RELATIONSHIP BETWEEN URBAN DEVELOPMENT AND POTENTIAL STREAM HEALTH

Urban development can have a significant impact on stream health. The relationship between different impervious measures and stream health potential simplifies the very complex relationships that have evolved between runoff patterns and the environment.

Some researchers have found that in-stream hydrologic data provides an even stronger indication of the level of impact to the stream ecosystem than imperviousness (Booth, 2005; Roy et al., 2005; Walsh et al., 2005b), while effective impervious area exhibits better correlation to some stream health measures (such as species diversity and pollutant loads) than total impervious area (Wang, 2001; Carter and Jackson, 2007). Indicators such as TIA and EIA are valuable for areas where more detailed watershed models are not feasible to create due to economic constraints (Brabec et al., 2002).

Although in-stream hydrologic data may provide a better correlation to stream health it does not permit a proactive management approach to guiding urban development. In-stream measures are a symptom of urbanization. Total impervious area and effective impervious area are better metrics to use as they can be easily measured, monitored and controlled. In-stream hydrologic data are valuable measures and can be used to assist in monitoring the impact of urban development and stormwater management plans (Figure 4).
Through a review of a diverse set of literature examining the relationship between impervious and numerous stream ecosystem health measures, Schueler (1995) summarized the findings of a number of studies and presented the results as the impervious cover model. In spite of the variation in methods and measurements used to examine the relationship between urbanization and stream health, Schueler (1995) found that the degree of imperviousness exhibited a consistent correlation to stream health measures. This model uses the urban metric of total impervious area which Schueler (1995) states is equal to the portion of a catchment that is not ‘green’. TIA ranging from 0% to 10% results in protected streams. As TIA increases stream health decreases, diminishing to a degraded state once TIA exceeds 25% (Figure 5).

This simple relationship between impervious surface area and stream health potential is one that is considered by planners, landscape architects and other professionals who contribute to the processes of land development and stream restoration.
Figure 5 - Impervious Cover Model depicting the relationship between stream health potential and total impervious area. 
Adapted from: CWP (2003)

The Center for Watershed Protection (CWP) (2003) identifies that there are limitations to the impervious cover model.

- It should be applied only to first, second and third order streams;
- The values presented estimate potential, not actual stream health; and,
- The values are only applicable in regions similar to where the relationship has been tested.

For a given level of imperviousness, different levels of degradation have been noted. Those sites that have better than expected stream health may have better management practices. Those catchments that exhibit lower than expected stream health may be influenced by other degrading variables beyond those that impact stormwater runoff (Walsh, 2000). As a result the trendline depicting the relationship between impervious measures and potential stream health
represent the upper limits of observed biological condition. The majority of observations lie below the trendline (Walsh et al., 2005b).

Some research shows that total impervious area is of limited value in providing an indication of ecological health. Differences in urban drainage infrastructure can have a significant effect on the impact of imperviousness. Valuing catchment imperviousness with the addition of drainage infrastructure provides a better metric for the estimation of potential stream health in an urbanized catchment (Walsh, 2000). The relationship between the level of imperviousness and stream health is more linear when effective impervious area is used compared to total impervious area (Walsh et al., 2005b).

2.4.1 IMPERVIOUS THRESHOLDS

Research frequently identifies critical levels of imperviousness above which stream health potential changes. There are conflicting opinions as to the presence of distinct threshold values (Brabec et al., 2002). Walsh et al. (2005a) note that there is a strong threshold relationship between the measured ecological indicators and catchment imperviousness when imperviousness is high and exhibits a high degree of connectedness to the stream system. Booth et al. (2003) indicate that there is no threshold effect when correlating imperviousness to in-stream biological conditions. Brabec et al. (2002) question the validity of threshold values in the relationship between imperviousness and stream health potential due to the wide variety of techniques used to define the imperviousness and degradation attributes.

Threshold effects are artifacts of the low resolution of the methods used to evaluate stream health. For such methods, significant change in stream health is required before they can be distinguished, resulting in correspondingly large shifts in imperviousness levels. Some
biological indicators show a continuous response to increasing levels of development when measured appropriately (Booth et al., 2003).

2.5 REDUCING THE IMPACT OF URBANIZATION ON NATURAL SYSTEMS

Traditional stormwater management practices tended to concentrate on runoff flow rates in an attempt to mitigate the negative effects of urban development. The focus was predominantly on the short-term health and well-being of the human population. Recently, increased attention is being given to understand and address the negative impact that urbanization has on the health of aquatic ecosystems (Walsh, 2000). For example, significant effort is put into remediating degraded urban streams. Motivating these efforts is a growing concern for environmental health, as well as the human centric concerns to increase amenity and economic value of these landscapes.

The primary cause of reduced stream health is the altered flow regime resulting from increased imperviousness. Brabec et al. (2002) and Walsh et al. (2005a) suggest that hydrologic response of a developed catchment should closely resemble that of the pre-development region. Mitigating the negative impact of urbanization by managing stormwater to behave as it would in a natural watershed may not be reasonable in the context of an urban ecosystem. Impervious area can exist in a stream catchment but its spatial distribution, quantity and degree of connection to the stream system (Walsh, 2000; Walsh et al., 2005b) must be managed carefully to ensure that it does not exert too great a disturbance on the natural flow regime. Adaptive management could be used to monitor and respond to the effect different stormwater mitigation approaches have on conserving and restoring urban stream environments.
2.5.1 REDUCING IMPERVIOUS SURFACE AREA

Significant reduction to the environmental impact of urbanization can be achieved by either disconnecting impervious areas from the drainage network or reducing the amount of impervious surface (Roy et al., 2005; Walsh et al., 2005a).

Disconnecting impervious area is accomplished by removing the efficient conveyance linkages between impervious surfaces and the stream system. This is most effectively done at the site level and not through end-of-pipe treatments. Walsh et al. (2005a) suggest that stream health can be maintained if the amount of directly connected impervious area can be reduced. Reducing the effective impervious area to 2% is possible even when the total impervious area is as high as 50% (Walsh et al., 2005a).

Careful urban development (Schueler, 1995) and the use of appropriate stormwater management devices can contribute to maintaining acceptable levels of imperviousness even in highly urbanized areas. Arnold and Gibbons (1996) and Walsh et al. (2005a) suggest that imperviousness can be reduced by 50% through better site design. Significant improvements in the efficiency of transportation infrastructure result in a reduced amount of impervious surface. Brander et al. (2004) examined the runoff volumes from four different development styles (conventional curvilinear, coving, new urbanism and cluster development). Styles that increase development density leaving higher portions of the site as natural open space had the lowest levels of stormwater runoff. Brander et al. (2004) also found that the amount of runoff could be reduced with the addition of infiltration devices in all four development styles.

Incorporating infiltration devices into areas that exhibit high-levels of impervious cover is critical to re-establishing an urban hydrologic regime that is supportive of other natural processes (Ferguson, 1994). While new construction can implement low-impact development
techniques, even with careful site design and implementation of infiltration devices, there still remains a substantial portion of development that is comprised of impervious roof area. There is the potential to mitigate the contribution of roof area by disconnecting them from drainage infrastructure or altering their design such that they behave less like an impervious surface.

Many roofs have been engineered to detain water but these designs respond similarly to much larger engineered detention ponds with limited effects on runoff volumes. Green roofs offer an alternative approach that is quickly gaining in popularity. Green roofs have been noted and promoted to reduce stormwater runoff by retaining and returning rain water to the atmosphere through evapotranspiration. This differentiates the stormwater management mechanism utilized by green roofs from that of detention ponds and infiltration devices.

With special interest groups promoting the implementation of green roofs they are likely to become more common in the urban fabric. Extensive green roofs can be integrated into new development, in-fill development and existing development with relative ease. With such an expanse of potential surface area that can be greened, the cumulative effect of their application is important to understand. Green roofs cost more to install and are expected to last longer than traditional impervious roof treatments. Converting roofs from areas that contribute to the degrading affect of urban development to areas that provide significant environmental benefit is desirable. Yet the stormwater performance of green roofs is variable and the resulting contribution to the environment is not well understood. There are claims that the environmental benefit of stormwater retention is the most important contribution green roofs make, yet empirical evidence is lacking. By reducing the amount of runoff a roof generates, green roofs have the potential to reduce the amount of connected impervious area in a stream catchment and influence stream health potential. The degree of environmental
benefit depends on the long term stormwater response of a green roof to specific climate and context conditions.

Professions involved in land development and management require more-complete information about the likely relationship of extensive green roofs to urban water balance, and hence stream health. Such information might include how green roofs affect the area of impervious surfaces (especially dynamically in response to climate) and how parts of the hydrologic cycle – like evaporation and transpiration – are affected by green roof design. Further, all of this information is context-specific, so the contributions of green roofs to urban water balance should refer to specific climate data.

2.6 GREEN ROOFS

Researchers and green roof advocates imply many benefits of green roofs rather than conventional roofs on a building, including improved aesthetics, increased biodiversity, additional habitat, reduced air pollution, absorption of noise, reduced stormwater runoff, evaporative cooling, increased roof service life, thermal insulation and lower albedo (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Oberndorfer et al., 2007). Of these, reduced stormwater runoff particularly affects urban stream health.

Monterusso et al. (2004) and DeNardo et al. (2005) have suggested that the ability to retain stormwater is the most significant environmental benefit provided by green roofs. Schmidt (2006) offers a refinement to this observation indicating that the ability to increase evapotranspiration losses in comparison to a conventional roof is the most important environmental benefit of green roofs. Although numerous studies have examined a variety of characteristics relating to green roof runoff, little research directly evaluates the environmental
impact of the green roof stormwater response. Few studies provide detailed descriptions or long-term data that can demonstrate the range of stormwater runoff responses likely to occur from green roofs as a result of different climate conditions and precipitation patterns. Research studies show that green roofs can significantly reduce the amount of stormwater runoff compared to that of conventional roof designs (Lui, 2003; VanWoert et al., 2005a). They also show that green roofs alter the runoff hydrograph, delaying runoff start, reducing peak flows and extending runoff beyond the end of precipitation events (Lui, 2003; DeNardo et al., 2005; Moran et al., 2005; VanWoert et al., 2005a; Mentens et al., 2006).

The environmental contribution of a green roof can be examined by testing how the urban hydrologic cycle is altered by the difference between conventional roof runoff and green roof runoff. The difference in runoff response can be defined as the changes in imperviousness and water balance. The level of imperviousness has shown particularly good correlation to potential stream health, making it a valuable metric of the environmental impact of the stormwater response of different surfaces.

During small storm events in an urbanized catchment larger amounts of runoff are delivered to the stream system than would occur in an undeveloped or natural catchment. Green roofs have the ability to retain some precipitation, in turn reducing the amount of runoff. This reduces the degree of imperviousness exhibited by the green roof surface compared to a conventional roof surface. The reduction in impervious area may contribute to reducing the frequency of flow disturbances on stream ecosystems. Carter and Jackson (2007) identified that the potential effect of green roofs on environmental health could be tested by examining the contribution green roofs could make to the imperviousness of a catchment. Green roofs may also impact environmental health through changes in runoff water quality.
The study by Carter and Jackson (2007) used the average retention response of a green roof from a series of precipitation events to determine a fixed impervious contribution of green roofs. It is understood that the factors that affect the relationship between imperviousness and stream health are sensitive to variables that respond at a scale much finer than that of annual values. A challenge to Carter and Jackson’s (2007) findings is that climate conditions cause the stormwater response of a green roof to be dynamic, yet the measured contribution to impervious area is fixed.

A second general impact that green roofs can impart on the environment is through the change in the water balance. DeNardo et al. (2005) suggest that the quantity of water retained by a green roof can make a significant contribution towards accomplishing the United States Environmental Protection Agency (USEPA) National Pollutant Discharge Elimination System II (NPDES II) requirement that site development must ensure that the water from a 2-year storm will infiltrate and result in no runoff from a site. While a green roof does reduce runoff, it does not contribute to the infiltration of rainwater into the ground (Jarrett et al., 2006; Schmidt, 2006). Runoff and infiltration are not mutually exclusive processes as water can also return to the atmosphere through evapotranspiration. Green roofs as noted by Schmidt (2006) impact the water balance by reducing runoff through the evapotranspiration of water back to the atmosphere.

2.6.1 OVERVIEW OF THE TYPES OF GREEN ROOFS

Intensive and extensive are two common categories of green roofs. The two are distinguished through a range of characteristics that include purpose, maintenance requirements, vegetation type, growing media thickness and supporting structural requirements (Table 3).
Table 3 - Comparison of the typical characteristics of intensive and extensive green roofs

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

Intensive green roofs often have thick layers of soil, large plants, and a structural support requirement beyond that provided by a conventional building roof. They are often similar to ground-level gardens that can be accessed and experienced by the users of the building.

An extensive green roof is often designed with self-sustaining vegetation and requires little maintenance (Hutchinson et al., 2003). It is possible to install an extensive green roof on most buildings with a low slope roof. Research in North America has been conducted on extensive green roofs with slopes ranging from 2% to 25% (Getter et al., 2007). There is some variation in the reported depth and weight of the extensive green roof. They are noted to have between 20 and 150 mm of growing media (soil) depth and can weigh between 70 and 170 kg/m$^2$ when fully saturated (Dunnett and Kingsbury, 2004; Oberndorfer et al., 2007). To minimize weight and maintain acceptable water retention characteristics, the growing media used is often a specialized lightweight mixture of organic and inorganic materials.

In satisfying building code requirements in Ontario, a building roof provides an excess structural capacity of 88 kg m$^{-2}$ that could be utilized by a lightweight green roof system (Dunnett and Kingsbury, 2004). Conventional flat roofs that use gravel or stone ballast need to
support 200 kg m\(^{-2}\) for every 40 mm of ballast depth (Dunnett and Kingsbury, 2004) a value that exceeds the saturated weight of an extensive green roof (Table 3). As such it is believed that the wide spread retrofit of green roofs in an urban area would most likely be accomplished with extensive green roof systems due to their minimal requirement for additional build roof structural capacity. An extensive green roof provides many of the benefits of an intensive green roof while being simpler and less expensive to install.

### 2.6.2 COMPONENTS OF AN EXTENSIVE GREEN ROOF

An extensive green roof is made up of five basic layers; vegetation, growing media, filter fabric, drainage layer and a moisture/root barrier (Figure 6). Some designs also incorporate a sixth layer; moisture retention.

Figure 6 - Typical cross-section of an extensive green roof
2.6.2.1 VEGETATION

Harsh environmental conditions including increased wind speeds, high sun exposure, shallow growing media, and restricted water supply limit the vegetation that can be used on an extensive green roof (White and Snodgrass, 2003; Durhman and Rowe, 2006). Compton and Whitlow (2006) suggest that plant selection is typically based on eliminating maintenance, lowering weight, providing good coverage, and providing tolerance to extreme weather and water stress. *Sedum* spp. are often used as they can survive in these demanding conditions (Villarreal and Bengtsson, 2005). Common *Sedum* spp. that have been studied on extensive green roofs include *Sedum acre*, *Sedum album*, *Sedum kamtschaticum*, *Sedum reflexum*, *Sedum sexangulare*, and *Sedum spurium*.

2.6.2.2 GROWING MEDIA

Green roof growing media is often manufactured with a composition similar to container mix such as that used for potting soil (Beattie and Berghage, 2004). In addition to supporting the vegetation, growing media can be designed to support other goals of the green roof system, including water retention performance.

Growing media must be able to provide a suitable rooting zone for the plant material (Beattie and Berghage, 2004; DeNardo et al., 2005). This depth is a function of the vegetation type, water availability, and seasonal low temperatures (Köhler and Schmidt, 2003). It should be of low density and high water holding capacity (DeNardo et al., 2005). The depth of growing media used must be optimized to achieve these goals while maintaining the weight of the green roof system within the structural limitations of the building.
A typical growing media is made up of approximately 80% non-organic material and 20% organic matter with a small amount of slow-release fertilizer (Beattie and Berghage, 2004). Materials such as expanded slate, shale, perlite, scoria, domolite and other volcanic materials make up the bulk of the growing media composition. Growing media compositions can have a significant effect on water retention performance. Changes in composition also alter the rate at which moisture can be absorbed and how easily it can be removed through evapotranspiration (Miller, 2003).

Horticultural professionals recommend that Sedum spp., commonly used on extensive green roofs, require 70-90mm of growing media depth (Jarrett et al., 2006). The minimum recommended growing media depth is also influenced by climate. Boivin et al. (2001) indicate that the amount of damage to green roof vegetation in cold climates is affected by the planting media depth. In regions where temperatures drop below 0°C, it is important to provide sufficient growing media depth to reduce frost damage. 100 mm is the recommended minimum depth of growing media to provide sufficient over-winter protection for green roof vegetation in colder climates (Boivin et al., 2001).

Increasing the depth of growing media has a number of benefits such as improving the rate of plant coverage (Durhman et al., 2007), providing insulation value to the building (DeNardo et al., 2005) and improving the rain water retention capacity of the green roof (VanWoert et al., 2005a). There is a limit to the stormwater retention benefits gained by increasing the depth of growing media. Adding growing media beyond this depth results in minimal retention improvement (Jarrett et al., 2006).
2.6.2.3 FILTER FABRIC

Underneath the growing media is the drainage layer which allows water to exit the roof. A layer of filter fabric is installed between the growing media and the drainage layer to prevent growing media from migrating through the drainage layer. Erosion losses due to sediment being carried away by runoff must be minimized to maintain the growing media depth. Growing media lost as a result of erosion is costly to replace on the roof and has a negative impact on runoff water quality.

2.6.2.4 DRAINAGE LAYER

The drainage layer facilitates rapid horizontal movement of percolated runoff from the roof. An extensive green roof typically uses a free-draining system that prevents flooding of the growing media. With the exception of a study conducted by Compton and Whitlow (2006) all green roof systems reviewed included drainage layers. Two reasons are given for incorporating a drainage layer into the extensive green roof design. First, the drainage layer virtually eliminates the possibility of flooding the growing media, thereby reducing the chance of water leaking through the roof structure and damaging the interior of the building. Second, it is important to ensure that the root system of the roof vegetation is not submerged in water, a condition that many plants cannot tolerate (Miller, 2003). The number of plants that can survive the drought conditions of an extensive green roof is quite limited. Adding the requirement to survive flooded conditions is likely to further reduce the selection of plant species that could survive within the green roof environment.

The assumption that a green roof must be free-draining is challenged by Compton and Whitlow (2006), who examined the potential of using non-draining design that incorporated flood
tolerant plants. Compton and Whitlow (2006) suggest that current testing is being overly constrained by perceived weight limits and assumptions that green roofs must be free-draining. Examining the range of load capacities in existing building roofs, Compton and Whitlow (2006) believe many could support higher loads than applied by a typical extensive roof. The knowledge generated in green roof studies is being limited by perceived load and environmental limitations rather than examining the way to optimize the retention performance of green roof systems (Compton and Whitlow, 2006).

2.6.2.5 MOISTURE RETENTION LAYER

A number of commercially available extensive green roof systems offer a moisture retention layer. They can be placed underneath the drainage layer, above the drainage layer or even integrated into the drainage layer. Retention layers are often a woven or rigid structure that is capable of storing water.

2.6.2.6 MOISTURE/ROOT BARRIER

The bottom layer of a green roof is the moisture/root barrier that prevents water and vegetation from infiltrating the underlying roof structure. It is recommended that this barrier be an inorganic material that the roof vegetation is not able to degrade or penetrate. Asphalt and bitumous based roof material can be compromised by the roots of vegetation. Typically inorganic materials such as ethylene propylene diene monomer (EPDM), polyvinyl chloride (PVC) or butyl rubber is used for this layer (Dunnett and Kingsbury, 2004).
2.6.3 HYDROLOGY OF EXTENSIVE GREEN ROOFS

Precipitation falling over a green roof can follow a number of different paths ending in evaporation, transpiration or runoff (Figure 7). As precipitation falls over a green roof it will first strike the vegetated canopy that covers the surface of the growing media. A portion of the water is intercepted, stored on the surface of the vegetation where some evaporates back to the atmosphere, while the remainder runs down the plant structure and infiltrates the growing media.

By design, the hydraulic conductivity of a green roof is high enough that the infiltration rate exceeds the precipitation rate of the most intense storm likely to be experienced by the site (Miller, 2003; Beattie and Berghage, 2004; Villarreal and Bengtsson, 2005). Achieving this prevents overland flow, ensuring that all moisture passes into the growing media. Overland flow is not desirable as it increases the likelihood of erosion and reduces the opportunity for the green roof to retain or detain a portion of the rain event.

As precipitation infiltrates the growing media the available storage capacity is consumed. Precipitation that exceeds the maximum storage capacity of the green roof will drain from the growing media. Water that drains from a green roof percolates through the growing media and filter fabric exiting the underside of the green roof system through the drainage layer to centralized roof drains. The lateral hydraulic conductivity of the drainage layer needs to be high enough to ensure that any moisture beyond the storage capacity of the growing media is able to drain away (Miller, 2003; Beattie and Berghage, 2004). Water that drains through a green roof is referred to as runoff.
Figure 7 - The path taken by precipitation as it enters a green roof
The amount of runoff is a common variable used to assess the stormwater response of a green roof. The portion of water that does not runoff the green roof is the quantity retained. The runoff depth plus the retained depth of water equals the total depth of precipitation. If a rain event exceeds the maximum water storage capacity of a green roof runoff may not begin immediately. Depending on the intensity of the precipitation event, a green roof can detain an additional depth of water beyond the storage capacity. The maximum water detention capacity of the green roof is dependent on the growing media composition and is dynamic, changing in response to precipitation intensity (Bengtsson et al., 2005; Villarreal and Bengtsson, 2005).

The detention characteristics of a green roof result in both a delay and reduction in the peak flow of runoff from a green roof (Lui, 2003; Bengtsson, 2005; Bengtsson et al., 2005; Villarreal and Bengtsson, 2005; VanWoert et al, 2005a), as well as an extension of the runoff period at the end of the rain event (VanWoert et al., 2005a). After a rain event, detained water can continue to drain for a number of hours (Hutchinson et al., 2003) until the water level is reduced to the maximum storage capacity of the green roof.

The focus of this study is not on the detention performance of a green roof as detained water will runoff at the conclusion of a precipitation event. The retained volume of water is of greater interest because it corresponds to the two measures associated to the potential environmental impact of the green roof: the degree of imperviousness exhibited by the green roof; and its contribution to the water balance. The detention capacity does not alter the retention behaviour of the green roof.
2.6.3.1 WATER BALANCE CONTRIBUTION

The retention of a green roof has been compared to that of other surfaces. Of five surfaces compared by Schmidt (2006), an established, 120 mm thick green roof provided the closest approximation to the annual evapotranspiration rate of a meadow. The study also observed that green roofs do not contribute to groundwater recharge.

Comparing the data published by Schmidt (2006) to the water balance of Arnold and Gibbons (1996) and the Ontario Ministry of Natural Resources (MNR, 2008) indicates that a 50 mm thick green roof provides comparable values of evapotranspiration as those of the natural landscape (Table 4).

Table 4 - Comparison of water balance contribution of different urban elements and pre-development areas

<table>
<thead>
<tr>
<th>Surface</th>
<th>Evapotranspiration (%)</th>
<th>Runoff (%)</th>
<th>Groundwater Recharge (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New green roof</td>
<td>42</td>
<td>58</td>
<td>0</td>
</tr>
<tr>
<td>50 mm green roof</td>
<td>63</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>120 mm green roof</td>
<td>72</td>
<td>28</td>
<td>0</td>
</tr>
<tr>
<td>Porous asphalt</td>
<td>24</td>
<td>28</td>
<td>48</td>
</tr>
<tr>
<td>Grass paver</td>
<td>49</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>Meadow</td>
<td>91</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Forest Area</td>
<td>40</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Natural Watershed</td>
<td>60</td>
<td>10</td>
<td>30</td>
</tr>
</tbody>
</table>

*Source of data: Arnold and Gibbons (1996); Schmidt (2006); MNR (2008)*

2.6.3.2 RETENTION PERFORMANCE

Storm water performance can be documented in terms of runoff or retention. Retention is taken as the difference between the measured precipitation depth and the runoff depth once the precipitation event has stopped (DeNardo et al., 2005). To simplify comparison across studies all values have been adjusted to the measurement of retention.
Table 5 - Long term retention response of extensive green roofs ranked by percent retention

<table>
<thead>
<tr>
<th>Study Period (months)</th>
<th>Total Rainfall (mm)</th>
<th>Retention (mm (%))</th>
<th>Growing media depth (mm)</th>
<th>Location</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>450</td>
<td>207 (46)</td>
<td>30</td>
<td>Malmö, Sweden</td>
<td>Bengtsson et al., 2005</td>
</tr>
<tr>
<td>12</td>
<td>658</td>
<td>314 (48)</td>
<td>100-115</td>
<td>Portland, Oregon</td>
<td>Hutchinson et al., 2003</td>
</tr>
<tr>
<td>24</td>
<td>1099</td>
<td>550 (50)</td>
<td>100</td>
<td>Germany</td>
<td>Köhler et al., 2001</td>
</tr>
<tr>
<td>6</td>
<td>450</td>
<td>245 (54)</td>
<td>150</td>
<td>Ottawa, Ontario</td>
<td>Lui, 2003</td>
</tr>
<tr>
<td>3</td>
<td>314</td>
<td>173 (55)</td>
<td>100</td>
<td>Raleigh, North Carolina</td>
<td>Moran, 2004</td>
</tr>
<tr>
<td>18</td>
<td>1514</td>
<td>961 (63)</td>
<td>51 - 102</td>
<td>Goldsboro, North Carolina</td>
<td>Moran, 2004</td>
</tr>
<tr>
<td>14</td>
<td>556</td>
<td>378 (68)</td>
<td>25 – 60</td>
<td>Michigan State University</td>
<td>VanWoert et al., 2005a</td>
</tr>
</tbody>
</table>

The stormwater performance of a green roof is often reported as the total depth of water retained expressed as a percentage of the total depth of precipitation that lands on the roof during the study period. Stormwater response can also be expressed as the total depth of retention. There is a wide range of depth of retention performance, while percent retention remains more constant across the studies (Table 5).

Averaging the response over the entire study period disguises the variable performance of the green roof. The retention response of a green roof can vary dramatically from one event to the next and from month to the next (Table 6 and Table 7). Once again, the way performance is reported (percent retention or depth of retention) plays a role in describing the ability of a green roof to retain precipitation. For example, when describing the maximum depth of precipitation that a green roof can retain for a single day Moran’s (2004) data show a peak performance of 100% retention. However, this only applied to a maximum of eleven millimetres of retention. The same green roof exhibited a far greater depth of retention during a different day when 40 mm of precipitation were retained by the green roof. While having retained almost four times the depth of precipitation the second example only retained two
thirds of the precipitation. When examining the retention performance of a green roof, it is important to examine both the depth of retention and percent retention as they provide different insights into the retention characteristics of a green roof in a particular context.

Table 6 - Range of monthly retention responses of extensive green roofs

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Observation</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum monthly retention by depth (percent of event)</td>
<td>0.3 mm (1%)</td>
<td>Köhler et al., 2001</td>
</tr>
<tr>
<td>Maximum monthly retention by depth (percent of event)</td>
<td>109 mm (58%)</td>
<td>Hutchinson et al., 2003</td>
</tr>
<tr>
<td>Minimum monthly retention by percent (depth of event)</td>
<td>1% (0.3 mm)</td>
<td>Köhler et al., 2001</td>
</tr>
<tr>
<td>Maximum monthly retention by percent (depth of event)</td>
<td>100% (9 mm)</td>
<td>Köhler et al., 2001</td>
</tr>
</tbody>
</table>

Table 7 - Range of event retention responses of extensive green roofs

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Observation</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum event retention by depth (percent of event)</td>
<td>4 mm (45%)</td>
<td>Moran, 2004</td>
</tr>
<tr>
<td>Maximum event retention by depth (percent of event)</td>
<td>40 mm (69%)</td>
<td>Moran, 2004</td>
</tr>
<tr>
<td>Minimum event retention by percent (depth of event)</td>
<td>18% (6 mm)</td>
<td>Moran, 2004</td>
</tr>
<tr>
<td>Maximum event retention by percent (depth of event)</td>
<td>100% (8 mm, 11 mm)</td>
<td>Moran, 2004</td>
</tr>
</tbody>
</table>

The average response reported by some studies is often based on a very limited amount of data. Frequently, studies do not collect even a full year of data. Year-to-year variation in total precipitation and precipitation distribution cannot be addressed if study time-frames do not provide at least two years worth of data. Of the six long-term stormwater response studies examined only Köhler et al. (2001) provide two full years worth of data allowing for a limited comparison of annual retention variation.

Using a long-term average from a study period exceeding one year can alter the perceived retention performance. Hutchinson et al. (2003) monitored the retention from a demonstration green roof project in Portland, Oregon (Figure 12). The overall retention
performance during the 15-month study was 53% (Hutchinson et al., 2003). The 15-month period included two spring seasons during which retention performance was much better during the second year. Limiting the data to a single year that included the 2002 spring months, the roof was subjected to 658 mm of precipitation of which 314 mm was retained returning an annual retention of 48%. Limiting the data to a 12-month cycle that included the 2003 spring months resulted in a higher amount of precipitation received (706 mm) and retained (458 mm) with an annual retention rate of 65%.

Managers and design professionals relying on an average retention performance figure from long-term studies may find that the reported behaviour and actual response of a green roof differ substantially. Subdividing long-term data into shorter reporting periods or providing more descriptive performance measures are needed to ensure that the variable behaviour is adequately described and can be accounted for in the design and analysis process.

Monthly retention performance follows a different pattern in each study context and can vary from one year to the next (Figure 8 through Figure 12).

Figure 8 - Monthly storm water performance of a 30 mm deep extensive green roof in Malmö, Sweden.
Data from: Bengtsson et al. (2005)
Figure 9 - Monthly stormwater response of a 75 mm deep green roof in Goldsboro, NC.
Data not available for Jan 2003 and March 2003.
Data from: Moran (2004)

Figure 10 - 1997 Monthly stormwater response of a 100 mm deep extensive green roof in Germany.
Data from: Bustorf (1999) in Köhler et al. (2001)
In a Portland, Oregon study (Hutchinson et al., 2003) little precipitation was reported during the spring and summer months. Potential evapotranspiration rates are high during this portion of the year, but there is little precipitation to consume, resulting in high percent retention but low depths of retention. The winter months exhibited lower retention performance when expressed as a percentage of monthly precipitation than the summer months. However, even with lower percent retention performance due to the high level of precipitation received.
during the winter months, the green roof retained a much greater depth of precipitation in the winter compared to the summer (Hutchinson et al., 2003).

Retention performance ranged from a low of 11% in March, 2002 to a high of 100% in July, August and October of 2002 (Figure 12). The lowest percent retention does not necessarily relate to the lowest depth of retention. In fact, some of the highest percent retention months also provided the least depth of retention.

Hutchinson et al. (2003) noted considerable difference in the retention performance for a three month period (January to March) in 2002 as compared to the same three month period in 2003. Retention for the three months in 2002 was 22% and increased to 59% in 2003. This indicates that corresponding seasons from one year to the next can exhibit significant variation in green roof retention performance. Hutchinson et al. (2003) suggest that vegetation maturity, temperature differences and precipitation patterns played a role in the significantly different performances.

Hutchinson et al. (2003) state that increased vegetation maturity was potentially the most significant factor leading to the improved retention. However, the roof had been installed in the fall of 1999 and no observations of the condition or coverage of vegetation were provided for the two study years so there are no data to support this relationship.

The average daily air temperature during the months of January through March was 1.3°C warmer in 2003 than 2002 which Hutchinson et al. (2003) state potentially increased the evapotranspiration rate and retention performance. However, Shaw and Pittenger (2004) suggest that a small change in air temperature has little impact on evapotranspiration rates. Hutchinson’s explanation for the change in performance is questionable.
Precipitation patterns may have influenced the retention response although insufficient data were provided to examine this relationship. In 2002, there was more even rainfall distribution while 2003 had greater variability of rainfall (Hutchinson et al., 2003). Both years had a very similar number of dry days (approximately 40) during the three month period (Hutchinson et al., 2003). The three month precipitation depth was 10% higher in 2003 compared with 2002.

A different retention pattern can be seen in a study Bengtsson et al. (2005) conducted in Malmö, Sweden (Figure 8). This thin (30 mm of growing media) extensive green roof exhibited the highest percent retention during the months of April, May and June. The retention performance ranged from 18% in January, 2002 to 88% in June, 2002. Retention percentages and retention depth varied in a similar fashion over the course of the 12-month study period. The months with the greatest percent retention also exhibited the greatest depth of retention. Those months with the lowest percent retention exhibited the least depth of retention. Retention was higher during warmer seasons and lower during the winter.

Moran (2004) suggests that monthly percent retention is a function of rainfall volume and distribution within that month. A month with rain events separated by a few days would have a higher retention than a month with rain events closer together. Over the 18-month study period, percent retention ranged from a low of 41% in September, 2003 to a high of 100% in July, 2003 (Figure 9). There was wide variation in the monthly percent retention response and the corresponding depth of retention. Annual retention values could not be provided as a number of months contain missing data.

Data published by Köhler (2001) illustrate the monthly retention performance of a green roof in Germany over a two year period (Figure 10 and Figure 11). Monthly precipitation depths varied considerably from one year to the next. Total depth of precipitation was almost 20%
greater in 1998 compared to 1997 yet the annual percent retention was nearly identical for the two years (Table 8).

**Table 8 - Annual retention on a green roof in Germany**

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Precipitation</th>
<th>Total Retention</th>
<th>Percent Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>496 mm</td>
<td>254 mm</td>
<td>51%</td>
</tr>
<tr>
<td>1998</td>
<td>592 mm</td>
<td>296 mm</td>
<td>50%</td>
</tr>
</tbody>
</table>

*Data from: Köhler et al. (2001)*

Data from a second green roof in Germany (Köhler et al., 2001) shows a similar relationship between total annual precipitation and percent retention. The total precipitation was 50% greater in 1987 as compared to 1989, while retention was only four percent less (Table 9).

**Table 9 - Retention response and evapotranspiration for an extensive green roof in Germany**

<table>
<thead>
<tr>
<th>Year</th>
<th>Precipitation</th>
<th>Potential Evapotranspiration</th>
<th>Retention (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>702 mm</td>
<td>641 mm</td>
<td>523 mm (75%)</td>
</tr>
<tr>
<td>1988</td>
<td>595 mm</td>
<td>696 mm</td>
<td>437 mm (73%)</td>
</tr>
<tr>
<td>1989</td>
<td>468 mm</td>
<td>750 mm</td>
<td>370 mm (79%)</td>
</tr>
</tbody>
</table>

*Data from: Köhler et al. (2001)*

Köhler (2001) provided potential evapotranspiration data, but found no apparent relationship between it and retention (Table 9). Potential evapotranspiration is defined as the depth of water that can be returned to the atmosphere by a standard crop of short grass, under standard growing conditions with a sufficient supply of water (Dunne and Leopold, 1978). Moran (2004) provided a comparison between monthly retention performance and potential evapotranspiration rates. Potential evapotranspiration was much higher than the observed retention during seven of nine study months and only one month provided evapotranspiration and retention values within ten percent of one another. The total potential evapotranspiration
for the nine month period was 56% greater than the observed retention. Again, potential evapotranspiration does not exhibit a correlation to retention performance.

Re-evaluating Moran's (2004) data such that evapotranspiration loss is only considered when moisture is likely to be available in the growing media provides a much better correlation to the observed retention performance. After adjusting evapotranspiration, five months have an evapotranspiration total that is within ten percent of the observed retention values and the overall retention is only one percent more than the adjusted evapotranspiration loss.

Green roof stormwater retention performance varies considerably, with daily retention performance showing much greater variation than monthly and annual average retention performance. The monthly pattern of retention varies over the course of a year, from one year to the next and from one context to the next. It is difficult to find similarities between green roof stormwater retention performance patterns as they are a function of precipitation patterns and evapotranspiration rates which are context specific and green roof design characteristics.

2.7 MODELING THE GREEN ROOF STORMWATER RESPONSE

Some very technical computer models have been developed that can be adapted to simulate the flow response of green roofs. Although such a model could be applied to the runoff and retention performance of a green roof, they are perhaps more complicated than need be. Specialized modeling software such as the USEPA’s Storm Water Management Model (SWMM) is not typically used by planners because of their complexity and intensive data requirements (Harbor, 1994; Elliott and Trowsdale, 2007).
Elliott and Trowsdale (2007) reviewed 10 existing stormwater modeling programs with a particular interest in the ability to use them for assessing the performance of a low impact urban stormwater drainage system. Of the models reviewed only one, the Water Balance Model (WBM) developed by the Greater Vancouver Regional District, had a component specifically developed to model the response of green roofs to storm events (Elliott and Trowsdale, 2007). However, the WBM does not provide a sufficient definition as to how values are calculated, eliminating its potential use as the basis of this research.

Traditional techniques using curve numbers (CN) or rational method runoff coefficients to determine the retention response of an extensive green roof have been performed by Moran et al. (2005) and Carter and Rasmussen (2006). These techniques apply only to specific design storms and growing media antecedent moisture conditions, from which the coefficient values were initially calculated. These values cannot be applied to different storm sizes or moisture conditions (Miller, 2000; 2004). It is not reasonable to apply the rational method to green roofs as their retention performance has been shown to vary significantly (Miller, 2000; 2004).

There are procedures for adjusting CN to different antecedent moisture conditions (Dunne and Leopold, 1978), but they likely do not apply to extensive green roofs. Miller (2000; 2004) indicates that CN and the rational runoff method are based upon the dynamics of surface runoff a process much different than the through-flow drainage runoff of a green roof. To predict the response of a green roof to precipitation, it is necessary to base the method on physical processes unique to a green roof (Miller, 2000; 2004). Elliott and Trowsdale (2007) recommend that in order to estimate the impact of antecedent moisture conditions on stormwater runoff performance it is necessary to use continuous long-term simulations.
Mentens et al. (2006) provided a formula for approximating the runoff from a green roof as a function of the amount of precipitation and the depth of the growing media. The formula is based on the relationship found within a large body of empirical data and does not take into account the physical processes that influence green roof retention restricting its application to a limited precipitation range and climatic context. Applying the formula outside of the specified context is likely to result in incorrect estimates of retention performance (Mentens et al., 2006).

An improvement to the approach taken by Mentens et al. (2006) would be to base the estimated green roof retention response as a function of the contextual factors as well as the green roof design variables.

2.7.1 WATER BALANCE MODEL

A water balance approach has been used by Mentens et al. (2003) and Jarrett et al. (2006) to estimate green roof retention performance and appears to be similar to the method used by the WBM (Elliott and Trowsdale, 2007). The method is based on modeling the relationship between three basic processes: estimating the amount of water that can be held by the green roof at any point in time; the amount of water added through precipitation; and, the amount of water removed through evapotranspiration and runoff. The processes require estimating evapotranspiration rates which are dependent on location, climate, vegetation, storage capacity of the green roof system, and the current moisture level of the growing media. These variables along with the precipitation record for the location of interest allows for the simulation of green roof retention performance for a specific time and location. Conceptually, this approach appears to be strong although no research has been found containing a
description extensive enough to allow for the replication of the method. No formal validation of this technique against observed green roof retention performance could be found.

The response of a green roof to a series of precipitation events is a balance between the rate at which storage capacity is replenished and the rate at which it is consumed. The buffer between these two processes is affected by the maximum storage capacity of the green roof system. Green roof retention performance is a function of many variables including those that can be controlled through the green roof system such as vegetation type, and depth and composition of growing media and those variables that are independent of the green roof system that are a function of location, climate and precipitation pattern. These variables can be related to the water balance model if they are categorized by the mechanism they affect: maximum storage capacity; available storage recharge; or, available storage reduction.

Jarrett et al. (2006) developed a model called the Annual Green Roof Response (AGRR) Model. This model predicts the response of a green roof to a series of individual precipitation events using the daily rainfall record, daily reference evapotranspiration rate record, and the maximum water storage capacity for the green roof system using a water balance approach. The water storage potential of the green roof at any point in time is the value of the maximum water storage capacity, less the current stored water depth. This available depth for additional storage at a given point in time is the water deficit. The water deficit for a given day is equal to the water deficit from the previous day plus the addition storage capacity gained through evapotranspiration less the storage capacity loss due to precipitation (Equation 1).
\[ D_i = D_{i-1} - P_i + RO_i + ET_i \]  

Equation 1

Where \( D_i \) is the water deficit at the end of the day \( i \) (mm), \( D_{i-1} \) is the water deficit from the end of the previous day (mm), \( P_i \) is the precipitation during day \( i \) (mm), \( RO_i \) is the runoff during day \( i \) (mm), and \( ET_i \) is the amount of evapotranspiration during day \( i \) (mm).

When the daily water deficit is equal to the maximum storage capacity, this indicates that the green roof is as dry as possible and is ready to absorb water to a value equal to the full storage capacity of the green roof. When the daily water deficit is equal to zero, the green roof is retaining the greatest amount of moisture possible. Beyond this point any additional water that lands on the green roof will contribute to runoff. To provide a conservative estimate of the retention capacity of the green roof, the AGGR model uses an initial water deficit equal to zero.

2.7.2 MAXIMUM STORAGE CAPACITY

The maximum storage capacity of the green roof is a combination of the interception storage capacity of the vegetation, the internal storage capacity of the vegetation, the retention capacity of the growing media and the retention capacity of the moisture retention layer (if included in the design). The majority of the storage capacity is provided by growing media.

2.7.2.1 VEGETATION: STORAGE CAPACITY

Few data exist for the interception storage capacities of vegetation suitable for use on an extensive green roof. Jarrett et al. (2006) suggest that Sedum spp. have the capacity to intercept one millimetre of precipitation depth. Research is available pertaining to the interception storage of trees and agricultural crops although this is of little value to extensive
green roof systems. Dunne and Leopold (1978) reported that interception by grass is related to its total surface area, a function of the cover density and grass height. For grass ranging in height from 100 mm to 480 mm, the corresponding interception depth ranged from 0.5 mm to 2.8 mm. Interception storage is insignificant in relation to the depth of precipitation delivered by a large storm (Dunne and Leopold, 1978), but may play a role in the response of a green roof to smaller rain events. Green roof retention is believed to exhibit a more pronounced environmental benefit through the retention of smaller storm events. As a result, improved understanding of the role of interception with respect to green roof retention performance may prove valuable.

Some *Sedum* spp. have been observed to survive for extended periods of time in soils with very little or no soil moisture (VanWoert et al. 2005b; Durhman et al., 2006). Under severe water stress condition *Sedum* consume water from within their tissue resulting in a reduction in plant size. Jarrett et al. (2006) estimate that *Sedum* can reduce to 70 - 80% of their well-watered volume during times of extended drought. Jarrett et al. (2006) suggest that *Sedum* has an internal storage capacity equivalent to ten millimetres of precipitation depth.

The contribution made by vegetation to maximum storage capacity is not well-documented in literature. Research data were not found concerning the processes relating to interception and internal water storage by green roof vegetation. Research has given greater attention to the storage capacity contribution made by growing media.

2.7.2.2 GROWING MEDIA: STORAGE CAPACITY

Growing media provides the majority of the water storage capacity of a green roof. One variable relating to the storage capacity that is regularly documented in green roof studies is
the field capacity of the growing media. Usually expressed as a percent of the growing media volume, the field capacity is the maximum amount of water that can be held by a freely draining sample of growing media (Bengtsson et al., 2005). When the growing media moisture reaches field capacity runoff will begin (Bengtsson et al., 2005). Estimating field capacity is accomplished by saturating a dry sample of growing media with a known volume of water. Excess water is allowed to drain from the sample. Once gravity can no longer draw additional water from the media the drained volume is measured and subtracted from the initial volume of water added to the sample. This returns the depth of water retained by the growing media sample (Bengtsson et al., 2005).

The storage capacity is not equal to the maximum moisture level that can be retained by the growing media. Field capacity represents the maximum moisture level the growing media can retain, while the lower limit to the moisture level is the wilting point. Vegetation cannot draw water out of the growing media below this level (Allen et al., 1998; Bengtsson et al., 2005; Jarrett et al., 2006). With field capacity representing the maximum water level and the wilting point representing the minimum water level, Bengtsson et al. (2005) state that the storage capacity of the growing media is equal to the difference between these two values. Growing media used in a study by Bengtsson et al. (2005), was 30mm deep with an average field capacity of 45% and a wilting point of 15%. The difference between the two values returns a storage capacity of 30% or 9mm of storage for the 30mm of growing media. The retention performance of the growing media was monitored in a field study of an extensive green roof in Malmö, Sweden, where it regularly retained 9-10mm of water per rain event when precipitation occurred after a dry period (Bengtsson et al., 2005). The estimated storage capacity of the growing media corresponded well with the peak retention measured during the field study.
The depth of growing media has been viewed as a critical variable in the stormwater retention performance of the extensive green roof (DeNardo et al., 2005). Monterusso et al. (2004), VanWoert et al. (2005a), and Mentens et al. (2006) all found that increased media depth corresponded to increased retention performance. Mentens et al. (2006) reviewed 18 German studies and summarized the retention performance as it related to growing media depth (Table 10). These values agree well with those reported by Schmidt (2006). Based on four years worth of data Schmidt (2006) found that a 50 mm green roof retained 63% and a 120 mm green roof retained 72% of the annual precipitation.

Table 10 - Relationship between growing media depth and annual stormwater retention.

<table>
<thead>
<tr>
<th>Media Depth</th>
<th>Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50 mm</td>
<td>62 %</td>
</tr>
<tr>
<td>50 – 150 mm</td>
<td>70 %</td>
</tr>
<tr>
<td>&gt;150 mm</td>
<td>80 %</td>
</tr>
</tbody>
</table>

Data from: Mentens (2006)

Jarrett et al. (2006) tested the performance of an extensive green roof using the Annual Green Roof Response Model (AGRR), to assess how green roof media depth might impact the retention response of a green roof to a series of precipitation events. Retention capacity was simulated from a minimum of 3 mm to a maximum of 76 mm. The simulated green roof with 3 – 6 mm of storage capacity was able to retain 25% to 40% of the average annual precipitation. The simulated green roof with 40 mm of storage capacity was able to retain approximately 50% of the average annual rainfall (Jarrett et al. 2006). Beyond 40 mm of storage capacity there was little improvement in retention of the average annual rainfall (Jarrett et al., 2006). Although the simulated thin roof had a storage capacity less than one tenth that of the thicker roof, its annual retention performance was only reduced by one-half that of the thick roof. The percent
average annual retention per unit depth of growing media was much higher for the thin green roof. The largest event included in the simulation delivered 41 mm rain. Had events larger than this size occurred with sufficient frequency, the plateau for retention performance may have come from a higher storage capacity green roof.

Research studies have documented a range of growing media field capacities from 15% (Berghage et al., 2007) to 67% (Getter et al., 2007). As a result, equal depths of different growing media would exhibit very different moisture retention capacities. The composition of growing media affects its field capacity. Köhler (2003), Beattie and Berghage (2004) and Getter et al. (2007) identified that the organic composition of a green roof changes over time, altering the field capacity of the growing medium. Organic material such as compost, coir and peat moss can add to the moisture retention capacity of the growing media, but these materials break down. Köhler (2003) and Beattie and Berghage (2004) observed that the organic content of growing media will stabilize between two and five percent. Getter et al. (2007) found that the organic content of the growing media increased over a period of three years. Along with the increase in organic content, Getter et al. (2007) found that the growing media field capacity increased as the media aged. In 2002, when the organic content was two percent the field capacity was 17%. In 2005 the organic content had doubled to four percent and the field capacity had increased to 67%.

In DeNardo et al. (2005) the growing media had a field capacity of 34%. With a growing media depth of 89 mm this represents a retention capacity of 30 mm. A number of storm events exceeded 20 mm yet the maximum observed stormwater retention depth was 13.6 mm. Estimating the maximum storage capacity of the growing media according to the definition Bengtsson et al. (2005) provides (water storage capacity is the difference between the field
capacity and the wilting point) and assuming that the growing media has a similar wilting point (15%) results in an estimated storage capacity of 19% (17 mm) a value closer to the observed retention response of the green roof.

Moran’s (2004) data shows that a green roof with 75 mm of growing media retained a maximum of 40 mm from a single storm event. From this, the storage capacity can be estimated to be 53%. The maximum event retention observed by Villarreal and Bengtsson (2005) was almost 15 mm during a 24 mm rain event. The growing media was 40 mm thick providing a storage capacity of 37%.

Other authors have only provided measurements or estimates of the field capacity of the growing media they used (Table 11). The average storage capacity as estimated from reported field capacities less a 15% wilting point was 29%. The data obtained from Berghage et al. (2007) were multiplied by a factor of 39 as it represented the average from 39 different media samples.

Table 11 - Storage capacity estimated as the difference between the reported field capacity less a wilting point of 15% for 4 different studies

<table>
<thead>
<tr>
<th>Average Field Capacity (%)</th>
<th>Storage Capacity (%)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>12</td>
<td>Jarrett et al. (2006)</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>VanWoert et al. (2005a)</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>Köhler et al. (2001)</td>
</tr>
<tr>
<td>17 (new growing media)</td>
<td>2</td>
<td>Getter et al. (2007)</td>
</tr>
<tr>
<td>67 (aged growing media)</td>
<td>52</td>
<td>Getter et al. (2007)</td>
</tr>
<tr>
<td>46*</td>
<td>31</td>
<td>Berghage et al. (2007)</td>
</tr>
<tr>
<td>34</td>
<td>19</td>
<td>DeNardo et al. (2005)</td>
</tr>
</tbody>
</table>

*Field capacity ranged from 15% to 65% for 39 different samples

A second method used to estimate storage capacity was through the observation of the maximum retention from a single storm event. This retention was expressed as a percentage of the growing media depth (Table 12). This method provides an average storage capacity of
35%. Finally, two studies provided actual estimates of the storage capacity (Table 13), with an average value of 25%. The average storage capacity of the three methods is 30%.

**Table 12 - Storage capacity estimated as the maximum retention observed for a single storm event in 3 different studies**

<table>
<thead>
<tr>
<th>Maximum Single Event Retention (mm)</th>
<th>Storage Capacity (% of growing media depth)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>53</td>
<td>Moran (2004)</td>
</tr>
<tr>
<td>15</td>
<td>37</td>
<td>Villarreal and Bengtsson (2005)</td>
</tr>
<tr>
<td>14</td>
<td>15</td>
<td>DeNardo et al. (2005)</td>
</tr>
</tbody>
</table>

**Table 13 - Storage capacity reported in 2 different studies**

<table>
<thead>
<tr>
<th>Average Field Capacity (%)</th>
<th>Storage Capacity (%)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>30</td>
<td>Bengtsson et al. (2005)</td>
</tr>
<tr>
<td>Not provided</td>
<td>20</td>
<td>Rezaei and Jarrett (2006)</td>
</tr>
</tbody>
</table>

### 2.7.2.3 MOISTURE RETENTION LAYER

Storage capacity can also be augmented through the use of a moisture retention layer. Some moisture retention layers have been shown to contribute less moisture retention on a per unit basis than growing media. Miller (2003) and VanWoert et al. (2005a) documented the performance of different moisture retention layers to be 13% and 16% water retention by depth of retention layer. Growing media typically has a field capacity much higher than the values reported for moisture retention layers. Removing the moisture retention layer, and replacing it with the same depth of growing media provides a higher water storage capacity and a growing environment that better supports vegetation through increased frost protection and a larger rooting zone (Boivin et al., 2001; Köhler and Schmidt, 2003; Beattie and Berghage, 2004; DeNardo et al., 2005; VanWoert et al., 2005a; Durhman et al., 2007).
Estimating the retention capacity per unit weight of green roof system was not examined in this review but may be another factor when considering the use of a moisture retention layer.

2.7.3 STORAGE CAPACITY REDUCTION: PRECIPITATION

The available storage capacity is reduced by precipitation and irrigation. However, in the case of an established extensive green roof, it is assumed that no irrigation will be provided. Moisture will be provided primarily through natural precipitation events. Schmidt (2006) suggests that condensation is another source of water for green roofs. This too would reduce the available storage capacity but there are no estimates as to the value of this contribution. It is not known if condensation is a significant source of water requiring accounting in the green roof water balance.

Jarrett et al. (2006) concluded using the Annual Green Roof Response (AGRR) Model that retention capacity need not be larger than the largest annual storm. Retention performance peaked when the storage capacity of the growing media was simulated to be 40mm. The largest storm event included in the Jarrett et al. (2006) precipitation series was 41 mm.

Lui (2003) collected six months of retention data from a test green roof in Ottawa, Ontario. The green roof did not perform as well during the month of June as it did in other months of the study. Lui (2003) suggests that the retention performance diminished as there was insufficient time between rain events to allow the green roof to replenish its storage capacity. The growing media remained saturated due to a much higher quantity and frequency of rain events during the month of June. Lui (2003) further suggests that the intensity of a storm event is not a significant factor in the retention capacity of a green roof although it does affect the detention capacity (Bengtsson et al., 2005).
Moran (2004) and Moran et al. (2005) noted that the monthly percent retention was a function of the rainfall volume and distribution within that month. A month with rain events separated by a few days would have a higher retention than a month with rain events closer together.

The long term retention performance of a green roof is affected by changes in precipitation patterns as established at a specific location (Köhler et al., 2001). The total depth and frequency of precipitation events impacts the retention performance of a green roof while the intensity of each precipitation event appears to have little impact.

2.7.4 STORAGE CAPACITY RECHARGE: EVAPOTRANSPIRATION

Evapotranspiration is the loss of water to the atmosphere through the process of evaporation from soil and transpiration from vegetation. These processes occur when energy is added to water causing it to change state from liquid to gas. The energy required to drive this process is primarily gained through direct solar radiation, but is also gained through convection. Water vapour moves from an area of high concentration to an area of low concentration. The concentration of water vapour is called water vapour pressure. If the air surrounding the plants and soil has a very high water vapour pressure, the rate of evapotranspiration diminishes. In general increases in wind speed can facilitate an increase in the evapotranspiration rate (Allen et al., 1998).

The storage capacity of a green roof is recharged by removing moisture from the growing media and from plant surfaces and tissues through evapotranspiration. The amount of available storage capacity in the green roof system increases as the rate of evapotranspiration and the time between precipitation events increases.

The rate of evapotranspiration is represented by the depth of liquid water lost in a given period of time. Evapotranspiration rates are typically measured in millimetres per day.
2.7.4.1 CALCULATING EVAPOTRANSPIRATION RATES

An excellent resource for understanding the processes and variables impacting evapotranspiration was published by Allen et al. (1998), through the Food and Agriculture Organization (FAO), a division of the United Nations (UN) titled, “Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56”.

The method described by Allen et al. (1998) will be referred to as the FAO Penman-Monteith Method. This method is based on the theoretical foundation of the Penman-Monteith method which has been shown to provide good correlation to evapotranspiration from green roofs (Rezaei et al., 2005; Rezaei and Jarrett, 2006; Schmidt, 2006).

2.7.4.2 THE FAO PENMAN –MONTEITH METHOD

The variables contributing to the rate of evapotranspiration are typically broken down into three categories: climate, plant characteristics and environmental conditions. These categories correspond to the three steps involved in calculating evapotranspiration rates (Figure 13).

Step 1:
- The influence of climate and location on evapotranspiration is established by calculating a reference evapotranspiration rate ($ET_o$). This is the evapotranspiration rate for a standardized crop under standard conditions.

Step 2:
- $ET_o$ is adjusted using a crop coefficient ($k_c$) that accounts for differences in vegetation characteristics between the standard crop and the vegetation of interest. This results in a value known as the crop evapotranspiration rate ($ET_c$).

Step 3:
- $ET_c$ must be adjusted from standard growing conditions to the actual growing conditions resulting from site management and environmental conditions. One coefficient of particular influence in the extensive green roofs environment is the limited supply of water. This factor is accounted for using the water stress coefficient ($k_s$). This results in a value known as the adjusted crop evapotranspiration rate ($ET_{adj}$).

Figure 13 - Basic process for determining evapotranspiration rates using the FAO Penman-Monteith Method
2.7.4.2.1 \( ET_o \) – REFERENCE EVAPOTRANSPIRATION RATE

The first step in the FAO Penman-Monteith method is the calculation of a reference evapotranspiration rate \( (ET_o) \). It is a reference rate as it only takes into consideration the effects of location and climate, assuming a standard reference crop (Table 14) and standard growing conditions (Table 15).

**Table 14 - Standard reference crop for the FAO Penman-Monteith Method**

<table>
<thead>
<tr>
<th>Standard Reference Crop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation type</td>
<td>Large area of short green grass</td>
</tr>
<tr>
<td>Height</td>
<td>0.12 m</td>
</tr>
<tr>
<td>Surface resistance</td>
<td>70 \text{sm}^{-1}</td>
</tr>
<tr>
<td>Albedo</td>
<td>0.23</td>
</tr>
</tbody>
</table>

*Data from: Allen et al. (1998)*

**Table 15 - Standard growing conditions for the FAO Penman-Monteith Method**

<table>
<thead>
<tr>
<th>Standard Growing Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>• All heat fluxes move upwards and not horizontally</td>
</tr>
<tr>
<td>• Goal is to achieve full production requiring excellent management and environmental conditions</td>
</tr>
<tr>
<td>• Grown in large field</td>
</tr>
<tr>
<td>• Crop has a uniform height</td>
</tr>
<tr>
<td>• Crop is actively growing</td>
</tr>
<tr>
<td>• Crop is well-watered</td>
</tr>
<tr>
<td>• Crop fully shades the soil surface</td>
</tr>
<tr>
<td>• Crop is disease free</td>
</tr>
<tr>
<td>• Crop is well fertilized</td>
</tr>
</tbody>
</table>

*Data from: Allen et al. (1998)*

To calculate \( ET_o \) using the FAO Penman-Monteith method four weather parameters are required along with the latitude (\(^{\circ}\)) and elevation (m) of a particular site. The weather parameters include solar radiation (Wm\(^{-2}\)), air temperature (\(^{\circ}\)C), wind speed (ms\(^{-1}\)), and relative humidity (%). \( ET_o \) increases with increases in solar radiation, air temperature and wind speed and decreases in vapour pressure (Allen et al., 1998; Pittenger and Shaw, 2004; Rezaei et al.,
Increases in solar radiation have the greatest impact on increasing the reference evapotranspiration rate. Increases in wind speed can increase the reference evapotranspiration rate but the effect is dependent upon temperature and vapour pressure. Wind speed will have a more pronounced effect during hot/dry conditions as compared to moist/warm conditions. Wind removes moist air from the vicinity of the vegetation. When ambient air is quite dry, wind will replace the moist air close to vegetation with dry air resulting in a higher vapour pressure deficit and evapotranspiration rate. When ambient air is quite moist, the vapour pressure deficit will be small resulting in a lower evapotranspiration rate.

2.7.4.2.2 $ET_c$ - CROP EVAPOTRANSPIRATION

Each plant species contributes differently to the rate of evapotranspiration. The crop coefficient accounts for differences between the reference crop and the crop of interest including the height, albedo, shading of soil, rooting characteristics and resistance to vapour transfer (Allen et al., 1998). These properties impact the amount of radiation absorbed by the vegetation, the ability to remove moist air from near the plants and soil, and shades the ground reducing the radiant energy that can be absorbed by the soil.

The crop coefficient is the ratio between the reference evapotranspiration rate and the crop evapotranspiration rate under standard growing conditions and remains constant across different climates and locations (Allen et al., 1998; Pittenger and Shaw, 2004). The method of determining reference evapotranspiration rates must match the technique used in determining crop coefficients (Allen et al., 1998).

The crop coefficient can be expressed as a single term that accounts for both transpiration and evaporation differences between the reference crop and the crop of interest or it can be split
into two separate terms, each identifying the specific contribution of evaporation and transpiration. The value of the crop coefficient can also be adjusted for crop development stages and seasonal performance.

Crop coefficients are well-defined for agricultural crops, but not for ornamental plant species such as those used in a green roof environment. Allen et al. (1998) suggest that crop coefficient ranges from 0.4 to 1.2 depending on the type of vegetation. Low end values are representative of sisal or pineapple tree with bare soil while larger values are characteristic of vegetation such as tomato, soybean, and potato (Allen et al., 1998).

Given the importance placed on the role of evapotranspiration in the performance of green roofs, it is surprising that few studies have been designed to identify the crop coefficients of typical green roof vegetation under standard growing conditions. Such a study would allow for the determination of crop coefficients valuable to understanding watering regime, water consumption and stormwater performance of green roofs.

Lazzarin et al. (2005), in a study to develop a numerical model for green roof runoff in North-eastern Italy identified that the average crop coefficient for Sedum spp. was 0.5 although it is not clear what method was used to determine these crop coefficients. Lazzarin et al. (2005) make reference to variables and techniques similar to those of the FAO Penman-Monteith method.

Rezaei (2005) reported that the winter crop coefficient of a mixed bed of Delosperma nubigenum and Sedum album (1:1 ratio) was 0.74 and the fall and spring crop coefficient was 1.97. The reference evapotranspiration rate needed to determine these coefficients was calculated using the Penman-Monteith method. The evapotranspiration data reported by Rezaei (2005) suggests that the plants were under an increased level of water stress, which is
not conducive to the standard growing conditions needed to determine a crop coefficient. The resulting coefficients provided by Rezaei (2005) may be a combination of crop and water stress coefficients.

2.7.4.2.3 \( ET_{CADJ} \) - ADJUSTED CROP EVAPOTRANSPIRATION

Differences in environmental variables (such as salinity, fertilizer, soil compaction, disease, and soil moisture) from the standard growing conditions can impact evapotranspiration rates and are accounted for through adjustment coefficients. Soil moisture is of particular interest in the rate of evapotranspiration from extensive green roofs as they frequently are subjected to moisture stress due to the irregularity of precipitation events. Unlike an agricultural crop, these irregularities are not supplemented through irrigation or capillary rise from deeper soil moisture reserves. Low soil moisture leads to a low actual evapotranspiration rate while high soil moisture leads to a higher evapotranspiration rate (Schmidt, 2006).

There are significant differences between the standard growing conditions and roof top growing conditions. Once established, green roof vegetation needs to remain viable but growth and development are not necessary. Supplemental irrigation is not typically provided and water delivery is not likely to match the maximum water requirements as assumed by the reference evapotranspiration rate. Evapotranspiration is only possible when moisture is present in the growing media. As the moisture level decreases in the growing media it becomes increasingly difficult for the vegetation to extract it, reducing the opportunity for transpiration.

The amount of water available for evapotranspiration is known as the total available water (TAW) which is equal to the storage capacity of the growing media. As described in section
2.7.2.2, storage capacity is equal to the difference between the field capacity of the growing media and the wilting point. Water is most easily drawn from the growing media when the moisture level is at field capacity. As moisture decreases in the growing media there is a threshold below which the force required by vegetation to draw it out increases. Once a certain percentage of the TAW has been consumed water stress begins, reducing the evapotranspiration rate. The proportion of the TAW that the vegetation can consume prior to exhibiting signs of water stress is the readily available water (RAW). RAW varies by vegetation and growing media and is equal to 30 to 70% of the TAW for a wide range of agricultural crops (Allen et al., 1998).

The data published by Rezaei and Jarrett (2006) show a sharp reduction in the evapotranspiration rate from the green roof sample plots once the water content was reduced by 60% or more of the TAW. This suggests that the RAW value is equal to 60% of the TAW, a value well within the typical range identified by Allen et al. (1998).

2.7.4.2.4 EVAPOTRANSPIRATION PERFORMANCE OF GREEN ROOFS

Green roof evapotranspiration rates have been reported to reduce to zero millimetres per day within one week without precipitation (Bengtsson et al., 2005; VanWoert et al., 2005b; Durhman et al., 2006).

There are seasonal changes in evapotranspiration rates that correspond to changes in the stormwater response of green roofs. Reference evapotranspiration rates differ over the course of a year and are typically highest during warm seasons and lowest during cold seasons. Rezaei and Jarrett (2006) observed that the actual evapotranspiration rates from small green roof test plots follow the seasonal changes in reference evapotranspiration (Table 16).
Table 16 - Seasonal changes in evapotranspiration rate from extensive green roof test plots

<table>
<thead>
<tr>
<th>Season</th>
<th>Average Air Temperature (°C)</th>
<th>Evapotranspiration loss six days after watering (mm)</th>
<th>Time to consume 60% of total available water (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>8</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>Fall/Spring</td>
<td>19</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Early summer</td>
<td>27</td>
<td>10.5</td>
<td>6</td>
</tr>
<tr>
<td>Hot summer</td>
<td>31</td>
<td>14.5</td>
<td>4</td>
</tr>
</tbody>
</table>

Data from: Rezaei and Jarrett (2006)

Table 17 - Peak evapotranspiration rate under well-watered conditions for Sedum spp.

<table>
<thead>
<tr>
<th>Species</th>
<th>Peak Evapotranspiration Rate Under Well-Watered Conditions (mm day⁻¹)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seven Sedum spp.</td>
<td>5.5</td>
<td>VanWoert et al. (2005b)</td>
</tr>
<tr>
<td>Sedum acre</td>
<td>5.0</td>
<td>Durhman et al. (2006)</td>
</tr>
<tr>
<td>Sedum kamtschaticum</td>
<td>6.4</td>
<td>Durhman et al. (2006)</td>
</tr>
<tr>
<td>Sedum reflexum</td>
<td>4.4</td>
<td>Durhman et al. (2006)</td>
</tr>
</tbody>
</table>

Compton and Whitlow (2006) examined the influence of two plant species, Solidago canadensis and Spartina alterniflora on the evapotranspiration loss from a non-draining green roof system to explore the use of supplemental grey-water irrigation. The plants had peak evapotranspiration rates between 40 and 45 mm day⁻¹, an order of magnitude higher than reported in studies examining the evapotranspiration performance of Sedum (Table 17). The calculated crop coefficient for Solidago canadensis was 3.8 and for Spartina alterniflora 3.4. This cannot be directly compared to other crop coefficients as the reference evapotranspiration was taken to be the rate from an evaporation pan. Crop coefficient is a function of the method of determining the reference evapotranspiration rate. If the method used to determine the reference evapotranspiration rate changes, so too will the crop coefficient.
2.7.5 PLANT WATER USE

Plant water usage varies with environmental conditions, management techniques and the stated goals for plant development and health (Figure 14).

Agricultural crop water requirements

- Precipitation supplemented by irrigation to ensure soil moisture sufficiently high that water is readily available for plants to consume
- Plants are actively growing (does not apply to dormant period)
- Large area of vegetation completely covered by a uniform crop
- The goal is to maintain conditions that optimize plant growth and development

Ornamental landscape maintenance water requirements

- Precipitation supplemented by minimal amounts of irrigation
- The area is comprised of a mixture of vegetation and is not a monoculture
- The vegetation canopy is not uniform, leading to areas of shading
- The goal is to maintain plant appearance

Established extensive green roof water requirements

- Precipitation is the only source of water. Supplemental irrigation not provided
- Area are relatively small as compared to agricultural crops
- Small area of vegetation completely covered by a uniform crop
- The goals are to maintain plant viability and consume water when available to improve stormwater retention capacity

Figure 14 - Water requirement assumptions for agricultural crops, ornamental landscapes and green roof environments

Estimating the consumption of water through evapotranspiration is critical to the management of agricultural crops, as it represents the crop water requirement for plant development and maximizing yields. If the amount of water supplied through natural precipitation is less than the adjusted evapotranspiration rate for the crop, the difference should be made up through supplemental irrigation. Providing water beyond the crop water requirements does not increase yields, but it does increase the cost of production. Agriculture identifies water
requirement as the water needed to maximize plant development and yield, and to minimize supplemental irrigation.

An alternative view has been taken by researchers interested in the maintenance of ornamental plants typical of commercial and residential landscaping. Water requirements of ornamental plants is defined as the minimum amount of water required to maintain an acceptable appearance after plants are established (Pittenger and Shaw, 2004; Shaw and Pittenger, 2004). During plant establishment, goals are similar to those used for agricultural crop water requirements as the goal is to increase plant size and coverage.

Research has been done to investigate the water needs of green roof plants (VanWoert, 2005b; Durhman et al., 2006), but no studies have been conducted with the aim of providing the values needed for estimating evapotranspiration rates as set out in the FAO Penman-Monteith Method. Green roof research into plant water use and stormwater retention could be enhanced if data were provided relating to the study location and climate, or better still, if study questions and methods were developed within the FAO Penman-Monteith framework. Data from existing green roof studies provide some insights into the variables needed to determine an adjusted crop evapotranspiration rate from green roof areas.

Vegetation plays a significant role in the removal of water from the soil, by increasing the rate at which storage capacity returns to the soil. Depending on the frequency and size of storm events, Berghage et al. (2007) found that green roof vegetation contributes up to 40% of the total retention capacity of a green roof. At times the evapotranspiration rate of a roof planted with Sedum spurium was twice that of the non-planted version of the same green roof system.

Berghage et al. (2007) observed that plants maximized the evapotranspiration potential of the green roof system when storms 13 mm in depth occurred every 3 to 5 days. As the number of
days between rain events increased, the evaporation contribution of the growing media without vegetation performed nearly identically to that of the vegetated version.

A balance occurs as increased media depth and higher rates of irrigation increase plant growth. This in turn increases the evapotranspiration consumption of media moisture by the vegetation requiring more frequent watering to maintain growth (VanWoert et al., 2005b). This may also indicate that during seasons with more precipitation, growth can be more vigorous and water consumption will increase improving the roof’s retention capacity to match the increase in precipitation frequency and that plants will conserve water in times of stress.

For a non-irrigated green roof, it is ideal if plants consume water when it is plentiful and conserve water when scarce (Berghage et al., 2007). Berghage et al. (2007) observed that Sedum spp. reduce in size to 80% of their well-watered size during times of extreme water stress. Sufficient watering after an extended dry period allows Sedum spp. to return to their well-watered size. Berghage et al. (2007) show that Sedum spurium, Sedum sexangulare and Delosperma nubigenum do not conserve water loss at all times. These plants responded to media moisture conditions. Moisture use was proportional to media moisture levels. When media moisture was high, water use was high. When media moisture was low, water use was low.

### 2.8 REGIONAL APPLICATION OF GREEN ROOFS

Research provides little guidance in understanding the potential effect of the wide-spread application of green roofs within a stream catchment. Hutchinson et al. (2003) suggest that it would be valuable to apply the stormwater response observed from a demonstration green roof over a greater area to evaluate the impact on stream systems. This is of particular interest
as rooftops represent 40% of the impervious surface in Portland, Oregon (Hutchinson et al., 2003). Applying green roofs might provide significant potential to reduce the total impervious area resulting from development.

Carter and Rasmussen (2005) and Carter and Jackson (2007) investigated the connection between green roofs and impervious cover in an urbanized area of watershed in Georgia, USA. Using GIS they identified the land cover for the study areas. Land coverage was classified as roofs, flat roofs, roads, parking, sidewalks, sports fields, or landscaping. Each land cover was also given a value of impervious or pervious. Expressing the combined area of each land use classified as impervious provided a TIA value for the study site of 53%. Sixteen percent of the catchment was covered by roof surfaces, half of which were flat. The majority of flat roofs were located in downtown and commercial areas, while very few existed in residential areas. If all the flat roofs in the study area were greened the TIA would reduce to 45%. Carter and Jackson (2007) concluded that applying green roofs to commercial development and government buildings would have the greatest impact on reducing catchment TIA.

2.9 LITERATURE REVIEW SUMMARY

In summary, research suggests that an increase in impervious area as a consequence of urban development may negatively impact the environment, and in particular, stream health. Impervious surface cover can degrade water quality and alter the quantity of water moving through the environment with adverse consequences on stream morphology, stream habitat and aquatic species. An impervious surface contributes larger volumes and more frequent occurrences of runoff from precipitation events compared to that from a naturally vegetated area. The increased frequency of runoff from an impervious surface is more pronounced during the summer and fall than it is during the spring. In addition to increasing runoff,
impervious surfaces change the water balance within the stream catchment by reducing infiltration and evapotranspiration. The environmental impact of urban development can be estimated by evaluating the amount of impervious surface cover within a stream catchment. As impervious cover increases beyond 25% of the stream catchment, stream health becomes degraded, non-supporting for many aquatic species.

“Green” areas such as parks, lawns, and gardens are surfaces that do not contribute to impervious surface cover within a stream catchment. Green roofs have been included as “green” area by Carter and colleagues (Carter and Rasmussen, 2005; Carter and Jackson, 2007) who examined the effect of the broad application of green roofs on total impervious area of a stream catchment. However, their assumption that green roofs do not contribute to impervious area has yet to be verified. It is well established in research that the stormwater response of a green roof is specific to the green roof design and location and is highly variable, reacting uniquely to a particular sequence of climate conditions. Annual variation in climate patterns is likely to have an impact on the range of runoff responses exhibited by a green roof. In fact, Köhler et al. (2001) show that green roof runoff can range from 0% to 99% of monthly precipitation. This suggests that green roofs do not always act as non-impervious surfaces as suggested by Carter and colleagues (Carter and Rasmussen, 2005; Carter and Jackson, 2007) and raises the question of whether green roofs should be classified as impervious or non-impervious.

To assess the imperviousness of a green roof, it is necessary to evaluate its stormwater response over a number of years, accommodating the range of climate conditions and precipitation patterns unique to a particular location. The size, frequency and seasonal distribution of green roof runoff need to be examined in order to provide insight into the
impervious characteristics of the green roof. Many studies do not provide the daily runoff data needed for this characterization, but rather report only average runoff response. Those studies that do provide daily runoff data do so for a very limited time thereby reducing the ability to evaluate seasonal or annual variation in runoff response which influences the imperviousness of the green roof.

Research is needed to assess the stormwater response of green roofs (quantified as the depth, frequency, and distribution of runoff events) to a number of years of climate and precipitation data in order to characterize the impervious contribution of green roofs. Furthering the understanding of how green roofs respond to precipitation events could improve the ability of landscape architects and allied professionals involved in land development to evaluate the potential environmental impact due to the broad application of green roofs. Predicting green roof contribution of impervious surface area would allow for an improved estimate as to whether green roofs can be applied at a rate high enough to reduce the amount of impervious area within a stream catchment to below 25% supporting the potential for improved stream health.

The next section of this thesis details the methods used to simulate the stormwater response of a green roof in a particular context.
3 METHOD

3.1 STUDY CONTEXT

The City of Waterloo was selected as the site context for this study. A familiarity with the study region and an interest in the feasibility and implementation of green roofs expressed by the City of Waterloo motivated its selection. Furthermore, the necessary climatic data required to simulate the stormwater response of a green roof were readily available for the City of Waterloo.

Waterloo is located in Southwestern Ontario at 43°30’N, 80°32’W, approximately 100 km west of Toronto. It has a temperate humid climate. 30-year climate averages from the Waterloo Wellington A weather station at 43°27.0’N, 80°22.8’W, 12 km east of downtown Waterloo, indicate that the daily average air temperature is 6.7°C, annual rainfall is 765 mm, and monthly average relative humidity ranges from a low of 84% in February to a high of 94% in August (Environment Canada, 2004a).

In 2005, the population of Waterloo was approximately 115000 and is expected to grow to 150000 by 2031 (City of Waterloo, 2005; 2006). Water quality and quantity are important issues within Waterloo as 80% of water is acquired from local groundwater supplies, while the remaining 20% is drawn from the Grand River (City of Waterloo, 2005; 2006). As the population of Waterloo increases, it is expected that water demand will exceed local supply. It is projected that a pipeline from the Great Lakes will be required by 2030 in order to augment the shortage in local water supply (City of Waterloo, 2005; 2006).

Downtown Waterloo is extensively developed and is composed of a high percentage of impervious surfaces with high density residential development surrounding the downtown core.
Future land development is anticipated to be achieved through infill within the existing city boundaries (City of Waterloo, 2006). This suggests that an intensification of land use will occur within Waterloo resulting in a probable increase in impervious cover. Waterloo identifies itself as a green city with interests in protecting aquatic habitats and preserving the natural environment (City of Waterloo, 2005).

The City of Waterloo published a report on the feasibility and city-wide implementation of green roofs (2005), which identifies that the broad application of green roofs may provide economic, aesthetic, recreational and environmental benefits to the city. Specifically, the study suggests that green roofs can benefit urban stream health by improving water temperature and quality, reducing erosion and promoting a healthier benthic community.

Six sites within the City of Waterloo have installed green roofs. These include the Grand River Hospital, Perimeter Institute, Accelerator Center, Canadian Institute for Governance Innovation, a multi-use building on Dorset Street and Waterloo City Hall.

### 3.2 STUDY PERIOD

The simulation was completed for four 220 day-long study periods, starting April 9th and ending November 16th for 2004 through 2007 inclusive.

These four years were selected as they contained relatively few errors (UW Weather Station, 2008c), exclude years when snow fall data was not available and provided a range of precipitation depths less than, equal to and greater than those of the 30-year climate norm (Table 22).

The model that was developed for this study is not appropriate for use during the portion of the year when precipitation occurs as snow and was not applied during the winter months.
The portion of the year when this is likely to occur was established by examining daily snowfall measurements for each of four years (Table 18). These data were obtained from the University of Waterloo Weather Station data archive (UW Weather Station, 2004b; 2005b; 2006b; 2007b; 2008b).

Table 18 - Selection of climate variables for the non-snow fall period during 2004 – 2007 for Waterloo, ON.

<table>
<thead>
<tr>
<th>Year</th>
<th>Day of last snowfall in spring</th>
<th>Day of first snowfall in fall</th>
<th>Average daily low air temperature (°C)</th>
<th>Average daily high air temperature (°C)</th>
<th>Average daily air temperature (°C)</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>104</td>
<td>311</td>
<td>9.1</td>
<td>19.7</td>
<td>14.4</td>
<td>551</td>
</tr>
<tr>
<td>2005</td>
<td>94</td>
<td>321</td>
<td>11.4</td>
<td>22.5</td>
<td>16.9</td>
<td>506</td>
</tr>
<tr>
<td>2006</td>
<td>95</td>
<td>336</td>
<td>8.6</td>
<td>18.3</td>
<td>13.4</td>
<td>762</td>
</tr>
<tr>
<td>2007</td>
<td>100</td>
<td>320</td>
<td>9.4</td>
<td>20.8</td>
<td>15.1</td>
<td>346</td>
</tr>
</tbody>
</table>

3.3 SIMULATED GREEN ROOF SPECIFICATIONS

The green roof design specifications used in this study are based on the performance requirements of a typical green roof that could be successfully implemented on a wide scale within the City of Waterloo context (Table 19). This takes into consideration contextual characteristics such as hardiness zone and precipitation patterns. These specifications were determined from the findings of previous studies discussed in sections 2.6 and 2.7.

Table 19 - Design characteristics assigned to the hypothetical green roof applied in the present study

<table>
<thead>
<tr>
<th>Green roof type</th>
<th>Extensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation</td>
<td>Sedum</td>
</tr>
<tr>
<td>Crop coefficient ($k_c$)</td>
<td>1.07</td>
</tr>
<tr>
<td>Growing media depth</td>
<td>100 mm</td>
</tr>
<tr>
<td>TAW</td>
<td>30% (30 mm)</td>
</tr>
<tr>
<td>RAW</td>
<td>60% of TAW (18 mm)</td>
</tr>
</tbody>
</table>
For green roofs to have any significant effect on the environment, it is assumed that they must be retrofitted to a significant number of the flat building roofs in an urban area. Extensive green roofs can usually be applied with little or no structural improvement required to the existing building making them the likely type of green roof to be retrofitted into an existing urban area.

The simulated extensive green roof accounts for the storm water response as a result of the green roof vegetation and growing media. The other components of a typical green roof such as filter fabric and the drainage layer are assumed not to impact the storm water response.

The vegetation selected for the simulated roof is *Sedum* as it was used for the demonstration green roof installed on the roof of Waterloo’s City Hall. *Sedum* is one of the most widely used plants in green roof studies, providing retention data and the related performance variables necessary for this study. *Sedum* is able to survive in the Waterloo hardiness zone 5a/5b (Agriculture and Agri-food Canada, 2000) and can survive the drought periods typical of the region. *Sedum* has been shown to remain viable even after 88 days without water (VanWoert et al., 2005b). During the four study periods the maximum separation between rain events was 15 days (See section 4.3, Figure 28).

The growing media depth was set at 100 mm. This exceeds the minimum depth (70 to 90 mm) recommended to adequately support *Sedum* (Jarrett et al., 2006) and is equal to the minimum depth recommended by Boivin (2001) to provide protection to vegetation from frost damage in a cold climate such as that of Waterloo, Ontario. Jarrett et al. (2006) found that growing media storage capacities that exceeded the largest storms in a region provided little additional benefit to retention performance. From the 30-year climate average it is observed that during the months of April through November the City of Waterloo averaged five days per year when
rainfall exceeds 25 mm (Environment Canada, 2004a). As a result a storage capacity much greater than 25 mm of precipitation probably provides little improvement in overall retention performance.

Composition of the growing media is not defined in this study, however two critical performance parameters relating to composition are defined; total available water (TAW) and readily available water (RAW). Taking an average of the data produced by these three methods used to define TAW in the literature review (see section 2.7.2.2) provides a TAW equal to 30% of the growing media depth. The growing media depth has been set to 100 mm providing a TAW depth of 30 mm. The green roof has the capacity to retain 30 mm of precipitation under dry antecedent moisture conditions exceeding the largest typical rainfall for the region by 20%. Rezaei and Jarrett (2006) indicated that there was a consistent reduction in the rate of evapotranspiration once TAW had been reduced by 60%. These are the best data available to define the RAW. For this study, 60% of TAW results in a RAW depth of 18 mm.

3.4 WATER BALANCE MODEL

The relationship identified between imperviousness and potential stream health by Schueler (1995), Arnold and Gibbons (1996), and CWP (2003) signifies that to understand the potential environmental impact of green roofs, it is necessary to understand their contribution to impervious cover. The degree of imperviousness is related to the amount of runoff generated by a surface and is often given a constant value. However, the runoff from a green roof varies considerably suggesting that it should not be viewed as providing a constant impervious value.

Often storm water performance is reported in time scales too large to demonstrate the degree of variation observed in stormwater response (Ferguson, 1994). If values determined by
monthly and annual averages are used to guide implementation and estimation of the impact of water management devices such as green roofs, significant underestimates of extreme conditions may occur. Long-term generalizations can be developed from continuous simulation data, but a more detailed assessment cannot be interpolated from long-term average values. To examine the environmental benefit of green roof stormwater response, it is necessary to observe the variation in runoff from the green roof over a series of precipitation events at a time interval that is precise enough to resolve the extreme values experienced in the region, but also to provide generalizations to the long-term environmental impact that can be expected of a green roof. To support these requirements this study examines the long-term daily storm water response of an extensive green roof over four 220 day study periods.

The output of the model must be simple and provide a reliable and valid relationship between the response of a green roof to a series of precipitation events and its impact on the potential health of streams. To do this, it is necessary to compare the depths of precipitation, runoff, retention, and evapotranspiration from the green roof for each day of the study period. A water balance model integrates the stormwater response processes of a green roof and provides the output identified as necessary for examining the potential environmental impact (i.e., potential stream health). The model constructed for this research is based on a water balance approach similar to that described by Allen et al. (1998), Ferguson (1994), Mentens et al. (2003), and Jarrett et al. (2006) (Equation 2). The water deficit ($D_i$) at the end of the day (mm) is presented as:

$$D_i = \text{depth of precipitation} - \text{runoff} - \text{retention} - \text{evapotranspiration}$$
\[ D_i = D_{i-1} - P_i + RO_i + ET_i \]  

Equation 2

Where \( D_{i-1} \) is the water deficit from the end of the previous day (mm), \( P_i \) is the precipitation during day \( i \) (mm), \( RO_i \) is the runoff during day \( i \) (mm), and \( ET_i \) is the amount of evapotranspiration during day \( i \) (mm).

The water balance model estimates the amount of water added, lost and stored by the green roof for a given day within the study period. This balance is influenced by evapotranspiration rates, precipitation patterns and the green roof design (Figure 15). Given that evapotranspiration rates and precipitation patterns are a function of the site context, the same green roof design will have a different stormwater response depending on location.

![Figure 15 - Schematic of the green roof stormwater retention response model](image)

The amount of water stored within the green roof growing media on a particular day is reported as the difference between the storage capacity (equal to total available water) less the current depth of retained water. This value is identified as the water deficit \( (D_i) \) and represents the amount of water that can be added to the green roof before to runoff begins. It
plays an important role in determining the rate at which evapotranspiration occurs. Each day, evapotranspiration increases the water deficit while precipitation reduces it. It is assumed that evapotranspiration will not remove water below the wilting point, which represents the maximum water deficit equal to the depth of Total Available Water (TAW) of the growing media. Once the moisture content of the growing media reaches the field capacity the water deficit is equal to zero. Therefore, the water deficit must be greater than zero and less than or equal to TAW.

### 3.4.1 CALCULATING EVAPOTRANSPIRATION RATES

The FAO Penman-Monteith Method (Allen et al., 1998) was used to estimate evapotranspiration losses from the green roof. There are three principal steps to this method (Figure 16). First a reference evapotranspiration rate, representing the evapotranspiration rate from a standard crop of grass under ideal environmental conditions is calculated. This rate is then adjusted to account for the difference in the evapotranspiration rate between a standard crop of grass and the green roof vegetation. Finally, the rate is adjusted to the non-standard environmental conditions of the green roof environment.

![Figure 16 - Three primary steps of the FOA Penman-Monteith Method of calculating evapotranspiration rates](image)

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3.4.1.1 REFERENCE EVAPOTRANSPIRATION: EFFECT OF CLIMATE

The reference evapotranspiration rate accounts for the impact of climate on the rate of evapotranspiration from a standard crop of grass maintained under standard growing conditions. Six different climate variables are required for the FAO Penman-Monteith method (Allen et al., 1998) used to calculate the daily reference evapotranspiration rate include the minimum daily air temperature, maximum daily air temperature, Minimum daily relative humidity, maximum daily relative humidity, average daily shortwave radiation, and the average daily wind speed measured at a height of 2 m above the ground (Table 20). Additional context data required for calculating reference evapotranspiration include the latitude and elevation of the site (Table 21).

The University of Waterloo weather station is located in Waterloo, Ontario with the coordinates of 43d 28' 25.6" N and 80d 33' 27.5" W at an elevation of 334.4 m. Four years worth of data, starting January 1st, 2004 through to December 31st, 2007 were obtained from the University of Waterloo Weather Station online data archives (UW Weather Station, 2004a; 2005a; 2006a; 2007a). The data obtained were recorded at 15 minute intervals. The variables used from the source data were: Incoming Shortwave Radiation (W m\(^{-2}\)), Relative Humidity (% RH), Ambient Air Temperature (°C), Wind Speed at Rain Gauge (m s\(^{-1}\)) and Precipitation (Tipping Bucket) (mm) (UW Weather Station, 2008a).

A number of errors and omissions were identified in the information obtained from the data archive and were corrected as follows:

- Negative incoming shortwave radiation values were identified in each of the four years of data. These were corrected by adjusting their value to zero.
- Hourly precipitation values within the 2005 data set were missing. These were corrected with daily values acquired through a second archive file (UW Weather Station, 2005c). Days 227, 231, 239, 242, 243, 248, 249, 251, 255, 257 and 258 required adjustment to the precipitation values.

- Ambient air temperature readings were missing from the 2005 data set but none were within the study period of interest. These occurred on days 329, 340 and 341.

Next the data were adjusted to provide the required values as identified by the FAO Penman-Monteith Method for determining reference evapotranspiration (Table 20).

Table 20 - Daily climate variables used to calculate reference evapotranspiration

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Variable</th>
<th>Measurement Units</th>
<th>Used in Equation(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{min}$</td>
<td>Minimum daily air temperature</td>
<td>°C</td>
<td>12, 14, 17, 21</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>Maximum daily air temperature</td>
<td>°C</td>
<td>11, 14, 17, 21</td>
</tr>
<tr>
<td>$RH_{min}$</td>
<td>Minimum daily relative humidity</td>
<td>%</td>
<td>13</td>
</tr>
<tr>
<td>$RH_{max}$</td>
<td>Maximum daily relative humidity</td>
<td>%</td>
<td>13</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Average daily shortwave radiation</td>
<td>MJm$^{-2}$day$^{-1}$</td>
<td>10, 18</td>
</tr>
<tr>
<td>$U_2$</td>
<td>Average daily wind speed at 2 m</td>
<td>m s$^{-1}$</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 21 - Site location variables used to calculate reference evapotranspiration

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Variable</th>
<th>Measurement Units</th>
<th>Used in Equation(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>Site latitude</td>
<td>Degrees</td>
<td>5</td>
</tr>
<tr>
<td>$z$</td>
<td>Site ground elevation</td>
<td>m</td>
<td>9, 22</td>
</tr>
</tbody>
</table>

Average shortwave radiation was calculated using the 15 minute interval data obtained from the data record. These values were then converted from W m$^{-2}$ to MJm$^{-2}$day$^{-1}$ using a factor provided by Allen et al. (1998) (Equation 3).
Seglenieks (2008), the University of Waterloo Weather Station Coordinator, identified that the university weather station measures the ‘Wind speed at rain gauge’ at a height of 2 m above the ground. Although this measurement is appropriate for calculating evapotranspiration under standard growing conditions, the values are not believed to be representative of the wind speeds found in the green roof environment. That is, the average daily wind speed measured at a roof top elevation will be different than that taken two metres above ground level as wind speed diminishes closer to the ground. The relationship between height and wind speed is described by a velocity profile and is a function of the frictional losses associated with the ground conditions (Dalgliesh and Boyd, 1962). Further, rural and urban contexts have very different velocity profiles. It is not known how this relationship impacts wind speed at the roof level. The edge condition of a roof could also have a considerable impact on wind speed above the vegetation. If the roof is surrounded by a parapet, a large portion of the roof could be sheltered from the wind, thereby decreasing evapotranspiration rates. Alternatively, significant uplift could occur near the perimeter and corners of a roof thereby increasing evapotranspiration rates. Such variables have not been evaluated nor has any published wind speed data been found for green roofs. Therefore, ‘Wind speed at Rain Gauge’ are the best wind speed data available for this study.
The following series of equations (Equation 4 – Equation 24) was then applied for each day of the study period (All equations taken from Allen et al., 1998). The solar declination (radians) was calculated as:

\[ \delta = 0.409 \sin \left( \frac{2\pi}{365} i - 1.39 \right) \]

Equation 4

where \( i \) was the day of the year.

The required unit of measurement for the site latitude was radians. Converting latitude from degrees to radians was accomplished using the following equation:

\[ \varphi = \frac{\pi L}{180} \]

Equation 5

where \( \varphi \) was the latitude in radians and \( L \) was the latitude in degrees.
The solar declination and site latitude were then used to determine the sunrise hour angle (radians) as:

\[ \omega_s = \cos^{-1}(- \tan \varphi \tan \delta) \]  
Equation 6

A daily correction factor for the distance between the sun and the earth was determined for each study day as:

\[ d_r = 1 + 0.033 \cos \left( \frac{2\pi i}{365} \right) \]  
Equation 7

Extraterrestrial radiation (MJ m\(^{-2}\) day\(^{-1}\)) was determined using the following equation:

\[ R_a = \frac{(24)(60)}{\pi} G_{SC} d_r (\omega_s \sin \delta \sin \varphi + \cos \varphi \cos \delta \sin \omega_s) \]  
Equation 8

where \( G_{SC} \) was the solar constant with a value of 0.082 MJ m\(^{-2}\) min\(^{-1}\) (Allen et al., 1998).

Next clear-sky solar radiation (MJ m\(^{-2}\) day\(^{-1}\)) was determined as:

\[ R_{so} = (0.75 + 2.0 \times 10^{-5} z) R_a \]  
Equation 9

where \( z \) was the site ground elevation in metres.

Net solar radiation (MJ m\(^{-2}\) day\(^{-1}\)) was determined using the following equation:

\[ R_{ns} = (1 - \alpha) R_s \]  
Equation 10

where \( \alpha \) was the albedo of grass reference crop with a value of 0.23 (Allen et al., 1998) and \( R_s \) was the average incoming shortwave radiation on day \( i \).

Saturation vapour pressure, actual vapour pressure and the slope of the vapour pressure curve were determined using Equation 11 through Equation 17.
The saturation vapour pressure in kPa on day $i$ at $T_{\text{max}}$ the maximum air temperature in °C measured on day $i$ was calculated as:

$$e_s(T_{\text{max}}) = 0.6108 \exp \left( \frac{17.27 T_{\text{max}}}{T_{\text{max}} + 237.3} \right) \quad \text{Equation 11}$$

The saturation vapour pressure in kPa on day $i$ at $T_{\text{min}}$ the minimum temperature in °C measured on day $i$ was calculated as:

$$e_s(T_{\text{min}}) = 0.6108 \exp \left( \frac{17.27 T_{\text{min}}}{T_{\text{min}} + 237.3} \right) \quad \text{Equation 12}$$

Next the actual vapour pressure in kPa was determined using the following equation:

$$e_a = \frac{e_s(T_{\text{max}}) \frac{RH_{\text{min}}}{100} + e_s(T_{\text{min}}) \frac{RH_{\text{max}}}{100}}{2} \quad \text{Equation 13}$$

where $RH_{\text{min}}$ was the minimum relative humidity on day $i$ and $RH_{\text{max}}$ was the maximum relative humidity on day $i$.

The mean daily air temperature in °C was determined as:

$$T_{\text{mean}} = \frac{T_{\text{max}} + T_{\text{min}}}{2} \quad \text{Equation 14}$$

The saturation vapour pressure in kPa on day $i$ at $T_{\text{mean}}$ on day $i$ was calculated as:

$$e^a = 0.6108 \exp \left( \frac{17.27 T_{\text{mean}}}{T_{\text{mean}} + 273.3} \right) \quad \text{Equation 15}$$

Next the slope of the vapour pressure curve in kPa°C$^{-1}$ at $T_{\text{mean}}$ using the following equation:
\[
\Delta = \frac{4099e^{\theta}}{(T_{\text{mean}} + 237.3)^2}
\]

Equation 16

The mean daily saturation vapour pressure in kPa was determined as:

\[
e_s = \frac{e_s(T_{\text{max}}) + e_s(T_{\text{min}})}{2}
\]

Equation 17

A cloudiness function was calculated using the following equation:

\[
f = 1.35 \frac{R_s}{R_{so}} - 0.35
\]

Equation 18

The apparent ‘net’ clear sky emissivity was determined as:

\[
\varepsilon' = 0.34 - 0.14\sqrt{\varepsilon_a}
\]

Equation 19

Next the net long wave radiation in MJ m\(^{-2}\) day\(^{-1}\) over the reference crop surface was determined using Equation 20 and Equation 21.

\[
R_{nl} = f\varepsilon' \sigma \left[ (T_{\text{max}} + 273.15)^4 + (T_{\text{min}} + 273.15)^4 \right] \frac{1}{2}
\]

Equation 20

where \(\sigma\), the Steffan-Boltzmann constant, was equal to 4.9 \times 10^{-9} \text{ MJ m}^{-2} \text{ d}^{-1} \text{ K}^{-4} \text{ (Allen et al., 1998)}.\)

Using the net solar radiation determined using Equation 10 and the net long wave radiation obtained using Equation 20 the net radiation over reference crop surface in MJ m\(^{-2}\) day\(^{-1}\) was determined as:

\[
R_n = R_{ns} - R_{nl}
\]

Equation 21
Atmospheric pressure in kPa was determined using the following equation:

$$
\beta = 101.3 \left( \frac{293 - 0.00652z}{293} \right)^{5.26}
$$

Equation 22

where $z$ was the site ground elevation in metres.

Next the psychrometric constant in kPa °C$^{-1}$ was calculated as:

$$
\gamma = 0.00163 \frac{\beta}{\lambda}
$$

Equation 23

where $\lambda$ was the Latent heat of vaporization with a value of 2.45 MJ kg$^{-1}$ (Allen et al., 1998).

Finally the reference evapotranspiration rate in mm day$^{-1}$ was calculated using the following equation:

$$
ET_o = \frac{0.408 \Delta(R_n - G) + \left( \frac{900\gamma}{T_{mean} + 273} \right) (U_2(e_s - e_a))}{\Delta + \gamma(1 + 0.34U_2)}
$$

Equation 24

where $G$ was the soil heat flux, assumed to equal 0 (Allen et al., 1998) and $U_2$ was the average wind speed at a height of 2 m on day $i$.

3.4.1.2 CROP EVAPOTRANSPIRATION: EFFECT OF VEGETATION

To adjust the reference evapotranspiration rate for the characteristics of *Sedum* it must be multiplied by the crop coefficient, $k_c$. Few studies have identified a crop coefficient for *Sedum*. An average of the three values (0.5, 0.74 and 1.97) reported by Lazzarin et al. (2005) and Rezaei (2005) provided a crop coefficient of 1.07. This crop coefficient accounts for differences in plant height, surface resistance and albedo between the reference crop and *Sedum* (Figure 18).
The crop evapotranspiration rate in mm day\(^{-1}\) was calculated for each day of the four study periods using the following equation:

\[
ET_c = k_c ET_o
\]

Equation 25

Figure 18 - Vegetation variables that impact the crop evapotranspiration rate (Step 2)

### 3.4.1.3 ADJUSTED CROP EVAPOTRANSPIRATION: EFFECT OF ENVIRONMENTAL CONDITIONS

Having adjusted the reference evapotranspiration rate to correspond the green roof vegetation it was then necessary to adjust the crop evapotranspiration rate from the standard growing conditions to those likely to be found in the green roof environment during the study periods.

This model addresses the influence of water stress on the evapotranspiration rate (Figure 19).
Multiplying the crop evapotranspiration rate by the water stress coefficient \((k_s)\), adjusts the evapotranspiration rate from the well watered standard growing condition. The adjusted crop evapotranspiration rate in mm day\(^{-1}\) was calculated as:

\[
ET_{c \text{ adj}} = k_s ET_c
\]

The water stress coefficient is dynamic and responds to variation in the water deficit. When the growing media moisture content is higher than the RAW level the water stress coefficient \((k_s)\) is equal to one. As moisture content drops below the RAW level the value of \(k_s\) decreases.
until it reaches zero. This is the point at which the growing media moisture level reaches its minimum value, the wilting point. The water stress coefficient was determined using the following equation:

$$k_s = \frac{TAW - D_{i-1}}{TAW - RAW}$$  \hspace{1cm} \text{Equation 27}

where $D_{i-1}$ was the water deficit in mm from the end of the previous day, $TAW$ was the total available water in mm and $RAW$ was the readily available water in mm.

### 3.5 GREEN ROOF STORMWATER RUNOFF SIMULATION

Runoff is determined by comparing the previous day’s water deficit depth to the present day precipitation depth (Figure 20). If the amount of precipitation on a given day exceeds the water deficit from the end of the previous day, this would cause the growing media moisture level to exceed its field capacity and excess precipitation will result in runoff. The runoff depth is equal to the difference between the previous day water deficit depth and the depth of the present day precipitation. All depths are measured in millimetres.

During the simulation, precipitation was applied prior to evapotranspiration loss as this provides a more conservative retention value. Had evapotranspiration been applied prior to precipitation it would have resulted in an increase in the storage capacity available, potentially resulting in a higher amount of precipitation retained on a particular day. This has a limited effect at large values of water deficit (when the growing media is quite dry), but for small values of water deficit (when there is little additional water storage available), the effect becomes more pronounced.
The water balance was repeated for each day of the four study periods using the process outlined in Figure 20. The result of this process provided evapotranspiration, runoff and water deficit values for each day of the study periods.

In order to estimate the probable starting moisture level for the green roof, the simulation was initiated one month prior to the first day of the study period with different water deficits to examine the resulting variation in moisture deficit on the first day of the study period. 1 mm, 15 mm and 29 mm water deficits on March 10th resulted in similar water deficits on April 10th of each study year with the exception of 2006 and 2007. These two years had higher starting water deficits when an initial water deficit of 29mm was used. As a result, an initial water deficit of 15 mm was selected, which provided a lower starting water deficit and reduced the
starting retention capacity of the simulated green roof resulting in a more conservative estimate of green roof performance.

### 3.6 ASSUMPTIONS

The following assumptions are required to understand the results.

**Evapotranspiration:**

- In determining the reference evapotranspiration rate, the soil heat flux was assumed to be zero.
- The size of the green roof vegetated area does not impact the way in which evapotranspiration is calculated.
- Evapotranspiration will not remove growing media moisture beyond the wilting point.

**Green Roof:**

- Vegetation is well established and fully developed with full coverage of the growing media surface for the entire length of the study periods
- Roof is flat
- The growing media will infiltrate all precipitation, eliminating any occurrence of overland flow
- The drainage layer will facilitate a high enough lateral hydraulic conductivity to ensure that any water that flows through the growing media is able to drain from the roof
- Vegetation does not contribute to storage capacity (through interception or by storing water internally)

**Climate:**

- Roof top wind speed is equal to the wind speed measured at a height of 2 m above ground level
- No microclimate effects (i.e., assume a consistent and maximum exposure to sunlight/radiation over the entire surface of the green roof)
Precipitation:

- Condensation as a potential source of water is excluded from this study.
- There will be no supplemental irrigation provided to the green roof vegetation. The sole source of water comes from precipitation.
- The effect of roof slope and orientation as well as wind speed, direction and rainfall intensity will not be considered in the depth of precipitation received by the green roof.
- Precipitation depth is constant over the entire roof area.
4  RESULTS AND DISCUSSION

The results and discussion section is broken down into nine sections: Climate Context, Retention Performance, Impervious Response of the Green Roof, Water Balance, Evapotranspiration Rates, Sensitivity Analysis, Potential Environmental Impact of the Green Roof Stormwater Response, Study Limitations, and Future Research. The first section compares the study period precipitation and climate data to those of the 30-year climate averages for the City of Waterloo. In the second section, overall retention performance is reviewed and compared to values obtained from previous studies. The third section includes a characterization of the impervious quality of the green roof stormwater response. The fourth section describes the contribution of the green roof to water balance, and provides an overview of the mechanisms used by the green roof in its stormwater response. These results are compared to values reported in previous studies. The fifth section examines the impact of selected climate and green roof design variables on the impervious response of the green roof. The sixth section examines the range and pattern of evapotranspiration rates and compares them to values reported in other studies. The seventh section summarizes the results and the potential environmental impact of the green roof stormwater runoff response. The final two sections discuss limitations of this research and possible future research.

4.1  CLIMATE CONTEXT

The variability of climate and precipitation patterns can be significant over the long term. Harbor (1994) suggests that the range of climatic data expected for a site should be determined by examining data from a 30-year standard period. The University of Waterloo Weather Station only contains data records from 1998 to 2008, insufficient to provide the climate data as defined by Harbor (1994). 30-year Canadian climate norms are available from
two different weather stations within the Waterloo region (Environment Canada, 2004a; 2004b). The first weather station, Waterloo Wellington A, provides a full range of climatic variables, while the second, Waterloo WPCP, only provides precipitation data. The Waterloo WPCP station is located within the urban center of Waterloo while the Waterloo Wellington A station is in a rural context close to an airport 12 km to the east of downtown Waterloo.

A comparison of the average daily wind speed, daily average temperature and precipitation patterns during the four study periods, to the 30-year averages shows a number of notable differences. First, daily average wind speed was much lower at the University of Waterloo Weather Station during the four study periods, with values 50% or less of the 30-year average wind speed measured at the Waterloo Wellington A weather station. The lower wind speed measured at the University of Waterloo weather station may be attributed to differences in surface roughness surrounding the weather stations, as well as the difference in measurement heights. Wind speed decreases as measurements are taken closer to the ground and as surface resistance increases (Dalgliesh and Boyd, 1962). Radecki (2008), an employee with the Ontario Climate Centre, confirmed that wind speed at the Waterloo Wellington A weather station is measured at a height of ten metres above the ground, while the University of Waterloo weather station takes wind speed measurements at a height of two metres (Seglenieks, 2008). The University of Waterloo weather station is an urban context with a higher surface resistance value than that of the Waterloo Wellington A weather station. These two factors could result in lower wind speeds recorded at the University of Waterloo weather station. Adjusting the University of Waterloo wind speed values using the wind profile power law published by Dalgliesh and Boyd (1962), the wind speed in m s⁻¹ at the height of interest can be calculated using the following equation:
Equation 28

\[ V_h = V_r \left( \frac{h}{h_r} \right)^k \]

where \( V_r \) is the average wind speed in m s\(^{-1}\) at \( h_r \) (reference height in metres), \( h \) is the height (m) of the wind speed of interest, and \( k \) is the exponent of best-fit for a particular development context. In an urban context, \( k \) is equal to 0.5 (Dalgliesh and Boyd, 1962). Equation 28 was applied in an urban context to adjust the wind speed measured at a reference height of two metres to a height of ten metres. The height-adjusted University of Waterloo weather station wind speed resulted in average winds speeds that are only 10% less than those of the 30-year average recorded at the same height. It is reasonable to suggest that this difference would be further reduced if the contribution of surface resistance was taken into account at the two different weather station sites. When averaged, the daily wind speed measurements taken at the University of Waterloo weather station during the four study periods are close to that of the 30-year average.

The average daily temperature for April through November of the four study years was between 13 and 14 °C, while the 30-year average was 12 °C.

The 30-year average rainfall for the months of April through November was 641 mm (Environment Canada, 2004b). 2006 was a wet year receiving 15% more rain than the 30-year average, while 2007 was a dry year. Compared to the 30-year climate norms, the 2007 study period received 34% less rain and had a lower high monthly rainfall value. 2004 and 2005 received 7% and 10% less rain respectively than the 30-year average. Peak rainfall measured as monthly totals were higher in 2004, 2005 and 2006 compared to the 30-year average. The low monthly total rainfall for each of the four study periods was less than half that of the 30-year
The size of daily rain events varies considerably between the 30-year average and the four study periods.

All four study periods exhibit far fewer daily rainfalls that exceeded 5 mm compared to the 30-year average. The frequency of days without rain was 41% to 63% more than the 30-year average frequency (Table 23). The average number of days per month with rain ranged from 17 to 21 for the 30-year average while each of the four study periods averaged 13 to 15 rain days per month.

Table 22 - Rainfall patterns in Waterloo, ON. during the months of April - November

<table>
<thead>
<tr>
<th>Weather Station</th>
<th>Waterloo WPCP</th>
<th>University of Waterloo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30-year Average</td>
<td>2004</td>
</tr>
<tr>
<td>Total rainfall (mm)</td>
<td>641</td>
<td>598</td>
</tr>
<tr>
<td>Peak monthly total rainfall (mm)</td>
<td>92 (Aug.)</td>
<td>145 (May)</td>
</tr>
<tr>
<td>Low monthly total rainfall (mm)</td>
<td>67 (Oct.)</td>
<td>28 (Sept.)</td>
</tr>
<tr>
<td>Single day extreme rainfall (mm)</td>
<td>103 (Aug.)</td>
<td>41 (July)</td>
</tr>
</tbody>
</table>

Table 23 - Frequency of daily rainfall depth in Waterloo, ON. during the months of April - November

<table>
<thead>
<tr>
<th>Weather Station</th>
<th>Waterloo WPCP</th>
<th>University of Waterloo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30-year Average</td>
<td>2004</td>
</tr>
<tr>
<td>Days without rain</td>
<td>87</td>
<td>123</td>
</tr>
<tr>
<td>&gt;= 0.2 mm</td>
<td>91</td>
<td>80</td>
</tr>
<tr>
<td>&gt;= 5 mm</td>
<td>39</td>
<td>17</td>
</tr>
<tr>
<td>&gt;= 10 mm</td>
<td>22</td>
<td>23</td>
</tr>
<tr>
<td>&gt;= 25 mm</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Total days with rain</td>
<td>157</td>
<td>121</td>
</tr>
</tbody>
</table>
4.2 RETENTION PERFORMANCE

The overall retention performance of the simulation green roof is similar to observed retention values from other studies for the months of April to November (Table 24). When comparing the eight month average retention to the average annual retention reported by Köhler et al. (2001), Hutchinson et al. (2003), and Bengtsson et al. (2005), the retention performance is decreased by 16%, 43% and 9% respectively. If the same relationship holds true in the Waterloo context the annual retention could decrease by 9 and 43% resulting in an average retention of 28 to 62%.

Table 24 - Precipitation and retention during the months of April through November

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Precipitation mm</th>
<th>Retention mm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>Waterloo, Ontario</td>
<td>554</td>
<td>402 (73)</td>
</tr>
<tr>
<td>2005</td>
<td>Waterloo, Ontario</td>
<td>505</td>
<td>345 (68)</td>
</tr>
<tr>
<td>2006</td>
<td>Waterloo, Ontario</td>
<td>695</td>
<td>421 (61)</td>
</tr>
<tr>
<td>2007</td>
<td>Waterloo, Ontario</td>
<td>346</td>
<td>323 (93)</td>
</tr>
<tr>
<td>Total</td>
<td>Waterloo, Ontario</td>
<td>2100</td>
<td>1491 (71)</td>
</tr>
<tr>
<td>Köhler et al., 2001 (1997 data)</td>
<td>Germany</td>
<td>333</td>
<td>219 (66)</td>
</tr>
<tr>
<td>Köhler et al., 2001 (1998 data)</td>
<td>Germany</td>
<td>421</td>
<td>271 (64)</td>
</tr>
<tr>
<td>Hutchinson et al., 2003</td>
<td>Portland, Oregon</td>
<td>203</td>
<td>184 (91)</td>
</tr>
<tr>
<td>Moran, 2004</td>
<td>Goldsboro, North Carolina</td>
<td>815</td>
<td>505 (62)</td>
</tr>
<tr>
<td>Bengtsson et al., 2005</td>
<td>Malmö, Sweden</td>
<td>494</td>
<td>272 (55)</td>
</tr>
</tbody>
</table>

Applying precipitation prior to evapotranspiration during the daily simulation resulted in a more conservative estimate of overall retention however, this change was not substantial. Changing the order of precipitation and evapotranspiration resulted in a 1% difference in the overall percent retention for the 2005 study period and a 2% difference for each of the other three study periods.
4.3 IMPERVIOUS RESPONSE OF THE GREEN ROOF

The degree of impervious response of a surface is assumed to be equal to the proportion of precipitation that runs off the surface. With this definition the simulated green roof responded to the total precipitation from the four study periods with an average 29% impervious level, from a high of 39% impervious in 2006 to a low of 7% impervious in 2007 (Table 25). This difference in performance corresponded to the amount of total amount of precipitation received during the study periods with the 2007 period being dry while the 2006 period was relatively wet (Table 22).

Table 25 - Overall impervious response during the April to November study periods

<table>
<thead>
<tr>
<th>Study Period</th>
<th>Precipitation (mm)</th>
<th>Runoff (mm)</th>
<th>Imperviousness</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>554</td>
<td>152</td>
<td>27%</td>
</tr>
<tr>
<td>2005</td>
<td>505</td>
<td>160</td>
<td>32%</td>
</tr>
<tr>
<td>2006</td>
<td>695</td>
<td>274</td>
<td>39%</td>
</tr>
<tr>
<td>2007</td>
<td>346</td>
<td>23</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2100</strong></td>
<td><strong>609</strong></td>
<td><strong>29%</strong></td>
</tr>
</tbody>
</table>

Examining the average runoff on a monthly basis shows that the range of impervious levels exhibited by the green roof is much greater than the average of each annual study period. The range of monthly imperviousness values varied in each study period. In 2007, a very dry year, the monthly impervious response varied by 22% while in 2004 the monthly variation was considerably higher at 82% (Figure 21). The 2004, 2005 and 2007 study periods each exhibited a few months with a 0% impervious response while the relatively wet 2006 study period did not. The lowest monthly impervious response in 2006 was 6%. The peak monthly impervious response ranged from 75% - 82% in 2004 – 2006 and was much lower (22%) during the relatively dry 2007 study period. In general, months with higher total precipitation exhibited higher levels of imperviousness. November exhibited the highest levels of imperviousness.
regardless of the total precipitation during the month. The four study periods exhibited few months with a total number of rain days equal to or greater than the 30-year average. This suggests that over a 30-year period, there are likely to be months with a greater number of rain days than experienced in the four study periods, which would likely result in more runoff and higher impervious values.

Figure 21 - Monthly runoff response for each of the four study periods
Figure 22 - Number of rain days resulting in different levels of imperviousness

In each of the four study periods, the majority (81% average over the four periods) of rain events are completely retained by the green roof, thereby reducing the frequency with which runoff occurs (Table 26). In 2007, only 10 rain days resulted in runoff while in 2006 31 rain days contribute to runoff (Figure 22 and Table 26). This suggests that the green roof would be classified as an impervious surface for only 5% of the 220 day long study period in 2007, and 14% of the study period in 2006.

Table 26 - Runoff resulting from rain days during the four study periods

<table>
<thead>
<tr>
<th>Study Period Year</th>
<th>Total Rain Days</th>
<th>Days with Impervious Response</th>
<th>Reduction in Days with Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>104</td>
<td>18</td>
<td>86</td>
</tr>
<tr>
<td>2005</td>
<td>92</td>
<td>13</td>
<td>79</td>
</tr>
<tr>
<td>2006</td>
<td>109</td>
<td>31</td>
<td>78</td>
</tr>
<tr>
<td>2007</td>
<td>86</td>
<td>10</td>
<td>76</td>
</tr>
</tbody>
</table>
The range of impervious values varies substantially at all reporting period time scales, with the daily response exhibiting the most extreme variation with larger values of impervious response (Table 27). The maximum impervious response exhibited by the green roof on a daily basis ranged from 85 – 98% over the study periods.

Table 27 - Range of impervious response as a function of averaging period

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Minimum Impervious Response (%)</th>
<th>Maximum Impervious Response (%)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study period response</td>
<td>7</td>
<td>39</td>
<td>32</td>
</tr>
<tr>
<td>Monthly response</td>
<td>0</td>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td>Daily response</td>
<td>0</td>
<td>98</td>
<td>98</td>
</tr>
</tbody>
</table>

The range of impervious responses in this study is very similar to the values reported by other long-term studies. Six long term studies (Köhler et al., 2001; Lui, 2003; Hutchinson et al., 2003; Moran, 2004; Bengtsson et al., 2005; VanWoert, 2005) demonstrated a range in average impervious response during the April to November time period of 9% to 45%. These same studies found that the annual impervious response was worse ranging from 32% to 54% (Köhler et al., 2001; Lui, 2003; Hutchinson et al., 2003; Moran, 2004; Bengtsson et al., 2005; VanWoert, 2005).

Monthly impervious response of the simulated green roof is similar to the minimum (0% impervious) and maximum (89% impervious) values observed by Köhler et al. (2001) and Hutchinson et al. (2003).

Both Moran (2004) and VanWoert et al. (2005a) provided daily response data as part of a long term study. They found that daily imperviousness ranged from 0% to 88% impervious. The
range of impervious response observed in the simulation was slightly larger with a minimum impervious response of 0% and a maximum of 98%.

Roy et al. (2005) indicate that the reduction in runoff from large storm events (storms with a return period greater than one year) is believed to have less importance than the reduction in runoff from small storm events (storms with a return period less than one year). The increase in runoff depth and runoff event frequency from impervious surfaces is larger during small storm events than large events in comparison to the runoff from naturally vegetated areas (Roy et al., 2005). Assuming that in the absence of the green roof, 100% of precipitation contributes to runoff, there is a large reduction in the frequency (Table 26) and amount of runoff that occurs with the application of the green roof particularly in the number of days with runoff less than 10 mm (Figure 23). One exception to this occurs during 2006 when the frequency of runoff between 5 and 10 mm only reduces from 11 to 9 days with the application of the green roof. The reduction in depth and frequency of runoff from a green roof is more similar to that of a naturally vegetated area than that of an impervious surface.
Figure 23 - Reduction in runoff resulting from the application of a green roof

The simulated green roof showed that stormwater runoff response is variable depending on the amount of daily rainfall (Table 28). The variance in minimum and maximum runoff values for each rainfall range also suggests that there are other determinants of the amount of runoff. Evapotranspiration rates and precipitation patterns prior to each day are two of these determinants (Table 28).
<table>
<thead>
<tr>
<th>Daily Rainfall Range (mm)</th>
<th>Average Imperviousness</th>
<th>Average Runoff (mm)</th>
<th>Minimum Runoff (mm)</th>
<th>Maximum Runoff (mm)</th>
<th>Average Daily Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2004</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td>2%</td>
<td>0.1</td>
<td>0.0</td>
<td>3.6</td>
<td>1.4</td>
</tr>
<tr>
<td>5-10</td>
<td>12%</td>
<td>0.8</td>
<td>0.0</td>
<td>4.8</td>
<td>6.7</td>
</tr>
<tr>
<td>10-15</td>
<td>19%</td>
<td>2.4</td>
<td>0.0</td>
<td>11.6</td>
<td>11.7</td>
</tr>
<tr>
<td>15-20</td>
<td>67%</td>
<td>11.1</td>
<td>0.0</td>
<td>16.5</td>
<td>16.2</td>
</tr>
<tr>
<td>20-25</td>
<td>33%</td>
<td>7.7</td>
<td>0.0</td>
<td>21.7</td>
<td>22.3</td>
</tr>
<tr>
<td>25-40</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
</tr>
<tr>
<td>40-45</td>
<td>61%</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
<td>40.6</td>
</tr>
<tr>
<td>45+</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
</tr>
<tr>
<td><strong>2005</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td>2%</td>
<td>0.1</td>
<td>0.0</td>
<td>2.0</td>
<td>1.3</td>
</tr>
<tr>
<td>5-10</td>
<td>24%</td>
<td>1.7</td>
<td>0.0</td>
<td>7.8</td>
<td>6.3</td>
</tr>
<tr>
<td>10-15</td>
<td>9%</td>
<td>1.4</td>
<td>0.0</td>
<td>9.7</td>
<td>12.4</td>
</tr>
<tr>
<td>15-20</td>
<td>0%</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>18.0</td>
</tr>
<tr>
<td>20-25</td>
<td>0%</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>21.4</td>
</tr>
<tr>
<td>25-30</td>
<td>43%</td>
<td>10.9</td>
<td>0.2</td>
<td>21.6</td>
<td>27.3</td>
</tr>
<tr>
<td>30-35</td>
<td>48%</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>30.8</td>
</tr>
<tr>
<td>35-40</td>
<td>86%</td>
<td>30.8</td>
<td>30.8</td>
<td>30.8</td>
<td>36.0</td>
</tr>
<tr>
<td>40-45</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
</tr>
<tr>
<td>45-50</td>
<td>39%</td>
<td>18.6</td>
<td>18.6</td>
<td>18.6</td>
<td>47.1</td>
</tr>
<tr>
<td>50-55</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
</tr>
<tr>
<td>55-60</td>
<td>72%</td>
<td>42.3</td>
<td>42.3</td>
<td>42.3</td>
<td>59.2</td>
</tr>
<tr>
<td><strong>2006</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td>3%</td>
<td>0.1</td>
<td>0.0</td>
<td>2.6</td>
<td>1.1</td>
</tr>
<tr>
<td>5-10</td>
<td>33%</td>
<td>1.9</td>
<td>0.0</td>
<td>5.5</td>
<td>7.0</td>
</tr>
<tr>
<td>10-15</td>
<td>43%</td>
<td>5.1</td>
<td>0.0</td>
<td>11.7</td>
<td>11.7</td>
</tr>
<tr>
<td>15-20</td>
<td>39%</td>
<td>7.4</td>
<td>0.0</td>
<td>14.7</td>
<td>17.4</td>
</tr>
<tr>
<td>20-25</td>
<td>62%</td>
<td>14.0</td>
<td>0.0</td>
<td>21.4</td>
<td>22.6</td>
</tr>
<tr>
<td>25-30</td>
<td>29%</td>
<td>7.7</td>
<td>0.0</td>
<td>23.5</td>
<td>27.3</td>
</tr>
<tr>
<td>30-35</td>
<td>19%</td>
<td>6.3</td>
<td>6.3</td>
<td>6.3</td>
<td>33.8</td>
</tr>
<tr>
<td>35-45</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
</tr>
<tr>
<td>45-50</td>
<td>82%</td>
<td>38.4</td>
<td>38.4</td>
<td>38.4</td>
<td>47.0</td>
</tr>
<tr>
<td>50+</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
</tr>
<tr>
<td><strong>2007</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td>6%</td>
<td>0.1</td>
<td>0.0</td>
<td>2.9</td>
<td>1.1</td>
</tr>
<tr>
<td>5-10</td>
<td>5%</td>
<td>0.4</td>
<td>0.0</td>
<td>6.1</td>
<td>6.9</td>
</tr>
<tr>
<td>10-15</td>
<td>0%</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>12.6</td>
</tr>
<tr>
<td>15-20</td>
<td>0%</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>15.7</td>
</tr>
<tr>
<td>20-25</td>
<td>0%</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>21.0</td>
</tr>
<tr>
<td>25-30</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
</tr>
<tr>
<td>30-35</td>
<td>13%</td>
<td>4.3</td>
<td>2.6</td>
<td>6.1</td>
<td>32.7</td>
</tr>
<tr>
<td>35+</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
<td>no events</td>
</tr>
</tbody>
</table>
Seasonal changes in the frequency and size of runoff disturbances is another way to evaluate the impervious response of a surface. Roy et al. (2005) suggest that impervious surfaces increase the frequency of runoff disturbance the most during summer and fall. During the spring, soil in naturally vegetated areas often becomes saturated resulting in overland flow and a higher occurrence of runoff from precipitation events (Roy et al., 2005).

During the summer (June 21 – September 21) the frequency of precipitation events that resulted in runoff was reduced the most. Over the course of the four summer periods there were 147 rain events of which only 13 resulted in runoff. The reduction in runoff events remained good during the spring (April 10 – June 20) with 126 rain events resulting in only 23 runoff events. The fall (September 22 – November 16) exhibited to worst performance with a total of 118 rain events, 36 of which resulted in runoff. Figure 24, Figure 25, Figure 26, and Figure 27 show the temporal distribution and size of runoff events in comparison to the distribution and size of the precipitation events. The four study years had fewer rain days than occurred during the 30-year average. An increase in the frequency of rain days would likely reduce the effectiveness of the green roof resulting in a higher number of days with runoff than observed during the 2004 – 2007 study periods.

Although the summer experienced the fewest runoff events they were the largest in depth (in excess of 25 mm). Fall runoff events were frequent and of moderate size often exceeding 15 mm in depth while in the spring runoff was less frequent did not typically exceed 15 mm in depth. Although there is a substantial reduction in the number of runoff events during each season the distribution is not typical of a natural vegetated area. The green roof delivered the greatest number of runoff disturbances during the fall while the greatest number of disturbances in a natural vegetated area would typically occur during the spring.
Figure 24 - 2004 runoff disturbance pattern for the simulated green roof in Waterloo, ON. from April 10th – November 16th

Figure 25 - 2005 runoff disturbance pattern for the simulated green roof in Waterloo, ON. from April 10th – November 16th
Figure 26 - 2006 runoff disturbance pattern for the simulated green roof in Waterloo, ON. from April 10\textsuperscript{th} – November 16\textsuperscript{th}

Figure 27 - 2007 runoff disturbance pattern for the simulated green roof in Waterloo, ON. from April 10\textsuperscript{th} – November 16\textsuperscript{th}
The majority (90%) of rain days occurred four or fewer days after the previous rain day (Figure 28). The average imperviousness ranges from a low of 0% in 2004 and 2005, to a high of 50% in 2006 for rain days separated by four or fewer days. Average imperviousness does not decrease with an increase in the separation between rain days as might be expected. In fact, for three of the four study periods the opposite occurs, as the average imperviousness increases as the separation between rain days increases. Once rain days are separated by five or more days, the average imperviousness drops to zero percent for each of the four study years (Figure 29).

Figure 28 - Frequency of rain day separation
The maximum imperviousness for a single rain day decreases as more time passes between rain events. When rain days occur back to back (zero days between rain days) imperviousness was as high as 98%. There was a substantial decrease in the maximum percent imperviousness between two and three day separation in rain events while maximum imperviousness reduced to zero percent once five or more days pass between rain days (Figure 30).

4.4 WATER BALANCE

The results of the simulation suggest that the majority of precipitation will leave the green roof through evapotranspiration, while a smaller amount will exit as runoff. No infiltration is provided by the green roof (Table 29). It is in this respect that green roofs do not behave in the same way as naturally vegetated surfaces which reduce runoff by moving 50% of precipitation into the ground through infiltration and returning 40% to the atmosphere through evapotranspiration (Arnold and Gibbons, 1996).
Table 29 - Water balance for the hypothetical green roof in Waterloo, ON.

<table>
<thead>
<tr>
<th>Study Period</th>
<th>Evapotranspiration (%)</th>
<th>Runoff (%)</th>
<th>Infiltration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>73</td>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>2005</td>
<td>66</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>2006</td>
<td>60</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>2007</td>
<td>93</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>70</td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

Growing media depth of the hypothetical green roof was 100mm

Study period only includes the portion of the year from April 10\textsuperscript{th} – November 16\textsuperscript{th}

The average water balance for the simulated green roof for all four study periods results in 70% evapotranspiration and 30% runoff. Schmidt (2006) reported that a green roof with 50 mm of growing media contributed 63% to evapotranspiration and 37% to runoff while 120 mm of growing media resulted in 72% evapotranspiration and 28% runoff. Given that the growing media in this study was 100 mm, it is reasonable to suggest that the results should be within the range of values reported by Schmidt (2006).

4.5 EVAPOTRANSPIRATION RATES

Comparing evapotranspiration rates to those noted in previous studies suggests that the green roof simulation provides reasonable values for the climate context and selected vegetation. Expected seasonal trends in reference evapotranspiration rates are present and the relationship between the reference evapotranspiration rates and the final adjusted crop evapotranspiration rates perform as expected.

During the four study periods the reference evapotranspiration rate ($ET_o$) fluctuated from a low of 0.4 mm day\textsuperscript{-1} to a high of 6.0 mm day\textsuperscript{-1}, while the adjusted evapotranspiration rate ($ET_{c,adj}$) ranged from a 0.0 to 5.5 mm day\textsuperscript{-1}(Table 30). The calculated maximum and minimum $ET_o$ rates are within the 1 – 7 mm day\textsuperscript{-1} range expected by Allen et al. (1998) for a temperate humid region, suggesting that the climate variables were appropriate to the region. The maximum
\( ET_{c,adj} \) rates from the simulation correspond to the observed maximum evapotranspiration rate of *Sedum* reported by VanWoert et al. (2005b) and Durhman et al. (2006) who reported maximum evapotranspiration rates that ranged from 4.4 to 6.4 mm\( \text{day}^{-1} \). This suggests that the values used for variables such as the crop coefficient are likely to be reasonable. If a larger crop coefficient had been used, the maximum \( ET_{c,adj} \) value would have been higher.

### Table 30 - Fluctuation in calculated evapotranspiration rates

<table>
<thead>
<tr>
<th>Year</th>
<th>( ET_0 ) (mm day(^{-1}))</th>
<th>( ET_{c,adj} ) (mm day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td>2004</td>
<td>5.4</td>
<td>0.4</td>
</tr>
<tr>
<td>2005</td>
<td>5.3</td>
<td>0.4</td>
</tr>
<tr>
<td>2006</td>
<td>6.0</td>
<td>0.4</td>
</tr>
<tr>
<td>2007</td>
<td>5.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

In general, higher reference evapotranspiration rates were recorded during the summer months of the study periods, while the spring and fall months had lower reference evapotranspiration rates. Daily fluctuation in evapotranspiration rates was large as shown in Figure 31, Figure 32, Figure 33, and Figure 34. When the green roof is subjected to water stress \( ET_{c,adj} \) values are less than \( ET_0 \). \( ET_{c,adj} \) values can exceed \( ET_0 \) when the growing media moisture is within the readily available water zone due to the application of a crop coefficient that is greater than one.
Figure 31 - 2004 study period: daily reference (ET₀) and adjusted (ET_{c adj}) evapotranspiration rates for Waterloo, ON.

Figure 32 - 2005 study period: daily reference (ET₀) and adjusted (ET_{c adj}) evapotranspiration rates for Waterloo, ON.
4.6 SENSITIVITY ANALYSIS

The simulation was examined for its sensitivity to three climate variables: average wind speed; average daily air temperature; and average relative humidity as well as two green roof design variables: crop coefficient; and total available water. Each variable was adjusted for the 2005 study period: daily reference (ET₀) and adjusted (ET_adj) evapotranspiration rates for Waterloo, ON.
study period and the resulting change in average imperviousness and frequency of runoff disturbance was observed (See Table 32 and Table 33 in Appendix B).

The University of Waterloo wind speed values (recorded at a height of two metres) used in the simulation may not appropriately represent the wind speed that occurs over a building roof. To examine the potential impact on imperviousness resulting from different wind speed values they were both doubled and halved. Doubling the observed two metre wind speed represents the estimated wind speed at a height of 10 metres using the wind profile power law (Dalgliesh and Boyd, 1962). The increase in wind speed decreased the average imperviousness for the 2005 study period from 32% to 30%. The number of runoff disturbances decreased from 13 to 12 (one less occurrence during the fall). Reducing all observed wind speed values by 50% resulted in the average imperviousness of the green roof increasing to 33% and the number of runoff disturbances increased to 15 (two additional occurrences in the fall).

The 30-year average daily air temperature (for April through November) was between 1 and 2°C lower than the average recorded during the study years. Decreasing the daily average air temperature values by 2°C resulted in a 1% increase in average imperviousness and one additional runoff event in the fall. Increasing the daily average air temperature by 2°C had the opposite effect and resulted in a 1% reduction in average imperviousness and one less runoff event in the fall.

The impact of reducing the daily average relative humidity values by 50% was larger than those observed due to changes in wind speed and temperature. Reducing the relative humidity values by 50% resulted in a decrease in average imperviousness to 25% and only 11 runoff disturbances.
Combining the 50% reduction in humidity and a 100% increase in wind speed resulted in a larger change to the simulation results. Average imperviousness was reduced to 21% and the number of runoff events dropped to 9. This impact is greater than simply adding the change caused by each variable.

Next, a 2°C decrease in average air temperature and a 100% increase in wind speed were applied to provide a simulation that closely represented the 30-year average climate conditions. In this case average imperviousness was reduced by 1% and there was one less runoff disturbance during the fall.

A crop coefficient, derived from previous studies (Lazzarin et al., 2005; Rezaei, 2005), of 1.07 was used in the simulation. To examine the model sensitivity to crop coefficient its value was increased to 1.2, the highest value in the range of common crop coefficients published by Allen et al. (1998) and then reduced to 0.5, the lowest crop coefficient reported for Sedum spp. (Lazzarin et al., 2005; Rezaei, 2005). When the crop coefficient was increased to 1.2, average imperviousness decreased to 30% and the number of runoff events was reduced by 2. When the crop coefficient was decreased to 0.5, average imperviousness increased to 45% and 23 days with runoff (two additional days during the spring, two in the summer, and six in the fall). Reducing the crop coefficient to 0.4, the lowest value in the range of common crop coefficients (Allen et al., 1998) the runoff response dramatically worsened with average imperviousness increasing to 53% and a total of 30 days with runoff. The impervious response of the green roof is very sensitive to low crop coefficient values.

The final variable examined was total available water (TAW). The estimated TAW values from previous research vary considerably (see section 2.7.2.2). To examine the potential impact of alternative TAW values the simulation was repeated for TAW values 15% greater than and 15%
less than the original simulation value. When TAW was increased to 45% there was a 10% reduction in the average imperviousness of the green roof. In addition there were three fewer runoff events, one during the spring and two during the fall. When TAW was reduced to 15% there was a 15% increase in average imperviousness and eight additional runoff events (one during the spring, three during the summer, and four during the fall). Increasing TAW had less of an impact on the frequency of runoff disturbance compared to reducing the value of TAW.

The changes to individual climate variables resulted in little impact on the depth and frequency of runoff events, however, changes in the growing media TAW and crop coefficient appear to have substantial impacts on the overall impervious response. Although greater validity could be gained through refining the roof top wind speed values used to estimate evapotranspiration rates, improving the reliability of the crop coefficient of *Sedum spp.* and ensuring a valid estimate of TAW appear to be more important factors affecting the impervious response of the green roof.

4.7 POTENTIAL ENVIRONMENTAL IMPACT OF THE GREEN ROOF STORMWATER RESPONSE

The size and frequency of runoff plays into the relationship between total impervious area and stream health. Yet current research assesses the impact of a static value of imperviousness on stream health. With traditional development this is perhaps quite valid but with the advent of stormwater management devices such as green roofs, their performance can be highly variable. Under one set of conditions a green roof can respond to a rain event with no runoff and under different conditions the same size rain event can result in significant runoff. This dynamic response to precipitation events may have a significant impact on TIA if green roofs are broadly applied within a stream catchment area.
What is clear from the results of this study is the substantial reduction in the depth and frequency of runoff from the green roof during each of the four study periods resulting in the green roof responding more like a non-impervious surface than an impervious one. However, the impervious response is not consistent over the course of the study period. The average study period runoff varied year-to-year from a low of 7% in 2007 (a very dry year) to a high of 39% in 2006 (a relatively wet year). This variability increases as the averaging period decreases. The variation in average monthly runoff was 82% and increased to 98% for daily runoff. The frequency days with rain that resulted in runoff during each of the four study periods ranged from a low of 12% in 2007 to a high of 28% in 2006. Over the course of the four study periods, the green roof prevented runoff from occurring during 82% of the rain days.

The distribution of runoff disturbances was highest in the fall, followed by the spring and was lowest in the summer. This differs from the runoff distribution pattern of a naturally vegetated area which would have the highest frequency of runoff events during the spring (Roy et al., 2005). The reduction in the frequency of days with runoff suggests that the green roof is responding more like a non-impervious surface however, the seasonal runoff distribution does not match that of a natural vegetated area.

Although the green roof appears to provide substantial reduction in runoff compared to that of an impervious surface it achieves this performance using an excessive amount of evapotranspiration. Natural forest areas contribute 10% of total precipitation to runoff, 40% to evapotranspiration and 50% to infiltration (Arnold and Gibbons, 1996) however, the green roof contributes 30% of total precipitation to runoff, 70% to evapotranspiration, while none of the precipitation is allowed to infiltrate the ground. Highly impervious (75% -100% impervious) land uses contribute 35% of total precipitation to runoff, 38% to evapotranspiration and 15% to
infiltration (Arnold and Gibbons, 1996). The water balance of a green roof is unique, resembling neither the water balance of a natural forest area or a highly impervious surface.

Even though the depth of precipitation received during the four study periods provided for a range of values greater than and less than the 30-year average, the four study periods did so with a much lower frequency of days with precipitation. The 30-year period had an average of 20 rain events per month while the four study periods only had an average of 14 rain events per month. Had the frequency of rain event been equal to or exceeded the 30-year average increased runoff would likely result, reducing the environmental benefit of the green roof storm water response.

4.7.1 EXTENDING THE APPLICATION OF THIS RESEARCH

The stormwater response framework documented in this study can be used to organize and design future studies that aid in understanding green roof retention performance.

Understanding the water balance contribution of green roofs also provides insight into the availability of water for other uses. Runoff from a green roof can be directed to infiltration devices, conveyance structures or water harvesting devices. Understanding the size and frequency of runoff events will aid in developing complementary systems. The net result of these integrated systems might allow the stormwater response of a site to more closely correspond to that of the pre-development condition than that of a green roof on its own. Understanding the stormwater response behaviour of green roofs and other stormwater management devices allows them to be appropriately implemented to provide positive effects on the urban hydrologic regime.
One of the degrading effects to stream health of impervious surfaces is their capacity to collect and transport pollutants. Conventional roofs have been shown to produce little pollution relative to the quantity contributed by transportation surfaces (Bannerman et al., 1993). Further, the concentration of pollutants in streams may increase with less dilution by relatively clean conventional roof runoff. Alternatively, green roofs may be a source of nitrogen, phosphorous, and other pollutants (Monterrusso, 2004; Moran et al., 2005; Berndtsson et al., 2006; Rowe et al., 2006) causing a further stress to the health of streams.

Further, the impact of the green roof stormwater runoff response on sources of pollution may also expand into other areas such as investigating the degree to which green roofs may assist in reducing combined sewer overflows (CSOs). The model used in this study would allow for a researcher to identify the size, frequency and distribution of green roof runoff contribution in urban regions that utilize combined sewer systems (CSS). This could lead to a better understanding of how effectively green roofs mitigate the potential for CSOs.

The model developed in this study could also be adapted to predict the water needs of green roof vegetation at different stages of development. During the establishment of green roof vegetation the water requirements are different than for an established green roof. Specifically, it needs more water to meet the needs of rapidly growing vegetation. Shortcomings in the delivery of water through precipitation need to be fulfilled through irrigation. The model could help establish the amount and frequency of irrigation required thereby increasing the survival and development rates of newly planted roofs. This also allows for one to estimate the potential viability of a particular plant within a particular green roof design and climate context. Perhaps this will allow for a wider range of species to be used in extensive green roof design.
The model presented in this study can also be used to determine the required design specifications of a green roof in order to meet performance targets. For example the model could be adapted to calculate the necessary growing media depth given a desired runoff response.

4.8 STUDY LIMITATIONS

Although the entire water balance model can be constructed using simple mathematical functions, some of the operations are more complex than desired. The reference evapotranspiration rate equations are quite extensive. A substantial amount of climate data is required, then increasing the perceived complexity. However, special programming skills are not required and commonly used computer spreadsheet programs can be used to construct and run this model.

The variability of climate and precipitation patterns can be significant over the long term. Harbor (1994) suggests that the full extent of historic data be used in such an assessment and that a 30-year period is recommended as it is the standard climate-averaging period. Using just four years worth of data may not represent the range of retention responses likely to be exhibited by a green roof over the long term in the Waterloo region. For example, during the four study periods, the average number of days with rain was 29% less than the 30-year monthly average. Years when the frequency of rain days exceeds the 30-year average would likely result in an increase in the depth and frequency of runoff, thereby increasing the average impervious response of the green roof.

The outcome of the model represents the potential gross impact of a green roof. Understanding the contribution of a retrofit application of a green roof is different than
understanding the stand-alone stormwater response of a green roof. Conventional roof designs have been shown to provide some stormwater retention. VanWoert et al. (2005a) found that over a fourteen month period, a gravel ballast roof retained nearly half the precipitation of that of a green roof. Lui (2003) reported that a conventional bituminous roof only retained 10% of the precipitation while a green roof averaged 55% retention during a six month period. As a result, the impact of a green roof on environmental health in a retrofit application should be identified as the difference between the conventional roof and green roof runoff response. To understand the net impact of a green roof, it is necessary to examine the difference in runoff response between the existing land use and the proposed green roof design. The environmental benefit resulting from this change is not equal to the performance reported in this study, as it does not take into consideration the retention performance of the conventional roof. In addition vegetation typically does not cover the entire roof as maintenance walkways and mechanical structures are often found in the roof environment, reducing the available surface area that can be “green”.

A number of attributes required to model the stormwater retention performance of green roofs are not well-defined in current literature. These include insufficient roof top wind data, poorly defined crop coefficients for green roof vegetation and a limited understanding of how green roof environmental conditions may impact evapotranspiration rates. Although what are believed to be the dominant factors impacting have been incorporated into the model, additional variables could be employed to further refine the evapotranspiration rates (e.g., dual crop coefficients and variable crop coefficients dependent on crop development stage and climate).
The model applies to established green roof vegetation as evapotranspiration rates and water requirements may differ for a newly planted roof.

There are a number of methods for determining reference evapotranspiration that require fewer inputs than those of the FAO Penman-Monteith Method used in this study. Future investigations could investigate the validity and reliability of evapotranspiration rates and retention performance predicted by the model developed for this study as well as the green roof performance determined using similar models that incorporate both basic and complex techniques for determining evapotranspiration rates.

The energy balance used in the reference evapotranspiration rate equations assumes that a negligible amount of energy is transmitted horizontally under standard crop conditions (Allen et al., 1998). Under standard crop conditions vegetation is grown as a large continuous mass. This assumption may not be valid in the case of a green roof where the vegetation patch size might not be particularly large or homogeneous.

Under standard crop growing conditions, soil heat flux is relatively small over a short period of time. When determining the reference evapotranspiration rate for a period of one to ten days, the soil heat flux can be assumed to be zero (Allen et al., 1998). It is not known if this is a valid assumption for the green roof environment.

Microclimate may have a significant impact on the rate of evapotranspiration from a green roof, as obstructions can significantly alter wind and radiation patterns on the roof top environment. Reference evapotranspiration rates are calculated, assuming that vegetation is planted on a relatively flat area. Mentens et al. (2003) observe that current methods for estimating reference evapotranspiration rates, such as the FAO Penman-Monteith Method, do not incorporate the ability to adjust the slope and orientation of the planted surface. Mentens
et al. (2003) investigated the impact of slope and orientation on evapotranspiration rate, likely in the northern hemisphere, and concluded that southern exposure had the highest evapotranspiration rate followed by east and west exposures with the lowest evapotranspiration rates occurring for northern exposure test plots. The effect of orientation diminishes on cloudy days as differences in radiation exposure based on slope and orientation become very small.

4.9 FUTURE RESEARCH

- One of the most immediate issues that future research should address is the validation of the model output. One opportunity would be to compare the precipitation and runoff depths from one of the existing green roofs in Waterloo, Ontario to data supplied by the model for the same time period.
- Further research needs to define crop coefficients under standard environmental conditions using standardized techniques for vegetation commonly applied on green roofs.
- Future research efforts could also provide further data relating to total available water and readily available water in order to understand how different growing media and vegetation affect these values.
- Additional research is needed to determine the dynamic impact of wind, temperature and vapour pressure gradients over a green roof in order to determine how a green roof might impact evapotranspiration.
- Another branch of research could examine the relationship between the reduction in impervious area due to the application of green roofs to specific stream health measures. Such research could attempt to identify whether green roofs have the same impact as other “green” (i.e., non-impervious) surfaces.
This thesis involved the development of a mathematical model that simulates the stormwater response of a green roof to a series of precipitation events. This model was based on the physical characteristics limiting precipitation retention and the process of evapotranspiration that removes water from the green roof. Green roof design characteristics impacting the stormwater response were selected based on average performance characteristics published in previous studies and recommendations found in other studies to ensure the long term viability of the green roof vegetation. The green roof specifications such as different growing media depths and water storage capacities as well as different types of vegetation can be altered to test alternative green roof designs.

Applying past climate data specific to Waterloo, Ontario to the model, allowed for the simulation of green roof stormwater retention for a number of long-term precipitation sequences. Contextual variables including latitude and elevation can be changed in order to apply the simulation to different locations.

The resulting stormwater response of a green roof is not transferable from one site to another nor is it applicable to other study periods. Stormwater response is a function of a specific series of precipitation events as well as the variables affecting evapotranspiration, such as site latitude and elevation, incoming solar radiation, relative humidity, wind speed, and ambient air temperature.

The model is believed to provide a reasonable simulation of the expected stormwater response of an extensive green roof in Waterloo, Ontario. The output from the model provided evapotranspiration rates and retention performance similar to observed values from other
studies. Ranges of retention response from the simulation over long-term (multiple months), monthly, and daily time periods are similar to values observed in field studies by Köhler et al. (2001), Lui (2003), Hutchinson et al. (2003), Moran (2004), Bengtsson et al. (2005), and VanWoert et al. (2005a). Peak evapotranspiration rates calculated by the model are within the range observed for Sedum spp. grown in an extensive green roof environment (VanWoert et al., 2005b; Durhman et al., 2006) and are within the range of values typical of the climate region (Allen et al., 1998).

The green roof stormwater response measure of runoff represents the relative contribution of the green roof to impervious area within Waterloo, Ontario. The combined simulation data from all four study periods shows that the green roof reduced the impact of urban development on the environment, as compared to a completely impervious surface. This reduction came in the form of a large reduction in the total depth of runoff and a substantial decrease in the number of days with runoff. The total reduction in runoff divided by the total precipitation received over the four consecutive study periods results in an average impervious response of 29%. The green roof stormwater response has been shown to be dynamic and varies with changes in climate conditions and precipitation patterns. This results in a wide range of runoff values corresponding to different levels of imperviousness. The response is shown to be variable from year to year and extreme variation occurs when assessing the data daily; for days with rain, the stormwater response varied from 0% to 98% impervious.

Small rain events (those with a return period of one year or less) occur frequently over the course of a year yet typically result in a substantial amount of runoff from impervious surfaces (Roy et al., 2005). The simulated green roof showed that a green roof has a positive impact on the environment by substantially reducing the size and frequency of daily runoff. Over the
course of the four study periods the green roof reduced the number of runoff events by 82% compared to an impervious surface. However, the distribution of the reduction in days with runoff is not typical of a natural forested area as the green roof tended to allow a higher percentage of days with runoff during the fall. In a natural forested area the majority of runoff events would occur during the spring (Roy et al., 2005).

The impact of green roofs on the environment is not entirely positive. Green roofs do not reduce stormwater runoff in the same way as natural ground cover areas. Natural ground cover areas contribute nearly equal amounts of stormwater to infiltration and evapotranspiration (Arnold and Gibbons, 1996), while green roofs make no contribution to infiltration. This indicates that while green roofs show a large decrease in runoff, they accomplish this through a disproportionate amount of evapotranspiration. The absence of infiltration has a negative affect by reducing groundwater supplies and baseflow to streams.

The disproportionate contribution that green roofs make to evapotranspiration may be of benefit in returning post-development evapotranspiration levels to those found in a naturally vegetated environment. However, the degree of application of green roofs should be carefully considered such that their contribution to evapotranspiration does not exceed pre-development levels.

Commercial, Industrial and Shopping centers are comprised of 75-95% impervious surfaces, with an average roof area contribution of 28% (Hopper, 2007). The model suggests that applying a green roof to 28% of these areas results in an 11% reduction in runoff and a 12% increase in evapotranspiration (Figure 35). Although the application of green roofs returns the evapotranspiration to a level resembling the natural ground cover condition and provides some relief to runoff, it results in no improvement to the infiltration contribution from such land use.
Figure 35 - Alteration of the water balance due to the application of a green roof to commercial, industrial and shopping centre land use.
The impervious value for these land uses range from 75%-95%.
The grey horizontal arrows provide a reference to 10% runoff typical of the forested condition. The actual runoff is shown by the black arrows.

The current assessment of the impact of imperviousness on stream health identifies impervious area as a static value. With traditional development this was perhaps a valid assumption but with the advent of stormwater management devices such as green roofs, their performance can be highly variable. Under one set of conditions a green roof can respond to a rain event with no runoff while under different conditions the same size rain event can result in significant runoff. This dynamic response to precipitation events may have a significant impact on impervious area if green roofs are applied extensively to a stream catchment area and if the green roof is assumed to behave as a natural ground cover (i.e., non-impervious surface).

5.1 SCALE OF APPLICATION

Landscape architects and other design professionals involved in land development need to be considerate of the dynamic behaviour of green roofs when recommending their use to satisfy
policy and incentive plans. For example DeNardo et al. (2005) suggest that green roofs can make a significant contribution towards accomplishing the USEPAs NPDES II requirement that site development must ensure water from a 2-year storm will infiltrate and result in no runoff from a site. Professionals involved in site design cannot rely on a green roof to provide a constant contribution in reducing runoff from a storm event. Due to the dynamic response of green roofs, they may be able to contribute to mitigating a portion of a 2-year storm on one occurrence but may have a negligible impact under a different set of precipitation and climate conditions. Furthermore, the mechanism of evapotranspiration means that green roofs do not meet the requirement to infiltrate all water from a precipitation event.

Carter and Jackson (2007) found that the greatest proportion of flat roofs occur in commercial and industrial districts. Targeting widespread application of green roofs to these areas within a highly impervious stream catchment may impact impervious area such that there is a noticeable benefit to the environment as measured by improved stream health. As the proportion of green roofs increases their stormwater response will provide a more pronounced reduction in the amount of impervious area found in the stream catchment.

The question remains, however, if the replacement of a single impervious surface type with a green roof will provide the typical improvement in stream health expressed by Schueler’s (1995) impervious cover model. If green roofs are employed on a very large scale, understanding and taking into account the implications of a dynamic impervious area contribution may be necessary to ensure future human and ecologic health.
5.2 FINAL REMARKS

The green roof has been shown to substantially reduce the total depth of runoff and number of days with runoff in comparison to an impervious surface. The size and frequency of runoff suggests that green roofs behave like non-impervious surfaces, however they accomplish this entirely through the process of evapotranspiration. To balance out the mechanism used by green roofs to mitigate stormwater runoff it is recommended that they be used as one part of a system of stormwater management devices whose performance could be coordinated to reduce impervious response to a level better resembling that of pre-development (i.e., natural ground cover).

Landscape architects along with allied professionals such as planners, ecologists and others involved in land development should be cognisant of the way in which site design impacts the hydrologic cycle. Furthermore, it is important to understand mechanisms used by each stormwater management device to ensure that their application will support environmental processes. The results of this study characterize the impervious response of a green roof and show that it can contribute in a positive way, in conjunction with other stormwater management devices and low impact development techniques, to reducing impervious area. That is, green roofs can play an important role in returning the hydrologic cycle and water balance of developed areas toward pre-development ratios, providing a benefit to the environment.
REFERENCES


http://climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html, Environment Canada.


Radecki, S. 2008, Email communication with author. 20 October.


Seglenieks, F. 2008. Email communication with author. 13 March.


- $D_{s,i}$: Start of day water deficit (End of previous day water deficit)
- $D_i$: End of day water deficit
- $P$: Precipitation
- $ET_o$: Reference evapotranspiration
- $ET_c$: Crop evapotranspiration
- $K_s$: Water stress coefficient
- $ET_{c, adj}$: Adjusted evapotranspiration

<table>
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<tr>
<th>Day of the year</th>
<th>Date</th>
<th>$D_{s,i}$ (mm)</th>
<th>$D_i$ (mm)</th>
<th>$P$ (mm)</th>
<th>$ET_o$ (mm/day)</th>
<th>$ET_{c, adj}$ (mm/day)</th>
<th>$K_s$</th>
<th>Runoff (mm)</th>
<th>Retention (mm)</th>
<th>Impervious Response (%)</th>
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</thead>
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<td>01-May</td>
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<td>1.0</td>
<td>3.2</td>
<td>0.0</td>
<td>0%</td>
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<tr>
<td>138</td>
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<tr>
<td>140</td>
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<td>22-May</td>
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<tr>
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<td>144</td>
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<td>0%</td>
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<tr>
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<td>25-May</td>
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<td>0.0</td>
<td>0%</td>
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<tr>
<td>146</td>
<td>26-May</td>
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<td>15.5</td>
<td>4.0</td>
<td>1.1</td>
<td>1.2</td>
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<td>1.2</td>
<td>0.0</td>
<td>4.0%</td>
</tr>
<tr>
<td>Day of the year</td>
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<td>$D_{i-1}$ (mm)</td>
<td>$D_i$ (mm)</td>
<td>$P$ (mm)</td>
<td>$ET_i$ (mm/day)</td>
<td>$ET_{c adj}$ (mm/day)</td>
<td>$X_r$</td>
<td>Runoff (mm)</td>
<td>Retention (mm)</td>
<td>Impervious Response (%)</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------</td>
<td>----------------</td>
<td>------------</td>
<td>---------</td>
<td>----------------</td>
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<tr>
<td>147</td>
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<tr>
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<td><strong>Total</strong></td>
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<td><strong>113.4</strong></td>
<td><strong>96.6</strong></td>
<td><strong>103.4</strong></td>
<td><strong>61.2</strong></td>
<td><strong>29.6</strong></td>
<td><strong>83.8</strong></td>
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</tbody>
</table>

Table 31 - Simulation Data for May, 2006.

*Retention is greater than $ET_{c adj}$ as more water is being retained in the growing media at the end of the month than at the start. Retention is equal to the difference between the start of month water deficit and the end of the month water deficit plus the total of $ET_{c adj}$. 
# Table 32 - Simulation sensitivity to climate variables during the 2005 study period

<table>
<thead>
<tr>
<th>Climate variables</th>
<th>Average Impervious-ness</th>
<th>Days With Runoff</th>
<th>Depth of runoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Data</td>
<td>32%</td>
<td>13</td>
<td>8 0.2 42 4 2 19 15 10</td>
</tr>
<tr>
<td>Increase average daily wind speed 100%</td>
<td>30%</td>
<td>12</td>
<td>8 &lt;1 42 4 2 18 13 9</td>
</tr>
<tr>
<td>Decrease average daily wind speed 50%</td>
<td>33%</td>
<td>15</td>
<td>8 &lt;1 42 4 2 19 16 10 &lt;1 2 2 5 22 32 2</td>
</tr>
<tr>
<td>Increase average daily air temperature 2°C</td>
<td>31%</td>
<td>12</td>
<td>8 &lt;1 42 4 2 18 14 9</td>
</tr>
<tr>
<td>Decrease average daily air temperature 2°C</td>
<td>33%</td>
<td>14</td>
<td>8 &lt;1 43 4 2 19 15 10</td>
</tr>
<tr>
<td>Decrease average daily relative humidity 50%</td>
<td>25%</td>
<td>11</td>
<td>7 &lt;1 41 3 1 18 12 8</td>
</tr>
<tr>
<td>Decrease average daily relative humidity 50% and increase average daily wind speed 100%</td>
<td>21%</td>
<td>9</td>
<td>6 40 3 1 18 10 6</td>
</tr>
<tr>
<td>Decrease average daily air temperature 2°C and increase average daily wind speed 100%</td>
<td>31%</td>
<td>12</td>
<td>8 &lt;1 43 4 2 19 14 10</td>
</tr>
</tbody>
</table>
Table 33 - Simulation sensitivity to green roof design specifications during the 2005 study period

<table>
<thead>
<tr>
<th>Green Roof Design Variable</th>
<th>Average Imperviousness</th>
<th>Days With Runoff</th>
<th>Depth of runoff (mm)</th>
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</thead>
<tbody>
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<td>32%</td>
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<td>8</td>
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<tr>
<td>Decrease crop coefficient to 0.5</td>
<td>48%</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>Increase crop coefficient to 1.2</td>
<td>30%</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Decrease TAW to 15%</td>
<td>48%</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>Increase TAW to 45%</td>
<td>22%</td>
<td>10</td>
<td>28</td>
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</table>