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STORMWATER REDUCTION BY GREEN ROOF TECHNOLOGY: A COMPARISON OF CANADIAN CLIMATES

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Abstract: In recent decades, urbanization has led to more frequent flood events in urban areas. To reduce the impact of urban floods, several measures have been taken, including the use of green roof technology. To investigate its feasibility in the Canadian climate, several cities across the country (Vancouver, Calgary, Regina, Toronto, London, and Halifax) were selected to determine the retention performance of green roof systems in different climates. The water balance equation along with evapotranspiration (ET) models were employed to simulate runoff that might be produced by green roofs in six Canadian cities. A seven-year simulation period was selected running from 2000 to 2006, with modeling conducted for eight months of the year, from March 1st to October 31st, using hourly time steps. The runoff simulations with the Penman-Monteith (PM) model was carried out for hypothetical green roof setups incorporating two different types of vegetation. The results showed that the performance of green roof depends on location, varying from 17% to 50% for low water use plants. The best performance in storm water reduction was predicted to occur in Regina and Calgary, while the poorest performance was predicted for Halifax and Vancouver.

1 INTRODUCTION

Ongoing rapid development and land use changes cause widespread reduction in water infiltration following precipitation events, as ground surfaces are made impervious by buildings, roads, and parking lots (Booth, 1991). Consequently, larger amplitude runoff rates occur over shorter time periods in comparison to pre-development conditions (Dingman, 1994). Of the current emerging storm water management practices, green roofs are a technology of considerable interest and hold potential to supplement existing storm water management systems as they retain storm water as well as attenuate and delay peak flows. A typical extensive green roof (substrate thickness less than 20 cm), which is used for the purpose of storm water reduction, mainly comprises of an impermeable and root resistant membrane, drainage layer, growth medium (substrate), and vegetation layer. Studies have shown that the application of green roof technology has other beneficial aspects including reduction in building energy consumption, mitigation of heat island effect, sound insulation, an increase in biodiversity in cities and so forth (Bianchini and Hewage, 2012a; Bianchini and Hewage, 2012b; Oberndorfer et al., 2007; Sailor, 2008; Susca et al., 2011)

Evapotranspiration (ET) plays a major role in retention performance of green roofs due to recover water storage in growth medium after precipitation events. Several experimental studies have shown that ET rates declined as substrate moisture content decreased (Berretta et al., 2014; Voyde et al., 2010b; Wolf and Lundholm, 2008; Young et al., 2014). The ET investigations on substrate type (Berretta et al., 2014; Young et al., 2014) and thickness (VanWoert et al., 2005b; Young et al., 2014) have shown that substrates with high organic matter, fine-grained porous media, and high thickness caused higher ET rates compared to low organic matter, coarse grain material and low substrate thickness. Several studies have shown a link between ET rates and vegetation types (MacIvor and Lundholm, 2011; Voyde et al., 2010b; Wolf and Lundholm, 2008). Experimental results of the greenhouse study demonstrated different ET rates from green roofs associated with dryland (e.g., *Empetrum nigrum*) and wetland species (e.g., *Vaccinium macrocarpon*) (MacIvor et al., 2011). *Rezaei (2005)* investigated the impacts of various climate conditions on ET rates in greenhouse. The results indicated that different ET rates were associated with various climate conditions.

In quantifying ET rates from green roofs, several studies measured ET rates from green roofs to examine the applicability of ET models developed primarily for agricultural applications to green roof systems (DiGiovanni et al., 2013; Feller, 2011; Hickman et al., 2010; Marasco et al., 2014; Rezaei, 2005; Voyde, 2011). The measured ET rates based on different simulated climate conditions in greenhouse (Rezaei, 2005), and based on the field studies (DiGiovanni et al., 2013; Voyde, 2011) have demonstrated that the Penman-Monteith model (PM) (Jensen et al., 1990) provided good prediction under no water stress conditions. The experimental ET study on a green roof site (Marasco et al., 2014) indicated that the ASCE-PM model estimated reasonable ET rates; however, ET rates were overestimated during the summer period. It should be noted that in this study the ET model did not take into account substrate moisture conditions. On-site measurement of ET rates (Feller, 2011; Hickman et al., 2010) showed that the PM model predicted better results compared to the Penman equation on a monthly basis. However, in these two studies the impacts of substrate moisture on the prediction of ET rates were ignored.

Several studies have shown that ET models should account for substrate moisture conditions (Berretta et al., 2014; Voyde, 2011; Wadzuk et al., 2013). *Voyde, (2011)* used different ET models to compare with measured ET rates obtained from field installation. They concluded that none of the studied ET models were appropriate for predicting ET rates from green roofs when water was limited. Given that, the results showed the Penman model with a revised wind function, and the PM model performed better than other ET models studied. *Berretta et al., (2014)* took into account the impacts of substrate moisture content and configuration-specific correction factor. The results demonstrated a close agreement between moisture loss from the sedum modules in the field with the simulated drying rates using PM and Haegreaves-Samani (HS) models (Hargreaves and Samani, 1985).

Water retention performance in green roofs has been investigated experimentally by several researchers. Studies have revealed that several factors including substrate type and depth (VanWoert et al., 2005a; Voyde et al., 2010a), rainfall depth and intensity (Carter and Rasmussen, 2006; Lee et al., 2013; Simmons et al., 2008), antecedent dry days (Lee et al., 2013; Stovin, 2010), and vegetation types (Dunnett et al., 2008; Nagase and Dunnett, 2012; Nardini et al., 2012; Schroll et al., 2011) have played major roles on produced runoff from green roofs. Obtained data (Voyde et al., 2010a) showed that substrate types and depths had no significant influence on storm water reduction at the study location; however, the experimental data (VanWoert et al., 2005a) demonstrated a direct relationship between substrate depth and water retention. An inverse correlation between water retention and rainfall depth and intensity have been reported in literature (e.g., (Carter and Rasmussen, 2006)). Also, several studies have highlighted the significance of available substrate storage volume (which is influenced by antecedent dry days) on water retention performance of green roofs (e.g., (Lee et al., 2013)).

In recent years, several modeling studies have been conducted either to evaluate the performance of green roofs in runoff reduction (e.g., (Hilten et al., 2008)) or to describe the hydrologic and hydraulic processes of green roof system (e.g., (Palla et al., 2009)). While most of these studies employed simple mathematical models (ignored the impact of porous media characteristics) (Kasmin et al., 2010; Roehr and Kong, 2010; She and Pang, 2010a; Sherrard and Jacobs, 2012; Stovin et al., 2013; Vesuviano et al., 2014; Vesuviano and Stovin, 2013; Zhang and Guo, 2013) and empirical approach (Mentens et al., 2006), a few modeling studies considered complex mathematical models (mechanistic approaches) (Hilten et al., 2008; Metselaar, 2012; Palla et al., 2009). In spite of a large number of studies on the beneficial aspects of green roof technology, there are limited studies on the retention performance of green roof associated with different climate conditions.

Roehr and Kong. (2010) applied a simple mathematical model to examine the influences of three distinct climate conditions, and two vegetation types on runoff reduction of hypothetical green roofs over a one-year period. The hypothetical sandy loam (150 mm depth) with field capacity, and wilting point of 31%, and 11% (vol./vol.) were assumed, respectively. The simulation was performed assuming daily time steps and initial water content of 20% (total volume). The water balance equation incorporating field capacity, wilting point, and irrigation amount along with the ET model (the HS model) were employed to quantify runoff reduction. Substrate moisture content was ignored in calculating of ET rates. Crop coefficient was implemented to account for non-standard type of vegetation. The results showed that the performance of green roofs in water retention varied in different climate locations (overall runoff reduction of 28% to 100% were obtained over the studied locations) and was affected by vegetation types. *Stovin et al. (2013)* applied water balance equation to evaluate the long-term storm water retention associated with climate change and at four various climate conditions in UK. No irrigation was considered in the simulation. Field capacity and the impacts of moisture content to obtain actual ET rates (Thornthwaite equation (Wilson, 1990)) were incorporated in the model. The model was validated using one year measured field data obtained from one of the study locations. A 30-year climate projection data related to four different climate conditions were used to study the performance of green roofs at each location. The results revealed that overall 19% and 59% of total rainfall were retained in cool and wet, and warm and dry climates, respectively. The results of sensitivity analysis on moisture retention capacity and crop coefficient showed that while both substrate with high moisture capacity and high water use plants increased retention performance of green roofs, the role of plant species was more significant.

Considering the research performed to date assessing green roof performance modeling in a broader sense, the majority of studies often focus on a particular location. While some studies seek to assess green roof performance in various climates(Roehr and Kong, 2010; Stovin et al., 2013), the assessment of a controlled and standardized green roof configuration within specific Canadian climates has not been completed. This provides an opportunity to assess the effectiveness and relative performance of green roofs within Canada and to understand where the technology might be most beneficial. Therefore, the primary objective of this study was to determine quantitatively through modeling the effectiveness of green roof technologies in the reduction of storm water runoff in various Canadian climates.

2 METHOD

2.1 Model Development

The governing equation used in this study was derived by applying the water balance equation for a green roof system (Hilten et al., 2008; Stovin et al., 2013):

[1] $\Delta \mathrm{MC} = \mathrm{P} - \mathrm{ET} - \mathrm{RO}$

where P is the precipitation, ET is the evapotranspiration, RO is runoff from the system, and $\Delta\mathrm{MC}$ is the change in soil moisture content.

A simple code was developed (using Microsoft Excel) to determine the soil moisture content of a 1-dimensional soil element at each time-step, based on the incident precipitation and other climate data, taking into account the effect of ET from the green roof. Each simulation is initiated with the soil at field capacity in the first time-step. To calculate the soil moisture content in the next time-step, the model checks the precipitation and evapotranspiration values in the previous time-step, as well as the runoff from the current time-step, and modifies the current moisture content value accordingly (Stovin et al., 2013):

[2] $MC_i = MC_{i-1} + P_{i-1} - ET_{i-1} - RO_i$

where MC_i represents calculated soil moisture content for the current time step (equivalent depth), MC_{i-1} is the moisture content from the previous time step, P_{i-1} is the incoming precipitation depth, from the previous time step, ET_{i-1} is the previous time step actual ET depth, and RO_i is the runoff from the current time step.

A similar approach was used to compute runoff from the green roof; the model sums the soil moisture content and the amount of precipitation from the previous time-step, and if the value exceeds the soil capacity all excess water is calculated as runoff (Stovin et al., 2013):

$$[3]\ RO_i = \begin{cases} MC_{i-1} + P_{i-1} - MC_{fc} & if\ (MC_{i-1} + P_{i-1}) > MC_{fc} \\ 0 & if\ (MC_{i-1} + P_{i-1}) \leq MC_{fc} \end{cases}$$

where MC_{fc} is the moisture content at field capacity. Field capacity was assumed to be equal to 30%, which is in the range of reported value in the literature (Berretta et al., 2014; Poe et al., 2015; Roehr and Kong, 2010; She and Pang, 2010b).

The PM model (Allen et al., 1998) were used in this study to predict the hourly ET rates as follow:

$$[4]\ ET_0 = \frac{0.408\Delta(R_n - G) + \frac{37\gamma}{T_{hr}+273.16} u_2\left(e^0(T_{hr}) - e_a\right)}{\Delta + \gamma(1 + 0.34\, u_2)}$$

where R_n is the net radiation at the grass surface ($MJm^{-2}hr^{-1}$), G is the soil heat flux density ($MJm^{-2}hr^{-1}$) ($0.1R_n$ for day time, $0.5R_n$ for nighttime), T_{hr} is the mean hourly air temperature (°C), Δ is the saturation slope vapour pressure curve at T_{hr} (kPa/°C), γ is the psychrometric constant (kPa/°C), $e^0(T_{hr})$ is the saturation vapour air pressure at air temperature T_{hr} (kPa)), e_a is the average hourly actual vapour pressure (kPa), and u_2 is the average hourly wind speed (m/s). All of the variables used in equation 4 are defined in the work by *Allen et al., (1998)*.

While ET_0 can be calculated at each time step using the above-mentioned model (Eq. 4), a number of conditions must first be met in order for ET_0 to be non-zero within a time step in the model: first, the current moisture content of the soil should exceed the prescribed minimum moisture content level; second, there should be no precipitation during the current time interval; and finally, the current ambient air temperature should exceed zero degrees Celsius.

The crop coefficient method (Allen et al., 1998) was used in conjunction with the PM models to provide and compare the performance of a green roof planted with high and low water use plants to the standard 'reference crop' as follow:

$$[5]\ PET = ET_0 \cdot K_C$$

where PET represents the potential crop ET rate (mm/hr), ET_0 is the reference crop ET rate (mm/hr), and K_C is the crop factor. Crop factors range from 0 to 1 for any given plant species, with larger crop factors indicating a greater water requirement.

To predict actual ET rates (AET), estimated ET rates were modified with the moisture correction factor as follow (DiGiovanni et al., 2013):

$$[6]\ AET = \left(\frac{MC_i - MC_{min}}{MC_{fc} - MC_{min}}\right) * PET$$

where MC_i is the current moisture content, MC_{min}, and MC_{fc} are minimum moisture content for ET (i.e., wilting point) and moisture content at field capacity, respectively.

2.2 Model Application

For the purpose of this study, six cities from across Canada were selected to represent a range of the diverse climatic conditions throughout the country. Listed from west to east, these are Vancouver, British Columbia; Calgary, Alberta; Regina, Saskatchewan; London, Ontario; Toronto, Ontario; and Halifax, Nova Scotia. A time discretization of one hour was used in the simulations, conducted over an eight-month period from March 1st to October 31st, as the model does not accommodate sub-zero temperatures. Simulations were completed on this annual basis over a seven-year period from 2000 to 2006 for each location, with the final results representing an average of annual results by location.

The method used to calculate and compare relative green roof performance in this study is determined by comparing the amount of runoff produced by green roof to the impervious control case in which all precipitation is assumed to generate an equal amount of storm water runoff. Therefore, runoff reduction is taken as the amount of water stored and/or evapotranspired by the green roof as a percentage of total runoff in the impervious control case, and is calculated using the following formula:

$$[7]\ RR_{Annual} = \left[\frac{P_{Annual} - RO_{Annual}}{P_{Annual}}\right] \cdot 100\%$$

where $\mathrm{RR}_{\mathrm{Annual}}$ is the annual runoff reduction (%), $\mathrm{P}_{\mathrm{Annual}}$ is the total annual precipitation depth, and $\mathrm{RO}_{\mathrm{Annual}}$ is the total annual runoff depth. Runoff reductions were presented on an annual (March – October) basis for each simulation period. The results of all simulation scenarios for each of the study locations were then averaged over the seven years and presented as runoff reduction percentages.

Table 1: Assumed parameters in the model and their values

Parameter	Input Assumptions
Soil Depth (mm)	100
Porosity	0.4
Min. MC for ET (wilting point) (mm)	10
Field capacity (volumetric moisture content)	0.3

3 RESULTS AND DISCUSSION

Figure 1 shows rainfall hyetograph for Toronto during May 2000. The simulated daily runoff, ET, moisture content associated with the hypothetical green roof set up and high-water use plants are presented. Daily average moisture content of growth medium started from around 19 mm (obtained from the analysis of the previous day, i.e. April 30th) at the beginning of the month. While it increases on May 2nd due to the rainfall, it decreases in the following days as a result of ET rates and lack of precipitation until around 8th of May. The error bar shows the extent of hourly soil moisture content during a day (Figure 1). After a dramatic raise due to a few days of consecutive rainfall, moisture content of growth medium reaches to field capacity (i.e. 30 mm), and then fluctuates around 25 mm for the rest of the month until it decreases to reach 20 mm at the end of May. Since the simulated moisture content is higher than minimum moisture content needed for ET (i.e. 10 mm), ET occurred each day during the month with the average rate of 2 mm per day for high water use plants (Figure 1). No runoff has occurred during the first 10 days due to low moisture content of growth medium which produces enough storage volume; however, there were two rainy days on 9th and 10th. Runoff started to occur after field capacity has reached on May 11th.

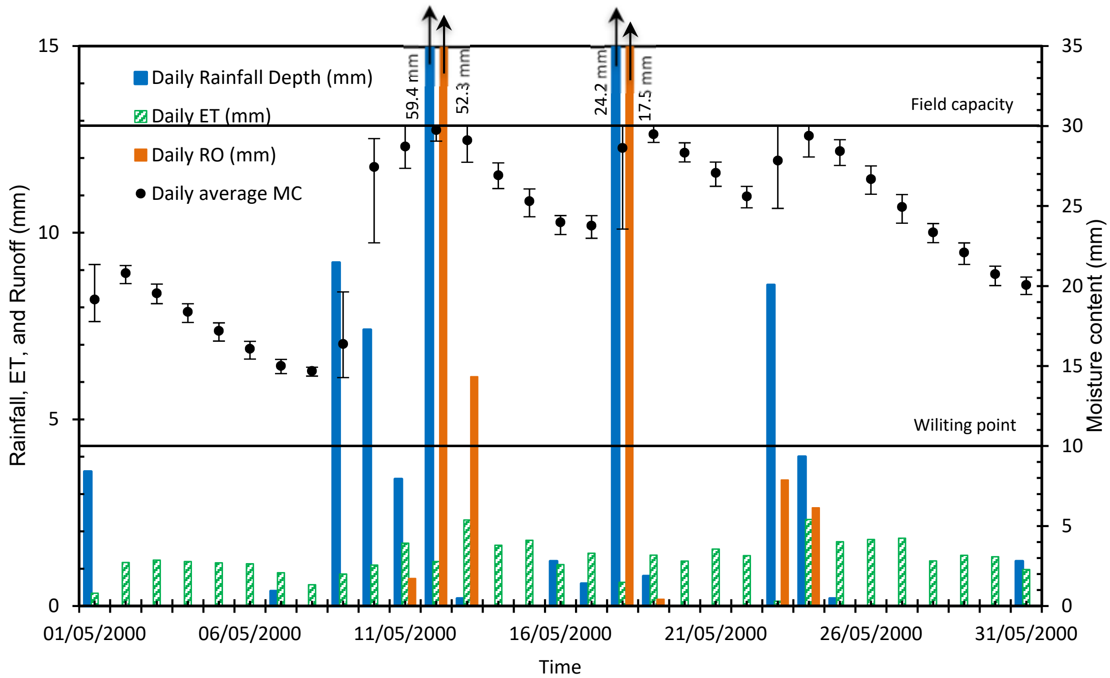

Figure 1: Daily rainfall, simulated runoff, ET and moisture content for a hypothetical green roof in Toronto during May 2000 associated with high water use plants

Storm water reduction of green roof at any location depends on the available storage volume for water in the substrate. High ET rates will remove more stored water from the substrate and subsequently enhances the water retention performance of green roof. ET rates are influenced by climate condition and the substrate moisture content. PET represents the maximum achievable ET (for specific vegetation) under a given climate condition where soil moisture is not limited (substrate remains at field capacity). The model predicted that Regina had the highest annual PET (Figure 2). The semi-arid climate in Regina including high average temperature and low average relative humidity (RH) during summer could lead to a high amount of PET at this location. High RH and mild temperatures produced the predictions of the lowest average annual PET in Vancouver and Halifax for the studied period.

Low substrate moisture content limits the amount of ET rates. The comparison between the actual ET (AET) and PET at one location reveals the influence of moisture limitation on ET (Figure 2). The model predicted that soil moisture conditions had the biggest impact on AET in Regina, mainly due to limited water availability as substrate approaches the wilting point. A small number of rainfall events with low rainfall amount resulted in predictions of low substrate moisture content in Regina (e.g., rainfall frequency in Regina was about 5% as opposed to about 13% in Halifax for the year 2001. Annual cumulative rainfall in Regina was about 270 mm compared to about 811 mm in Halifax for the year 2001). Substrate moisture limitation had a significant impact on Calgary also, as it has almost the same climate as Regina. Substrate moisture limitation had a moderate influence on AET in other locations as periods of moisture limitation were less frequent.

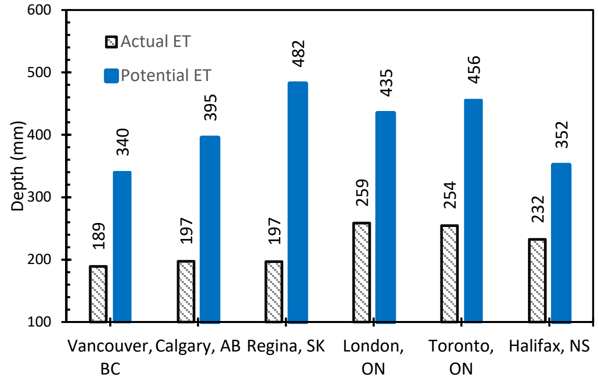

Figure 2: The comparison of average annual actual and potential ET associated with high water use plant at each location using the PM model

Figure 3 compares predicted runoff reduction (in volume and percentage) attributed to green roofs by location and vegetation type between 2000 and 2006.

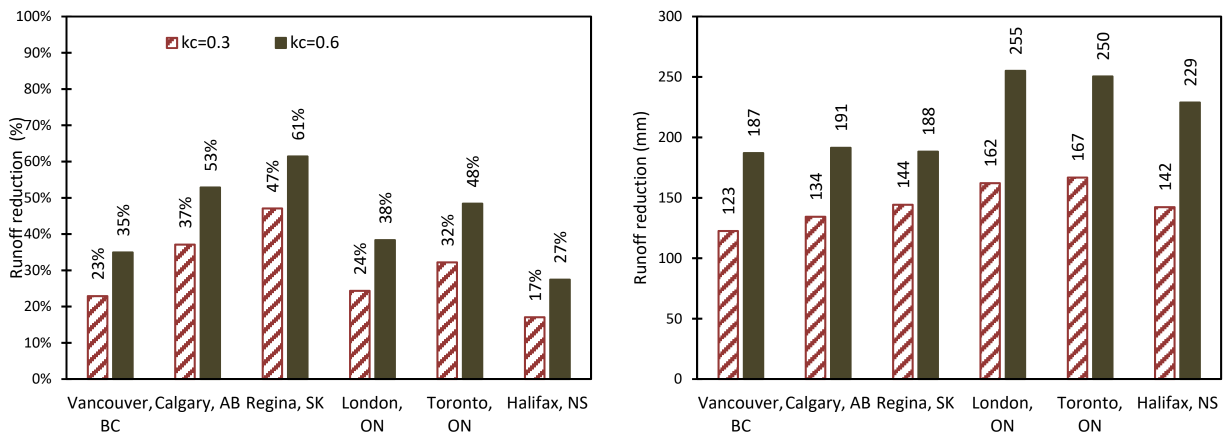

Figure 3: Runoff reduction (%) (left), and the amount of runoff reduction (mm) (right) associated with two vegetation types for the base scenario during the period 2000-2006.

The best performance in % runoff reduction was predicted for Regina and Calgary: around 61% (188 mm/yr) and 53% (191 mm/yr), respectively, for high water use plants and 47% (144 mm/yr) and 37% (134 mm/yr), respectively, for low water us e plants. The small amount of rainfall in Regina and Calgary with low rainfall frequency (long antecedent dry periods) compared to other locations (results are not shown) are the main factors leading to the greater storm water reduction as these led to low moisture conditions and high storage volume in the green roof substrate and retention of subsequent rainfall (e.g., rainfall frequency in Calgary and Regina was about 6% as opposed to about 13% in Halifax and Vancouver for the year 2001. Annual cumulative rainfall in Calgary and Regina was about 275 mm compared to about 750 mm in Vancouver and Halifax for the year 2001). The lowest % reduction in runoff was achieved in Halifax: 27% (228 mm/yr) for high water use plants and 17% (142 mm/yr) for low water use plants since the high rainfall with high frequency (short antecedent dry periods) in Halifax led to high substrate moisture contents and small available volumes for storage (e.g., average simulated moisture content just before rainfall events including 95% confidence interval was 27.2 ± 0.6 (mm) for Halifax compared to 24.2 ± 1.2 (mm) for Regina associated for low water use plants for the year 2001). The other locations (Toronto, London, and Vancouver) had intermediate levels of runoff reduction. Toronto led these three with a runoff reduction of 48% (250 mm/yr) and 32% (166 mm/yr) for high and low water use plants, respectively. It is worth to mention that although

Halifax had the lowest performance in percentage of runoff reduction, the amount of retained runoff by green roof at this location was higher than that in Regina and Calgary where had the best performance in percentage of runoff reduction.

4 CONCLUSION

This research contributes to an improved understanding of the effects of a green roof system on storm water runoff reduction in different diverse Canadian climates. A simple water budget model was developed to simulate runoff from green roofs located at different locations with hurly time resolution. The simulated moisture content was employed to incorporate the impact of water availability on calculated ET. The model was employed to obtain runoff for continuous period of raining and drying events. The results showed that substantial runoff reduction could be achieved across Canada through the installation of green roofs system. The annual runoff reduction of 20% to 50%, and 30% to 65% for low and high water use plants for the base design configuration, respectively were predicted by the model. The results showed that the green roof technology was more effective in some regions than in others. There is considerable potential for storm water runoff reduction in Regina and Calgary. Toronto, London and Vancouver present opportunities for modest runoff reductions. The relatively small runoff reduction in Halifax can be enhanced by optimizing the green roof design (application of suitable substrate material with high storage capacity or higher soil depth).

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