Modeling the Stormwater Benefits of Green Roofs in the City of Toronto

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Stormwater best management practices (BMPs) provide a number of tools to reduce the quantity and improve the quality of stormwater runoff at the source, along the drainage system and at the drainage outlet. These include devices such as downspout disconnection, stormwater gardens, green roofs, rain barrels, infiltration trenches, stormwater exfiltration/filtration systems, sand filters, bio-retention areas, wet and dry detention ponds, and constructed wetlands (Banting et al. 2005). Most end-of-pipe BMPs require a significant amount of land to host them, which is not generally available in downtown urban environments. The opportunity for green roofs to act as source level viable BMPs is logical in cities such as Toronto, since flat rooftops recreate the open space, previously at ground level, that has otherwise been eliminated for vegetation (Jennings et al. 2003). This chapter focuses on green roofs and presents a case study of the stormwater and combined sewer overflow control benefits of implementing GRT over the City of Toronto (Banting et al 2005).

Green roof technologies (herein after GRT) are not totally new and can be defined as a green space created by adding layers of growing medium and plants on top of a traditional roofing system. This should not be confused with the traditional roof garden, where planting is done in freestanding containers and planters, located on an accessible roof terrace or deck. GRT have been around in different forms all over the world for years and their insulative qualities have been used to keep dwellings cool in Tanzania, and

warm in Scandinavia. The stormwater performance of GRT is dependent upon the soil substrate and the vegetation which in combination provide interception, storage, evapo-transpiration, and attenuation of stormwater.

There are two categories of GRT. Intensive GRT are characterized by deep substrate (greater than 300 mm) and large vegetations (e.g. shrubs and trees) while extensive GRT are characterized by shallow substrate (less than 300 mm) and ground covering vegetation (e.g. sedum and turf). Extensive GRT are primarily used in existing buildings with structural limitations. Based on the Ontario Building Codes's loading requirements, Au (2007) estimated the maximum substrate depth of extensive GRT for residential, commercial, and industrial buildings in Ontario are 150 mm, 200 mm, and 200 mm respectively. Intensive GRT are usually designed for new buildings as the loading support can be incorporated in the structural design of the new buildings. For instance, the Isuzu dealership building in Singapore has a SUV driving test range on the top of the six storey building with 1 m depth substrate and safari vegetations. Extra structural support was incorporated into the structural design of the building.

Studies have shown that GRT could provide both quantity and quality control of storm runoff in urban areas (Dramstad et al. 1996; Graham and Kim 2003; TRCA 2006). While greenroofs may not provide adequate control over large storms, they have the ability to intercept, store, and attenuate most of the moderate and small events (Li 2006). Thompson (1998) found that a typical extensive GRT can retain 60 to 100% stormwater. According to the Zinco planning guide (1998), GRT are expected to retain 70-90% and 40-50% stormwater during the summer and winter months respectively. Liesecke (1993; 1998) estimated that a GRT of 2 to 4 cm and 60% of substrate can retain 40-50% and 60% of the annual rainfall respectively. Based on a 15-month field monitoring results, Liptan et al. (2003) found that 69% of the rainfall was retained by a GRT. Jennings et al. (2003) and Rowe et al. (2003) found that a GRT can retain up to 100% of rainfall volume dependent upon the volume, intensity, and interevent time of rainfall events. Additionally, Jennings et al. (2003) and Liu (2003) found that a GRT can also attenuate the peak flow of a light rain (19 mm in 6.5 h) to up to almost 95 minutes.

While the above research studies have indicated the stormwater control performance of a GRT, there are not many studies that focus on their performance on a watershed basis. Marshall Macklin Monaghan Ltd. (2004) developed HSPF's Unit Response Functions (URF) of GRT using the 2003 field monitoring data of the York University GRT (TRCA 2006). Using the HSPF's URF of GRT, Aqua Beech Inc. (2004) simulated the effectiveness

of implementing GRT within the Markham Branch of Highland Creek and found annual runoff volume could be reduced by 5%. Casey Trees and LimnoTech (2007) developed a green build-out model to quantify the stormwater management benefits of trees and green roofs in Washington, DC. A methodology to estimate the stormwater benefits of greenroofs in the City of Toronto, Ontario, Canada is described below.

17.1 Methodology

17.1.1 Identification of GRT Potential in Toronto

At the time of study, it was necessary that an eligible building be defined for green roof application. Green roof application was considered viable for (i) “flat roof” with slopes less than 2%; (ii) buildings with roof area great than 350 m²; (iii) areas other than underground parking garages or at grade level; and (iv) roofs with at least 75% roof area available. It was also assumed that the minimum thickness of a green roof was 150 mm.

After the review of other studies on green roofs’ benefits and costs, it was decided that a Geographic Information System (GIS) environment be utilized to identify buildings suitable for green roofs and analyze their associated benefits and costs in Toronto. Digital data of buildings, sewer networks, aerial photographs, sewershed boundaries, land use, roads, and spot elevations were provided by the City of Toronto’s Works and Emergency Services Department. These data were checked using digital orthophotographs supplied by the City and standardized in an ArcMap 9.0 format. Criteria used to select appropriate buildings include the available roof area (>60% of total roof area), age of buildings (for loading consideration), and type of buildings. For each land use (residential, commercial, and industrial), sample neighbourhoods are selected for GRT implementation. Using these, the total area available for installation of green roofs was aggregated using GIS over subwatersheds and watersheds.

17.1.2 Modeling of Stormwater Benefits

The approach to quantify the stormwater benefits of GRT in Toronto was based on the HSPF’s URF of GRT (Aqua Beech Inc. 2004) and the aggregation of these URF using GIS throughout the whole city. A URF was defined as the hydrological response of 1 ha test catchment, representing a

particular land use type, soil, and connectivity configuration with sewers, associated with a certain set of meteorological conditions. The URF of GRT for different land uses were simulated in HSPF using a pervious and an impervious land segments. The total runoff consists of the surface runoff and the net outflow from the infiltrated portion of the precipitation. Table 17.1 shows the land use categories used in the study and the annual runoff with and without green roofs. These URF were estimated by:

- adopting the URF generated in the Highland Creek case study if there was a corresponding land use category; or
- averaging the unit response functions generated in the Highland Creek case study if there were a few similar land use categories

The URF were applied across the City of Toronto by assigning predicted runoff, based on records of usable roof areas, for each land use in each subwatershed. GIS then enabled summing of the stormwater diversions for watersheds and for the whole City of Toronto to demonstrate the reduced demands on the stormwater drainage network hydrologically.

Three types of the stormwater benefits were considered:

- saving of other stormwater BMPs due to the application of green roofs;
- pollutant reduction; and
- reduction of receiving stream erosion.

After reviewing the best management practice bundles used in the Toronto Wet Weather Flow Master Plan (2003), three types of BMPs with higher costs might be substituted by green roofs in a generic manner. They were pervious pavements in residential highrise and commercial areas and underground storage in commercial area. Table 17.2 shows the unit costs of BMPs, which may be substituted by green roofs. This table was derived from the unit costs of BMPs including maintenance in the Toronto Wet Weather Flow Master Plan while the cost saving was the difference in unit costs between green roofs and other BMPs. The total area of green roofs and the unit cost savings of best management practices in Table 17.2 were used to determine the saving of other BMPs by green roofs.

The pollutant reduction benefit (P) and erosion benefit (E) were estimated using the following equations in the City of Waterloo's green roof study (Totten Sims Hubicki 2004).

$$\begin{aligned}
 P &= 0.5 * \$5,460 / ha \text{ of } greenroof \\
 E &= \$5,055 * ha \text{ of } greenroof
 \end{aligned}
 \tag{17.1}$$

Table 17.1 Unit response functions for runoff calculations.

Land Use Description	Runoff-No Greenroof, m ³ /ha	Runoff-With Greenroof, m ³ /ha
Commercial	6019	4913
Commercial Bigbox	6223	5067
Commercial Downtown	6019	4913
Commercial-industrial	5742	4912
Commercial-residential	4054	3480
Commercial Strip Mall	6210	5063
Educational/Institutional	2222	1827
Greenspace: parks	875	729
Industrial	5260	4757
Industrial Bigbox	5260	4757
Resource-Industrial	4571	4070
Prestige Industrial	4571	4070
Resource-Industrial	2723	2400
Open Space -golf	653	534
Open hydro corridor	875	729
Open Space/Park Land	875	729
Open TRCA land	430	339
Open Valley Lands	430	339
Park	875	729
Residential, open area	1254	1254
Residential High Density	2415	2415
Residential High Rise	3305	3060
Residential Low Density	1254	1254
Residential Medium Density	1897	1897
Residential, open area	1254	1254
Commercial	6019	4913
Government-Institutional, o	1254	1254
STP, Park, commercial-indust	2501	2205
Government-Institutional, z	1254	1254
Downsview airport	1386	1313
Highway Corridors	1078	1078
Roadways	1078	1078

Table 17.2 Comparison of unit costs of best management practices and estimation of cost saving of green roofs.

Type of BMPs	Total cost (\$/ha)*
Rooftop gardens for strip mall	65800
Rooftop gardens for big box	104800
Rooftop gardens for downtown	183780
Residential high density foundation drain disconnection	265010**
Residential highrise and institution pervious pavement/parking	398720**
Commercial underground storage	14400
Commercial pervious pavement in parking	151030**
Note: The above unit costs were used in the Toronto Wet Weather Study. *Total cost includes capital and O&M over 50 years. **based on 80% imperviousness	
GRT for mall and big box	85300
GRT for downtown	183780
Average GRT	134540
BMP with higher costs than GRT	Unit cost
Residential highrise and institution pervious pavement/parking	398720
Commercial underground storage	144040
Commercial pervious pavement in parking	151030
Green roofs	134540
BMP substitution	Unit cost saving (\$/ total ha)
Low estimate of BMP saving (Commercial underground storage)	9500
High estimate of BMP saving (Residential highrise pervious pavement)	264180
BMP substitution	Unit cost saving (\$/ha of GRT)
Low estimate of BMP saving (Commercial underground storage)	570***
High estimate of BMP saving (Residential highrise pervious pavement)	15850***
Note: *Total cost includes capital and O&M over 50 years per ha of drainage area. **Based on 80% imperviousness.***Assume 6% of the total area is green roof.	

17.1.3 Modeling of Combined Sewer Overflow Reduction Benefits

Combined sewer overflow (CSO) reduction benefit was estimated by determining the reduction of storage required for the control of CSO in Toronto. The City of Toronto has developed a continuous simulation model (i.e. QQS model) to simulate the CSO condition. Using the QQS model, it

was predicted that the total annual CSO volume to Black Creek, Humber River, West Don River, Massey Creek, Lower Don River, Western Beaches, Inner Harbour, Eastern Beaches, and Scarborough Lake would be 10,187,056 m³. The total CSO drainage area is 9100 ha. It was also recommended in the Toronto Wet Weather Flow Master Plan (2003) that underground storage of 258,955 m³ be required for the whole CSO area.

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

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

- the whole CSO area was assumed to be one sewershed for modeling purposes; and
- it was assumed that green roof could replace a minimum 5% and a maximum 15% of the total impervious area in the combined sewer area.

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

The SUDS model was first calibrated to produce the total annual CSO volume of 10,187,056 m³ (predicted by QQS). Table 17.3 summarizes the input and calibrated data for the SUDS model. The SUDS model was then used to simulate the following scenarios:

1. existing CSO condition without green roof;
2. existing CSO condition with 5% green roof;
3. existing CSO condition with 15% green roof;
4. future CSO condition with the Toronto Wet Weather Study's recommended underground storage;
5. future CSO condition with the Toronto Wet Weather Study's recommended underground storage and 5% green roof; and

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

The CSO benefit of green roofs was estimated by the reduction of underground storage for the same level of CSO control and a unit cost of \$1,340/m³ for underground storage (TWWFMP 2003).

Table 17.3 Input and calibrated data for the SUDS model.

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

17.2 Results and Discussions

17.2.1 Potential Green Roof Area

Using the methodology in Section 17.1.1, the potential green roof area in the City of Toronto was estimated to be 4984 ha or 8% of the total land area of Toronto (Table 17.4).

Table 17.4 Available areas for green roof implementation.

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

17.2.2 Stormwater Benefits

Based on a 4,984 ha of potential green roof implementation, the stormwater benefits were estimated to be:

- a BMP infrastructure saving from \$2.8 to \$79 million;
- a pollutant reduction benefit of \$14 million; and
- savings from erosion control measures of \$25 million

The total stormwater benefit could range from \$42 to \$118 million.

17.2.3 Combined Sewer Overflow Reduction Benefits

Based on the SUDS model simulation, the existing and future CSO volumetric controls were determined to be 17.4% and 59.7% respectively (Table 17.5). With 5% and 15% of potential green roofs, the existing CSO volumetric control could be improved by 17.8% and 18.8% respectively. To achieve the future 59.7% volumetric control, the reduction of underground storage due to 5% and 15% of potential green roofs were estimated to be 11,712 m³ and 34,752 m³ respectively. The total infrastructure saving for 5% and 15% of potential green roofs could be \$15.7 million and \$46.6 million respectively. If the proposed underground storage were to be built in addition to the proposed GRT in Toronto, the average annual number of CSO and the average annual percent of runoff controlled could be improved by 1.3 CSO reductions and 2.3% volumetric reduction respectively. These reductions of CSO could result in additional benefits such as reduction of beach closure and/or other environmental benefits.

Table 17.5 Analysis of CSO scenarios using the SUDS model.

Analysis Scenarios	Average annual number of CSO (#/year)	Average annual % of runoff volume controlled
1) Existing condition without the recommended underground storage	34.1	17.4
2) with 5 % green roof	34.0	17.8
3) with 15% green roof	33.5	18.8
4) Future condition with the recommended underground storage	16.6	59.7
5) with 5% green roof	16.2	60.8
6) with 15% green roof	15.3	63.0

Note: Existing condition refers to the current CSO situation without the Toronto Wet Weather Study's recommended underground storage.

Future condition refers to the future CSO situation with the Toronto Wet Weather Study's recommended underground storage.

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

17.3 Conclusions

Roofs in urban cities represent large impervious areas of unused space. With increasing concern over stormwater impacts after urbanization, these large areas can be retrofitted to provide stormwater management benefits. There are needs to quantify the stormwater benefits of greenroofs as more cities are in the process of setting up stormwater utilities. While there are many studies (based on either monitored sites or computer simulations) on the stormwater performance of GRT at individual buildings, there are few studies which determine their overall performance on a watershed basis. The study describes in this chapter is an attempt to model the stormwater benefits on a citywide basis using GIS and the HSPF model. The URF is a consistent approach to model the stormwater reduction of GRT on a watershed basis. It depends on the land use, soil, and connectivity configuration with sewers associated with a certain set of meteorological conditions. While the linear assumption of URF may not be appropriate for peak flow calculations, it may be acceptable for annual runoff volume calculations.

Modeling the combined sewer overflow reduction across the City of Toronto is challenging as the detailed QQS model requires a fair amount of time to develop. For preliminary analysis of combined sewer overflows, the SUDS has been found to provide consistent simulation results. The calibrated SUDS can be used to simulate combined sewer overflow reduction due to green roof implementation on a watershed basis.

Last but not least, GIS provides an efficient platform to screen potential greenroofs in different land uses.

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