

# Treatment Performance of an Extensive Vegetated Roof in Waterloo, Ontario

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Vegetated roof technologies are used as treatment measures to mitigate the effects of urban stormwater. A mass balance approach was used to assess the treatment performance of a vegetated roof located on the City Hall in Waterloo, Ontario. The vegetated and control roof sections were instrumented to measure precipitation, storage, and outflow for 18 storm events from June to October, 2006. Concentrations of suspended solids, total phosphorus (TP), and SRP (SRP) in precipitation and roof (vegetated and control) runoff were measured. A total of 155.6 mm of rain fell during the study period. The vegetated roof retained 64.5 mm (43.9%) of the total rainfall while the control roof retained approximately 5.1 mm (4.0%). For individual rain events, the vegetated roof retained an average of 3.5 mm (47.6%), while the control roof retained approximately 0.3 mm (4.7%). Water retention varied with storm size, season, and frequency of storm events. The vegetated roof retained 80.1% of precipitation for storm events  $\leq 3.5$  mm, and 34.9% for storm events  $> 3.5$  mm. TP and SRP concentrations from the vegetated roof were significantly higher than either the precipitation or runoff from the control roof.

*Key words:* green roof, source control, treatment performance, water quality, suspended solids, phosphorus

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## Introduction

The effects of stormwater runoff on the health of aquatic ecosystems (Novotony and Olem 1994), flooding (U.S. EPA 1999; Paul and Meyer 2001), and drinking water supplies (Marsalek et al. 2006) are well documented. Accordingly, there is increasing interest globally to implement sustainable urban drainage systems (SUDS) which employ a variety of source, conveyance, and end of pipe controls designed to reduce the volume of stormwater runoff (Marsalek and Chocat 2002; Graham et al. 2004). Vegetated roofs are increasingly being recognized as one source control measure that could be effectively implemented in both new and retrofit buildings to reduce runoff volume (TRCA 2006). Much of the innovation in vegetated roof technology, policy, and research (Ngan 2004; GRHC 2005; Cannata 2005; Getter and Rowe 2006) was initially developed in Germany and has subsequently been used to develop regulations in Europe that promote the application of vegetated roofs for stormwater management (Ngan 2004; GRHC 2006). In North America, however, several barriers (financial constraints, public awareness, quantifiable research, technical expertise, and industry standardization) limit broad application of vegetated roof technology as a viable source control measure (Getter and Rowe 2006).

The application and treatment performance of various vegetated roof technologies vary due to a range of climatic conditions which limit broader adoption of the technology (VanWoert et al. 2005). The implementation and effectiveness of vegetated roofs can vary at the city

and regional scale and especially between localities that have financial incentives for vegetated roof construction, i.e., Toronto, Chicago, and Portland (Peck and Goucher 2005; Getter and Rowe 2006). Consequently, there is a need to assess the treatment performance of vegetated roofs across varying geographical locations, and to develop and implement relevant policies for their use as source control measures. Such information is required to create vegetated roof building and performance standards, and to lower cost by adopting financial incentives or stormwater fee rebates that may encourage green roof industry growth.

Given the need to increase knowledge of the utility of vegetated roofs as a viable source control measure, the objective of this paper was to evaluate the treatment performance of an extensive vegetated roof located on a municipal building in the City of Waterloo, Ontario. The vegetated roof and a control roof were instrumented to measure precipitation inputs, storage, and runoff during 18 storm events that occurred between June 2 and October 22, 2006. The rates and magnitude of water storage and loss from the vegetated roof and a control roof are reported. Event mean concentrations and temporal variability of suspended solids (SS), total phosphorus (TP) and SRP (SRP) in precipitation and roof runoff are presented.

## Methods

### Description of Study Site

The vegetated and control roof are located on the Waterloo City Hall building in Waterloo, Ontario

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(43°28'02.16"N, 80°30'59.44"W). The vegetated roof was installed September, 2005 and covers an area of 1,650 m<sup>2</sup>. The section of vegetated roof monitored in this study has an area of 424.3 m<sup>2</sup>, defined by the drainage bay. Structurally, the vegetated roof consists of vegetation and growth medium, water retention fleece, a drainage layer, and a root resistant waterproof membrane. The vegetation layer is composed of a *XF 301* precultivated sedum-moss combination blanket composed of eight species of *Sedum spp.* and nylon mesh filled with a growth substrate. The growth substrate was a *XF xero terr* growing mix and consisted of a 35-mm mineral substrate composed of 60% porous materials (inert crushed brick, pumice, or expanded slate). The growing mix had a maximum particle size of 1 mm and was comprised of 25% fine washed sand, 14% weed free organic compost, and 1% dolomite (Xero Flor 2006a). A 12-mm *XF 158 D* water retention fleece (composed of synthetic fibres of polyester, polyamide, polypropylene, and acrylic) with a water holding capacity of 1,200 g/m<sup>2</sup> was located beneath the growth substrate (Xero Flor 2006b). An *XF 108 H* drainage filter fleece with water holding capacity of 800 g/m<sup>2</sup> of water was used to filter excess draining water. The bottom layer of the vegetated roof was a *XF 112* root resistant water membrane composed of a polyethylene sheet that prevented root and water penetration (Xero Flor 2006b). The vegetated roof was 6.2-cm thick, weighed 45.9 kg/m<sup>2</sup>, and held 28.8 L/m<sup>2</sup> when fully saturated. An irrigation system was not installed with the vegetated roof; rather, manual watering was included as part of the vegetated roof maintenance. The control roof (no vegetation) was covered with a bituminous single ply material, located approximately 30 m from the vegetated roof and drained an area of 246.61 m<sup>2</sup>.

### Meteorological Data

A meteorological station was located on the roof of the Waterloo City Hall. Wind speed was measured with a Wind Speed Smart Sensor ( $\pm 1.1$  m/sec [2.4 mph]). Ambient air temperature and relative humidity were measured with a Temperature/RH Smart Sensor. Precipitation was measured with a tipping bucket rain gauge ( $\pm 1.0$  % at up to 20 mm/hour). Data from all sensors were stored on an Onset Computer Data Logger at 5 minute intervals and downloaded with a USB cable to a laptop computer using HOBO weather station software.

### Flow Measurement and Sample Collection

To measure runoff, cylinder weirs were inserted into the drains of both the vegetated and control roofs and sealed with a marine sealant. The weirs were calibrated for a range of flow rates using a garden hose, and a corresponding weir height (cm) was measured with a 730 Bubble Module ( $\pm 0.015$  m) (ISCO 2003) and recorded by the ISCO 6700. These data were used to program the ISCO 6700 water sampler with Flow link software to

convert weir height to discharge.

Composite rainfall samples were collected in an acid-washed triple-rinsed 18-L bottle connected to a tipping bucket rain gauge. Samples of runoff from the vegetated and control roofs were collected with an ISCO 6700 automatic sampler. A two-part, flow-weighted program (Part A and B) was used to sample runoff. During Part A, six duplicate runoff samples were collected every 28 L, and during Part B, six duplicate samples were taken every 280 L.

The treatment performance of the vegetated roof was determined by measuring percent effluent flow reduction and percent concentration reduction using the following two equations:

$$\% \text{ effluent flow reduction} = 100(Q_i - Q_o)/Q_i \quad (1)$$

$$\% \text{ concentration reduction} = 100(C_i - C_o)/C_i \quad (2)$$

where  $Q_i$  = rainfall depth (mm),  $Q_o$  = runoff (mm),  $C_i$  = contaminant concentration,  $C_o$  = effluent contaminant concentration ( $\mu\text{g/L}$ ;  $\text{mg/L}$ ), and  $A$  = Area (m<sup>2</sup>) (Mulamootil et al. 1999).

### Water Quality

The temperature, conductivity, and pH of each sample was measured in the laboratory using an Orion 105A+ Conductivity Meter and Orion Conductivity Cell ( $\pm 2\%$ ) following Standard Method 2510 B (APHA et al. 1995). The pH of each sample was measured with a calibrated Orion 250A and Orion pH probe ( $\pm 2\%$ ) according to Standard Method 4500 H<sup>+</sup> (APHA et al. 1995). SS concentrations were determined by filtration (Standard Method 2540 D) (APHA et al. 1995).

TP concentration was determined using the stannous chloride ammonium molybdate colorimetric method after a persulfate digestion (Standard Method 4500 P B; D). To determine SRP concentrations, runoff and rainfall samples were filtered with a 0.45- $\mu\text{m}$  filter into a plastic vial and stored in a refrigerator (Standard Method 4500 P A). TP and SRP concentrations were measured using a Technicon AutoAnalyzer (APHA et al. 1995). The method detection limit was 1  $\mu\text{g/L}$ .

## Results and Discussion

### Stormwater Retention and Storage Capacity

During the study period, total monthly rainfall measured on the vegetated roof was 28.2, 136.4, 72.2, 113.2, and 113.0 mm for June, July, August, September, and October, respectively (Table 1). Total event precipitation ranged from 0.8 to 20.8 mm for the 18 rain events monitored from June 2, 2006 to October 22, 2006. Retention of stormwater on the vegetated roof varied from 0.0 to 100.0%, and from 0 to 23.0% on the control roof (Table 1). Overall, the vegetated roof retained 41.5% (64.5 mm

TABLE 1. Stormwater retention in the Waterloo vegetated and control roofs

| Storm event<br>(date in 2006) | Storm<br>Size<br>(mm) | Runoff                    |                         | Retention                 |                         |                          |                        | Difference:<br>stormwater<br>retention<br>(%) |       |
|-------------------------------|-----------------------|---------------------------|-------------------------|---------------------------|-------------------------|--------------------------|------------------------|-----------------------------------------------|-------|
|                               |                       | Vegetated<br>roof<br>(mm) | Control<br>roof<br>(mm) | Vegetated<br>roof<br>(mm) | Control<br>roof<br>(mm) | Vegetated<br>roof<br>(%) | Control<br>Roof<br>(%) |                                               |       |
| June 2–3                      | 12.6                  | 7.5                       | 12.5                    | 5.1                       | 0.1                     | 40.5                     | 0.8                    | 39.7                                          |       |
| June 8                        | 2.6                   | 0                         | 2.3                     | 2.6                       | 0.3                     | 100.0                    | 11.5                   | 88.5                                          |       |
| June 19                       | 0.8                   | 0                         | 0.7                     | 0.8                       | 0.1                     | 100.0                    | 12.5                   | 87.5                                          |       |
| June 19                       | 0.6                   | 0                         | 0.5                     | 0.6                       | 0.1                     | 100.0                    | 16.7                   | 83.3                                          |       |
| June 27                       | 0.8                   | 0                         | 0.8                     | 0.8                       | 0.0                     | 100.0                    | 0.0                    | 100.0                                         |       |
| June 28–29                    | 11.0                  | 2.6                       | 10.9                    | 8.4                       | 0.1                     | 76.4                     | 0.9                    | 75.5                                          |       |
| July 26                       | 7.8                   | 4.1                       | 7.6                     | 3.7                       | 0.2                     | 47.4                     | 2.6                    | 44.9                                          |       |
| August 14                     | 6.8                   | 1.1                       | 5.9                     | 5.7                       | 0.9                     | 83.8                     | 13.2                   | 70.6                                          |       |
| August 19                     | 4.0                   | 0.9                       | 3.8                     | 3.1                       | 0.2                     | 77.5                     | 5.0                    | 72.5                                          |       |
| August 25                     | 7.6                   | 1.5                       | 6.5                     | 6.1                       | 1.1                     | 80.3                     | 14.5                   | 65.8                                          |       |
| September 2–3                 | 13.0                  | 7.9                       | 12.3                    | 5.1                       | 0.7                     | 39.2                     | 5.4                    | 33.8                                          |       |
| September 18                  | 17.6                  | 7.3                       | 17.6                    | 10.3                      | 0.0                     | 58.5                     | 0.0                    | 58.5                                          |       |
| September 22–23               | 17.4                  | 16.9                      | 16.6                    | 0.5                       | 0.8                     | 2.8                      | 4.5                    | -1.7                                          |       |
| September 27                  | 20.8                  | 1.5                       | 19.4                    | 17.4                      | 1.4                     | 83.7                     | 6.7                    | 76.9                                          |       |
| September 30–October 1        | 13.8                  | 9.8                       | 13.7                    | 4.0                       | 0.1                     | 29.0                     | 0.7                    | 28.3                                          |       |
| October 3                     | 3.4                   | 3.3                       | 3.5                     | 0.1                       | -0.1                    | 2.9                      | -2.9                   | 5.9                                           |       |
| October 19                    | 5.8                   | 11.3                      | 5.8                     | -5.5                      | 0.0                     | -94.8                    | 0.0                    | -94.8                                         |       |
| October 22                    | 9.2                   | 16                        | 9.3                     | -6.8                      | -0.1                    | -73.9                    | -1.1                   | -72.8                                         |       |
| AVERAGE                       | 8.6                   | 5.2                       | 8.4                     | 3.5                       | 0.3                     | 47.6                     | 4.7                    | 42.9                                          |       |
| TOTALS:                       |                       |                           |                         |                           |                         |                          |                        |                                               |       |
|                               | June                  | 28.4                      | 10                      | 27.6                      | 18.4                    | 0.8                      | 64.8                   | 2.8                                           | 62.0  |
|                               | July                  | 7.8                       | 4.1                     | 7.6                       | 3.7                     | 0.2                      | 47.4                   | 2.6                                           | 44.9  |
|                               | August                | 18.4                      | 3.5                     | 16.2                      | 14.9                    | 2.2                      | 81.0                   | 12.0                                          | 69.0  |
|                               | September             | 68.8                      | 33.1                    | 66.8                      | 35.7                    | 2.0                      | 51.9                   | 2.9                                           | 49.0  |
|                               | October               | 32.2                      | 40.4                    | 32.3                      | -8.2                    | -0.1                     | -25.5                  | -0.3                                          | -25.2 |
|                               | Sample Period         | 155.6                     | 91.1                    | 150.5                     | 64.5                    | 5.1                      | 41.5                   | 3.3                                           | 38.2  |

of 155.6 mm) of total rainfall, while the control roof retained 3.3% (5.1 mm of 155.6 mm) of total rainfall; a difference of 38.2% (59.4 mm).

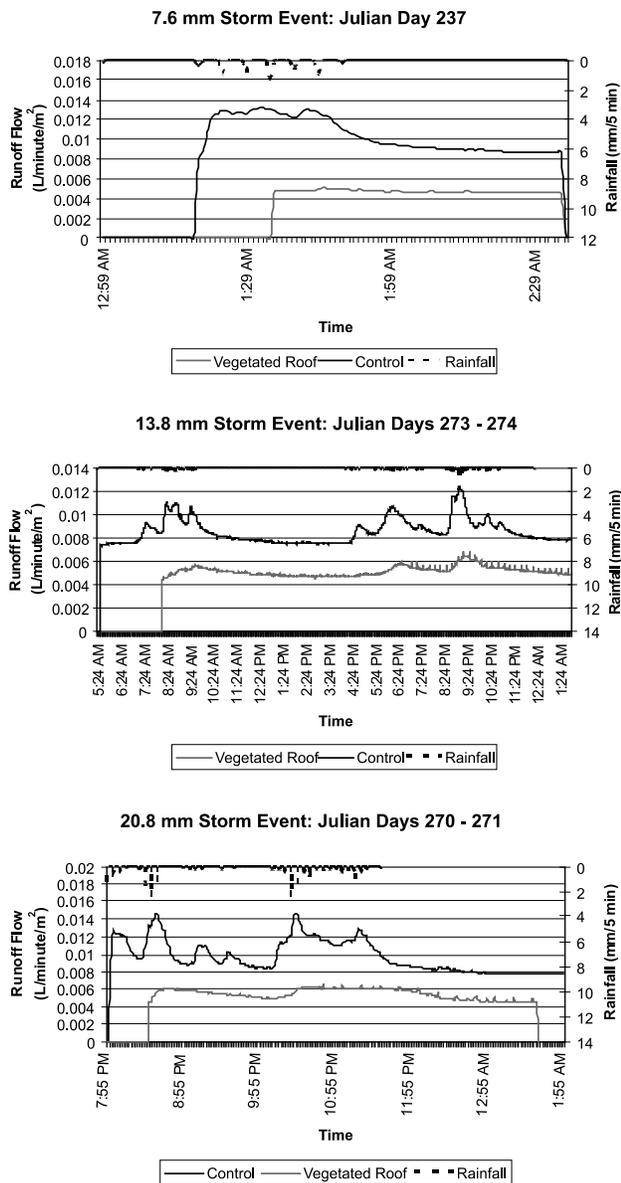
During storm events, storage capacity (the volume of water retained) of the vegetated roof ranged from 0 to 17.4 mm, and from 0 to 1.4 mm for the control roof. The mean vegetated roof storage capacity was 3.5 mm, and mean stormwater retention was 47.6%. The mean control roof storage capacity was 0.3 mm and mean stormwater retention was 4.7%. This represents an increase in average storage capacity and stormwater retention by the vegetated roof of 3.1 mm (42.9%). On three of four occasions, the vegetated roof retained 100% of rainfall during the month of June when a minimum of five antecedent dry days preceded the rain events. The largest storm event to be completely retained was 2.6 mm. Negative retention rates (runoff volume exceeds rainfall input volume) for the vegetated roof (-25.5%) and the control roof (-0.3%) were observed during the month of October when evapotranspiration rates were low and the vegetated roof was saturated from previous rain events.

Stormwater retention varied with storm size. Increases in storm size are related to increases in vegetated roof storage capacity, while increases in control roof storage capacity were smaller. For storm events  $\leq 3.5$  mm, the vegetated roof mean storage capacity was 1.0 mm, and for storm events  $> 3.5$  mm, storage capacity increased to 4.4 mm. The control roof storage capacity only increased

slightly when rain events exceeded 3.5 mm, with mean storage capacity increasing from 0.1 mm to 0.3 mm.

Several studies have reported mean or total storm water retention rates  $\geq 50\%$  (Jennings et al. 2003; Liu 2003; Connelly and Liu 2005; DeNardo et al. 2005; LaBerge et al. 2005; Liu and Minor 2005; Moran et al. 2005; Carter and Rasmussen 2006; Mentens et al. 2006; TRCA 2006). The higher retention rates reported in the literature compared with the measured retention rates of the Waterloo vegetated roof could be due to several reasons such as: growth medium thickness, substrate composition, rainfall distribution, temperature variability. VanWoert et al. (2005) noted that increasing growth medium thickness increases storm water retention rates. The Waterloo vegetated roof growth medium was 35-mm thick and had a 12-mm water retention fleece (total thickness, 47 mm) while the majority of previous studies were conducted on vegetated roof growth mediums with a thickness ranging from 75 to 150 mm. Results of the Waterloo study are comparable to a 20-mm vegetated roof in Michigan (Monterusso et al. 2004) and a 30-mm vegetated roof in Sweden (Bengtsson et al. 2005).

In addition to the physical and biological characteristics, several factors, including storm size, wetting history, and seasonality, influence stormwater retention of a vegetated roof. The Waterloo vegetated roof showed an inverse relationship between storm size and stormwater retention ( $p < 0.05$ ), which is consistent with the observations of several previous studies



**Fig. 1.** Hydrographs for precipitation events of varying magnitude.

(LaBerge et al. 2005; VanWoert et al. 2005; Carter and Rasmussen 2006). The wetting history of the vegetated roof influences the amount of stormwater retention (Moran et al. 2005). The results of the present study show increased stormwater retention with an increasing number of antecedent dry days ( $p < 0.05$ ) and are consistent with observations of Jennings et al. (2003) and Carter and Rasmussen (2006). Seasonal variability in rainfall, temperature, and evapotranspiration influenced the amount of stormwater retained on the Waterloo vegetated roof. Frequent rainfall, low temperatures, and lower rates of evapotranspiration during fall and winter months reduced retention rates as previously reported by Liu (2003).

## Lag Time, Peak Flow, and Runoff Flow Time

Hydrographs for precipitation events of varying magnitudes are presented to compare the lag time, peak flow, and runoff flow time for the Waterloo vegetated and control roofs (Fig. 1). The hydrographs demonstrate that the vegetated roof markedly increased runoff lag time, decreased runoff peak flow, and increased runoff release time relative to the control roof. The mean lag time for the vegetated roof was 74 minutes compared with 15 minutes for the control roof, which represents an increase in lag time by the vegetated roof of 79.7%. The mean peak flow of the vegetated roof was 0.0056 L/minute/m<sup>2</sup>, and the mean control roof peak flow was 0.0124 L/minute/m<sup>2</sup>. This translates to a reduction in peak flow of 54.8% or 0.0068 L/minute/m<sup>2</sup> by the vegetated roof. With decreased flow rates, the vegetated roof would sometimes increase the runoff release time by several hours. Average vegetated roof flow time was 26.02 h, and 19.8 h for the control roof, which constitutes an increase in average flow time by the vegetated roof of 6.2 h.

Overall, the rainfall response of the vegetated roof did not fluctuate as much as the control roof during a range of rainfall conditions. An increase in storm size and rain intensity showed greater changes in rainfall response from the control roof characterized by a reduction in lag time and an increased runoff peak flow. The rainfall response from the vegetated roof varied to a lesser degree because of the reduction in lag time and increase in peak flow.

Rainfall responses varied with storm size and roof type. Increases in storm size did not impact runoff lag time. However, storm size had an impact on peak flow from the control roof (the flow rate ranged from 0.0081 to 0.0140 L/minute/m<sup>2</sup>) but not on the vegetated roof (the flow rate ranged from 0.0047 to 0.0063 L/minute/m<sup>2</sup>). During rain events  $\leq 3.5$  mm, mean peak flow of the control roof was 0.0103 L/minute/m<sup>2</sup>, while it was 0.0048 L/minute/m<sup>2</sup> for the vegetated roof. During rain events  $> 3.5$  mm, mean peak flow from the control roof was 0.0127 L/minute/m<sup>2</sup>, and 0.0058 L/minute/m<sup>2</sup> from the vegetated roof. This represents a mean peak flow reduction of 54.3% by the vegetated roof. Storm size also influenced runoff flow time. Larger storms increased runoff flow times from both roofs. Storm events  $\leq 3.5$  mm had an average runoff flow time from the control roof of 7.2 h, and 7.97 h from the vegetated roof. For storm events  $> 3.5$  mm, average runoff flow time from the control roof was 21.9 h, and 29.03 hrs from the vegetated roof.

Several factors including soil moisture, substrate depth, storm size, rain intensity, air temperature, and relative humidity influence lag times and the magnitude of peak flow in vegetated roofs (TRCA 2006). Compared with the control roof, the runoff lag time of the Waterloo vegetated roof significantly increased ( $p < 0.05$ ), and the results were comparable to several other studies (Jennings et al. 2003; DeNardo et al. 2005; Liu and Minor 2005; Moran et al. 2005; VanWoert et al. 2005). Lag time

decreased significantly ( $p < 0.05$ ) with increasing rainfall intensity for the Waterloo vegetated and control roof. Compared with the control roof, the peak runoff flow was significantly reduced ( $p < 0.05$ ) in the Waterloo vegetated roof. The increase in vegetated runoff flow time was due to the dampening effect on rainfall infiltration through the multiple layers of the vegetated roof system.

### Vegetated Roof Water Quality Treatment

Despite the potential of vegetated roofs to improve stormwater quality (Johnston and Newton 1996; Peck et al. 1999), relatively few studies have examined the water quality treatment performance of vegetated roofs in Canada. The first studies of green roof water quality were conducted in Germany (VanWoert et al. 2005; Getter and Rowe 2006). Subsequent studies report vegetated roofs as a source of phosphorus and show they may not be an effective technology for metals removal in stormwater (Berndtsson et al. 2006; TRCA 2006). In the following, treatment performance of the Waterloo vegetated roof for selected water quality parameters are presented and compared with the results of previous studies.

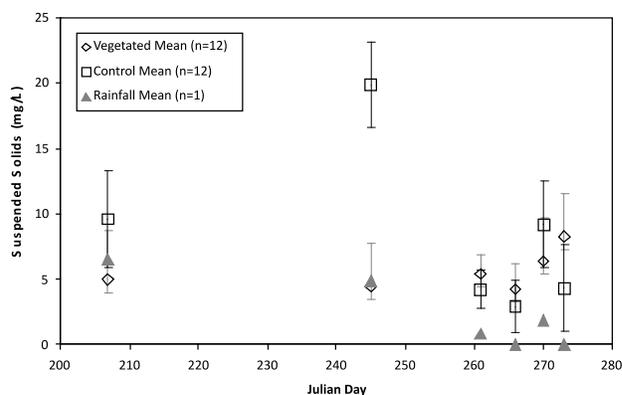
### Total Dissolved Solids

The average total dissolved solids (TDS) in vegetated roof runoff was significantly greater than in either rainfall or control roof runoff ( $p < 0.05$ ). No other previous studies have reported TDS concentrations in vegetated roof runoff. The elevated TDS concentrations are likely related to the presence of dissolved materials from both the vegetated roof growth medium and fertilizer application.

The highest concentration of TDS in runoff was measured from the vegetated roof during the study period. The mean TDS concentration in runoff from the vegetated roof was 0.131 mg/L with a range of 0.036 to 0.235 mg/L. The mean TDS concentration in control roof runoff was 0.035 mg/L with a range of 0.003 to 0.144 mg/L. The mean TDS concentration of rainfall was 0.013 mg/L and ranged from 0.009 to 0.024 mg/L. During individual storm events, TDS concentrations in vegetated roof runoff typically increased, and control roof runoff concentrations decreased over the sampling period of the storm event.

### Suspended Solids

Temporal variability of SS measured in rainfall and runoff from the vegetated and control roof is shown in Fig. 2. Average SS concentration in the control roof was 8.3 mg/L with a range of  $\leq 0.1$  to 66.0 mg/L over the sample period. The vegetated roof had a lower mean SS concentration of 5.6 mg/L with a range of  $\leq 0.1$  to 15.0 mg/L. Average vegetated roof SS concentration was 32.5% (2.7 mg/L) less than the control roof average SS concentration. Rainfall had the lowest mean SS



**Fig. 2.** Suspended solids concentration (mean  $\pm$  standard deviation) in rainfall and runoff from the vegetated and control roofs.

concentration of 2.3 mg/L, which ranged from  $\leq 0.1$  to 6.5 mg/L.

Total suspended solids (TSS) concentrations were lower in runoff from the vegetated roof than the control roof, but not significantly different. Levels of TSS measured in runoff from the Waterloo vegetated roof are comparable to a previous study which reported an 85.4% reduction in TSS concentration in vegetated roof runoff (TRCA 2006). The lower TSS concentrations in the vegetated roof runoff are likely due to the filter cloth layer in the Waterloo vegetated roof system which is designed to prevent the loss of organic material from the growth medium.

### Total and Soluble Reactive Phosphorus

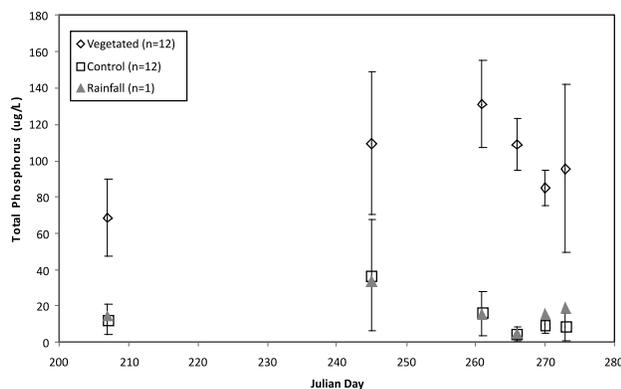
Temporal variation in TP concentration measured in the rainfall and in runoff from a vegetated and a control roof is illustrated in Fig. 3. The mean TP concentration of vegetated roof runoff was over five times greater than that in rainfall, and four times greater than in runoff from the control roof. The average TP concentration of the vegetated roof runoff was 99.8  $\mu\text{g/L}$ , with a range from 33.8 to 204.8  $\mu\text{g/L}$ . The average TP concentration in runoff from the control roof was 15.4  $\mu\text{g/L}$  and ranged from 1.0 to 102.9  $\mu\text{g/L}$ . In rainfall, the average TP concentration was 16.9  $\mu\text{g/L}$  and ranged from 4.5 to 33.3  $\mu\text{g/L}$ . During individual storm events, TP concentrations from the vegetated and control roofs varied temporally over the storm event. Concentrations of TP in runoff from the vegetated roof were quite variable depending upon the timing and duration of the storm event. During storm events, TP concentrations in runoff from the control roof fluctuated but typically decreased over time.

Temporal variation in SRP measured in the rainfall and in runoff from a vegetated and a control roof is illustrated in Fig. 4. In runoff from the vegetated roof, the mean SRP concentration was 40.0  $\mu\text{g/L}$ , with a range from 7.7 to 98.0  $\mu\text{g/L}$ . A majority of runoff samples from the control roof had SRP concentrations below the method detection limit of 1  $\mu\text{g/L}$ . The mean SRP

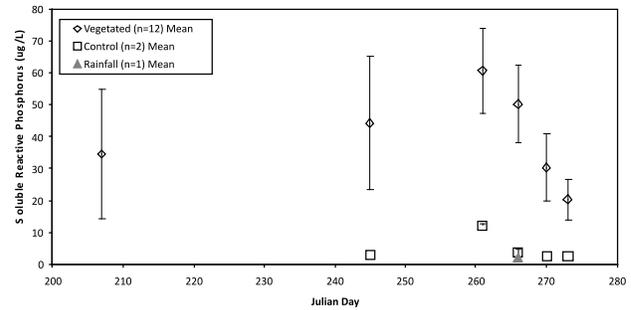
concentration of the control roof runoff was 3.8 µg/L, with a range from 1 to 12.5 µg/L. The concentration of SRP in rainfall was below the detection limit of 1 µg/L with the exception of one storm event when it was 2 µg/L. Overall, SRP concentrations in runoff from the vegetated roof were ten times greater than that measured in runoff from the control roof, and twenty times greater than concentrations measured in rainfall.

TP and SRP concentrations in runoff from the Waterloo vegetated roof were significantly greater than in either the rainfall or the control roof runoff ( $p < 0.05$ ). Levels of TP measured in the present study exceed the provincial water quality objective for TP (30 µg/L; OMEE 1999). However, concentrations of TP in the control roof were comparable to levels measured in rainfall and were well below the limits set by the provincial water quality objectives. The results of the present study are comparable to previous studies (Moran et al. 2005; Berndtsson et al. 2006; TRCA 2006) and demonstrate that the Waterloo vegetated roof is a source of both TP and SRP.

The primary source of phosphorus in the vegetated roof is likely related to the biogeochemical nature of the growth medium and the application of fertilizer (Jennings et al. 2003; Berndtsson et al. 2006; TRCA 2006). The Waterloo vegetated roof growth medium consisted of 14% organic material, and fertilizers (3.5% P<sub>2</sub>O<sub>5</sub>) were applied June 9, 2006 (Xero Flor 2006b). Fertilizers were used in the maintenance of the Waterloo vegetated roof to help establish plant growth and coverage (Berndtsson et al. 2006). Both TRCA (2006) and Berndtsson et al. (2006) recommend the use of slow release fertilizers to limit nutrient input and to reduce phosphorus leaching. Older established vegetated roofs with limited nutrient input have been shown to retain phosphorus. In Germany, Köhler and Schmidt (2003) documented phosphorus retention of 67% by a 15-year-old vegetated roof. In addition, studies indicating the potential of a vegetated roof as a phosphorus source have reported decreases in phosphorus concentrations over time. TRCA (2006) reported a 214% decrease in phosphorus from a vegetated roof over a one year study period.



**Fig. 3.** Total phosphorus concentration (mean ± standard deviation) in rainfall and runoff from the vegetated and control roofs.



**Fig. 4.** SRP concentration (mean ± standard deviation) in rainfall and runoff from the vegetated and control roofs.

## Conclusions

The wet weather performance of an extensive vegetated roof was evaluated in Waterloo, Ontario. The results of the study provide a better understanding of the utility of vegetated roofs as a source control best management practice for stormwater. The Waterloo vegetated roof had an average stormwater retention rate of 47.6% compared with 4.7% in the control roof. Mean storage capacity of the vegetated roof was over ten times greater than for the control roof.

Storm size, the number of antecedent dry days between storms, and seasonal changes in temperature, rainfall, and evapotranspiration influenced stormwater retention rates. The vegetated roof had an increased lag time, reduced peak flow, and extended runoff flow time compared with the control roof. Rain intensity and storm size influenced rain responses from both roof types. The vegetated roof did not significantly improve water quality and was a source of TP and SRP compared with the control roof. Phosphorus loss from the vegetated roof exceeded limits set by provincial water quality objectives. Sources of TP and SRP in vegetated roof runoff are likely due to the organic content present in the vegetated roof growth medium and fertilizer application. The Waterloo study demonstrates the utility of vegetated roofs as a source control measure to enhance stormwater retention. The application of vegetated roofs should be considered particularly when new buildings are being designed for infill projects in urban areas with little stormwater infrastructure.

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## References

- APHA, AWWA, WEF. 1995. Standard Methods for the Examination of Water and Wastewater. Jointly published by the American Public Health Association, American Water Works Association and Water Environment Federation. Washington, D.C.
- Bengtsson L, Grahn L, Olsson J. 2005. Hydrological function of a thin extensive green roof in southern Sweden. *Nordic Hydrology* 36:259–268.
- Berndtsson JC, Emilsson T, Bengtsson L. 2006. The influence of extensive vegetated roofs on runoff water quality. *Sci. Tot. Environ.* 355:48–63.
- Cannata P. 2005. We can still win the green roof race. *Municipal World* 115:9–10.
- Carter TL, Rasmussen TC. 2006. Hydrologic behaviour of vegetated roofs. *J. Am. Water Resour. Assoc.* 42:1261–1274.
- Connelly M, Liu K. 2005. Green roof research in British Columbia – An Overview. *In* Greening rooftops for sustainable communities. Washington, D.C., May 4–6, 2005.
- DeNardo JC, Jarrett AR, Manbeck HB, Beattie DJ, Berghage RD. 2005. Stormwater mitigation and surface temperature reduction by green roofs. *American Society of Agricultural Engineers* 48:1491–1496.
- Getter KL, Rowe DB. 2006. The role of extensive green roofs in sustainable development. *Hortscience* 41:1276–1285.
- Graham P, Maclean L, Medina D, Patwardhan A, Vasarhelyi G. 2004. The role of water balance modeling in the transition to low impact development. *Water Qual. Res. J. Can.* 39:331–342.
- GRHC (Green Roofs for Healthy Cities and The Cardinal Group Inc). 2005. Green Roof Design 101 Introductory Course: Participant's Manual. Unpublished.
- GRHC (Green Roofs for Healthy Cities and The Cardinal Group Inc). 2006. Green Roof Policy Development Workshop: Participant's Manual. Unpublished.
- Isco Inc. 2003. 730 Bubbler Module: Installation and Operation Guide. Unpublished.
- Jennings G, Hunt B, Moran A. 2003. A North Carolina field study to evaluate green roof runoff quantity, runoff quality and plant growth, p. 446–460. *In* ASAE Annual International Meeting. Las Vegas, Nevada, July 27–30, 2003.
- Johnston J, Newton J. 1996. Building green: A guide to using plants on roofs, walls and pavements. The London Ecol. Unit, London.
- Köhler M, Schmidt M (Cacanindin, S. transl). 2003. Study of an extensive green roof in Berlin, Part III: retention of contaminants. Available on-line at: [www.roofmeadow.com/water\\_quality.htm](http://www.roofmeadow.com/water_quality.htm) [Accessed: March 5, 2006].
- LaBerge K, Worthington K, Mulvaney P, Bolliger R. 2005. City of Chicago green roof test plot study: Stormwater and Temperature results. *In* Greening Rooftops for sustainable communities. Washington, D.C., May 4–6, 2005.
- Liu K. 2003. Engineering performance of rooftop gardens through field evaluation. NRCC-46294, Institute for Research in Construction. Ottawa, Canada
- Liu K, Minor J. 2005. Performance evaluation of an extensive green roof. *In* Greening rooftops for sustainable communities. Washington, D.C., May 4–6, 2005.
- Marsalek J, Chocat B. 2002. International report: Stormwater management. *Water Sci. Technol.* 46:1–17.
- Marsalek J, Watt WE, Anderson BC. 2006. Trace metal levels in sediments deposited in urban stormwater management facilities. *Water Sci. Technol.* 53:175–183.
- Mentens J, Raes D, Hermy M. 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21<sup>st</sup> century? *Landscape and Urban Planning* 77: 217–226.
- Monterusso M, Rowe DB, Rugh CL, Russell DK. 2004. Runoff water quantity and quality from green roof systems. *Acta Horticulturae* 639:369–373.
- Moran A, Hunt B, Smith J. 2005. Hydrologic and water quality performance from green roofs in Goldsboro and Raleigh, North Carolina. *In* Greening rooftops for sustainable communities. Washington, D.C. May 4–6, 2005.
- Mulamoottil G, McBean EA, Rovers F. 1999. Constructed wetlands for the treatment of landfill leachates. Lewis Publishers, Boca Raton, FL.
- Ngan G. 2004. Green roof policies: tools for encouraging sustainable design. Available on-line at: [www.gnla.com](http://www.gnla.com) [Accessed: January 25, 2006].
- OMEE (Ontario Ministry of Environment and Energy). 1999. Water management policies, guidelines and provincial water quality objectives of the ministry of environment and energy. Queen's Printer for Ontario, Ontario.
- Paul M, Meyer J. 2001. Streams in the urban landscape. *Annual Review of Ecological Systems* 32:333–365.
- Peck SW, Callaghan C, Peck and Associates, Bass B, Kuhn ME. 1999. Greenbacks from green roofs: Forging a new industry in Canada. CMHC, Toronto.
- Peck, SW, Goucher D. 2005. Overview of North American policy development and the policy development process. *In* Greening rooftops for sustainable communities. Washington, D.C., May 4–6, 2005.
- TRCA (Toronto and Region Conservation Authority). 2006. Evaluation of an extensive green roof, York University, Toronto, Ontario, Final Draft. Unpublished.
- U.S. EPA (United States Environment Protection Agency). 1999. Preliminary data summary of urban storm water best management practices. Federal Printer for the United States, Washington, D.C.
- VanWoert ND, Rowe DB, Andresen JA, Rugh CL, Fernandez RT, Xiao L. 2005. Green roof stormwater retention: Effects of roof surface, slope, and media depth. *J. Environ. Qual.* 34:1036–1044.
- Xero Flor. 2006a. Sedum Mix (XF301) 3-Part Long form Specification. Available on-line at: <http://www.xeroflora.com/index.htm> [Retrieved January 6, 2007].
- Xero Flor. 2006b. Xero Flor Canada Product Information. Xero Flor Canada Ltd, Brantford, ON.

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