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Evaluation of Green Roofs for Runoff Retention, Runoff Quality, and Leachability

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This three-year study evaluates the quantity and quality of runoff from an extensive green roof on a multistory building in Toronto. Laboratory physical, chemical, and leachate analyses of eleven commercially available green roof growing media were also undertaken to help identify the potential influence that the growing media may have on runoff chemistry. Continuous precipitation and runoff data collected over 18 months outside of the winter period indicated that the green roof discharged 63% less runoff than a neighbouring conventional modified bitumen roof. Runoff volumes from the green roof averaged 42% less than the conventional roof in April and November, and between 70 and 93% less during the summer months. Water samples were collected from both roofs during 21 rain events in 2003 and 2004 and analyzed for general chemistry (e.g., pH, total suspended solids), metals, nutrients, bacteria (n = 16), and polycyclic aromatic hydrocarbons (n = 18). Loads of most chemical variables in green roof runoff were lower than from the conventional roof. Exceptions included constituents such as calcium, magnesium, and total phosphorus, which were either naturally present in the media or were added to promote plant growth. Total phosphorus concentrations in green roof runoff were significantly higher than the conventional roof (α = 0.001), and regularly exceeded the Ontario receiving water objective (0.03 mg/L). Phosphorus concentrations fell significantly after the first year of monitoring (α = 0.001), suggesting that the nutrient is being leached from the media. Chemical analyses of green roof growing media showed that levels of most constituents were similar to or lower than typical background concentrations for agricultural soils in Ontario. However, leachate concentrations from several media exceeded receiving water standards for phosphorus, aluminum, copper, iron, and vanadium. This study highlights the importance of engineering green roof media to minimize leaching of nutrients and other contaminants while maintaining their ability to support plant growth.

***Key words*: green roof, phosphorus, growing media, runoff quality**

Introduction

Controlling runoff at source has become a cornerstone of good stormwater management practice both in older built-up areas and new developments within the Greater Toronto Area (GTA). Green roofs offer significant advantages over other source controls because they can be installed in dense urban areas where space for structural practices is not available, and they function well in areas where low permeability soils may limit the effectiveness of stormwater infiltration technologies such as bioretention areas or permeable pavements. In addition to their ability to retain stormwater, and their obvious aesthetic qualities, green roofs offer numerous advantages over traditional roofs, including energy conservation (Onmura et al. 2001; Liu and Baskaran 2005), mitigation of the urban heat island effect (Bass et al. 2003; Wong et al. 2003), and improved urban biodiversity (Brenneisen 2003). However, these advantages come at a cost as green roofs in North America are typically more expensive to construct than conventional roofs, and structural modifications may be needed to support the additional weight of a vegetated roof (TRCA 2007). To help overcome this barrier, some GTA municipalities have implemented or are currently exploring the possibility of implementing green roof incentive programs.

Most research on the stormwater management benefits of green roofs has focused on the ability of green roofs to attenuate peak flows and reduce the total volume of stormwater runoff by retaining rain water in the growing media. In a comprehensive review of international green roof literature on rainfall runoff relationships, Mentens et al. (2006) reported a median annual retention rate of 45% for extensive green roofs with substrate depths between 3 and 14 cm (median: 10 cm). Most North American studies indicate runoff retention during the growing season of at least 60% on roofs with gentle slopes (<10%) and growing medium depths of 6 cm or more (Hutchinson et al. 2003; Rowe et al. 2003; Carter and Rasmussen 2006; Getter et al. 2007; Hathaway et al. 2008). These rates typically decline to roughly 40% on growing media between 2- and 4-cm deep (Liesecke 1998; Russell and Schickedantz 2003), with some exceptions (Rowe et al. 2003). Getter et al. (2007) reported a 10% rise in mean retention associated with a decrease in roof slope from 25 to 2%. Retention of rainfall has also been shown to extend the duration of flow and reduce peak flow rates by between 50 and 85% (e.g., Hutchinson et al. 2003; Johnston et al. 2004; Liu and Minor 2005; Hathaway et al. 2008), thereby reducing the erosive power of stream flows.

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In studies of the stormwater management benefits of green roofs, the quality of runoff has received much less attention than the volume and rate of runoff. The main sources of contaminants on roofs are atmospheric deposition and leaching from roofing materials. Several researchers have shown that conventional roof runoff may contain elevated levels of polycyclic aromatic hydrocarbons (PAHs), organic halogens, and heavy metals such as lead, copper, zinc, and cadmium (Thomas and Greene 1993; Clark et al. 2001; Van Metre and Mahler 2003). Green roofs would normally be expected to discharge fewer of these contaminants than conventional roofs, but there are few published studies that have quantified this difference for metals, hydrocarbons, and other organic compounds.

In a field study of a green roof in Germany, Forster and Knoche (1999) reported higher heavy metal concentrations in green roof runoff than in rainwater, but lower concentrations of PAHs. The difference in metal concentrations was attributed to leaching from unprotected metal surfaces around the roof. Studies of nutrients in green roof runoff in North Carolina (Hathaway et al. 2008) and Oregon (Hutchinson et al. 2003) identified phosphorus as a potential concern. In both studies, green roof runoff concentrations of phosphorus were well above receiving water standards. However, Hathaway et al. (2008) did not find a statistically significant difference between green roof and conventional roof nutrient loads. Composted cow manure, which made up 15% of the growing medium, was identified as a likely source of nutrients in the North Carolina study. In a study of four extensive green roofs in southern Sweden, Berndtsson et al. (2006) also found elevated levels of phosphorus, which they suggested was likely a result of fertilizer application. The green roofs in this study were also a source of zinc, copper, and lead, although concentrations were well below those typical of urban runoff.

In a follow-up to the North Carolina study, Hunt et al. (2006) postulated a relationship between nutrient concentrations in runoff and the type and quantity of compost in the growing media. Concentrations were particularly elevated when the compost contained cow manure. In the same study, laboratory testing of 3 growing media showed a decrease in total nitrogen with 10 applications of synthetic rainwater over a 10-week period, but there was no trend in total phosphorus. Sampling at field sites also showed no statistically significant trend in phosphorus or nitrogen compounds.

The primary purpose of the present study was to evaluate the impact of rooftop green roofs on the quantity and quality of stormwater runoff from a typical green roof installation under climate conditions characteristic of the GTA. Laboratory physical, chemical, and leachate analyses of several commercially available green roof growing media were also undertaken to help identify potential concerns about the quality of green roof runoff.

Materials and Methods

Study Site

The monitoring study was conducted on the roof of a multistory building at York University in the City of Toronto (Fig. 1). The study area consisted of two surfaces: (i) a 131-m^2 shingled, modified bitumen roof, hereafter referred to as the conventional roof, and (ii) a 241-m^2 green roof vegetated with wildflowers. Both roof surfaces had a 10% slope. Installed in 2002, the 14-cm growing medium on the green roof was composed of crushed volcanic rock, compost, blonde peat, cooked clay, and washed sand. It was designed to be light weight, retain water, and resist compaction. The green roof irrigation system came on every night during the first summer (June to October), and thereafter, when soil moisture content fell below 20%, or on average, once every two days.

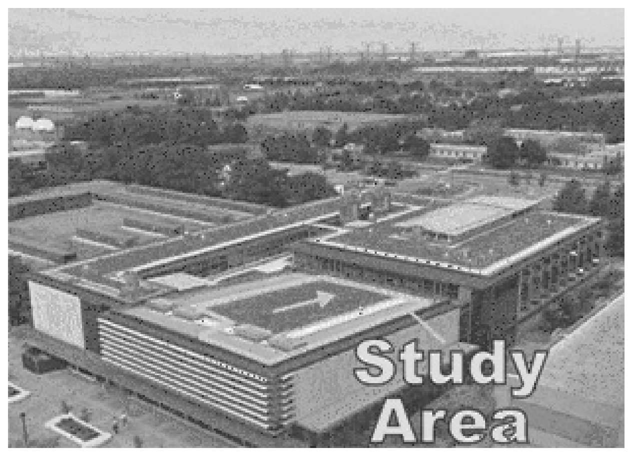

Fig. 1. Study area on the York University Computer Science Building.

Field Monitoring

Figure 2 shows the location of monitoring instruments. Measurements included precipitation, flow, water quality, soil moisture, relative humidity, air temperature, and the temperature of the growing medium. Precipitation at the site was measured using a tipping bucket rain gauge. Nearby Atmospheric Environment Service (AES) stations provided back-up data on rain or snow conditions when site data were not available (Environment Canada 2006).

The green roof and conventional roof drained to separate eaves troughs at the bottom of the sloped study area. Runoff from the green roof and conventional roof were monitored continuously with two magnetic induction instruments (MAGmeters). Flow rates were recorded at 1 minute intervals to a measurement accuracy of ±0.5%.

Green roof and conventional roof runoff samples were collected for water quality analysis using two automated water samplers. The sampling interval was selected based on the average duration of runoff. The conventional roof and green roof samplers collected samples at 5 and 10 minute intervals, respectively. Atmospheric deposition during wet and dry weather was monitored using an open polyethylene bag lining a 48-cm diameter bucket. Samples were collected after rain events. All samples were preserved and submitted according to Ontario Ministry of the Environment (OMOE) guidelines (OMOE 2003) and analyzed at OMOE laboratories in Toronto. The runoff samples were analyzed for general chemistry (e.g., total suspended solids [TSS], alkalinity), nutrients (phosphorus and nitrogen compounds), metals, bacteria, and PAHs. The precipitation samples were analyzed for general chemistry and nutrients and metals.

Samples were analyzed in the laboratory following principles outlined in *Standard Methods* (APHA et al. 1998). Briefly, metals were unfiltered totals analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Nutrients were determined by colourimetry. *Escherichia coli* was determined through membrane filtration. TSS was determined by gravimetry using a 1.5- to 2.0-micron glass fibre filter. Analysis of PAHs was conducted by liquid/liquid extraction followed by gas chromatography–mass spectrometry.

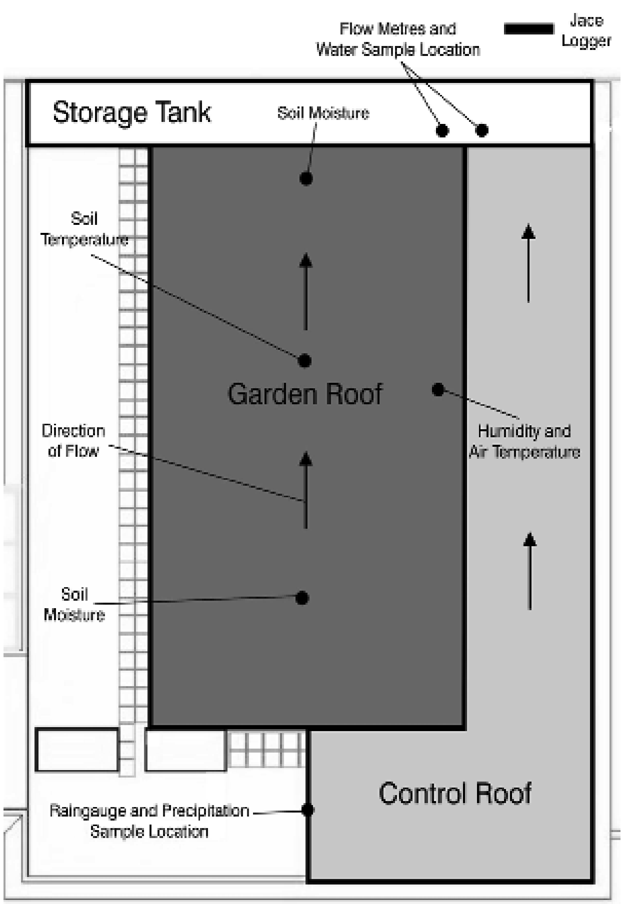

Fig. 2. Schematic of monitoring setup.

Data Analysis

The water quality data were graphically analyzed and found to be log normally distributed; therefore, the mean and confidence intervals were performed on log-transformed data sets. Concentrations of variables below laboratory detection limits were represented by half the detection limit. Confidence intervals are not presented for variables with detection frequencies of less than 50% due to the bias caused by the substituted data. Detection frequencies provide the basis for comparison of these variables.

Unit area loads from the conventional roof and green roof were calculated separately for the sampled and unsampled events, and subsequently summed to arrive at an overall load calculation for the two years of water quality sampling (2003 to 2004). The sampled event loads represented the sum of the individual loads for each sampled event ($n = 21$). For sampled events, each individual event load represents the event runoff volume multiplied by the sampled concentration for the same event. The unsampled event loads for each of the two sampling years (2003 and 2004) were calculated as the total measured runoff volume for the unsampled events multiplied by the mean concentration for the sampled events. This method assumes that the mean concentration for the sampled and unsampled events is similar, which is reasonable given that the variables analyzed did not exhibit a relationship between event concentration and event size. Including the unsampled events allowed for several small rain events, for which there was little or no green roof runoff, to be represented in the overall load calculation.

Analyses of Green Roof Growing Media

Chemical (bulk soil and leachate) and physical analyses were conducted on 11 green roof growing media currently available commercially in order to determine the potential impact of growing media constituents on runoff chemistry. Analyses of the physical and chemical quality of growing media were conducted by a certified private laboratory (Entech) in Mississauga, Ontario. Variable groups analyzed included general chemistry, metals (EPA 3050B/200.7), and nutrients (EPA 351.2/365.1) using standard United States Environmental Protection Agency methods (U.S. EPA 1983). Grain size distribution was determined by passing the samples through a 2-mm screen. The material that did not pass through the screen was deemed to be gravel. The material that passed through the screen was analyzed using a hydrometer to determine the percentages of sand, silt, and clay that made up the remaining portion of the sample.

Leachate tests were also conducted on the 11 growing media. These tests were not intended to mimic actual runoff quality from an established green roof since the media samples were not planted or layered in the same way as they would have been on an actual roof.

Instead, the purpose of the tests was to identify the types of pollutants that may be leached from the media, their concentration relative to surface water criteria, and the extent to which leachability of pollutants may vary among the growing media. Each media sample was leached four times in order to identify the chemical constituents that may be susceptible to leaching, and the general direction in which pollutant concentrations may be expected to change over time.

The laboratory leaching procedure was based a standard waste management leachate method (EPA 1311) (U.S. EPA 1996) with minor modifications to suit the objectives of this study. A minimum of 100 grams of each sample was placed in an extractor vessel made of inert material (polytetrafluoroethylene for inorganics, type 316 stainless steel for organics), and a quantity of reagent water (pH of 6) equal to 20 times the weight of the solid phase was added. The vessel was placed in a rotary agitation device and rotated end-over-end at 30 ± 2 rpm for 18 ± 2 hours, with ambient temperature maintained at 23 ± 2°C. For media with particles greater than 1 cm in its narrowest dimension, particle size reduction was performed prior to agitation. Following agitation, the liquid and solid phases were separated using a borosilicate glass fibre filter with a pore size of 0.6 to 0.8 µm. This process was repeated on the same sample three more times. The first and fourth liquid extracts were collected and analyzed for general chemistry, nutrients (EPA 353.1, 353.2, 350.1; EPA 365.1) (U.S. EPA 1983), and metals (EPA 200.7, 200.15, 3005) (U.S. EPA 1983, 1994, 1996 [respectively]) by Entech laboratories.

Results

Hydrology

Runoff and precipitation were monitored during 154 runoff events from May to November 2003, June to November 2004, and April to August 2005. An event consisted of all rainfall from the start of the storm until runoff from the conventional and green roofs ceased, including those for which there was no green roof runoff. Data were not available during the winter from January to March.

Compared with regional climate normals (1971 to 2000), rainfall over the monitoring period was 19% greater and temperatures were on average 2.3°C warmer. The 2003 and 2005 monitoring seasons were the wettest, with roughly 30% more rainfall than the 30 year average. By contrast, the 2004 season was 2% drier and average temperatures were only 0.6°C warmer than the historical average.

Figure 3 presents air temperature, precipitation, and retention rates by month for the study period. Overall, the green roof discharged 63% less runoff than the conventional roof. Runoff retention rates were lower in 2003 than in later years because of relatively large amounts of precipitation in September and November of that year, and more frequent irrigation, both of which adversely influenced the green roof's capacity to retain water. During 2003, the green roof retained only 54% of precipitation, while in 2004 and 2005 approximately 75% of precipitation was retained. The conventional roof retained 2% of total rainfall over the study period.

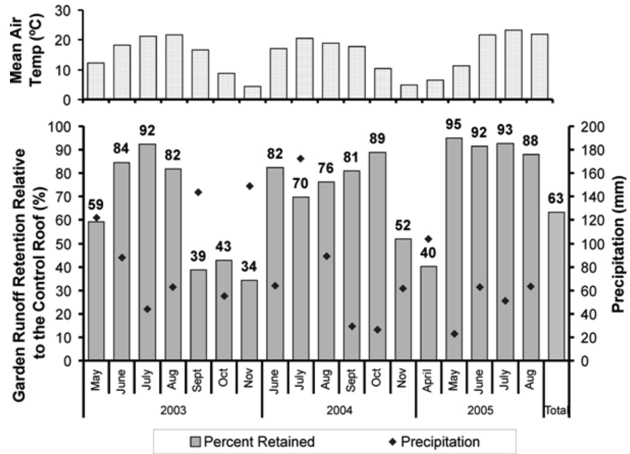

Fig. 3. Mean monthly air temperature, precipitation and the percent of runoff retained by the green roof relative to the conventional roof.

Rainfall volumes, evapotranspiration rates, and antecedent moisture content were the key factors explaining monthly and event-by-event variations in green roof retention rates. As the days became shorter and air temperatures dropped, the green roof retained less water. Retention rates for summer events were between 78 and 85%, compared with spring and fall retention rates of between 39 and 64% (Fig. 3). Figure 4 illustrates the declining capacity of the green roof to retain water and reduce peak flows as event size increased. Rainfall in November and April tended to be less effectively retained because evapotranspiration rates are much lower during these months. Retention rates were also generally lower during the second of two back-to-back events due to higher antecedent moisture conditions.

Water Quality

Precipitation and runoff water quality analysis was completed for 21 events from September to November, 2003, and June to November, 2004. Table 1 presents the quality of dry and wet precipitation over the monitoring period. The rain was relatively acidic (pH of 5.9) and contained low levels of dissolved solids. Phosphorus, nitrogen, and metal concentrations were generally low, although maximum values indicate that atmospheric contributions can be a significant source of these constituents.

Table 2 presents detection frequencies, mean concentrations, 95% confidence intervals, and differences between the conventional and green roofs at the indicated significance level. The precipitation was

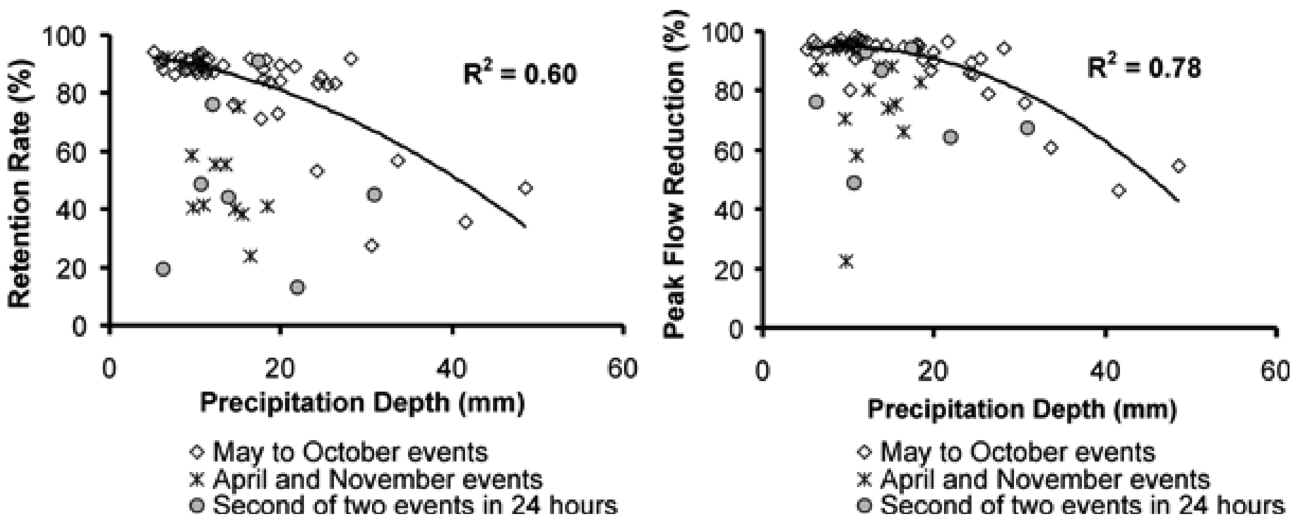

Fig. 4. Relationships between precipitation depths and retention rates for events greater than 5 mm. Trend lines and R^2 values relate to events occurring between May and October.

TABLE 1. Characterization of wet and dry precipitation

Variable	*Units*	*MDL* [a]	*n*	*Minimum*	*Maximum*	*Median*
Conductivity	µS/cm	1	19	7	27	16
pH	none	—	19	4.41	6.86	5.89
Nitrogen; ammonia+ammonium	mg/L	0.002	19	0.10	1.27	0.37
Nitrogen; nitrate+nitrite	mg/L	0.005	20	0.01	1.43	0.34
Nitrogen; TKN	mg/L	0.02	17	0.26	1.52	0.56
Phosphorus; phosphate	mg/L	0.0005	18	0.0003	0.009	0.002
Phosphorus; total	mg/L	0.002	18	0.01	0.04	0.01
Copper	µg/L	1.6	18	4.0	23.2	11.0
Zinc	µg/L	0.6	18	5.4	25.6	11.3
Lead	µg/L	5	18	<MDL	12.20	<MDL

[a] MDL = reporting method detection limit.

chemically altered as it filtered through the green roof growing media, resulting in higher concentrations of major ions (e.g. Mg, Ca, S, Cl, Na), pH, and hardness (as $CaCO_3$) relative to the conventional roof. Runoff from both roofs contained very low levels of turbidity and TSS. Detection frequencies of lead, nickel, cadmium, molybdenum, and beryllium were greater in green roof samples, but concentrations were below Ontario receiving water guidelines (OMOE 1994). Runoff from the conventional roof had higher mean concentrations of copper (α = 0.001), zinc (α = 0.1), and manganese (α = 0.001), and higher PAH detection frequencies. While zinc levels were generally low, concentrations of copper in runoff from both roofs regularly exceeded the Ontario receiving water guideline.

Green roof growing media are typically engineered to include nutrients in order to promote plant growth. This is evident from the much higher levels of phosphorus, total Kjeldahl nitrogen (TKN), and potassium in green roof runoff. Levels of other nitrogen species (nitrate, nitrite, ammonia) were higher in runoff from the conventional roof. Total phosphorus is of particular concern since green roof concentrations were several times higher than the Ontario receiving water standard of 0.03 mg/L, established to protect against excess algae and plant growth in rivers and streams.

Unit area loads from the two roofs are presented in Table 3. Conventional roof loads of most chemical constituents of concern were considerably greater than green roof loads, which was to be expected since the green roof generated much less runoff. Even variables with higher concentrations in green roof runoff, such as TKN, vanadium, and nickel, were discharged in larger quantities (by mass) from the conventional roof. By contrast, green roof loads of total phosphorus were more than triple that of the conventional roof over the monitoring period. Most of the phosphorus was transported as phosphate, which is more biologically

TABLE 2. Mean concentrations and 95% confidence limits for green roof (G) and conventional roof (C) runoff samples

Variable (units)	*MDL* [a]	*PWQO* [b]	*n*	*Green roof*				*Conventional roof*				*Comparison, significance level* [d,e]
				% >MDL	*Geo mean*	*LL* [c]	*UL* [c]	*% >MDL*	*Geo mean*	*LL*	*UL*	
Chloride (mg/L)	0.2		21	100	9.0	6.8	11.8	95	1.0	0.7	1.4	G>C (0.001)
Mercury (µg/L)	0.02	0.2	19	0	<MDL	–	–	5	<MDL	–	–	N/A
Sodium (mg/L)	0.1		21	100	6.1	5.6	6.7	100	1.1	0.9	1.2	G>C (0.001)
Potassium (mg/L)	0.05		21	100	6.6	5.6	7.8	100	1.9	1.7	2.1	G>C (0.001)
Hardness as $CaCO_3$ (mg/L)	1		21	100	86.5	77.2	97.0	100	15.3	13.3	17.5	G>C (0.001)
Sulphate (mg/L)	2.5		21	100	19.4	15.6	23.9	90	4.3	3.4	5.5	G>C (0.001
TSS (mg/L)	2.5		21	33	<MDL	–	–	95	5.8	4.4	7.6	N/A
Conductivity (µS/cm)	1		18	100	209	187.9	231.9	100	45	39.6	50.6	G>C (0.001)
pH (none)	none	6.5–8.5	18	100	8.10	7.9	8.3	100	7.26	7.2	7.3	G>C (0.001)
Alkalinity (mg $CaCO_3$/L)	2.5		18	100	62.0	56.7	67.7	100	13.7	12.3	15.3	G>C (0.001)
Turbidity (FTU)	0.01		10	100	1.22	0.90	1.66	100	2.61	1.96	3.48	C>G (0.05)
Nitrogen; nitrate (mg/L)	0.005		21	100	0.156	0.11	0.23	100	0.412	0.31	0.56	C>G (0.01)
Nitrogen; nitrite (mg/L)	0.001		21	100	0.019	0.02	0.02	100	0.029	0.02	0.03	C>G (0.05)
Nitrogen; NH_3 + NH_4 (mg/L)	0.002		21	80	0.008	0.00	0.02	100	0.213	0.16	0.29	C>G (0.001)
Nitrogen; TKN (mg/L)	0.02		21	100	1.110	0.88	1.41	100	0.616	0.49	0.77	G>C (0.05)
Total phosphorus (mg/L)	0.0005		21	100	0.318	0.23	0.45	90	0.053	0.04	0.07	G>C (0.001)
Phosphate (mg/L)	0.002	0.03 [f]	21	100	0.241	0.16	0.36	100	0.009	0.005	0.019	G>C (0.001)
Escherichia coli (CFU/100mL)		100	16	100	113	34.4	372.2	100	25	9.5	66.8	no diff. (0.1)
Aluminum (µg/L)	11	75 [f]	20	100	47.7	42.7	53.3	100	58.2	46.7	72.6	no diff. (0.1)
Barium (µg/L)	0.2		20	100	13.2	11.7	14.8	100	3.3	2.7	3.9	G>C (0.001)
Beryllium (µg/L)	0.02	11	20	50	<MDL	–	–	5	<MDL	–	–	N/A
Calcium (mg/L)	0.005		20	100	20.53	18.07	23.32	100	4.59	4.01	5.25	G>C (0.001)
Cadmium (µg/L)	0.6	0.1 [f]	20	25	<MDL	–	–	13	<MDL	–	–	N/A
Cobalt (µg/L)	1.3	0.9	20	10	<MDL	–	–	13	<MDL	–	–	N/A
Chromium (µg/L)	1.4	8.9	20	5	<MDL	–	–	14	<MDL	–	–	N/A
Copper (µg/L)	1.6	1 or 5 [f,g]	20	100	44.8	33.5	59.8	100	108.1	86.4	135.3	C>G (0.001)
Iron (µg/L)	0.8	300	20	100	25.5	19.8	32.9	100	34.2	25.9	45.2	no diff. (0.1)
Magnesium (mg/L)	0.008		20	100	4.16	3.3	5.2	100	0.73	0.6	0.9	G>C (0.001)
Manganese (µg/L)	0.2		20	100	1.41	1.2	1.7	100	8.33	6.6	10.4	C>G (0.001)
Molybdenum (µg/L)	1.6	40	20	15	<MDL	–	–	0	<MDL	–	–	N/A
Nickel (µg/L)	1.3	25	20	60	1.3	1.0	1.6	15	<MDL	–	–	N/A
Lead (µg/L)	10	1–5 [f,h]	20	30	<MDL	–	–	0	<MDL	–	–	N/A
Strontium (µg/L)	0.1		20	100	85.3	77.0	94.6	100	15.2	13.3	17.4	G>C (0.001)
Titanium (µg/L)	0.5		20	25	<MDL	–	–	90	1.17	0.8	1.6	N/A
Vanadium (µg/L)	1.5	6	20	80	1.84	1.5	2.3	25	<MDL	–	–	N/A
Zinc (µg/L)	0.6	20 [f]	20	100	6.89	5.4	8.8	100	9.85	8.3	11.7	C>G (0.1)
Phenanthrene (ng/L)	10	30	18	39	10.1	–	–	89	60.9	33.7	109.9	N/A
Anthracene (ng/L)	10	0.8	18	0	<MDL	–	–	50	<MDL	–	–	N/A
Fluoranthene (ng/L)	10	0.8	18	28	<MDL	–	–	89	78.7	40.7	152.2	N/A
Pyrene (ng/L)	10		18	28	<MDL	–	–	72	51.7	24.9	107.0	N/A
Benzo(a)anthracene (ng/L)	20	0.4	18	6	<MDL	–	–	56	28.3	18.0	44.3	N/A
Chrysene (ng/L)	10	0.1	18	6	<MDL	–	–	67	31.7	16.9	59.6	N/A
DMBA (ng/L) [i]	10		18	0	<MDL	–	–	0	<MDL	–	–	N/A
Benzo(b)fluoranthene (ng/L)	10		18	6	<MDL	–	–	72	33.3	17.8	62.2	N/A
Benzo(k)fluoranthene (ng/L)	10	0.2	18	11	<MDL	–	–	67	27.1	14.9	49.2	N/A
Benzo(e)pyrene (ng/L)	10		18	6	<MDL	–	–	67	23.7	13.6	41.4	N/A
Benzo(a)pyrene (ng/L)	3		18	22	<MDL	–	–	78	23.4	10.8	50.9	N/A
Perylene (ng/L)	10	0.07	18	0	<MDL	–	–	56	11.4	7.9	16.6	N/A
Indeno(1,2,3-c,d)pyrene (ng/L)	20		18	6	<MDL	–	–	56	32.5	19.4	54.4	N/A
Dibenzo(a,h)anthracene (ng/L)	20	2	18	0	<MDL	–	–	6	<MDL	–	–	N/A
Benzo(g,h,i)perylene (ng/L)	20	0.02	18	0	<MDL	–	–	56	26.8	17.3	41.5	N/A

[a] MDL = reporting method detection limit.
[b] Provincial Water Quality Objective (OMOE 1994).
[c] LL = lower confidence limit; UL = upper confidence limit.
[d] Comparison between green and conventional roofs with significance level reported in parenthesis ($\alpha = x$) for variables with detection frequencies >50%.
[e] n/a = Not applicable.
[f] Interim PWQO.
[g] 1 and 5 µg/L at hardness <20 mg/L and > 20 mg/L, respectively.
[h] 1, 3, and 5 µg/L at hardness <30 mg/L, 30 to 80 mg/L, and >80 mg/L, respectively.
[i] DMBA = 7,12-dimethylbenz(a)anthracene.

available than particulate phosphorus, and thus presents a more serious concern. Over the monitoring period, 86% of green roof total phosphorus loads were in the form of phosphate, compared with only 46% from the conventional roof.

Figure 5 presents time series plots for phosphorus, phosphate, nitrate, and copper. These were the only variables analyzed with mean concentrations in green roof runoff that were significantly different ($\alpha = 0.01$) between the 2003 ($n = 9$) and 2004 ($n = 12$) monitoring seasons. The influence of year-to-year variations in flow volumes, event precipitation depths, and rainfall chemistry on runoff concentrations was investigated as a possible source of observed changes, but regression analysis showed these factors to be insignificant.

The direction of change differed among the variables shown in Fig. 5. While total phosphorus and phosphate concentrations in green roof runoff decreased, nitrate and copper increased. There was no significant difference in mean conventional roof concentrations of total phosphorus, nitrate, and copper, but orthophosphorus concentrations declined ($\alpha = 0.05$). The change in green roof concentrations of phosphorus was much greater than observed for the other variables. Mean 2004 concentrations of total phosphorus (0.18 mg/L) were less than one third of mean concentrations observed in 2003 (0.7 mg/L). Despite lower concentrations in 2004, phosphorus loads from the green roof remained higher than those from the conventional roof.

Growing Media Chemical and Physical Analyses

Eleven samples of green roof growing media were obtained from manufacturers and analyzed for general chemistry, nutrients, and metals. Analyses were conducted to determine the chemical and physical composition of bulk samples, as well as the quality of leachate from each of these media. Table 4 provides manufacturer descriptions of each media tested and the laboratory grain size test results. Composition information is not provided for J

TABLE 3. Unit area loads and percent difference relative to the conventional roof for the 2003 and 2004 monitoring seasons

Variable	*Unit area load (mg/m²)* [a]		*% Difference (conventional roof versus green roof)*
	Green roof	*Conventional roof*	
Chloride	4,310.2	1,333.7	-223.2
Sodium	2,606.3	1,212.7	-114.9
Potassium	2,463.2	2,091.5	-17.8
Hardness as $CaCO_3$	39,604.2	17,944.5	-120.7
Sulphate	8,890.3	5,310.9	-67.4
Suspended solids	763.2	6,752.0	88.7
Nitrogen; nitra te	40.8	450.1	90.9
Nitrogen; nitrite	7.5	31.4	76.2
Nitrogen; ammonia +ammonium	6.1	245.7	97.5
Nitrogen; total Kjeldahl	575.3	677.7	15.1
Phosphorus; phosphate	207.2	26.1	-694.1
Phosphorus; total	241.7	69.5	-247.6
Escherichia coli	1,437,568	1,612,196	10.8
Aluminum	19.6	63.1	68.9
Barium	6.04	3.77	-60.2
Beryllium	0.0151	0.0112	-34.8
Calcium	9,510.4	5,300.2	-79.4
Cadmium	0.175	0.364	51.9
Cobalt	0.283	0.709	60.1
Chromium	0.302	0.739	59.1
Copper	15.6	110.8	85.9
Iron	14.3	38.5	62.8
Magnesium	2,329.0	904.1	-157.6
Manganese	0.59	9.09	93.5
Molybdenum	0.45	0.84	46.2
Nickel	0.75	0.78	4.2
Lead	1.62	3.45	53.0
Strontium	36.1	17.5	-106.4
Titanium	0.17	1.40	87.7
Vanadium	0.77	0.94	18.5
Zinc	3.37	11.02	69.5

[a] *E. coli* unit area loads are expressed as co lony forming units (CFU) per m².

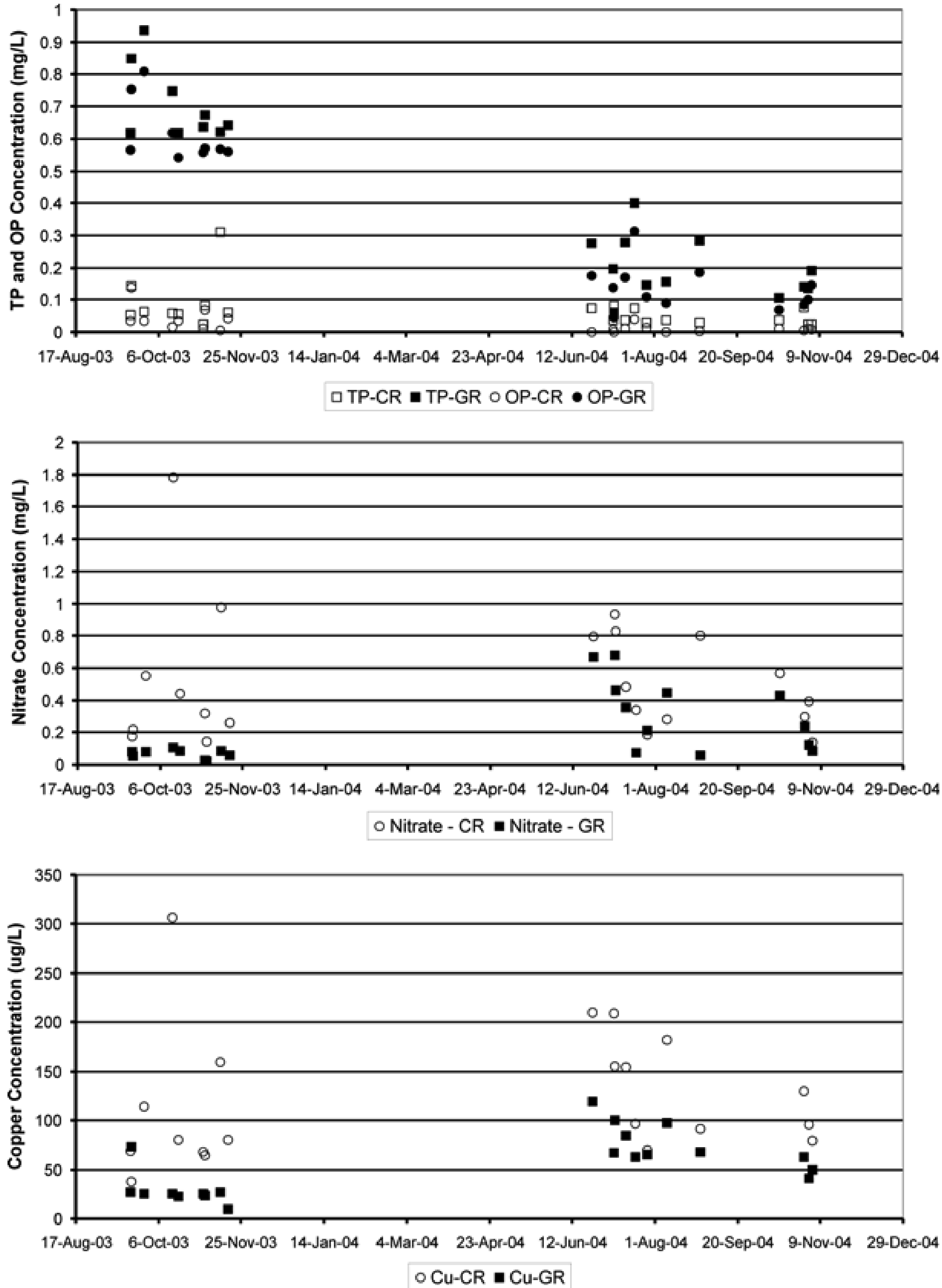

Fig. 5. Green roof (GR) and Conventional roof (CR) concentrations of total phosphorus, orthophosphorus, nitrate, and copper.

TABLE 4. Growing media composition (as provided by manufacturers) and grain size laboratory test results

Growing media	*Composition*	*Grain size test results* [a] *(%)*				*Comments*
		Gravel	*Sand*	*Silt*	*Clay*	
A	5–10% organic matter and 70% porous mineral aggregate (by volume)	75	21	3	2	Crushed brick, blond peat, perlite, sand and compost from vegetable matter
B	50–60% organic matter, 30% mineral aggregate (by volume)	7	58	17	18	Bark compost, perlite, blond peat, and compost from vegetable matter
C	10–15% organic matter and 55% porous mineral aggregate (by volume)	63	30	4	3	Crushed brick, blond peat, perlite, sand and compost from vegetable matter
D	75% expanded clay and 8% organic matter (by weight)	53	39	4	3	Remaining 17% are materials balanced to the needs of the project. Expanded clay is in the form of gravel sized aggregates.
E	100% expanded clay	97	2	0.6	0.3	Drainage layer used under growing media. Expanded clay is in the form of gravel sized aggregates.
F	25% compost, 25% Solite coarse, 25% perlite, 25% sand (by volume)	77	19	3	1	
G	25% fine compost, 25% Solite fine, 25% perlite, 25% sand (by volume)	20	67	10	3	
H	30% slag, 10% perlite, 30% compost and 30% sand (by volume)	54	40	4	3	
I	25% coarse sand, 25% fine brick, 25% compost and 25% limestone screenings (by volume)	13	77	7	3	
J	Not available	65	6	23	6	
K	Not available	84	13	2	1	
YU [b]	Not available	Not available				Crushed volcanic rock, compost, blonde peat, cooked clay and washed sand

[a] Size classes as follows: gravel: >2mm; sand: 0.05 – 2 mm; silt: 0.002 – 0.05 mm; clay: <0.002 mm.
[b] YU = York University green roof.

and K as per the manufacturers' request. The York University growing media is no longer manufactured, and thus a leachate test was not conducted on this sample. Bulk chemistry analysis of the York University growing media was conducted at the outset of the study.

Grain size analyses showed that 8 of the 11 media tested consisted of more than 50% gravel (>2 mm). These large particles in the media are usually lighter and less dense than typical gravel to ensure that the structural load on the roof is kept to a minimum. Medium E consists primarily of gravel-sized particles because, strictly speaking, it is not a growing medium but rather a drainage layer intended for use in conjunction with one of the other growing media.

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Table 5 presents the results of the bulk media chemistry analyses and typical background concentrations for agricultural soils in Ontario (OMOE 1998). Most constituents in the media were similar to or lower than the background concentrations. The sodium adsorption ratio and conductivity levels were slightly elevated, but not to levels that would adversely affect plant growth. Soil background concentrations were not available for nutrients. However, relative to one another, medium D had the highest phosphorus concentrations (1,469 µg/g), followed by the York University growing medium (1,100 µg/g). The drainage layer, medium E, also displayed high phosphorus levels (960 µg/g). The median phosphorus concentration for substrates A to K was 516 µg/g.

Medium I, with the highest percentage of sand (Table 4), had the lowest phosphorus and nitrogen concentrations overall. This medium was the only one of the 11 with TKN concentrations below 1,000 µg/g. There was an abundance of calcium and iron in the media, but trace metal concentrations were generally low. Medium D contained the highest concentrations of several metals, including barium, chromium, cobalt, copper, and nickel.

Growing media samples were leached four times. The first and fourth samples were analyzed for water chemistry. The pH and turbidty of leachates were higher than observed in the field, probably due to the lower level of dilution in the leachate tests. In the fourth set of leachates, the pH and turbidity of media ranged from 9.1 to 9.6, and 13 to 56 NTU, respectively. The higher turbidity was likely a result of small clay particles less than 1.5 microns, as leachate concentrations of TSS were low (2 to 8 mg/L). The range of leachate alkalinity concentrations varied within the same general range as the field samples (50 to 74 mg $CaCO_3$/L versus 43 to 86 mg $CaCO_3$/L for field samples).

Figure 6 presents leachate results and bulk media concentrations (where available) for nutrients (P and N) and variables with leachate concentrations that frequently exceeded Ontario receiving water standards (OMOE 1994). Exceedances of the standards should not be interpreted as a violation since the standards were not intended for this purpose. Results show a decline in nitrogen and phosphorus concentrations from the first to fourth leachate test for most media. Nitrate concentrations in the fourth leachate were below 0.1 mg/L for all media except medium D. Although total phosphorus levels decreased from a median concentration of 1.2 mg/L in the first leachate to 0.69 mg/L in the fourth leachate, levels remained well above the target of 0.03 mg/L.

The concentration of metals in media leachates varied substantially among growing media (Fig. 6). Copper was leached at relatively low concentrations from 8 of the 11 media tested. Aluminum concentrations were above receiving water standards in several media, and often increased from the first to the fourth leachate. Iron and vanadium levels decreased after the first leachate in most media. Leachate concentrations of lead and zinc were below their respective standards of 5, 1, and 20 µg/L in all media except F (Zn: 92 µg/L; Pb: 6.0 µg/L) and the drainage layer E (Zn: 72 µg/L; Pb: 6.5 µg/L).

Physical properties had little apparent effect on the levels of nutrients or metals in the leachate samples (Table 4 and Fig. 6). One possible exception is the expanded clay drainage layer (medium E), which exhibited lower nutrient leaching and higher concentrations of aluminum, iron, zinc, copper, and lead than most other media. Growing medium B, with 50 to 60% organic matter, had the highest leachate concentrations of phosphorus, but nitrogen levels were relatively low. Media F and G, with 25% compost, had nutrient levels comparable to those observed in other growing media with less compost.

The chemical composition of bulk media was not correlated with the quality of leachates from the same media (Fig. 6). There were several instances in which concentrations were low relative to other media, but leachate concentrations were high (e.g., copper in medium F), and vice versa (e.g., phosphorus in media D and E).

Leachate concentrations of phosphorus (0.22 to 1.63 mg/L) were generally higher than concentrations in runoff from the York University green roof (0.06 to 0.85 mg/L). The green roof also showed lower levels of aluminum, iron, and vanadium than the leachates from the 11 growing media tested, despite generally higher bulk media concentrations. By contrast, total nitrogen levels were lower in the fourth leachate tests (0.04 to 0.83 mg/L) than in the green roof runoff (0.56 to 2.52 mg/L). Copper concentrations in the University green roof runoff were also higher than the leachates, with the exception of the fourth leachate concentrations of media E (118 µg/L) and F (127 µg/L). Copper flashing downstream of the green roof discharge point and upstream of the sampling point may have contributed to elevated copper levels in runoff.

Discussion

By reintroducing natural processes of evapotranspiration and soil water retention into the urban environment, green roofs help to protect streams and replicate the natural hydrologic cycle that existed prior to urbanization. Although green roofs do not infiltrate water or contribute to groundwater recharge, the seasonal pattern of flow volumes closely resembles that to which receiving streams and aquatic life are adapted. This resemblance would be even closer if green roofs were combined on the same site with other stormwater infiltration best management practices, such as permeable pavements, that help to promote groundwater recharge and augment stream baseflows in urban areas.

Runoff results indicated that the green roof retained 63% more rainfall than the conventional roof over the 18 month monitoring period, excluding the winters. Liu and Minor (2005) reported a comparable retention rate of 57% for two green roof plots on a building in Toronto. These two plots were monitored over a similar time period (March to November, 2003 and 2004), but had thinner substrates (7.7 and 10 cm) and a more gentle slope (<2%) compared with the present study. In Ottawa, a green roof with a 15-cm substrate and a 2% slope was found to retain approximately 54% more rain than a similar sized conventional roof (Liu 2003). The Ottawa study included monitoring during the winter (November 2000 to November 2001), when retention of runoff drops to approximately 20 to 30% (Mentens et al. 2006). Together these studies suggest that, for stormwater planning purposes, an annual runoff coefficient of between 0.45 and 0.55 (depending on the slope and substrate depth) should be assigned to extensive green roofs in southern Ontario.

Green roofs help to improve stream water quality

TABLE 5. Chemical characterization of bulk growing media[a]

Variable (units)	Ontario bkg. conc.[b]	MDL[c]	Bulk growing media[d,e] A	B	C	D	E	F	G	H	I	J	K	MDL[f]	York University growing media[g]
GENERAL CHEMISTRY															
Total volatile matter (%)	–	–	8.4	62.0	17.7	10.3	0.2	6.0	6.3	10.0	3.2	7.0	5.3	–	–
Oil & grease (µg/g)	–	20	1,248	5,693	1,913	537	71	1,027	1,128	1,330	615.4	840.8	403.7	–	–
CEC (meq/100g)	–	–	14.9	12.7	14.5	20.3	4.6	41.6	33.8	52.9	23.8	14.7	51	–	–
pH (–)	–	–	7.4	6.0	6.7	6.7	7.3	8.2	7.8	8.0	8.1	7.3	7.9	–	–
SAR (–)	1	–	1.41	1.46	1.59	2.95	0.67	4.79	5.37	3.33	0.51	2.88	1.88	–	–
EC (mS/cm)	0.47	–	1.40	1.75	0.72	1.18	0.21	0.72	0.93	0.40	0.30	0.54	0.03	–	0.48
NUTRIENTS															
Total phosphorus (µg/g)	–	1	489	375	565	1,469	960	639	420	657	239	511	516	20	1,100
Total organic carbon (%)	–	0.1	8.5	35.4	13.7	4.9	0.6	3.4	4.6	5.32	1.69	7.24	3.69	–	–
Total Kjeldahl nitrogen (µg/g)	–	5	1,739	2,986	3,071	2,174	3,324	1,984	1,367	1,731	191	3,196	1,440	10	1,200
METALS															
Antimony (µg/g)	1	1	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	–	–
Arsenic (µg/g)	14	1	3	1	3	4	7	1	2	2	2	4	2	–	–
Barium (µg/g)	190	1	90	111	82	194	182	12	15	137	70	114	85	0	78
Beryllium (µg/g)	1.2	0.5	<MDL	<MDL	<MDL	<MDL	0.66	<MDL	<MDL	0.77	<MDL	<MDL	<MDL	0	0.8
Cadmium (µg/g)	1	1	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	0	0.4
Calcium (µg/g)	–	50	11,323	14,089	13,898	13,384	10,516	10,348	85,304	84,897	82,727	20,874	64,065	0	9,100
Chromium (µg/g)	67	1	10	6	9	87	29	6	6	15	8	15	11	0	31
Cobalt (µg/g)	19	1	5	2	4	14	11	2	3	4	3	7	3	0	12
Copper (µg/g)	56	1	15	17	19	49	24	6	8	26	5	26	11	0	10
Iron (µg/g)	–	10	13,411	4,619	11,439	15,178	21,717	4,418	4,970	7,755	7,493	10,252	8,532	0	19,000
Lead (µg/g)	55	2	7	8	7	<MDL	26	3	4	10	<MDL	20	4	0	1
Manganese (µg/g)	–	1	317	397	336	528	1,182	234	202	1,122	296	404	524	0	300
Mercury (µg/g)	0.16	0.05	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	0.01	0.0005
Molybdenum (µg/g)	2.5	2	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	0	0.25
Nickel (µg/g)	43	2	10	5	9	39	30	6	10	9	6	13	5	0	37
Selenium (µg/g)	1.4	1	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	–	–
Silver (µg/g)	0.35	0.3	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	–	–
Vanadium (µg/g)	91	1	14	9	15	19	41	3	4	11	10	15	14	0	38
Zinc (µg/g)	150	1	76	100	81	75	91	25	27	133	45	68	61	0	31
Chromium (VI) (µg/g)	2.5	1	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	–	–

[a] Acronyms and abbreviations: MDL = method detection limit; bkg = background; conc. = concentration; CEC = cation exchange capacity; SAR = sodium adsorption ratio; EC = electrical conductivity.
[b] Typical background concentrations for agricultural soils in Ontario (OMOE 1998).
[c] MDL for samples analyzed by Entech laboratories.
[d] Samples analyzed by Entech laboratories.
[e] Underlined values represent concentrations above background concentrations.
[f] MDL for samples analyzed by Ontario Ministry of the Environment laboratories.
[g] Samples analyzed by Ontario Ministry of the Environment laboratories.

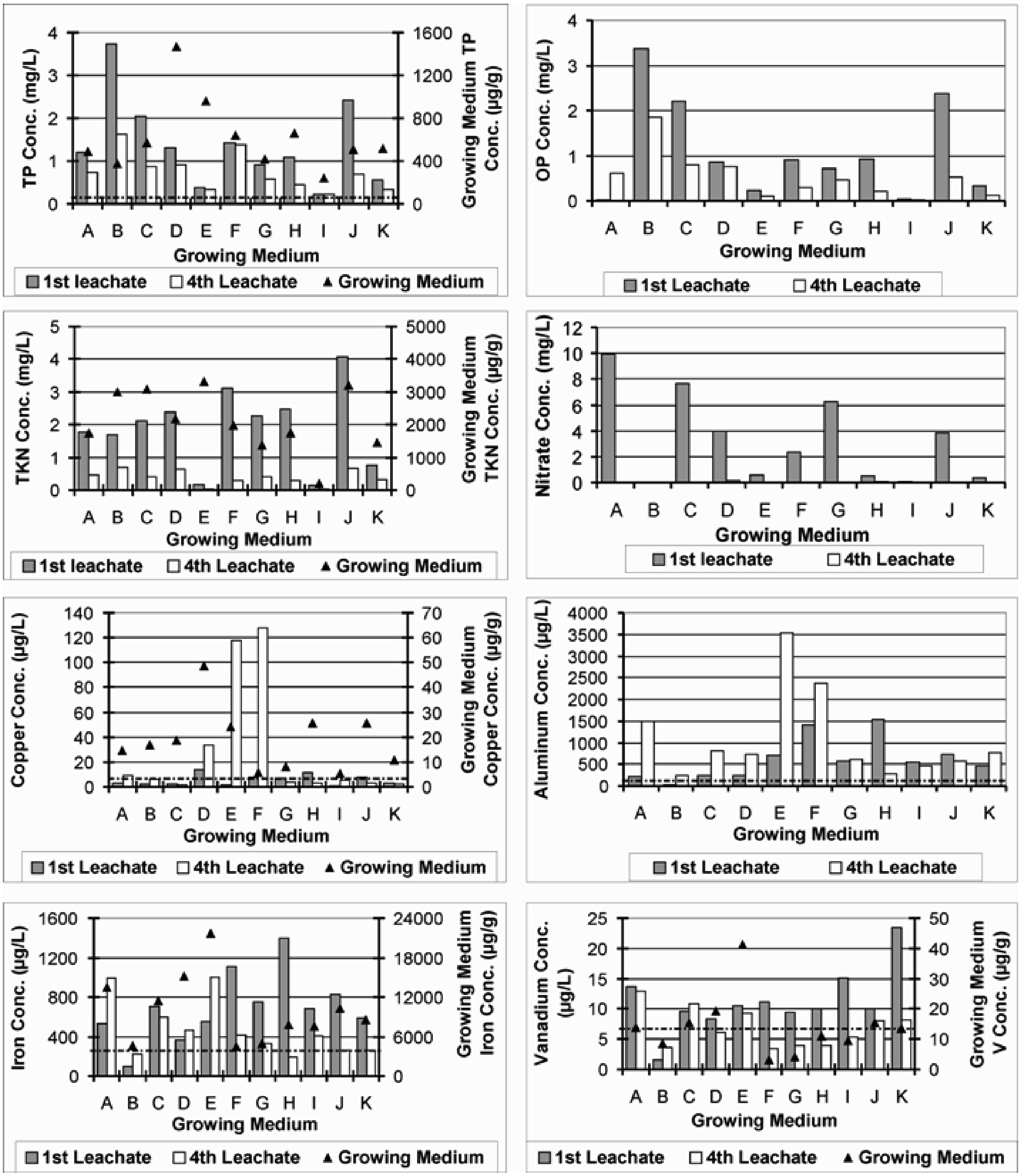

Fig. 6. Leachate and growing media concentrations, where available, for 11 growing media. Note: Black dashed lines represent Ontario receiving water guidelines (OMOE 1994). There are no Ontario guidelines for orthophosphate, nitrate and TKN.

by capturing and retaining atmospheric pollutants, and replacing traditional roofing materials with more natural surfaces. Typical contaminants leached from conventional roof materials include zinc, lead, copper, and PAHs. Coal tars and pitches used in roofing shingles are a source of lead and PAHs (Clark et al. 2001; Van Metre and Mahler 2003). Elevated levels of zinc are common on metal roofs (Van Metre and Mahler 2003). In this study, the conventional asphalt roof was found to contain higher levels of zinc, copper, and PAHs than the green roof, although zinc rarely exceeded receiving water objectives. The metals are of particular concern because, unlike the green roof, the conventional roof had relatively low hardness levels, which increases the potential toxicity of zinc and copper to aquatic life. The ability of green roofs to neutralize acid precipitation and increase water hardness is an important water quality benefit of the technology.

Phosphorus was the main contaminant of concern in green roof runoff, as concentrations were well above the receiving water guideline, and green roof phosphorus loads were considerably higher than the conventional roof. The decline in concentrations over time likely represents a process of leaching whereby soil phosphorus is gradually flushed from the growing medium during the first few years of operation. This would suggest that phosphorus levels may have been even higher during the first year of operation, prior to initiation of monitoring, and that levels may continue to decline in the future, possibly even to concentrations meeting receiving water objectives (0.03 mg/L). As soil phosphorus declines, however, fertilizers may need to be added to support continued plant growth, initiating a renewed cycle of leaching.

The green roof concentrations of total nitrogen (TN: 0.6 to 2.5 mg/L) and total phosphorus (TP: 0.06 to 0.94 mg/L) in this study were lower than reported by Hathaway et al. (2008) in North Carolina, where composted cow manure comprised 15% of the green roof media. In the North Carolina study, TN and TP concentrations ranged from 0.7 and 6.9 mg/L and 0.6 to 1.4 mg/L, respectively. A lower TP range was reported by Hutchison et al. (2003) on two green roofs in Portland (0.2 to 1.1 mg/L). In Pennsylvania, Berghage et al. (2007) found phosphorus concentrations in runoff from three green roofs (mean: 0.28 to 0.58 mg/L) that were more in line with those observed in our study. Nitrate concentrations in the Pennsylvania study were also similar, with the exception of two spikes close to 5.0 mg/L in March (TN was not reported). In Estonia, Teemusk and Mander (2007) reported very moderate levels of TP (0.03 to 0.09 mg/L) in green roof runoff, but TN concentrations (1.0 to 2.1 mg/L) similar to those in our study. The differences among studies may be attributed to a variety of factors, including the composition of growing media, the type and extent of vegetative cover, fertilizer use, and the age of the roofs.

Further testing would be needed to explain the unexpected increase in copper and nitrate concentrations from 2003 to 2004 (Fig. 5). Seasonal effects may have been a factor since the higher concentrations and ranges were generally observed during the months of June, July, and August in 2004, while there were no data for these months in 2003. However, corresponding seasonal changes were not observed for other metals and nitrogen species, as may be expected if season had played a dominant role. Chemical reactions and biologically mediated transformations within the growing media over the winter and spring are other possible causes, but more data would be needed to speculate on the mechanism by which these reactions may affect copper and nitrate concentrations.

There has been some interest in the potential reuse of green roof runoff for toilet flushing, laundry, and irrigation. On the York University green roof, high levels of bacteria and colour would likely prevent such a consideration in the absence of treatment. *E. coli* densities ranged from a low of 4 CFU/100 mL to a high of 5,100 CFU/100 mL, well beyond the acceptable range for reuse, even as irrigation (Exall et al. 2004). While samples were not analyzed for colour, there was a visible tint to all green roof water samples, likely from the fulvic and humic acids in the peat and organic matter. Berghage et al. (2007) reported a similar result in Pennsylvania, indicating a colour range for individual green roof runoff events of roughly 100 to 1,000 PtCo colour equivalents. While the samples from York University had a distinct colour, they were very clear, with turbidity levels below 3 FTU, and TSS less than 5 mg/L.

Green roof growing media are typically composed of light weight materials, such as expanded slate, clay, or perlite with a relatively small amount (<20%) of organic matter (e.g., peat, humus, compost) to provide the chemical properties needed for plant growth. Starters or slow release fertilizers are often added to aid in establishing plants soon after the medium is installed (Beattie and Berghage 2004). The chemical composition of bulk media analyzed in this study generally fell within the range of what may be expected of agricultural soils in Ontario (Table 5). The inclusion of clay minerals rich in aluminum and iron in the growing media can result in high runoff concentrations of these constituents initially (Fig. 6), but field results suggest that concentrations stabilize over time to levels below receiving water standards (Table 2). Leachate concentrations of copper, zinc, and lead were elevated in 3 of the 11 media, suggesting that media may differ substantially in their ability to leach these contaminants. Under field conditions, this study and others (Berndtsson et al. 2006; Berghage et al. 2007) suggest that green roofs may act as a source of some metals, but concentrations are generally much lower than urban runoff, except when drainage water comes into contact with metal roofing and piping materials (Forster and Knoche 1999; Berndtsson et al. 2006).

The absence of any clear relationship between the chemical composition of growing media and leachate concentrations was expected since the potential for leaching will depend on whether constituents are present in the growing media in readily leachable forms. In general, particulate forms that make up part of the mineral substrate would leach less readily than the same constituents present as soluble precipitates. Artificial fertilizers added to promote start-up growth of vegetation would be particularly susceptible to leaching. In Germany and Sweden, the use of coated slow release fertilizers has been shown to help reduce leaching of nutrients (Fischer and Jauch 2002; Emilsson et al. 2007).

Conclusions

The results of this study indicate that vegetated roofs help to mitigate the adverse effects of stormwater on receiving waters by reducing runoff volumes, controlling peak flows, altering the timing of flows, and improving the quality of roof runoff for most constituents. During the growing season, runoff from the green roof was 63% less than from the conventional roof. The capacity of the green roof to retain water combined with more natural vegetated surfaces (relative to traditional roofs) translated into lower loads of most pollutants of concern relative to the conventional roof.

In green roof runoff, phosphorus was the only variable that posed a potential threat to receiving waters. Phosphorus loads from the green roof were considerably greater than from the conventional roof. A significant decrease in phosphorus concentrations from the first to the second year of sampling suggested that phosphorus is leached from the media over time, and that further decreases may be expected as the green roof ages. Nitrate concentrations in runoff were very low and the green roof may even act as a sink for nitrate.

An analysis of the chemical and leachate quality of various growing media available commercially also showed that phosphorus is leached at relatively high levels from most media. Reductions in phosphorus leaching may be achieved by filtering runoff through reactive materials that render phosphorus insoluble by binding it to sediment. Several materials that have shown promise in lakes and coastal areas (e.g., Berg et al. 2002; Robb et al. 2003) require testing in green roof applications. In general, growing media containing phosphorus-rich fertilizers should be avoided.

The laboratory tests indicated that other constituents of concern in green roof runoff may include copper, aluminum, iron, and vanadium, but field results suggest that elevated concentrations of these do not persist over the long term. Copper was the only constituent for which median green roof runoff concentrations exceeded Ontario standards, and in that case roof materials other than the growing medium may have contributed to elevated levels. To help preserve water quality, construction materials and growing media used in green roof installations should be selected to minimize leaching of contaminants into runoff.

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