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Effect of a modular extensive green roof on stormwater runoff and water quality

Bruce G. Gregoire[1], John C. Clausen*

University of Connecticut, Department of Natural Resources and the Environment, 1376 Storrs Rd., Unit 4087, Storrs, CT 06269-4087, United States

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ABSTRACT

Runoff quantity and quality from a 248 m^2 extensive green roof and a control were compared in Connecticut using a paired watershed study. Weekly and individual rain storm samples of runoff and precipitation were analyzed for TKN, $NO_3 + NO_2$–N, NH_3–N, TP, PO_4–P, and total and dissolved Cu, Pb, Zn, Cd, Cr, and Hg. The green roof watershed retained 51.4% of precipitation during the study period based on area extrapolation. Overall, the green roof retained 34% more precipitation than predicted by the paired watershed calibration equation. TP and PO_4–P mean concentrations in green roof runoff were higher than in precipitation but lower than in runoff from the control. The green roof was a sink for NH_3–N, Zn, and Pb, but not for TP, PO_4–P, and total Cu. It also reduced the mass export of TN, TKN, $NO_3 + NO_2$–N, Hg, and dissolved Cu primarily through a reduction in stormwater runoff. Greater than 90% of the total Cu, Hg, and Zn concentrations in the green roof runoff were in the dissolved form. The growing media and slow release fertilizer were probable sources of P and Cu in green roof runoff. Overall, the green roof was effective in reducing stormwater runoff and overall pollutant loading for most water quality contaminants.

1. Introduction

Nonpoint sources are responsible for a significant amount of water quality impairments in the United States (USEPA, 2009). In urban areas, roof surfaces contribute excess nutrients and toxic metals to receiving waters (Bannerman et al., 1993; Egodawatta et al., 2009; Förster, 1996; Van Metre and Mahler, 2003). These surfaces can cover from 12% in residential areas to 21% in commercial areas (Bannerman et al., 1993; Boulanger and Nikolaidis, 2003).

Green roofs are becoming more common in North America as a means to control runoff and nonpoint source pollution from urban areas, and for their aesthetic value, insulation and noise reduction, and wildlife habitat (Getter and Rowe, 2006; Teemusk and Mander, 2006; USEPA, 2005b). Green roofs are classified as either extensive or intensive and are often added to an existing roof. The difference between the two types is based primarily on the thickness of the growing media and the vegetation present. Extensive green roofs typically have thin ($\leq$10 cm) media and drought tolerant vegetation, whereas intensive green roofs have thicker growing media and may include trees and shrubs (Berndtsson, 2010; Carter and Fowler, 2008; Getter and Rowe, 2006). All green roof construction typically consists of a root barrier, drainage material layer, filter fabric, growing media, and vegetation (Berndtsson, 2010; Clark et al., 2008; Getter and Rowe, 2006).

Research on the effectiveness of extensive green roofs to reduce stormwater runoff has shown that they intercept, retain, and evapotranspire between 34% and 69% of precipitation with an average retention of 56% (Fig. 1). The range in retention observed is partly due to time of year studied, sampling methods, climate, and the method used to calculate retention. The amount of precipitation retained by a green roof is improved by the number of increasing antecedent dry days preceding precipitation, lower rainfall amount, higher temperature and evapotranspiration, and a higher water holding capacity of growing media (Berndtsson, 2010; Bengtsson et al., 2005; Berghage et al., 2009; Carter and Rasmussen, 2005; DeNardo et al., 2005; Getter and Rowe, 2006; Hathaway et al., 2008; Simmons et al., 2008; Teemusk and Mander, 2007). While many green roof studies have utilized a control roof, to compare to stormwater runoff from a green roof, only VanWoert et al. (2005) reports the treatment effects statistically. Also, many green roof studies have been at the plot scale ($\approx$5 m^2), most of which are replicated, but results from these studies were not compared using standard statistical approaches.

Studies of nutrients in runoff from green roofs have had mixed findings. The majority of studies conclude that the green roof was a source of phosphorus in runoff (Berndtsson et al., 2006, 2009; Hathaway et al., 2008; Hutchinson et al., 2003; Köhler and Schmidt, 2003; Liptan and Strecker, 2003; MacMillan, 2004;

* Corresponding author. Tel.: +1 860 486 0139; fax: +1 860 486 5408.
E-mail addresses: bruce.gregoire@uconn.edu (B.G. Gregoire), john.clausen@uconn.edu (J.C. Clausen).
[1] Tel.: +1 860 486 1874; fax: +1 860 486 5408.

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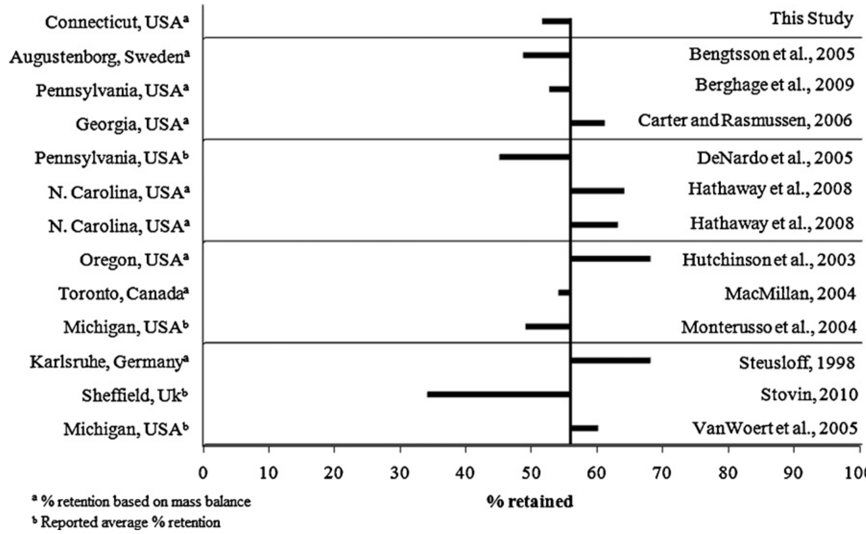

Fig. 1. Meta-analysis of green roof precipitation retention. The solid vertical line represents an average retention of 56%.

Monterusso et al., 2004; Teemusk and Mander, 2007). The percentage of compost in the soil media and the fertilizer used are the two key components apparently contributing to nutrients in runoff (Berndtsson et al., 2009; Emilsson et al., 2007; Hathaway et al., 2008; Teemusk and Mander, 2007).

Copper (Cu) and zinc (Zn) have been the two metals most commonly analyzed in green roof runoff (Alsup et al., 2010; Berghage et al., 2009; Berndtsson et al., 2006, 2009; Hutchinson et al., 2003; Köhler et al., 2002; Liptan and Strecker, 2003; MacMillan, 2004; Retzlaff et al., 2008; Steusloff, 1998). The majority of these studies have concentrated on total metals and ignored dissolved species, with copper (Cu) being the only metal analyzed in the dissolved form (Hutchinson et al., 2003; Liptan and Strecker, 2003). Dissolved metals can be more toxic to aquatic life (Makepeace et al., 1995). In addition, few studies have conducted water quality analysis on a broad list of constituents that included nitrogen (N), phosphorus (P), and heavy metals in green roof runoff (Berndtsson, 2010; Berndtsson et al., 2006, 2009).

While green roof studies have been conducted on roof surfaces or on green roof platforms, no studies have evaluated a modular extensive green roof system that is commonly utilized in the United States (Velazquez, 2003). Green roof platforms simulate roof surfaces. Unlike existing roof surfaces, the underside of the roof surface is open to the atmosphere (Monterusso et al., 2004; Stovin, 2010; VanWoert et al., 2005). A modular green roof system has removable trays, containing all the normal green roof components, that can be added to the roof surface (Velazquez, 2003). The objective of this study was to evaluate the effect of a modular green roof system in the northeastern United States on stormwater runoff and water quality for nutrients, and total and dissolved metals.

2. Materials and methods

2.1. Site description

The 248 m^2 green roof (Fig. 2) was installed September 2, 2009, on a public plaza at the University of Connecticut in Storrs. The plaza is located on a roof of a building that is set into a hillside and is accessible from street level. The green roof consisted of 334 extensive GreenGrid® modules (Weston Solutions Inc., West Chester, PA) each 1.2 m long, 0.6 m wide, and 10.2 cm thick, covering 81% of the 307 m^2 roof top watershed area. Each module had drainage holes and contained a root barrier/filter fabric that was overlain with 10.2 cm of growth media that consisted of 75% lightweight expanded shale, 15% composted biosolids, and 10% perlite (GreenGrid® Northeast Extensive Media). This material had a maximum water holding capacity of 31.8% and an organic matter content of 2.6% (PSU, 2008). Each module was planted with a mixture of 10 *Sedum* species, with 12 plugs in each module, on April 22, 2009. The *Sedum* varieties utilized were *S. album* 'Murale', *S. foresterianum* subsp. *elegans* 'Silver Stone', *S. kamtschaticum*, *S. kamtschaticum* var. *floriferum* 'Weihenstephaner Gold', *S. reflexum*, *S. selskianum*, *S. sexangulare*, *S. spurium* 'Dragons Blood', *S. spurium* 'Fuldaglut', and *S. spurium* 'John Creech'. After planting, the modules were fertilized with Espoma, Plant-tone® 5-3-3 slow release fertilizer at a rate of 586 g/m^2. A second fertilizer application in mid-May used Harrell's Live Roof Formula® 16-5-11 slow release fertilizer at a rate of 49 g/m^2. The modules received a total of 37 g/m^2 of N and 20 g/m^2 of P as fertilizer. Prior to installation on September 2, 2009, a 0.56 mm Easy Gardener, Inc. Pro WeedBlock® was placed over the existing roof surface.

The pre-existing roof, in order of increasing height from bottom to top, consisted of a concrete slab overlain with a 4-ply bituminous coal tar roof membrane system, a polyurethane film separator,

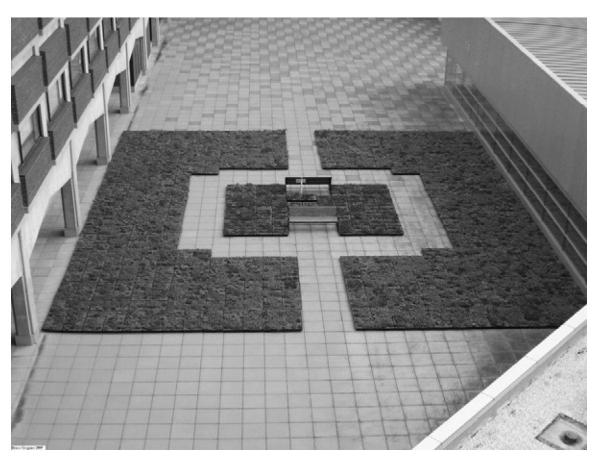

Fig. 2. Photograph of the plaza green roof. University of Connecticut, Storrs. For scale, each block is 0.61 m by 0.61 m.

a drainage board, 7.6 cm of rigid insulation, filter fabric, and 0.61 m × 0.61 m × 5.1 cm pre-cast concrete pavers on adjustable pedestals. The plaza was designed as a series of rectangular watersheds, each flowing to a single central drain, with a slope of 1.04 cm/m. The control roof was 178 m^2 and also located on the plaza, 38 m from the green roof study area.

2.2. Sampling and analysis

The experimental approach was the paired watershed design (Clausen and Spooner, 1993). This approach required the use of two time periods: calibration and treatment and two watersheds: control and treatment. The control watershed accounts for year-to-year differences such as climate, and receives no treatment. The purpose of the calibration period is to develop significant regressions between paired runoff observations from both watersheds. In addition, the variance due to individual differences between the two watersheds can be controlled.

Flow was monitored at 15 min intervals from January 25, 2009 until February 1, 2010 in pipes draining from the watersheds of the two roof surface areas (control and treatment) of the plaza using ISCO 4230 Bubbler Flow Meters (Lincoln, NE), and ISCO Flow Poke™ metering inserts, with 60° v-notch weir plates. Paired observations of flow were made during the calibration period from January 25, 2009, to September 1, 2009. These paired observations continued during the treatment period, from September 2, 2009, to February 1, 2010, when the green roof was installed on the treatment watershed while the control watershed remained unchanged. Paired water quality data was collected from precipitation, green roof runoff, and control watershed runoff during the treatment period. During the installation of the green roof, the effective size of the control watershed changed. Runoff from the control watershed was adjusted to account for the new control watershed area.

Evapotranspiration (ET) was measured using a weighing lysimeter and manometer. The lysimeter was constructed from two 20 mm × 800 mm rubber bladders (tire tubes) that were filled with 100% propylene glycol antifreeze. The bladders were connected to a manometer, containing a Win-Situ Inc. (Lincoln, NE) miniTroll™ for level recording, with 9.5 mm braided tubing. The manometer was calibrated in a greenhouse to determine that 1 mm of level change was equivalent to 0.292 mm of precipitation (R^2 = 0.994). After the green roof was installed, a 0.74 m^2 green roof module was placed on the lysimeter and level was recorded at 15-min intervals. Daily evapotranspiration was calculated as the difference in the change in the average daily level from the preceding day (i.e. Daily ET = Δ Daily level × 0.292 mm). Precipitation was measured using a tipping-bucket recording rain gage and an Onset Computer Corp. (Bourne, MA) HOBO™ data logger. Total weekly precipitation was also measured using a standard 20.3 cm non-recording rain gage. The rain gages were located on top of a building abutting the green roof.

Water quality sampling was conducted from September 2, 2009, until February 1, 2010 using ISCO 3710 samplers. Composite samples, drawn at 300 ml volumes, were collected automatically every 0.14 m^3 of flow through the drainage pipe for both the control and treatment watersheds. All tubing used for the portable samplers consisted of 11 mm ID teflon, with the exception of the sampler pump tubing, which consisted of a 80 cm length of 12.7 mm Silastic® medical grade silicon rubber. All tubing connectors and couplings were made from high density polyethylene (HDPE). Water samples were collected in two 4 L HDPE containers in a refrigerator at 4 °C. One container was lined with an ISCO low density polyethylene (LDPE) 7.6 L ProPak bag for metals analysis. The second container was used for nutrient analysis. Precipitation samples were collected with a bulk deposition collector (Likens et al., 1967) using a 2 L HDPE container lined with an ISCO ProPak bag. The bulk deposition collector was located adjacent to the rain gages. Snowfall was collected in a 20 L HDPE container washed in 1N hydrochloric acid (HCL). The container was capped for transport and the snow/ice melted in the laboratory at room temperature. Precipitation and stormwater discharge samples were collected weekly and/or by rainstorm.

Samples for metal analyses were split using a 5 L churn splitter. Two 500 ml samples were immediately drawn, one for dissolved metals using a 0.45 μm Millipore membrane filter and one unfiltered for total metals. The filter and assembly were pre-washed with 125 ml of 4N nitric acid (HNO_3) and rinsed with 500 ml of deionized (DI) water. Samples for metal analyses were placed in new, acid washed, 125 ml HDPE containers and acidified with 2 ml of HNO_3. Samples for mercury (Hg) analysis were placed in new, acid washed, 250 ml glass containers and acidified with 5 ml of 12N HCL. Samples were analyzed for Cu, lead (Pb), Zn, cadmium (Cd), and chromium (Cr), using inductively coupled plasma-optical emission spectrometry (ICP-OES) (EPA Method 200.7) (USEPA, 1994) and for Hg by cold vapor atomic fluorescence spectrometry (CVAFS) (EPA Method 245.7) (USEPA, 2005a). Samples for nutrient analysis were placed in clean, acid washed HDPE containers. All samples were analyzed for organic nitrogen (N_{org}) using Standard Methods 4500-N_{org} (Clesceri et al., 1998), ammonia-nitrogen (NH_3–N) using EPA Method 350.1 (USEPA, 1993a), nitrate + nitrite–nitrogen ($NO_3 + NO_2$–N) using EPA Method 353.2 (USEPA, 1993b), total phosphorus (TP) using EPA Method 365.1 (USEPA, 1993c), and orthophosphate–phosphorus (PO_4–P) using EPA Method 365.1 (USEPA, 1993c) on a Lachat colorimetric flow injection system. Samples for TP were digested prior to analysis. Total Kjeldahl nitrogen (TKN) was calculated as the sum of N_{org} and NH_3–N. Total nitrogen (TN) was calculated as the sum of TKN and $NO_3 + NO_2$–N. All water quality analysis was performed by the Center for Environmental Sciences and Engineering at the University of Connecticut.

2.3. Statistics

Analysis of variance (ANOVA) of regression was used to determine the significance of the regression relationships between paired observations for the calibration period and then again for the treatment period. Analysis of covariance (ANCOVA) was used to determine whether significant differences due to the treatment existed between slopes and intercepts of the flow regressions for the calibration and treatment periods using SAS™ version 9.1 (SAS Institute Inc., 2003). Water quantity and quality data were log transformed prior to analysis, as the data was found to be log-normally distributed. No calibration was conducted for water quality observations. Analysis of variance (ANOVA) and the Tukey–Kramer HSD means comparison was used to determine if significant differences existed in mean nutrient and metal concentrations between precipitation, green roof, and the control watershed runoff during the treatment period, using JMP™ version 5.01a (SAS Institute Inc., 2002). A value of one-half the detection limit was used for any analytes reported as "not detected" if the total number of non-detects was < 15% (USEPA, 2000). A trimmed mean was calculated if the number of non-detects was between 15 and 50% (USEPA, 2000). A Chi-square test was used to determine if differences existed in the proportion of the number of samples below detection between the control and treatment watersheds (USEPA, 2000). The percent change in runoff after the addition of the green roof, using the paired watershed study design, was calculated from the difference between runoff predicted by the calibration equation and

Table 1
Green roof overall water balance for the period September 2, 2009 to February 1, 2010, Storrs, CT.

	cm	%
Input		
Precipitation	48.1	100
Output		
Green roof runoff	28.1	58.4
Green roof ET	20.2	42.0
Residual	−0.2	0.4

observed runoff as: % change = [(Treatment observed − Treatment predicted)/Treatment predicted] × 100. The percent retention for nutrients and metals mass export (kg ha^{-1} yr^{-1}) in runoff from the green roof and control watersheds was calculated as: % retention = [(input − export)/input] × 100.

3. Results and discussion

3.1. Precipitation

From January 25, 2009 to February 1, 2010, 130.7 cm of precipitation from 97 storms fell at the study site, which was 0.4% below the 30-year normal for Storrs, Connecticut (NOAA, 2008). From December 5, 2009 to February 1, 2010, the majority of the precipitation was in the form of snow. Monthly departures from normal ranged from −60 to +67% during this study.

3.2. Water balance

The green roof retained 41.6% of the precipitation during the treatment period based on the water balance [(precipitation − runoff)/precipitation)] × 100 (Table 1). Extrapolating the 81% green roof coverage to 100%, on a per unit area basis, resulted in a retention of 51.4%. The average runoff coefficient (ratio of runoff to precipitation) during the calibration period was 0.70 and 0.71 for the control and treatment watersheds, respectively. During the calibration period, the mean runoff was 0.55 and 0.67 cm wk^{-1} for the control and treatment watersheds, respectively (Table 2). Both the calibration and treatment regressions were found to be significant ($p < 0.001$). The calibration regression equation (Treatment = $1.23\mathrm{Control}^{0.77586}$) was used to predict the expected mean runoff from the treatment watershed (1.63 cm wk^{-1}) given the mean runoff observed from the control watershed (1.44 cm wk^{-1}) (Table 2). Based on the mean difference between the runoff predicted and observed, the weekly runoff from the green roof decreased 34% ($p < 0.001$) (Table 2). The average runoff coefficient for the green roof during the treatment period also decreased from 0.71 to 0.55. Evapotranspiration from the green roof was 42% of total precipitation during the study period based on the weighing lysimeter data (Table 1). The average evapotranspiration rate from the green roof during the study period was 1.6 mm d^{-1}. The interval between rainstorms ranged from one to seven days with an average of three antecedent dry days between rainstorms. In the fall, during a seven-day period with no precipitation, the average water loss from the green roof was 1.28 mm d^{-1}. By comparison, the average water loss from green roof, lysimeter test beds in Pennsylvania, during the first seven days in a 14-day dry period, was similar at ∼1.25 mm d^{-1} (Berghage et al., 2009).

The retention of precipitation by this green roof was less than the average retentions for other green roof studies reported in the literature (Fig. 1). The plaza roof watershed displayed characteristics of a natural watershed, by storing water on the underlying roof surface and subsequent loss through evaporation. Berghage et al. (2009) found that even the flat, rolled asphalt roofs in a Pennsylvania green roof study retained 14% of precipitation. And VanWoert et al. (2005) observed that the 2-cm gravel ballast roof in the green roof study in Michigan retained 27.2% of the precipitation. The control roof in this study retained 26.8% of the precipitation.

Differences in the performance of green roofs to reduce stormwater runoff will vary based on the green roof characteristics and weather conditions (Berndtsson, 2010). In addition, the period of study would influence green roof retention. Green roof studies in Michigan and Pennsylvania occurred in a similar regional climate as this study and resulted in similar retention results (Fig. 1) (Berghage et al., 2009; VanWoert et al., 2005).

From a design standpoint, results from several green roof studies indicate that the mass balance retention is similar to long-term evapotranspiration. Based on normal 30-year annual precipitation (NOAA-NWS, 2010) and average annual discharge values (USGS, 2010), there was a significant relationship between precipitation − discharge = watershed evapotranspiration and % retention ($R^2 = 0.879$) for this study and five other studies (Table 3). This analysis did not include results from Oregon (Hutchinson et al., 2003; Spolek, 2008), which had either much greater or less than expected retention, perhaps due to climate patterns. We also did not include results from Germany, Sweden, and the UK for which long term precipitation and discharge data were not readily available.

3.3. Nitrogen and phosphorus

TN and $NO_3 + NO_2$–N concentrations were not significantly different between green roof runoff and precipitation, but the control watershed runoff concentrations were significantly ($p = 0.002$) higher (Table 4). NH_3–N concentrations in precipitation were significantly ($p < 0.001$) higher than in green roof and control runoff. TN concentrations in green roof runoff ranged from 0.275 mg L^{-1} to 1.264 mg L^{-1} which was lower than that reported in other green roof studies (Berndtsson et al., 2009; Hathaway et al., 2008; Teemusk and Mander, 2007). For example, in North Carolina, the mean concentration of TN in green roof runoff ranged from 0.07 mg L^{-1} to 6.9 mg L^{-1} (Hathaway et al., 2008). Possible reasons for the lower concentration of TN in the green roof runoff compared to other studies include differences in wet deposition input, fertilizer, and the growing media. In Connecticut, wet deposition of TN in rural sites was estimated to be 7.8 kg ha^{-1} yr^{-1} (Nadim et al., 2001). Berndtsson et al. (2006) estimated wet deposition of

Table 2
Mean predicted and observed values and percent change from the treatment (green roof) and control watersheds during the calibration and treatment periods for the plaza in Storrs, CT. from January 25, 2009 to February 1, 2010.

Characteristic	Calibration period (n = 29)		Treatment Period (n = 18)			Calibration equation	% Change	ANCOVA	
				Treatment (Green roof)					
	Control	Treatment	Control	Observed	Predicted			F	p
Adjusted runoff (cm wk^{-1})	0.55	0.67	1.44	1.07	1.63	$T = 1.23C^{0.77586}$	−34	63.81	<0.001

C = control; T = treatment.

Table 3
Comparison of green roof retention to calculated watershed evapotranspiration (ET) for six studies in North America.

Location	Normal precipitation (mm)	Average runoff (mm)	Calculated ET %	Reported retention %	Green roof reference
Athens, GA	1215	449	63.0	62.4	Carter and Rasmussen (2006)
E. Lansing, MI	829	347	58.1	60.6	VanWoert et al. (2005)
Goldsboro, NC	1093	357	67.3	64.0	Hathaway et al. (2008)
Storrs, CT	1312	624	52.4	51.4	This study
Toronto, CA	818	350	57.2	54.1	MacMillan (2004)
University Park, PA	1087	535	50.8	52.6	Berghage et al. (2009)

Table 4
Summary of geometric means and multiple range test for green roof runoff, control site runoff, and precipitation from the plaza green roof in Storrs, CT from September 2, 2009 to February 1, 2010 for nutrients and metals.

Variable	Runoff		Precipitation	*F* value	*p* Value[*]
	Green roof	Control site			
TN[a] ($mg\,L^{-1}$)	0.490a	0.896b	0.510a	6.927	0.002
TKN[a] ($mg\,L^{-1}$)	0.111a	0.132a	0.227a	2.626	0.082
NO_3+NO_2–N[a] ($mg\,L^{-1}$)	0.369a	0.702b	0.265a	12.507	<0.001
NH_3–N[a] ($mg\,L^{-1}$)	0.023a	0.019a	0.101b	14.950	<0.001
TP[a] ($mg\,L^{-1}$)	0.043b	0.197c	0.007a	120.703	<0.001
PO_4–P[a] ($mg\,L^{-1}$) ($mg\,L^{-1}$)	0.025b	0.165c	0.004a	193.094	<0.001
Zn (total)[b] ($\mu g\,L^{-1}$)	11a	64c	30b	22.417	<0.001
Zn (dissolved)[b] ($\mu g\,L^{-1}$)	11a	60c	29b	24.417	<0.001
Hg (total)[c] ($ng\,L^{-1}$)	4a	3a	5a	3.034	0.067
Hg (dissolved)[c] ($ng\,L^{-1}$)	4ab	2a	5b	7.215	0.004
Cu (total)[b] ($\mu g\,L^{-1}$)	6[d]	–	–	–	–
Cu (dissolved)[b] ($\mu g\,L^{-1}$)	6[d]	–	–	–	–

[*] Concentrations followed by the same letter are not significantly different at $p = 0.05$.
[a] $n = 19$.
[b] $n = 14$.
[c] $n = 9$.
[d] Trimmed mean.

TN for the green roof study in Sweden to be 9.1 $kg\,ha^{-1}\,yr^{-1}$. In this study, wet deposition of TN was 6.3 $kg\,ha^{-1}\,yr^{-1}$ (Table 5). Furthermore, green roof studies have found that slow release fertilizers result in less N and P in runoff, compared to conventional fertilizers (Berndtsson et al., 2006; Emilsson et al., 2007). The media used in this green roof was primarily expanded shale, which has been shown to be effective in the sorption of pollutants found in precipitation (Long et al., 2006).

TP and PO_4–P concentrations in runoff from the green roof and control watersheds were significantly greater ($p < 0.001$) than in precipitation (Table 4). Also, TP was greater in control runoff than in green roof runoff (Table 4). TP and PO_4–P concentrations in green roof runoff ranged from 0.018 $mg\,L^{-1}$ to 0.096 $mg\,L^{-1}$ and 0.003 $mg\,L^{-1}$ to 0.079 $mg\,L^{-1}$, respectively, which were lower than reported in other green roof studies (Berghage et al., 2009; Berndtsson et al., 2009; Hathaway et al., 2008; Hutchinson et al., 2003; Liptan and Strecker, 2003). In Sweden, the fertilizer used during plant establishment was cited as a probable source of P in green roof runoff (Berndtsson et al., 2009). Though the green roof was a source of P compared to the input by precipitation, the lower

Table 5
Mass input and export ($kg\,ha^{-1}\,yr^{-1}$) and (% retention) of nutrients and metals in runoff from the plaza green roof and control watershed, Storrs, CT from September 2, 2009, to February 1, 2010.

Nutrients[1]	TN	TKN	NO_3+NO_2–N	NH_3–N	TP	PO_4–P
Input						
Precipitation	6.29	2.56	3.73	1.47	0.11	0.05
Export						
Green roof	4.27	1.39	2.88	0.18	0.32	0.21
% Retention	(32.1)	(45.7)	(22.8)	(87.8)	(−191)	(−320)
Control	10.82	2.27	8.55	0.34	2.00	1.71
% Retention	(−72.0)	(11.3)	(−129)	(76.9)	(−1718)	(−3320)

Metals	Total				Dissolved			
	Cu[a]	Pb[a]	Zn[a]	Hg[c]	Cu[b]	Pb[b]	Zn[b]	Hg[c]
Input								
Precipitation	0.02	0.11	0.38	4.30E−5	0.03	0.12	0.41	5.61E−5
Export								
Green roof	0.03	0.00	0.13	1.68E−5	0.02	0.00	0.12	2.51E−5
% Retention	(−50.0)	(100)	(65.8)	(60.9)	(33.3)	(100)	(70.7)	(32.5)
Control	0.03	0.00	0.65	1.42E−5	0.02	0.00	0.56	1.74E−5
% Retention	(−50.0)	(100)	(−71.1)	(67.0)	(33.3)	(100)	(−36.6)	(69.0)

[a] $n = 19$.
[b] $n = 14$.
[c] $n = 9$.

than expected concentration of P in runoff may be attributed to the growing media and fertilizer, which has been cited to influence P concentrations (Emilsson et al., 2007; Long et al., 2006).

The only nutrients not retained well by the green roof were TP and PO_4–P (Table 5). The higher P in runoff could have come from either the modules or storage on other components of the roof. In addition, mass export by the green roof was lower for all nutrients compared to control watershed export (Table 5). Total P export was less than that reported in green roof studies in Sweden and Pennsylvania (Berghage et al., 2009; Berndtsson et al., 2006). In North Carolina, a column study of the green roof media determined that the compost in the media was the source of the TP and TN in green roof runoff (Hathaway et al., 2008). It was suggested that the source of P in green roof runoff in Sweden was possibly fertilization during plant establishment (Berndtsson et al., 2006, 2009). In Estonia (Teemusk and Mander, 2006), the green roof was not fertilized and the media was comprised of 66% lightweight aggregate, 30% humus, and 4% clay. The Estonia green roof retained both TP and PO_4–P during moderate runoff, but was a source of TP and PO_4–P during rainstorms with high runoff. Concentration of TP in the green roof runoff ranged from 0.026 mg L^{-1} during periods of moderate runoff to 0.090 mg L^{-1} during high runoff and was lower than for other green roof studies (Teemusk and Mander, 2006). In this Connecticut study, P concentrations in runoff did not increase with higher weekly precipitation. Total P concentrations in green roof runoff ranged from 0.018 mg L^{-1} to 0.096 mg L^{-1}; the highest TP concentration in green roof runoff of 0.096 mg L^{-1} was observed during one period of snowmelt. Phosphorus concentrations in green roof runoff were similar to that observed in Estonia (Teemusk and Mander, 2006). Although the concentration of P in green roof runoff was lower than most other studies, the growing media and slow release fertilizer may still be a source of P.

3.4. Metals

Copper was detected in 74% of the green roof runoff samples. Copper concentrations ranged from the detection limit of 5 $\mu g\,L^{-1}$ to 9 $\mu g\,L^{-1}$ for total and 6 $\mu g\,L^{-1}$ to 8 $\mu g\,L^{-1}$ for dissolved, with a trimmed mean of 6 $\mu g\,L^{-1}$ for both forms (Table 4). Copper was detected in only 27% and 43% of the precipitation and control runoff samples, respectively. The green roof runoff dissolved Cu concentration is similar to that reported in Oregon (Hutchinson et al., 2003; Liptan and Strecker, 2003), and less than observed for total Cu in Sweden and Germany (Berndtsson et al., 2009; Göbel et al., 2007). A potential source for Cu in green roof runoff may be the Harrell's fertilizer which contained 0.042% water soluble Cu in the form of a polymer coated copper sulfate ($CuSO_4$).

Cadmium was not found at concentrations above the detection limit of 1 $\mu g\,L^{-1}$. Chromium was detected in precipitation and green roof runoff at a maximum value of 8 $\mu g\,L^{-1}$ and 2 $\mu g\,L^{-1}$, respectively, with >73% of the samples at or below the detection limit of 1 $\mu g\,L^{-1}$.

The green roof was a sink for Zn, with the geometric mean concentration in precipitation and the control runoff significantly higher in both total and dissolved Zn than in green roof runoff (Table 4). Zinc concentrations in precipitation ranged from 6 $\mu g\,L^{-1}$ to 93 $\mu g\,L^{-1}$ and 6 to 59 $\mu g\,L^{-1}$, for total and dissolved Zn, respectively. Runoff from the green roof contained from 6 $\mu g\,L^{-1}$ to 54 $\mu g\,L^{-1}$ for both total and dissolved Zn. Total Zn concentrations in green roof runoff were similar to those reported in Pennsylvania (Berghage et al., 2009) and less than reported in Sweden (Berndtsson et al., 2009). The retention of heavy metals, such as Zn, may be due to stabilization in the media through repeated wetting and drying cycles (Han et al., 2001) and the formation of chelates with organic materials (Kadlec and Knight, 1996). Additionally, in one study, composted biosolids were found to lower the solubility of Zn and increase Zn retention (Madrid and Florido, 2010). Overall, the green roof retained over 65% of the Zn input from precipitation (Table 5).

Interestingly, during the period October 27 to November 24, 2009, Pb was observed in precipitation at concentrations ranging from 10 $\mu g\,L^{-1}$ to 101 $\mu g\,L^{-1}$ total and 10 $\mu g\,L^{-1}$ to 95 $\mu g\,L^{-1}$ dissolved. Lead was not detected in precipitation again until December 15, 2009 to February 1, 2010, with concentrations ranging from 13 $\mu g\,L^{-1}$ to 35 $\mu g\,L^{-1}$ and 6 $\mu g\,L^{-1}$ to 12 $\mu g\,L^{-1}$ for total and dissolved Pb, respectively. The occurrence of Pb in the precipitation samples may have been associated with construction and excavation being conducted near the study site. Until the early 1980s, the primary source of Pb in roadside soils was from the burning of gasoline with lead additives by automobiles (Turer et al., 2001). The excavation in the surrounding areas may be responsible for the re-mobilization of the Pb (Turer et al., 2001) from the soil to the atmosphere and subsequent scavenging and deposition in precipitation. Similar to Zn, the composted biosolids may contribute to the retention of Pb in the green roof (Madrid and Florido, 2010).

No significant differences in total Hg concentrations were found between precipitation, green roof, and control roof runoff (Table 4). However, dissolved Hg concentrations in precipitation were significantly higher than in control runoff (Table 4). The mean total Hg concentration in Connecticut precipitation has been reported to be 6.2 ng L^{-1} (Xu et al., 2000) which was higher than the 5 ng L^{-1} observed in this study (Table 4).

4. Conclusions

Overall, this green roof retained 34% more precipitation than predicted. Using a water balance, the green roof retained 51.4% of the precipitation when extrapolated to total coverage of the watershed. When designing green roofs in most of the U.S., their expected retention can be estimated from the average evapotranspiration based on the difference between the normal annual precipitation and average discharge for a locality. The green roof acted as a sink for NH_3–N, Pb and Zn, with minor retention of TN and TKN, perhaps due to the expanded shale and biosolids media. However, the green roof was a source of NO_3 + NO_2–N, TP, PO_4–P, and Cu. The Harrel's fertilizer used on the green roof was a likely source of Cu. Greater than 90% of the Cu, Hg, and Zn concentrations found in the green roof runoff were in the dissolved form. The combination of the vegetation, lightweight expanded shale and composted biosolids reduced the export of TN, TKN, NO_3 + NO_2–N, NH_3–N, dissolved Cu, Pb, and Zn through the retention of precipitation, and the utilization, transformation, and/or storage of the pollutants. Overall the green roof was effective in reducing stormwater runoff and overall pollutant loading reduction for most water quality contaminants.

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