Plot Scale Evaluation of the Hydrologic and Water Quality Benefits of Blue Roofs Compared to Green and Conventional Roofs

Research

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Highlights

- There were no significant differences ($\alpha = 0.05$) in rainfall retention between blue and green roofs.
- Blue roofs appear to be a viable option to green roofs when the priority is stormwater management.
- Blue and green roofs need to be studied on larger scales to gain more confidence in the treatment provided.

Abstract. *Impervious surfaces caused by urbanization alter hydrologic conditions. In ultra-urban areas (75% or more impervious), rooftop stormwater control measures (SCMs), such as green roofs, exploit underutilized rooftop space. Green roofs reliably attenuate rainwater, but associated water quality treatment results are not as consistent. This study explored the viability of blue roofs, an emerging technology, as an alternative to green roofs. Nine adjacent plots consisting of three each of conventional (control), green, and blue roofs were constructed in Raleigh, NC. As a part of hydrology monitoring, on-site rainfall was measured using a tipping bucket and verified using a manual gauge. Water quantity data were collected using water level loggers in storage bins placed under the roof plots to record outflow. Measured rainfall retention was similar for blue and green roofs, and both systems were significantly ($\alpha = 0.05$) and substantially (50%) more retentive than control roofs. A comparison of evaporation rates suggested blue roofs may be more effective at regenerating storage capacity than green roofs. Thirteen water quality events were sampled, and the mean total nitrogen (TN) concentration from the green and blue roofs was 5.83 and 2.18 mg/L, respectively. Similarly, the mean total phosphorus (TP) concentration from the green and blue roofs was 2.75 and 0.25 mg/L, respectively. Total suspended solids (TSS) data were collected, but seven of 13 samples were below the practical quantitation limit (2.5 mg/L), and the data were not statistically analyzed. Total kjeldahl nitrogen (TKN), TP, and orthophosphate ($O\text{-}PO_4^{3-}$) concentrations from green roof treatments were significantly ($\alpha = 0.05$) larger than concentrations from blue roofs. Except for nitrate/nitrite nitrogen ($NO_{2,3}$-N), there were no significant differences between blue and control roof pollutant concentrations. However, green roofs often discharged substantially higher pollutant loads than control roofs for every pollutant other than $NO_{2,3}$-N and total ammonical nitrogen (NH_3-N). While blue roofs may lack the aesthetic appeal of green roofs, this study suggests blue roofs are a relatively cost-effective option, likely preferable, when solely focused on the benefits of stormwater management from rooftops.*

Keywords. *Blue roofs, Conventional roofs, Green roofs, Hydrology, Monitoring, Stormwater control measures, Water quality.*

As impervious surfaces replace natural areas, their hydrologic cycle is disrupted, causing flooding from increased stormflow and potentially high pollutant loads discharged to downstream water bodies (Hall and Ellis, 1985; Jennings and Jarnagin, 2002). The US Environmental Protection Agency (US EPA) recognizes urban nonpoint source pollution as the second leading source of national surface water impairment after agricultural runoff (US EPA, 2009). Low impact development (LID) designs for stormwater management attempt to maintain pre-development hydrology through evapotranspiration, reuse, recharge, and infiltration (Holman-Dodds et al., 2003; US EPA, 2000). Pollutant loads are thus mitigated

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through these hydrologic design mechanisms and by reducing concentrations via physical and biogeochemical processes (Ahiablame et al., 2012; DER, 1999; Dietz, 2007).

Rooftops constitute a large portion (40% to 50%) of impervious areas in cities (Dunnett and Kingsbury, 2008) and are historically underutilized for stormwater treatment. Numerous studies have shown green roofs with vegetation can reduce runoff volume by 34% to 80% and mitigate peak flow rates by 44% to 92%, both of which are considered LID benefits (Carpenter and Kaluvakolanu, 2011; Carter and Rasmussen, 2006; DeNardo et al., 2005; Ercolani et al., 2018; Fassman-Beck et al., 2013; Getter et al., 2007; Gregoire and Clausen, 2011; Hathaway et al., 2008; Liu et al., 2019; Mentens et al., 2006; Morgan et al., 2013; Speak et al., 2013; Stovin, 2010; Stovin et al., 2012; Van Seters et al., 2009; VanWoert et al., 2005).

Conversely, water quality related findings for green roofs are highly variable. Some studies suggest green roofs act as a pollutant source, where fertilizer and/or organic matter needed in the media to establish plant communities can leach into runoff (Harper et al., 2015; Hathaway et al., 2008). Moran et al. (2003) found effluent from North Carolina green roofs had total nitrogen (TN) concentrations between 0.8 and 8.0 mg/L, with a mean of 3.6 mg/L. A study on Missouri green roofs by Harper et al. (2015) observed initial TN concentrations greater than 60 mg/L but found concentrations decreased to approximately 10 mg/L nine months post-construction. In contrast, some studies have determined green roofs act as a pollutant sink for TN (Gregoire and Clausen, 2011; Teemusk and Mander, 2007). Green roofs are generally considered to reliably treat other pollutants, such as metals (e.g., Berndtsson et al., 2006; Berndtsson et al., 2009).

As with water quality, there are also conflicting results regarding the economic viability of green roofs. The lack of widespread adoption of this SCM has been attributed to the disparity between installation costs for green and conventional roofs (Clark et al., 2008). Clark et al. (2008) and Niu et al. (2010) found the benefits of green roofs (aesthetics, energy savings, stormwater management, roof longevity, etc.) yield a positive net present value. However, Carter and Keeler (2008) and Sproul et al. (2014) determined these associated benefits do not offset initial costs. Thus, (1) the prevalence of conventional roofing (and the lost treatment opportunities associated with it) coupled with (2) the water quality and economic concerns associated with green roofs have motivated the exploration of alternate rooftop SCMs.

Blue roofs, with only light rock type materials, have been suggested as an alternative to green roofs by mitigating runoff without soil or vegetation. While blue roofs generally lack aesthetic appeal, Almaaitah et al. (2022) found blue roofs with tray orifices of 2.4 mm performed similar to green roofs (52% retention). Additionally, blue roofs appear to require less maintenance, have lower loading on roofs, construction costs, and do not include vegetation, which eliminates the risk of leaching fertilizer and organic matter. This study explores the viability of using blue roofs as an alternative to green roofs. Using plot-scale runoff collected data, this research compares hydrologic mitigation and water quality (nutrient, total suspended solids (TSS)) treatment of blue and green roofs vis-à-vis a control.

Materials and Methods

Site Description

This study was conducted at the North Carolina State University (NCSU) Sediment and Erosion Control Research and Education Facility (SECREF) in Raleigh, NC. The site was free of overhead and adjacent obstructions, including trees (a minimum distance of 40 m), thus mimicking rooftops. Nine roof plots built of lumber were set 1.5 m above the ground to minimize influence from the ground (wind, heat, radiation, vegetation, buildings, etc.), yet provide maintenance access. Tarp walls were mounted around each plot to prevent wind flow underneath the structure. To simulate rooftops, waterproof membranes and centralized drains were installed. Plots were randomly assigned to one of three treatments (blue, green, or control), resulting in three replicates for each treatment (fig. 1).

Control roofs were constructed with a 45-mil ethylene propylene diene monomer (EPDM) pond liner at a slope of less than 0.01%. EPDM is a highly durable synthetic rubber commonly used for roofing applications on low-slope buildings. A single layer of 1.5 m x 1.5 m liner with a 15 cm hole cut in the center was affixed along the outside edges of the plot surface using 8 mm staples. This membrane and slope configuration was applied to each treatment replicate.

Green roofs were constructed using pre-vegetated modular trays purchased from GreenGrid Roofs (West Chester, PA). Pre-vegetated trays are commonly used in extensive green roof applications because the trays are relatively inexpensive and easy to install. The GreenGrid trays used in this project were made with 100% pre-consumer high molecular

Figure 1. Control roof (CR), blue roof (BR), and green roof (GR) plots at NCSU SECREF, Raleigh, NC.

weight polyethylene with ultra-violet (UV) inhibitors and stabilizers. Each modular tray had dimensions of 61 cm x 61 cm x 11 cm (W x L x D) and a maximum saturated weight of 146 kg/m^2 when filled with the recommended mid-Atlantic media.

Each tray was filled with 11 cm of rooflite extensive MC media, which consists of a proprietary blend of lightweight mineral aggregates combined with 30 to 45 g/L of composted organic matter to promote vegetation growth in mid-Atlantic climates (J. Markham, personal communication, 2017). This media meets guidelines published by Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) (Philippi, 2005), a German standard-setting entity in the green roof industry.

Green roof vegetation was grown from GreenGrid's standard mid-Atlantic *Sedum* mat. This mat was chosen to provide immediate full coverage and reduce any potential variation in performance as the *Sedum* matured. The *Sedum* species included in the study were: *album, sexangulare, acre, spurium, kamtschaticum, takesimensis, floriferum, stefco, reflexum, rupestre, and immergrunchen*. The plants were grown to maturity at Sunny Brook Nurseries (Kensington, CT), incorporated into substrate-filled trays, and shipped to the project site as fully vegetated modules with 90 to 95 percent plant coverage (M. Krol, personal communication, 2024). The coverage represented a typical green roof after a full growing season, and plant height ranged from 5 to 15 cm at full maturity.

Based on measurements, the green roof media allows for approximately 25 mm of rainfall storage or plant available water, with orifices drilled in the bottom of the tray. Although moving drainage holes to the side walls of the green roof trays would promote additional rainfall storage or ponding before runoff occurs, a few issues would arise. Prolonged media saturation is not ideal for sedum; planted species would have to tolerate frequently wet conditions. Additional rainfall storage on a green roof would also increase structural loading on the building. The concept of allowing water to flow out the bottom of green roof trays followed industry practice.

Blue roof plots were designed to match green roof storage and were constructed using modified green roof modular trays without vegetation. The blue roof trays were filled with an expanded slate aggregate called Stalite to act as a ballast. The ideal blue roof substrate is lightweight and porous to maximize water storage while alleviating roof loading concerns. Stalite has a porosity of 49% and a density of 800 kg/m^3 (Stalite, 2020). The trays had eight 0.64 cm radius holes (two per side wall) located 6.35 cm from the bottom of the tray (fig. 2). Based on measurements taken during dry conditions that also

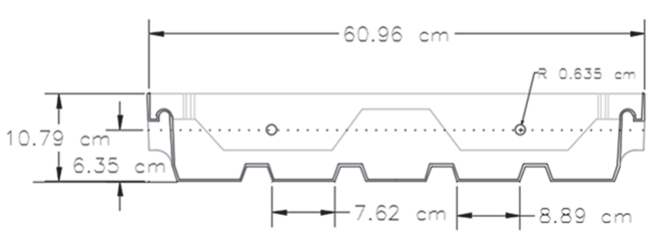

Figure 2. Schematic of modified drainage holes for blue roof application.

accounted for the aggregate, this configuration allowed for 0.20 cm of ponding before runoff occurred. Tables 1-3 summarize blue and green roof plot characteristics.

For each treatment replicate, a 10-cm drainage orifice with a slight bevel was cut in the center of the plywood plot surface (DeGaetano, 2017). A 30 cm x 30 cm piece of EPDM liner was affixed to a standard 10 cm PVC slip coupling using caulk and an internal PVC ring. The plot liner was then sealed to the PVC affixed liner using caulk, and a 10 cm PVC drainage pipe was glued into the coupling. The drainage system was configured in this manner to preserve a watertight surface.

Hydrology Monitoring

Prior to field deployment, a stage-storage equation was developed by incrementally adding a known volume of water to a level bin equipped with an Onset HOBO U20L-04 water level logger and then recording the time and water depth. For each plot, a water level logger was installed at the bottom of a 106 L Rubbermaid container stored below the plot on a level platform to calculate outflow (fig. 3). One designated HOBO logger was deployed onsite to record atmospheric pressure during sampling. Manual measurements of volume verified the logger data. The amount of rainfall retained by the plot was calculated using equations 1 and 2.

Table 1. Blue and green roof characteristics.

Parameter	Blue Roof	Green Roof
Trays	GreenGrid G4	GreenGrid G4
Dimensions (cm)	60.96 W x 60.96 L x 10.79 D	60.96 W x 60.96 L x 10.79 D
Hole position	Side	Bottom
Hole count	8	40
Hole diameter (cm)	1.27	0.64
Media	Stalite 19.05 mm aggregate	rooflite extensive MC
Surface color	Graphite	Green
Estimated albedo[a]	0.25	0.20
Density (kg/m^3)	800	880
Saturated weight (kg/m^3)	1.36	1.28
Porosity	49%	36%
Supplier location	Salisbury, NC	New Milford, CT
Vegetation	None	Sedum Mix
Vegetation Supplier	N/A	Kensington, CT

[a] Levinson et al. (2014) and Susca et al. (2011)

Table 2. Particle size distribution for green roof media (rooflite, 2022).

Proportion of Particles	Mass (%)
< 0.05 mm	≤ 15
< 0.25 mm	5 – 30
< 1.00 mm	10 – 50
< 2.00 mm	30 – 70
< 3.20 mm	40 – 80
< 6.30 mm	65 – 95
< 9.50 mm	80 – 100
< 12.50 mm	100

Table 3. Particle size distribution for Stalite 19.05 mm aggregate (Stalite, 2020).

Proportion of Particles	Mass (%)
< 4.75 mm	0-15
< 9.5 mm	10-50
< 19 mm	90-100
< 25 mm	100

Figure 3. Constructed green roof plot with central drain emptying into runoff storage bin.

$$RV = P * SA * 1000\ L/m^3 \tag{1}$$

where
RV = rainfall volume on plot (L)
P = depth of rainfall event (m)
SA = surface area of plot (m^2).

$$R = 1.0 - O/RV \tag{2}$$

where
R = retention (unitless)
O = measured outflow volume (L)
RV = rainfall volume on plot (L).

An additional blue roof tray with eight 0.64 cm radius holes and without a 10 cm drainage orifice was used to explore the evaporation dynamics of the blue roofs. The tray was placed on an isolated stand adjacent to the plots and outfitted with an Onset HOBO U20L-04 water level logger (Evap1). A second logger (Evap2) was installed in a blue roof plot to corroborate the evaporation rates recorded by Evap1. Blue roof evaporation data showed a distinct diurnal fluctuation; water levels remained consistent overnight and sharply declined during the day due to solar radiation. Evaporation rates were calculated by subtracting the overnight water level from that of the previous day. Evapotranspiration (ET) from the green roof plots was calculated using equation 3, the Penman-Monteith method (Allen et al., 1998), adjusted by a crop coefficient. The crop coefficient described by Lazzarin et al. (2005) was used in equation 3 because plants are generally not water stressed post rainfall and evapotranspire at a relatively high rate (Sherrard and Jacobs, 2012). A water balance between evaporation/ET, rainfall, and storage was not calculated for the roof plots. The evaporation and ET rates were tested for normality using the Shapiro-Wilk test (Shapiro and Wilk, 1965) and Q-Q plots of the residuals. Data that did not follow a normal distribution were log-transformed, and differences in blue roof evaporation and green roof ET rates were determined using a t-test in SAS version 9.4 software.

$$ET_c = K_c \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u^2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u^2\right)} \tag{3}$$

where
ET_c = crop coefficient evapotranspiration (mm/day)
K_c = crop coefficient (unitless)
R_n = net radiation at the crop surface (MJ/m^2/day)
G = soil heat flux density (MJ/m^2/day)
T = mean daily air temperature at 2 m height (°C)
u = wind speed at 2 m height (m/s)
e_s = saturation vapor pressure (kPa)
e_a = actual vapor pressure (kPa)
Δ = slope of vapor pressure curve (kPa/°C)
γ = psychrometric constant (kPa/°C).

Climate Monitoring

The daily average climatological data needed for equation 3 were collected at the Lake Wheeler Road Field Lab (Station LAKE) of the North Carolina State Climate Office. This station, located approximately 600 m NE from the roof plots, was assumed to adequately represent the study site. Rainfall was measured onsite with a Davis Rain Collector II tipping bucket rain gauge equipped with a HOBO pendant event logger and backed up by a manual WeatherShack rain gauge. Both gauges were installed on a wooden post located 3 m NW from the roof plots at a height of 1.5 m from the ground surface. Data from the two gauges were compared to ensure minimal variation between the tipping bucket measured rainfall and the manual rain gauge. The manual data were used to correct the event total by the tipping bucket data, if needed.

Water Quality Monitoring

Runoff from each plot was routed from the central drain into the Rubbermaid container. Within 24 hours of a rainfall event's cessation, samples were collected from each bin for water quality analysis. Prior to retrieving samples, the bins were agitated to re-suspend particulates. Aliquots were placed in bottles designated for each analyte: a 1000 mL plastic bottle for TSS, a 125 mL amber glass bottle for P species, and a 125 mL pre-acidified (0.3 mL of 50% sulfuric acid) plastic bottle for N species. Samples were placed on ice, kept below 6°C, and transported to a laboratory for analysis within one hour after collection, on average. Each sample was analyzed for TKN, $NO_{2,3}$-N, TN, NH_3-N, TP, O-PO_4^{3-}, and TSS (table 4) by the Center for Applied Aquatic Ecology (CAAE) in Raleigh, NC. For statistical analysis using SAS version 9.4 software, a value of one-half the reporting limit was used for concentrations found below the practical quantitation limit (PQL) (Clausen and Spooner, 1993). Pollutant loads were calculated by multiplying the outflow concentration by the total outflow volume. The total outflow was quantified by integrating the measured outflow volumes over the course of the storm event. Nutrient concentrations in the green roof media and blue roof substrate were analyzed using the methods described in table 5.

Rainfall Data Processing

Onset HOBOWARE version 3.7.10 software was used to offload rainfall data and account for atmospheric pressure. Total rainfall depths greater than 2.5 mm with an antecedent dry period (ADP) longer than 6-hr were considered individual storms (Driscoll et al., 1989). Tipping bucket rainfall

Table 4. Lab analytical methods and reporting limits (Clausen and Spooner, 1993).

Pollutant	Pollutant Name	Analytical Method	Reporting Limit (µg/L)
$NO_{2,3}$-N	Nitrate/nitrite nitrogen	SM 4500-NO_3-F[a]	5.6[b], 11.2
NH_3-N	Total ammoniacal nitrogen	SM 4500-NH_3-G[a]	7[b], 17.5
TKN	Total kjeldahl nitrogen	SM 4500 N Org D[a]	280
TN	Total nitrogen	TKN + $NO_{2,3}$-N	-
O-PO_4^{3-}	Orthophosphate	SM 4500 P F[a]	6[b], 12
TP	Total phosphorus	SM 4500 P F[a]	10
TSS	Total suspended solids	SM 2540 D[a]	2500

[a] APHA (2012)

[b] Practical quantitation limit used for sample analysis before 09/09/2016

Table 5. Lab analytical methods for green roof media and blue roof substrate (US EPA, 1993).

Pollutant	Pollutant Name	Analytical Method
$NO_{2,3}$-N	Nitrate/nitrite nitrogen	EPA Method 353.2
NH_3-N	Total ammoniacal nitrogen	EPA Method 351.2
TKN	Total kjeldahl nitrogen	EPA Method 351.2

data were adjusted to account for discrepancies between logged and manually measured depths. Manual rain gage values were assumed to be correct for total depth. To account for discrepancies, a correction factor was calculated by dividing the total manual depth by the total tipping bucket depth. Each 0.25 mm tip was multiplied by the factor to obtain the adjusted values.

STATISTICAL ANALYSES

SAS version 9.4 software was used for all statistical analyses, and the data were tested for normality using the Shapiro-Wilk test (Shapiro and Wilk, 1965) and Q-Q plots of the residuals. Data that did not follow a normal distribution were log-transformed to achieve normality. Water quality and hydrologic data from each treatment and its replicates were characterized with descriptive statistics. For both data sets, a linear mixed-effects model with a parameter-wise familywise error rate was used to investigate treatment effects. Mixed linear modeling allows for repeated measurements (storm events) made on the same statistical units (plots) (e.g., Madsen and Thyregod, 2010), and unlike analysis of variance (ANOVA), it does not require additional corrections for missing data (e.g., Alexeyeva, 2017; Finch, 2016). Tukey's procedure was used to conduct all three pairwise comparisons at a level of significance (α) of 0.05 (Tukey, 1949). Residual plots were used to verify the model's performance and legitimacy. Effluent TN and TP concentrations were also compared to target concentrations established by McNett et al. (2010) for stream benthic macroinvertebrate health using exceedance probability plots.

RESULTS AND DISCUSSION

HYDROLOGY

Thirty-one rainfall events were captured during the monitoring period of 1 August 2016 to 10 May 2017. Rainfall ranged from 2.8 to 59.2 mm, and data from two extreme events (208 mm on 10/08/2016 and 215 mm on 04/24/2017) were not included in the analyses due to the runoff exceeding bin storage capacity. Descriptive statistics for rainfall depth and antecedent dry period (ADP) are summarized in table 6 and figure 4. For the observed storm events, the minimum ADP was 12 hrs.

Cumulatively, green and blue roof plots retained 56% and 55% of the total rainfall recorded, respectively. These values are consistent with those of previously monitored green and blue roofs (Almaaitah et al., 2022; Fassman-Beck et al., 2013; Morgan et al., 2013; Speak et al., 2013; Stovin, 2010; Stovin et al., 2012). Descriptive statistics for rainfall retention (R, eq. 2) and measured outflow are included in tables 7 and 8, respectively. Note that complete storm retention (100% of rainfall is retained) resulted in a retention value of 1.00.

The mixed linear model showed no significant difference in rainfall retention between blue and green roof plots (p-value = 0.9092). Conversely, both treatments demonstrated significantly greater retention than control roofs (p-value < 0.014). Factors such as storm size and frequency appeared to influence blue and green roof retention (Berghage et al., 2009; Bliss et al., 2009; Carson et al., 2013; Fassman-Beck et al., 2013; Hathaway et al., 2008; Todorov et al., 2018; Voyde et al., 2010a). Small rainfall storms (< 15 mm) often did not produce outflow, and outflow was proportional to rainfall depths greater than storage capacity. Seasonality did not appear to influence rainfall retention (p-value < 0.05) in contrast to other green roof studies (Berghage et al., 2007; Mentens et al., 2006; Todorov et al., 2018; Voyde et al., 2010b; Wadzuk et al., 2013). Figure 5 summarizes the cumulative runoff from treatment.

There were no significant (α = 0.05) differences between Evap1 and Evap2, where Evap1 refers to the evaporation measured in a standalone blue roof tray and Evap2 refers to the evaporation measured in a blue roof plot. The lack of significant differences indicates the evaporation rates recorded by Evap1 are representative of the evaporation rates within the blue roof trays. The mean evaporation rate from the blue roofs was 4.0 mm/day, or 1700 mL/day. When fully saturated, the blue roof trays held 7500 mL of water; thus, if full, on average 4.5 days without any rainfall were needed to evaporate all the water from the trays. Both blue and green roofs had higher evaporation rates immediately following rainfall, which is consistent with green roof literature (Voyde et al., 2010b; Wadzuk et al., 2013). However, estimated green roof evapotranspiration rates were significantly

Table 6. Descriptive statistics for storm event rainfall and ADP events.

Season	Variable	Number of Storms	Rainfall (mm)	ADP (day)
Spring	Mean	12	10.9	5.2
	Median		9.1	3.6
	Range		2.8-24.1	0.5-14.4
Summer	Mean	4	20.1	7.9
	Median		17.9	6.0
	Range		6.1-38.4	0.9-18.9
Fall	Mean	7	29.4	9.8
	Median		24.9	5.1
	Range		4.8-59.2	0.7-35.0
Winter	Mean	8	11.9	9.7
	Median		13.0	9.6
	Range		4.8-18.3	1.2-20.8

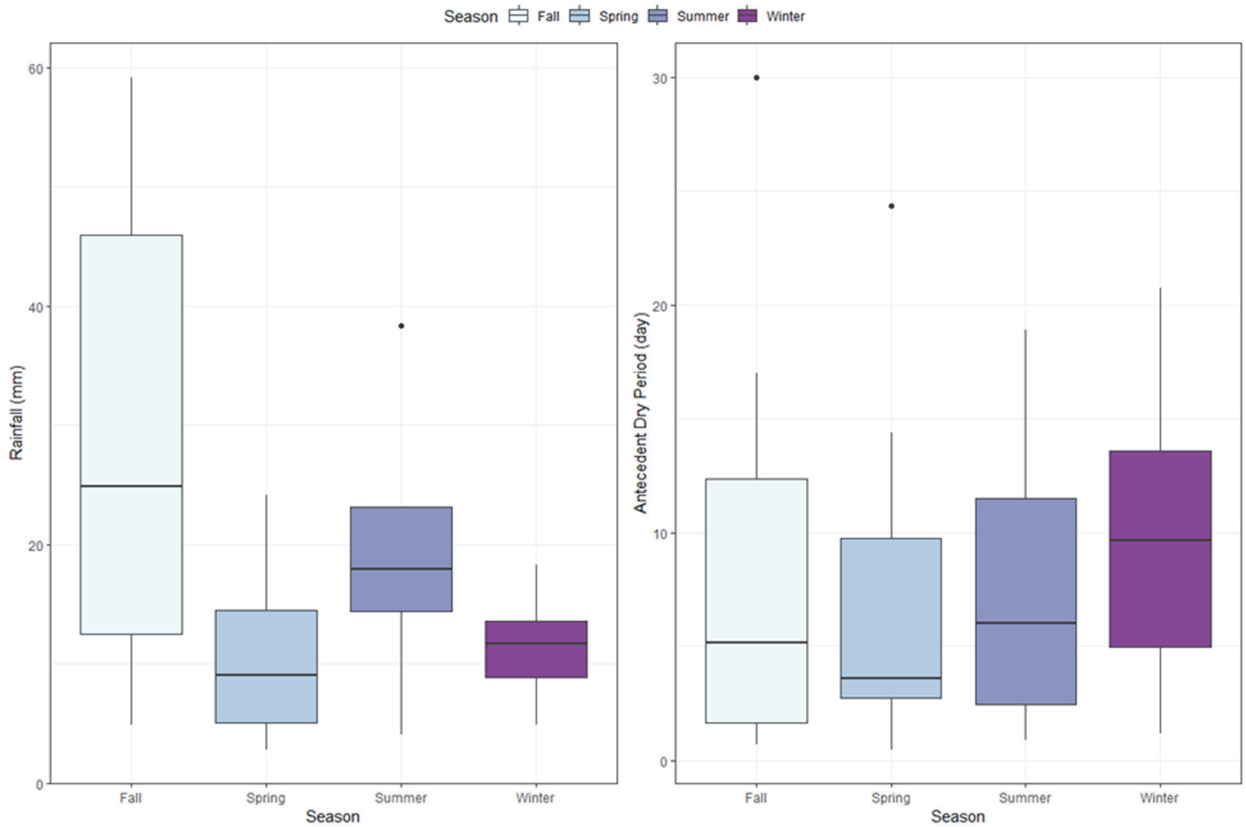

Figure 4. Observed rainfall depths and ADPs.

Table 7. Descriptive statistics for storm event rainfall retention.

Treatment	Replicate	Number of Storms	Minimum	Mean	Median	Maximum
Blue	1	31	0.09	0.79	0.93	1.00
	2		0.07	0.79	0.97	1.00
	3		0.12	0.82	0.97	1.00
	Mean		-	0.80	-	-
Control	1	31	0.00	0.07	0.00	0.69
	2		0.06	0.43	0.28	1.00
	3		0.00	0.14	0.05	1.00
	Mean		-	0.21	-	-
Green	1	31	0.13	0.77	0.90	1.00
	2		0.14	0.78	0.94	1.00
	3		0.14	0.77	0.94	1.00
	Mean		-	0.77	-	-

Table 8. Descriptive statistics for measured outflow.

Treatment	Replicate	Number of Storms	Minimum (L)	Mean (L)	Median (L)	Maximum (L)
Blue	1	31	0	10	0	72
	2		0	10	0	70
	3		0	9	0	65
	Mean		-	10	-	-
Control	1	31	0	25	20	89
	2		0	21	16	85
	3		0	25	19	86
	Mean		-	23	-	-
Green	1	31	0	10	2	64
	2		0	10	0	66
	3		0	11	1	70
	Mean		-	10	-	-

lower than measured blue roof evaporation rates (p-value < 0.01) despite having similar albedos (0.20 versus 0.25) (Levinson et al., 2014; Susca et al., 2011). Differences between the rates were most likely due to storage capacity and the uncertainty of rates predicted by the evapotranspiration model (DiGiovanni et al., 2013; Penman, 1948; Wadzuk

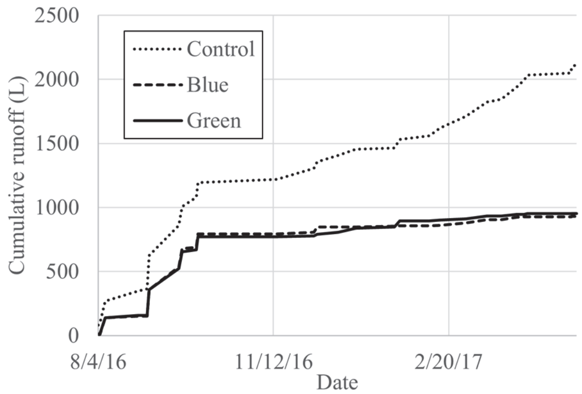

Figure 5. Cumulative runoff by treatment.

et al., 2013). The blue roof trays contained aggregate with a 72-hr absorption rate of 5% by mass; thus, up to 680 mL of rainfall could be absorbed (Stalite, 2020), indicating relatively high porosity of the aggregate (fig. 6).

WATER QUALITY

Thirteen storm events were sampled for water quality, and the rainfall depth for these events ranged from 10.9 to 59.2 mm. Due to the storage capacities of the collection bins, water quality data were only collected for storms with depths between 15 and 63.5 mm to ensure the composite sample was representative of the entire outflow. Sampling personnel's availability during the spring and summer limited the number of water quality events collected during those seasons. TSS data were collected, but seven of the 13 samples had TSS concentrations below the PQL (2.5 mg/L), and these data were not analyzed. Excluding NH_3-N, the concentrations from the control roof plots and blue roof replicates one (B1) and two (B2) were less than those of green roof concentrations (table 9; fig. 7). Data from blue roof replicate three (B3) were excluded from analyses because of the consistently elevated N concentrations.

Sampling began immediately after installation, and research has shown that nutrients leached from green roofs decrease with age (e.g., Harper et al., 2015; Kuoppmäki et al., 2021; Lim, 2023; Malcom et al., 2014). However, there was no decrease in concentrations from the green, blue, or control roof plots over the course of the study. This may be due to a lack of microbial activity (Buffam et al., 2016; John et al., 2017) and/or plant uptake (Emilsson et al., 2007; Xu et al., 2012). The concentrations from the control roofs are comparable to nutrient concentrations measured in rainfall along the East Coast of the United States. Song and Gao (2009) reported that the $NO_{2,3}$-N concentrations in rainfall measured in Newark, NJ, ranged from 0.32 to 4.32 mg/L. Irwin and Kirkland (1980) found TN and TP concentrations in rainfall throughout Florida varied between 0.50 and 2.4 mg/L and 0.03 and 0.30 mg/L, respectively. Average TN and TP concentrations in rainfall measured in Storrs, CT, were 0.51 and 0.007 mg/L, respectively (Gregoire and Clausen, 2011). Concentrations from the blue roofs may have been higher than the control roofs due to leaching from the substrate; measured concentrations of TKN, $NO_{2,3}$-N, and NH_3-N in the substrate were 3.1, 0.55, and 0.86 mg/kg, respectively. Malcom et al. (2014) reported that gravel roof plots discharged TN and TP, albeit the mean TN concentrations ranged from 0.1 to 0.5 mg/L and TP concentrations varied between 0.1 and 0.2 mg/L.

Figure 6. Blue roof trays with Stalite.

Table 10 summarizes the cumulative pollutant loads from each replicate. The TN and TP loads discharged from the blue roof plots ranged from 229 to 635 mg and 11 to 108 mg, respectively. For the green roofs, the TN and TP loads varied between 1,019 and 2,542 mg and 268 and 505 mg, respectively. Nutrient loads from control roof plots are within the range of pollutant loads discharged from blue roof plots. The TN and TP loads were between 388 and 600 mg and 18 and 36 mg, respectively. These results suggest blue roofs do not provide better water quality than conventional roofs but do appear to release lower loads than green roofs.

Elevated TKN and $NO_{2,3}$-N concentrations were observed in green roof replicate three (G3). The elevated $NO_{2,3}$-N concentrations were attributed to a lack of vegetative cover during the initial stages of the study (table 9). Previous research has shown a thriving plant community is necessary for NO_3 uptake (Xu et al., 2012), and bare media can export NO_3 load at concentrations greater than 10 times that of vegetated media (Aitkenhead-Peterson et al., 2011; Emilsson et al., 2007). Additionally, the high P concentrations from the green roof plots can be attributed to leaching (Berndtsson et al., 2009; Bliss et al., 2009; Harper et al., 2015; Hathaway et al., 2008; Razzaghmanesh et al., 2014; Teemusk and Mander, 2007; Van Seters et al., 2009). The average TN and TP concentrations for the green roof plots are within the values reported by Harper et al. (2015) and Teemusk and Mander (2007).

Limited information is available to determine the cause of B3's consistently elevated N concentrations. The aggregate from the three blue roof replicates was analyzed post-monitoring for TKN, NH_3-N, and NO_3, and there were no differences in concentrations among the replicates. This suggests the B3 aggregate did not contain excess nutrients compared to B1 and B2, and instead there was an external source of "nutrients." Previous research has shown animal excreta is a water quality concern (Berndtsson, 2010; Hall and Ellis, 1985). Bird feces were regularly found on B3 and, more importantly, not on the other plots; any influence from the fecal matter was likely exacerbated by the plot's relatively small contributing surface area.

Statistical analyses were performed without B3 data. Significant ($\alpha = 0.05$) differences existed between the blue and green roof treatments for TKN, TP, and O-PO_4^{3-}

Table 9. Mean nutrient concentrations measured in water samples from 13 storm events among three treatments.[a]

Treatment	Replicate	TKN (mg/L)	$NO_{2,3}$-N (mg/L)	TN (mg/L)	NH_3-N (mg/L)	TP (mg/L)	O-PO_4^{3-} (mg/L)
Blue	1	1.16	0.55	1.71	0.63	0.12	0.09
	2	2.03	0.63	2.66	0.83	0.38	0.34
	3	8.32	0.72	9.04	3.23	1.85	2.14
	Mean with B3	3.84	0.63	4.47	1.56	0.78	0.86
	Mean without B3	1.60[a]	0.59[a]	2.18[a,b]	0.73[a]	0.25[a]	0.21[a]
Green	1	3.90	0.83	4.73	0.25	2.70	2.61
	2	3.61	0.29	3.90	0.16	4.32	4.10
	3	6.08	2.78	8.86	0.91	1.23	1.08
	Mean	4.53[b]	1.30[a,b]	5.83[a]	0.44[a]	2.75[b]	2.59[b]
Control	1	0.73	0.16	0.89	0.42	0.04	0.03
	2	1.49	0.23	1.72	0.72	0.11	0.09
	3	0.86	0.15	1.01	0.45	0.05	0.04
	Mean	1.03[a]	0.18[b]	1.21[b]	0.53[a]	0.07[a]	0.05[a]

[a] Superscripts indicate significant differences among treatments (p-value < 0.05).

Table 10. Cumulative pollutant loads per replicate from 13 storm events.

Treatment	Replicate	TKN (mg)	$NO_{2,3}$-N (mg)	TN (mg)	NH_3-N (mg)	TP (mg)	O-PO_4^{3-} (mg)
Blue	1	130	99	229	64	11	7
	2	247	104	351	84	34	28
	3	526	109	635	208	108	107
Mean with B3	-	301	104	405	119	51	47
Mean without B3	-	189	102	290	74	23	18
Green	1	1,006	256	1,262	38	441	420
	2	971	49	1,019	26	505	489
	3	1,526	1,016	2,542	84	268	234
Mean	-	1,168	440	1,608	49	405	381
Control	1	316	72	388	183	18	13
	2	517	82	600	247	36	29
	3	335	68	403	185	22	16
Mean	-	390	74	464	205	25	20

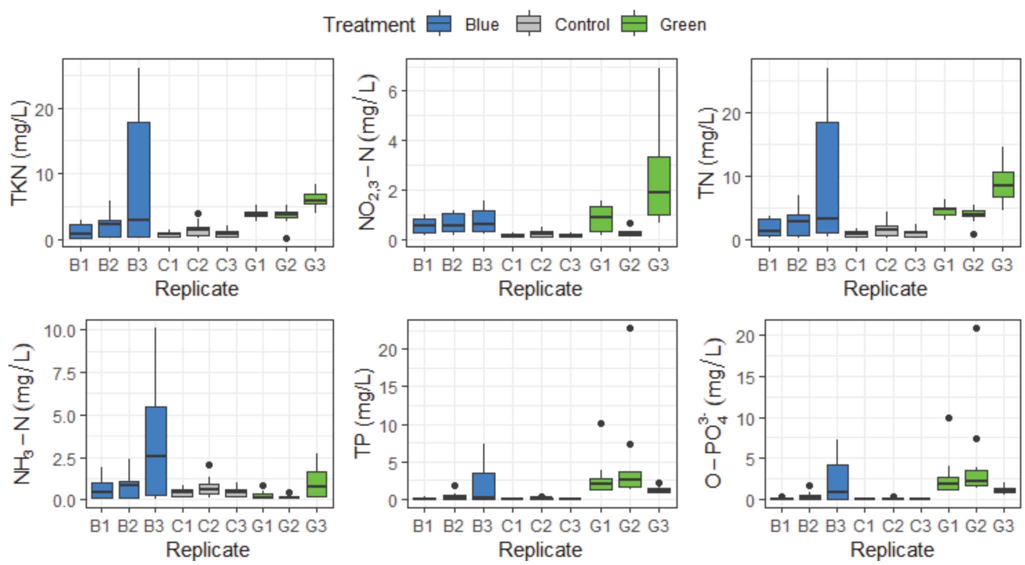

Figure 7. Boxplots of replicates of blue (B – B1, B2, B3), control (C – C1, C2, C3), and green (G – G1, G2, G3) roof plots.

concentrations (table 9). Except for $NO_{2,3}$-N, there were no significant differences in water quality concentrations between blue and control roofs. However, significant differences did exist between green and control roofs for every pollutant concentration, except for $NO_{2,3}$-N and NH_3-N. Significant differences between the blue and green roof concentrations may be caused by the export of organic matter and fertilizer incorporated into green roof media for plant growth (Gregoire and Clausen, 2011; Harper et al., 2015; Hathaway et al., 2008; Razzaghmanesh et al., 2014). Other factors potentially influencing N export from green roofs include age, media depth, and maintenance. Previous studies have shown green roofs' water quality performance improves with age, increased media depth, and limited fertilizer application (i.e., maintenance) (Berndtsson, 2010; Berndtsson et al., 2006; Monterusso et al., 2004; Speak et al., 2013).

Implications of the Study

Each treatment's mean TN and TP concentrations (table 9) were compared to target effluent concentrations established by McNett et al. (2010). These target concentrations were developed to gauge SCM nutrient treatment vis-à-vis the sensitivity of stream benthic macroinvertebrate populations. In the Piedmont ecoregion of NC, the "good" effluent TN concentration is 0.99 mg/L. All three treatments' mean concentrations exceeded this threshold. However, the mean of 1.21 mg/L for the control roof TN concentration (table 9) met the "fair" threshold (2.16 mg/L), and the blue roof concentration (2.18 mg/L) exceeded this limit by 0.02 mg/L (fig. 8). Green roof effluent (5.83 mg/L) exceeded the "fair" criteria by 3.67 mg/L. With respect to TP, only the control roof effluent (0.07 mg/L) met the Piedmont "good" concentration of 0.11 mg/L (fig. 9). Blue roof effluent (0.25 mg/L) exceeded the "fair" criteria by 0.03 mg/L, and green roof effluent (2.75 mg/L) exceeded the "poor" threshold by a factor of 4.4.

Conclusions

This experimental study explored the viability of blue roofs, an emerging technology, as an alternative to green roofs, by evaluating water quality samples collected from nine adjacent plots consisting of blue, green, and control roofs in triplicate. ANOVA models with Tukey's procedure (Tukey, 1949) were used to evaluate the effectiveness of each treatment, and the following conclusions were drawn:

- Rainfall retention was similar, with no significant difference, for blue and green roofs, and both systems were statistically different ($\alpha = 0.05$) from, and retained more water than, the control roofs. A comparison of measured evaporation rates suggested that this blue roof design may be more effective at regenerating storage capacity than green roofs in this climate due to the aggregate's absorption rate. Blue roof designs that include less porous aggregate may provide less rainfall retention than green roofs.
- Green roofs had elevated TN and TP discharge concentrations with a mean of 5.83 and 2.75 mg/L, respectively. The control roof mean TN concentration was 1.21 mg/L, and when excluding replicate 3 due to fouling, the blue mean concentration was 2.18 mg/L. For blue and control roofs, mean TP concentrations were 0.25 and 0.07 mg/L, respectively. There were significant differences between the blue and green roof treatments for TKN, TP, and O-PO_4^{3-}. Except for $NO_{2,3}$-N, there were no significant differences in observed pollutant concentrations between blue and control roofs. However, there were significant differences between green and control roofs for every pollutant concentration, except for $NO_{2,3}$-N and NH_3-N.
- Blue roofs appear to release lower nutrient concentrations and loads when compared to green roofs. Data from this study also show this blue roof design's outflow nutrient concentrations are similar, albeit slightly higher, to those of a conventional roof and that blue and green roofs need to be studied on larger scales for similar evaluations to gain more confidence. Further study is also needed regarding the evaporation rates from blue roofs vis-à-vis green roof evapotranspiration, although this study indicates blue roofs do not provide better water quality than conventional roofs.
- Blue roofs appear to be a viable, perhaps preferable, option to green roofs when the sole focus of SCM selection is stormwater management. Clearly, other ecosystem provision by green roofs (e.g., carbon sequestration, biodiversity) will exceed those by blue roofs, and in many cases, the suite of green roof benefits will likely outweigh those of blue roofs. Additional treatment may be achieved by combining blue or green roofs with another SCM (e.g., downspout disconnection) (Taguchi et al., 2019).

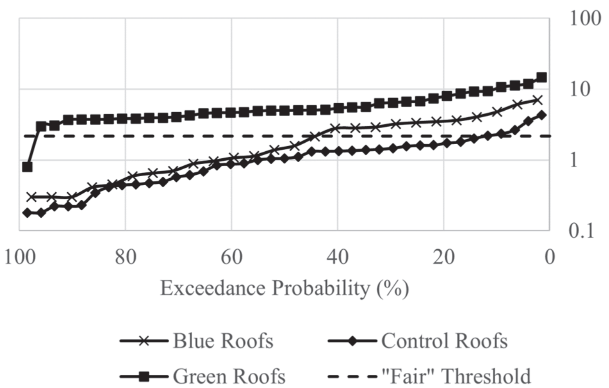

Figure 8. TN exceedance probability plots for replicates (excluding B3) for "fair" threshold of 2.16 mg/L (McNett et al., 2010).

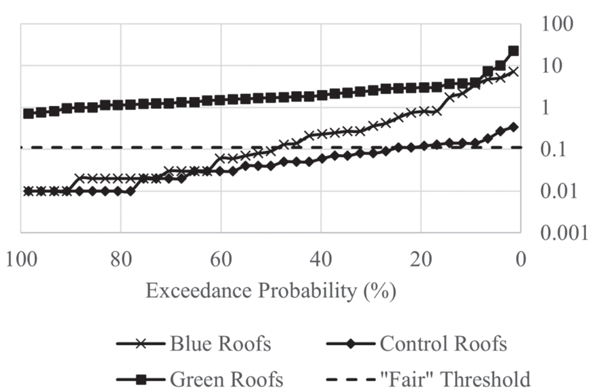

Figure 9. TP exceedance probability plots for replicates for "fair" threshold of 0.22 mg/L (McNett et al., 2010).

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