Thermal Mitigation of Urban Storm Water by Level Spreader–Vegetative Filter Strips

R. J. Winston, A.M.ASCE[1]; W. F. Hunt, A.M.ASCE[2]; and W. G. Lord[3]

Abstract: A study was conducted in Louisburg, North Carolina, to determine the effect of level spreader–vegetative filter strip (LS-VFS) storm-water control measures (SCMs) on runoff temperature and thermal loading. Two LS-VFS systems draining an urban catchment were monitored during the summers of 2008 and 2009. The first VFS was 7.6 m wide and entirely grassed. The second was 15.2 m wide, with the first-half grassed and the second-half wooded. Runoff temperatures and thermal loads from the urban catchment tended to peak toward the beginning of a storm event. Median and maximum storm temperatures were significantly reduced across both the 7.6-m and 15.2-m LS-VFSs. However, median and maximum effluent temperatures for both filter strip lengths were significantly greater than the 21°C trout threshold. Mean and median effluent temperatures from the 15.2-m LS-VFS were slightly lower (< 1°C) than those from the 7.6-m LS-VFS, which may show the impact of increased filter strip width and/or the shading from wooded vegetation on effluent temperatures. Expected differences between influent and effluent temperatures (both median and maximum) were greater as the influent temperature increased. Substantial and statistically significant ($\alpha = 0.05$) thermal load reductions were observed in both LS-VFSs because of measured reductions in both temperature and flow volume. Thermal load was eliminated in seven of 38 storm events because of infiltration of the entire runoff volume in the filter strips. The ability of LS-VFS systems to reduce storm-water temperatures and thermal loads supports their use in thermally sensitive watersheds. **DOI:** 10.1061/(ASCE)EE.1943-7870.0000367. *© 2011 American Society of Civil Engineers.*

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Introduction

Storm-water control measures (SCMs), also referred to as best management practices (BMPs), are typically designed to mitigate peak flow rates, reduce runoff volumes, and reduce pollutant loads in storm-water runoff. SCMs have been evaluated for many pollutants, including nitrogen, phosphorus, sediment, hydrocarbons, and heavy metals. One pollutant that has not traditionally been evaluated with respect to SCMs is temperature. Multiple anthropogenic stressors, including impervious surfaces, effluent from industrial facilities and power plants, as well as destruction of riparian vegetation, increase stream temperature (LeBlanc et al. 1997; Van Buren et al. 2000b; Wilkerson et al. 2006; Encina et al. 2008). Trout and salmon species require maximum daily stream temperatures below 21°C to survive and procreate (Coutant 1977). Rossi and Hari (2007) found that the maximum temperature for a 1-h exposure for 100% trout survival was 25°C. Armour (1991) showed that lethal temperature for brown trout was inversely related to exposure time. The author estimated that a 1-min burst of 32°C stream temperature would be lethal to 50% of the population, and a 7-day exposure time is needed to be lethal at 22°C.

Summer daily maximum asphalt surface temperatures of 60°C have been observed (Diefenderfer et al. 2006). Consequently, runoff temperatures typically exhibit short-term spikes toward the beginning of a storm event. Runoff temperatures exceeded 29°C from highway runoff in Louisiana (Sansalone et al. 2005) and were greater than 30°C for a parking lot in Lenoir, North Carolina (Jones and Hunt 2009). Runoff temperature spikes lead to subsequent spikes in stream temperature; urbanized stream reaches in Maryland exhibited temperature surges of 3.5°C on 10% of summer days, with maximum temperature surges of > 7°C (Nelson and Palmer 2007). To combat impacts of runoff temperature, the U.S. Congress recently included a provision in the Energy Independence and Security Act requiring all federally funded construction exceeding 464 m^2 (5,000 ft^2) to restore predevelopment hydrology with respect to "temperature, rate, volume, and duration of flow" (U.S. Congress 2007).

Increases in stream temperature can have profound effects on stream ecology, including reduced oxygen solubility and increased metabolic rates, raising the susceptibility of organisms to heavy metals, parasites, and diseases (Jones 1975; Wahli et al. 2002). In many cases, aquatic organisms depend on water temperature for growth, development, and reproduction. Long-term thermal impacts have been associated with evolutionary, behavioral, and physiological responses in fish (Matthews 1987; Hinz and Wiley 1997). Trout are among the most sensitive fish to changes in water temperature and are an important game fish in North Carolina.

Some SCMs have been evaluated for their ability to mitigate runoff temperatures before they adversely affect cold-water streams. Studies have shown that thermal impacts of storm-water runoff can be exacerbated by traditionally designed, noninfiltrating

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SCMs (Galli 1990; Lieb and Carline 2000; Van Buren et al. 2000a; Kieser et al. 2004; Herb et al. 2009; Jones and Hunt 2010). In particular, wet ponds often have little shading, allowing thermal radiation effects to occur, which often cause this SCM to be a source of thermal pollution. When compared to an untreated watershed, practices that impound water, such as dry ponds, wet ponds, and storm-water wetlands, will often release storm water with elevated temperatures over longer durations (Herb et al. 2009; Jones and Hunt 2010). Conversely, SCMs located underground, free from sun exposure, have shown the ability to mitigate temperature (Natarajan and Davis 2010).

Aboveground SCMs that temporarily store runoff belowground (such as bioretention) can also reduce thermal loads. Four bioretention areas studied in the mountain ecoregion of North Carolina reduced maximum storm-flow temperatures, with coolest effluent temperatures from cells with deeper soil media depth (Jones and Hunt 2009). Proportionally larger cells reduced the frequency of outflow. Dietz and Clausen (2005) found that shallow soil media depth (0.6 m) may be insufficient to improve storm-water temperatures. Although runoff temperatures in both aforementioned bioretention studies were not reduced to the trout threshold of 21°C, bioretention areas show promise for future use in mitigating the impacts of thermal pollution.

One SCM that has not been studied for its effects on runoff temperature is the level spreader–vegetative filter strip (LS-VFS). Level spreaders provide diffuse flow across the upslope end of a grassed or forested VFS, with the VFS providing the storm-water treatment; these systems have been tested for hydrologic, nutrient, sediment, and heavy metal attenuation (Yu et al. 1993; Line and Hunt 2009; Hunt et al. 2010; Winston et al. 2011). Since LS-VFS systems may have a canopy cover and can infiltrate storm flow (depending on underlying soil type), reason suggests they may be an effective SCM to reduce the thermal loads of urban storm-water runoff to cold-water streams (thermal load is the product of flow volume and temperature). Four LS-VFS studies showed reduction in flow volumes ranging from 36 to 80% (Yu et al. 1993; Line and Hunt 2009; Hunt et al. 2010, Winston et al. 2011). Infiltrated water will cool through heat transfer with soil particles before entering a cold-water stream as baseflow or contributing to aquifer recharge. If soil and vegetation temperatures in the filter strip are lower than that of the thermally enriched runoff, thermodynamic theory suggests that outflow temperature will be necessarily lower than that of inflow. Also, thermal load reduction from a LS-VFS may occur from reduction in flow volumes. The study presented herein evaluated two side-by-side LS-VFS SCMs for their impact on runoff temperature over two consecutive summers.

Site Description

Two retrofit level spreaders were constructed in winter 2007–2008 to drain a small, highly impervious catchment in Louisburg, North Carolina (36°05′ N; 78°19′ W). The 30-year mean annual precipitation for Louisburg was 1,163 mm (North Carolina Climate Office 2010). The VFSs consisted of volunteer vegetation and existing slopes were not adjusted. Designs for the LS-VFSs were based on design guidance in the North Carolina Department of Environment and Natural Resources, Division of Water Quality, Storm-water BMP Design Manual (NCDENR 2007).

The drainage area was composed of rooftop (0.04 ha), an associated parking lot (0.19 ha), landscaped area (0.12 ha), and portions of North Carolina Highway 56 (0.05 ha) (Fig. 1). Runoff from the catchment entered a small forebay, where flow was stilled, and then flow was split proportionately to each LS-VFS by using 15-cm-diameter PVC pipes (Fig. 2).

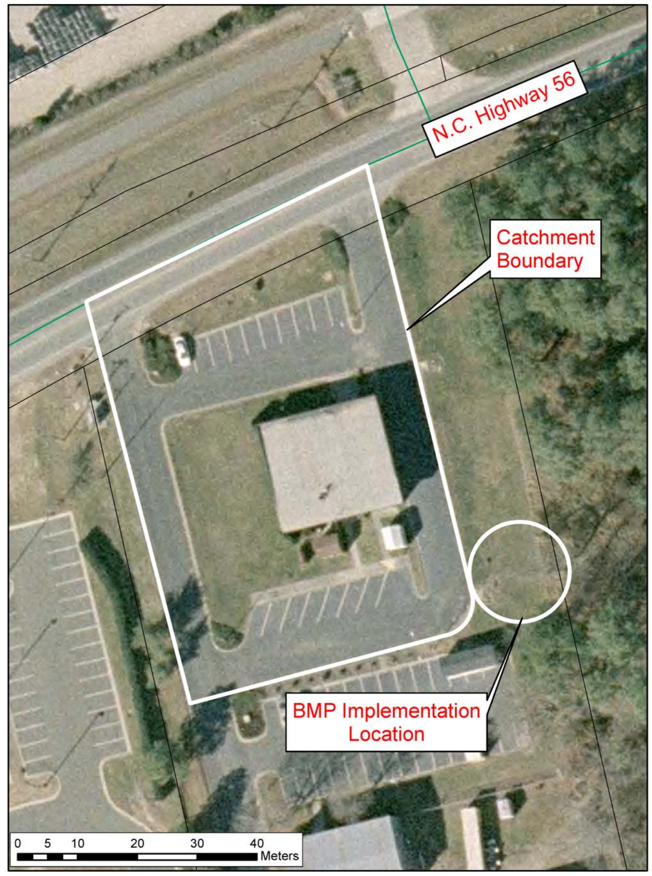

Fig. 1. Plan view of catchment and approximate location of LS-VFSs (aerial photo from NC One Map, http://www.nconemap.org/)

Two concrete level spreaders, each 4.0 m in length, were constructed to disperse flow across the upslope end of two VFSs. Water passed from the forebay into two "blind" swales (small swales used to pond water behind the level lip), over the level spreader, and into the filter strip for treatment (Fig. 2). The smaller VFS was 4.0 m

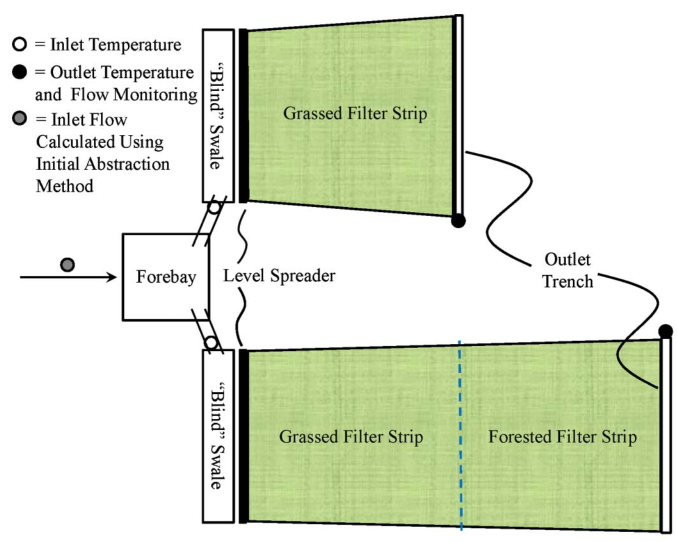

Fig. 2. Plan view of LS-VFSs and associated monitoring locations

wide and 7.6 m long, with the width increasing to 5.4 m at the downslope end. Total VFS surface area was 38.9 m^2. Warm-season grasses (primarily centipede) were the predominate land cover for the 7.6 m filter strip, and longitudinal slope was 4.9%. The larger VFS was 4.0 m in width and 15.2 m in length, with the width increasing to 6.2 m at the downslope end of the VFS. Total VFS surface area was 86.5 m^2, with a longitudinal slope of 7.0%. Warm-season grasses were prevalent for the first 7.6 m of VFS length, with a wooded buffer comprising the latter 7.6 m. For further details on the catchment, soils, level spreaders, and filter strips, see Winston et al. (2011).

Methods

Data Collection

Total rainfall depth was measured using a nonrecording manual rain gauge. Rainfall data from a tipping bucket recording rain gauge were corrected on a storm-by-storm basis to reflect rainfall depths measured by the manual rain gauge. Rainfall intensities were then calculated from corrected tipping bucket rainfall data.

The research site was outfitted with four temperature sensors to monitor inlet and outlet temperatures of both the 7.6 m and 15.2 m VFSs (Fig. 2). A temperature sensor was fixed to the bottom of each inlet pipe; the temperature sensors used were HOBO TMC50-HD, which can accurately measure water temperatures between −40°C and 50°C with an accuracy of ±0.21°C (Onset Computer Corp.). Influent temperatures were statistically similar and never varied by more than 0.4°C; therefore, an average influent temperature was used for all data analysis. Temperature measurements were also logged at the outlet to both the 7.6-m and 15.2-m LS-VFSs by affixing the temperature sensor in a PVC pipe draining the outlet structure.

Temperature sensors were connected to HOBO U12-008 four channel loggers, which were downloaded every 3 weeks. Temperature data were logged both during and after rain events; analyses were performed only on data obtained while flow was occurring, as determined by flow measurements taken at the inlet and outlet. All temperature measurements were recorded on a 2-min interval.

Flow measurements were obtained or computed at three locations (Fig. 2). Influent flow volumes were calculated using the initial abstraction method (Li et al. 2009) for the two land-use types (pervious lawn and impervious surfaces) (Fangmeier et al. 2006), which was corrected for antecedent moisture conditions (Table 1). This method assumes that all rainfall above the calculated initial abstraction was transmitted as runoff. Effluent flow volumes were determined by using a 30° *v*-notch weir with an ISCO 730 bubbler module that measured stage over the weir. The standard 30° *v*-notch weir equation was used to calculate flow rates (Eq. (1)); the area under the hydrograph was calculated to generate outflow volumes

Table 1. Variations in Curve Number and Initial Abstraction Based on Antecedent Moisture Conditions (USDA-NRCS 2004)

Antecedent moisture condition	Curve number and (initial abstraction): Pervious land use	Curve number and (initial abstraction): Impervious land use	Antecedent dry period
1 (dry)	41 (73.1 mm)	94 (3.2 mm)	> 120 h
2 (average)	61 (32.5 mm)	98 (1.0 mm)	48 to 120 h
3 (wet)	78 (14.3 mm)	99 (0.5 mm)	< 48 h

$$Q = 373.2 \times H^{2.5} \tag{1}$$

where Q = flow rate (L/s); and H = head (m).

Data were collected during the summer months (May–September) of 2008 and 2009.

Data Analysis

Influent and effluent storm-water temperatures were compared on a storm-by-storm basis. Storm events had a minimum rainfall depth of 2.5 mm and a minimum antecedent dry period (ADP) of 6 h. Analysis of temperature data occurred only during storm flow. Temperature data were only analyzed during May through September, since these are the warmest months for storm-water temperatures (Jones and Hunt 2009). Minimum, median, and maximum influent and effluent temperatures were compared statistically to determine if LS-VFSs mitigated thermal impacts of urban storm water.

Median, mean, and maximum monthly storm-flow temperatures were compared to monthly ambient air temperatures. Also, summary statistics for storm-water temperatures over the 8-month monitoring period are presented and compared to past research. These were the only analyses in this paper that were not carried out on a storm-by-storm basis.

Thermal load is widely applied in surface water-quality modeling and heat budgets, and represents the heat applied to a system. In this case, the system would be the storm water flowing through a LS-VFS, and the heat would be applied or lost between the inlet and the outlet of the SCM. Thermal load is often calculated with Eq. (2) (Thomann and Mueller 1987; Bedient and Huber 1992; Kieser et al. 2004)

$$W = Q \times \rho \times T \times C \times t \tag{2}$$

where W = thermal load (J); Q = flow rate (m^3/s); ρ = density of water (assumed constant at 1,000 kg/m^3); T = water temperature (°C); C = heat capacity of water (assumed constant at 4,186 J/kg/°C); and t = time (s). Dissecting this equation demonstrates that a storm-water SCM may reduce thermal-loading effects on cold-water streams by (1) reducing the effluent temperature (T) or (2) reducing the flow rate (Q) at a given time. Thermal loads were analyzed in a manner similar to temperature.

Statistical Analysis

Nonparametric statistical analyses were conducted using SAS software, version 9 (SAS Institute Inc., Cary, North Carolina). The potential impact of runoff to streams was determined by comparing inflow and outflow temperatures to 21°C by using the Wilcoxon signed rank test. Comparisons between inlet and outlet temperatures were made by using the Mann-Whitney-Wilcoxon test (Mann and Whitney 1947). Storm event median and maximum temperatures were used to determine if influent and effluent temperatures differed. Only storms with measurable outflow were included in this analysis, which precluded the use of some storms in which rainfall depths were less than 7.5 mm. Influent and effluent pollutant loads were statistically compared by using a Wilcoxon signed rank test after efforts to normalize the data were unsuccessful. Pollutant load analysis included seven storms during the monitoring period with no outflow. For all statistical tests, significance was established by using a 95% confidence interval ($\alpha = 0.05$).

Probability plots were also used to evaluate LS-VFS performance for median and maximum temperature reduction over a variety of influent temperatures. Single storm event temperature and thermal-load profiles were also presented to discern changes in these parameters during the course of the storm event.

Results and Discussion

Monitoring of temperature and flow parameters for the two LS-VFSs occurred during the summers of 2008 and 2009. Because ambient air temperatures are warmest during the summer months, the resulting thermal loads to surface waters are much larger than during winter months; therefore, year-round monitoring was not undertaken, similar to past studies (Jones and Hunt 2009; Herb et al. 2009; Jones and Hunt 2010). Temperature data were not obtained during May and June of 2009.

Comparison of Rainfall and Air Temperature with Historical Data

Rainfall data collected on-site were compared to a National Weather Service (NWS) Co-op rain gauge located at 36.10278°N and 78.30389°W, or 3.06 km from the site (North Carolina Climate Office 2010). Measured rainfall in the summer of 2008 was less than the 40-year average rainfall during May through August, with a total rainfall deficit for those months of 123.8 mm (Table 2). Rainfall data collected at the Louisburg research site for the summer of 2009 differed substantially from the 40-year average, as both August and September received roughly one-half normal rainfall. Monthly rainfall totals measured on-site were less than those measured at the NWS Co-op for both the 2008 and 2009 data. On-site rainfall data were not reliable during July 2009 because of clogging of the rain gauge; therefore, during July 2009 only, NWS Co-op data was used instead.

Historical temperature data summary statistics for the summer months are presented in Table 3 along with data from the 2008 and 2009 monitoring periods. Historically, mean air temperatures in Louisburg are below the 21°C trout threshold in May and September; however, historical mean air temperatures exceed 21°C from June to August. In both 2008 and 2009, daily maximum air temperatures were above 30°C in these months. Temperatures in 2008 and 2009 were quite similar to 30-year average temperatures.

Storm Event Characteristics

Thirty-eight storm events were analyzed to determine the LS-VFS's effect on storm-water temperature. During summer 2008, 26 storms were captured. Twelve more storms were monitored during July–September 2009 (Table 4). Mean and median rainfall depths for the analyzed storms were 12.4 mm and 8.9 mm, respectively. The maximum rainfall depth monitored with accompanying temperature data was 67.7 mm. Storm event duration ranged from 18 min to 22 h. Peak 5-min rainfall intensity ranged from 6.1 mm/h to 143.2 mm/h. Antecedent dry period (ADP) varied from 0.35 days to 11 days.

Table 3. Historical and Observed Monthly Air Temperature Statistics for Louisburg, North Carolina

Temperature parameter (°C)[a]	May	June	July	August	September
30-year max	26.3	30.3	32.4	31.5	28.1
30-year mean	18.4	22.9	25.4	24.3	20.8
2008 max	24.9	32.9	31.5	31.6	27.4
2008 mean	17.7	24.2	25.1	24.7	21.8
2009 max	26.3	30.2	30.9	32.2	26.6
2009 mean	19.9	23.8	24.6	26.2	20.7

Note: Data from North Carolina Climate Office 2010.
[a]National Weather Service Co-op Station #315123 (36.10278° N and 78.30389° W).

LS-VFS Impact on Storm-Water Temperature

Summary statistics are presented in Table 5 for all 3,475 data points collected during the summers of 2008 and 2009. The maximum inlet temperature of 32.07°C was observed on July 23, 2008 at 2:50 p.m. (Table 5). The maximum effluent temperatures of 30.09°C were recorded during the storm event on July 17, 2008 at 4:30 p.m. Median and mean inlet temperatures were approximately 23°C. Temperatures were reduced across both the 7.6-m and 15.2-m LS-VFSs, with mean and median effluent temperatures for both VFS widths approaching 21°C. The inlet temperature variance was 10.75°C, whereas that of the 7.6 m and 15.2 m effluent was 4.53°C and 6.32°C, respectively. Effluent temperature from an LS-VFS SCM had substantially less variability than that from an urban catchment. However, these LS-VFSs did not produce as consistent an effluent temperature as did bioretention cells examined in North Carolina, which varied by only 0.2–0.3°C (Jones and Hunt 2009).

Median and maximum runoff temperatures from the watershed were significantly ($p < 0.05$) warmer than the trout threshold of 21°C during every month of the monitoring period (except May 2008). Because 21°C is a generally accepted trout survival threshold (Coutant 1977), this catchment without an SCM would clearly not support trout habitat. Median and maximum effluent temperatures from the 7.6-m LS-VFS were significantly ($p < 0.05$) greater than 21°C. However, median effluent temperatures for the 15.2-m LS-VFS were not significantly ($p > 0.05$) different from 21°C, perhaps showing the benefit of the shading from the wooded portion of the VFS and/or the benefit of greater VFS treatment area (versus the 7.6-m VFS). Maximum effluent temperatures from the 15.2-m LS-VFS were statistically greater than 21°C.

Median inlet temperatures were significantly greater than median effluent temperatures for both the 7.6-m and 15.2-m LS-VFSs. Similar results were found for maximum storm temperatures. Thus, LS-VFS systems can provide reduction in storm-water

Table 2. Observed and 40-Year Average (1967–2006) Rainfall Depths in Louisburg, North Carolina

	Louisburg, North Carolina, rainfall (mm)				
Month	40-year average rainfall[a]	On-site measured rainfall (2008)	Louisburg NWS rainfall[a] (2008)	On-site measured rainfall (2009)	Louisburg NWS rainfall[a] (2009)
May	108.0	80.9	90.9	No Data	99.8
June	94.1	72.2	91.2	No Data	122.4
July	117.3	77.7	120.9	No Data	94.0
August	129.5	94.3	98.0	48.3	52.1
September	101.6	166.7	177.3	60.2	71.6

Note: Data from North Carolina Climate Office 2010.
[a]National Weather Service Co-op Station #315123 (36.10278° N and 78.30389° W).

Table 4. Rainfall Characteristics of Analyzed Storm Events

Event date	Rainfall depth (mm)	Storm event duration (h)	Average rainfall intensity (mm/h)	Peak 5-min intensity (mm/h)	ADP (h)
5/15–5/16/2008	7.4	11.97	0.62	10.7	79.2
5/16/2008	12.6	0.3	42.00	105.1	9.7
5/18/2008	10.5	1.47	7.14	19.8	48
5/20/2008	7.1	1.33	5.34	32	29.7
5/24/2008	3.4	5.73	0.59	4.6	81
5/27–5/28/2008	11.6	17.2	0.67	19.8	87.5
6/14/2008	7.1	14.73	0.48	13.7	265.2
6/16/2008	8.7	4.93	1.76	77.7	24.7
7/5/2008	15.5	2.43	6.38	57.9	14.4
7/6/2008	7.6	6.03	1.26	4.6	19.1
7/8/2008	10.5	0.53	19.81	45.7	44.1
7/9/2008	3.7	2.37	1.56	16.8	20.8
7/14/2008	11	3.97	2.77	15.2	110
7/18/2008	8.4	1.1	7.64	25.9	76.4
7/23/2008	13.9	2.5	5.56	41.1	116.7
8/10/2008	1.8	2.07	0.87	27.4	255.9
8/27/2008	25.2	22.1	1.14	19.8	260
8/28/2008	3.2	7.43	0.43	13.7	8.5
8/28/2008	29.4	8.8	3.34	74.7	10
8/30/2008	11.6	0.9	12.89	47.2	42.9
8/31/2008	4.2	0.63	6.67	16.8	8.9
9/5–9/6/2008	67.7	21.97	3.08	42.7	118.3
9/10/2008	22.1	14.57	1.52	143.2	89.9
9/16/2008	17.6	13.23	1.33	10.7	127.7
9/25–9/26/2008	46.5	6.93	6.71	91.4	12.7
9/27/2008	4.2	2.83	1.48	15.2	20.8
7/5–7/6/2009	9.7	ND	ND	ND	ND
7/17–7/18/2009	6.4	ND	ND	ND	ND
8/11/2009	4.8	0.57	8.42	32	ND
8/22/2009	6.4	9.23	0.69	13.7	21.6
8/23/2009	7.6	4.93	1.54	47.2	17.7
8/31/2009	3.8	14.07	0.27	10.7	177.8
9/7/2009	19.1	10.3	1.85	21.3	163.2
9/17/2009	12.2	13.03	0.94	7.6	215.1
9/22/2009	3.3	2.0	1.65	7.6	124.6
9/22/2009	11.2	5.93	1.89	29	8.7
9/27/2009	3.6	12.63	0.29	6.1	99.9
9/28/2009	9.1	10.63	0.86	18.3	46.5

Note: ND = no data, tipping bucket rain gauge clogged during these storms.

Table 5. Summary Temperature Statistics for the LS-VFSs

Parameter	Inlet temperature (°C)	7.6 m outlet temperature (°C)	15.2 m outlet temperature (°C)	Range of effluent temperature data at four bioretention cells (Jones and Hunt 2009)
Median	23.05	21.41	21.10	19.8–22.5
Mean	22.98	21.75	21.12	Not presented
Maximum	32.07	30.09	30.09	23.2–30.3
Variance	10.75	4.53	6.32	0.2–0.3

temperatures through heat transfer between the storm water and the soil and vegetation in the filter strip. However, often the greatest reduction in temperature occurred during the initial phase of the storm event, when thermal gradients were largest between the soil and storm water. As storms progressed, the difference between influent and effluent temperatures tended to decrease [Figs. 3(a) and 3(b)].

Reductions in storm-water temperature tended to be greater during daytime [Fig. 3(a)] as opposed to nighttime storm events [Fig. 3(b)], where a smaller difference between runoff temperature and soil temperature presumably existed. Overnight storms were defined as those with rainfall occurring between 9 p.m. and 6 a.m., and afternoon storms occurred between 12 p.m. and 7 a.m. Thirteen afternoon storms and nine overnight storms occurred during the monitoring period. The mean temperature of the median and maximum temperatures for all afternoon and overnight storm events is presented in Table 6. As expected, both influent and effluent temperatures were warmer for the afternoon storms. It is also evident that median and maximum temperature reduction provided by the VFS is larger in magnitude for afternoon storms than for overnight storms; this is presumably because of a greater thermal gradient

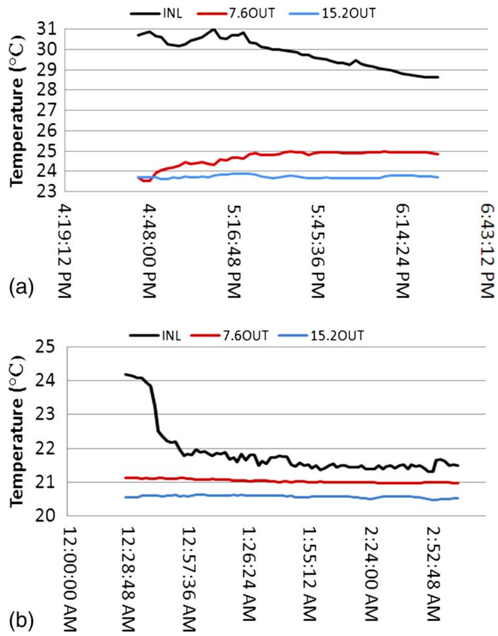

Fig. 3. (a) Temperature profile for August 11, 2009, (daytime) storm event; (b) temperature profile for July 6, 2009, (nighttime) storm event

Table 6. Comparison of Overnight and Daytime Storm Event Temperature Statistics

Parameter	Afternoon storms ($n = 13$) Inlet	7.6-m outlet	15.2-m outlet
Mean of median temperatures	27.01	23.45	22.54
Mean of maximum temperatures	28.18	24.44	24.07
Parameter	Overnight storms ($n = 9$)		
Mean of median temperatures	21.69	20.51	20.33
Mean of maximum temperatures	22.30	20.72	20.55

during afternoon storms between influent storm water and the soil/vegetation in the VFS.

Monthly mean, median, and maximum temperatures were calculated for all months during the monitoring period using all temperature data points collected in the corresponding months (Table 7). Interestingly, monthly maximum inlet temperatures, which are representative of the temperature of the runoff from the 70% impervious urban catchment, do not exceed the maximum monthly air temperature (Table 3 and Table 7) for most months, with exceptions in May 2008, July 2008, and September 2009. This difference in temperature between monthly maximum air temperature and monthly maximum inlet temperature never exceeded 1.7°C. The observations were that maximum air temperature appeared to be associated with maximum runoff temperature.

During July 2009, the maximum and mean influent runoff temperatures were 6.6°C and 1.9°C, respectively, lower than the maximum and mean recorded air temperature for that month (Table 3). Although this may seem counterintuitive, this is attributed to the timing of the two storm events during that month. The storm event on June 5–6, 2009, began at 9:50 p.m. and ended at 3:42 a.m., and the storm event on June 17–18, 2009, began at 11:26 p.m. and ended at 1:16 a.m. Because the rainfall for both storms commenced well after sunset, the pavement and rooftop would have cooled, limiting the ability of the impervious surfaces to thermally enrich runoff. So, even during the hottest month (on average, Table 3) of the year, runoff temperatures may not approach ambient maximum air temperature if the rainfall occurs during the overnight hours.

Median temperatures at the inlet, the outlet of the 7.6-m VFS, and the outlet of the 15.2-m VFS are presented in Fig. 4. During some storms, a substantial decrease in temperature was not observed between the inlet and outlet of the filter strips. These storms tended to occur in May and September, when inlet temperatures were at their coolest. This suggests that filter strips may only be able to cool storm-water runoff when they have been thermally enriched beyond the 21°C trout threshold. The largest reduction in median temperature (5.31°C) for the 7.6-m LS-VFS occurred on August 31, 2008, and that for the 15.2-m LS-VFS (5.70°C) occurred on August 11, 2009. Median storm-water temperatures increased after passing through the VFS for only three of 39 storm events for both the 7.6-m and 15.2-m VFSs; these increases never exceeded 0.54°C. The tendency of temperatures rarely increasing after passing through LS-VFS systems is a marked difference from how other SCMs (noninfiltrating detention systems) perform, where outflow temperatures usually increase (Galli 1990; Kieser et al. 2004; Herb et al. 2009; Jones and Hunt 2010). At the very least, these LS-VFS SCMs were not thermal sources, unlike wet ponds and wetlands.

Influent and effluent probability plots have been used as a tool to evaluate SCM performance for common storm-water pollutants in

Table 7. Monthly Mean, Median, and Maximum Storm-Flow Temperatures for the LS-VFSs

Monitoring location	May 2008	Jun. 2008	Jul. 2008	Aug. 2008	Sep. 2008	Jul. 2009	Aug. 2009	Sep. 2009
Mean temperature (°C)								
Inlet	20.3	25.3	26.5	24.1	21.6	22.7	27.3	22.6
7.6-m LS-VFS outlet	18.1	21.6	25.0	22.6	21.7	21.4	23.8	21.2
15.2-m LS-VFS outlet	17.3	22.0	23.9	22.7	21.8	20.9	23.4	20.9
Median temperature (°C)								
Inlet	20.9	25.1	25.8	22.4	21.3	22.6	28.1	22.3
7.6-m LS-VFS outlet	18.2	21.6	23.5	22.6	22.8	21.1	24.3	20.9
15.2-m LS-VFS outlet	17.3	22.0	22.8	22.4	22.6	20.7	23.6	20.3
Maximum temperature (°C)								
Inlet	25.7	27.1	32.1	30.6	25.7	24.3	31.0	28.3
7.6-m LS-VFS outlet	21.8	21.6	30.1	26.4	24.1	22.6	25.2	27.0
15.2-m LS-VFS outlet	24.2	22.2	30.1	26.1	24.4	21.8	25.3	27.0

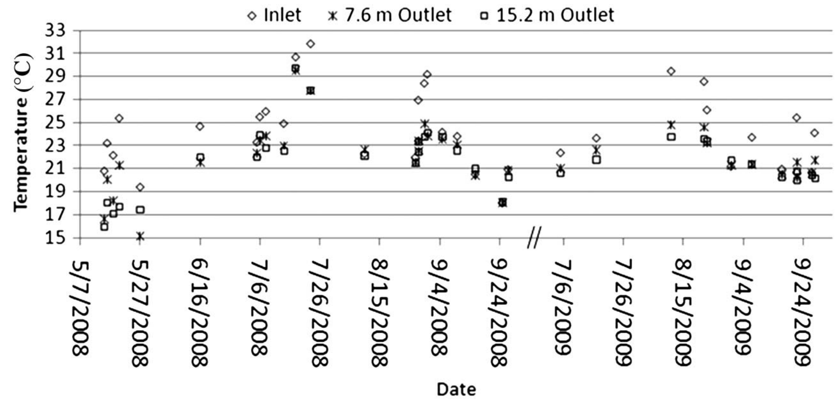

Fig. 4. Median temperature by storm event for the LS-VFSs

SCM studies (Burton and Pitt 2002; Li et al. 2009; Hathaway et al. 2009). They illustrate the variation, expected range, and probability distribution type of the data set. A cumulative probability plot of influent and effluent median temperatures is presented in Fig. 5. Median influent and effluent temperatures were compared to the 21°C trout threshold; of 35 storm events, eight events had mean inlet temperatures less than 21°C. For the 7.6-m and 15.2-m VFS outlets, 10 and 13 storms, respectively, were lower than the threshold. In most cases, the median effluent temperatures from the 15.2-m LS-VFS are modestly lower than those from the 7.6-m LS-VFS, perhaps because of the shade produced by tree cover or larger filter strip area in the 15.2-m VFS.

Maximum temperatures at the inlet, the outlet of the 7.6-m VFS, and the outlet of the 15.2-m VFS are illustrated by Fig. 6. Similar to the median temperature data, the smallest differences between maximum inlet and outlet temperatures typically occurred during the cooler months of May and September. The largest reduction in maximum temperature occurred for the storm on August 31, 2008, with the 7.6-m VFS reducing maximum temperature by 6.69°C, whereas the temperature reduction for the 15.2-m VFS was 6.11°C. Maximum storm-water temperatures increased during only one storm event for both the 7.6-m and 15.2-m VFSs (August 31, 2009); these increases did not exceed 0.14°C, which is within the measurement accuracy of the temperature sensors.

A cumulative probability plot for influent and effluent maximum temperatures is presented in Fig. 7. Of 35 storm events, influent runoff maximum temperatures were less than the trout threshold three times. Effluent maximum temperatures from the 7.6-m and 15.2-m LS-VFSs were less than the trout threshold nine

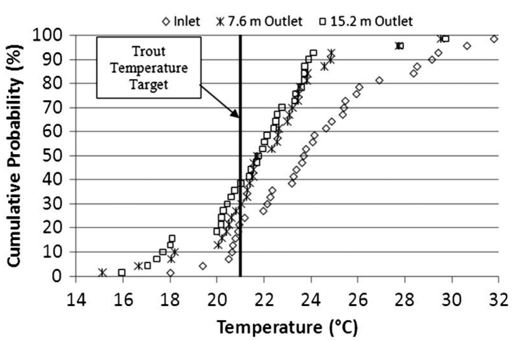

Fig. 5. Median temperature cumulative probability plot

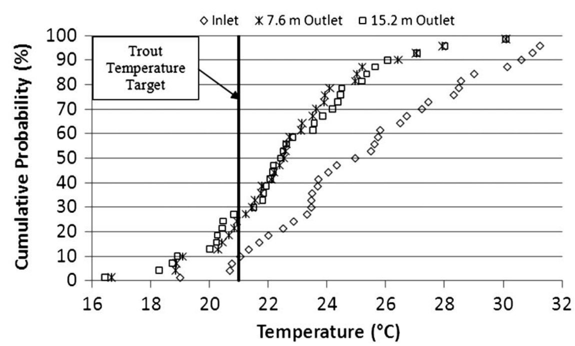

Fig. 7. Maximum temperature cumulative probability plot

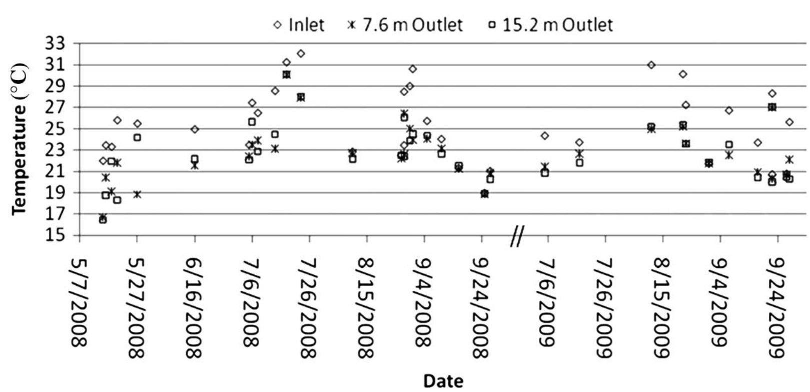

Fig. 6. Maximum temperature by storm event for the LS-VFSs

and 10 times, respectively. The probability of meeting any given threshold temperature is higher for the effluent temperatures than for the influent, showing that, in general, the filter strips were serving to reduce maximum storm-water temperatures.

Thermal Load Reductions of LS-VFSs

Load reductions are a frequently used metric to assess SCM performance, as they take into account flow volume reduction. Total storm event thermal load (W_s) was calculated using

$$W_S = \sum_{i=1}^{n} (Q_i \times \rho \times T_i \times C \times t) \tag{3}$$

where ρ, C, and t (120 s) = constants defined in Eq. (2); and n = number of time steps in a given storm event. To reduce thermal load, an SCM may either reduce flow volume through infiltration or reduce temperature through heat transfer, or both.

A profile of thermal load versus time for a specific storm event is presented in Fig. 8. This 4.2-mm event occurred during the early afternoon of August 31, 2008. The inlet thermal load profile shows a potential first flush behavior, where a majority of the thermal load is transmitted during the first half of the storm event. This trend was typical of storm events that occurred as afternoon thundershowers, where initally intense rainfall was thermally enriched, resulting in a local maximum in thermal load near the beginning of runoff. Both the 7.6 m and 15.2 m VFSs substantially reduced both total thermal load and peak thermal load. For storm events that occurred at night, the shape of the thermal load profile was not as strongly front-weighted as in Fig. 8, potentially resulting from cooling of the impervious surfaces caused by diurnal temperature fluctuations.

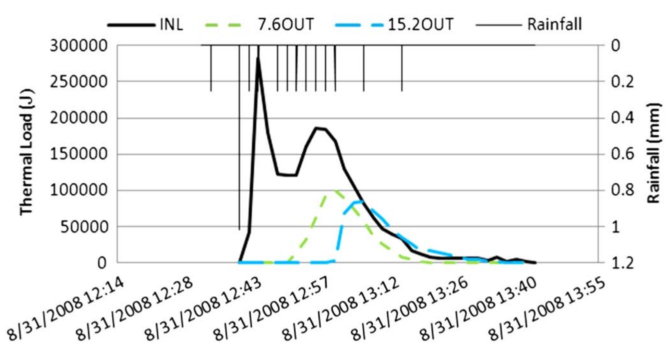

Fig. 8. Thermal load profile during August 31, 2008, storm event

Percent thermal load reductions for all monitored storm events are presented in Fig. 9 for both the 7.6-m and 15.2-m LS-VFSs; rainfall depth for each storm event is presented on a secondary axis. Median thermal load reductions for the entire monitoring period were 73% and 81% for the 7.6-m and 15.2-m LS-VFSs, respectively; mean thermal load reductions were 67 and 70%, respectively. However, these data were perhaps skewed by the storm events that were monitored in the summer of 2009. The median rainfall depth for storms in 2009 was 7 mm, much smaller than the median of 10.5 mm in 2008. Also, both of the 2009 storms with rainfall depths > 10 mm (September 7, 2009, and September 17, 2009) were preceded by an ADP of 8 days or more, allowing the soils in the filter strips to infiltrate a greater fraction of the following storm event. Median and mean thermal load reduction for the 7.6-m LS-VFS were 57% during 2008 and those for the 15.2-m LS-VFS were 65% and 61%, respectively, during the same period. During the summers of 2008 and 2009, seven storm events were entirely captured (i.e., no outflow occurred) in both the 7.6-m and 15.2-m LS-VFSs; the largest of these events had a rainfall depth of 7.1 mm and was preceded by an 11-day ADP.

The thermal load reductions were very similar for the 7.6-m and 15.2-m LS-VFSs for the summers of 2008 and 2009. Median effluent temperatures for the 7.6-m LS-VFS were often greater than those from the 15.2-m LS-VFS, but usually by less than 1°C. Similarly, volumetric reductions over the study period were very similar in both the 7.6-m and 15.2-m LS-VFSs; this was probably because of field observed reconcentration of surface flow in the wooded portion of the 15.2-m LS-VFS (Winston et al. 2011). In theory, reconcentration causes the same amount of water to pass through a smaller cross-sectional area of the filter strip, causing an increase in velocity (Helmers et al. 2005; White and Arnold 2009). This leads to diminished volumetric reduction in the wooded portion of the filter strip, as there was less contact time between the storm water and the soil. Had reconcentration been avoided, the 15.2-m LS-VFS would likely have had superior performance because of its larger surface area.

Conclusions

The results of this study on the effectiveness of LS-VFS systems for reducing storm-water runoff temperatures provided these findings:

1. Unlike many conventional SCMs (such as wet ponds and wetlands) that rely on detention, LS-VFSs actually reduced runoff temperature, significantly and substantially. The probable reasons for this were contact time with a cooler substrate

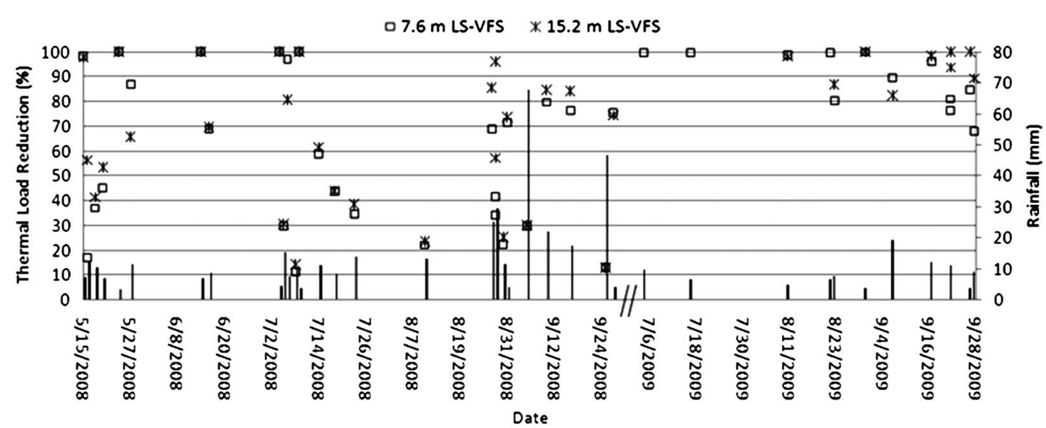

Fig. 9. Percent thermal load reduction by storm event for the LS-VFSs

and infiltration of the earliest (and most thermally enriched) influent runoff.
2. The VFS with more shade, which also had the larger surface area, reduced temperatures slightly more than the unshaded, grass-only filter strip. This is suspected to be a minor benefit of tree-dominated filter strips.
3. Thermal loads from both filter strips were dramatically reduced when compared to influent runoff thermal loads. There was no substantial difference in thermal load reduction between the two VFS types. LS-VFS systems exhibit this behavior because they infiltrate large portions of rainfall events. As suggested by Jones and Hunt (2009) in their discussion of mitigation of thermal loads by bioretention, infiltration is the main tool for designers to reduce thermal pollution.
4. Despite a demonstrated mitigation of temperature and thermal load, both LS-VFS systems had months where median effluent temperatures exceeded 21°C (June–September 2008, July–August 2009). To date, no aboveground SCM has been documented in peer-reviewed literature to prevent the release of outflow with temperatures that exceed the 21°C benchmark.
5. Treatment of thermally enriched runoff from urban areas is critical, as runoff from this catchment exceeded the trout threshold of 21°C in all but one warm-weather month studied (May 2008). If unmitigated, this runoff could prove detrimental to trout waters.

Recommendations for Future Research

Because of the wide variety of possible configurations of LS-VFS systems (changes in width, length, vegetation type, soil characteristics, watershed area to filter strip area ratio, could all affect performance), further research is needed to examine the effects of varying designs on performance of these systems. Results need to be confirmed in other regions of the world where cold-water fisheries are a concern. Also, little research has been done to determine if reductions in observed temperature and flow volumes from SCMs will affect in-stream temperature and stream flows. This is an area of great need, as the long-term goal of SCM implementation is an observed improvement in surface-water quality and quantity. Furthermore, additional monitoring and modeling efforts could focus on the ecological impacts of SCM effluent, including benthic macroinvertebrates and stream morphology. While further research is needed, it is apparent from this study that LS-VFSs, if properly designed and constructed, can function to reduce stormwater temperature and thermal loading from an urban watershed.

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