Bioretention Impact on Runoff Temperature in Trout Sensitive Waters

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Abstract: A study was conducted in western North Carolina, along the southeastern extent of the U.S. trout populations, to examine the effect of bioretention areas on runoff temperature. Four bioretention areas were monitored during the summers of 2006 and 2007. It was found that smaller bioretention areas, with respect to the size of their contributing watershed, were able to significantly reduce both maximum and median water temperatures between the inlet and outlet. The proportionately larger bioretention areas were only able to significantly reduce maximum water temperatures between the inlet and outlet; however, these systems showed evidence of substantial reductions in outflow quantity, effectively reducing the thermal impact. Despite temperature reductions, effluent temperatures still posed a potential threat to coldwater streams during the peak summer months. During the summer months, effluent temperatures were generally coolest at the greatest soil depths, supporting evidence of an optimum drain depth between 90 and 120 cm. The ability of bioretention areas to reduce storm-water temperature and flows supports their application to reduce the thermal impacts of urban storm-water runoff.

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Introduction

Water temperature is an important habitat constraint in aquatic environments directly impacting the metabolism, behavior, enzyme function, and reproduction of many aquatic organisms. Although water temperatures exhibit natural daily and seasonal temperature fluctuations, it has been observed that heat from anthropogenic discharges can have a substantial impact on the aquatic ecosystem, reducing both the abundance and diversity of aquatic organisms (Hocutt et al. 1980). The thermal impact of industrial discharges has been reduced through the use of better heat exchange processes; however, there are few mechanisms available to mitigate nonpoint sources of thermal pollution.

One major nonpoint source of thermal pollution is urban storm-water runoff. Paved surfaces elevate runoff temperatures by capturing solar radiation and transferring this stored energy to runoff during rainfall events, which is especially a concern during the summer months. Asphalt typically has a low thermal conductivity and reflectivity, causing heat from the solar radiation to concentrate near the surface, which can lead to asphalt surface temperatures in excess of 60°C (Asaeda et al. 1996). Because heat is concentrated near the surface, runoff temperatures typically exhibit a short-term temperature spike and cool down as a storm progresses. Heated runoff from urban watersheds has been shown to increase the temperature of water bodies above their normal levels (Kieser et al. 2004).

Although temperature affects many aquatic organisms, trout, and other salmonids are among the fish most sensitive to water temperature changes and are important game fish in many parts of the country. Due to a variety of complex factors, it is difficult to predict the actual fish behavior in response to elevated temperatures, which is evidenced by inconsistencies between laboratory and field research data (Hocutt et al. 1980). Despite these complexities, trout and salmon have been observed to generally avoid water temperatures in excess of 21°C (Coutant 1977). In many states where trout and salmon reside, temperature is listed as a pollutant of concern within lists of impaired waters required by Sec. 303(d) of the Clean Water Act; however, the high variability of natural water temperatures has made implementation of total maximum daily load (TMDL) programs for temperature control difficult. Although it is likely that many North Carolina streams have been negatively impacted by elevated temperatures from anthropogenic sources, criteria to assess thermal impacts on coldwater stream environments have not been incorporated into the N.C. Index of Biotic Integrity (North Carolina Department of Environment and Natural Resources 2007).

One urban storm-water best management practice (BMP) that has gained popularity due to its ability to simultaneously satisfy storm-water and landscaping requirements is bioretention. In N.C., a bioretention area typically consists of an underdrain system surrounded by a gravel envelope and overlain by 0.7–1.2 m of fill soil media, all of which is contained in an excavated basin (Fig. 1). In locations where the hydraulic conductivity of the underlying soil is substantial, underdrains may not be required. Generally, the fill soil media is predominantly sand with a small percentage of fine particles and organic matter. These systems are typically mulched and vegetated and often located immediately adjacent to their contributing watershed. During moderate inflows, runoff infiltrates into the soil media and leaves the system

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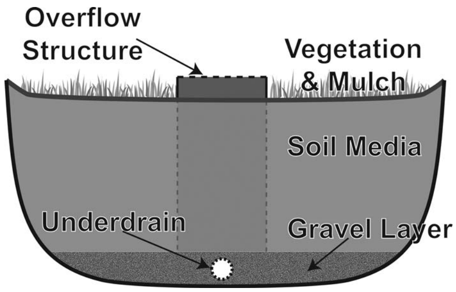

Fig. 1. Cross section of a typical bioretention area

either through the underdrains, seepage into the underlying soil, or evapotranspiration. These systems are generally designed to bypass additional water after collecting runoff from approximately 25 mm of rainfall. In N.C., bioretention areas are commonly designed to occupy an area between 5 and 7% of the contributing watershed.

The effect of bioretention areas on storm-water runoff temperature has not been thoroughly examined. Because soil temperature is largely regulated by radiation and convective heat exchanges at the surface and heat conduction within a soil column is relatively slow, deeper layers of soil are able to maintain a relatively stable temperature over long periods of time (Mohseni et al. 2002). At a shallow (60 cm) bioretention area in the northeastern United States, seasonal mean water temperatures were not significantly different between rooftop runoff and underdrain outflow (Dietz and Clausen 2005). In a study of soil temperature profiles during irrigation with warm and cool water, it was noted that water temperature approaches that of the soil as it infiltrates, causing little variation in soil temperature at depths greater than 100 cm (Wierenga et al. 1970). The researchers also noted that irrigation with both warm and cool water led to soil temperatures lower than a nonirrigated plot due to the cooling associated with evaporation and higher heat capacity of the saturated soil. Bioretention areas also facilitate infiltration into the shallow groundwater, which serves as a major water source for many coldwater streams and helps maintain water temperatures below that of the ambient air during the warmer portions of the year. Research has shown that the effluent volume from bioretention areas can be less than 50% of the influent volume with the greatest reductions evident during the warmer times of the year (Hunt et al. 2006).

There has been some previous research into the effect of storm-water wetlands and wet ponds on runoff temperature. A study in western N.C. showed that wetlands and wet ponds increased the temperature of the water they received with large temperature fluctuations near the surface, making it difficult to predict effluent temperatures (Jones and Hunt, unpublished monitoring results, 2008). Kieser et al. (2004) demonstrated that a well-shaded storm-water wetland could reduce the thermal load of urban storm-water runoff; however, cooling was limited to the temperature of the ambient air. Because storm-water wetlands and wet ponds do not generally decrease runoff volumes, substantial temperature reductions are required to mitigate the impact of thermal pollution from the urban storm-water runoff.

Although the impact of urban storm-water runoff on stream temperatures has been shown, there are few mechanisms available to limit these thermal impacts. Stormwater BMPs, such as bioretention areas, are being installed throughout the country to satisfy storm-water regulations and present an opportunity to limit thermal pollution from urban watersheds. By examining bioretention areas in western N.C., which constitutes the southeastern extent of the U.S. trout populations, it should be possible to evaluate the effect of bioretention areas on runoff temperature and identify any design criteria that can be modified to better mitigate thermal pollution.

Table 1. Bioretention Flow Monitoring Strategy for Each Monitoring Location

Bioretention location	Inflow monitoring	Outflow monitoring
Asheville	Rainfall	Weir box
Lenoir	Rainfall	Weir box
Brevard East	Weir box	Weir box
Brevard West	Weir box	Weir box

Materials and Methods

To investigate the effect of bioretention on runoff temperature, a monitoring study was conducted at four bioretention areas in western N.C. during the summers of 2006 and 2007. Water temperatures were measured at all inlets and underdrain outlets. Additionally, temperatures were measured at evenly spaced depths within the soil column at some bioretention areas. Pulley-float stage recorders were used in conjunction with v-notch weirs to measure outflow at all sites. Inflow measurements were obtained using pulley-float stage recorders with v-notch weirs or estimated using rainfall data (Table 1). Due to complications with the flow monitoring equipment, flow data were used primarily to identify periods of flow over the temperature sensors and not to measure specific flow rates. Measurements from all temperature and flow monitoring equipment were logged at 5 min intervals. Vegetative cover of each bioretention area was estimated by creating a composite overhead image of the site and digitally comparing areas of exposed mulch or soil to vegetated areas.

Rainfall data were collected at each site using tipping bucket rain gauges with a resolution of 0.25 mm (0.01 in.). Temperature measurements were collected with a combination of HOBO Water Temp Pro (H20-001) and HOBO 4 channel loggers (H08-008-04 and U12-008) with temperature sensors attached (TMCX-HD). All temperature loggers were manufactured by Onset Computer Corporation (Bourne, Mass.).

Statistical analysis was conducted using SAS software, Version 9 (SAS Institute Inc., Cary, N.C.). The potential thermal impact to trout populations was ascertained by comparing water temperatures to 21°C, the temperature at which trout begin to experience thermal stress, using a signed rank test. Comparisons of influent, effluent, and soil temperatures were conducted using the Wilcoxon Rank Sum test (Wilcoxon 1945). Individual storm medians and maximums were used in the analysis of BMP influent and effluent temperatures and only storms that generated measurable outflow were used in the comparison of influent and effluent temperatures. During the course of the monitoring study, the runoff from many relatively small storms was able to infiltrate into the bioretention areas and underlying soils without generating measurable outflow. Linear regression was used to examine the correlation between the time of day and influent or effluent temperatures. In order for a linear relationship to exist, the timescale was centered about noon, where the dependent variable used in the regression analysis was the length of time from noon to the beginning of the storm event each day. Linear regression was also used to examine the correlation between influent and effluent tem-

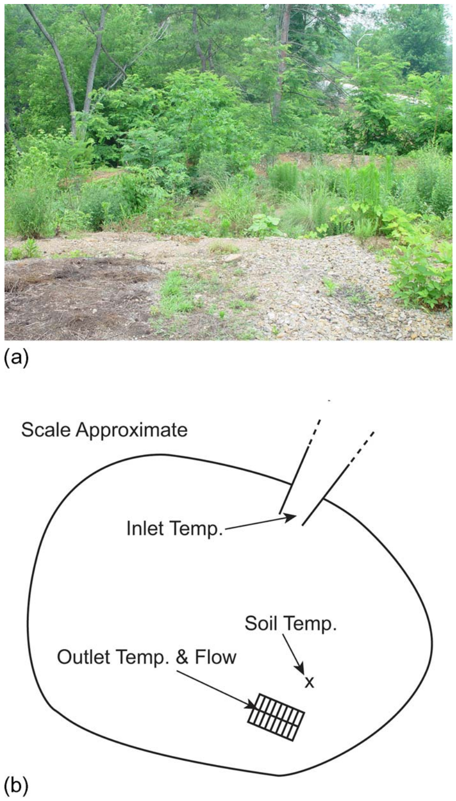

Fig. 2. Photo of the Asheville bioretention and a diagram of the equipment layout

peratures. Statistical significance was established within a 95% confidence interval ($p<0.05$).

Site Description

The 45 m^2 Asheville bioretention area was located on the campus of the University of North Carolina at Asheville (35°36′46″N, 82°33′54″W) and received runoff from 280 m^2 of asphalt parking lot (Fig. 2). The bioretention area and contributing parking lot were constructed during the summer of 2005, at which time a light colored chip seal was applied to the parking surface in an attempt to reduce pavement temperatures. Runoff was routed by a speed bump into a 5.75 m long asphalt channel, which led directly into the bioretention area. The bioretention area was drained by 10 cm perforated PVC pipes and outflow was discharged directly through a 15 m length of 38 cm smooth-walled corrugated plastic tubing (CPT) into Reed Creek. The bioretention area was not mulched and naturally progressed from no vegetative cover in June of 2005 to an estimated 55% vegetative cover in late August 2006 (Table 2). Temperature probes were installed at the inlet

Table 2. Bioretention Site Characteristics

Bioretention location	Underdrain depth	% of vegetative cover	% of watershed area
Asheville	135 cm	55%	16%
Lenoir	95 cm	79%	4%
Brevard east	48 cm	43%	7%
Brevard west	43 cm	43%	11%

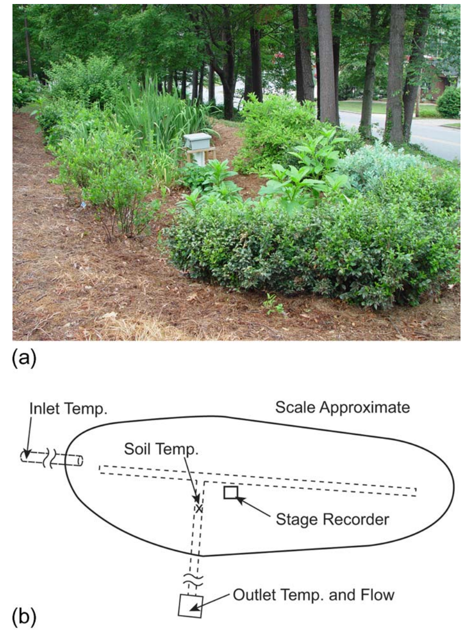

Fig. 3. Photo of the Lenoir bioretention and a diagram of the equipment layout

channel, inside the outlet weir box, and at five evenly spaced depths within the soil column from the surface to the underdrain depth.

The 30 m^2 Lenoir bioretention area (35°55′20″N, 81°31′24″W) received runoff from a 674 m^2 asphalt parking lot and a 95 m^2 area of concrete sidewalk comprised of two separate sections (Fig. 3). The bioretention area and adjacent parking surface were shaded by a mature tree canopy. The surface of the bioretention area was covered by hardwood mulch and vegetation within the system provided shading for 79% of the surface. Runoff entered the system through a 4.9 m length of buried 22 cm PVC pipe. Effluent was collected by a network of 10 cm perforated CPT underdrains and discharged onto the adjacent street curb, located approximately 10 m away, where it entered the municipal storm-water drainage network. Temperature probes were installed in the inlet pipe, outlet weir box, and at four evenly spaced depths within the soil column from the surface to the underdrain depth. Soil temperatures were only monitored at this site during the summer of 2007.

Adjacent bioretention areas were monitored in Brevard, N.C. (35°14′20″N, 82°43′52″W). Both systems were mulched with pine needles. Water from these bioretention areas, as well as others in the parking lot, was routed by an underground drainage network to Kings Creek, which was adjacent to the property. The Brevard east bioretention area covered a 37 m^2 area and received runoff from approximately 525 m^2 of asphalt parking lot (Fig. 4). Water left the bioretention area through a 10 cm perforated CPT underdrain network located approximately 48 cm below the soil surface. An estimated 43% of this bioretention area was shaded by low-lying plants. Temperature probes were located in the inlet weir box and outlet pipe and soil temperature was measured at a depth of 48 cm during the summer of 2007.

The Brevard west bioretention area covered a 36 m^2 area and received runoff from approximately 325 m^2 of asphalt parking lot (Fig. 5). Water left the bioretention area through a 10 cm perforated CPT underdrain network located approximately 43 cm below the soil surface. An estimated 43% of this bioretention area

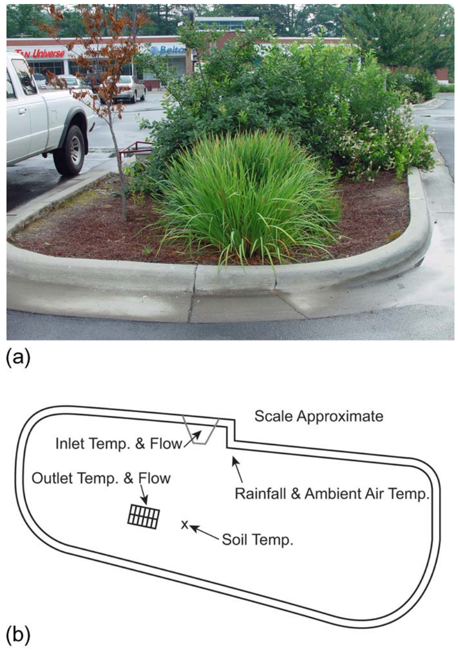

Fig. 4. Photo of the Brevard east bioretention and a diagram of the equipment layout

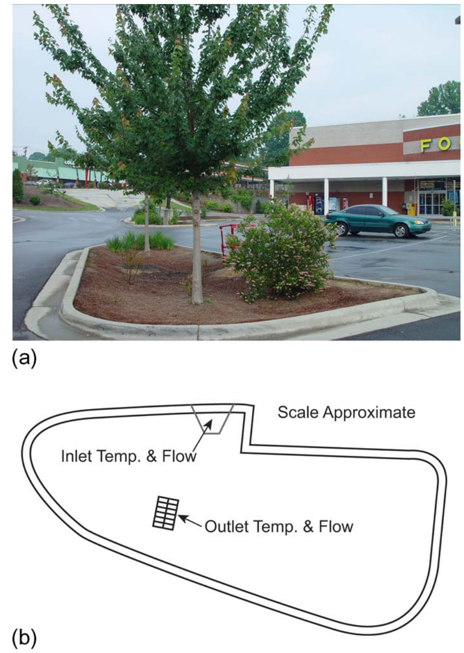

Fig. 5. Photo of the Brevard west bioretention and a diagram of the equipment layout

was shaded, primarily by two maple trees. Temperature probes were located within the inlet and outlet weir boxes.

Results and Discussion

Both influent and effluent temperatures were warmest at the Brevard east bioretention site, while the coolest temperatures were observed at the Asheville location (Table 3). The maximum influent temperature reading of 39.2°C was made at the Brevard east bioretention area at 2:00 p.m. on 07/01/2006. The maximum effluent temperature reading of 30.3°C was also recorded at the Brevard east site at 2:25 p.m. on 06/24/2006. During 2007, rainfall depths at all sites were substantially lower than the 30-year normal depths (Table 4).

At the Asheville bioretention area, maximum runoff temperatures were significantly warmer than 21°C for the entire monitoring period, while median runoff temperatures were significantly warmer than 21°C only when the cooler months of May and October were excluded from the analysis. Since 21°C is considered the upper avoidance temperature for N.C. trout species, there was evidence that direct runoff from this site would negatively impact the thermal environment of the nearby Reed Creek. There was no significant difference between median effluent temperatures and the 21°C threshold when examining the entire monitoring period; however, median effluent temperatures were significantly cooler than 21°C when the month of August was excluded. Both influent and effluent temperatures exhibited substantial seasonal variations with the warmest influent and effluent temperatures during the month of August (Fig. 6).

There was no significant difference between median influent and effluent temperatures at the Asheville bioretention area, indicating that the bioretention area was not able to consistently reduce runoff temperatures over the course of an entire storm. Maximum effluent temperatures were significantly cooler than the maximum influent; however, maximum effluent temperatures were not significantly different from the 21°C threshold. A reduction in maximum water temperatures suggests that the bioretention area was able to reduce the initial runoff temperature spike but unable to adapt to the cooler runoff as a storm progresses.

At the Lenoir bioretention area, median and maximum influent temperatures were significantly warmer than 21°C for the entire monitoring period, suggesting potentially negative impacts if runoff were directly discharged into trout waters. Median and maximum effluent temperatures were both significantly lower than influent temperatures at the Lenoir bioretention area, which indicates that the bioretention area was able to reduce the thermal impact associated with the storm-water runoff. Despite the reduction in water temperature resulting from bioretention treatment, median effluent temperatures were not significantly different from 21°C and maximum effluent temperatures were significantly warmer than 21°C. Although thermal impacts were reduced, the effluent from this bioretention area still posed some risks to the thermal environment of trout waters. Similar to the Asheville bioretention area, influent and effluent temperatures varied seasonally (Fig. 7).

At the Brevard east bioretention, median and maximum inlet temperatures were significantly warmer than 21°C, meaning direct runoff would have been a source of thermal pollution. Median and maximum effluent temperatures were significantly

Table 3. Median Summary Statistics for the Bioretention Area at Each Location

	Asheville	Lenoir	Brevard east	Brevard west
Median influent (°C)	20.6	26.0	27.9	23.3
Median effluent (°C)	19.8	22.3	23.7	22.5
Maximum influent (°C)	23.2	26.9	30.3	27.1
Maximum effluent (°C)	20.2	23.0	24.9	23.8
Inlet variance (°C)	1.9	0.9	0.9	1.0
Outlet variance (°C)	0.2	0.2	0.2	0.3

Table 4. Observed and 30-Year Average (1971–2000) Rainfall Depths near the Bioretention Locations

Observed	Asheville[a] (cm)		Lenoir[b] (cm)		Brevard[c] (cm)	
	Average	Observed	Average	Observed	Average	Observed
May 2006	7.2	9.0	3.1	11.9	11.8	15.0
June 2006	10.2	8.2	9.2	11.3	10.4	14.6
July 2006	7.7	7.5	10.4	11.2	22.4	13.0
August 2006	9.2	8.5	12.5	9.8	21.3	13.7
September 2006	9.6	7.6	13.8	11.3	18.1	13.0
October 2006	6.1	6.1	10.5	9.2	16.5	12.3
2006 annual	98.5	95.7	92.2	125.0	167.5	168.1
May 2007	1.9	9.0	1.5	11.9	4.3	15.0
June 2007	3.8	8.2	8.4	11.3	12.5	14.6
July 2007	9.3	7.5	9.6	11.2	8.2	13.0
August 2007	2.8	8.5	6.0	9.8	7.4	13.7
September 2007	6.8	7.6	7.4	11.3	8.4	13.0
October 2007	0.6	6.1	0.0	9.2	0.5	12.3
2007 annual	53.3	95.7	78.7	125.0	92.03	168.1

Note: Source: North Carolina Climate Office (2008).

[a]National Weather Service Coop Station # 310301 (35°35′43″N, 82°33′24″W).

[b]National Weather Service Coop Station # 314938 (35°54′42″N, 81°32′2″W).

[c]National Weather Service Coop Station # 311055 (35°16′6″N, 82°42′11″W).

cooler than influent temperatures; however, effluent temperatures were also significantly warmer than 21°C. Similar to the Lenoir bioretention, the Brevard east bioretention was able to reduce but not eliminate the thermal impact to a coldwater stream environment. Also similar to other sites, influent and effluent temperatures were coolest during the spring and fall, which corresponds to spawning seasons for N.C. trout species (Fig. 8).

At the Brevard west bioretention, median and maximum inlet temperatures were significantly warmer than 21°C. Although there was no significant difference between median influent and effluent temperatures, there was a significant difference between maximum influent and effluent temperatures. These temperature results indicate that the bioretention area was likely able to reduce the initial spike in runoff temperatures but could not adapt to the cooler runoff temperatures later in a storm. Median and maximum effluent temperatures were both significantly warmer than 21°C, indicating potential thermal impacts to a coldwater stream environment. Seasonal trends in influent and effluent temperatures were not as well defined during 2007, possibly due to the impact of the drought throughout the region (Fig. 9).

The median influent temperature at the Brevard east bioretention area was significantly warmer than the inflow into the Brevard west bioretention area; however, there was no significant temperature difference in median effluent temperature between the two systems. With immediately adjacent locations, similar soil properties, drain depth, and bioretention size, the primary difference between these systems was the size of their contributing watershed. The area occupied by the Brevard east bioretention was equal to 7% of the contributing watershed, while the area of the Brevard west bioretention was equivalent to 11% of the contributing watershed. Temperature results from this pair of bioretention areas indicate that there were minimal benefits of moderately oversizing a bioretention area with regards to thermal pollution. However, one benefit of a proportionally larger biore-

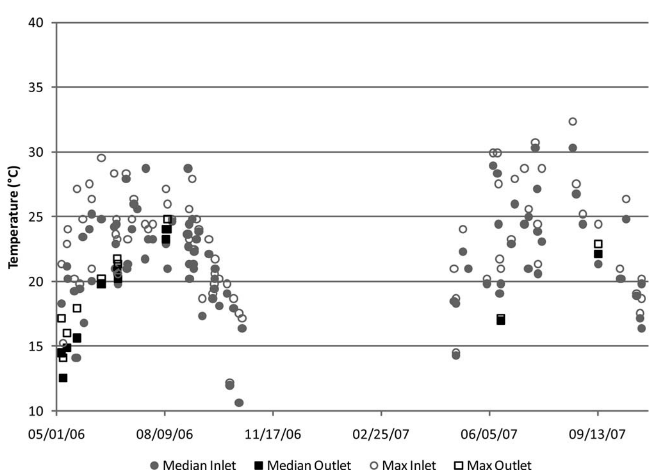

Fig. 6. Influent and effluent temperatures at the Asheville bioretention area

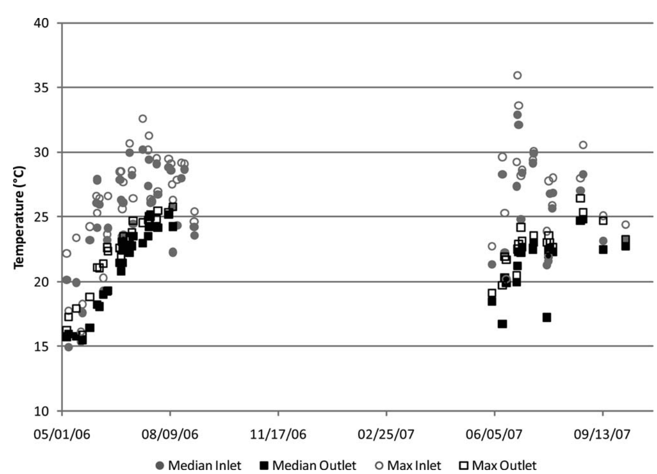

Fig. 7. Influent and effluent temperatures at the Lenoir bioretention area

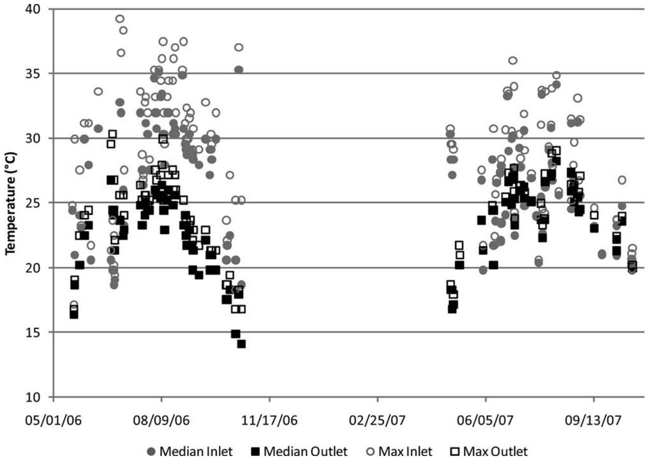

Fig. 8. Influent and effluent temperatures at the Brevard east bioretention area

tention area that is not evident directly from temperature measurements was the ability of the larger system to infiltrate runoff without generating outflow. When seepage occurs and water leaves the bioretention area through the underlying soil and not the drainage pipes, the thermal impact from the runoff is effectively eliminated. Despite receiving the same rainfall, measurable outflow occurred in response to 76% of rainfall events at the Brevard east bioretention area, while only 27% of rainfall events at the Brevard west bioretention area generated outflow (Table 5). Even during storms that generate outflow, substantial reductions in runoff volume and consequently thermal load are likely, due to seepage and evapotranspiration.

Storm events generally had a negligible effect on soil temperatures at the Asheville bioretention area (Fig. 10). Even during the largest storms, runoff temperatures appeared to reach thermal equilibrium with the surrounding soil after infiltrating only 60 cm. The relative stability of soil temperatures likely had an impact on the ability of the Asheville bioretention area to mitigate thermal pollution. A significant difference between maximum influent and effluent temperatures was evident because initial runoff temperatures were warmer than soil deep within the bioretention area. When pavement temperatures cooled as a storm progressed, runoff became cooler than soils deep within the bioretention area,

Table 5. Measurable Inflow and Outflow Events at Each Bioretention Area

	Inflow events	Outflow events	Inflow events with outflow
Asheville	89	11	12%
Lenoir	58	46	79%
Brevard east	127	96	76%
Brevard west	128	34	27%

causing the bioretention area to raise the temperature of infiltrating water above that of the influent during the later portions of a storm. Although a large bioretention area, such as the one at Asheville, may result in predictable effluent temperatures, the inability of soils to cool in response to cooler runoff is a substantial disadvantage toward their role in mitigating thermal pollution.

Soil temperatures below the surface at the Lenoir bioretention area were much more dynamic than those at the Asheville bioretention area (Fig. 11). Soil temperatures generally increased at all depths in response to a storm event. Median influent temperatures at the Lenoir bioretention were significantly warmer than those at the Asheville bioretention, which may have been responsible for some of the differences in soil temperature responses. Another substantial difference between the two systems was the area they occupied in relation to their contributing watershed. The Lenoir bioretention covered an area equivalent to 4% of the contributing watershed, while the Asheville bioretention occupied the equivalent of 16% of the contributing watershed. With approximately four times more soil relatively available to absorb heat at the Asheville site, it is reasonable that soil media temperature changes during a storm would be limited to shallow soil depths. Diurnal soil temperature fluctuations near the surface were larger at the Asheville bioretention area, which was likely due to the relatively smaller amount of vegetative shading that site received. Soil temperatures near the surface at both bioretention areas often cooled following storm events, probably due to heat losses from evaporation and cooler air temperatures.

Similar to the Lenoir bioretention area, soil temperature fluctuations were also observed at the Brevard east bioretention area in response to storm events (Fig. 12). Although the depth of the underdrains was relatively shallow at 48 cm, the size of the bioretention area fell within general sizing guidelines at 7% of the

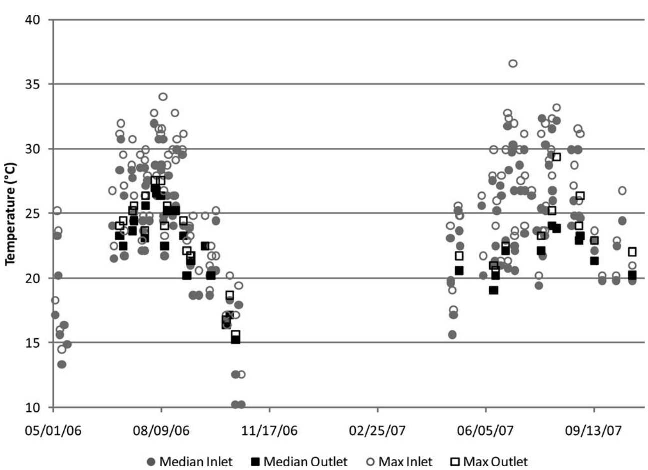

Fig. 9. Influent and effluent temperatures at the Brevard west bioretention area

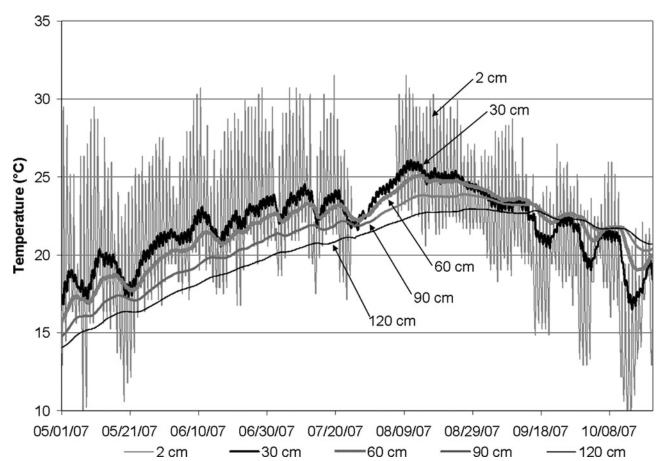

Fig. 10. Soil temperatures within the Asheville bioretention area during 2007

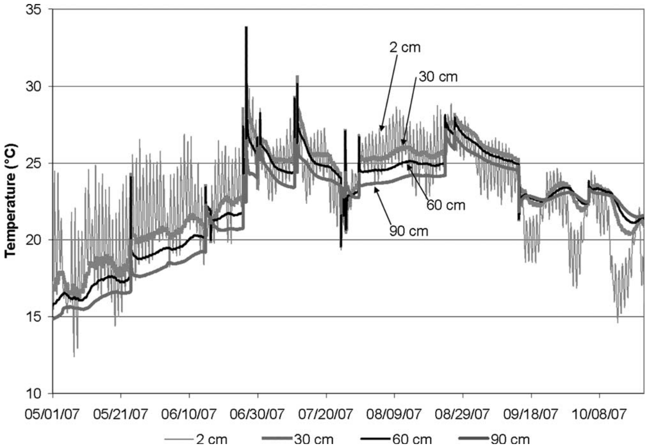

Fig. 11. Soil temperatures within the Lenoir bioretention area during 2007

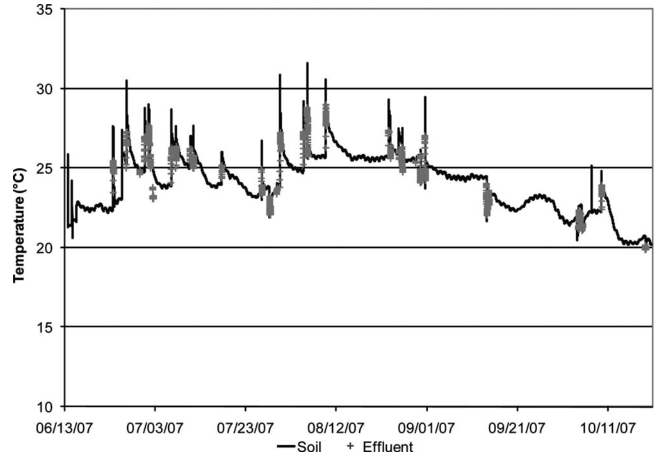

Fig. 12. Brevard east soil temperature at a depth of 40 cm during 2007

contributing watershed. At times, the effect of storms on soil temperatures was prolonged, taking several days for the soil to cool to antecedent temperatures. Differences between soil and effluent temperatures at all three sites, where soil temperature was monitored, suggest that additional cooling occurs as water is collected by the underdrain network and discharged.

Analysis of temperature trends at specific soil depths provided insight into optimum underdrain depths. With the exception of nighttime surface temperatures, soil temperatures were coolest at the bottom of the bioretention soil column during the summer months. Soil temperatures at the bottom of the bioretention areas also exhibited the smallest fluctuations in response to storms or diurnal and seasonal temperature changes. However, the stability of soil temperatures at greater depths poses a potential risk of increasing the temperature of infiltrating water during latter portions of a storm when cooler runoff prevails. Although there were several exceptions during late night storms, soils at a depth of 90 cm or greater remained cooler than soils at shallower depths for most storms. Beginning in September, soil temperatures were often warmest at the bottom of the bioretention areas, which raises potential concerns of warm effluent from deep bioretention areas during spawning seasons in the fall when preferred temperatures are cooler.

The time of the beginning of each storm bore a significant negative linear correlation with median and maximum influent and effluent temperatures at both the Brevard east and Brevard west bioretention areas. The correlation between time and effluent temperature may be attributed to the warmer influent temperatures or warmer soil temperatures due to the shallow drain depth. Overall, the correlation may indicate the inability of relatively shallow bioretention areas to buffer temperature changes near the surface. There was a significant negative linear correlation when time was compared to median and maximum influent temperatures at the Lenoir bioretention area and Asheville bioretention area; however, there was no significant linear correlation between time and median or maximum effluent temperatures at those sites. It is not surprising that time of day did not have a significant effect on effluent temperatures at the deeper bioretention areas of Asheville and Lenoir since the greater soil depths should buffer any diurnal effects due to the insulating properties of the soil. The greater soil depths also allowed for runoff temperatures to equilibrate with the surrounding soil, reducing the effects of varying influent temperatures.

There was a significant positive correlation between median and maximum influent and effluent temperatures at the Lenoir, Brevard east, and Brevard west sites, with warm influent indicating warm effluent. This correlation is supported by changes in soil temperatures in response to storm events. No significant correlation between maximum influent and effluent temperatures was observed at the Asheville bioretention area. There was a small but significant positive correlation between median influent and effluent temperatures at the Asheville site. Because soils deep within the Asheville bioretention area did not exhibit temperature changes in response to storm events, it is not surprising that influent and effluent temperatures were not strongly correlated. The variance of influent temperature within each storm was significantly greater than the variance in effluent temperature at all four bioretention areas. The reduced variance at the outlet may be indicative of the ability for deeper soils within the bioretention areas to buffer changes in both water and soil temperature experienced near the surface during a storm.

Conclusions and Summary

Monitoring results suggest that bioretention areas are a viable option for reducing the thermal impacts of urban storm-water runoff. The two bioretention cells that covered a smaller area with respect to their watershed (Lenoir and Brevard east) were able to significantly reduce both maximum and median water temperatures between the inlet and outlet. Because it is not possible for runoff flows to increase as a result of bioretention treatment, these systems clearly reduced the thermal load associated with urban storm-water runoff. This reduction in temperature differs from the results Dietz and Clausen (2005) obtained at a bioretention area in the northeastern United States, which may be attributed to the warmer influent temperatures observed at the N.C. locations and increased measurement frequency. Although the two bioretention cells that covered a larger area with respect to their watershed (Asheville and Brevard west) were only able to significantly reduce maximum water temperatures between the inlet and outlet, there was evidence that these systems generated less outflow, effectively reducing the thermal load. The ability of bioretention areas to decrease runoff temperatures and reduce runoff volumes through seepage suggests that they may be better suited for cold-water stream environments than storm-water wetlands and wet ponds. Despite these temperature reductions, effluent temperatures were still warmer than the 21°C temperature threshold for trout, indicating additional cooling may be necessary to completely eliminate the thermal impact from urban storm-water runoff.

The ability of bioretention areas to reduce runoff volumes was considered to be a major benefit of their use in trout sensitive regions. When runoff volumes are reduced, the thermal impact to the receiving stream is decreased as long as there are not large increases in temperature resulting from bioretention treatment. Furthermore, bioretention areas mimic predevelopment hydrology by recharging shallow groundwater supplies, which constitute a major water source for many coldwater fisheries. The ability of bioretention areas to mimic predevelopment hydrology is distinctly different from other storm-water BMPs, such as storm-water wetlands and wet ponds, where water largely remains on the surface and volume reductions are relatively minimal.

The largest runoff volume reductions are expected for locations where the hydraulic conductivity of the soil underlying the bioretention area is substantial. In some of these locations, underdrains may not be required; however, when underdrains are not incorporated into the bioretention design, there is an increased risk of generating overflow during a storm event. When the hydraulic conductivity of the underlying soil is high enough to completely drain the bioretention area between storm events, the thermal impact of overflow is likely minimal since the overflow would occur later in a storm when runoff temperatures have cooled. If the bioretention area has not been adequately drained between storm events, overflow may begin early in a storm event when the warmest runoff temperatures were observed, negating the temperature reductions of the bioretention area. An alternative design where a storage layer is included below the underdrains or an upturned elbow is used to create an internal water storage zone would allow for increased seepage into the underlying soil while also minimizing the risk of surface overflow.

The behavior of soil temperatures within the monitored bioretention areas provided insight into how the systems functioned. At the Asheville bioretention area, proportionately the largest system studied, soil temperature trends were in general agreement with results Wierenga et al. (1970) obtained when irrigating soil with warm water, with water temperature equilibrating with the surrounding soil after infiltrating through less than 1 m of soil. At bioretention areas falling within conventional sizing guidelines, soil temperatures fluctuated throughout the entire soil column in response to storm events, which can be attributed to higher mass transfer rates per unit of soil area. Although fluctuations existed, the magnitude of temperature change was reduced deep within all bioretention areas, increasing the predictability of effluent temperatures. Effluent temperatures also followed seasonal patterns corresponding to soil and pavement temperatures. The ability to predict effluent temperatures from a bioretention area has important implications for the development of temperature TMDL programs.

Bioretention design parameters appear to play an important role in the effectiveness of bioretention areas in mitigating thermal pollution from urban storm-water runoff. Installation of larger bioretention areas with respect to the watershed size does not seem to have substantial benefits with regard to temperature reduction; however, greater reductions in runoff volume appear to have major implications for reducing the thermal load to coldwater stream environments. Bioretention areas should not be lined and should be sited in locations with high underlying soil hydraulic conductivities when possible to encourage movement of storm-water runoff into the shallow groundwater. When compared with storm-water wetlands and wet ponds, the ability of bioretention areas to reduce runoff volumes may be the BMP's greatest asset. Monitoring results indicate that during the summer months, water temperatures were typically coolest after reaching greater soil depths indicating that deeper bioretention areas may be better suited in regions where thermal pollution is a concern. It is possible for soil depth to be too great for temperature reduction since the temperature of deep soils does not decrease in response to cooler runoff temperatures and temperatures at greater depths are warmer than shallower depths during trout spawning seasons in the fall. Despite these concerns, underdrain depths between 90 and 120 cm appear to be practical for most applications.

Due to the wide variety of possible bioretention configurations, additional research is needed to examine the effects of these varying designs. Additionally, results should be confirmed for other regions around the world, where coldwater fisheries are a concern, since N.C. lies along the southeastern extent of the U.S. trout populations. Although the thermal impacts of bioretention treatment were assessed in the current study, there are a number of complex factors that affect the thermal impact of storm-water discharges on the temperature of coldwater stream environments. Specifically, detailed measurements of storm-water and stream flows and temperatures are required. Additional monitoring and modeling efforts are needed to better understand the effect of direct storm-water discharges and BMP effluents on these waters and evaluate ecological impacts. Based on the results of this study, it is evident that with careful consideration in BMP design, bioretention areas should serve as suitable treatment mechanisms for thermal pollution from urban storm-water runoff.

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