Technical Note

Effect of Urban Catchment Composition on Runoff Temperature

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Abstract: Urban runoff adversely impacts cold-water stream environments due to sporadic fluxes of thermally enriched runoff. This adversely impacts tourism in regions that support trout and salmon streams. Research on storm water control measures (SCMs) has shown that meeting the 21°C trout threshold is not consistently feasible with current SCM technologies. Thus, it is important to consider other factors in storm water temperature management, such as catchment characteristics. Median and maximum runoff temperatures from a shaded parking lot were consistently lower than those from a nearby unshaded lot. This suggests the need to implement a tree canopy cover in trout-sensitive catchments. A light-colored chip seal pavement was compared to a traditional hot-mix asphalt pavement; the light-colored chip seal produced median storm water temperatures that were 1.4°C lower than the standard hot-mix asphalt. It was shown that runoff temperature measurement location is critical when evaluating SCM performance, and that underground conveyances can substantially reduce runoff temperature.
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Introduction

As advances in aquatic ecology have coincided with increased urbanization, it has become evident that augmented stormwater runoff temperatures can negatively impact coldwater stream environments. Although increased water temperatures affect a variety of aquatic organisms, trout and salmon often receive special attention due to their economic and ecological importance (U.S. EPA 2003). Specific effects of increased water temperatures on trout include increased feeding, disorientation, increased metabolism, reduced reproduction, and possible mortality (Hokanson et al. 1977; Caissie 2006). Thermal impacts of urban storm water runoff are of particular concern in western North Carolina, because this region of the state lies along the southeastern extent of United States trout populations. As a result, relatively small thermal impacts can cause water temperatures to exceed trout temperature thresholds.

Furthermore, recent national legislation (Energy Independence and Security Act) requires the restoration of storm water temperature to predevelopment conditions on all federally funded construction projects (U.S. Congress 2007). These stimuli have spurred a need to understand thermal loading from storm water runoff and to develop methods to reduce its deleterious effects. Recent research into storm water control measures (SCMs) has shown that storm water practices that impound water above ground, such as storm water wetlands and wet retention basins, tend to increase thermal loads to streams (Lieb and Carline 2000; Herb et al. 2009; Jones and Hunt 2010). One study on underground detention showed a mean reduction in storm water temperature of 1.6°C (Natarajan and Davis 2010). A study of two vegetative filter strips showed reductions in maximum and median storm water temperature (Winston et al. 2011). Jones and Hunt (2009) found substantial reductions in temperature at four bioretention cells in the mountains of North Carolina.

Additionally, when designing in cold water regions, it is important to consider SCMs that infiltrate storm water, such as bioretention, filter strips, sand filters, and permeable pavement, because infiltration effectively reduces the thermal load to the stream (Jones and Hunt 2009; Winston et al. 2011; Roseen et al. 2011). To date, no SCM has been shown to consistently release storm water at temperatures below 21°C; thus, other factors, such as watershed composition (Janke et al. 2011), must be considered to reduce the impact of urbanization on trout and salmonid species.

Asphalt parking lots pose specific thermal pollution hazards because heat is concentrated near the surface and can be rapidly transferred to runoff flows (Kieser et al. 2004). Because of the thermal properties of asphalt, surface temperatures can exceed 60°C (Asaeda et al. 1996), well in excess of the 21°C temperature threshold for many trout species (Coutant 1977). Urbanization causes more thermal energy to be captured at the pavement surface as a result of decreases in solar reflectivity and tree canopy removal (Akbari and Konopacki 2005). Paving also decreases evapotranspiration, which contributes to cooler surface temperatures. Perhaps most importantly, paving decreases shallow groundwater flows, which many coldwater stream habitats rely upon to maintain their baseflow temperatures.

Although the effects of thermally enriched urban storm water runoff on aquatic environments have been realized, the effect of watershed characteristics on runoff temperature is not fully understood. Because urban watersheds vary greatly with regard to configuration and design, there may be opportunities to reduce thermal pollution impacts at the runoff source. This paper presents an initial

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exploration of the effect of parking lot composition and layout on runoff temperature, which can allow planners and engineering designers to better anticipate the thermal impacts of development while incorporating measures to reduce those impacts.

Materials and Methods

Runoff temperatures were monitored at several locations in western North Carolina in conjunction with a study into the effect of SCMs on runoff temperature in trout sensitive waters (Jones and Hunt 2009, 2010). However, these prior publications did not discuss catchment characteristics. The monitoring sites were located in Asheville, Brevard, and Lenoir. Monitoring was conducted from May through October of 2006 and 2007. Inflow measurements were obtained using pulley-float stage recorders with v-notch weirs or estimated using rainfall data. Because of 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. Rainfall data were collected using tipping bucket rain gauges with a resolution of 0.25 mm. Temperature measurements were collected with a combination of HOBO Water Temp Pro (H20-001) and HOBO 4-channel loggers (H08-008-04 & U12-008) with temperature sensors attached (TMCX-HD). All temperature loggers were manufactured by Onset Computer Corporation.

Statistical analysis was conducted using SAS software, version 9 (SAS Institute, Inc. 2006) Cary, NC. The potential impact of runoff temperature on trout populations was ascertained by comparing water temperatures to 21°C, the temperature at which trout begin to experience thermal stress (Coutant 1977), using a signed rank test. Comparisons of water temperatures at different locations were conducted using the Wilcoxon rank sum test (Wilcoxon 1945). Unless otherwise noted, analysis was conducted using storm event median and maximum temperatures. Statistical significance was established within a 95% confidence interval ($p < 0.05$).

Site Descriptions

The Asheville hot-mix asphalt parking lot was located on the campus of the University of North Carolina at Asheville (35°36′52″N, 82°33′48″W) and was estimated to be 7,350 m^2. The parking area was used routinely by faculty and staff of the university and was partially surrounded by mature trees along its perimeter [Fig. 1(a)]. Beginning in the spring of 2006, the uppermost section of the parking lot (3,820 m^2) underwent construction. A temperature logger was installed at the base of a drop inlet that received water from a representative portion of the catchment.

The Asheville chip seal parking lot was also located on the campus of the University of North Carolina at Asheville (35°36′46″N, 82°33′54″W) and the contributing catchment was 280 m^2 [Fig. 1(b)]. The parking lot was constructed during the summer of 2005, at which time a light-colored chip seal was applied to the parking

Fig. 1. Contributing catchments: (a) Asheville chip seal site; (b) Asheville hot-mix asphalt site; (c) Lenoir full sun site; (d) Lenoir shade site; (e) Brevard bioretention areas

Fig. 2. Light-colored chip seal applied to the pavement surface

surface in an attempt to reduce pavement temperatures (Fig. 2). A stand of mature deciduous trees lined the northern boundary of the parking lot. Runoff was routed to a bioretention area by a 5.75-m-long asphalt channel, where a temperature sensor was installed.

The total contributing catchment area at the Lenoir full sun site (35°54′1″N, 81°31′18″W) was 56,500 m^2, consisting of a rooftop and asphalt parking lot. The catchment received minimal shading from surrounding trees [Fig. 1(c)]. When the sun was at the highest point in the sky (solar noon), less than 1% of the watershed was shaded. A temperature logger was installed at the base of a drop inlet that received water from a representative portion of the parking lot.

The Lenoir shade site (35°55′20″N, 81°31′24″W) consisted of a 674-m^2 asphalt parking lot and a 95-m^2 concrete sidewalk. The parking surface was nearly completely shaded by a mature deciduous tree canopy [Fig. 1(d)]. At solar noon, approximately 65% of the watershed was shaded. Runoff entered a bioretention area through a 4.9-m length of buried 22-cm PVC pipe, which contained a temperature probe that measured runoff temperatures from the parking lot.

Adjacent bioretention areas were monitored in Brevard, NC (35°14′20″N, 82°43′52″W). The Brevard East site received runoff from approximately 525 m^2 of asphalt parking lot, and the Brevard West site received runoff from approximately 325 m^2 of asphalt parking lot [Fig. 1(e)]. Both catchments were part of a commercial parking lot, with no tree canopy present to shade the lot. Temperature sensors were installed within the inlet weir boxes at both sites.

Weather Summary

Weather at the monitoring locations was representative of western North Carolina, with mean summer air temperatures between 20 and 25°C; however, Brevard is located in an area that receives more rainfall on an annual basis than most of the eastern United States (Table 1). National Weather Service data were used to quantify normal rainfall and mean air temperature near each research site, and monthly rainfall data were monitored at each research site. During 2007, all monitoring sites experienced a substantial rainfall deficit as part of a drought affecting the southeastern United States.

Results and Discussion

Runoff Temperature Results

Runoff temperatures at all sites were warmest in the late afternoon. Typically, runoff temperatures cooled during the course of a storm

Table 1. Observed and 30-Year Normal (1971–2000) Weather Measurements near Monitoring Locations

	Asheville[a]		Lenoir[b]		Brevard[c]	
Period of record	Rainfall (mm)	Mean air temperature (°C)	Rainfall (mm)	Mean air temperature (°C)	Rainfall (mm)	Mean air temperature (°C)
May 2006	72	17.1	31	17.2	118	16.0
June 2006	102	21.4	92	22.7	104	20.3
July 2006	77	24.2	104	25.3	224	22.5
Aug. 2006	92	24.6	125	25.6	213	22.1
Sep. 2006	96	18.4	138	19.6	181	17.6
Oct. 2006	61	12.4	105	13.4	165	9.2
2006 annual	985	14.1	922	14.8	1675	12.9[d]
May 2007	19	18.4	15	18.8	43	16.5[d]
June 2007	38	22.1	84	23.8	125	20.9[d]
July 2007	93	22.5	96	23.7	82	21.1[d]
Aug. 2007	28	25.5	60	27.2	74	24.3
Sep. 2007	68	21.1	74	22.5	84	19.9
Oct. 2007	6	16.5	0	17.9	5	14.9
2007 annual	533	14.3	787	15.1	920	31.1
May Normal	90	17.3	119	18.3	150	16.3
June Normal	82	21.2	113	22.4	146	19.9
July Normal	75	23.3	112	24.7	130	22.0
Aug. Normal	85	22.6	98	23.9	137	21.2
Sep. Normal	76	19.3	113	20.4	130	18.2
Oct. Normal	61	13.6	92	14.3	123	12.3
Annual Normal	957	13.2	1250	13.9	1681	12.1

Note: Source, State Climate Office of North Carolina (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).
[d]National Weather Service Coop Station # 316805 (35°16′6″N, 82°42′11″W).

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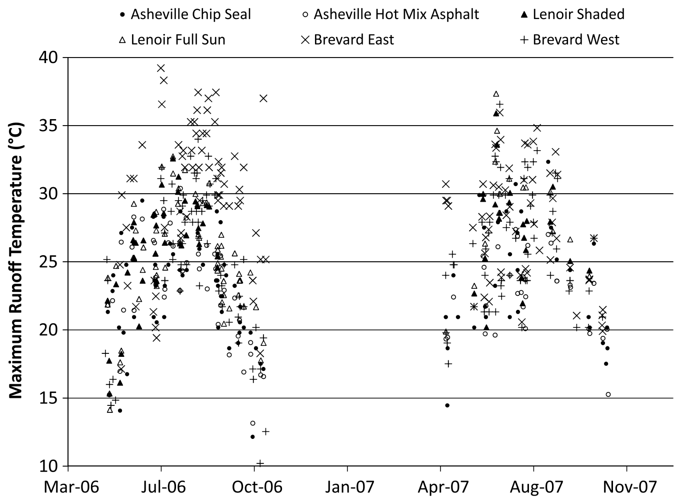

Fig. 3. Storm maximum runoff temperatures at all monitoring locations

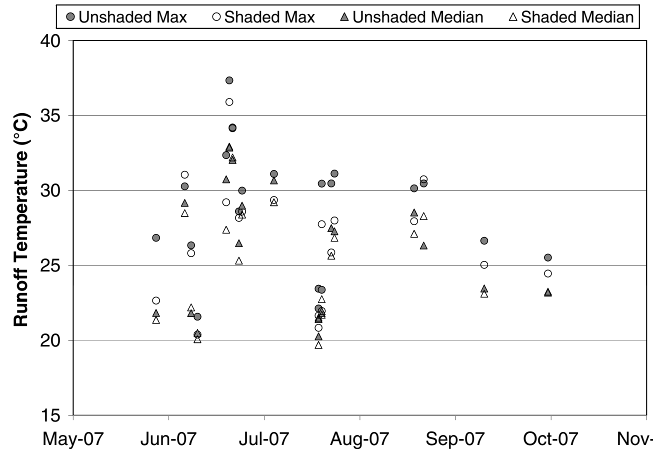

Fig. 4. Measured runoff temperatures at the Lenoir shaded site (bioretention area) and Lenoir unshaded site (wet pond)

as heat stored within the asphalt dissipated. Runoff temperatures exhibited seasonal fluctuations at all six parking lots, with the warmest temperatures during the peak summer months of July and August (Fig. 3). During the summer months of June through August, median runoff temperatures at all monitoring locations were significantly warmer than the 21°C trout temperature threshold. The maximum recorded runoff temperature (39.2°C) was recorded at the Brevard East site on July 1, 2006. The coolest median runoff temperatures were observed at the Asheville chip seal catchment, and the warmest median temperatures were found at the Brevard East catchment (Table 2). The median temperature variance for individual storm events, which provided an estimation of intra-storm temperature variability, was approximately 1.0°C. However, the runoff temperature variance exceeded 10°C during a few storm events; this occurred most often at the Brevard sites, perhaps due to the high albedo parking surface and lack of shading [Fig. 1(e)]. These events tended to occur during the afternoon, during the peak heat of the day.

Effect of Tree Canopy

One mechanism for reducing the thermal impact of urban storm water runoff is to decrease the surface temperature of the contributing catchment by providing a mature tree canopy. An evaluation of the effect of a mature tree canopy surrounding the parking surface was conducted by comparing the catchments at the Lenoir shade and full sun sites, located 2.4 km apart. The bioretention site was surrounded by a mature tree canopy, while the wet pond site received minimal shading from vegetation [Figs. 1(c and d)].

A Wilcoxon signed rank test showed that temperatures of runoff leaving the unshaded wet pond parking lot were significantly warmer than runoff leaving the shaded parking lot during the 2007 monitoring period (Fig. 4). During the 2006 monitoring period, there was a significant difference in storm maximum temperatures, but not storm median temperatures. Over the entire monitoring period, median runoff temperatures leaving the shaded parking lot were 0.3°C cooler than runoff leaving the parking lot without shading (Table 2). Maximum temperatures over the entire monitoring period were substantially different (3.2°C) between the shaded and unshaded sites. These results suggest that shading an impermeable surface may indirectly minimize the thermal impact of treated storm water runoff by reducing SCM influent temperatures.

Table 2. Median Summary Statistics for Runoff Temperatures at Monitoring Sites

Site name	Median (°C)	Maximum (°C)
Asheville chip seal (bioretention)	20.6	23.2
Asheville hot-mix asphalt (wetland)	22.0	23.0
Brevard East	27.9	30.3
Brevard West	23.3	27.1
Lenoir shade (bioretention)	26.0	26.9
Lenoir full sun (wet pond)	26.3	30.1

Effect of Pavement Material

The effect of pavement material on runoff temperature was analyzed at the pair of monitoring sites in Asheville, which were located approximately 400 m apart. At the Asheville bioretention site, a light-colored chip seal had been applied to the asphalt parking lot surface. The light-colored chip seal was installed during construction of the parking lot in an effort to reduce the contribution of the asphalt surface to the urban heat island effect. Because the nearby hot-mix asphalt parking lot contributing water to the Asheville storm water wetland did not have a chip seal applied to its surface, it was possible to compare runoff temperatures from these sites to evaluate the impact of the light-colored chip seal on runoff temperatures.

Over the course of the 2006 monitoring period, a Wilcoxon rank sum test showed no significant difference between storm median runoff temperatures measured at the two parking lots (Fig. 5). Despite the lack of a statistical difference, the hot-mix asphalt parking lot produced a median storm water temperature of 22.0°C, whereas the chip seal lot median temperature was 20.6°C. This is a substantial difference, especially considering the 21°C trout threshold. Maximum storm runoff temperatures were not significantly different between the two parking lots.

When examining all measured runoff temperatures over the course of the 2006 monitoring period, rather than storm medians, median runoff temperatures were 0.73°C cooler at the chip seal parking lot. Several factors likely contributed to cooling runoff temperatures at the conventional asphalt location that were not present at the chip seal location. The hot-mix asphalt parking lot was surrounded (partially shaded) by a canopy of mature trees, which may have contributed to cooler surface temperatures [Fig. 1(b)]. The hot-mix asphalt lot was also lighter in color than a typical

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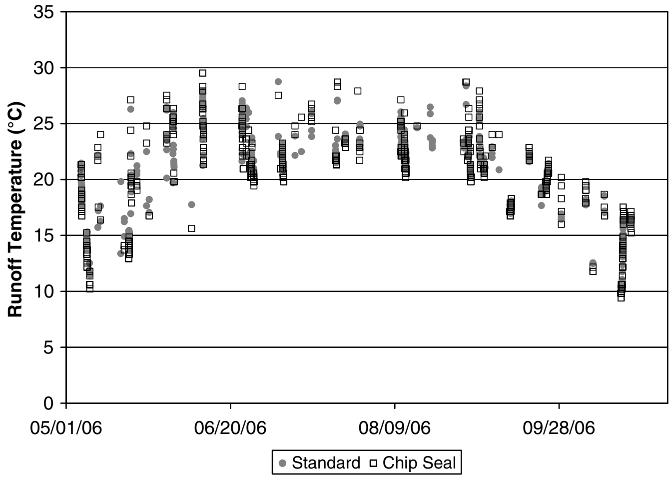

Fig. 5. Recorded parking lot runoff temperatures at the Asheville bioretention area (chip seal) and storm water wetland (hot-mix asphalt) during the 2006 monitoring period

newly paved surface due to normal aging processes. Although there was no significant difference in runoff temperatures between the two monitoring locations, results suggest that it is possible that the light-colored chip seal had similar cooling effects as a parking lot with an aged parking surface and a mature tree canopy. Further studies are needed to definitively evaluate the effect of low albedo pavements on runoff temperature.

Effect of Runoff Temperature Measurement Location

At the Lenoir wetland site, runoff temperatures were measured directly leaving the parking lot surface and within a culvert beneath the drop inlet. Thus, runoff temperature sensors measured the temperature of the water as it immediately fell into the inlet and after being conveyed underground from other drop inlets. A Wilcoxon signed rank test showed that maximum runoff temperatures measured within the surface collection apparatus were significantly warmer than runoff measured in the culvert below; however, there was no significant difference in median runoff temperatures (Fig. 6). This analysis suggests that data used in

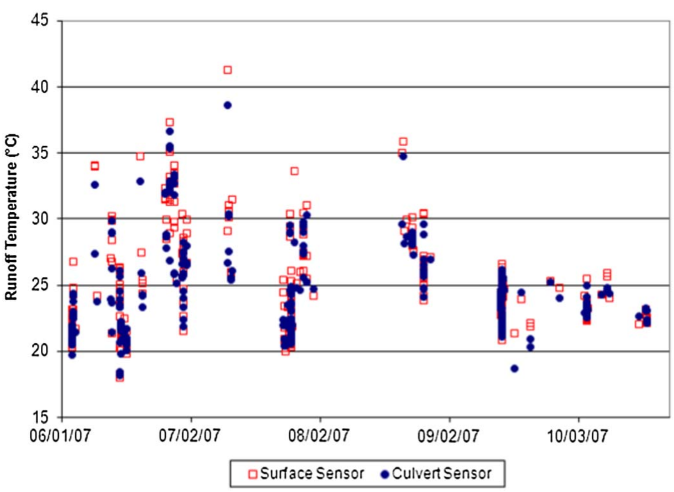

Fig. 6. Temperature of runoff collected immediately downstream of the pavement surface and conveyed within the underlying culvert at the Lenoir wet pond site

evaluating runoff temperature are sensitive to measurement location. If a culvert or sewer system conveys water to an SCM, temperature measurements taken directly from the pavement surface may overpredict SCM performance if they are used as the inlet temperature to the practice, especially when considering maximum temperatures. However, some SCMs, such as bioretention, often receive direct runoff from parking lots.

Additionally, the effects of buried metal and concrete pipes must be considered by watershed managers and engineers working in salmonid watersheds. Jones and Hunt (2010) showed that buried metal pipes reduced storm water temperatures (by more than 7°C in some cases), often to below the 21°C trout threshold. The authors also suggest that the higher thermal conductivity of a metal pipe compared to a concrete pipe may be responsible for producing lower median temperatures (median difference of 1–4°C, depending upon month). Perhaps underground treatment and conveyance may be a primary method of temperature reduction, along with infiltrating SCMs.

Conclusions and Summary

Current SCM technologies, including bioretention, sand filters, filter strips, swales, wet ponds, and wetlands, have been unable to consistently provide thermal mitigation of storm water runoff to the trout threshold of 21°C during the summer months (Jones and Hunt 2009, 2010; Herb et al. 2009; Roseen et al. 2011; Winston et al. 2011). Therefore, other factors, such as thermal management of storm water in the catchment itself, must be considered if coldwater fisheries are to be protected. A mature tree canopy was shown to reduce median and maximum parking lot runoff temperatures, and should be considered a key design criterion in cold-water regions. In retrofit situations, applying a light-colored chip seal is particularly beneficial to reduce runoff temperatures, because it can be applied to most asphalt parking lots in conjunction with routine maintenance. A chip seal parking surface was shown to function (for temperature mitigation) equally well as a partially shaded parking lot with aged, light-colored hot-mix asphalt. Measurement location for runoff temperature must be accounted for when assessing the performance of SCMs, because runoff temperatures can be substantially reduced in underground conveyances. Further research in the area of SCM design and catchment-wide control of storm water temperature is needed to maintain the health of coldwater fisheries.

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