Effect of Storm-Water Wetlands and Wet Ponds on Runoff Temperature in Trout Sensitive Waters

Matthew P. Jones[1] and William F. Hunt, P.E., M.ASCE[2]

Abstract: With increasing development in areas of trout sensitive waters, the effect of urban storm-water runoff temperature on the aquatic ecosystem has become a concern. A study was conducted in western North Carolina, along the southeastern extent of U.S. trout populations, to determine the effect of storm-water wetlands and wet ponds on the temperature of urban storm-water runoff. Measurements included temperature at the inlets, outlets, and at several depths within the best management practices (BMPs). Parking lot runoff temperatures were significantly higher than the 21°C temperature threshold for trout during peak summer months and water temperatures consistently increased from the inlet to the outlet in the storm-water wetland and wet pond, implicating these BMPs as sources of thermal pollution. Despite similar inflow temperatures, effluent temperatures from the wet pond were significantly warmer than those from the storm-water wetland for the period from June to September. Substantial cooling was observed as runoff was conveyed from the parking surface to the BMPs through buried pipes, which could be incorporated into BMP design to achieve thermal pollution mitigation goals. Temperatures at the bottom of the water columns were cooler than water leaving the current outlet structures, providing support for the installation of modified outlet structures in regions with cold water fisheries.

DOI: 10.1061/(ASCE)IR.1943-4774.0000227

CE Database subject headings: Runoff; Stormwater management; Water temperature; Thermal factors; Ponds; Wetlands; North Carolina.

Author keywords: Runoff; Storm-water management; Water temperature; Thermal pollution; Ponds; Wetlands.

Introduction

Especially during the summer months, paved surfaces elevate runoff temperatures by capturing solar radiation and transferring this stored energy to runoff during rainfall events. Due to the low thermal conductivity and reflectivity of asphalt, heat from solar radiation concentrates near the surface and can lead to asphalt surface temperatures in excess of 60°C (Asaeda et al. 1996). Streams exhibit natural diurnal temperature fluctuations; however, the direct discharge of thermally enriched runoff can lead to temperature increases in water bodies well above normal levels (Kieser et al. 2004). Even though temperature spikes are greatest in the afternoon, runoff can be discharged at temperatures substantially higher than stream temperatures during the night and early morning (Lieb and Carline 2000).

Thermally enriched runoff is a concern because of the negative effects it can have on an aquatic ecosystem. While most fish species can tolerate slow seasonal changes in temperature, rapid changes have been proven to be lethal (Agersborg 1930). Trout and salmon are among the fish species most sensitive to water temperature changes and serve as important game fish in many parts of the country (U.S. Environmental Protection Agency 2003). In general, trout and salmon have been found to avoid water temperatures in excess of 21°C (Coutant 1977). The full effect of elevated stream temperatures on aquatic ecosystems is unknown due in part to complex interactions between organisms in the same thermal niche (Huff et al. 2005).

Even though most best management practices (BMPs) were not designed to mitigate thermal pollution, their role in capturing and treating storm-water runoff can affect the temperature of storm-water runoff. Research has found that the effluent water temperature can be higher than the temperature of the incoming runoff in a wet pond (Kieser et al. 2004). The suspected reason for this increase is that most wet ponds are not adequately shaded and incoming solar radiation heats the water above the temperature of the ambient air. A study of the thermal balance of an on-stream wet pond found that under calm weather conditions, water at the surface was on average 3.6°C warmer than the water 1 m below the surface (Van Buren et al. 2000). It has been observed that a storm-water wetland can mitigate thermal loading when well shaded, with the net heat reduction attributed to evapotranspiration and infiltration (Kieser et al. 2004).

Research has indicated that storm-water runoff can increase the temperature of cold water streams and that this temperature increase can have a direct impact on the aquatic ecosystem. Previous thermal pollution research has focused on BMPs designed to treat runoff from large urban drainage networks, leaving the effect of wetlands and wet ponds sized for individual develop-

[1]Former Graduate Student, Dept. of Biological and Agricultural Engineering, North Carolina State Univ., 4011 Westchase Blvd., Suite 500, Raleigh, NC 27607. E-mail: mjones@hazenandsawyer.com

[2]Associate Professor and Extension Specialist, Dept. of Biological and Agricultural Engineering, North Carolina State Univ., Campus Box 7625, Raleigh, NC 27695 (corresponding author). E-mail: bill_hunt@ncsu.edu

Note. This manuscript was submitted on June 3, 2009; approved on January 10, 2010; published online on January 25, 2010. Discussion period open until February 1, 2011; separate discussions must be submitted for individual papers. This technical note is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 136, No. 9, September 1, 2010. ©ASCE, ISSN 0733-9437/2010/9-656–661/$25.00.

J. Irrig. Drain Eng. 2010.136:656-661.

ments on runoff temperatures unknown. By monitoring temperatures throughout a storm-water wetland and wet pond, the effect of these BMPs on runoff temperatures will be evaluated and design parameters that influence temperature reduction capacity can be identified. Additionally, the impact of conveyance systems on runoff temperature reduction will be investigated.

Materials and Methods

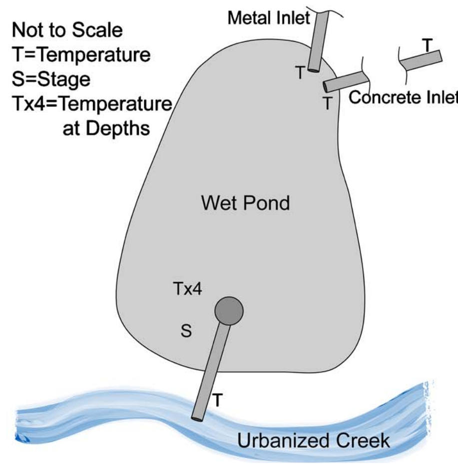
Monitoring was conducted at a storm-water wetland in Asheville, North Carolina, and a wet pond in Lenoir, North Carolina. Temperature, flow, and rainfall were monitored at both sites, with measurements of temperature and flow logged at 5-min intervals. Data were recorded for the storm-water wetland from July to mid-October, 2005, and at both the storm-water wetland and wet pond from May to mid-October, 2006. Due to mechanical complications with the flow monitoring equipment, equipment installed at the major inlets and outlets of the wetland was used to identify periods of flow, but could not be used to quantify flow rates. Only stage was recorded within the wet pond. Rainfall data were collected at each site 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 and U12-008) with temperature sensors attached (TMCX-HD).

Site Descriptions

The wet pond was located in Lenoir, North Carolina (35°54′1″N, 81°31′18″W), and captured runoff from an estimated 56,500 m^2 of rooftop and asphalt parking lot impervious surfaces. The wet pond's surface area was 2,545 m^2, and it received water from a 122-cm-diameter corrugated metal pipe and a 122-cm-diameter reinforced concrete pipe. The corrugated metal pipe had a perennial discharge into the wet pond, which likely originated from groundwater seeping through pipe joints. The outlet structure was designed for water to exit the wet pond through two 60-cm orifices in the concrete structure; however, poorly sealed joints and a potential leak in the emergency drawdown pipe allowed inflow, lowering the normal pool elevation approximately 120 cm below these outlet orifices. This wet pond discharged water directly into a heavily urbanized creek. There was a substantial amount of algae covering the pond for much of the year. Temperature probes were located inside a drop inlet at the parking lot, inside the corrugated metal pipe inlet to the wet pond, inside the reinforced concrete pipe inlet, inside the outlet pipe, as well as at four depths near the outlet structure (Fig. 1). Throughout this text, depth refers to the distance below the static normal pool elevation. Storm-water runoff entering at the monitored drop inlet traveled through 320 m of buried pipe and was combined with flow from a number of additional drop inlets before entering the wet pond through the reinforced concrete pipe inlet.

The storm-water wetland was located in Asheville, North Carolina (35°36′52″N, 82°33′48″W), on the campus of the University of North Carolina at Asheville, and received runoff primarily from an estimated 7,350-m^2 asphalt parking lot. The parking area was partially surrounded by mature trees. Beginning in spring of 2006, the uppermost section of the parking lot (3,820 m^2) underwent construction. The storm-water wetland covered a 724-m^2 area, of which an estimated 70% was covered by vegetation during midsummer of 2006. Vegetative cover was estimated by examining a series of eight random overhead images and digitally comparing areas of open water to the total area. Water was conveyed from the parking surface to the storm-water wetland through a 168-m-long 71-cm-diameter buried corrugated metal pipe and a separate vegetated channel. Water was discharged from the wetland through a flashboard riser structure and corrugated metal pipe into Reed Creek, which is approximately 10 m from the wetland. Temperature probes were located inside a drop inlet at the parking lot, the corrugated metal pipe inlet to the wetland, the vegetated channel inlet, and the outlet structure. Additionally, four probes were spaced at 30-cm depths from the normal pool elevation to the base of a deep pool near the outlet structure (Fig. 2).

(a)

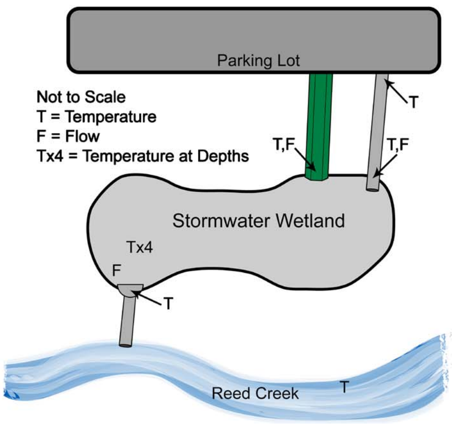


(b)

Fig. 1. Site photo and simplified equipment layout for Lenoir wet pond

The weather at both monitoring locations was typical for this region of North Carolina, with ambient air temperatures exceeding 21°C during the months of June to August (North Carolina Climate Office 2007). Statistical analysis was conducted using SAS software, Version 9 (SAS Institute Inc., Cary, North Carolina). The potential impact of water temperature on trout habitat at various stages in the runoff conveyance and treatment system 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 water temperatures at different locations in the BMPs were conducted using the Wilcoxon rank sum test (Wilcoxon 1945). Comparisons between the wet pond and wetland were limited to data collected during 2006. Analysis

(a)



(b)

Fig. 2. Site photo and simplified equipment layout for Asheville storm-water wetland

was conducted using monthly storm median and maximum temperatures. Statistical significance was established within a 95% confidence interval ($\alpha = 0.05$).

Results and Discussion

The temperature of runoff leaving the parking surface at the Lenoir wet pond site was significantly warmer than 21°C for June to September (Table 1). The maximum runoff temperature of 32.7°C at the Lenoir site occurred on July 14, 2006 at 2:05 p.m. At the Asheville storm-water wetland site, runoff temperatures leaving the parking surface were significantly warmer than 21°C for June to August (Table 2), with the maximum runoff temperature of 30.4°C occurring on July 11, 2006 at 1:05 p.m. These elevated runoff temperatures indicate that there is the potential for runoff directly from these parking surfaces to impact trout populations. While storm-water temperatures do not provide a direct indication of creek conditions and trout impacts, temperatures in excess of 21°C do not contribute to suitable thermal conditions for trout and salmon. In general, runoff temperatures were warmest near the beginning of a storm and cooled as rainfall progressed and heat stored in the asphalt diminished.

Effect of Conveyance in Buried Pipes

Both median and maximum water temperatures were significantly cooler after traveling through the buried corrugated metal pipe from the parking lot drop inlet to the Asheville wetland inlet for the period from May to August. Cooling in the buried pipe generally persisted throughout the duration of a storm event. A decrease in runoff temperatures as storms progressed was also observed at the wetland inlet, suggesting that the water may not have reached thermal equilibrium with the soil surrounding the pipe over the 168-m distance (Fig. 3). At times, water was cooled by more than 7°C and runoff temperatures in excess of 21°C were cooled below the trout temperature threshold before water entered the wetland or wet pond.

Runoff temperatures were also significantly cooler after traveling from the monitored drop inlet at the Lenoir wet pond to the concrete pipe inlet. Storm-water runoff entering the wet pond from the concrete pipe was significantly warmer than runoff entering from the metal pipe at the same site for the months of June to September (Table 1). The higher thermal conductivity of the metal pipe may be responsible for the temperature differences; however, further research is needed to evaluate this impact since there were differences in watershed composition and pipe configuration.

Wet Pond

The effluent temperature from the wet pond never dropped below 21°C for the months of June to August, with the maximum effluent temperature of 29.2°C logged on 7/20/2006 (Table 1). There was no significant difference between the temperature of the wet pond effluent and direct runoff from the parking lot surface. Median pond effluent temperatures were significantly warmer than water entering the pond from the concrete and metal pipe inlets, with temperature differences sometimes exceeding 10°C. The difference in influent and effluent temperatures implies that the pond was a consistent source of thermal pollution.

Due to thermal stratification within a pond, one potential

Table 1. Lenoir Wet Pond Temperature Summary

	May	June	July	August	September	October
Median runoff temperature (°C)	18.03	24.70	26.55	25.72	22.61	19.94[a]
Median metal inlet temperature (°C)	15.23	18.66	18.76	21.71	18.28	15.90[a]
Median concrete inlet temperature (°C)	16.38	22.19	23.05	24.61	21.52	17.43[a]
Median effluent temperature (°C)	19.39	24.94	27.74	26.18	23.26	18.45[a]
Median temperature at 120-cm depth (°C)	17.90[a]	23.24[a]	25.56	25.56	21.71	17.90[a]
Median temperature at 80-cm depth (°C)	18.28[a]	23.63[a]	25.95	25.95	21.33	17.14[a]
Median temperature at 40-cm depth (°C)	20.18[a]	22.86[a]	27.12	26.34[a]	22.09	17.52[a]
Median temperature at normal pool elevation (°C)	—	24.40[a]	27.91[a]	24.01[a]	22.0[a]	16.38[a]

[a]Data set not complete for the entire month.

J. Irrig. Drain Eng. 2010.136:656-661.

Table 2. Asheville Storm-Water Wetland Temperature Summary for 2005 and 2006

	May	June	July	August	September	October
2005						
Median pipe temperature (°C)	—	—	—	22.20	20.39	20.29[a]
Median channel temperature (°C)	—	—	—	23.02	—	—
Median effluent temperature (°C)	—	—	—	23.06	—	—
Median temperature at 90-cm depth (°C)	—	—	23.74	22.75[a]	20.96	19.46[a]
Median temperature at 60-cm depth (°C)	—	—	24.17	23.16[a]	21.15	19.37[a]
Median temperature at 30-cm depth (°C)	—	—	24.24	23.86[a]	21.68[a]	19.89[a]
Median temperature at normal pool elevation (°C)	—	—	24.17[a]	24.73[a]	—	19.67[a]
2006						
Median runoff temperature (°C)	18.85	24.67	25.00	23.34	20.40	16.25[a]
Median channel temperature (°C)	18.15	20.25	22.60	21.29	—	—
Median pipe temperature (°C)	17.53	20.63	21.19	22.83	21.12	16.57[a]
Median effluent temperature (°C)	18.34	22.14	23.76	23.28	21.30	15.47[a]
Median temperature at 90-cm depth (°C)	15.37	20.41[a]	22.39[a]	22.56	19.75	16.23[a]
Median temperature at 60-cm depth (°C)	16.30	21.53	23.52	23.33	19.32	13.64[a]
Median temperature at 30-cm depth (°C)	17.56	22.23	23.88	23.83	19.56	13.93[a]
Median temperature at normal pool elevation (°C)	19.27	22.92[a]	24.41[a]	23.88[a]	20.70[a]	13.62[a]

[a]Data set not complete for the entire month.

mechanism to reduce effluent temperatures is to modify the outlet structure to draw water from the bottom of the water column. Temperatures at all depths (0, 40, 80, and 120 cm) were significantly different from each other for the entire monitoring period, with the warmest temperatures near the surface.

During storm events, such as the storm on August 11, 2006, water temperatures at all depths generally decreased and approached the temperature of the deepest water in the pond (Fig. 4). Because cooling of the effluent was primarily associated with the reduction in runoff temperatures as storms progressed, the pond did little to reduce temperatures itself, but was able to convey the benefits of cooler influent.

The temperature of water leaving the current outlet was significantly warmer than the water temperature at a depth of 120 cm for June to October (with a maximum difference in monthly medians of 2.18 °C), suggesting that a modified outlet that draws from the bottom waters would be beneficial for thermal pollution mitigation. At the same time, the water temperature at a depth of 120 cm was still significantly warmer than the metal pipe influent and the 21 °C trout temperature threshold. Based on these results, the wet pond is expected to increase runoff temperature regardless of outlet structure configuration.

Storm-Water Wetland Results and Discussion

Median effluent temperatures from the storm-water wetland were significantly warmer than 21 °C for the months of June to September. Additionally, median effluent temperatures were significantly warmer than piped inflow temperatures (Table 2), and maximum effluent temperatures were significantly warmer than runoff directly leaving the parking surface for the period from June to September, suggesting that the wetland was a source of thermal pollution. A number of storms during the monitoring period were captured entirely by the wetland without generating outflow, inherently mitigating the thermal load to Reed Creek.

Water temperatures at the bottom of the storm-water wetland were the coolest and also exhibited the smallest diurnal fluctua-

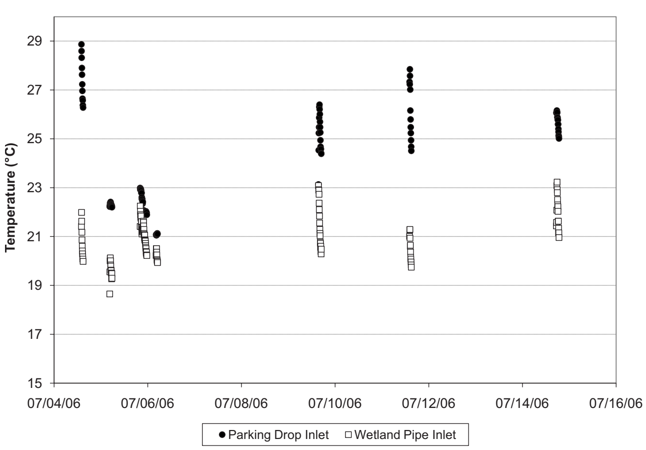


Fig. 3. Temperature of runoff exiting parking lot and entering the wetland after traveling 168 m in a buried corrugated metal pipe

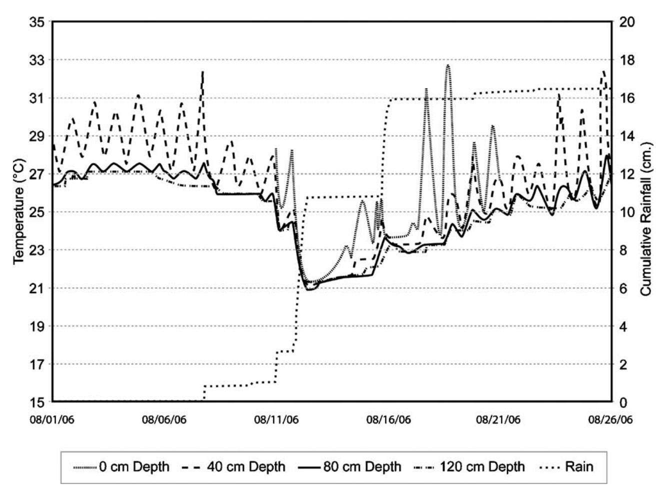


Fig. 4. Temperature distribution within the wet pond water column near the outlet

J. Irrig. Drain Eng. 2010.136:656-661.

tions. Water at the bottom of the wetland was significantly cooler than 21°C for the months of May, June, September, and October, 2006, and with the exception of several storms in August, water temperatures during storms at the 90-cm depth were consistently cooler than the current effluent. There was no significant difference in temperature between the piped influent and water at a depth of 90 cm for every month in the monitoring period. These results suggest that a modified outlet structure may discharge temperatures suitable for trout; however, because inflow temperatures were already cool, it is unlikely that substantial temperature reductions will result from wetland treatment.

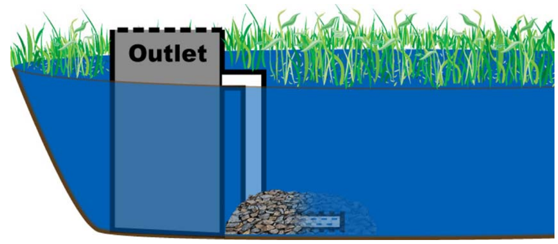


Fig. 5. Illustration of modified outlet structure drawing from bottom waters

Comparison of Wetland and Wet Pond Results and Discussion

Effluent temperatures from the wet pond were significantly warmer than those from the storm-water wetland for the months of June to September. There were no significant differences in the temperature of water entering the wetland and wet pond during the entire monitoring period, suggesting that warmer effluent temperatures from the wet pond were not attributed to higher inflow temperatures. Additionally, mean water temperatures just 30 cm below the normal pool elevation of the storm-water wetland and deeper were significantly cooler than mean water temperatures measured at the bottom of the wet pond during the months of June to October. Diurnal temperature fluctuations within the water column were also significantly greater in the wet pond than the storm-water wetland for the months of July to October. Differences in water temperatures between the wetland and wet pond are likely attributed to the presence of vegetation in the wetland and its associated cooling through shading and evapotranspiration. Any shading of water within the Lenoir wet pond was provided by algae covering the pond surface. While the algae shielded deeper water within the system from radiation, much of this radiation was captured by the algae itself and the water near the surface was consequently heated through conduction, reducing any benefits of shading. This phenomenon is similar to the one observed by Dale and Gillespie (1976) in a pond covered by *Lemnaceae* (duckweed). The wetland and wet pond sites were separated by approximately 100 km and associated differences in weather could account for some of the differences observed.

Alternative Outlet Structure Designs

Although currently used for reservoirs and other large water bodies, an outlet structure that draws from the deepest point in the water column has not been previously recommended for storm-water wetlands and wet ponds. With a modified outlet structure, effluent temperatures significantly cooler than the 21°C temperature threshold for trout appear to be attainable for storm-water wetlands, but unlikely for wet ponds in borderline trout regions. Implementation of a modified outlet structure could consist of a section of perforated plastic tubing along the bottom of the wetland or pond surrounded by a gravel envelope and connected by nonperforated tubing to the outlet structure at the normal pool elevation (Fig. 5). However, there are several potential concerns related to this outlet structure associated with maintenance, effluent pollutant concentrations, and effluent dissolved oxygen levels that merit further investigation. If a standard outlet configuration is used, effluent flows should be limited during the early periods of a storm since monitoring results indicated that effluent temperatures decrease with time.

Summary and Conclusions

With a standard outlet configuration that draws water from the normal pool elevation, neither the storm-water wetlands nor wet ponds were capable of consistently reducing runoff temperatures and often served as sources of thermal pollution. Due to the large fluctuations in water temperature near the surface, outlet temperatures were not only elevated, but subject to large fluctuations, making the estimation of effluent impacts difficult. These large fluctuations make it difficult to consistently evaluate the role of a storm-water wetland or wet pond in a temperature total maximum daily load (TMDL) program.

Effluent temperatures were warmer at the wet pond than the storm-water wetland, with differences primarily attributed to the amount of vegetative shading. In addition to cooling through transpiration, the broad leaf plants covering the storm-water wetland likely intercepted and reflected substantial amounts of solar radiation above the water surface, insulating the water from this heat. The cooling aspects associated with the presence of vegetation provide a benefit to the storm-water wetland that the wet pond lacks, indicating a storm-water wetland may inherently be better suited for regions of cold water fisheries.

Because runoff is frequently piped underground to wetlands or wet ponds, reduced inflow temperatures appear to be attainable for many wetland and wet pond installations. Although there is evidence that cooler influent to a wetland or wet pond will result in cooler effluent, the benefit of cooling runoff before it enters these BMPs is substantially reduced when the water within these systems is warmer than the original runoff. Consequently, conveying water through buried pipes should be incorporated after treatment in a wetland or wet pond for substantial temperature reductions to be realized.

Because North Carolina trout waters are located along the southeastern extent of trout populations, it is important to minimize the thermal impacts associated with urbanization and storm-water treatment since small changes in temperature can have substantial impacts on the aquatic ecosystem. With proper BMP design, implementation of modified outlet structures, emergent vegetation, and conveyance in buried pipes when practical, it should be possible for these systems to achieve sediment, nutrient, and metal removal goals, while minimizing, but not eliminating, thermal impacts to trout waters.

Acknowledgments

This research was funded by the North Carolina Department of Environment and Natural Resources (NCDENR), Division of Water Quality. The writers would like to thank Jonathan Smith, Dan Willits, Garry Grabow, Aziz Amoozegar, Jon Calabria, Allen

J. Irrig. Drain Eng. 2010.136:656-661.

Caldwell, Eric Caldwell, Seth Nagy, and Jason Zink, all of whom are currently or formerly of NC State University, for their assistance in selecting research sites and support throughout the project.

References

Agersborg, H. P. (1930). “The influence of temperature on fish.” *Ecology*, 11, 136–144.

Asaeda, T., Ca, V. T., and Wake, A. (1996). “Heat storage of pavement and its effect on the lower atmosphere.” *Atmos. Environ.*, 30(3), 413–427.

Coutant, C. C. (1977). “Compilation of temperature preference data.” *J. Fish. Res. Board Can.*, 34, 740–745.

Dale, H. M., and Gillespie, T. (1976). “The influence of floating vascular plants on the diurnal fluctuations of temperature near the water surface in early spring.” *Hydrobiologia*, 49(3), 245–256.

Huff, D. D., Hubler, S. L., and Borisenko, A. N. (2005). “Using field data to estimate the realized thermal niche of aquatic vertebrates.” *N. Am. J. Fish. Manage.*, 25(1), 346–360.

Kieser, M. S., Spoelstra, J. A., Feng Feng, A., James, W., and Li, Y. (2004). *Stormwater thermal enrichment in urban watersheds*, IWA, London.

Lieb, D. A., and Carline, R. F. (2000). “Effects of urban runoff from a detention pond on water quality, temperature and caged *Gammarus minus* (Say) (Amphipoda) in a headwater stream.” *Hydrobiologia*, 441(1), 107–116.

North Carolina Climate Office. (2007). “NC CRONOS Database.” ⟨http://www.nc-climate.ncsu.edu/cronos⟩ (August 31, 2007).

U.S. Environmental Protection Agency. (2003). *EPA region 10 guidance for pacific northwest state and tribal temperature water quality standards, EPA 910-B-03-002*, Region 10 Office of Water, Seattle.

Van Buren, M. A., Watt, W. E., Marsalek, J., and Anderson, B. C. (2000). “Thermal balance of an on-stream storm-water management pond.” *J. Environ. Eng.*, 126(6), 509–517.

Wilcoxon, F. (1945). “Individual comparisons by ranking methods.” *Biometrics*, 1(6), 80–83.