

# URBAN Waterways

## Stormwater BMPs for Trout Waters

### *Coldwater Stream Design Guidance for Stormwater Wetlands, Wet Ponds, and Bioretention*

*As our understanding of aquatic ecology has advanced, it has become clear that the effects of stormwater runoff and urbanization are detrimental to organisms living in streams and rivers. To reduce these negative impacts, a variety of stormwater best management practices (BMPs) have been implemented to decrease stormwater flow into streams and remove pollutants, such as metals, nutrients, and bacteria. While these systems have become effective tools for treating many stormwater pollutants, one contaminant has not been historically considered in BMP design: thermally polluted stormwater runoff.*

### THERMAL POLLUTION AND ITS IMPACT

Especially during the summer months, pavement and rooftop materials capture solar radiation, reaching temperatures much higher than those of natural surfaces. During a storm event, heat is transferred from pavement and rooftops to stormwater runoff, with runoff temperatures at times exceeding 110°F. Because most of the heat is concentrated near the pavement or rooftop surface, runoff at the beginning of a storm often exhibits a temperature spike with temperatures decreasing as rainfall continues and surfaces cool. The effect of runoff on coldwater stream environments depends upon both the temperature and flow of water, making urban stormwater runoff especially dangerous with high temperature and heavy flow.

Water temperature affects numerous aspects of an aquatic ecosystem. Many

aquatic organisms, such as fish and insects, are *ectotherms*, meaning their body temperatures are regulated by their surroundings. Increased water temperatures can lead to behavioral changes, such as increased feeding or aggressiveness, as well as physiological changes, such as increased metabolism or loss of motor function. Fish, especially trout and salmon, possess some of the most stringent temperature requirements. Most trout and salmon prefer water temperatures between 40 to 70°F, with increased temperatures leading to injury or death.

In addition to the direct effects of increased temperature, warm water has a lower *dissolved oxygen content*, another vital habitat constraint for aquatic organisms. The dynamics of an aquatic ecosystem are impossible to predict. Some life forms thrive under increased temperatures, while others perish. This complexity indicates the importance of maintaining natural temperature ranges

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in streams and rivers to preserve the health of the aquatic ecosystem. The survival of fish is important to both the ecosystem and the economy. For example, according to the U.S. Fish and Wildlife Service, an estimated 1.3 million anglers fishing in North Carolina spend more than \$1 billion a year.

## RECENT RESEARCH

A study conducted by the Biological and Agricultural Engineering Department (BAE) at North Carolina State University (NCSSU) during the summers of 2005 and 2006 examined the effect that common urban stormwater BMPs have on the temperature of stormwater runoff. With the wide implementation of stormwater BMPs to intercept runoff before it is discharged into streams, it is important to understand the effects that these systems have on runoff temperature. Research was performed in western North Carolina at a stormwater wetland, a wet pond, and four bioretention areas. Temperatures and flows for all major inlets and outlets, as well as some specified depths, were remotely logged every 5 minutes. The research objectives were to:

1. Determine whether stormwater BMPs increase or reduce runoff temperatures.
2. Identify BMP design parameters that influence temperature reduction.

**Figure 1. North Carolina counties containing trout waters and locations of research sites**

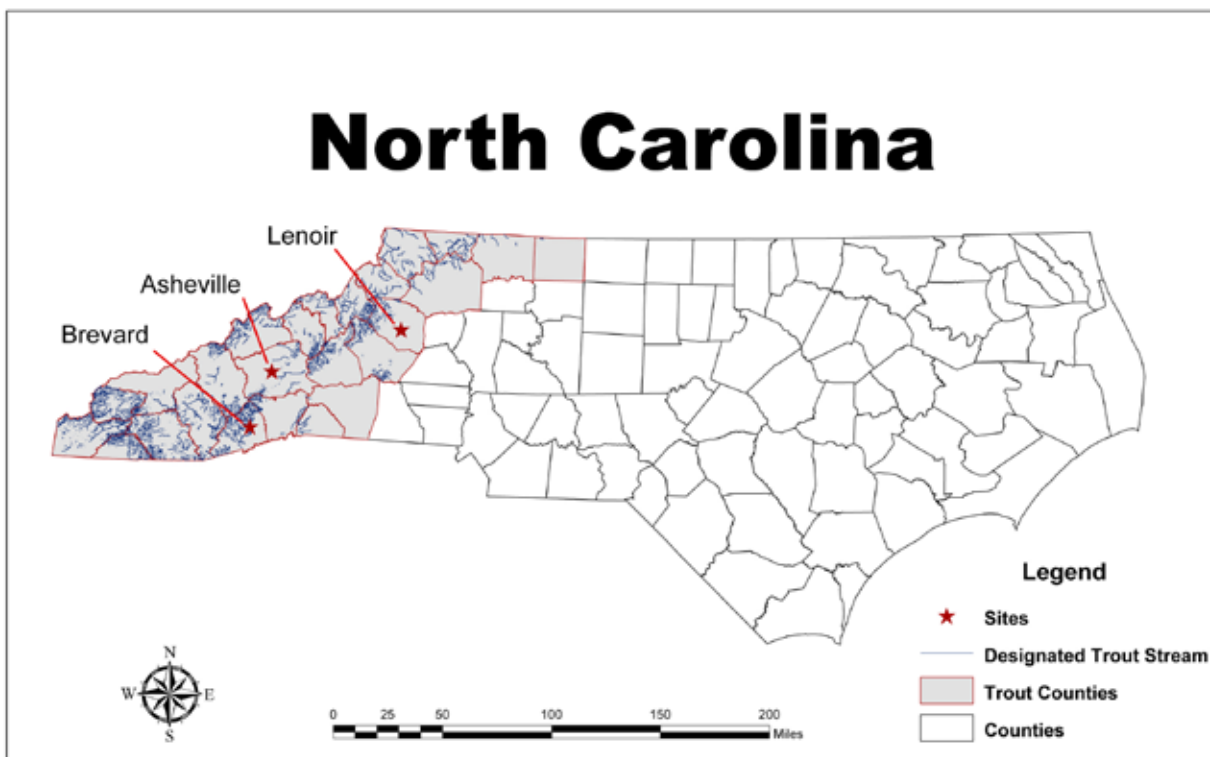
## WHERE IS HEATED STORMWATER RUNOFF A CONCERN?

Although heated runoff potentially can affect any aquatic ecosystem, it is especially a concern in *cold-water stream* environments. These environments exist in streams and rivers capable of supporting coldwater fish, such as trout and salmon. They typically have water temperatures below 70°F in the summer. In North Carolina, these areas are located in the western counties containing designated trout waters (Figure 1).

## HOW MUCH RUNOFF SHOULD A BMP CAPTURE?

For most conventional pollutants, the highest pollutant concentrations occur early in a storm during the *first flush*. As a result, many stormwater BMPs are specifically designed to capture the most polluted first-flush runoff. While some regional variation exists, the first flush for western North Carolina has been established as runoff from the first inch of rainfall.

Conventional pollutants, such as some nutrients and metals, wash from impervious surfaces early in a storm and may require hours or days of deposition to reach levels of concern. While runoff temperatures typically decrease as a storm progresses, it is possible for temperatures to return to higher levels after only a short break in rainfall. Temperatures during a storm can also vary greatly depending upon weather characteristics. Although runoff temperatures may still be warm enough to pose a threat to trout, monitoring results indicate that additional cooling of runoff after the



first inch of rainfall is unlikely. Consequently, based on this research, BMPs should be designed to capture the conventional first-flush depth. Several design recommendations for BMPs are summarized below.

## PARKING LOT DESIGN

Incorporating temperature considerations into parking lot design can reduce thermal impacts from runoff at the source. A number of practices that lower surface temperatures to combat the urban heat island effect may reduce runoff temperatures as well. These recommendations include shading with tree and vegetation canopies, reducing the amount of impervious areas, and using light-colored pavement materials. These measures may result in cooler runoff leaving the parking surface, but the benefit of this cooler water may be negligible if runoff is exposed to higher temperatures, such as a warm pond, before being discharged into a stream environment.

Perhaps the most effective way to reduce the effects of heated runoff from parking lots is to promote infiltration of stormwater runoff throughout the watershed. By infiltrating runoff, coldwater stream environments can be supplied by cooler groundwater supplies instead of warm surface flows. In a natural system, coldwater streams maintain their cool temperatures due to proportionately higher groundwater flows. Many low impact development (LID) practices help to maintain predevelopment hydrology and encourage infiltration, which serves as an important treatment mechanism.

## STORMWATER WETLAND DESIGN

Stormwater wetlands have become a popular stormwater BMP in North Carolina due to their aesthetics and the variety of pollutant removal mechanisms they employ. Stormwater runoff is routed through regions of deep pools, shallow water, and temporary inundation zones, with the deepest regions typically no deeper than 3 feet. Due to their relatively shallow water depths, stormwater wetlands typically cover a large surface area. For example, Figure 2 depicts a stormwater wetland in Buncombe County (Asheville).

Because a stormwater wetland is exposed to the sun, it can heat up, with the warmest water normally near the surface. During a storm, the water level within the wetland rises and the water at the surface typically flows through an outlet structure to a nearby creek or waterway. Because this surface water is sometimes warmer than runoff directly leaving the parking lot, the combination of warm surface waters and heated stormwater runoff can impact coldwater



**Figure 2.** Stormwater wetland located in Buncombe County stream environments.

**VEGETATION.** Vegetation plays an important role in reducing the temperature of stormwater runoff exiting a wetland. First, incorporating vegetation, particularly broadleaf vegetation (Table 1, Figure 3), into a wetland reduces direct heating by the sun. Plants with broad leaves above the water are preferred to plants with leaves in direct contact with the water surface because air between the leaves and water surface insulates the water from the sun’s heat. Vegetation also reduces water temperatures through transpiration. Consult someone familiar with wetland plants to ensure specific plants are suitable for certain geographic regions and locations within the wetland.

**Table 1. Wetland vegetation for runoff temperature reduction**

Common Name	Scientific Name	Water Depth
American lotus	<i>Nelumbo lutea</i>	At least 18 in.
Pickeralweed	<i>Pontederia cordata</i>	1 to 6 in.
Arrow arrum	<i>Peltandra virginica</i>	1 to 6 in.
Arrowhead	<i>Sagittaria</i> spp.	1 to 6 in.
Hibiscus (swamp rose)	<i>Hibiscus coccineus</i>	Water’s edge

**OUTLET STRUCTURE DESIGN.** Because the deep water in a stormwater wetland is buffered from the sun, it typically remains cooler than water near the surface. The coolest discharge temperatures can be obtained by designing the outlet to draw water from the bottom of a deep pool during a storm event. The intake should be placed very close to the bottom of the pool. Thermal exchanges at the soil-water interface can make this water cooler than that even 1 foot above the wetland bottom. One outlet configuration that draws water from the pool bottom consists of corrugated plastic

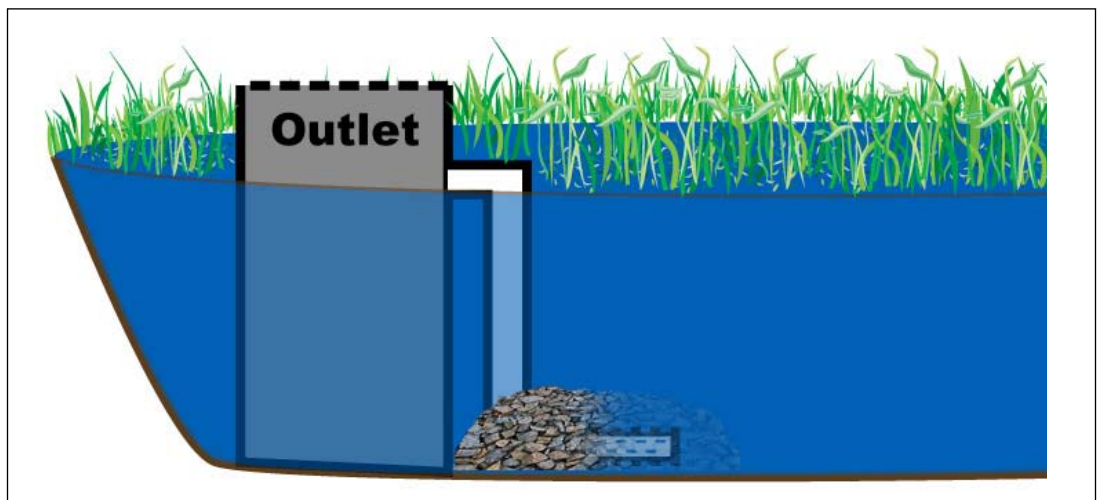


**Figure 3. Pickerelweed (A) and arrowhead (B)**

tubing with large perforations, surrounded by a gravel envelope to reduce the likelihood of clogging (Figure 4). This perforated tubing can then be connected by impermeable pipe to the outlet structure at the normal pool elevation.

Because water drawn from the pool bottom would likely have a low dissolved oxygen content, another important habitat constraint for trout, it is important to aerate the water before it enters a stream. Aeration can be accomplished by simply allowing water to flow over rocks or a similar aeration structure before entering the stream.

**Figure 4. Schematic of a modified outlet structure**

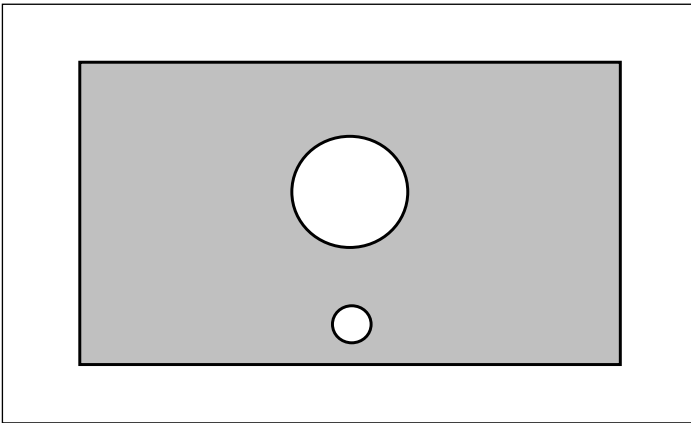


Maintenance for this type of outlet structure is imperative, both at the outlet structure itself and the wetland forebay, to prevent sediment deposits from reaching the outlet (see AGW-588-07, *Maintaining Stormwater Wetlands and Wet Ponds*). Although a stormwater wetland with this outlet configuration can yield lower discharge temperatures, it is useful only if a proper maintenance program can be ensured. Consistent runoff temperature reductions are unlikely without a modified outlet structure.

In wetlands where it is not practical to draw water from the bottom of a deep pool, a different outlet structure can be designed to reduce the likelihood of an initial thermal shock during a storm event. As noted above, the beginning of a storm poses the greatest threat to a coldwater stream environment because the highest runoff temperatures occur then, and warm water near the stormwater wetland surface is being flushed through the outlet. To combat this effect, the outlet structure can be designed to minimize outlet flows during the beginning of a storm by incorporating a staged drawdown (Figure 5). Reducing flows near the beginning of a storm allows incoming water to cool as it mixes within the wetland and as pavement and rooftop surfaces cool.

### WET POND DESIGN

Wet ponds are the most frequently used stormwater practice in North Carolina because they provide flood mitigation. Stormwater wetlands also can be designed to mitigate large event peak flows. These open bodies of water temporarily retain runoff during and immediately after a rain event. Wet ponds occupy a large land area for a given drainage area, but are relatively smaller than stormwater wetlands. A wet pond located in Caldwell County, which contains trout waters, is shown in Figure 6.



**Figure 5.** Example of staged drawdown flashboard riser. The smaller hole restricts outflow at the beginning of storms, when effluent temperature is the highest.



**Figure 6.** Wet pond located in Caldwell County

Similar to a stormwater wetland, a wet pond can be heated by the sun. Unlike stormwater wetlands, a wet pond is not typically vegetated, which means little, if any, shading of the water surface occurs. This lack of shading typically leads to water temperatures higher than those in a stormwater wetland. In fact, monitoring results indicate that effluent temperatures from a wet pond are consistently higher than incoming runoff for most of the summer. The outlet structure recommendations outlined for stormwater wetlands also apply to wet ponds and should be incorporated whenever possible. Even with the implementation of a modified outlet structure, however, the likelihood of reducing runoff temperatures through treatment in a wet pond is small. For this reason, flowrate reduction during the early stages of a storm—through use of a staged drawdown flashboard riser (Figure 5)—should be a key component of thermal mitigation for wet pond systems. Flashboard riser structures are discussed in detail in AGW-588-12, *Stormwater Wetland Design Update*.

## BIORETENTION AREA DESIGN

The use of bioretention cells, also known as rain gardens, continues to increase as developers appreciate their ability to both treat runoff and meet landscape requirements. Bioretention is essentially a vegetated filter system made up of three components: (1) an underdrain system overlain by (2) an engineered soil media, with (3) vegetation growing in the media (Figure 7). Most bioretention cells in North Carolina are planted with shrubs and small trees and are covered in mulch. Figure 7 shows a bioretention cell in western North Carolina.



**Figure 7.** Cross-section of a typical bioretention area (top) and photo of an example (bottom)

Of the three BMP types studied, a bioretention area appears to be the only system capable of reducing runoff temperature spikes using its standard design. Similar to stormwater wetlands and wet ponds, the temperatures deep within a bioretention area are lower than those near the surface. Because heat penetration is slower through soil than water, deep soil is buffered from heat near the surface and storm effects, exhibiting minimal short-term temperature fluctuations (Table 2). As runoff infiltrates through the soil, it releases or absorbs heat to approach the tempera-

ture of the surrounding soil. This causes the effluent temperature of a deep bioretention area to consistently approach the temperature of the deepest soil. Because soil temperatures deep within a bioretention area are typically cooler than temperatures observed during the initial spike in runoff temperatures, a bioretention area is able to mitigate a thermal spike.

One concern with bioretention areas is that the stability of soil temperatures deep within the system can cause problems when runoff temperatures cool to a temperature below that of the soil. For example, runoff may cool to a temperature below soil temperatures after extended rainfall has cooled the pavement surface or during a nighttime storm. However, the benefits of this cooler runoff will not be realized as the water infiltrates through the bioretention area and warms up to the temperature of the surrounding soil.

**VEGETATION AND MULCH.** As for stormwater wetlands, broadleaf vegetation with distance between the leaves and soil surface should be incorporated into bioretention design to provide insulation from the sun’s heat. Vegetation should be included for both shade and the cooling it provides through evapotranspiration. Light-colored mulches are recommended for use in bioretention. Dark-colored mulches and soil media can absorb elevated levels of solar radiation, leading to higher temperatures near the surface.

**OVERFLOW STRUCTURE DESIGN.** Because the primary temperature reduction mechanism in a bioretention area is infiltration through the soil media, the overflow structure design should provide adequate storage of runoff within the area. During a storm event, runoff can absorb heat from the mulch and surface soil, in addition to heat from the pavement surface. With adequate storage, this heat is removed as the runoff infiltrates through the soil profile. However, when runoff is allowed to bypass via the overflow structure early in a storm, thermal energy from the pavement surface and the soil surface will directly impact creeks and streams. The same problem could occur if a bioretention area is not maintained and clogging causes water to exit the system through the overflow rather than infiltrating through the soil media. For a well-maintained system, conventional first-flush designs should store enough runoff to prevent warm water from being directly discharged via the overflow device. For more information on bioretention design and maintenance, see AGW-588-05, *Bioretention Performance, Design, Construction, and Maintenance*.

**SOIL MEDIA DEPTH.** Designing a bioretention area with the correct soil depth is critical for runoff temperature reduction (Table 2). Research has shown that soil temperatures at 4 feet and below are the coolest, and they also do not exhibit substantial daily fluctuations. In a bioretention area with little shading, soil depths of 3 feet or less could increase the temperature of stormwater runoff exiting the system due to heating at the surface. Therefore, a soil media depth of 4 feet or greater is recommended for bioretention areas located in regions with trout waters. Although soil temperatures at a depth of 4 feet or greater are the coolest within the system, they are likely warm enough to pose a concern to trout populations and may heat runoff if water temperatures have cooled due to an extended storm or nighttime rainfall. Consequently, the main advantage of deep soil in a bioretention area is the ability to mitigate heat from the initial temperature spike in a storm.

Another advantage of bioretention areas is their ability to infiltrate water and recharge groundwater supplies. As mentioned earlier, many streams are cool enough to support trout because they rely upon groundwater supplies rather than surface waters. With research indicating that the effluent from many stormwater BMPs is warmer than water temperatures preferred by trout, infiltrating runoff throughout the watershed may be the best approach to mitigating the effects of thermal pollution. Incorporating greater soil depth into bioretention design will encourage infiltration into the shallow groundwater.

**Table 2. Overview of bioretention soil temperatures relative to soil depth**

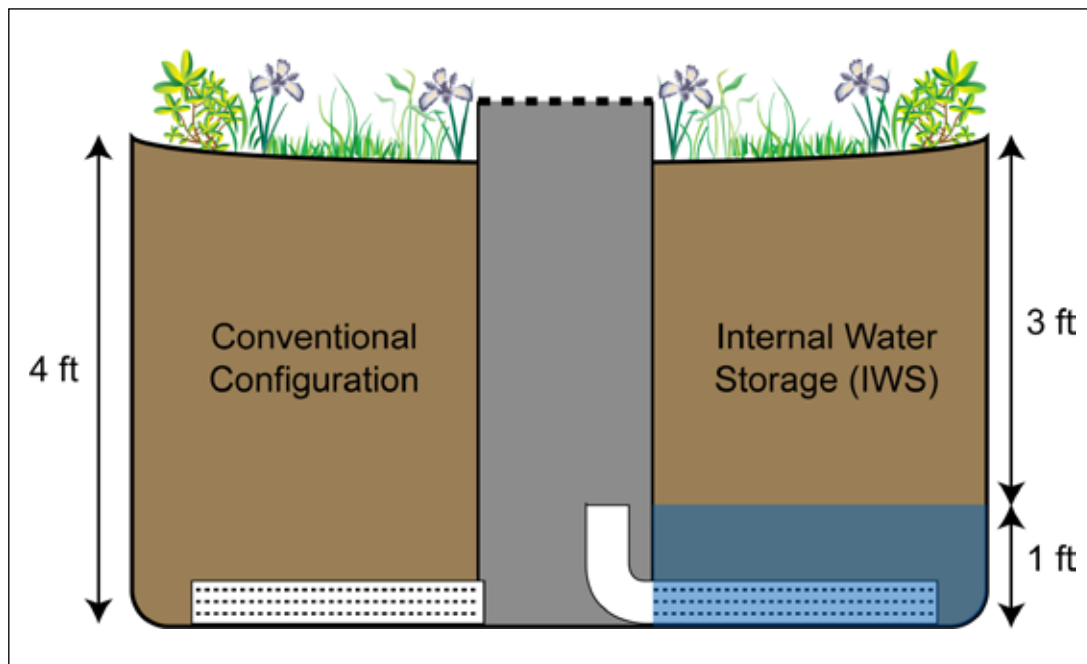
Soil Depth	Temperature Description
<2 ft	<ul style="list-style-type: none"> <li>Major daily fluctuations</li> <li>Likely temperature increase</li> </ul>
2-3 ft	<ul style="list-style-type: none"> <li>Reduced daily fluctuations</li> <li>Possible temperature increase</li> </ul>
3-4 ft	<ul style="list-style-type: none"> <li>Minimal daily fluctuations</li> <li>Possible reduction in runoff temperature spike</li> </ul>
>4 ft	<ul style="list-style-type: none"> <li>Insignificant daily fluctuations</li> <li>Likely reduction in runoff temperature spike</li> </ul>

**UNDERDRAIN CONFIGURATION.** While this design change has not been tested for temperature reduction, it is likely that a simple change in underdrain design would decrease effluent temperature from bioretention. By incorporating an internal water storage (IWS)

layer, shown in Figures 8 and 9, runoff can be temporarily stored in the bottom depths of the bioretention soil media. Increasing the water's contact time with cooler soil will probably decrease outflow temperature. This drainage configuration is only recommended for bioretention cells with at least 4 feet of soil media. Current recommendations indicate the top of the IWS layer should be no closer than 3 feet to the soil surface.



**Figure 8.** Installing a small upturn in the drawdown pipe will create an internal water storage (IWS) layer in a bioretention cell.



## SUMMARY

The results of research at NCSU indicate that special design consideration for BMPs is required in areas where coldwater stream environments occur to limit the potential impacts of heated runoff from pavement surfaces and stormwater BMP treatment. A summary of these design

**Figure 9.** A schematic of an IWS layer compared to the conventional drainage configuration. The IWS layer here is pictured for use in trout waters.

## CONVEYANCE MECHANISM DESIGN

The way in which stormwater runoff is transported to and from a stormwater BMP can have a substantial impact on its temperature. Some of the most prevalent conveyance mechanisms in North Carolina include buried pipes, vegetated channels, paved channels, and direct sheet flow. Conveyance through a paved channel has the potential to further increase runoff temperatures and should be avoided when possible. Some data indicate that runoff is cooled while being conveyed through a vegetated channel, but further analysis is needed to substantiate these findings. By transporting runoff through a buried pipe, stormwater runoff can be cooled substantially through indirect contact with the surrounding soil, which is cooler than the ambient air or soil near the surface. For example, monitoring results showed that runoff traveling through 550 feet of buried corrugated metal pipe to a stormwater wetland could be cooled by more than 10°F.

Although buried pipes may reduce runoff temperatures, they won't reduce other pollutant loads or runoff flows, which have a crucial impact on water quality. Also, the benefits of cooling stormwater runoff in a pipe before it reaches a wetland or wet pond may be irrelevant if the water already in these systems is warm. Incorporating conveyance in a buried pipe *after* water has been treated by a stormwater wetland or wet pond can be used to cool BMP effluent, but only if the effluent is aerated *before* being discharged into a coldwater stream environment.

recommendations can be found in Table 3. Coldwater stream inhabitants, such as trout, are vital components of the ecosystem and economy. We must consider their preservation through effective management of runoff temperatures. As with all aspects of stormwater management, it is important to evaluate project goals and constraints. Recommendations for temperature

reduction may conflict with other water quality goals. With implementation of the BMP design recommendations presented here, it should be possible to retain the water quality benefits of stormwater BMPs while limiting the effects of heated runoff on the aquatic environment.

**Table 3: Summary of BMP design recommendations to mitigate heated runoff**

<b>Stormwater Wetland</b>	
Outlet Structure	<ul style="list-style-type: none"> <li>• Draw water from the bottom of the deep pool at the wetland’s outlet.</li> <li>• Aerate water before discharging into stream.</li> <li>• Limit outflow rates early in a storm.</li> </ul>
Vegetation	<ul style="list-style-type: none"> <li>• Keep water well shaded using broadleaf vegetation with a separation between the leaves and water surface.</li> </ul>
<b>Wet Pond</b>	
Outlet Structure	<ul style="list-style-type: none"> <li>• Draw water from the bottom of the deep pool at the wet pond’s outlet.</li> <li>• Aerate water before discharging into stream.</li> <li>• Limit outflow rates early in a storm.</li> </ul>
<b>Bioretention Area</b>	
Soil Depth	<ul style="list-style-type: none"> <li>• Create a soil depth of 4 ft or greater.</li> </ul>
Vegetation	<ul style="list-style-type: none"> <li>• Keep soil well shaded using broad leaf vegetation with a separation between the leaves and soil surface.</li> </ul>
Mulch	<ul style="list-style-type: none"> <li>• Use light-colored mulch.</li> </ul>
Drainage Configuration	<ul style="list-style-type: none"> <li>• Incorporate an internal water storage (IWS) layer at the bottom of the bioretention media. The top of the IWS layer should be at least 3 ft from the soil media surface.</li> </ul>
<b>Watershed</b>	
Conveyance Mechanism	<ul style="list-style-type: none"> <li>• Convey treated water through buried pipes when appropriate.</li> </ul>
Parking Lot Design	<ul style="list-style-type: none"> <li>• Incorporate shading.</li> <li>• Promote infiltration.</li> </ul>

## RESOURCES

U.S. Department of the Interior, Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau. *2001 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation*. Shepherdstown, W.Va.: U.S. Fish and Wildlife Service, NCTC Publications Unit. Online: <http://www.census.gov/prod/2002pubs/FHW01.pdf>

**RELATED FACT SHEETS** in the Urban Waterways series, North Carolina Cooperative Extension, NCSU:

Hunt, W. F. *Urban Stormwater Structural Best Management Practices (BMPs)* (AG-588-01). Online: <http://www.bae.ncsu.edu/stormwater/PublicationFiles/UrbanBMPs1999.pdf>

Hunt, W. F., and B. A. Doll. *Design of Stormwater Wetlands for Small Watersheds* (AG-588-02). Online: <http://www.bae.ncsu.edu/stormwater/PublicationFiles/SWwetlands2000.pdf>

Hunt, W. F., and N. White. *Designing Rain Gardens (Bio-Retention Areas)* (AG-588-03). Online: <http://www.bae.ncsu.edu/stormwater/PublicationFiles/DesigningRainGardens2001.pdf>

Hunt, W. F., and W. G. Lord. *Bioretention Performance, Design, Construction, and Maintenance* (AGW-588-05). Online: <http://www.bae.ncsu.edu/stormwater/PublicationFiles/Bioretention2006.pdf>

Hunt, W. F., and W. G. Lord. *Maintenance of Stormwater Wetlands and Wet Ponds* (AGW-588-07). Online: <http://www.bae.ncsu.edu/stormwater/PublicationFiles/WetlandMaintenance2006.pdf>

Hunt, W. F., M. R. Burchell, J. D. Wright, and K. L. Bass. *Stormwater Wetland Design Update* (AGW-588-12). Online: <http://www.bae.ncsu.edu/stormwater/PublicationFiles/WetlandDesign2007.pdf>

## RELATED WEB SITES

NCSU-BAE Stormwater BMPs and Runoff Temperature Web site:

<http://www.bae.ncsu.edu/topic/bmp-temperature/>

NCSU-BAE Stormwater Engineering Group Web site  
<http://www.bae.ncsu.edu/stormwater/>

State of North Carolina  
NCDENR Stormwater Web site  
<http://h2o.enr.state.nc.us/su/index.htm>

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