URBAN Waterways

Bioretention Performance, Design, Construction, and Maintenance

Bioretention has become a common stormwater treatment practice in communities across North Carolina. Recent state and federal rules, including those for the Neuse and Tar-Pamlico river basins and EPA Stormwater Phase II, require that innovative devices, such as bioretention, be used in treating stormwater. In Cary and Greensboro, for example, bioretention is one of the two most frequently installed practices.

Basic design guidance for bioretention (also termed rain gardens) was provided in 2001 in Designing Rain Gardens (Bio-Retention Areas)*, AG-588-3 part of this* Urban Waterways *Series by W. F. Hunt and N. M. White. Since the publication of that fact sheet, much research has been conducted on the effectiveness of bioretention in North Carolina and surrounding states. Findings from this research and anecdotal observation of bioretention function have led to more specific design, construction, and maintenance recommendations. These recommendations now address designing bioretention cells specifically to remove target pollutants, as well as preserve the fragile nature of bioretention cells.*

OVERVIEW OF RESEARCH

Research in North Carolina by NC State University has examined the performance of bioretention cells installed in Greensboro, Chapel Hill, Louisburg, and Charlotte. Findings from this research reveal that bioretention cells will efficiently remove nutrients and other pollutants from stormwater. The four studies are summarized in Table 1.

GREENSBORO. Two cells located off Battleground Avenue were studied from 2002 through 2004. One cell was filled with a high P-Index soil media[1] and had a standard drainage configuration. The second cell contained a medium P-Index media and utilized an alternative drainage configuration, an internal water storage (IWS) zone (Figure 1). Both cells were four feet deep.

[1] P-Index, or Phosphorus Index, is the measure of phosphorus already present in soil. The value is determined by testing at the North Carolina Department of Agriculture and Consumer Services soil analysis laboratory in Raleigh. Values greater than 100 are considered very high. Values ranging between 50 and 100 are considered high. Values between 25 and 50 are medium; values less than 25 are low. A soil with a very high or high P-Index is less able to retain phosphorus because it is already "full."

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FIGURE 1. An Internal Water Storage Zone (IWS) is incorporated into a bioretention cell by forcing water to move "uphill" through the underdrain system.

The first cell, with a high P-Index (86-100), *increased* phosphorus loads by 240 percent during the first year of study. During the second and third years, total phosphorus (TP) loads also increased, but by less than 40 percent. It is possible that initial phosphorus loads were being washed out during the study. The second cell, with a lower P-Index (35-50), marginally decreased TP load (9 percent) during the second and third years of testing.

The cells also reduced the amount of total nitrogen (TN) entering the storm sewer by 33 percent, 40 percent, and 43 percent, depending on the cell and year examined. The variation in load reduction reflected the amount of nitrogen entering the cell: cleaner influent equaled lower pollutant load removal. Similar findings held for copper and zinc, as load reduction ranged from 56 percent to 99 percent.

Chapel Hill. One cell was studied from 2002 through 2003 at University Mall. The fill soil, which had a low P-Index (4-12), was four feet deep. During the year-long study, TP was reduced by 65 percent and TN was reduced by 40 percent.

Louisburg. Two cells were examined from 2004 through 2005 at Joyner Park. The fill soil in both cells had a very low P-Index (1-2), and the soil was nominally 2.5 feet deep. TN removal from both cells was between 60 and 70 percent. TP removal ranged from 22 to 66 percent, depending on the cleanliness of the influent runoff. In Louisburg, outflow TP concentrations were the lowest among those measured at all four locations. This indicated that the lowest P-Index fill soil released the lowest amount of phosphorus.

Charlotte. One cell was studied at the Hal Marshall county government complex from 2004 through 2005. The cell was nominally 4 feet deep and was constructed with low P-Index (7-14) soil. Both nitrogen and phosphorus load removals exceeded 60 percent. This cell was also tested for pathogen removal and was found to remove well over 90 percent of fecal coliform bacteria.

TABLE 1. SUMMARY OF RESEARCH FINDINGS ON BIORETENTION EFFICIENCY.

Cell (Study Period)	Soil P-Index	TN Removal	TP Removal	Other Findings
Greensboro–cell 1 (2002-2004)	86 – 100	40% - year 1 133% - year 2-3	240% increase – yr 1 39% increase – yr 2-3	Cu and Zn reduced 65 to 99%
Greensboro–cell 2 (2003-2004)	35 – 50	43% - year 2-3	9% - year 2-3	Cu and Zn reduced 56 to 86%
Chapel Hill (2002-2003)	4 – 12	40%	65%	
Louisburg – cell 1 (2004-2005)	1 – 2	64%	66%	Higher inflow [TP]= higher TP removal
Louisburg – cell 2 (2004-2005)	1 – 2	68%	22%	Low inflow [TP] = lower TP removal
Charlotte (2004-2005)	7 - 14	65%	68%	Fecal coliform removal > 90%

When examined together, these four studies yielded the following information:

(1) Nitrogen load removal from bioretention is high, typically meeting or exceeding 40 percent.
(2) Phosphorus removal can be enhanced with proper fill-soil selection. Using low P-Index fill soils reduced phosphorus loads, while high P-Index fill soils increased phosphorus loads in the effluent drainage.
(3) Cleaner runoff coming into the bioretention cells decreases load removal. Low concentrations of pollutants in inflow tend to decrease load removal efficiency.
(4) When designed to remove particular pollutants, bioretention cells appear to be very effective.
(5) Bioretention cells can partially recharge ground water supplies, even in the clayey soils of piedmont North Carolina. This feature of bioretention grows more important as concerns about water supplies increase.

The main reason for pollutant load reduction is that runoff entering the bioretention cell partitions into outflow drainage, exfiltration, evapotranspiration, and high-flow bypass (during large storms). During most storm events, only the outflow drainage directly enters the storm sewer network. All six cells studied exhibited substantial reductions in outflow volume, ranging from 33 percent to well over 50 percent. Even if the inflow and outflow pollutant concentrations were the same, load removal would still occur. Outflow volume reduction is a very important part of bioretention function. Without outflow reduction, most bioretention systems would actually increase some pollutant loads.

POLLUTANT-SPECIFIC BIORETENTION DESIGN

In current bioretention design standards, one general guideline is used to locate, size, and design bioretention cells. This design guideline gives no regard to target pollutants. However, the research discussed earlier, in addition to studies conducted at the University of Maryland, Pennsylvania State University, and NC State University, allows more refined design guidelines to be developed. These pollutant-specific guidelines are summarized in Table 2.

Total suspended solids (TSS). The trapping mechanism for most TSS is sedimentation. This occurs in the bioretention cell's depression storage volume, which temporarily stores runoff. Some fine suspended particles are removed by filtration through the very top portion of the media and mulch layer. No specific fill-soil depth is required because nearly all TSS removal occurs before water infiltrates the cell. Higher infiltration rates (exceeding 2 inches per hour) for the fill media work best. When located in drainage areas with high TSS loads, however, a maintenance issue will arise, as is discussed later.

Metals. A study conducted by researchers at the University of Maryland showed that more than 95 percent of metal removal occurred in the top 8 inches (20 cm) of bioretention fill soil. Metal accumulation rates in Maryland and North Carolina are not high enough to retard plant growth or pose a disposal problem in most applications. Fill-soil depth in bioretention cells does not need to exceed 18 inches to effectively remove metals from stormwater runoff. The infiltration rate of the media can vary. It is best that the cell's top layer remain unsaturated, so infiltration rates exceeding 2 inches per hour may be most appropriate.

Pathogens/bacteria. While limited data exist for bacteria removal by bioretention systems, most scientists and engineers agree that bacteria die-off occurs at the surface where stormwater is exposed to sunlight and the soil can dry out. While no minimum soil depth is required to remove pathogens, it is best for these bioretention cells to *not* be densely vegetated. Minimal plant coverage allows for greater exposure to sunlight and consequent die-off of bacteria.

Temperature. Increased temperature is a form of pollution important to western North Carolina's trout fisheries, but very little information has been collected on bioretention's ability to reduce outflow temperature. Some data were collected in the Greensboro study in 2003 showing that the two bioretention cells reduced temperature by 5 to 10°F. It is recognized that deeper soil media and ample shade can reduce the temperature of effluent. Whether this means bioretention cells should contain fill-soil depths of 2 feet or 4 feet, for example, has yet to be determined. An IWS volume at the bottom of the fill media, where it is cooler, may reduce temperature as well.

Total nitrogen (TN). Research conducted at Penn State University found that nitrogen removal can be improved by retaining water in the bioretention cell for a longer period. Soil media infiltration rates of 1 inch per hour are preferable to higher rates. Tests examining the effectiveness of introducing an IWS zone (Figure 1) have not yielded any statistically significant results; however, it does appear that the introduction of the IWS layer may reduce the outflow concentration of NO_3-N and, consequently, TN. A minimum fill-media depth of 30 inches is recommended for TN removal; 36 inches are preferred.

Total phosphorus (TP). Lower P-Index soils reduce phosphorus loads leaving the bioretention cell. If phosphorus is a target pollutant, it is imperative that the fill soil be tested to verify it has a relatively low P-Index, ranging between 15 and 30. P-Indices lower than 15 either retard or do not support plant growth. Infiltration rates greater than 1 inch per hour are likely the best for effective TP removal. As with metals, it is important that the zone where phosphorus is collected, the surface layer, does not become saturated, which would cause some of the trapped phosphorus to go into solution and leave the bioretention cell. If an IWS layer is used for TN removal, it is important to keep the "top" of this zone at least 18 inches from the surface of the bioretention cell. A minimum fill-soil depth of 24 inches is recommended.

TABLE 2. BIORETENTION DESIGN GUIDELINES FOR SPECIFIC POLLUTANTS.

Target Pollutant	Minimum Fill Media Depth	Target Infiltration Rate	Other Design Guidance
TSS	No minimum fill depth required	Any rate is sufficient. 2 to 6 inches per hour recommended	If high TSS influent, frequent maintenance required.
Pathogens	No minimum fill depth required	Any rate is sufficient. 2 to 6 inches per hour recommended	Limiting plant coverage allows more direct sunlight to kill pathogens.
Metals	18 inches	Any rate is sufficient. 2 to 6 inches per hour recommended	Must keep top layer of cell from being saturated for extended periods.
Temperature	To be determined. Conservatively, at least 36 inches	To be determined. Slower rates may be preferable (less than 2 inches per hour)	Introduction of IWS volume at the bottom of the cell may reduce effluent temperature.
Total Nitrogen (TN)	At least 30 inches (36 inches preferred)	1-2 inches per hour. Slower rates are better.	Introduction of IWS volume may reduce TN concentrations.
Total Phosphorus (TP)	24 inches	2 inches per hour	A low P-Index is essential. Recommended range is from 15 to 30.

SPECIFYING FILL-SOIL MEDIA

Fill-soil selection is a crucial component of bioretention design, particularly in the tighter clay soil regions of North Carolina's piedmont, because fill media:

- Provide adequate drainage.
- Reduce pollutant levels.
- Support plant growth.

The following "recipe" for a bioretention soil media, or fill-soil mix, works best:

- 85 to 88 percent sand. A washed, medium sand is sufficient. A USGA greens mix is not necessary and can be costly.
- 8 to 12 percent fines. Fines include both clay and silt.

- 3 to 5 percent organic matter. Studies in Maryland have shown newspaper mulch to be an ideal source of organics. In North Carolina, peat moss has been successfully used.

When mixing soil components to create the engineered media, it is essential that the components be well mixed and consistent.

If the fill mix is designed to capture a specific pollutant, the percentage of fines may change, depending on what the target pollutant is. When nitrogen removal is the goal, for instance, an infiltration rate of 1 inch per hour is needed. Incorporating a higher percentage of fine soil particles will reduce the infiltration rate. Roughly 12 percent of the fill soil should be made up of fines to achieve the 1-inch-per-hour rate that is best for removing nitrogen. To remove phosphorus, metals, and other pollutants, a 2-inch-per-hour infiltration rate is recommended, and the fines mixture should be approximately 8 percent. Organic matter, the lesser ingredient in the fill-mix "recipe," will not change volume based on target pollutant, and its portion should remain the same—3 to 5 percent.

Organics are included to "kick-start" nitrogen removal and plant growth while the bioretention cell matures. If the original organic matter is depleted by microbial activity, the bioretention system is expected to provide some organic content to the fill through mulch decomposition, grass clippings, and root infiltration.

To support plant growth while removing phosphorus from runoff, the fill soil must have a P-Index between 15 and 30. If the bioretention area is not designed to reduce phosphorus in runoff, a P-Index for the fill soil of 30 to 50 is recommended. In addition to having a low P-Index, it is best for fill media to have a relatively high cation exchange capacity (CEC). Higher CECs describe soils that have a greater ability to capture and retain phosphorus. Some "designer" soils with low P-Indices and higher infiltration rates have been tested and found to have CECs exceeding 20. While a minimum CEC has yet to be established, CECs exceeding 10 are expected to work relatively well at removing target pollutants in bioretention systems.

The types of vegetation expected to grow in the bioretention cell also affect the depth of media selected. Grassed covers do not need more than 15 to 18 inches of media to survive, while certain small trees specified to grow in bioretention require a minimum of 36 inches. Most bioretention shrubs can survive and even flourish with a minimum of 24 inches of fill media.

SELECTING VEGETATION

A detailed list of plant species is provided in *Designing Rain Gardens (Bio-Retention Areas)* and in other documents. (Refer to www.bae.ncsu.edu/topic/raingarden for more information on plant choices.)

Most vegetation does not survive when planted in the middle, or deepest part, of the bioretention cell. Most shrubs and trees suggested in bioretention planting guides grow much better if they are located along the edge of the cell. Certain tree species, such as River Birch *(Betula nigra)*, do well in the "bottoms" of cells, but they must be staked during the first year of growth, so that the roots can establish themselves. Being toppled by wind is always an issue in hurricane-prone North Carolina (Figure 2).

FIGURE 2. While River Birch (*Betula nigra*) typically grows well in bioretention cells, saplings need to be staked during the first year to keep them from being blown over in hurricane-prone North Carolina.

A horticulturalist should be consulted for plant selection. Bioretention vegetation can be classified as either "dry," "average," or "wet." Most species cannot tolerate all three conditions. A few species observed to tolerate a wide degree of wetness include Virginia Sweetspire *(Itea virginica)*, Inkberry *(Ilex glabra)*, River Birch *(Betula nigra)*, and Red Maple *(Acer rubrum)*.

The vegetation of choice for some bioretention cells is grass. Varieties of centipede, Bermuda, and zoysia can survive in cells that are well drained. Bioretention cells with higher percentages of fines tend to be wetter, making it difficult for these grasses to grow. Because of this, grass-only bioretention cells are not currently recommended for TN removal.

PROTECTING YOUR INVESTMENT

Bioretention is a fragile stormwater practice. Across the state, thousands of dollars have been wasted because measures were not taken to prevent bioretention cells from becoming clogged with sediment during construction. Much of this cost could have been avoided if simple precautions had been taken.

Bioretention placement. Avoid locating bioretention cells near disturbed areas. Excessive sedimentation ruins bioretention. During construction of bioretention cells, take protective measures, such as lining the perimeter of the cell with either straw bales or a silt fence.

Construction phasing of a bioretention cell is critical and must be well planned and executed. Sometimes timing the construction of the bioretention cell may be complicated. The principal excavation of the cell may occur any time during the construction process. Often, sediment traps or basins are transformed into bioretention cells (Figure 3). This is an excellent use, provided the sediment trap is excavated prior to its conversion to a bioretention cell. If the bioretention facility is constructed as a median in a parking lot, it is best to wait until the parking lot's base gravel course is placed before installing the underdrains, gravel layer, or fill media of the bioretention cell. Ideally, the initial asphalt layer is placed before bioretention construction (postexcavation) starts. Once the fill soils are brought on site, paving of the parking lot can be completed. When the parking lot and surrounding landscape are stable, vegetation can be planted and mulch can be spread.

FIGURE 3. This sedimentation basin was converted to a bioretention cell at the end of construction. The concrete outlet was later utilized as the high-flow bypass. The sediment drawdown skimmer was attached to the concrete structure in the same location as the bioretention cell's underdrains.

FIGURE 4. An out-parcel was not stabilized (foreground), leading to the clogging of the bioretention cell pictured next to the pickup truck. The trail of sediment from the out-parcel to the bioretention cell is clearly visible, as is the sediment eyebrow around the bioretention cell.

Be wary of out-parcel development (future development occurring upslope). Even if the bioretention cell immediately treats a stable parking lot, subsequently developed out-parcels, such as a bank or fast-food establishment constructed after the main portion of the shopping center is built, can add sediment to the bioretention cell, causing it to clog (Figure 4).

When to use permeable geofabric. Recently, designers have debated whether to use a permeable filter fabric between the gravel layer and the overlying fill soil. If the designer has any concern regarding the stability of the site during construction or if out-parcels may be developed at a later time, filter fabric should be avoided. In lieu of the permeable fabric, a thin layer (nominally two inches) of choking stone (such as #8 stone) can be incorporated between the gravel drainage layer (typically a washed 57 stone) and a thin, 2- to 4-inch

layer of pure sand. The fill media is placed on top of the pure sand layer (Figure 5). If the drainage area where the bioretention cell is to be installed is stable, which is often the case when bioretention is retrofitted, using filter fabric to separate the gravel drainage layer from the fill soil is acceptable. Filter fabric does prevent the migration of finer soil particles through underlying gravel. A choking stone can also prevent this migration if designed correctly. To verify whether a choking material will keep overlying soil in place, the following equations (from the Federal Highway Administration) can be utilized:

$$D_{15} \text{ open-graded base} \div D_{50} \text{ choke stone} < 5$$
and
$$D_{50} \text{ open-graded base} \div D_{50} \text{ choke stone} > 2$$

D_X is the particle size at which X percent of particles are finer. For example, D_{15} is the diameter at which 85 percent of the gravel particles are coarser and 15 percent of the materials are finer. This information is provided by the quarry supplying the material. If both equations are satisfied, the choking material will not migrate.

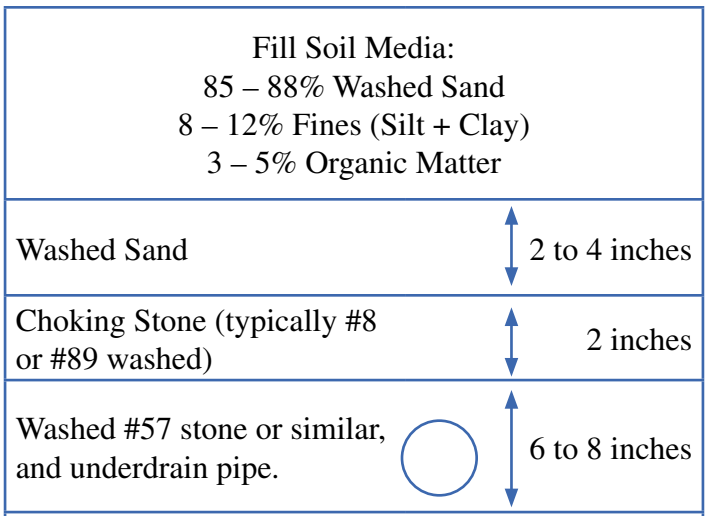

FIGURE 5. Schematic of bioretention bottom layers constructed without filter fabric.

PRETREATMENT. To prevent premature clogging of bioretention cells, designers are strongly recommended to specify pretreatment devices. The most commonly used in North Carolina, in descending order, are: (1) gravel verge (thin strip) with sod surrounding the perimeter, (2) grass swale, and (3) forebays. A level gravel verge between the pavement edge and vegetation helps disperse flow entering the bioretention area. The gravel strip should be the width of a garden rake (approximately 8 inches). Installing sod downslope of the verge provides an immediate layer of pretreatment before runoff enters the bioretention cell proper. The sod serves as a grassed filter strip (Figure 6). The minimum width required for the sod filter strip is three feet, with four to five feet recommended. In addition to trapping pollutants before they reach the bioretention cell, the sod immediately stabilizes the perimeter of the bioretention cell, preventing "internal" erosion from occurring. Centipedegrass has been successfully used as a sod verge in central and eastern North Carolina. Fescue and bluegrass are best suited for western North Carolina.

FIGURE 6. Installing a gravel verge and sod stabilizes the perimeter of bioretention cells and is highly recommended. The resulting filter strip shown here is 5 feet wide.

A simple grassed swale is another pretreatment option. A minimum length is not specified, but most suspended sediment has been observed to fall out in the first 10 to 15 feet of the swale (Figure 7). The exact minimum length depends on drainage area size and composition and the swale's slope, width, and cover.

Occasionally, large bioretention areas incorporate a forebay for pretreatment. The forebay should be sized so that it stills runoff water entering the bioretention cell, allowing some sediment to settle. Forebay depth ranges between 18 and 30 inches. Bioretention applications utilizing forebays are limited to locations where standing water is not considered a hazard and there is not enough room to incorporate either a sod/gravel verge or a grassed swale. Forebays must be hydraulically isolated from the underdrains so that

FIGURE 7. Two other methods of pretreatment: (a) a grassed swale leading from the roadway to the bioretention cell; and (b) a bioretention forebay constructed adjacent to a parking lot.

runoff does not short-circuit the bioretention media. Forebays can be lined to prevent direct flow into the underdrains.

Bioretention maintenance. To preserve bioretention performance, the cells must be maintained. Like any landscape feature, bioretention areas must be pruned, mulched, and even initially watered and fertilized (Figure 8.) Grassed bioretention cells are usually mowed.

Because plants are an important monetary investment and essential to the aesthetic appeal of bioretention systems, they need to be established as quickly as possible. The need for rapid establishment requires bioretention cells to be limed, if indicated by a soil test. Additionally, plants may need to be spot-fertilized to ensure growth and survival in low P soils. Watering the plants every 2 to 3 days for a month or two helps ensure vegetation survival. The frequency of these tasks varies seasonally, with more frequent maintenance required in summer than in winter.

Maintenance tasks unique to bioretention include occasional removal of mulch and the top layer of fill soil. Because clogging occurs most frequently at the top of the soil column, the bioretention basin rarely needs to be completely excavated. However, this has been necessary when the bioretention cell was located in an unstable drainage area. Table 3 lists some bioretention maintenance tasks and the frequencies with which they should be conducted.

TABLE 3. BIORETENTION MAINTENANCE TASKS.

Task	Frequency	Maintenance Notes
Pruning	1 – 2 times / year	Nutrients in runoff often cause bioretention vegetation to flourish.
Mowing	2 – 12 times / year	Frequency depends upon location and desired aesthetic appeal.
Mulching	1 – 2 times / year	
Mulch removal	1 time / 2 – 3 years	Mulch accumulation reduces available water storage volume. Removal of mulch also increases surface infiltration rate of fill soil.
Watering	1 time / 2 – 3 days for first 1 – 2 months. Sporadically after establishment	If droughty, watering after the initial year may be required.
Fertilization	1 time initially	One time fertilization for “first year” vegetation.
Remove and replace dead plants	1 time / year	Within the first year, 10 percent of plants may die. Survival rates increase with time.
Miscellaneous upkeep	12 times / year	Tasks include trash collection, spot weeding, and removing mulch from overflow device.

FIGURE 8. Various bioretention maintenance activities: (a) annual to semi-annual pruning, (b) an initial fertilization to ensure plant survival, (c) and (d) removal of biological films, which cause the bioretention cell to clog and may be needed every 2 to 3 years.

OTHER RESOURCES

Designing Rain Gardens (Bio-Retention Areas). 2001. W. F. Hunt and N. M. White. AG-588-3.
North Carolina Cooperative Extension Service. Raleigh, N.C.
For information on: general design guidelines for bioretention areas, how bioretention works, plant selection, construction cost estimates.
Available at: http://www.bae.ncsu.edu/stormwater/PublicationFiles/DesigningRainGardens2001.pdf

Urban Stormwater Structural Best Management Practices (BMPs). 1999. W. F. Hunt. AG-588-1.
North Carolina Cooperative Extension Service. Raleigh, N.C.
For information on: overview on grass swale and vegetated filter strip design.
Available at: http://www.bae.ncsu.edu/stormwater/PublicationFiles/UrbanBMPs1999.pdf

NCSU Backyard Rain Garden Web Page
http://www.bae.ncsu.edu/topic/rain-garden
For information on: bioretention vegetation selection for North Carolina, images of bioretention cells/rain gardens from across N.C. and surrounding states.

NCSU BAE Stormwater Web Page
http://www.bae.ncsu.edu/stormwater
For information on: clearinghouse of bioretention and other BMP information including fact sheets, reports, images for download, upcoming design workshops, and design specifications.

State of North Carolina Stormwater BMP Manual
http://h2o.enr.state.nc.us/su/stormwater.htm
For information on: detailed stormwater practice design guidelines, including bioretention, grass swales, and vegetated filter strips.

State of North Carolina Stormwater Page
http://www.ncstormwater.org
For information on: stormwater issues, technical and nontechnical, from across North Carolina, including related news, upcoming workshops, and educational public service announcements.

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