WETLANDS & WATERSHEDS

The Next Generation of Stormwater Wetlands

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The Next Generation of Stormwater Wetlands

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Executive Summary

Stormwater wetlands are just one of many stormwater treatment practices (STPs) that can be used to mitigate the water quality and quantity impacts resulting from land development. When properly sited and used in conjunction with other runoff reduction practices, stormwater wetlands can be very effective practices to protect downstream water resources because they mimic the pollutant removal and flood control functions of natural wetlands. They have well-documented pollutant removal rates, are widely adaptable to different climates, and can provide a host of secondary benefits, including aesthetics and wildlife habitat. However, few new stormwater wetlands are currently being installed in communities across the U.S., due, in large part, to both real and perceived limitations about their performance. In the hopes of rejuvenating their use as an STP, this article presents information about a new generation of stormwater wetlands with improved performance and community acceptance.

This article provides a look back at the evolution of stormwater wetland design and summarizes lessons learned from implementation to guide the next generation. The four classic stormwater wetland design variations first presented in Schueler (1992) are examined, with the recommendation that the ED wetland and pocket wetland no longer be used. It proposes a set of new design objectives for stormwater wetlands that includes enhanced pollutant removal and habitat. This is followed by a summary of the literature on the pollutant removal capacity and performance of emergent stormwater wetlands and of natural wetlands receiving wastewater and stormwater. The literature suggests that the addition of trees and shrubs into wetland designs can maximize pollutant removal performance and provide a host of other benefits.

The article presents two new stormwater wetland designs: an emergent wetland/pond system and a wooded wetland. The goal of these new designs is to enhance pollutant removal, increase habitat value, and minimize problems with invasive species and mosquitoes, while minimizing construction costs and maintenance burden. The authors recommend their use in place of the classic shallow marsh and pond/wetland system designs, and discuss some ways to further develop and test these new prototypes.

Guidance on adapting the new stormwater wetland designs is provided for cold climates, arid climates, karst terrain and other special conditions. The new wetland designs can be applied to most types of new development and redevelopment, and can be utilized in both residential and

non-residential areas. Although they may not be applicable in higher density developments because of land consumption, they may be a good fit for headwater areas that drain to zero-order streams. The wetlands may also be applied in retrofit situations.

These designs are promoted as part of an approach to stormwater management that focuses on reducing the *volume* of stormwater generated at a site. This tiered approach encourages 1) conservation of natural areas and native soils, 2) use of conservation design to reduce and disperse impervious cover, 3) use of small-scale, distributed STPs (such as rooftop disconnection, bioretention areas and infiltration) to reduce runoff volume, and 4) use of wetlands or other structural practices to meet the remaining stormwater management requirements. The first three techniques in this approach reduce the runoff volume, thus reducing the size and cost of structural STPs needed at the development site. Therefore, when wetlands are used in this treatment train approach, their cost may go down significantly.

The new designs presented here are intended to provoke dialogue on how to get to the next generation of stormwater wetlands. The reader is cautioned not to turn these conceptual designs into new STP specifications without additional comment from stormwater engineers and other practitioners. The authors invite the design community to provide active feedback on how to take these concepts to final design.

About the Wetlands & Watersheds Article Series

The Wetlands & Watersheds article series was developed by the Center for Watershed Protection (CWP) in cooperation with the United States Environmental Protection Agency (USEPA). Funding for this project was provided by USEPA under cooperative agreements number CD-83192901-0 and WD-83264101-0.

Collectively, wetlands provide many watershed benefits, including pollutant removal, flood storage, wildlife habitat, groundwater recharge, and erosion control. While watersheds and wetlands are interconnected systems, their management is often segregated along regulatory and jurisdictional lines. Recent initiatives, such as the National Wetlands Mitigation Action Plan, provide a potential framework to integrate wetland protection in the context of larger local and state watershed planning efforts. However, no specific guidance exists for managing wetlands in the context of local watershed plans, and local governments often lack the tools and knowledge to effectively protect critical wetlands. This project was designed to fill this gap by expanding CWP's current watershed protection guidance, tools, and resources to integrate wetlands into larger watershed protection efforts. A key message conveyed in this new guidance is that wetlands should not be managed separately from other water resources because they are integral to water resource management.

This project included *research* on urban wetlands and local protection tools, *synthesis* of the research into a series of articles, and *transfer* of wetland protection tools and resources to wetland and watershed professionals across the country. The audience for the articles includes local natural resources managers and land planners who would benefit from guidance on local tools for protecting wetlands. The Wetlands & Watersheds article series includes the following:

Article 1: Direct and Indirect Impacts of Land Development on Wetland Quality
This article reviews the direct and indirect impacts of urbanization on wetlands, and describes the benefits wetlands provide at the watershed scale.

Article 2: Using Local Watershed Plans to Protect Wetlands
This article presents detailed methods for integrating wetland management into the local watershed planning process.

Article 3: Adapting Watershed Tools to Protect Wetlands
This article describes 37 techniques for protecting wetlands through local programs and ordinances.

Article 4: A Local Ordinance to Protect Wetland Functions
This article outlines the key elements of an effective ordinance to protect wetlands from the indirect impacts of land development, and provides adaptable model ordinance language.

Article 5: The Next Generation of Stormwater Wetlands
This article revisits the design of stormwater wetland systems based on lessons learned from the field, and presents new concepts and design objectives for stormwater wetlands.

Article 6: The Importance of Protecting Vulnerable Streams and Wetlands at the Local Level

This article makes the case for expanded local protection of vulnerable streams and wetlands that may not be fully protected by state or federal law due to their perceived isolation from perennial or navigable waters. This article summarizes state and local approaches to closing this gap.

Other wetland-related products of this project include wetland slideshows, an annotated bibliography of wetland research, a listing of key wetland web resources, and more products available on the newly expanded CWP wetlands website at www.cwp.org/wetlands/index.htm.

The Center for Watershed Protection project team included Tom Schueler, Mike Novotney, Lisa Fraley-McNeal and Karen Cappiella. Special thanks to Tiffany Wright for her research assistance.

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Introduction

Stormwater wetlands can be defined as constructed systems that are explicitly designed to capture and remove pollutants from runoff associated with urban development. Consisting of shallow pools and channels, which create growing conditions suitable for a variety of wetland plants (Figure 1), stormwater wetlands treat stormwater runoff through a number of pollutant removal processes, including sedimentation, filtration and biological uptake. The combination of complex microtopography, wetland plants and biological activity create an ideal environment for the removal of stormwater pollutants.

Figure 1. Stormwater Wetlands (photo on left courtesy of Tim Schueler)

Stormwater wetlands are just one of many stormwater treatment practices (STPs) that can be used to mitigate the water quality and quantity impacts resulting from land development. STPs are an important component of a comprehensive approach that can be used to protect and restore urban watersheds (Schueler, 2004; CWP, 2005). They may be installed in new developments or as retrofit applications in existing developments.

When properly sited and used in conjunction with other runoff reduction practices (e.g., conservation design, infiltration practices, bioretention), stormwater wetlands can be very effective practices to protect downstream water resources because they mimic the pollutant removal and flood control functions of natural wetlands. They have well-documented pollutant removal rates, are widely adaptable to different climates, and can provide a host of secondary benefits, including aesthetics and wildlife habitat. However, few new stormwater wetlands are currently being installed in communities across the U.S., due, in large part, to both real and perceived limitations about their performance. In the hopes of rejuvenating their use as an STP, this article presents information about a new generation of stormwater wetlands with improved performance and community acceptance.

Two new stormwater wetland designs are presented in this article based on a proposed new set of design objectives. Guidance on adapting the new designs for various climates, terrain, and other special conditions is provided. The article also provides a look back at the evolution of stormwater wetland design and summarizes lessons learned from implementation to guide the next generation. It includes a summary of the literature on the pollutant removal performance of stormwater wetlands and the potential performance of the new designs. The article also discusses some ways to further develop and test these new prototypes.

The new designs presented here are intended to provoke dialogue on how to get to the next generation of stormwater wetlands. The reader is cautioned not to turn these conceptual designs into new STP specifications without additional comment from stormwater engineers and other practitioners. We invite the design community to provide active feedback on how to take these concepts to final design.

The Evolution of Stormwater Wetland Design

The use of constructed wetlands to treat stormwater runoff was first considered in the mid-1980s based on studies that showed the great potential of wetlands, both natural and constructed, to remove nutrients from municipal wastewater (Kadlec and Hammer, 1980; Nichols, 1983; Watson et al., 1989). Based on these studies, a handful of demonstration stormwater wetlands were constructed during the 1980s (Figure 2) (Strecker et al., 1992). These systems were installed despite a lack of standard design guidance and agreement on the key design elements of stormwater wetlands. Box 1 illustrates the evolutionary timeline of stormwater wetland design. A glossary of terms related to stormwater wetlands is provided in Attachment A.

Figure 2. The first generation of stormwater wetlands

Box 1. Evolution of Stormwater Wetland Design

- **1980s:** First stormwater wetland designs are adapted from surface wastewater wetlands.
- **1980s:** Some communities also direct stormwater into natural wetlands to document their pollutant removal benefits.
- **late 1980s:** Numerous prototype wetland designs are installed as retrofit projects.
- **1990s:** Experts agree that discharge of untreated stormwater into natural wetlands causes degradation and is discouraged.
- **1992:** *Design of Stormwater Wetland Systems* is published.
- **1990s:** Stormwater wetlands gain in popularity and their use becomes increasingly common.
- **2002:** West Nile Virus concerns slow down stormwater wetland implementation. Some communities no longer accept them.
- **2000s:** Interest in Low Impact Development increases. Fewer people promote the use of stormwater wetlands, instead favoring the use of small-scale distributed practices.
- **2004:** Several researchers begin to explore the use of trees in stormwater wetland designs.
- **Present:** Few stormwater wetlands are constructed for new development. Those that are implemented are modeled after emergent freshwater wetlands.

The first generation of stormwater wetlands constructed in the 1980s and 1990s were modeled after emergent freshwater wetlands. They had fairly uniform topography and were basically shallow ponds planted with emergent vegetation (Figure 2). Because of their uniformity, these wetlands often became dominated by one or two plant species and offered few benefits other than stormwater treatment.

In 1992, the first widely accepted stormwater wetland design guidance was published. The *Design of Stormwater Wetland Systems* (Schueler, 1992) encouraged an integrated and comprehensive approach to wetland design. Due in large part to its publication, stormwater wetlands became an increasingly common stormwater management practice throughout the 1990s. Four basic designs for stormwater wetlands were presented in this document and are summarized in Table 1 and Figure 3:

1. Shallow Marsh

The shallow marsh has a large surface area, and requires a reliable source of baseflow or groundwater supply to maintain the hydrology necessary to support a community of emergent wetland plants. Consequently, the shallow marsh design requires a lot of space and a sizeable contributing drainage area (often in excess of 25 acres) to support a shallow permanent pool.

2. Extended Detention (ED) Wetland

In extended detention (ED) wetlands, extra runoff storage is created above the surface of the shallow marsh by temporary detaining stormwater runoff. The ED feature enables the wetland to consume less space, as temporary vertical storage is partially substituted for shallow marsh storage. A vegetative zone is created along the gentle side-slopes of ED wetlands that extends from the normal pool elevation to the maximum ED water surface elevation. The frequent water fluctuations create difficult growing conditions for plants, often resulting in low plant diversity and habitat value.

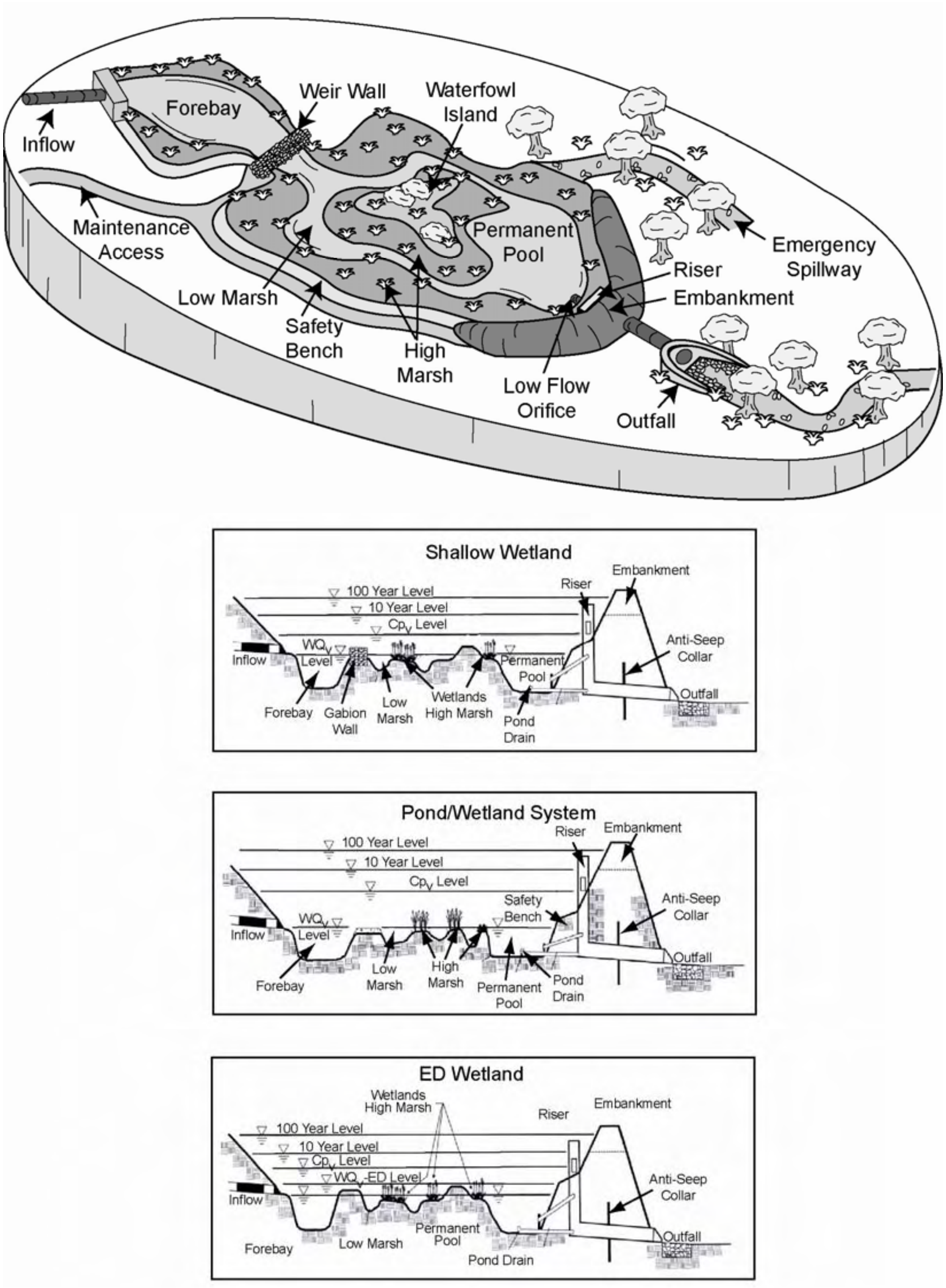

Figure 3. Classic Stormwater Wetland Designs

3. Pond/Wetland System

The pond/wetland design utilizes two separate cells for stormwater treatment. The first cell is a wet pond and the second cell is a shallow marsh. The multiple functions of the wet pond are to trap sediments, reduce incoming runoff velocity, and to remove pollutants. The pond/wetland system consumes less space than the shallow marsh, because the bulk of the treatment volume is provided by the deeper pool rather than the shallow marsh.

Table 1. Characteristics of Existing Stormwater Wetland Designs

Characteristic	Shallow Marsh	ED Wetland	Pond/Wetland	Pocket Wetland
Construction Cost	Moderate to high, particularly when considering the cost of land	Moderate, vertical ED storage reduces	Moderate	Moderate to high
Land Consumption	High, shallow wetland storage consumes space	Moderate, vertical ED storage replaces shallow wetland storage	Moderate, wet pond replaces shallow wetland storage	Moderate, but can be shoehorned into site
Pollutant Removal Capability	Moderate, reliable removal of sediments and nutrients	Moderate, less reliable than shallow wetland	Moderate to high, reliable removal of sediment and nutrients	Low to moderate, pollutants can be subject to re-suspension
Runoff Volume and Peak Discharge Control	Moderate to high	High	High	Moderate to high
Runoff Reduction	Moderate	Moderate	Low to moderate	Moderate
Risk of Thermal Impacts	Moderate to high, due to lack of shading	Moderate to high, due to lack of shading	Moderate to high, due to lack of shading	Moderate to high, due to lack of shading
Native Plant Diversity	Moderate, with wetland complexity	Low to moderate, fluctuating water levels create difficult growing conditions	Moderate, with wetland complexity	Low, due to small surface area and fluctuating water levels
Habitat Value	Moderate, with wetland complexity and buffer	Low to moderate, due to fluctuating water levels and limited plant diversity	Moderate, with wetland complexity and buffer	Low, due to small area and low plant diversity
Risk of Mosquito Proliferation	Variable, depending on design elements, perception of risk may be high	Variable, depending on design elements, perception of risk may be high	Variable, depending on design elements, perception of risk may be high	Variable, depending on design elements, perception of risk may be high
Maintenance Burden	Moderate, includes vegetation management and sediment removal	Moderate	Moderate	High
Safety and Aesthetics	Moderate to high	Moderate, due to fluctuating water levels	Moderate to high	Low to moderate, due to fluctuating water levels

4. Pocket Wetland

Pocket wetlands are adapted to serve smaller sites from one to ten acres. Because of their small drainage areas, they usually do not have a reliable source of baseflow, and therefore exhibit widely fluctuating water levels. In most cases, water levels in the wetland are supported by excavating down to the water table. In drier areas, the wetland is supported only by stormwater runoff, and during extended periods of dry weather, will not have a shallow pool at all. Due to their small size and fluctuating water levels, pocket wetlands often have low plant diversity and poor wildlife habitat value.

When properly designed and constructed, each of the four wetland designs is capable of providing reliable pollutant removal and peak runoff control, effectively mimicking the stormwater treatment and flood control functions of natural wetlands. However, these classic stormwater wetland designs, in particular the ED wetland and the pocket wetland, have struggled to replicate other functions of their natural counterparts, such as habitat, aesthetics and species diversity. For these and other reasons described above, we no longer recommend use of the ED wetland or pocket pond design for stormwater treatment. We also promote modification of the pond/wetland system and shallow marsh designs to improve performance and habitat value, as described later in this article.

Following the publication of *Design of Stormwater Wetland Systems*, wetland designs gradually evolved to provide more diverse topography and better habitat diversity, but were still modeled after the emergent freshwater wetland (Figure 4). Interest in stormwater wetlands increased in the 1990s, but it has since declined, due to the limitations described in Table 1, as well as to both real and perceived concerns about mosquitoes and West Nile Virus.

Figure 4. The second generation of stormwater wetlands

Since the turn of the century, stormwater management has begun to shift from the use of large STPs, such as ponds and wetlands, treating large drainage areas (e.g., 20 acres or more), to the use of small-scale, distributed practices, such as filter strips, rain gardens and green rooftops, that treat much smaller drainage areas (e.g., five acres or less). Although this trend has resulted in decreased interest in stormwater wetlands, it has also spurred an interest in the potential of vegetation, particularly trees, to remove pollutants from stormwater runoff. Experts in stormwater and wastewater management and environmental remediation have recently started documenting these benefits and are now promoting the integration of trees into STPs, such as stormwater wetlands, to enhance their pollutant removal performance (Cappiella et al., 2006a).

Some of the stormwater wetlands in existence today were not actually designed to be wetlands at all. Instead they were designed to be dry ponds. Over time, these dry ponds evolved into wetlands due to changes in hydrology and a lack of maintenance (Figure 5). Although the conversion of these dry ponds into stormwater wetlands was not intentional, it was for the better, as wetlands have been shown to provide pollutant removal that is superior to that of dry ponds (CWP, 2007). For these reasons, conversion of a pond to a wetland is now an accepted retrofitting practice (Figure 6).

Figure 5. Dry pond turned into a wetland

Figure 6. Retrofitting a dry pond into a wetland

This article promotes a new generation of stormwater wetlands that have enhanced performance, improved aesthetics and increased habitat value. Two major design modifications are proposed: 1) the addition of trees and shrubs, and 2) reduced water level fluctuations (WLF). The addition of woody vegetation draws from the literature information about the pollutant removal benefits of trees and shrubs and acknowledges that, just as natural wetlands can be forested or emergent, so can constructed wetlands. Although the majority of constructed stormwater wetlands that have been or are being built are of the emergent freshwater variety, nearly half of the natural wetlands in the U.S. are forested wetlands (Dahl, 2006). The same dichotomy may be desirable in stormwater wetland systems. The reduced WLF is recommended based on research that pinpoints changes in WLF as the cause of habitat decline, including decline in species richness and an increase in invasive plant species. Incorporating a multi-cell pond-wetland system significantly reduces the frequency and magnitude of WLF in the wetland without increasing the footprint of the wetland.

Lessons Learned About Stormwater Wetlands

The Center for Watershed Protection recently reviewed more than 50 state and local stormwater design manuals from across the U.S. and Canada. This review revealed that, in terms of stormwater wetland design guidance, not much has changed since the *Design of Stormwater Wetland Systems* was published. In fact, most of the stormwater manuals provide information that is very similar to the information presented in the 1992 publication. Although not much new information can be gleaned from the nation's stormwater manuals, a number of important lessons learned can be drawn from the collective experience with stormwater wetland systems over the past 15 years. Some of these lessons are summarized in Box 2.

Box 2. Lessons Learned About Stormwater Wetland Design

- Well-designed wetlands do not create mosquito breeding conditions but the perception continues that they are a major mosquito habitat (Adams et al., 1983; Galli, 1992; Brauman, pers. comm).
- Pollutant removal performance of stormwater wetlands is generally comparable to other STPs, including wet ponds, but the removal of some pollutants, particularly nutrients and organic carbon, is somewhat more variable (CWP, 2007).
- After a period of relatively high phosphorus removal following wetland construction, phosphorus removal steadily decreases with time as bonding sites within wetland soils become saturated (Oberts, 2000).
- Many stormwater wetlands wind up looking more like shallow ponds with sparse plant coverage and fairly uniform topography.
- Many stormwater wetlands become overrun with invasive species (often creating a monoculture), and their habitat values decrease. Research on the impacts of stormwater on natural wetlands may help to explain this decline. Studies show that water level fluctuations greater than 8-10 inches above the normal water surface elevation cause a decline in species diversity and richness (Richter and Azous, 1995; Chin, 1996; Horner et al., 1997; Azous et al., 1997). Others show that increased sediment and nutrient loads in natural wetlands cause a decline in species richness and an increase in invasive species (Werner and Zedler, 2002; Gleason et al., 2003; U.S. EPA, 2002).
- When not considering the cost of land, wetlands are considerably cheaper to build than wet ponds because of the reduced need for excavation (Wossink and Hunt, 2003).
- It is unclear whether confusion over how to address the issues of minimum drainage area, water balance, groundwater interception, perched water tables, water elevation or minimum inflow rates has limited the application of stormwater wetlands or if these criteria are even necessary.

The lessons learned over the past 15 years provide some insight into the changes that are needed to enhance the function, performance, acceptability and success of stormwater wetland designs. Some designers are already using this information to continually adapt their projects. Box 3 provides one example from Staten Island, New York.

Box 3. Staten Island Bluebelt Wetlands

The Staten Island Bluebelt program was initiated in the late 1980s by New York City's Department of Environmental Protection and is one of the Northeast's most ambitious stormwater management efforts. The overall goal is to provide the necessary stormwater drainage infrastructure for a 12,000-acre region on the southern end of the island while at the same time preserving the last great stand of freshwater wetlands in New York City. The bluebelt uses a series of carefully placed best management practices (BMPs) at the storm sewer/wetland interface to reduce flooding and improve water quality. Creation of a self-regulating ecosystem that is native to the Staten Island region is of primary importance to the program.

BMPs used in the bluebelt include stormwater wetlands, stream restoration, outlet stilling basins, and sand filters. Ninety-two stormwater wetlands are planned for the project, about half of which have been constructed to date. In order to integrate the wetlands into the natural ecology, the construction process is advised by restoration specialists since general contractors are typically not trained in proper plant selection and installation. The planting design focuses on quick establishment of the preferred successional communities that will complement the surrounding landscape, before invasive species take over the site. Lessons learned from creating stormwater wetlands over the past 10 years in the bluebelt include:

- Protect young plants from herbivores (e.g., geese, muskrats)
- Limit maximum dry weather water depth up to 18 inches
- Restrict stormwater flow into wetlands for one growing season
- Select plants based on water quality
- Promote vegetation by providing gentle slopes
- Provide flexibility in outlet structure for manipulating water level
- Some shrubs may thrive in the extended detention zone (e.g., buttonbush) but most trees should be planted above this zone
- Use locally grown container stock for trees and shrubs - bare root or rooted cuttings are also okay if planted in spring. Use live plugs (spring planting) for emergent species.
- No problems have been found with use of stock that is not wet-acclimated
- Vary the size and age of plant materials to promote diverse structure
- Apply a layer of tree and shrub seed to further vary the age range
- Apply seeds at 3 times the rate recommended by the manufacturer to quickly establish ground cover
- No problems with mosquitoes have been found, and this is attributed to good habitat for mosquito predators and the absence of mosquito breeding conditions
- Establish an herbicide contract to control invasive plant species by annually servicing sites beyond the guarantee period
- Amend planting holes with compost or coir and a small amount of fertilizer – little new topsoil (1-2 inches max) is needed with this approach
- Protect planting areas from compaction during construction

Sources: Vokral et al. (2003); Gumb (2005); Brauman, pers. comm.

Because stormwater wetlands are often designed to experience frequent and significant WLF and treat runoff with high pollutant loads, it is no surprise that they cannot replicate all of the functions of their natural counterparts. Unless there is a change in the way that stormwater wetlands are designed, they will continue to function simply as treatment systems with little to offer in terms of habitat value. One Maryland-based firm has recognized this dilemma, and is developing and implementing stormwater wetland systems as part of a holistic approach to ecosystem restoration. Box 4 summarizes these innovative designs.

Box 4. Underwood and Associates' Stream and Wetland Ecosystem Restoration Techniques

Underwood and Associates, an Annapolis-area restoration firm, has developed a holistic ecosystem restoration approach to address stormwater problems. The techniques raise groundwater, create wetlands, and reconnect streams to the floodplain. They also detain large volumes of water on the landscape. They provide a host of benefits beyond just stormwater, such as creation of high quality plant and wildlife habitat, and minimal site disturbance, and result in aesthetically pleasing, self-sustaining systems that have had no problems with mosquitoes.

One specific design variant is the Regenerative Stormwater Conveyance (RSC) system, which replaces traditional pipe outfalls and re-establishes stream valley ecosystems. Conveyance through these systems replicates a forested wetland system with seepage and involves construction of a system of step pools, weirs, and plantings that are able to control the 100-year storm. The RSC utilizes proprietary riffle weir grade control structures, constructed of native materials, and shallow aquatic beds, underlain with a seam of sand, to reduce runoff velocity, remove pollutants and recharge groundwater, essentially restoring spring heads to stream and wetland ecosystems.

In the RSC, an entry pool is used for initial energy dissipation. Existing soils are replaced with 3 feet of manufactured sand and the landscape is stepped down in 1-foot intervals. Native boulders, cobble, and rootwads are used to create riffles and armor the channel. A wide range of native vegetation is then planted within the systems, including submerged aquatic vegetation, shrubs, and trees. The major runoff and pollutant removal processes of RSCs include infiltration, seepage, and exfiltration. No data is available yet on the pollutant removal performance of these systems.

RSCs have been utilized primarily in the Coastal Plain of Anne Arundel County, Maryland, with a focus on restoration of Atlantic White Cedar habitat. However, they can be implemented in almost any region with some minor adaptations. Some practical applications include treatment of runoff from road or surface drainage, channel protection downstream of stormwater management facility outfalls, and collection and conveyance of stormwater.

For more information, see Underwood and Associates webpage: www.ecosystemrestoration.com

Until these more innovative and holistic designs become widely accepted, most communities will continue to utilize and adapt the more traditional approaches to stormwater management. New design objectives to guide the next generation of stormwater wetlands are presented in the following section.

New Design Objectives for Stormwater Wetlands

Two new stormwater wetland designs are presented in this article: an emergent wetland/pond design and a wooded wetland design. These designs are modifications of the original pond/wetland system and shallow marsh designs presented by Schueler (1992). Goals associated with these new designs are enhanced pollutant removal, increased habitat value, reduced problems with invasive species and mosquitoes. Considerations have also been made to ensure that these modifications do not increase construction costs and maintenance burden beyond those of standard wetlands or wet ponds. Specific design objectives to meet these goals are proposed in Box 5. These objectives are somewhat ambitious, but designs meeting these objectives will represent a major improvement over the existing stormwater wetland designs.

Box 5. New Design Objectives for Stormwater Wetlands

- Minimize construction costs (i.e., similar to those of wet ponds)
- Minimize land consumption
- Improve pollutant removal performance, particularly for nitrogen and phosphorus
- Detain or delay floodwaters so they do not cause downstream flooding problems
- Reduce stormwater runoff volumes through evaporation, evapotranspiration and infiltration
- Minimize thermal impacts associated with urban stormwater runoff
- Create and maintain a diverse native plant community that includes trees, shrubs and emergent wetland plants
- Create and maintain valuable habitat for birds, amphibians, dragonflies and other wetland organisms
- Discourage nuisance problems, including mosquitoes, geese and odors
- Minimize long-term maintenance costs (i.e., similar to those of wet ponds)
- Create a safe and attractive amenity for nearby residents

Pollutant Removal Capacity of Stormwater Wetlands

The pollutant removal performance of emergent stormwater wetlands under widely different environmental and runoff conditions has been documented in numerous research studies. This section describes the primary pollutant removal mechanisms in wetlands, and summarizes the measured pollutant removal rates for emergent stormwater wetlands. It also discusses projected removal rates for forested stormwater wetlands, and how key pollutant removal pathways can be enhanced through improved design.

Pollutant Removal Pathways in Wetlands

The basic intent of a stormwater wetland is to create a shallow matrix of sediment, plants, water and detritus that collectively removes pollutants through a series of complementary physical, chemical and biological pathways (Figure 7). Wetlands use several mechanisms to remove pollutants such as sediment, nutrients, metals, and bacteria. These mechanisms include: sedimentation, filtration, adsorption, chemical precipitation, microbial transformation and biological uptake. Table 2 summarizes the pollutants removed by each mechanism and the conditions that promote each process.

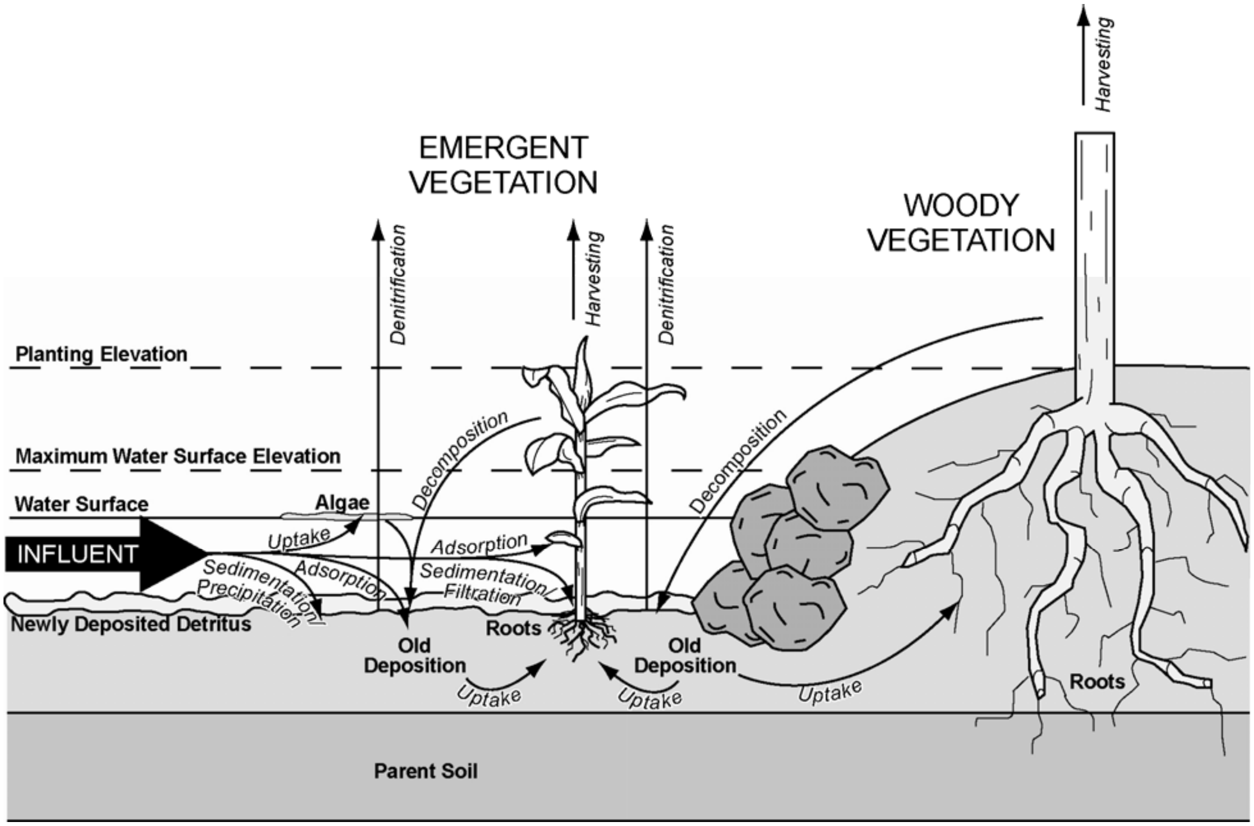

Figure 7. Wetland pollutant removal pathways

Sedimentation and filtration are physical processes that remove particulate matter, debris and even trash. Filtration occurs when wetland plants screen pollutants from runoff as it passes through the wetland, while sedimentation occurs when suspended particles settle to the bottom of the wetland. Another key removal process is adsorption - the adherence of pollutants to sediment, vegetation or detritus in the wetland. One drawback of adsorption is that bonded pollutants may be released back into the water column under certain conditions. A less common removal mechanism is chemical precipitation, which occurs under alkaline conditions. Precipitation is the formation of a solid from dissolved pollutants, such as phosphorus and metals.

The complex surfaces within stormwater wetlands provide favorable conditions for active microbial growth. Microbial processes are effective in removing nitrogen (via the nitrification/denitrification process) and organic matter (via aerobic decomposition). Nitrification is the transformation of ammonium to nitrate by specific bacteria under aerobic conditions.

Bacteria then convert the nitrate to nitrogen gas under anaerobic conditions. This process is called denitrification and it requires a carbon source (e.g., plants) and a long water retention time. In order to completely remove nitrogen from the wetland system, conditions must be right for both nitrification and denitrification to occur. A wetland's unique mix of aerobic and anaerobic conditions, combined with the presence of plants and other organic matter, provides an ideal setting for both processes.

Another removal process is biological uptake of pollutants, primarily from the wetland soils. Wetland plants (including trees, shrubs, emergent and submergent plants), algae, and microbes located on wetland plant and soil surfaces take up pollutants and may relocate, use or transform these pollutants over time. Biological uptake is seen as only a temporary removal process because the pollutants may be returned to the system when the plant dies, unless it is harvested.

Table 2. Summary of Pollutant Removal Mechanisms in Stormwater Wetlands (Compiled from Schueler, 1992; Brix, 1993; Donovan et al., 2000; and Hunt and Doll, 2000)

Mechanism	Pollutants Affected	Promoted by
Sedimentation: settling of suspended particles to the bottom of the wetland	Sediment and sediment-bound pollutants (e.g., phosphorus, nitrogen, metals, some pathogens, and synthetic organics), particulate COD and BOD	• Sheetflow • Low flow velocity • Rooted wetland vegetation (stabilizes sediments) • Long residence time
Filtration: filtering of pollutants from runoff by plants	Sediment, trash and debris	• Sheetflow • Low flow velocity • Presence of dense wetland vegetation
Adsorption: adherence of pollutants to sediment, vegetation, or detritus in the wetland	Soluble phosphorus, dissolved metals, some hydrocarbons	• Sheetflow • Low flow velocity • Long residence time • Complex microtopography • Dense emergent vegetation • Organic soils • Accumulation of wetland detritus
Chemical Precipitation: formation of a solid from dissolved pollutants	Dissolved phosphorus and metals	• Low flow velocity • Long residence time • High alkalinity
Microbial Transformation: conversion of nutrients and other materials to other forms through microbial processes (e.g., nitrification, denitrification, decomposition)	Nitrogen, organics, pathogens	• Combination of aerobic and anaerobic conditions • Long residence time • Presence of dense wetland vegetation • Accumulation of organic matter • Complex microtopography • Fluctuating water tables
Biological Uptake: utilization of pollutants by wetland plants, microbes and algae	Phosphorus, nitrogen, metals, hydrocarbons	• Presence of rooted wetland vegetation • Large volumes of standing water (for algal uptake)

Pollutant Removal Performance of Emergent Stormwater Wetlands

A large population of emergent stormwater wetlands has been monitored for pollutant removal performance (Table 3). Results indicate that the removal rates of emergent stormwater wetlands are similar to wet ponds, but are somewhat more variable, especially for nutrients and organic carbon. Studies from North Carolina found that wetlands and wet ponds are both effective at trapping sediment, but wetlands remove nutrients and mitigate temperatures more efficiently (Hunt et al., 2007).

Table 3. Range of Reported Removal Rates for Emergent Stormwater Wetlands
Source: Schueler et al. (2007)

Pollutant	Low End[a]	Median	High End[a]
Total Suspended Solids	45	70	85
Total Phosphorus	15	50	75
Soluble Phosphorus	5	25	55
Total Nitrogen	0	25	55
Organic Carbon	0	20	45
Total Zinc	30	40	70
Total Copper	20	50	65
Bacteria[b]	40	60	85
Hydrocarbons[c]	50	75	90
Chloride	0	0	0
Trash/Debris[c]	75	90	95

[a] Low End and High End are the 25th and 75th quartiles.

[b] Only three studies measured bacteria removal by constructed wetlands. Research profiled in Strecker et al. (2004) indicated bacterial removal rates for constructed wetlands is generally positive, but typically lower than wet ponds. It was therefore assumed that bacteria removal rates would be at least 10% lower than in wet ponds.

[c] Due to data gaps, engineering judgment was used to derive pollutant removal rates. Hydrocarbon and trash/debris removal rates should be considered provisional until additional pollutant removal performance data becomes available.

Notes:

- Removal rates, expressed as a percent, refer to the pollutant reduction from the inflow to the outflow of the system. Removal rates were rounded to the nearest 5% for ease of use
- 40 monitoring studies were available to define rates for total suspended solids, total phosphorus, soluble phosphorus, total nitrogen, organic carbon, total zinc and total copper for constructed wetlands.

Projected Pollutant Removal Performance of Forested Wetlands

Forested stormwater wetlands have been utilized infrequently and therefore limited data is available to document their performance. However, we do know that wetland plants are very important for the pollutant removal processes that occur within wetlands. Wetland plants filter out pollutants and slow down runoff, which promotes sedimentation. Plants provide surfaces for pollutants to adsorb to and a substrate on which microbes transform nutrients. Wetland plants use oxygen from the atmosphere and pump it down to their root zones, creating pockets of aerobic conditions within an otherwise anaerobic environment, which is ideal for nitrogen removal. Plants also provide a carbon source for the denitrification process and uptake nutrients and other pollutants directly through their root systems.

Plant uptake most often occurs through plant roots and is increased with plants having high transpiration rates and fast growth (Shaw and Schmidt, 2007). Transpiration depends on the plant type, leaf area, nutrients, soil moisture, temperature, wind conditions, and relative humidity. In general, trees and shrubs have greater capacity to transpire water than emergent vegetation. Table 4 provides transpiration rates for individual trees, in comparison to grasses and herbaceous plants on a per area basis.

Table 4. Transpiration Rates of Various Plant Species
(Source: ITRC, 2001)

Plant Name	Plant Type	Transpiration Rate*
Common reed	Emergent	0.44 inches/day
Great bulrush	Emergent	0.86 inches/day
Sedge	Emergent	1.90 inches/day
Cottonwood	Tree (2 years old)	2.00-3.75 gpd/tree
Hybrid poplar	Tree (5 years old)	20-40 gpd/tree
Cottonwood	Full mature tree	50-350 gpd/tree
Weeping willow	Full mature tree	200-800 gpd/tree

* gpd = gallons per day

While the influence of different types of wetland vegetation on pollutant removal processes in wetlands is still not fully understood, dense emergent wetland vegetation appears to be important for nitrogen removal (through denitrification and adsorption), while woody vegetation is more beneficial as a sink for phosphorus (and carbon) though uptake. Trees and shrubs also promote infiltration near their root systems, which can filter out additional pollutants. As a result, stormwater wetlands designed with both emergent and woody vegetation may be most effective from a pollutant removal standpoint because they incorporate a variety of removal processes.

Adding trees to stormwater wetlands provides many other benefits, as trees absorb nitrogen dioxide, carbon monoxide, ozone, and particulate matter from the atmosphere. They reduce air temperature, thereby reducing the formation of temperature-dependant pollutants such as ozone. Trees and shrubs also reduce runoff through rainfall interception and evapotranspiration. Integrating trees and shrubs into a wetland with emergent vegetation provides a greater variety of habitat types for various wildlife species.

Despite the lack of data on pollutant removal in forested stormwater wetlands, the potential performance of these systems can be inferred from:

- Studies of nutrient removal by natural riparian forested wetlands receiving agricultural runoff
- Literature on phytoremediation - the use of trees to clean up contaminated soils and groundwater
- Research on natural forested wetlands receiving wastewater

Natural Riparian Forested Wetlands Receiving Stormwater

Much of the literature concerning natural riparian forested wetlands focuses on bottomland hardwood forests, cypress and hardwood swamps, and pocosin or bay forest ecosystems in the southeastern U.S. Although these wetlands vary in size, hydrology, soils, and tree species composition, they have many functional similarities in terms of nitrogen and phosphorus removal. Table 5 presents removal efficiencies for nitrogen and phosphorus from seven such studies, conducted on riparian forested systems of the Southeastern coastal plain receiving agricultural and/or urban runoff (Kuenzler, 1988a).

Table 5. Nutrient Removal by Riparian Forested Wetlands Receiving Agricultural and Urban Runoff (Adapted from Kuenzler, 1988a)

State	Runoff Source(s)	% TN Removal	% TP Removal	Reference
MD	Agriculture	89	80	Peterjohn and Correll, 1984
NC	Agriculture	22	37	Yarbro et al ,1984
NC	Intensive agriculture	80	81	Chescheir et al., 1987
GA	Agriculture	68	30	Lowrance et al.,1984
LA	Agriculture	26	41	Kemp and Day, 1984
SC	Agriculture, urban wastewater	N/A	50	Kitchens et al, 1975
GA	Agriculture, urban runoff and wastewater	N/A	20	Tietjen and Carter, 1981

The percent of total nitrogen removed by the riparian forested wetlands is generally similar to or higher than the median removal of emergent stormwater wetlands (Table 3). The most important nitrogen removal process in southern forested wetlands is denitrification (Walbridge, 1993). Other important processes include uptake by plants and microbes (Walbridge, 1993). The total phosphorus removed by riparian forested wetlands is quite variable when compared to the median value for emergent stormwater wetlands (Table 3). Walbridge (1993) cites sedimentation and adsorption (which is enhanced by flooding and saturated soil conditions) as the most important phosphorus removal processes in southern forested wetlands. Also important are uptake by plants and microbes (Walbridge, 1993).

Phytoremediation

Phytoremediation is the process of using plants to remove contamination from soil and water. Plants can be used to clean up certain metals (e.g., cadmium and zinc), pesticides, solvents, explosives, crude oil, polycyclic aromatic hydrocarbons, and landfill leachates (U.S. EPA, 1999). Tree species typically used for phytoremediation include willow, poplar (cottonwood hybrids), and mulberry, because they have deep root systems, fast growth, a high tolerance to moisture, and are able to control migration of pollutants by consuming large amounts of water (Puckette, 2001; Metro, 2002; IRTC, 2001).

The major processes at work with phytoremediation include plant uptake, adsorption and microbial activity. Once pollutants are taken up by plants, one or more activities may occur. Pollutants can be moved into the above-ground portions of the plants, accumulate in the root zone, be broken down through natural processes of plant growth, or be transformed into inert material then discharged through plant leaves or shoots.

Pollutant removal rates for phytoremediation technologies vary greatly. One study estimated that one sugar maple growing along a roadway removed 60 mg of cadmium, 140 mg of chromium, 820 mg of nickel, and 5,200 mg of lead from the environment during a single growing season (Coder, 1996). Pulford and Dickinson (2006) found that cadmium, copper, nickel and lead are removed by willows from contaminated soil on the order of tens of grams per hectare per year. Zinc removal was about 100 times higher than this.

Natural Forested Wetlands Receiving Wastewater

Studies of natural forested wetlands receiving wastewater also provide some insight into their pollutant removal capability for stormwater applications, although it is important to remember that nutrient loading in these situations is often an order of magnitude greater than what is found in stormwater runoff. Studies of natural wetlands receiving wastewater have predominately focused on forested systems, with cypress, red maple, willow, black gum, and spruce trees (Kadlec and Knight, 1996). Table 6 provides the total nitrogen and total phosphorus removal efficiencies from a study conducted of riparian forested systems of the Southeastern coastal plain receiving wastewater (Kuenzler, 1988a).

Table 6. Nutrient Removal by Riparian Forested Wetlands Receiving Wastewater. Adapted from Kuenzler (1988a).

State	Wastewater Type	% TN Removal	% TP Removal	Reference
NC	Sewage lagoon	92	102	Kuenzler, 1988b
NC	Secondary treatment	80	87	Kuenzler, 1988b
FL	Secondary treatment	90	98	Boyt et al., 1977
FL	Secondary treatment	87	62	Winchester and Emenhiser, 1983
FL	Municipal septic tank	N/A	46	Nessel and Bayley, 1984
FL	Secondary treatment	88	92	Dierberg and Brezonik, 1984

The percent of total nitrogen and total phosphorus removed by the forested wetlands receiving wastewater is consistently higher than removal by emergent stormwater wetlands shown in Table 3. Results from several similar studies in Louisiana also indicate that nutrient reductions are high, often greater than 80% removal (Table 7) (Day et al., 2004). This can be attributed to the high inflow nutrient concentrations of wastewater and regular, controlled inflow rates. The literature suggests that nitrogen removal efficiency increases linearly with nitrogen loading rates and does not decrease over time (Blahnik and Day, 2000; De Busk and Reddy, 1987). In comparison, Nichols (1983) notes that the saturation of adsorption sites apparently decreases phosphorus removal efficiency after a few years of sewage loading.

Table 7. Nutrient Reductions by Forested Wastewater Treatment Wetlands in Coastal Louisiana (Adapted from Day et al., 2004).

Site	Nutrient	% Reduction*
Amelia	TKN	66
	TP	92
Breaux Bridge	NO3-N	100
	TP	87
St. Bernard	TKN	89.7
	TP	95
Thibodaux	NO3-N	100
	TKN	69
	TP	66

TKN = total kjeldahl nitrogen
TP = total phosphorus
NO3-N = nitrate nitrogen
*pollutant removal rate determined based on comparison of effluent concentrations at wetland inflow and outflow points

Design Factors that Enhance Pollutant Removal

The pollutant removal capability of an individual stormwater wetland depends heavily on several factors: how the wetland is sized in relation to the target water quality volume (WQv), the surface area to volume ratio of the wetland, the length of the internal flowpath (Figures 8 and 9), presence of a forebay, and treatment redundancy (Schueler, 1992). The surface area to volume ratio can either be achieved by increasing the surface area of the wetland, or by increasing the number of surfaces within the wetland (e.g., internal structural complexity), which sharply increases the surface area available for adsorption and microbial activity. Features that create conditions suitable for denitrification, such as the presence of organic matter/detritus, long water retention time, and dense stands of vegetation, may also be important to enhance nitrogen removal.

Specific design features that influence pollutant removal within stormwater wetlands are presented in Table 8. Features in the lefthand column are characteristic of designs that can achieve the median removal rates listed in Table 3, while use of the features in the righthand column is likely to achieve removal rates at the high end of the range presented in Table 3. These features are identified based on studies of emergent stormwater wetland performance (as outlined in CSN and CWP, 2008), and findings from studies of natural wetlands, wastewater wetlands and phytoremediation.

Figure 8. A short internal flowpath from inlet to outlet decreases wetland pollutant removal performance

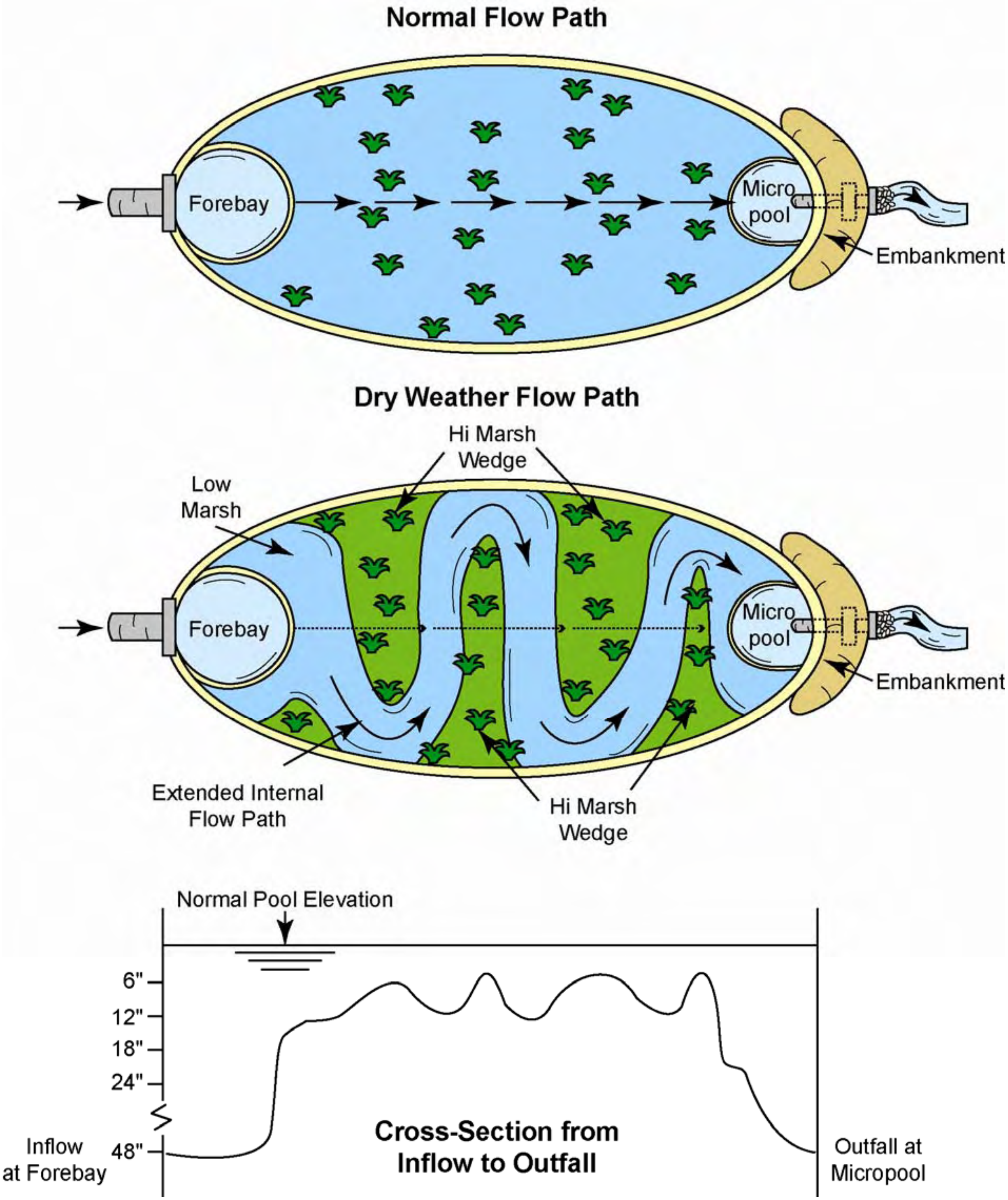

Figure 9. Placement of hi and lo marsh wedges creates a long internal flowpath *Although the flow path of runoff during storms is governed by the distance between the inlet and outlet of the wetlands, the effective flowpath during dry weather can be much longer if wedges of hi marsh (1-6” deep) are placed at right angles to the normal direction of flow.*

Table 8. Design Features that Influence Pollutant Removal in Stormwater Wetlands (Adapted from CSN and CWP, 2008)

Features That Achieve Median Removal Rates	Features That Increase Removal Rates
Target water quality volume = that to be provided	Target water quality volume < that to be provided
Wetland surface area < 3% of contributing drainage area	Wetland surface area >3% of contributing drainage area
Single wetland cell	Multiple wetland cells
ED wetland	No ED in wetland
Flow path from inlet to outlet 1:1 or less	Flow path from inlet to outlet 1.5:1 or more
Uniform wetland depth	Diverse micro-topography
Mean wetland depth more than one foot	Mean wetland depth less than one foot
Groundwater inputs to wetland	No groundwater inputs to wetland
Regular wetland design	Pond/wetland design
Emergent wetland vegetation	Woody and emergent wetland vegetation
Sparse wetland plant cover	Dense wetland plant cover
Deciduous vegetation	Deciduous and evergreen vegetation
Wetland bottom clear of organic matter/detritus	Wetland bottom covered with organic matter/ detritus

Conceptual Designs for the Next Generation

Two new wetland designs are presented in this section: an emergent wetland/pond model and a wooded wetland model. Each is intended to work towards meeting the design objectives proposed in this article, including enhanced pollutant removal, increased habitat value and reduced problems with invasive species and mosquitoes (Box 6). Another goal is to minimize costs so they are less than or no greater than that of a wet pond. We encourage designers to explore ways to minimize costs as these designs are further developed and implemented.

Box 6. Reducing Mosquito Concerns

Research on mosquito breeding in stormwater wetlands has found that certain conditions, such as standing water and shallow pools (1-3”), are associated with high mosquito populations. Recommendations for wetland design that reduce mosquito breeding potential without compromising pollutant removal performance include (Walton, 2003; Apperson et al., 2005; Knight et al., 2003; Hunt et al., 2007):

- Incorporate deep pools (30”) free from vegetation to provide predator habitat (e.g., mosquitofish)
- Shallow pools should be connected to the general flow path
- Maintain constant water flow to disrupt mosquito production
- Avoid emergent macrophytes that develop dense monocultural stands (e.g., cattails)
- Limit emergent zone width to allow access for predators and mosquito control (e.g., pesticides)
- Plant herbaceous species that attract mosquito predators (e.g., dragonflies)
- Target planting density of 3-4 trees per 10,000ft^2 when planting in the wetland (a greater density at higher elevations, including the wetland fringe and buffer, is okay)

A number of studies have shown that mosquitoes are not a major problem in properly designed stormwater wetlands (Adams et al., 1983; Galli, 1992; Brauman, pers. comm.), but they may still be perceived as a problem. Incorporating mosquito assessments into regular monitoring efforts and enhancing public knowledge about mosquito risk can help to allay these concerns.

The stormwater wetland design variants presented in this article may not be applicable in all landscape settings or regions of the country. In general, stormwater wetlands work well in flat terrain with a high water table because minimal excavation is needed to create a permanent pool and adequate water balance. In areas without high groundwater tables, stormwater wetlands typically require large drainage areas to support wetland hydrology and may not be feasible on small sites or in ultra-urban areas (see Box 7). Special regional design considerations for stormwater wetlands in cold climates, arid climates and karst terrain are discussed on page 33 and in Caraco and Claytor (1997).

Box 7. Wetlands for Low Impact Development

One of the persistent limitations of stormwater wetlands has been the large surface area they consume, which has curbed their use as an on-site low impact development (LID) practice. Although it depends on site characteristics, most stormwater wetlands require fairly large drainage areas (e.g. 25 acres) to support wetland hydrology. This is reflected in the minimum contributing drainage area requirement that appears in many of the existing stormwater wetland designs. The pocket wetland has been an exception to the “significant contributing drainage area rule”, and, in the past, has been applied to drainage areas as small as 1 acre in size. However, due to their size, unreliable water supplies and widely fluctuating water levels, pocket wetlands often have limited plant diversity, poor habitat value and, consequently, are no longer recommended for general use. This leaves practitioners without a stormwater wetland design that can be widely applied to drainage areas less than 5 acres in size.

A new stormwater wetland design variant is needed that can be applied as an on-site LID practice. Some options to explore for such a design include a) using stormwater wetlands in conjunction with rainwater harvesting and b) experimenting with wetlands that are designed to dry out periodically, just like many natural wetlands.

Linking a small stormwater wetland with a rainwater harvesting system would provide the steady water supply that is needed to support wetland hydrology. In larger stormwater wetlands, this steady supply of water is provided by a pond (in the new pond-wetland system) or by baseflow, both of which require a relatively large contributing drainage area. On small sites, a rainwater harvesting system could be used to replace the function that ponds serve on larger sites. The steady supply of water provided by a rainwater harvesting system would help to reduce water level fluctuations and maintain plant diversity within the wetland.

It may also be possible to construct functional stormwater wetlands that do not have a steady supply of water. In nature, these wetlands, known as ephemeral wetlands, provide valuable habitat, pollutant removal and flood control. Ephemeral wetlands temporarily hold rainfall and runoff during periods of heavy rainfall, typically in the spring and early summer, and periodically dry up when rainfall amounts decrease, often in mid-to-late summer. Although additional research is needed, it may be possible to apply these concepts to stormwater wetland design. The result may be a form of rain garden that includes wetland vegetation and retains water for extended periods of time. This is certainly an opportunity for further exploration.

The new wetland designs can be applied to most types of new development and redevelopment, and can be utilized in both residential and non-residential areas. Although they may not be applicable in higher density developments because of land consumption, they may be a good fit for headwater areas that drain to zero-order streams. The wetlands may also be applied in retrofit situations. Schueler et al. (2007) provides detailed guidance on how to select, evaluate, and prioritize locations for stormwater retrofits.

The new wetland designs are promoted as part of an approach to stormwater management that focuses on reducing the *volume* of stormwater generated at a site. This tiered approach encourages 1) conservation of natural areas and native soils, 2) use of conservation design to reduce and disperse impervious cover, 3) use of small-scale, distributed stormwater treatment practices (such as rooftop disconnection, bioretention areas and infiltration) to reduce runoff volume, and 4) use of wetlands or other structural practices to meet the remaining stormwater management requirements. The first three techniques in this approach reduce the runoff volume, thus reducing the size and cost of structural STPs needed at the development site. Consequently, when the new wetland designs are applied in the context of this treatment train approach, their construction costs may be significantly reduced.

New Emergent Wetland/Pond Design

The new emergent wetland/pond design presented below incorporates many of the lessons learned over the last 15 years. It is essentially a modification of the original pond/wetland system, and is recommended for use in place of the classic pond/wetland and shallow marsh designs. It includes an on-line wet pond cell that supplies a steady supply of water to an off-line shallow wetland cell. This configuration significantly reduces the frequency and magnitude of WLF within the wetland cell, which have been shown to reduce plant diversity and decrease habitat value (Horner et al. 1997; Werner and Zedler, 2002).

There is no minimum contributing drainage area to the emergent wetland/pond system provided that an adequate water balance exists to maintain a permanent pool in the wet pond and wetland cells. The required footprint of the practice will vary depending upon the hydrology of the site and the amount of runoff reduction that is provided upstream, but the system should consume approximately 3% or less of the contributing drainage area. Enhanced pollutant removal performance in stormwater wetlands has been associated with shallow water depths and minimal WLF, which has typically been achieved by consuming more land (typically more than 3% of the contributing drainage area as noted in Table 8). In the new emergent wetland/pond design, the wetland cell is located off-line and is provided with a steady supply of water, which allow for shallow water depths and minimal WLF in the wetland without driving up land consumption.

The system should be a long, linear feature, with a minimum length to width ratio of 3:1, although a length to width ratio of around 5:1 or 6:1 is preferred. Wetland siting should take into account the location and use of other site features such as natural depressions, buffers, and undisturbed natural areas, and should attempt to aesthetically “fit” the system into the landscape. Figure 10 illustrates the new emergent wetland design. Key design elements are described below.

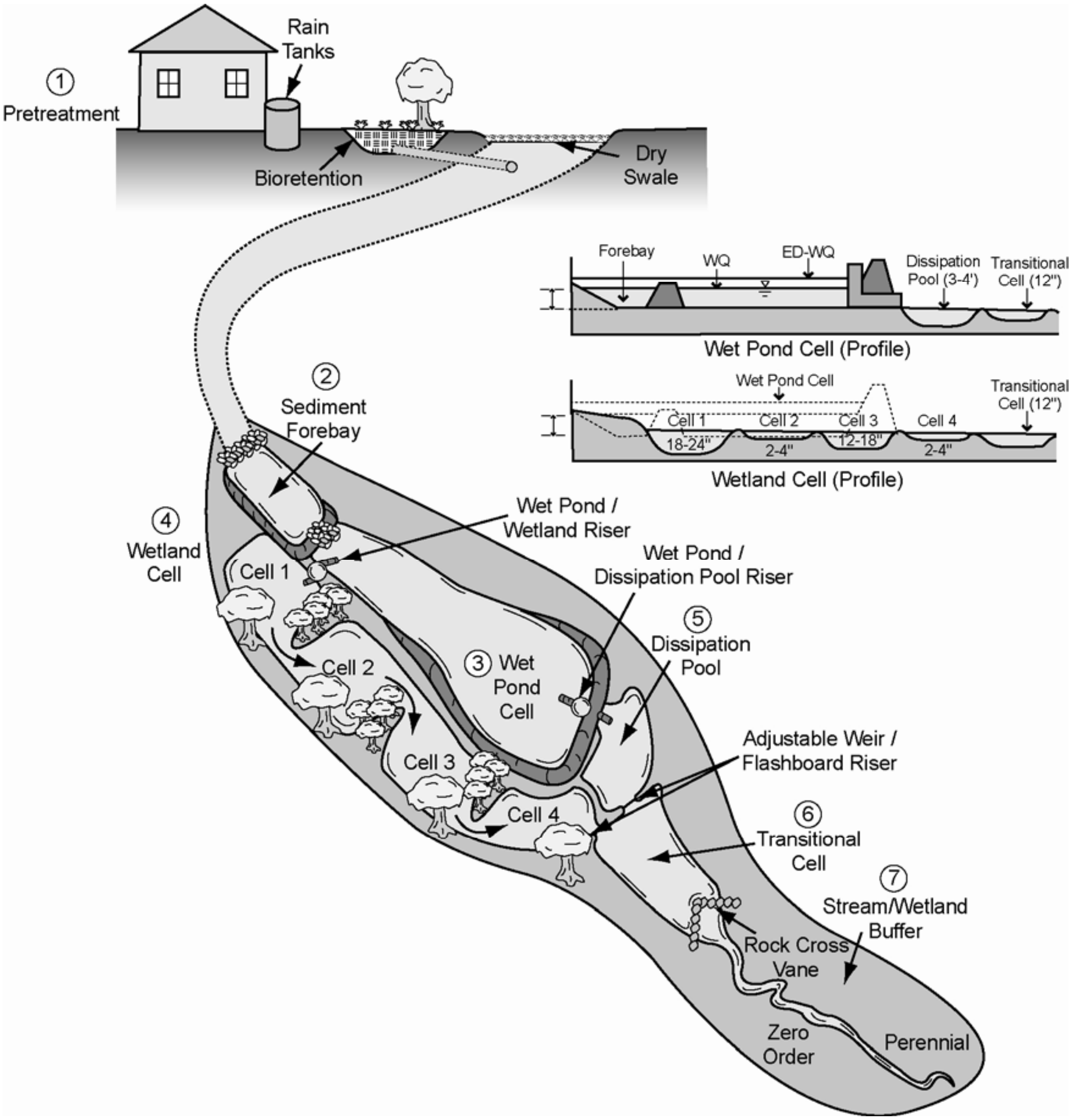

Figure 10. New Emergent Wetland/Pond Design

1. Pretreatment
Stormwater runoff should be pretreated to the maximum extent possible before it reaches the emergent wetland/pond system. The use of small-scale, distributed STPs, such as rooftop disconnection, bioretention areas and dry swales, within the contributing drainage area can effectively reduce stormwater runoff velocities, volumes and pollutant loads before they reach the wetland/pond system. They can also help reduce the overall size and cost of the system.

2. Forebay
A separate sediment forebay cell should be provided immediately upstream of the wetland/pond system. The forebay cell helps reduce the velocity of runoff entering the system and promotes sediment removal ahead of the wet pond and wetland cells. The forebay should be a separate cell, which can be formed by gabions, earth or native stone. It should comprise at least 10% of the water quality storage volume that is provided in the wetland/pond system, and should be

approximately 4 to 6 feet deep. Direct maintenance access to the forebay should be provided for heavy equipment, and it is preferable if the bottom of the forebay is hardened to make cleanouts easier.

3. Wet Pond Cell

A primary component of the new wetland/pond system is the wet pond cell. It serves a number of useful purposes in the design, as it:

- Provides additional pretreatment prior to the wetland cell
- Provides a small, but steady, supply of stormwater runoff to the wetland cell to support wetland hydrology between storm events
- Provides detention of larger storm events (e.g. channel protection, overbank flood and extreme flood events) before routing them downstream

The wet pond cell provides initial treatment of the water quality storage volume. It should be designed to retain at least 70% of the water quality storage volume in a permanent pool. The remaining water quality storage volume should be treated via extended detention above the surface of the permanent pool and slowly released to the wetland cell, through a reverse slope pipe and concrete or corrugated metal riser and barrel, over an extended 12 to 24 hour period. The maximum extended detention-water quality water surface elevation should be no greater than 18 inches above the water surface elevation of the permanent pool.

The permanent pool should be designed with sufficient depth to allow for two reverse slope pipes to extend into it (Figure 11). These two reverse slope pipes, which extend from the riser and barrel structure, provide the hydrologic connection between the wet pond and wetland cells and a steady supply of water to the wetland cell.

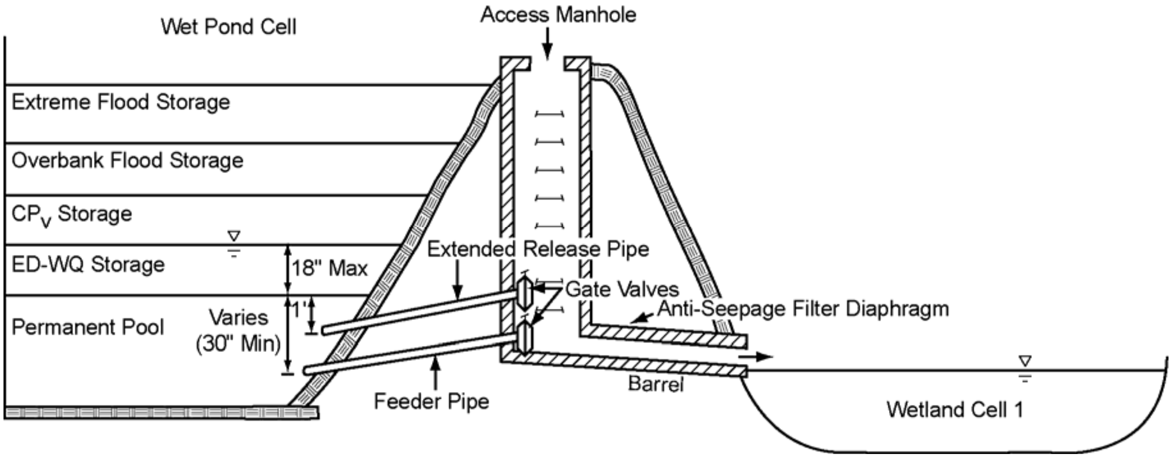

Figure 11. Wet Pond/Wetland Riser

The first of the reverse slope pipes should be designed as a “feeder pipe” to provide a small, but steady, supply of water to the wetland cell between storm events. A general rule of thumb is that a flow rate of approximately 0.002 cfs per acre must be supplied to a stormwater wetland to maintain adequate hydrology during dry weather (Schueler, 1992). To ensure that adequate storage is provided in the permanent pool to feed the wetland cell between storm events, the invert of the feeder pipe should be submerged an adequate distance below the elevation of the permanent pool, as determined through a water balance calculation. At a minimum, the invert of the feeder outlet should be placed 30 inches below the elevation of the permanent pool. The feeder pipe should also be equipped with an adjustable gate valve or other mechanism (such as removable weir plates or orifice reducing caps) that can be used to adjust the amount of flow that is supplied to the wetland cell.

The other reverse slope pipe should be designed as an "extended release pipe" to convey the remaining water quality storage volume into the wetland cell over a 12 to 24 hour period. The invert of the extended release pipe should be submerged approximately 1 foot below the elevation of the permanent pool to prevent clogging in the pipe. The extended release pipe should be fitted with an adjustable gate valve that can be used to adjust detention time in the wet pond cell.

Control of larger storm events, such as the channel protection, overbank flood and extreme flood events, can be accomplished within the wet pond cell. These storm events can be detained within the wet pond cell and released downstream through a separate concrete or corrugated metal riser and barrel located at the downstream end of the wet pond cell (Figure 12). A typical wet pond/dissipation pool riser configuration consists of a channel protection outlet with an invert at the maximum water surface elevation of the extended detention water quality volume, and an overbank flood protection outlet with an invert at the maximum water surface elevation of the channel protection volume. The extreme flood event usually passes through an opening at the maximum water surface elevation of the overbank flood event. Since the entire water quality storage volume is conveyed into the wetland cell, no outlet is provided for this volume in the wet pond/dissipation pool riser.

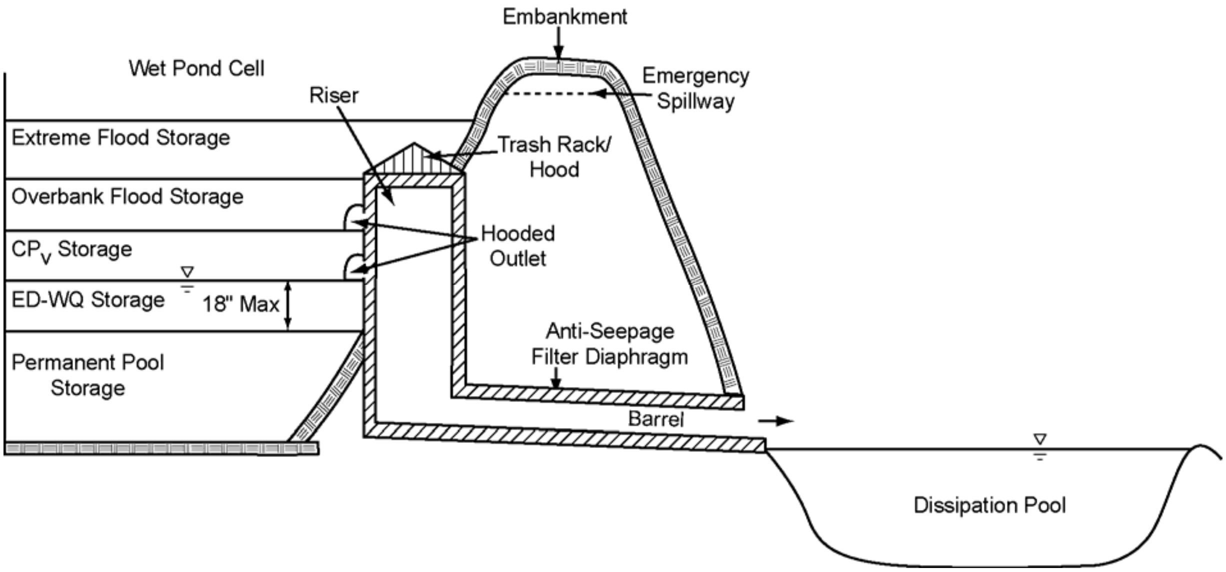

Figure 12. Wet pond/dissipation pool riser

When a significant amount of runoff reduction is provided upstream of the emergent wetland/pond system, it may be possible to treat the runoff from larger storm events in the wetland cell without drastically increasing the amount of storage that must be provided within the wet pond cell or significantly increasing the water level fluctuations that take place within the wetland cell. It may even be necessary to do this in order to provide a steady supply of water to the wetland cell. In this case, simplified outlet structures, such as hooded v-notch and broad-crested weirs, may be used for both the wet pond/wetland and wet pond/dissipation pool outlets.

4. Wetland Cell

The other primary component of the new emergent wetland/pond system is the wetland cell, which provides additional treatment of stormwater runoff, particularly for soluble pollutants. It also provides benefits such as native plant diversity and increased habitat value. By limiting water level fluctuations within the wetland cell, a higher native plant diversity and habitat value can be maintained. As a general rule of thumb, the water surface elevation of the wetland cell should increase by no more than about 6 inches.

The wetland cell should be a long, linear feature, with a minimum length to width ratio of 3:1, although a length to width ratio of around 5:1 or 6:1 is preferred. To extend the dry weather flow path and increase the hydraulic residence time within the wetland, internal dikes or berms should be used to create multiple cells. A minimum of four wetland cells is recommended. Each cell should consume about 25% of the total surface area of the wetland cell and each serves a particular purpose:

- *Cell 1* – The first cell is the deepest of the wetland cells, as it is used to collect inflow from the wet pond and distribute it as sheet flow into the remaining the cells. This cell should be between 18 and 24 inches deep and can support emergent wetland plant species that live 3-18" below the water. It provides year-round habitat for mosquito predators and refuge for aquatic organisms during periods of extended drought (Hunt et al., 2007).
- *Cell 2* – The second cell should be shallow, with a depth of 2 to 4 inches, and may contain a landscaping island that extends up to 12 inches above the normal water surface elevation. This cell can support a variety of emergent wetland plant species that live 1-3" above the water, as well as species that prefer drier conditions.
- *Cell 3* – The third cell should be approximately 12 to 18 inches deep and can support emergent wetland plant species that live 3-18" below the water. It provides additional habitat for aquatic organisms and acts as a deepwater link between the adjacent shallow water cells.
- *Cell 4* – The fourth cell is located at the discharge point from the wetland cell. It should be approximately 2 to 4 inches deep. Although the primary discharge from the wetland will be through evaporation, infiltration and transpiration, some surface outflow is expected. Therefore, the final wetland cell should be equipped with an adjustable weir or flashboard riser (see Hunt et al., 2007) to regulate water levels and release rates.

The alternating deep and shallow wetland cells will provide a sequence of aerobic and anaerobic zones that will enhance nitrogen removal within the wetland system through the processes of nitrification and denitrification. They will also provide a range of landscaping zones that will support a variety of wetland vegetation without having to create complex microtopography within the wetland cell. The transitional areas between the deep and shallow wetland cells should be designed with a maximum slope of 3:1 to ensure soil stability at the bottom of the wetland.

The dikes used to create the individual wetland cells should extend across at least 80% of the total width of the wetland cell to create a meandering flow path through the wetland and prevent short circuiting. They should be constructed using native stone, coconut fiber logs or other suitable material and backfilled with a soil mix that can support the desired plant growth. The peninsulas can be planted with grasses, herbaceous or woody species, but the goal should be to achieve a plant cover that includes some combination of the three. Guidance on planting trees in stormwater wetland peninsulas is provided on page 32.

In general, the side slopes of the wetland cell should be very gentle. Since the wetland cell is located off-line and will not experience significant water level fluctuations, the side slopes of the wetland cell that are not immediately adjacent to the wet pond cell should be designed at a slope of 6:1 or less. The sides of the wetland cell that are immediately adjacent to the wet pond cell may need to be designed with steeper side slopes, but should not exceed 3:1.

5. Dissipation Pool

At the downstream end of the wet pond cell is a dissipation pool. The purpose of the dissipation pool is to reduce the velocity of stormwater runoff being discharged from the wet pond cell and provide additional removal of any sediments that may have made their way through the pond during larger storm events. The dissipation pool should comprise approximately 10% of the water quality storage volume and should be approximately 3 to 4 feet deep. The pool should be equipped with an adjustable weir or flashboard riser to regulate water levels and release rates.

6. Transitional Cell

At the downstream end of the new emergent wetland/pond system is a transitional cell that receives inflow from both the wet pond and wetland cells. This cell should be long and linear, and function as a transition between the wetland/pond system and receiving waterbody. The water surface elevation of the transitional cell should be approximately 12 inches deep and a rock cross vane should be used to separate the transitional cell from the receiving waterbody.

7. Wetland Buffer

The wetland should be separated from adjacent land uses by a vegetated buffer. A buffer adds to the habitat value of the wetland, helps alleviate potential nuisances (e.g. geese) and increases the diversity of wildlife that utilize the wetland. For example, trees and shrubs in buffer areas provide critical perching, nesting and cover requirements for many bird species. To provide maximum habitat benefits, the buffer should extend at least 50 feet from the outward edge of the maximum water surface elevation. Wherever possible, the buffer should be directly connected to the stream corridor so that wildlife movement and migration can occur. Galli (1992) reports greater wildlife diversity for wetlands that are connected to the stream corridor than for those that are not.

Preferably, existing forests should be preserved to provide a wetland buffer. When this cannot be accomplished, the entire buffer zone of the wetland/pond system should be planted with tree species that are adapted to the site growing conditions (see Attachment C). The goal should be to achieve at least 80% canopy coverage within the buffer area. In many cases, tree planting clusters may need to be provided to increase survival and promote rapid growth of planted tree species (see page 31 for more on tree clusters).

Wooded Wetland Design

A wooded wetland (Figure 13) is a variant of the classic shallow marsh design to incorporate woody vegetation. The combination of trees and shrubs with emergent vegetation takes advantage of natural processes to maximize nutrient removal for both nitrogen and phosphorus and provides a greater range of habitat over the standard emergent wetland design. Trees also help to deter geese, a common nuisance problem in stormwater ponds and wetlands, and regulate the temperature of water leaving the wetland, reducing potential thermal impacts downstream. Trees provide a host of other benefits, such as improved air quality and soil stabilization.

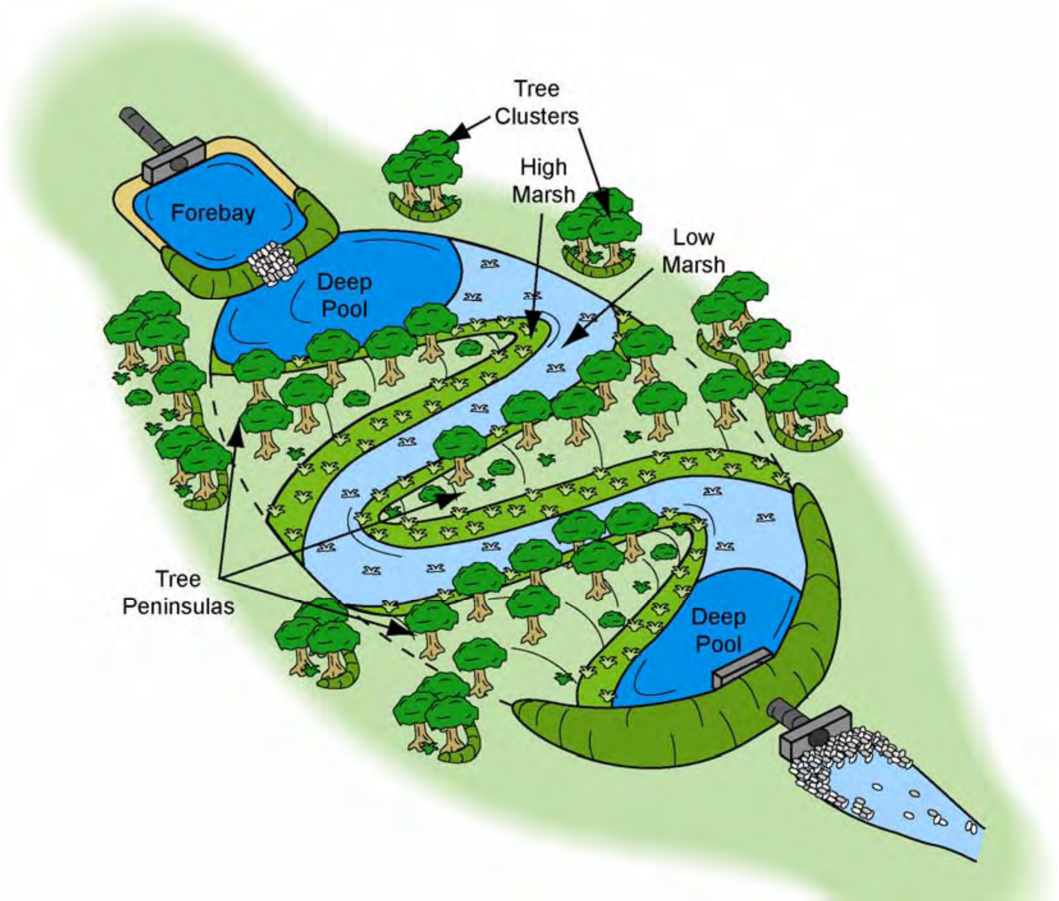

Figure 13. Wooded Wetland

Modifications have been made to the conventional stormwater wetland design to address potential conflicts between trees and functionality, promote better growing conditions, and reduce mosquito breeding potential and maintenance burden. Perhaps most important is the long-term plan for vegetation management, which is often overlooked when creating stormwater wetlands, but is a key ingredient in the success of the system. Key design elements for wooded wetlands are presented in Box 8 and described further below.

Box 8. Key Design Elements for Wooded Wetlands

- Complete a water balance for the site to make sure it can sustain a permanent water surface in the wetland.
- Include a separate-cell forebay for pre-treatment and to allow for cleanout without damaging wetland vegetation.
- Limit the maximum extended detention water surface elevation to no more than 8-10 inches above the normal pool to reduce potential impacts to the wetland community from frequent water level fluctuations.
- Wetland should have a minimum length to width ratio of 3:1. Wetland side slopes should be a minimum of 3:1
- Use an outlet structure that resists clogging, and include backup measures in case clogging occurs.
- Prohibit trees within 15 feet of the embankment toe and maintenance access areas.
- Use a micropool for outlet protection and to help enforce the setback between embankment and trees.
- Create variable microtopography and water depths throughout the wetland – include a mix of high marsh, low marsh, deep pools and shallow pool areas.
- Deep pools should comprise 20 to 50% of the wetland area and be located perpendicular to flow (Hunt et al., 2007; Walton, 2003). Locating a deep pool just below the forebay provides flow dissipation and some additional treatment.
- Shallow pools should have a maximum depth of 1 foot and deep pools around 3 to 4 feet. A simple water balance equation can be used to determine the minimum depth necessary for deep pools to ensure they retain water during a drought (Hunt et al., 2007).
- Incorporate 2-3 tree planting peninsulas in each wetland to enhance treatment.
- Locate planting peninsulas and marsh wedges perpendicular to flow so they extend the length of the internal flowpath
- Plant trees on side slopes in clusters based on inundation tolerance – clusters allow trees to share rooting space and permit mowing around trees if desired.
- Incorporate features that reduce mosquito breeding potential and provide habitat for mosquito predators. Regular monitoring and public education may also provide some reassurance to local residents and officials about safety.
- Select plant species based on tolerance of inundation and other site conditions – in general, trees and shrubs should be planted above the ED zone (with a few exceptions)
- In areas to be planted with trees, overplant with small stock of fast-growing successional species to quickly establish canopy closure and shade out invasive species
- Have a landscape architect develop a landscaping plan for the wetland
- Emphasize long-term vegetation management in the wetland maintenance plan.

Outlet Structure

A weir with a v or rectangular notch and hood is recommended as the outlet structure for wooded wetlands to reduce potential for clogging by woody debris (Figure 14). This control structure should be designed to address seepage and uplift on the weir wall, for example, by providing for seepage through the structure by using weep holes or by allowing sufficient travel distance along the base of the weir wall (so it behaves as an anti-seep collar). See USACE (1989) for additional guidance on floodwall and retaining wall design. Another viable outlet structure option is a reverse slope pipe, which withdraws water within one foot of the normal pool and is equipped with a gate valve to adjust detention times.

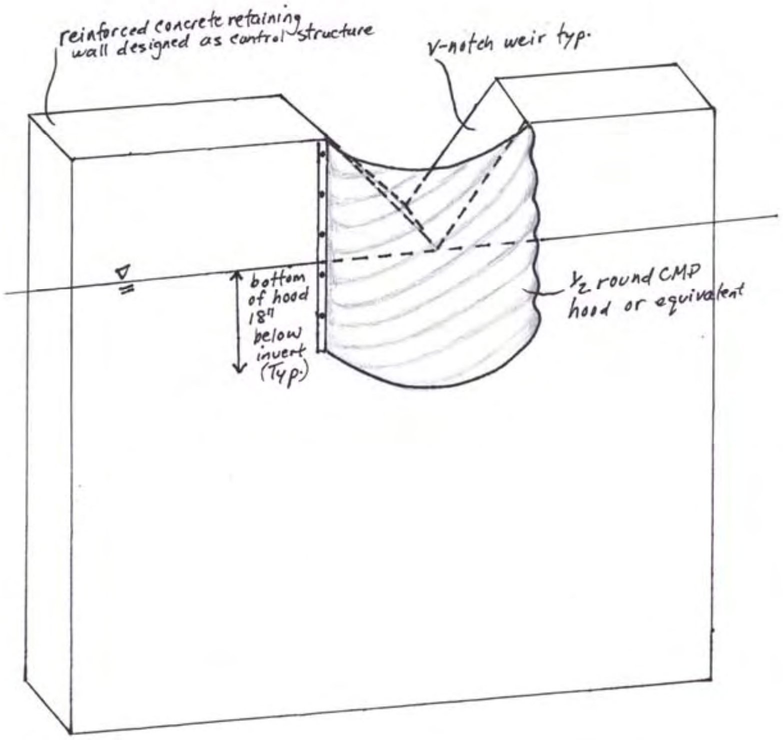

Figure 14. V-notch weir

It is also recommended to include measures to keep permanent pools at relatively safe elevations even when outlets clog. For example, Montgomery County, Maryland, incorporates perforated underdrains surrounded by stone along the face of each dam. The underdrains connect to flow restrictors within the embankment to ensure that the required flow controls are met. The designs also include a small (secondary) riser, which the underdrains and flow restrictors tie into (Figure 15). This secondary riser allows for a small amount of ponding if the underdrains become clogged. The resulting water surface elevation increase is relatively small and still allows for unclogging of underdrain flows without much problem.

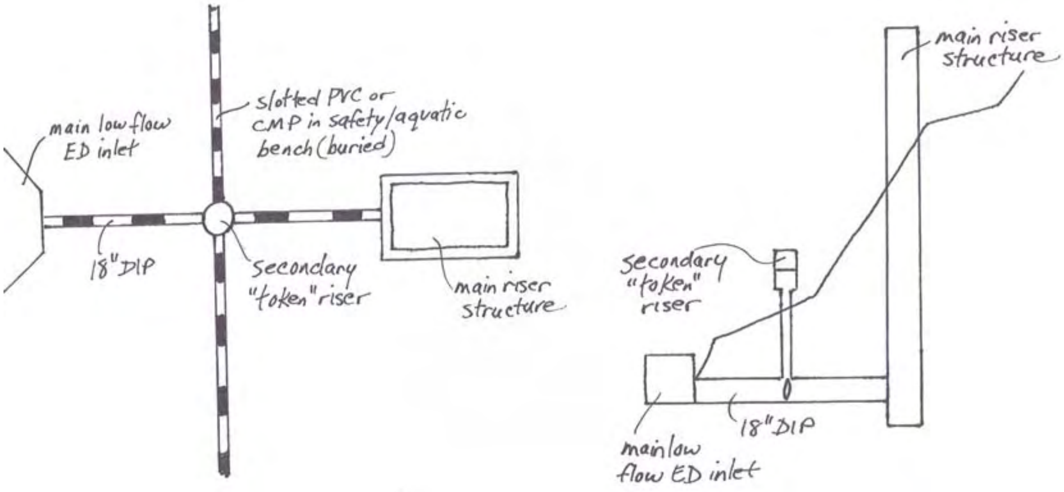

Figure 15. Secondary riser

Putting the Wooded in Wooded Wetland

The incorporation of trees is the most notable difference between the wooded wetland and the conventional stormwater wetland design. Trees and shrubs are included in two locations: planting peninsulas and wetland side slopes. Each is described below.

Planting peninsulas extend down from side slopes across the wetland perpendicular to the flowpath (Figure 16). The peninsulas provide a place for incorporating trees and shrubs to enhance pollutant removal and also serve the purpose of lengthening the flowpath. If desired, peninsulas may extend all the way across the wetland and a seepage feature can be used to allow flow through the peninsula.

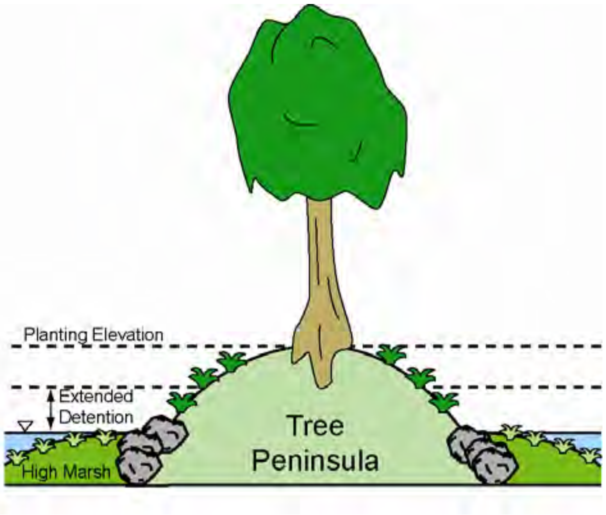

Figure 16. Tree planting peninsula

The surface elevation of the peninsulas is approximately 3 feet above the bottom of the wetland at the lowest point of the peninsula. Peninsula width is approximately 8 feet to provide sufficient space for large trees (recommended minimum 400 cubic feet per tree as per Urban, 1999). Peninsula slope is more gradual than the side slopes. Approximately 2-3 peninsulas should be incorporated in each wetland (depending on the size of the wetland) and they should be stabilized using rootwads or native stone.

Trees are also planted in a series of interconnected planting holes or clusters on wetland side slopes (Figure 17 and Figure 18). This increases the available soil volume for trees, a common constraint on compacted side slopes. Tree clusters can be used at various elevations on side slopes ranging from 10:1 to 3:1 and should greatly increase tree cover surrounding the wetland. Clusters incorporate small berms to capture runoff and allow some ponding during storms. The clusters can be arranged so that runoff from sides of one cluster will be directed downhill to the next cluster. Clusters of trees are not recommended in the wetter portions of the wetland, as they can create ideal conditions for mosquito habitat (Hunt et al., 2007).

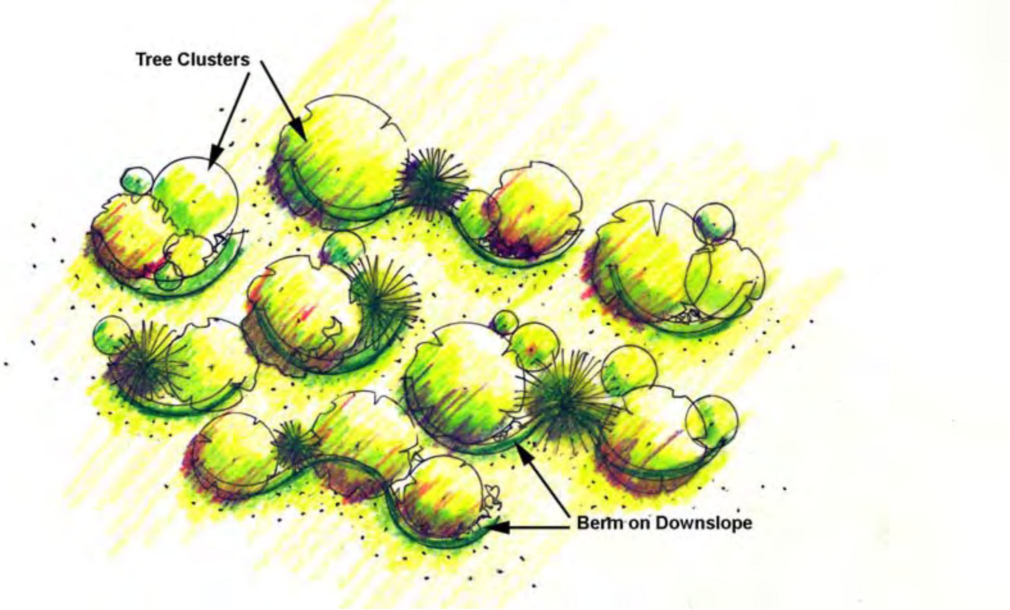

Figure 17. Tree clusters – plan view (Graphic by Matt Arnn)

Figure 18. Tree clusters – profile (Graphic by Matt Arnn)

The initial tree and shrub planting strategy should include overplanting with small stock of fast-growing species. This will result in faster canopy closure, which will reduce invasive species. Thinning, invasive plant removal, and/or addition of more desirable species can be done at a later date.

The most limiting factor in terms of tree and shrub species selection for the wetland is likely to be tolerance of inundation. The depth, duration and frequency of inundation are all important to consider in species selection. Some species may tolerate extended periods of inundation, but may become stressed when faced with shorter but very frequent inundation periods. Other species may be tolerant of standing water depths up to 5 feet – but only for a short period of time. Unfortunately, most data on inundation tolerance of tree and shrub species do not usually provide this level of detail. A good rule of thumb is to plant species in a somewhat drier zone than the data suggests they can tolerate, and let them move in over time down to lower elevations if they can tolerate it. A handful of resources provide some level of detail for several regions of the country – these are summarized in Attachment C. Box 9 lists recommended species for the Northeast U.S. when planting on peninsulas and side slopes in wooded wetlands.

Box 9. Recommended Trees and Shrubs for Wooded Wetlands in the Northeast U.S.

For areas with frequent, extended inundation (from permanent pool to top of ED zone)*

Trees:

- Atlantic white cedar
- Bald cypress

Shrubs:

- Buttonbush
- Virginia sweetspire
- Marsh elder
- Streamco willow
- Silky dogwood
- Elderberry
- Arrowwood viburnum

For areas with infrequent inundation or saturation (above the ED zone)**

Trees:

- Box elder
- Gray birch
- Green ash
- Sweetgum
- Loblolly pine
- Northern white cedar
- Poplar
- Red maple
- Pin Oak
- Willow

Shrubs:

- Smooth alder
- Groundsel tree
- Sweet pepperbush
- Fetterbush
- Wax myrtle
- Swamp azalea
- Swamp rose

*These species tolerate semi-permanent to permanent inundation or saturation 76% to 100% of the growing season (Thunhorst, 1993; Brauman, pers. comm.)

** These species tolerate regular inundation or saturation 26% to 75% of the growing season (Thunhorst, 1993; Brauman, pers. comm.)

Pondscaping

Pondscaping is a technique that utilizes native trees, shrubs, herbaceous plants and wetland species to meet specific functional design objectives within a stormwater wetland system. Eleven steps are proposed for pondscaping the new stormwater wetlands presented in this article. Attachment B provides pondscaping specifications that follow these eleven steps, with a primary focus on the Mid-Atlantic region. Additional guidance on preparing planting sites, selecting trees, and planting and maintaining trees is provided in Cappiella et al. (2006b).

Step 1: Prepare the Final Pondscaping and Grading Plans
Step 2: Grade the Wetland to Interim Elevations
Step 3: Add Topsoil/Wetland Mulch Amendments
Step 4: Grade the Wetland to Final Elevations (e.g., peninsulas)
Step 5: Provide Standing Time for the Wetlands
Step 6: Stake Planting Depths and Create Internal Features
Step 7: Propagate the Stormwater Wetland
Step 8: Reforest the Wetland Fringe/Buffer Area and Install Tree Clusters
Step 9: Install Reinforcement Plantings
Step 10: Inspect Wetland Cells Annually to Control Invasive Species
Step 11: Thin and Harvest Woody Growth

Adapting Stormwater Wetland Designs for Special Climates, Terrain and Other Conditions

The new stormwater wetland design concepts presented in this paper were primarily developed for rolling terrain in humid and temperate climatic regions. Designers will need to adapt them to reflect special conditions in other regions. Some key adaptations to consider are provided below:

Cold Climates: Wetland performance decreases when snowmelt runoff delivers high pollutant loads. Shallow constructed wetlands can freeze in the winter, which allows incoming runoff to flow over the ice layer and exit without full treatment. In addition, inlet and outlet structures may also freeze, further diminishing wetland performance. Salt loadings are also higher due to winter road maintenance. High chloride levels have a detrimental effect on native wetland vegetation, and can shift the wetland community to more salt tolerant species such as cattails and *Phragmites* (see Article 1 for complete review of studies). Several design adaptations can improve winter time performance, including:

- Treat larger runoff volumes in the spring by adopting seasonal operation of the permanent pool (MSSC, 2005)
- Select salt-tolerant tree and emergent wetland plants within the wetland.
- Do not submerge inlet pipes and provide a minimum 1% pipe slope to discourage ice formation
- Locate low flow orifices so they withdraw at least six inches below the expected ice layer
- Angle trash racks to prevent ice formation
- Increase forebay size if road sanding is expected in the wetland’s contributing drainage area

Arid and Semi-Arid Climates: Constructed wetlands are hard to establish in regions with low annual rainfall and high evapotranspiration rates. These climates make it difficult to establish a constant pool elevation throughout the year. Designers should check to see whether an adequate water balance to support the wetland during dry periods, otherwise the risk of variable water elevations, algal blooms and odors increases sharply. When in doubt, install clay or geosynthetic liners to prevent water loss via infiltration. Also, keep in mind that wetland vegetation will flourish, given the warm temperatures and long growing season, so consider regular mowing or harvesting to keep wetland growth in check. Designers should also check with wetland scientists whether there is a reference forested wetland community in their region, and if not, switch to an emergent wetland design.

Karst Terrain: Even shallow pools in active karst regions can increase the risk of potential sinkhole formation and groundwater contamination, so designers should conduct geotechnical investigations to assess this risk. Designers may choose to employ an impermeable liner for the wetland and maintain three feet of vertical separation from the underlying karst layer.

Flat Terrain: Stormwater wetlands built in the flat terrain of the coastal plain or similar areas pose special design challenges, given the low head available and the proximity of the water table to the surface. In general, the wooded wetland design is preferred over the emergent wetland/pond design. The basic design approach is to expand on the current ditch system to create a series of linked shallow wetland cells, and thereby minimize head loss through the system. Both off-line and on-line cells can be employed, with the goal of linking 5 to 10 cells together like a bead on a string. It may also be advisable to install a few submerged gravel cells in the wetland string to promote seasonal denitrification. Figure 19 shows an example of such a system from Delaware.

Figure 19. Aerial view and on-site photo of a tax ditch restored to a wetland system in Delaware (photo of left courtesy of Delaware Department of Natural Resources and Environmental Control)

Trout Streams: The wooded wetland design is clearly preferred to minimize downstream warming. Deep pools and extended detention should be avoided, and designers should strive to maximize forest canopy over the wetland.

Sandy Soils: If the proposed site has an infiltration in excess of one inch per hour, the designer should re-evaluate the need for a stormwater wetland, and investigate how to utilize natural infiltration available at the site. In some cases, this may involve a two-cell design, where a small, on-line stormwater wetland is used for pretreatment, and runoff is then diverted into an off-line wooded infiltration area.

Maintenance

Unlike natural wetlands, stormwater wetlands are not self-maintaining. They require active maintenance over their entire lifespan, but more so during the first few years. A unique aspect of stormwater wetland maintenance is the need to actively manage the vegetation to ensure that the desired plant community is established. The overall approach is to plan for succession and work towards a diverse native plant community that provides high quality habitat.

During wetland design, a long-term vegetation management plan should be developed, typically on the order of 10 years. The plan should address needed vegetation management activities that will take place immediately after planting as well as those that will take place each year after wetland startup. A maintenance agreement should be secured to ensure that vegetation management is performed on a routine basis by a qualified professional (e.g., a wetland ecologist). Approximately ten percent of the project budget should be allocated to vegetation management.

Vegetation management should include care of existing desirable vegetation (watering, pruning, thinning), supplemental plantings, and management of invasive species or other unwanted plants. During the early stages of wetland succession, tree shelters may be needed to protect seedlings from mowers and deer. In embankment and maintenance access areas, Integrated Vegetation Management (IVM) is recommended, which entails maintaining low-growing vegetation (e.g., 6 ft high) through mowing, hand removal of vegetation, or selection spraying (with herbicide approved for aquatic use) of individual trees in early growing stages (Genua, 2000). Wetland side slopes should not be mowed, if at all possible.

In addition to vegetation management, routine inspection and maintenance is necessary for a stormwater wetland to operate as designed on a long-term basis. The pollutant removal, channel protection, and flood control capabilities of the wetland system will decrease if wetland pool elevations fluctuate dramatically, debris blocks the outlet structures, pipes and risers are damaged, invasive plants out-compete native wetland plants, sediment accumulation reduces storage capacity or the structural integrity of the embankment, weir, or riser is compromised.

Stormwater wetland maintenance activities range in terms of the level of effort and expertise required to perform them. Routine stormwater wetland maintenance, such as mowing and removing debris or trash, is needed multiple times each year, but can be performed by citizen volunteers. More significant maintenance, such as removing accumulated sediment, is needed less frequently but requires more skilled labor and special equipments. Inspection and repair of critical features such as embankments and risers, needs to be performed by a qualified professional that has experience in the construction, inspection and repair of these features. CWP (2004) contains guidance on wetland maintenance, while Attachment D provides links to some excellent regional resources on stormwater wetland maintenance.

Summary

This article presented two new modifications of classic stormwater wetland designs to provoke thought and dialogue on how to improve the performance and other benefits of stormwater wetlands. It is the authors' hope that the design community will continue to improve on these and put them in the ground to see how they work. Again, the reader is cautioned not to turn these conceptual designs into new stormwater treatment practice (STP) specifications without additional comment from stormwater engineers and other practitioners.

One of the major barriers to innovation in the design of STPs is the "pipeline problem," whereby it can take up to seven years to adopt new design criteria, go through the design and approval process on an individual development site, wait for the practice to stabilize after construction, instrument the site for monitoring, and then conduct the requisite minimum of two years of monitoring to determine its actual performance. This means that it might not be until 2015 that we can definitively describe the performance and functions of the new emergent pond/wetland and wooded wetland systems proposed in this article. The key question is how to compress the design-construction-testing pipeline so stormwater managers can have greater confidence in adopting the new stormwater wetland approaches. Several strategies are proposed to achieve this objective in a more rapid fashion.

1. Construct prototype wetland designs as retrofits on public land over the next two years. Utilize a technology incentive grant program to provide funds for design, construction and monitoring.

2. Immediately monitor the pollutant removal and runoff reduction performance of existing Regenerative Stormwater Conveyance systems installed by Underwood and Associates in Anne Arundel County, Maryland and other stormwater wetlands that are similar in design to the prototype wetland designs described here.

3. Conduct a cross-sectional survey of older stormwater wetlands (aged ten years or more) or dry ED ponds that have accidentally evolved into stormwater wetlands over time following the methods outlined in Law et al. (2008). By studying a large population of these facilities, it may be possible to identify both emergent and forested wetland species that flourish over time, take sediment cores to measure rates of nutrient accumulation and look to see how groundwater elevations have changed over time due to the stormwater treatment. The same population can be scrutinized to identify design features that improve longevity or cause maintenance problems. This information can be used to further improve the designs so they can be implemented with greater confidence in their success.

4. Continue to research the pollutant removal processes that take place in stormwater wetlands to better inform the new designs.

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Attachment A: Wetland Glossary

Emergent wetland: A type of natural or stormwater wetland characterized by aquatic plants that are rooted in the sediment but whose leaves are at or above the water surfaces. These plants grow in water depths of one to eighteen inches.

Ephemeral wetland: a type of natural wetland that temporarily holds water in the spring and early summer or after heavy rains. These wetlands have no permanent inlet or outlet and often dry up in mid to late summer.

Extended detention wetland: a stormwater wetland design where the total treatment volume is equally split between shallow marsh and temporary detention of runoff above the marsh. The extra runoff is stored for up to 24 hours to allow pollutants in stormwater to settle out.

Forested wetland: a type of natural or stormwater wetland that is typified by mixed structure of trees, shrubs, and herbaceous plants that is frequently found along floodplains and river bottoms.

High marsh: pondscaping zone within a stormwater wetland that exists from the surface of the normal pool to a depth of six inches. The high marsh zone typically has the greatest diversity and density of emergent wetland plants

Low marsh: pondscaping zone within a stormwater wetland that extends from 6 inches to 18 inches below the normal pool. The low marsh zone is suitable for the growth of several emergent wetland species.

Mitigation wetland: Constructed wetlands that are created to compensate for the loss of natural wetlands under the criteria established by federal, state or local permitting authorities. A primary goal is to replicate the species diversity ecological functions and the general type of the lost wetland.

Natural wetland: Areas in the landscape where water is the primary factor controlling the environment and the associated plant and animal life. Natural wetlands are transitional habitats between upland and aquatic environments where the water table is at or near the surface of the land, or where the land is permanently or temporarily inundated by shallow water.

Planting peninsula: earthen planting areas in a stormwater wetland that are elevated above the permanent pool and provide space for planting trees. Peninsulas are located to extend the length of the flowpath and may extend all the way across the wetland using a seepage feature to allow flowthrough if desired.

Pocket wetland: a stormwater wetland design adapted for small drainage areas with no reliable source of baseflow. Pocket wetlands often have a surface area of a tenth of an acre or less, and provide pollutant removal at very small development sites.

Pond/wetland system: a two cell stormwater wetland design that utilizes a wet pond in combination with a shallow marsh

Pondscaping: a technique that utilizes native trees, shrubs, herbaceous plants and wetland species to meet specific functional design objectives within a stormwater wetland. Species are selected for use in various planting zones based on their relative tolerance for inundation/soil saturation.

Shallow marsh: a stormwater wetland design that emphasizes the use of extensive areas of low and high marsh to promote the removal of pollutants in urban stormwater

Stormwater wetland: a constructed shallow pond system that creates suitable growing conditions for wetland plants and is explicitly designed to maximize pollutant removal from urban stormwater runoff.

Tree clusters: A series of interconnected planting holes located on stormwater wetland or pond side slopes. Tree clusters are used to allow trees to share rooting space, which may be limited in compacted side slopes. Species for clusters are selected based on relative tolerance to inundation/soil saturation and the planting elevation.

Wastewater wetland: A constructed wetland that is explicitly designed to remove pollutants from wastewater.

Wetland mulching: technique for rapidly establishing stormwater or mitigation wetland whereby the top few inches of a “donor” natural wetland soils are spread over the surface of the constructed wetlands. The seedbank in the wetland soil is used.

Wooded wetland: a stormwater wetland design that emphasizes the use of trees in combination with areas of high and low marsh to maximize removal of pollutants in urban stormwater and enhance habitat diversity.

Attachment B: Supplemental Pondscaping Specifications for Wetlands in the Mid-Atlantic Region

A pondscaping plan is required for any stormwater wetland and should be jointly developed by the engineer and a wetlands expert or experienced landscape architect. The final pondscaping plan is not produced until after the stormwater wetland has been constructed. This allows the designer to select appropriate species and soil amendments based on field confirmation of soils properties and existing moisture/inundation conditions at the site. In some cases, the planting of the pondscape may not occur until one year after the stormwater wetland has been constructed. In the interim, the designer can establish the actual depths and inundation frequencies experienced by the wetland, and therefore, develop a more effective plan. Second, the pondscaping plan outlines a detailed program for the care, maintenance and possible reinforcement of the pondscape for up to ten years after the original planting. The pondscaping plan can be developed through an 11 step process, as outlined below:

Step 1: Prepare the Final pondscaping and grading plans for the wetland.

At this stage the engineer, landscape architect, and wetland expert work jointly to prepare a pondscaping and grading plan for the wetland. It is also an appropriate time to order the wetland plant stock from aquatic nurseries, since up to six to nine months lead time may be need to fill order for all the required plant stock.

Step 2: Grade the Wetland to Interim Elevations

Once the basic excavation of the stormwater wetland has been completed, it is time to create the major topographic features within the wetland, such as wedges, benches, peninsulas, and deepwater channels. A skid loader or other excavator can be used to form the internal complexity within the wetland. These topographic features can only be added while working in the “dry.” Spot surveys should be made to ensure that the interim elevations are three to six inches below the final elevations for the wetland (see Step 3).

Step 3: Add Topsoil/Wetland Mulch Amendments

Since most stormwater wetlands are excavated to deep sub-soils, they often lack the nutrients and organic matter needed to support vigorous growth of wetland plants. It is therefore essential to add sand, compost, topsoil or wetland mulch to all depth zones in the wetland. The importance of soil amendments in excavated wetlands cannot be over-stressed; poor survival and future wetland coverage are likely if these soils are not added (Bowers, 1992). Fertilizers and other soil amendments are not needed if topsoil or wetland mulch are used. The original topsoil should be stockpiled during construction of the wetland so that it can be used as a 3 to 6 inch amendment during the pondscaping. In addition, the seedbank within the topsoil can add considerable diversity to the pondscape, as well as the mycorhyzzial bacteria that are documented to dramatically enhance the growth and survivability of the plants.

Step 4: Grade the Wetland to Final Elevations

After topsoil or wetland mulch has been added to the stormwater wetland, it is time to grade the wetland to its final elevations. This is normally done by "roughing up" the interim elevations with a skid loader or other equipment to achieve the desired microtopography across the wetland. All wetland features above the normal pool should be temporarily stabilized by hydroseeding or seeding over straw.

Step 5: Provide Standing Time for the Wetland

Once the final elevations are attained, the pond connection should be opened to allow the wetland cell to fill up to the normal pool. In most cases, nothing should be done in the stormwater wetland for six to nine months (or until the next March to June planting season). This standing time is needed so that the designer can more precisely predict a) where the pondscaping zones are located in and around the wetland, and b) whether the final grade and wetland microtopography will persist over time.

Step 6: Stake Planting Depths and Create Internal Features

The stormwater wetland is surveyed and staked at the onset of the planting season. Depths in the wetland should be measured to the nearest inch to confirm the original planting depths of the planting zone. At this time, it may be necessary to modify the pondscape plan to reflect altered depth or the availability of wetland plant stock. Surveyed planting zones should be marked on the as-built or design plan, and also located in the field using stakes or flags.

Step 7: Propagate the Stormwater Wetland

Three techniques are used in combination to propagate the emergent community over the wetland bed:

- *Initial planting of container grown wetland plant stock* The transplanting window extends from early April to mid-June. Planting after these dates is quite chancy, as emergent wetland plants need a full growing season to build the root reserves needed to get through the winter. If at all possible, the plants should be ordered at least six months in advance to ensure the availability of desired species. Five to seven species of emergent wetland plants should be planted, including three emergent species selected from the "aggressive colonizer" group suggested by Athanas (1986 and 1992): duck potato, common three-square and soft-stem bulrush. Additional species noted as reliable colonizers of stormwater wetlands by Hunt et al (2007) that may be substituted include: pickerelweed, broadleaf arrowhead, bur-reed, Lizard's tail, woolgrass, sedges, and the common rush. The remaining four species should be chosen to add diversity to the wetland. Species such as swamp milkweed, blue flag iris, cardinal flower, rose mallow, and Joe-pye weed are good candidates and often survive in stormwater wetlands according to Hunt et al. (2007). No more than 25% of the wetland surface area need be planted. If the appropriate planting depths are achieved, the entire wetland should be colonized within three years. Individual plants should be planted 18 inches on center within each single species "clump." After the second growing season, reinforcement plantings may be needed to expand the spatial coverage of the wetland.

- *Broadcasting Wetland Seed Mixes*: The higher wetland elevations should be established by broadcasting wetland seed mixes to establish diverse emergent wetlands. Seed information for Northeastern wetland species has been prepared by Garbisch and McIninch (1992). Seeding of switchgrass or Envirens wet-mix as a ground cover is recommended for all zones above three inches below the normal pool. Hand broadcasting or hydroseeding can be used to spread seed depending on the size of the wetland cell

- *Allowing "volunteer" wetland plants to establish on their own*. The remaining areas of the stormwater wetlands will eventually be colonized by volunteer species from upstream or the forest buffer within 3 to 5 years.

Step 8: Reforest the Wetland Fringe/Buffer Area

The wetland fringe/buffer area generally extends from 1 to 3 feet above the normal pool (from the shoreline fringe to about half of the maximum 2 year storm water surface elevation) and may include specific features such as planting peninsulas, depending on wetland design. Consequently, plants in this zone are infrequently inundated (5 to 10 times per year), and must be able to tolerate both wet and dry periods. Deeper-rooted trees and shrubs that can extend to the stormwater wetland's local water table do very well in this area. See Box 8 for recommended tree and shrub species for stormwater wetlands in the Mid-Atlantic region.

A good planting strategy includes varying the size and age to promote diverse structure. Locally grown container or bare root (if planting in Spring) stock is usually most successful. It is recommended that planting areas be overplanted with small stock of fast-growing successional species to achieve canopy closure quickly and shade out invasive plant species. Trees may be planted in clusters if desired to allow for shared rooting space. This is especially helpful on wetland side slopes, whose extremely compacted soils make root establishment difficult. A layer of tree and shrub seed may be applied (at triple the rate recommended by the manufacturer) to further vary the age range. Planting holes should be amended with compost (2:1 ratio of loose soil to compost) before planting. It is recommended that the buffer area extend outward 50 feet from the wetland and achieve 80% canopy coverage. See Cappiella et al. (2006a) and (2006b) for more on planting trees in stormwater wetlands.

Step 9: Install Reinforcement Plantings

Regardless of the care taken during the initial planting of wetland and buffer it is probable that some areas will remain unvegetated, and some species will not survive. Poor survival can result from many unforeseen factors, such as predation, poor plant stock, changes in water levels, drought, and many other unpredictable factors. Thus, it is advisable to plan (and budget) for an additional round of reinforcement planting after one or two growing seasons. The records on wetland plant species distribution collected during routine inspections are invaluable to guide plant selection for the reinforcement planting.

Step 10: Inspect Wetland Cells Annually to Control Invasive Species

It may become necessary to control undesirable invasive species, such as cattail and Phragmites over time in the wetland cell. Hunt et al. (2007) recommend removal of the majority (if not all) cattails from stormwater wetlands in residential or commercial areas if cattails colonize more than 15% of the wetland, due to concerns about mosquitoes. Although the application of herbicides is not recommended, some types, such as Glyphosate, have been used to control cattails with some success. Extended periods of dewatering may also work, as can early manual removal provides only short-term relief from invasive species. While it is difficult to exclude invasive species from stormwater wetlands, their ability to take over the entire wetland can be reduced if the designer creates a wide range of depth zones and complex internal structure within the wetland.

Step 11 Thin and Harvest Woody Growth

Thinning or harvesting of excess woody growth may be periodically needed to guide the forested portions of the wetland (e.g., the buffer or side slopes) into a more mature state. These operations should be conducted five and ten years after initial wetland construction. Removal of woody species near the embankment or maintenance access areas may also be needed on an annual basis. Integrated Vegetation Management may be used for this purpose.

Attachment C: Regional Wetland Plant Lists and Resources

Northeast

Thunhorst, G.A. 1993. Wetland Planting Guide for the Northeastern United States: Plants for Wetland Creation, Restoration and Enhancement. Environmental Concern, Inc. St. Michaels, MD.

G.E. Crow and C.B. Hellquist. 2006. Aquatic and Wetland Plants of Northeastern North America. Volume 1. Pteridophytes, Gymnosperms, and Angiosperms: Dicotyledons. University of Wisconsin Press. Madison, WI.

G.E. Crow and C.B. Hellquist. 2006. Aquatic and Wetland Plants of Northeastern North America. Volume 2. Angiosperms: Monocotyledons. University of Wisconsin Press. Madison, WI.

Tiner, R.W. 1987. A Field Guide to Coastal Wetland Plants of the Northeastern United States. University of Massachusetts Press. Amherst, MA.

Mid-Atlantic trees and shrubs that tolerate semi-permanent to permanent inundation or saturation (76% to 100% of growing season). Source: Thunhorst, 1993			
Tree or Shrub	**Flood Tolerance**		
	Duration	**Depth**	**Notes**
Buttonbush	Inundated or saturated up to 100% of GS	Up to 3 feet	
Virginia sweetspire	Inundated or saturated 13% to 100% of GS	Up to 0.5 feet	
Marsh elder			Found in tidal zone near mean high water and above to upland
Streamco willow	Inundated or saturated 26% to 100% of GS		
Atlantic white cedar	Inundated or saturated up to 100% of GS, with fluctuating water table depth		
Bald cypress	Inundated or saturated up to 100% of GS		Seedlings cannot tolerate long periods of inundation during GS

Mid-Atlantic trees and shrubs that tolerate regular inundation or saturation (26% to 75% of growing season). Source: Thunhorst, 1993

Tree or Shrub	Flood Tolerance		
	Duration	Depth	Notes
Smooth alder	Inundated or saturated 13% to 75% of GS	Up to 3 inches	
Groundsel tree	Inundated or saturated 13% to 75% of GS	Up to 0.5 feet	
Sweet pepperbush	Frequent temporary inundation 13% to 75% of GS		
Fetterbush	Inundated or saturated 13% to 75% of GS		Needs intervals of dry-down
Wax myrtle	Inundated 26% to 75% of GS		
Swamp azalea	Inundated or saturated 13% to 75% of GS		
Swamp rose	Saturated up to 75% of GS		
Box elder	Frequent temporary inundation up to 75% of GS		
Gray birch	Frequent temporary inundation up to 75% of GS		
Green ash	Frequent temporary flooding up to 75% of GS		
Sweetgum	Inundated or saturated up to 75% of GS		
Loblolly pine	Inundated or saturated up to 50% of GS		Needs intervals of dry-down
Black willow	Inundated or saturated up to 75% of GS		Needs intervals of dry-down
Northern white cedar	Saturated 13% to 75% of GS		

Southeast

Garber, M.P. and D.J. Moorhead. 1999. Selection, Production and Establishment of Wetland Trees and Shrubs. University of Georgia Cooperative Extension Service. Athens, GA.

Tiner, R.W. 1993. Field Guide to Coastal Wetland Plants of the Southeastern United States. University of Massachusetts Press. Amherst, MA.

Godfrey, R.K. and J.W. Wooten. 1981. Aquatic and Wetland Plants of Southeastern United States: Dicotyledons. University of Georgia Press. Athens, GA.

Godfrey, R.K. and J.W. Wooten. 1979. Aquatic and Wetland Plants of Southeastern United States: Monocotyledons. University of Georgia Press. Athens, GA.

Hunt, W. F., and B. A. Doll. 2000. Urban Waterways. Designing Stormwater Wetlands for Small Watersheds. North Carolina Cooperative Extension.

Trees and Shrubs for Stormwater Wetlands in North Carolina (from Hunt and Doll 2000)		
Wetland Zone	**Trees**	**Shrubs**
Deep pool (> 2.5' deep)	Bald cypress	N/A
Shallow water (0" – 12" deep)	Atlantic white cedar Bald cypress Black willow Overcup oak Swamp tupelo Water tupelo	Sea ox-eye Swamp dog-hobble Swamp rose
Shallow land (0" – 12" above water)	Black willow Green ash Pond pine River birch Sweetbay Water oak Willow oak	Buttonbush Coastal dog-hobble Elderberry

North Central

Shaw, D. and R. Schmidt. 2003. Plants for Stormwater Design: Species Selection for the Upper Midwest. Minnesota Pollution Control Agency. St. Paul, MN.

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Recommended Trees for Stormwater Wetlands in the Upper Midwest (Shaw and Schmidt, 2007)	
Wetland Zone	**Recommended Species**
Submergent zone (1.5 to 6 feet of water)	None
Emergent zone (0-18 inches of water)	Buttonbush
Wet meadow zone (permanent moisture)	indigo bush, shrubby cinquefoil, Bebb's willow, shining willow, black willow, red-berried elder
Floodplain zone (flooded during snowmelt/large storms)	red maple, silver maple, speckled alder indigo bush, black chokeberry, river birch, hackberry, buttonbush, silky dogwood, red-osier dogwood, black ash, green ash, ninebark, eastern cottonwood, swamp white oak, bur oak, Bebb's willow, pussy willow, sandbar willow, shining willow, black willow, American elderberry, red-berried elder, meadowsweet, American basswood, American elm, nannyberry, highbush cranberry

Inundation Tolerance of Trees and Shrubs of the Upper Midwest (from Shaw and Schmidt, 2003)				
Name	**Normal Water Level**	**Inundation Tolerance**		
		Frequency	**Depth**	**Duration**
Silver maple	S	Mod	60	L20
Speckled alder	M-S (6)	High	24	L6
Black chokeberry	M-S	Mod	12	S 2
River birch	M-S	High	60	L5
Hackberry	M-D	Mod	60	L5
Buttonbush	S-I (36)	Mod	24	L 45+
Silky dogwood	M-S	Low	36	L 30+
Gray dogwood	D-S	Mod	6	S 2
Red-osier dogwood	M-S	Mod	36	L 30+
Black ash	M-S	High	60	L5
Green ash	M-S	High	60 (spring) 24 (summer)	L 10 (spring) ML 4 (summer)
Winterberry	M-S	Mod	18	MS 3
Tamarack	M-S	Low	12	L 5
Ninebark	D-S	Mod	18	MS 3
Eastern cottonwood	M-S	High	60	L 30
Quaking aspen	M-D	Low	18	MS 3
Swamp white oak	M-S	Mod	60	L 15
Pussy willow	S-I (6)	Mod	24	L6
Red maple	M	High	60	L 20
Indigo bush	M-D	High	18	MS 3
Shrubby cinquefoil	D-S	High	30	L 6
Bebb’s willow	M-S	High	48	L 8
Shining willow	M-S	High	48	L 8
Bur oak	S-D	High	48	L 6
American elderberry	M-S	High	48	L 8
American basswood	M	High	24	MS 3
Sandbar willow	S-I (6)	High	36	L 30+
Black willow	S	High	60 (spring) 24 (summer)	L10 (spring) ML4 (summer)
Red-berried elder	M	Mod	18	MS 3
Meadowsweet	S-I (3)	Mod	18	L 5
Nannyberry	M-S	Mod	18	MS 3
High bush cranberry	M-S	High	18	MS 3
American elm	M-S	High	60	L 25
Northern white cedar	M-S	High	24	ML 4

Key:
Normal Water Level: S = saturated soils, M = moist/mesic soils, I = inundation, D = dry soils. Depth of inundation normally tolerated may be indicated in ( )
Frequency: refers to the frequency of inundation (low, moderate, or high) the species can handle without significant stress.
Depth: depth of inundation in inches the species can handle for the time period listed under Duration.
Duration: H = high, ML = medium long, MS = medium short, S = short. Followed by number of days.
Note: for some species, the depth notes cannot be tolerated for the entire duration listed – the species can tolerate some level of flooding for that duration but it is assumed the depth will slowly decrease over time.

North Plains

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Larson, G.E. 1993. Aquatic and Wetland Vascular Plants of the Northern Great Plains. General Technical Report RM-238, Fort Collins, CO: U.S. Dept. Agriculture, Forest Service, Rocky Mountain Forest and Range Expt. Station, 681 pp.

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South Plains

Haukos, D.A., L.M. Smith. 1997. Common Flora of the Playa Lakes. Texas Tech University Press. Lubbock, TX

Southwest

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Northwest

City of Portland. 2003. Portland Plant List.

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Hawaii

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Attachment D: Links to Maintenance Specifications

Maintenance Specifications for Stormwater Wetlands			
State/Province	**Manual**	**Year**	**Website**
California	New Development and Redevelopment Stormwater Best Management Practice Handbook	2004	http://www.cabmphandbooks.com/Development.asp
Denver, Colorado	Urban Storm Drainage Criteria Manual	2001	http://www.udfcd.org/downloads/down_critmanual.htm
Connecticut	2004 Connecticut Stormwater Manual	2004	http://dep.state.ct.us/wtr/stormwater/strmwtrman.htm#download
Georgia	Georgia Stormwater Management Manual	2001	http://www.georgiastormwater.com/
Maryland	Maryland Stormwater Design Manual	2000	http://www.mde.state.md.us/Programs/WaterPrograms/SedimentandStormwater/stormwater_design/index.asp
Minnesota	Minnesota Stormwater Manual	2005	http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html
New Jersey	New Jersey Stormwater Best Management Practices Manual	2004	http://www.njstormwater.org/bmp_manual2.htm
New York	New York State Stormwater Management Design Manual	2003	http://www.dec.state.ny.us/website/dow/toolbox/swmanual/index.html
North Carolina	Draft Stormwater BMP Manual	2005	http://h2o.enr.state.nc.us/su/bmp_updates.htm
Ontario	Stormwater Management Planning and Design Manual	2003	http://www.ene.gov.on.ca/envision/gp/4329eindex.htm
Eugene, Oregon	Stormwater Management Manual	2006	http://www.eugene-or.gov/portal/server.pt?open=512&objID=687&PageID=1776&cached=true&mode=2&userID=2
Portland, Oregon	Stormwater Management Manual	2004	http://www.portlandonline.com/bes/index.cfm?c=dfbbh
Pennsylvania	Draft Pennsylvania Stormwater Best Management Practices Manual	2006	http://www.dep.state.pa.us/dep/subject/advcoun/Stormwater/stormwatercomm.htm
Austin, Texas	City of Austin, Texas Environmental Criteria Manual	2007	http://www.ci.austin.tx.us/watershed/stormwater_treatment.htm
Vermont	Vermont Stormwater Management Manual	2002	http://www.anr.state.vt.us/dec/waterq/stormwater.htm
Western Washington	Stormwater Management Manual for Western Washington	2005	http://www.ecy.wa.gov/programs/wq/stormwater/manual.html
N/A	Pond and Wetland Maintenance Guidebook	2004	http://www.stormwatercenter.net/Manual_Builder/Maintenance_Manual/introduction.htm