Stormwater Wetlands and Ecosystem Services

While they improve water quality and mitigate flooding, stormwater wetlands provide other ecosystem services *that have economic, social, and ecological value. Wetland design and implementation can enhance these services and increase a stormwater wetland's value to the nearby community.*

The use of stormwater wetlands throughout North Carolina has grown in the past decade. The principal drivers for the increased use are documented improvements in water quality and the state's crediting of the nitrogen removal benefits that stormwater wetlands provide. In addition to water quality improvement and flood mitigation, constructed stormwater wetlands provide other benefits or *ecosystem services*. In this design bulletin, we discuss the concept of ecosystem services and review how stormwater wetlands provide many of these services. We also describe how wetland design can enhance the provision of ecosystem services.

WHAT ARE ECOSYSTEM SERVICES?

The term *ecosystem services* refers to any of the benefits that ecosystems—both natural and seminatural—provide to people (MEA, 2005). These services include food and raw material provision, air and water purification, biodiversity maintenance, and aesthetic and other cultural benefits. Ecosystem services are products of the structure (for example, plant and animal community composition) and processes (such as nutrient cycling and decomposition) that characterize an ecosystem. These services can be ascribed economic, social, and ecological values. Ideally, the inherent value of these services will guide management and policy decisions regarding the use and preservation of ecosystems (Figure 1). The concept of ecosystem services was introduced in the early 1970s. Since then, investigations into how our health depends on properly functioning ecosystems have surged, as have attempts to assign monetary values to ecosystem services. In one of the most widely cited ecosystem service valuation studies, Costanza et al. (1997) estimated the value of the services provided by Earth's ecosystems to be at least $33 trillion per year. (For comparison, the global gross national product when Costanza et al. conducted their study was $18 trillion.) Of the types of ecosystems included in the study, the services provided by wetlands were among the most valuable, with a global average value of $6,000 per acre. A brief summary of the services provided by natural and created wetland ecosystems is provided in Table 1, along with the economic value of these services as estimated by Costanza et al. (1997), where applicable.

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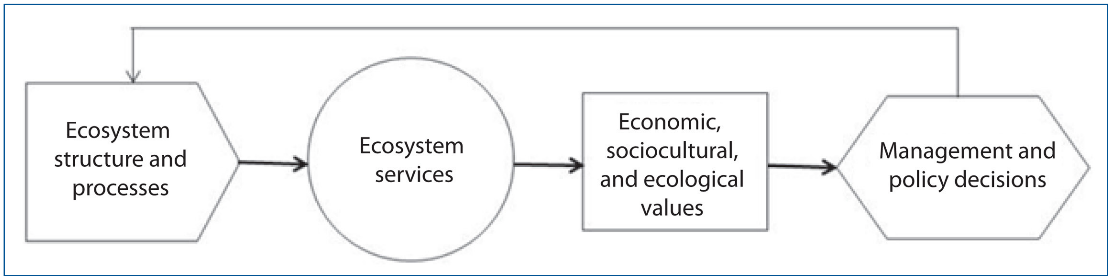

Figure 1. Relationship between ecosystem services, structure, and processes, and their value in decision making (Adapted from de Groot, 2002).

Table 1. Ecosystem services provided by natural and created wetlands[1]

Service	Examples of Goods and Services Derived	Estimated value (1994 US $/$ac^{-1}$ yr^{-1})[a]
REGULATION SERVICES		
Water quality		
Erosion control and sediment retention	Sediment filtration and storage capabilities that prevent downstream migration of sediment and improve downstream water quality.	NA
Waste treatment	Reduction of excess nutrient, organic, and metal loadings reduced through microbial degradation and/or sorption to improve water quality. Reduction of runoff temperature via shading and water's heat capacity.	1,690
Nutrient cycling	Reduction of nitrogen and phosphorus concentrations through denitrification and biological uptake.	NA
Hydrologic regulation	Moderation of the rate, volume, and frequency of surface runoff to provide flood and storm surge protection.	1,860
Climate regulation		
Greenhouse gas regulation	Maintenance of air quality and CO_2/CH_4 balance (through C sequestration); regulation of gases also influences climate effects.	54
Microclimate regulation	Maintenance of a favorable climate (such as temperature, precipitation) for human habitation, health, and cultivation.	NA
Soil formation	Building of land surface through the accumulation of organic material in wetlands.	NA
HABITAT SERVICES		
Refugia	Maintenance of biological and genetic diversity through provision of suitable habitat for resident or migratory plant and animal species. Includes the maintenance of populations of commercially harvested species and biological pest control services. This diversity forms the basis of many other ecosystem services.	123
PRODUCTION SERVICES		
Food production	Production of fish, game, fruits for small-scale hunting/gathering or aquaculture.	104
Raw materials	Production of trees, peat, and other biomass appropriate for lumber, fuel, or fodder.	43
INFORMATION SERVICES		
Recreation	Provision of opportunities for hunting, bird-watching, hiking, or other recreational uses.	232
Cultural	Provision of opportunities for noncommercial uses, including the use of wetlands for school excursions/education and for scientific research. Aesthetic, artistic, and spiritual values are also included.	357

[1]Adapted from Costanza et al., 1997, and de Groot, 2006)

[2]Value estimates for each service taken from Costanza et al. (1997). A listing of NA for individual services indicates that a formal valuation of this service had not yet been conducted.

ECOSYSTEM SERVICES AND STORMWATER MANAGEMENT

As land is developed for residential and commercial use, its ability to provide ecosystem services diminishes. This is particularly evident in urban areas, which are characterized by reduced flood and climate regulation ability, poor air and water quality, and a loss of native biodiversity. Ecologically engineered stormwater best management practices (BMPs), however, can help to restore the landscape's ability to provide some of these services. Because many of the services provided by these engineered systems have tangible economic value, developers and municipalities alike can benefit by selecting stormwater practices based on the suite of ecosystem services they provide. Additionally, space limitations in urbanizing areas magnify the need to design stormwater BMPs that provide flows of multiple services – such as carbon sequestration, biodiversity, and recreation and education opportunities – in addition to runoff quantity and quality management.

STORMWATER WETLANDS AND ECOSYSTEM SERVICES

Among stormwater BMPs, stormwater wetlands have the potential to provide a great quantity and quality of ecosystem services. Indeed, naturally-occurring and created wetland ecosystems made up the most valuable terrestrial ecosystem service providers included in Costanza et al.'s (1997) economic review. In the following sections, we describe how wetlands, and specifically constructed stormwater wetlands, have the potential to provide the regulation, habitat, production, and information services summarized in Table 1.

REGULATION SERVICES

Water treatment

Water treatment services comprise perhaps the most widely recognized service provided by stormwater wetlands, and much of stormwater wetland design is geared to drive water quality benefits. As noted in Table 1, water-quality-related services include waste treatment, nutrient cycling, and erosion control via sediment and stormwater retention. Although naturally-occurring wetlands have provided water treatment services since the beginning of civilization, the use of constructed wetlands as low-cost alternatives to fossil-fuel-driven treatment technologies was not adopted in the United States until the 1970s for wastewater treatment and until the 1980s for stormwater treatment (Cappiella et al., 2008). In some NC communities, constructed stormwater wetlands have become one of the most, if not *the* most, common structural stormwater control practice. Wetlands remove and transform pollutants through a combination of physical, chemical, and biological processes. These complementary processes, which include sedimentation, filtration, adsorption, chemical precipitation, microbial transformation, and biological uptake, are summarized by Hunt and Doll (2000) in *Designing Stormwater Wetlands for Small Watersheds* (AG-588-2), a publication in the Urban Waterways series published by NC Cooperative Extension.

Nitrogen and other organic constituents are removed from runoff primarily through the work of bacteria and microfilms living in association with wetland plants and sediments. The unique juxtaposition of aerobic and anaerobic environments within wetland soils, combined with an abundant supply of organic material, creates an ideal environment for microbial denitrification. High removal rates for nitrate (80 percent) and total nitrogen (60 percent) have been observed from stormwater wetland systems in North Carolina (Hathaway and Hunt, 2010). Substantial phosphorus removal and total suspended sediment (TSS) removal by stormwater wetlands have also been documented. Recently, researchers investigated runoff temperature reductions by stormwater wetlands, a service particularly beneficial in the state's trout-sensitive watersheds (Jones and Hunt, 2010). Ranges of reported pollutant concentration removal rates are displayed in Table 2 to demonstrate a stormwater wetland's capacity to treat stormwater for a variety of pollutants. A wetland's ability to mitigate nutrient loads (nitrogen plus phosphorus) is the principal reason for the use of constructed wetlands in North Carolina.

Table 2. Range of reported removal rates for stormwater wetlands with emergent vegetation (from Cappiella et al., 2008)

Pollutant	25th percentile	Median	75th percentile
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	40	60	85
Hydrocarbons	50	75	90
Trash/debris	75	90	95

The water quality benefits provided by a wetland are influenced by many environmental factors; however, the wetland's design also plays a major role in the system's pollutant removal capacity. Cappiella et al. (2008) stress the importance of the following design parameters in determining water quality benefits: the wetland's size relative to the target water quality volume, the surface area to volume ratio, the length of the internal flowpath, and the inclusion of a forebay. These parameters can be controlled by the designer to some extent and should be considered in the design of stormwater wetlands.

Hydrologic regulation

Due to the history of hurricane activity in North Carolina, residents here are familiar with the need for hydrologic regulation. Hydrologic regulation services include the regulation of the peak rate, volume, and frequency of surface runoff from the landscape. Researchers have identified the substantial flood control services provided by naturally-occurring wetlands within urban areas. For example, the U.S. Army Corps of Engineers opted to purchase floodplain wetlands along the Charles River to protect the city of Boston from flooding after determining that flood damages could increase by $17 million per year if the wetlands in the river basin were drained and disconnected from the river (Mitsch and Gosselink, 2007). Although smaller in scale than a corridor of floodplain wetlands, individual stormwater wetlands also serve to regulate the flashy hydrology of urban areas to some extent. This is typically accomplished through peak rate control; stormwater wetlands are usually designed to reduce peak runoff flow rates by temporarily storing a design runoff volume (typically from that of a 1-inch rainfall event) and slowly releasing it over a 48-hour period (see Hunt and Doll, AG-588-2, for more design details). Research shows that stormwater wetlands effectively reduce peak flow rates. For example, Line et al. (2008) reported median peak flow reductions of 99 and 97 percent for two stormwater wetlands in North Carolina.

Although the peak runoff rate can be controlled solely by providing an adequate storage volume and properly sized outlet orifice, runoff volume and frequency control also rely upon evapotranspiration (ET) and infiltration between runoff events. While ET can represent a major outflow pathway in stormwater wetlands, infiltration losses are often small due to high water tables or underlying soils that are compacted during construction to prevent the wetland from drying out. Consequently, surface flow wetlands are generally not considered as part of the low impact development (LID) tool palette, which emphasizes the use of infiltration-based stormwater practices. Still, depending on site and climatic conditions, stormwater wetlands can appreciably reduce the volume of runoff leaving a site. For example, a stormwater wetland in North Carolina's sandy coastal area reduced runoff volumes by 54 percent over a 10-month monitoring period (Lenhart and Hunt, 2011).

Climate regulation

Microclimate. Wetlands can play an important role in climate regulation at a local scale and may also contribute to climate regulation on a global scale. Climate regulation at the local scale is of particular interest in urban areas, where urban heat island effects may raise the temperature by as much as 5°F (3°C). Although this service has not been adequately quantified, the potential cooling effects of stormwater wetlands and other green infrastructure have been acknowledged (Bolund and Hunhammar, 2007). The primary mechanism through which stormwater wetlands may regulate the urban microclimate is ET, which occurs in both the open-water and vegetated areas of stormwater wetlands. This process consumes a great deal of heat energy, thus helping to regulate temperatures during the summer.

Global climate and carbon sequestration. Wetlands are also widely recognized for their role in regulating carbon dioxide (CO_2) and methane (CH_4), two greenhouse gases implicated as main drivers of global climate change. Wetland vegetation removes CO_2 from the atmosphere and stores it in above- and belowground tissues. When this vegetation dies, the saturated conditions typical of wetland soils create an anaerobic environment in which organic matter decomposition proceeds at a relatively slow rate, thus promoting a buildup of carbon in the soil. Through the ongoing processes of carbon accumulation and subsequent burial, naturally-occurring wetlands hold massive soil carbon stores, representing the largest component of the earth's terrestrial biological carbon pool, although they occupy less than 8 percent of the earth's surface (Mitsch and Gosselink, 2007). These functions could be heavily valued in the future with the coming of a carbon market and could provide another means for developers, landowners, and others in North Carolina to gain economic value from wetlands.

Saturated soil conditions also promote the generation of CH_4, a potent greenhouse gas. CH_4 is produced when anaerobic bacteria degrade organic matter, particularly after supplies of more energetically favorable electron acceptors, such as nitrate, manganese, iron, and sulfate, have been exhausted. Although methanogenic bacteria decompose organic matter slowly, significant quantities of methane can be evolved; when rice paddies are included, wetlands are estimated to account for about 30 percent of global methane emissions (Mitsch and Gosselink, 2007).

The balance between carbon sequestration and methane production by a wetland is difficult to quantify, and few researchers have attempted to do so. This is particularly true of constructed stormwater wetlands, for which carbon sequestration potential is just beginning to be considered. Despite the lack of quantitative data, stormwater wetlands have the potential to act as net carbon sinks. The U.S. Geological Survey (USGS) has documented significant quantities of carbon capture by wetlands constructed along the Sacramento-San Joaquin River Delta in a pilot "carbon farming" project (USGS, 2009). Though not specific to stormwater wetlands, carbon sequestration rates by created and restored wetland systems have ranged from 2.7 to 4.5 tons acre^{-1} year^{-1} (Anderson and Mitsch, 2006; Euliss et al., 2006). Other authors have noted that the carbon accumulation capacity of constructed wetlands can be high, particularly as the vegetation is establishing (Mitsch and Gosselink, 2007). Nutrient and sediment loads delivered to stormwater wetlands in urban runoff may also serve to promote carbon sequestration. Nutrients promote the growth of a productive, carbon-capturing plant community while potentially limiting methane production by encouraging the growth of denitrifying bacteria over methanogenic bacteria (Stadmark and Leonardson, 2005). Sediment deposition accelerates the burial of carbon sequestered in wetland soils while presenting the opportunity to capture carbon present in sediments washed from the landscape (McCarty et al., 2008).

Air quality regulation

Air quality is a concern in urban and urbanizing areas, especially where transportation and other activities contribute to air pollution. The effect of green infrastructure, particularly trees, on air quality in urban areas is receiving increased attention. The main process by which vegetation improves air quality is through physical filtering pollutants from the air, though local climatic changes caused by vegetation can also impact air quality. For example, model simulations by Taha (1997) indicated that if tree cover in the Los Angeles area were increased by 2 percent, the cooling effect would slow photochemical reactions and ozone production such that ambient air quality standards for ozone during peak smog conditions would be exceeded 14 percent less frequently. The air quality benefits of wetlands have not been quantified; however, a survey of urban land uses indicated that urban wetlands have the potential to provide this service (Bolund and Hunhammar, 2007). The potential for stormwater wetlands to improve air quality by filtering particulates will depend on the types of vegetation in the wetland and the ratio of vegetated area to open water.

HABITAT SERVICES

Wetlands provide habitat for a wide variety of plant and animal species, including fish, birds, amphibians, and aquatic invertebrates. Nearly all freshwater fish depend on wetlands for some part of their life cycle, often laying their eggs in a wetland's slower moving waters during spring flooding cycles (Mitsch and Gosselink, 2007). Coastal wetlands provide valuable nursery habitat for many saltwater species, a number of which are commercially harvested (MEA, 2005). Wetlands are a major provider of habitat for birds; nearly a third of North America's total resident bird population relies on wetlands for some part of its life cycle (Kadlec and Knight, 1996).

Researchers have reported that stormwater wetlands provide habitat services when designed properly and support diverse bird (Duffield, 1986), aquatic macroinvertebrate, and vegetative communities (Jenkins and Greenway, 2007) (Figure 2). However, because stormwater wetlands serve to accumulate contaminants from the urban landscape, some have questioned the value of the wildlife habitat these ecosystems provide. Sparling et al. (2004) investigated the effects of contaminant exposure on red-winged blackbirds nesting in stormwater wetlands near Washington, DC. They found that the hatching success of stormwater wetland blackbird populations compared favorably to national averages, although zinc concentrations were elevated in the tissues of birds inhabiting wetlands in industrial areas. The authors concluded that the benefits of the habitat provided by stormwater wetlands likely outweighed the negative impacts of contaminant accumulation in wildlife and that the habitat provided by stormwater wetlands may be especially valuable in urban areas where such habitat is scarce. However, the long-term effects of stormwater contaminant exposure on other wetland biota have yet to be explored.

Wetland habitat provision is crucial as the biological and genetic diversity maintained within a wetland forms the basis for most of its other ecosystem services (de Groot, 2002). For instance, a diverse plant community may contribute to improved water treatment services (Engelhardt and Ritchie, 2001; Line et al., 2008) and increase the stormwater wetland's resilience to environmental stressors, such as pollutant pulses, extreme climatic events, or disease (Hansson et al., 2005). The fish and macroinvertebrate populations supported by a

Figure 2. Stormwater wetlands can support a diverse vegetative community, as well as animals such as frogs and green herons and insects such as dragonflies.

stormwater wetland also provide a form of biological pest control to manage mosquito populations. Stormwater wetlands across North Carolina have been found to support populations of mosquitofish (*Gambusia affinis*), as well as aquatic macroinvertebrates such as water boatman, backswimmers, and dragonfly larvae, all of which prey voraciously on mosquito larvae (Hunt, Apperson, and Lord, 2005, AG-588-4). The extent to which each stormwater wetland provides habitat for terrestrial and aquatic organisms depends largely upon its location within the urban landscape and its connectivity with other natural ecosystems.

PRODUCTION SERVICES

Many of the plants and animals present in wetland ecosystems can potentially provide beneficial consumptive uses to people, such as food and raw materials. Ducks, geese, and other waterfowl supported by wetland ecosystems comprise an important part of the hunting industry. The fishing industry also relies heavily on the provisioning services of wetlands; in 1998, the harvest of wetland-dependent saltwater fish and shellfish totaled nearly $950 million (Mitsch and Gosselink, 2007). Naturally-occurring wetlands also produce an abundance of plant species valued for timber, such as bald cypress, tupelo, and oaks. Stormwater wetlands generate many of the same provisioning services, though the urban context in which they are located and the perceptions of local citizens may limit the practicality of harvest. However, there are possibilities. Beavers and muskrats, which are often considered nuisances in stormwater wetlands, could be treated as a resource by harvesting them for their pelts. Likewise, geese, which are notorious for eating young wetland vegetation, could also be harvested as a food source. Most stormwater wetlands support productive herbaceous vegetative communities that hold potential as sources of energy, fiber, and other commodities, though this potential has not been widely explored in the United States (Mitsch and Gosselink, 2007). Many wetland plants are also edible and include species found abundantly in stormwater wetlands, such as duck potato (*Sagitaria latifolia*), cattails (*Typha* spp.), and blackberries. However, contaminant accumulation in wetland sediments may limit the value of food production services by stormwater wetlands (Deng et al., 2004). Until further research is conducted, it is probably not wise to consume plants, particularly root tissues, in direct contact with wetland sediments. The ornamental value of some stormwater wetland plants, such as water lilies (*Nymphaea odorata*), has yet to be exploited as well.

INFORMATION SERVICES

Information services contribute to our well-being by providing information about places for recreation, education, and aesthetic experiences as well as opportunities for reflection, spiritual enrichment, and even artistic inspiration (de Groot, 2006). Stormwater wetlands are particularly well-suited to provide information services as they are located near residential areas and schools and are often easily accessible. Increasingly, stormwater wetlands are being integrated into urban landscapes to provide recreational and aesthetic amenities to the surrounding community (Figure 3). For instance, walking trails, boardwalks, and wildlife viewing areas can be maintained around and through stormwater wetlands to provide hiking and bird-watching opportunities. Educational signs can also be placed around stormwater wetlands to inform the public of the wetlands' regulating, habitat, and provisioning services.

Communicating the value of stormwater wetlands as recreational and aesthetic amenities can help improve the overall public perception of these water treatment systems (Adams et al., 1984). The value of recreational and aesthetic services can also translate to economic benefits, particularly for developers. The EPA found that homebuyers were willing to pay up to $18,000 more for lots adjacent to aesthetically designed stormwater wetlands and wet ponds (USEPA, 1995).

Figure 3. Incorporating walking trails, picnic areas, and educational signs (such as these in Charlotte, NC) enhances the value of the information services provided by stormwater wetlands.

DESIGNING STORMWATER WETLANDS FOR ECOSYSTEM SERVICES

Ultimately, the design of any stormwater wetland system will depend on project objectives and local site constraints. Fortunately, many of the services described above are not mutually exclusive, so a designer can design a system to provide multiple ecosystem services. Because the biological and genetic diversity of an ecosystem underpin many of the services it generates, promoting vegetative diversity through design and construction practices also supports ecosystem services. The following sections describe design elements that can enhance biodiversity, and thus ecosystem service provision, by stormwater wetlands.

Internal wetland zones

Hunt et al. (2007, AG-588-12) describe several different hydrologic zones that can be created within stormwater wetlands, which include deep pools, transition, shallow water, temporary inundation, and upper bank areas. Including these hydrozones in stormwater wetlands will encourage the establishment of a diverse community of floating and emergent macrophytes, rushes, and sedges that are adapted to varying degrees and frequencies of inundation. Repeated wetting and drying of the areas designed to be temporarily inundated can help facilitate nutrient cycling, especially with respect to phosphorus mineralization (Bazter and Sharitz, 2006). Wetting and drying cycles can also affect carbon sequestration. Altor and Mitsch (2008) reported that alternating wet and dry cycles reduced methane emissions from a created wetland system when compared to maintaining a steady flow hydrology. Hydrologic pulsing effects were especially pronounced in deeper, open-water areas from which methane emissions are generally higher and carbon accumulation rates lower as compared to shallower, vegetated regions (Anderson and Mitsch, 2006). Thus, managing the hydroperiod of stormwater wetlands by incorporating hydrozones could also improve carbon sequestration services. Hunt, Apperson, and Lord (2005, AG-588-4) advise incorporating these zones so that multiple permanent pools are distributed throughout the wetland. Doing so will help promulgate wetland pest control by providing habitat for mosquito predators (such as *Gambusia* spp.) throughout the wetland. Distributing deep pool refugia throughout the wetland also enables these predators to more rapidly recolonize shallow water areas following drought.

Plant selection

Wetland designers can also encourage vegetative diversity and the development of other ecosystem services through the planting scheme. Selecting flowering plants such as pickerelweed (*Pontedaria cordata*) adds aesthetic appeal while attracting mosquito predators such as dragonflies and damselflies, which deposit their eggs into wetland waters. The potential provisioning services of wetland plants can also be considered when selecting vegetation.

Soil amendments

Although wetland soils are generally rich in organic carbon, the subsoils in which stormwater wetlands are typically constructed are limited in organic materials. Amending wetland substrates with topsoil or other sources of organic matter at construction will help plants establish while also providing the organic fuel needed to drive denitrification for runoff treatment. In addition to providing vital carbon sources, topsoil can also enhance vegetation development and diversity through the seedbank and mycorrhizal bacteria already present in the soil (Burchell et al., 2007; Cappiella et al., 2008).

Adjustable outlet structure

One challenge to maintaining a diverse vegetative community in stormwater wetlands is the drastic water level fluctuations these systems experience during storms. As reviewed by Cappiella et al. (2008), multiple studies have shown that water level fluctuations greater than 8 to 10 inches above the normal water surface elevation lead to declines in species diversity and richness. Such water level fluctuations can be particularly detrimental to newly planted vegetation. Hunt et al. (2007, AG-588-12) suggest limiting the water level fluctuation to no more than 4 to 6 inches during the first growing season. Initial results from plant diversity and density surveys of stormwater wetlands throughout North Carolina indicate that maximum water level fluctuations of less than 6 inches are more likely to support a diverse plant community.

An adjustable outlet structure can help to minimize water level fluctuations until wetland plants are established. Incorporating flashboard risers allows the ponding depth to be adjusted, as described by Hunt et al. (2007). Their *Stormwater Wetland Design Update* (AG-588-12) provides design guidance for outlet structures. Further construction guidance for these systems is provided by Burchell et al. (2010) in *Stormwater Wetland Construction Practices* (AG-588-13).

SUMMARY

Naturally-occurring wetlands are recognized as one of the world's most valuable ecosystems by virtue of the free services they provide to society, including water treatment; flood and greenhouse gas regulation; biodiversity maintenance; food and raw material production; and recreational, educational, and aesthetic experiences. Though currently designed for runoff treatment in North Carolina and, to some degree, flood regulation, stormwater wetlands may provide many of the other services provided by naturally-occurring wetlands. Because they are generally located in urban areas, stormwater wetlands have the potential to provide air and microclimate regulation services. This potential in particular merits further investigation by researchers and others involved in stormwater mitigation. Carbon sequestration by stormwater wetlands is another area for future exploration with potential economic benefits for developers and NC municipalities through the carbon market.

The types of ecosystem services provided by a stormwater wetland will partly depend on its design. Current design guidance, particularly including various hydrozones and maintaining maximum water level fluctuations to less than 6 inches while vegetation is establishing, will encourage a more diverse community of wetland vegetation. Much of the literature points to this diversity as a driver for providing other ecosystem services.

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RELATED FACT SHEETS

These fact sheets in the Urban Waterways series (AG-588) published by the NC Cooperative Extension Service at NC State University, Raleigh, are available on the Stormwater Engineering website: http://www.bae.ncsu.edu/stormwater/pubs.html

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