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Design of Constructed Stormwater Wetlands

by

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Course 172
4 PDH (4 Hours)

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Introduction:
This course is an overview of the design of constructed stormwater wetlands to provide water quality control for urban and rural runoff. Constructed wetlands are useful for treating stormwater and also provide an array of other environmental and aesthetic benefits. A description of the features that go into a well designed, well constructed, and well maintained wetland are included.

When you complete this course you should be familiar with the design, construction, and maintenance of construction stormwater wetlands. You should be able to decide if a constructed wetland is appropriate for your particular site and you should able to determine how to construct the wetland and what plantings can be placed within it. Finally, a design procedure for vegetated filter strips (which are often used as a pre-treatment device in conjunction with constructed stormwater wetlands) is also included.

There are several references dealing with the design of constructed stormwater wetlands. The two main references used in this course are: (i) The New Jersey Department of Environmental Protection's Best Manangement Practices Manual and (ii) the New York State Stormwater Management Design Manual.

Overview of Constructed Stormwater Wetlands:
Land development generally requires stormwater facilities to provide attenuation of peak storm events as well as quality control to prevent the movement of debris and pollutants downstream. A design engineer has many choices when deciding what type of stormwater facility to use to accomplish these ends. A standard detention basin is very useful in attenuating peak flood discharges but provides little or no stormwater quality treatment. A constructed wetland, on the other hand, can be designed to provide a maximum benefit in both reducing peak flood flows and filtering the stormwater. In fact, a well-designed constructed stormwater wetland can be thought of as a multi-purpose detention basin. In smaller storms (which generally flush the majority of the pollutants downstream) the stormwater is filtered by a combination of settling in the pond and marsh areas and by biotic treatment by the plants. In the case of larger storms, the upper reaches of the system can be designed to temporarily store floodwaters as is done by conventional detention basins.

Naturally occurring wetlands are extremely efficient at filtering pollutants out of runoff. In addition, they provide many other significant environmental benefits including the following:

1. They provide habitat for aquatic, semi-aquatic, and terrestrial wildlife.
2. They reduce the frequency and severity of flooding.
3. They can provide erosion control by slowing down floodwaters.
4. The can enhance groundwater recharge.

In order for a constructed stormwater wetland to function properly it should replicate, as nearly as possible, a naturally occurring wetland. No constructed wetland would be expected to provide all of the benefits of natural wetlands because constructed wetlands generally lack the complexity and diversity found in natural systems. However, a constructed wetland can approximate a natural wetland and provide some of these same benefits.

The photograph below shows a well-designed constructed wetland in New Jersey. This wetland was constructed primarily to provide stormwater quality and quality control but also provides wildlife habitat and serves as an outdoor classroom for a local school.

Types of Constructed Wetlands:
There are several types of constructed stormwater wetlands and they are generally classified by the depth of their permanent pool (if any). The main types listed below will be considered in this course:

1. Pond wetlands: These wetlands consist mainly of ponds with standing water depth greater than 4 feet, in conjunction with associated marsh areas. Generally it is the pond, itself, that provides for the majority of the particulate matter removal. However, the filtration is augmented greatly by the forebay if one is present. The marsh zones provide additional treatment of the runoff, especially for soluble pollutants. Pond wetlands generally achieve the highest rate of pollutant removal of any constructed wetland type.
2. Marsh wetlands: These wetlands typically consist of marsh zones with standing water up to 18" deep during dry periods. In some ways marsh wetlands present more challenges to the design engineer than other types of wetlands. For one thing, they often require both larger contributing drainage areas and a larger area for the wetland, itself, to ensure that the marsh zones do not dry out. Flow paths through the marsh wetland should be sinuous to increase the time of concentration within the complex and also to increase the contact zone. It is also important that the flow velocities within the wetland are sufficient to prevent the area from becoming a mosquito breeding area.
3. Extended detention wetlands: This type of wetland differs in many respects from both pond wetlands and marsh wetlands. Generally, these wetlands have a relatively small permanent pool and marsh zone and store excess runoff in the semi-wet zone. However, a pond wetland or a marsh wetland can easily be designed as an extended detention wetland by simply providing additional storage above the permanent pool levels. The outlet structure for extended detention wetlands usually incorporate orifices and/weirs to reduce the peak rate of runoff out of the system. These types of constructed wetlands have the dual function of providing both stormwater peak and stormwater quality control.
4. Swale wetlands: Ditches and swales can be planted with wetlands plants as a way of filtering out pollutants. Generally, the swales should have the minimum slope required to allow the water to pass through without stagnating and becoming a mosquito breeding area. In addition, because the swales will generally only carry water during and after storm events, plants should be selected that can withstand longer periods of dry conditions.

The picture below is taken from the Raleigh, North Carolina government site and shows an extended detention type constructed stormwater wetland. Note the semi-wet area above the permanent pool.

Design of Constructed Stormwater Wetlands:

Constructed wetlands should be sized to store runoff from the "water quality" or first –flush storm, which is a low intensity, high frequency rainfall event that carries a relatively high pollutant load. The exact characterization of this storm varies from state to state. If the wetlands are also designed to attenuate peak flood flows, then they must be sized to handle the runoff from the chosen design storm.

The New Jersey Department of Environmental Protection (NJDEP) gives the following general guidelines for the design of the various types of constructed stormwater wetlands. The NJDEP does not regulate swale type wetlands.

Wetland Design Feature	Pond Wetland	Marsh Wetland	Extended Detention Wetlands
Minimum Drainage Area (Acres)	25	25	10
Minimum Length to width Ratio	1:1	1:1	1:1
Allocation of Stormwater Quality Design Storm Runoff Volume (Pool/Marsh/Semi-wet)	70/30/0	30/70/0	20/30/50
Allocation of Pool Volume (Forebay/Micro pond/Pond)	10/0/60	10/20/0	10/10/0
Allocation of Marsh Volume (High Marsh/Low Marsh)	20/10	45/25	20/10
Sediment Removal Frequency (Years)	10	2 to 5	2 to 5
Outlet Configuration	Reverse-Slope Pipe or Broad Crested Weir	Reverse-Slope Pipe or Broad Crested Weir	Reverse-Slope Pipe or Broad Crested Weir

A description of the various features within the wetlands is included below:

Pool Zone: The pool zone generally has a standing water depth of greater than 2 feet. If the depth is significantly greater than 2 feet then safety features may need to be built into the design, especially if the wetland is to be constructed in a residential area. These safety features can include a safety ledge or bench (discussed later), a fence around the pool, or other devices. The pool zone can be further divided into the forebay, micro-pond, and pond zones.

A. The forebay is generally located at the upstream end of the constructed wetland. It serves two main purposes. First it stops the concentrated flow that comes into the wetland and breaks up the potentially erosive velocities of this flow. Secondly, it serves as a pre-treatment unit because it allows coarse sediments, trash, and debris to settle out of solution before the water is passed into the main body of the wetland.

B. The micro pond generally has a standing water depth of 4 feet to 6 feet. It is smaller than a standard pond and is usually located immediately upstream of the outlet of the wetland.
C. The Pond generally has a standing water depth of 4 to 6 feet. In some constructed wetlands the pond comprises the largest portion of the wetland. Because the water will generally stay in the pond for an extended period of time with little or no velocity, this area generally provides for the majority of the particulate settling within the wetland.

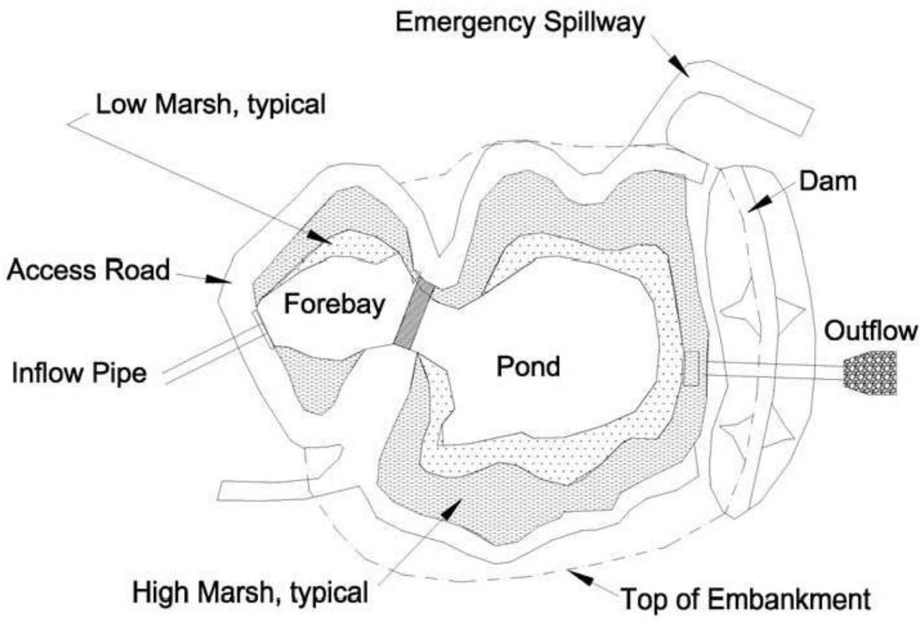
Marsh Zone: The marsh zone has a shallower standing water depth than a pool zone; generally in the area of 6" to 18". This water depth is suitable to support emergent wetland vegetation. The marsh zone is further subdivided into a high marsh and a low marsh depending on the exact water depth. These zones are described below:

A. The low marsh zone has a standing water depth of between 6 and 18 inches. Several emergent plant species will grow within this zone.
B. The high marsh zone has a maximum water depth of 6". Because of its shallower water depth it will generally support a greater density and diversity of vegetation than the low marsh zone.

Semi-Wet Zone: The semi-wet zone in a constructed wetland is located immediately above the permanent pools that comprise the pond and marsh zones. This area is inundated for short period of times during and immediately after storm events. As a result, this zone can support both wetland and upland plants. This is the area that is used for temporary stormwater runoff.

The photograph below shows the marsh zone of a constructed stormwater wetland. This photograph was taken during a relatively dry period, but the emergent vegetation in this wetland appears to be thriving.

A schematic plan of a constructed stormwater wetland is shown below:



Schematic Constructed Wetland Plan

The actual areas devoted to ponds, high marsh, and low marsh will vary from wetland to wetland but most constructed wetlands will include several of the features included in the schematic shown above.

The constructed stormwater wetlands shown below is taken from the Horry County, South Carolina website. This is a marsh type constructed wetland. Note that the emergent vegetation within the marsh appears to be thriving. Note also that the vegetation in semi-wet zone is standing outside the water but within saturated soil.

Planting the Wetland:
Because much of the filtration of the stormwater runoff in a constructed wetland is accomplished by the vegetation, it is essential to choose appropriate plantings. The wetlands described in this course have a variety of hydrologic regimes (from standing water zones to dry slopes). Several authorities recognize six separate hydrologic regimes within a wetland complex. There is some overlap within these zones, however, and care must be taken to ensure that the plants chosen will survive within the specific hydrologic regime where they are planted. Therefore, the plantings must be selected with the specific zones in mind. The following planting guidelines are taken from the NJDEP Best Management Practices Manual, but virtually the same guidelines are promulgated by the New York State Department of Environmental Conservation.
The specific plantings listed below for each hydrologic regime found within the constructed wetland are suitable for the Mid-Atlantic States. In other areas, different species will have to be specified. In may be advantageous to consult with a local horticultural expert when planning the wetland planting plan.

Zone 1: Planting in Deep Water Pools (1 to 6 feet deep): The best plants for this zone are submergent plants. However, this area is often not planted because there are few commercially-available plants that will thrive in deep water habitats. In addition, there is some concern that significant growth in this zone can clog the stormwater outlet structure. In well constructed wetlands this zone will often become planted through natural colonization. If plantings are proposed in this zone their main functions are to improve oxidation of the pool, reduce sedimentation, and provide for a better aquatic habitat. Plantings within this zone must:

- Be able to withstand constant inundation.
- Be able to enhance pollutant uptake.
- Provide food and cover for aquatic insects and other wildlife.

Some suggested planting in this zone (in New Jersey and nearby states) include:

- Spatterdock (*Nuphar luteum*)
- Water lily (*Nymphaea ordorata*)
- Duckweed (*Lemna* spp.)

Zone 2: Planting in the Shallow Water Benches (6" to 12" water depth): This is the primary area where emergent vegetation will grow within stormwater wetlands. This area corresponds to areas of low marsh and high marsh and can be located at the fringes of a pool or on low mounds of earth below the water surface within a pool. In a well constructed wetland the plantings in this zone can provide a variety of functions including: (i) filtering stormwater pollutants (ii) providing a habitat for a variety of aquatic and semi-aquatic wildlife and (iii) reducing the necessity of pesticides by providing habitat for natural insect eaters.

Plants selected for this zone must be able to:

- Withstand constant inundation of shallow depth.
- Provide the same benefits as listed for the pool zone plantings, above.

Plants in this zone also stabilize the edge of the pond, reduce the possibility of erosion, slow the velocity of the water and cause more solids to drop out of the stormwater. In addition, plantings in this zone have an aesthetic benefit and also can conceal drawdowns during periods of dry weather.

There are many commercially-available plants that will thrive within this zone. Some suggested plantings within this hydrologic regime include:

- Water plantain (*Alisma plantago-aquatica*)
- Smartweed (*Polygonum, spp*.)
- Bulrushes (*Scirpus, spp*.)
- Arrow arum (*Peltandra virginica*)
- Lizard tail (*Saururus cernuus*)
- Pickerelweed (*Pontederia cordata*)

The photograph below shows some of the variety of plants that will grow in Zones 2 and 3 of a constructed wetland.

Zone 3: Plantings in the Shoreline Fringe (regularly inundated): This zone is found around the fringe of a permanent pool and extends about a foot (or more depending on the topography) from the pool. In most constructed wetlands (and, especially, in extended detention wetlands) this zone will be regularly inundated. It can be difficult to establish vegetation within this zone because the area can be wet or dry for fairly extended periods depending on the season. However, in order to stabilize the soil along the fringe of a permanent pool it is essential to establish a significant vegetative cover in this zone. Plantings within this zone have a multitude of functions to perform including the following:

- Stabilize the shoreline against erosion caused by wind, waves, and fluctuating water levels.
- Shade the shoreline to reduce water temperature in the summer months.
- Be located to reduce human access to potentially hazardous areas without blocking maintenance access to the pool.

- Have low maintenance requirements because access to this area in the wetland is often difficult.
- Enhance pollutant uptake.
- Provide food and cover for aquatic, semi-aquatic, and terrestrial wildlife.
- Be resistant to disease.

Many of the emergent plants listed as appropriate for zone 2 will also thrive in this zone. Other herbaceous plants that will do well include Cardinal flower (*Lobelia cardinalis*), Marsh marigold (*Caltha palustris*), switchgrass (*panicum virgatum*), Swamp milkweed (*Asclepsis incarnata*), and many others. If shading along the bank is required, a wide variety of woody plants are recommended including the following:

- River birch (*Betula nigra*)
- Pussy willow (*Salix discolor*)
- Highbush blueberry (*Vaccinium, spp*.)
- Grey dogwood (*Cornus racemosa*)
- Willow oak (*Quercus phellos*)

Any other native trees and/or shrubs that can tolerate the expected conditions can be planted as well.

Zone 4: Plantings in the Riparian Fringe (periodically inundated): This zone corresponds to the area just above Zone 3 and is generally thought of as extending from one foot to four feet beyond the permanent pool. Plants in this zone are generally inundated for fairly short periods of time and may experience saturated or semi-saturated soils during and after rainfall events. Plants selected for this zone should be able to:

- Withstand both periods of inundation and drought.
- Stabilize the ground by preventing erosion.
- Provide shade to prevent warming of the water in summer.
- Be located to reduce pedestrian access to the deeper pool areas

Among the variety of plants that are able to thrive in this zone are the following:

- Asters (*aster*, spp.)
- Goldenrods (*Solidago*, spp.)
- Serviceberry (*Amelanchier arborea*)
- Bayberry (*Morella pensylvanica*)
- River birch (*Betula nigra*)
- Red Maple (*Acer rubrum*)

Zone 5: Plantings in the Floodplain Terrace (frequently flooded): This zone represents the majority of the semi-wet zone described above. In an extended detention basin, this zone is regarded as the area between the maximum water surface achieved within the wetland basin during a 2 year storm and the maximum water surface achieved during a 100 year storm. In other words, this area is ordinarily inundated only once every few years. Floodwaters in this zone generally recede quickly and plants located within this zone are only expected to be inundated for periods of less than 24 hours. The main functions of the plantings in this area are to stabilize the steep slopes that are characteristic of this zone and to establish low-maintenance natural vegetation. Attractive plantings placed within this zone can add significantly to the visual appeal of the stormwater wetland.

Plants selected in this zone should be able to:

- Withstand very occasional inundations, occasional saturated soil, and be somewhat drought-hardy.
- Stabilize the steep basin slopes.
- Be very low maintenance. If herbaceous plantings are selected for this zone they should not require mowing. If geese are present in the area and considered a nuisance species, they can be deterred by planting a dense tree and/or shrub cover in this zone in lieu of herbaceous plantings.
- Provide habitat for songbirds and other wildlife.

Placement of plant material is critical due to the steep slopes and the potential for erosion. Care must be taken to ensure that the plantings in this zone thrive, especially in the first growing season. If this does not occur, a different mix of plantings may be required to re-establish and re-stabilize this area.

Suggested plantings for this Zone include the following:

- Phlox (*Phlox*, spp.)
- Solomon's seal (*Polygonatum biflorum*)
- Viburnums (*Viburnum*, spp.)
- Virginia Rose (*Rosa virginiana*)
- American hornbeam (*Carpinus caroliniana*)
- Hickories (*carya*, spp.)

Zone 6: Upland slopes (seldom or never flooded): This zone differs from all of the other zones within the constructed wetland complex in many ways. For one thing, it is located above the 100 year maximum flood elevation in the basin and, consequently, is only subject to brief periods of flooding during catastrophic storm events, if at all. In addition, this zone includes the buffer of the constructed wetland and may include bike paths, walkways, maintenance access roads and similar improvements. The design engineer should choose plantings in this area that will not overcrowd any of these pathways. The plants should be selected based on soil conditions and expected light levels.

Placement of plants in this zone is important for the overall visual affect of the wetland. These upland plants can frame desirable views or block undesirable items in the landscape from view. In addition, these plantings should be selected with an eye for texture and seasonal color in mind. Above all, the plants chosen must not interfere with existing utilities or obstruct sight lines on the local roads.

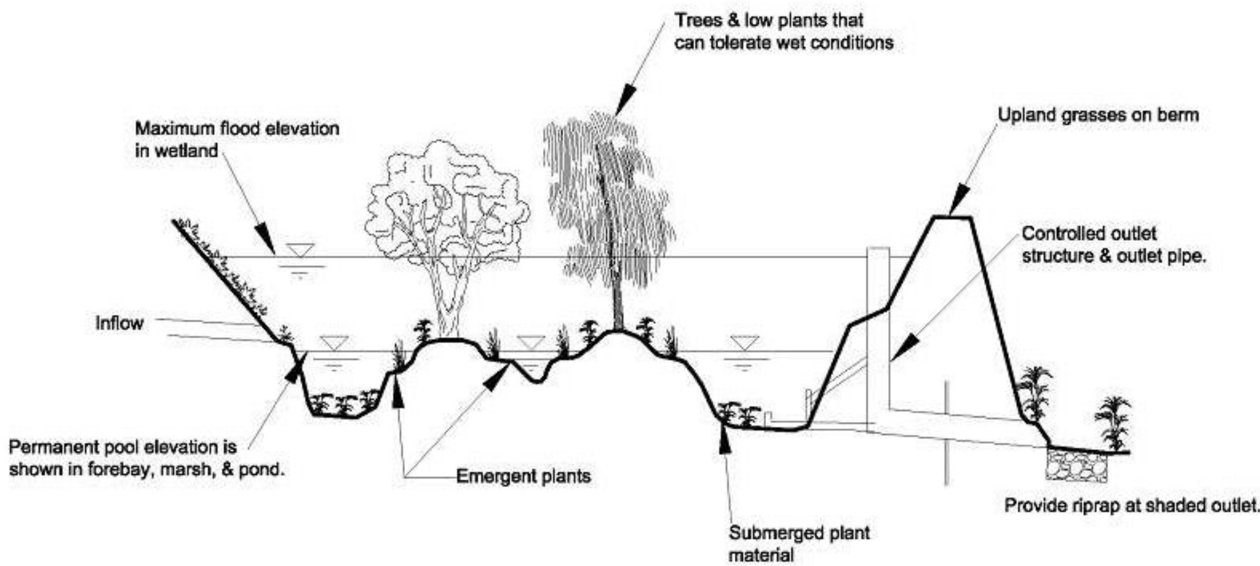
A very great variety of upland plants are appropriate for placement in this zone. Some examples include:

- Flowering dogwood (*Cornus florida*)
- Sassafras (*Sassafras albidum*)
- American beech (*Fagus grandifola*, spp.)
- White ash (*Fraxinus americana*)
- White oak (*Quercus alba*)
- Pines (*Pinus*, *spp*.)

If deer are present in the region in great numbers, care should be taken to install plants in this zone that will be at least somewhat deer resistant.

The photograph at the left shows the diversity of plantings across several zones of a constructed wetland. Note that there are a variety of deciduous and coniferous plantings located on the upland slopes bordering the wetland and that these give color and texture to the system as a whole.

The schematic below shows how these plantings are integrated into a typical extended detention constructed wetland.



Constructed Wetland Planting Schematic

Additional Design Considerations:
There are several miscellaneous parameters that must be considered and decisions that must be made by the design engineer, in addition to the above, when designing a constructed wetland. Some of the major ones are discussed below:

On-line and Off-line Systems: Constructed stormwater wetlands can be constructed either on-line or off-line and there are important differences between the two. In an on-line system all of the runoff from the contributing drainage area reaches the constructed wetland. These types of wetlands often serve a dual purpose; providing both water quality control in smaller storms and stormwater peak flow attenuation during larger storms. In this type of system it is imperative that the wetland be designed to safely pass the peak runoff from a large storm. In off-line systems a diversion is provided upstream of the wetland and larger storms are routed around the facility. The area required for an off-line wetland is generally smaller than that required for an on-line system.

Drainage Area: The minimum drainage area required for a constructed stormwater wetland generally varies from about 10 to 25 acres. However, even for contributing areas of this size, it is imperative to analyze the water budget of the system to ensure proper functioning of the constructed wetland. Water budget considerations are discussed in some detail later in this course.

Site Constraints: There are several site constraints that must be considered when designing the wetland. The most obvious and important of these is determining that adequate water is available to keep the wetland functioning throughout the year. This is discussed in much more detail under the water budget heading below. However, there are a number of other site constraints that must be worked into the design. For instance, the wetland must be located such that it will not negatively interact with any other site improvements. The NJDEP recommends that the wetland be constructed at least the following minimum distances from any existing or proposed features:

- Distance to a septic system: 50 feet.
- Distance from a septic tank: 25 feet.
- Distance to a property line: 10 feet.
- Distance from a private well: 50 feet.

The US Environmental Protection Agency (EPA) also lists the following as areas that are constrained in regards to constructed stormwater wetlands:

1. In arid and semi-arid regions it is difficult to keep enough water in the wetland. A water budget analysis is especially critical in these areas.
2. In densely-developed urban areas there is often not sufficient area available for constructed wetlands.
3. Constructed stormwater wetlands must be used with caution in stormwater hot spots (defined by the EPA as areas that generate highly contaminated runoff). A car wash and a gas station are typical examples of stormwater hot spots. Wetlands can accept runoff from these areas but they should have a significant separation between the bottom of the wetland and the high water table. Therefore, in stormwater hotspots with shallow groundwater constructed wetlands should not be used.
4. In areas that drain into cold water streams (especially trout streams) constructed wetlands should be used with caution. Wetlands that incorporate a permanent pool can warm the water exiting the system, and this can have a detrimental effect on the receiving stream. One study, conducted in Maryland, indicated that the average temperature of stormwater exiting a constructed wetland was 3^0F warmer than the water in the receiving stream. This can be ameliorated somewhat by shading the pool and the outlet by the plantings suggestions made in this course.

The design engineer should be aware of other factors specific to a particular site that might make the use of a constructed wetland undesirable. In areas where mosquito breeding is of concern (for instance in residential areas or near horse farms) wetlands may not be viable.

Regulatory issues: When designing the wetland the engineer should be aware that other regulatory issues may become applicable. For instance, the berm that impounds the wetland may be classified as a dam by the state environmental commission. In this case, the engineer will need to ensure that appropriate safety measures are built into the design in the form of an emergency spillway. Even though it is man-made, the wetland, itself, once it is constructed may be regulated under the state's wetlands regulations.

Outlet Configuration: The outlet configurations of a constructed wetland should serve several purposes:

- It must allow for a controlled outlet downstream to attenuate the peak runoff flows (if it is a dual purpose system) and at least provide for an outlet velocity that is not erosive (if it is not).
- It must allow for complete draining of the wetland for maintenance or for emergency purposes.
- It should be configured so as to prevent clogging of the outlet pipe by sedimentation.

The NJDEP recommends the use of a hooded outlet with an invert or crest at least 1 foot below the normal pool elevation. However, the design engineer may choose other configurations as long as they address the required functions stipulated above.

As part of the overall outlet configuration, the wetland should be provided with an emergency spillway that can safely pass flows greater than the design storm. The emergency spillway is sometimes built into the principal outlet structure by means of an open top with a grate. However, a separate emergency spillway is preferable because it will continue to function if the main outlet pipe becomes blocked. If the flow over or downstream of the emergency spillway is expected to be erosive, the spillway and/or exit channel should be armored with riprap, gabions, or similar materials.

Safety Ledges: Any constructed with a permanent pool greater than 3 feet deep must be equipped with safety ledges. The ledges should be at least 4 to 6 feet wide and should be between 1 and 1.5 feet below the normal standing water elevation. If the pool is significantly deeper than 3 feet, two safety ledges may be required, separated vertically be approximately 1 to 1.5 feet. In residential areas or other areas where children may be present it may be necessary to provide further safety by providing plantings and/or a fence to keep pedestrians away from the pool area of the wetland.

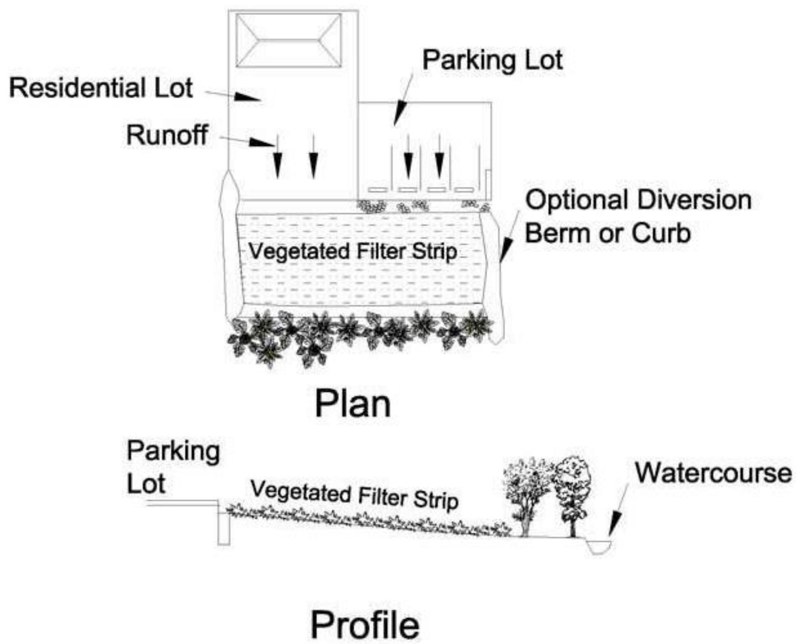
Pre-treatment: The effectiveness and, potentially, the life-span of any stormwater quality control feature can be increased by the use of a pre-treatment device. This can take the form of a sand filter, a manufactured treatment device, or other means. However, in the case of a constructed wetland the pre-treatment devices chosen are generally one that will fit in with and become part of the wetland landscape. A vegetated filter strip or vegetated swale is often used in this regard. A discussion of the design process for a vegetated filter strip is included below. The constructed wetland, itself, is often provided with a sediment forebay, which is a very effective way of pre-treating the stormwater because it causes much of the suspended solids and other pollutants to drop out of solution.

Vegetated Filter Strip Design:
A vegetated filter strip is a stormwater control feature in its own right, but it will be considered here simply as a pre-treatment device placed upstream of the constructed stormwater wetlands. The vegetation in the filter strip can range from turf grasses to herbaceous plantings to woods. The vegetation can be either planted or indigenous. Using indigenous vegetation will increase the effectiveness and overall stability of the filter strip but this is not possible or practical in many cases. The Total Suspended Solids (TSS) removal rate of the filter strip will vary with the type of vegetation, the width of the strip and the slope of the strip. The NJDEP assigns the following TSS removal rates for various types of vegetated filter strips.

Vegetative Cover	Maximum NJDEP Adopted TSS Removal Rate (See explanation below for achieving maximum removal rate)
Turf Grass	60%
Planted Grasses, Meadow, and Planted Woods	70%
Indigenous Woods	80%

Vegetated filter strips, if properly designed and installed, are effective in reducing sediment and other suspended solids as well as hydrocarbons, heavy metals, and nutrients. It treats these pollutants with a variety of removal mechanisms including sedimentation, filtration, adsorption, infiltration, biological uptake, and micro bacterial activity. Although not nearly as versatile as constructed stormwater wetlands, vegetated filter strips can also provide a number of environmental benefits. Filter strips with planted or indigenous woods can shade water bodies, provide a habitat (or a habitat corridor) for wildlife and be a source of detritus for fish and other aquatic organisms.

A plan & profile of a typical Vegetated Filter Strip is shown below:



Vegetated Filter Strip Schematic

A vegetative filter strip can only be used to treat stormwater runoff as sheet flow and is not applicable for treating concentrated flow. This limits the use of vegetative filter strips in two ways. For one thing, it can only be used on relatively mild slopes and it must be uniformly graded, or in the case of indigenous woods, it must have surface features that retard, pond or disperse the runoff generally over the entire width of the strip. Secondly, because the runoff to a filter strip must enter the strip as sheet flow the area draining into the strip must (i) have be relatively uniformly graded (to avoid concentrating the runoff)and (ii) have a relatively horizontal edge where it meets the upstream edge of the filter strip. Parking lots, driveways, and residential yards often have these features and filter strips can be effective in providing stormwater quality control for these features. Conversely, vegetated filter strips cannot be used to treat concentrated stormwater runoff from storm sewer outlets or other point discharges.

There are several additional factors that must be considered when designing a vegetated filter strip. The major ones are as follows:

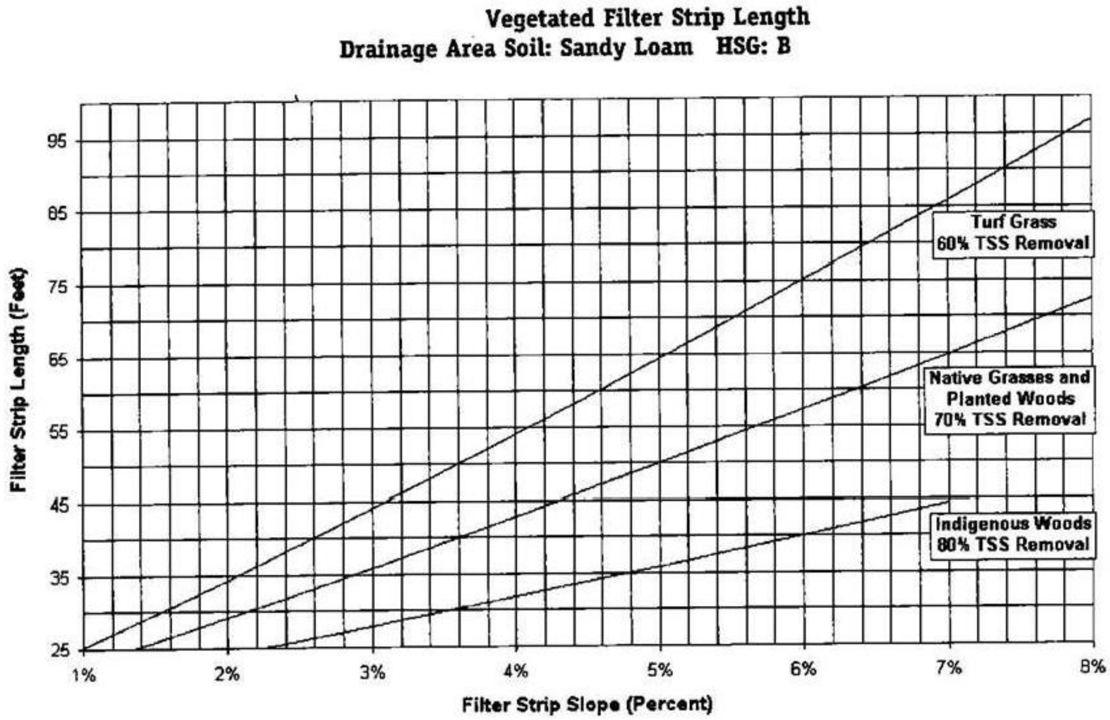
- The vegetation within the strip (whether herbaceous or wooded) must be dense and remain healthy. In the case of woods, a significant mulch or leaf litter cover should be present. As a general rule, planted woods should have a 3" (minimum) mulch layer and indigenous woods should have at least a 1" layer of leaves and/or other organic matter.
- The filter strip must be protected by an easement or other legal instrument that will ensure that it is not destroyed.
- The filter strip can be used alone or in conjunction with other stormwater quality control features. If it is used in conjunction with another feature (such as the constructed wetlands discussed herein) then an appropriate transition should be provided at the interface.

The photograph below shows filter strips planted on either bank of a natural stream to provide water quality control. Note that these strips include herbaceous plantings and also incorporate existing mature trees. Note also the relatively gentle slopes of the banks and the fairly horizontal edge of the lawn to the left of the filter strip on the left bank. The result is a well-vegetated area to filter the runoff entering the stream.

The three main design parameters vegetated for filter strips are its slope, vegetation type, and its soils. The maximum filter strip slope can be determined from the table below:

Filter Strip Soil Type	Hydrologic Soil Group	Maximum Slope (Turf Grass, Native Grasses, & Meadows)	Maximum Slope (Planted & Indigenous Woods)
Sand	A	7%	5%
Sandy Loam	B	8%	7%
Loam or Silt Loam	B	8%	8%
Sandy Clay Loam	C	8%	8%
Clay Loam, Silty Clay, or Clay	D	8%	8%

The required filter strip length is based on a combination of the slope and the vegetative cover. In no case should the strip be less than 25 feet wide. The graph below shows the relationship between slope, cover, and length for vegetated filter strips placed on sandy loam. This graph shows the minimum filter strip length required to achieve the maximum NJDEP-adopted TSS removal rates. The NJDEP assigns maximum TSS removal rates of 60% for turf grasses, 70% for native grasses and planted woods, and 80% for indigenous woods. The NJDEP has similar charts for the other soil types.



Vegetated Filter Strip Design Example:
Assume that a filter strip is required downslope of a parking lot to treat stormwater runoff entering a trout-production stream. Because the stream is classified as trout production, the reviewing agency is requiring at least a 70% TSS removal rate. Based on the topography the filter strip will have a slope of 5%. The area that will be used for the filter strip is presently poorly vegetated and experiencing erosion.

Solution: In order to provide a 70% TSS removal rate, either native grasses, planted woods, or indigenous woods are needed. However, based on the description given in the problem the area is not presently wooded. Therefore, native grasses or planted woods will be used. Referring to the chart above, find the middle line (for native grasses and planted woods) at 5% slope and follow to the left to find that the required minimum depth of the vegetated filter strip is 50 feet.

Additional Vegetated Filter Strip Considerations:

1. As shown in the graph and design example above, filter strips work best on shallower slopes. The slopes in the chart above should be considered as absolute maximums. Whenever possible, lesser slopes should be used.
2. Routine maintenance should be done on filter strips including mowing the vegetation (if applicable) removing invasive species, cleaning out debris, etc.

3. The most common, naturally occurring vegetated filter strips may be upland stands associated with floodplains or along watercourses. Where possible, these filter strips should be protected by easements or other legal instruments to ensure their longevity. Supplemental plantings or removal of invasive species within these natural filter strips can increase their ability to treat stormwater.

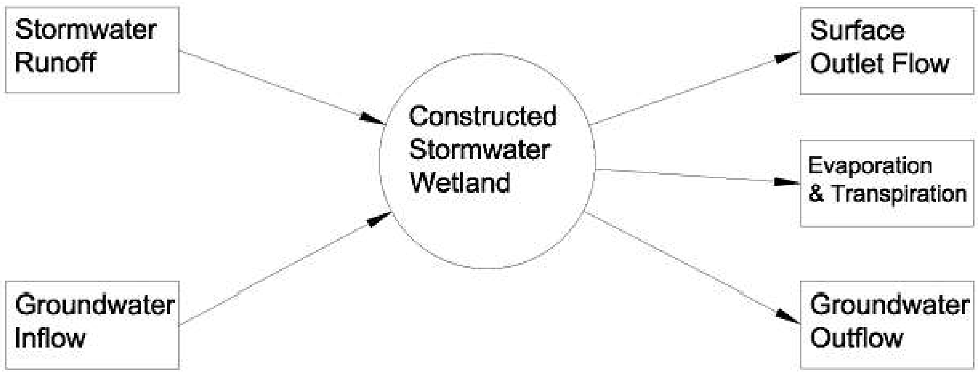
Water Budget Calculations:

As mentioned above, it is absolutely necessary to ensure that the constructed wetlands will not dry out. Various studies have shown that drying periods of greater than two months in New Jersey (shorter periods in other areas of the country) are sufficient to cause the wetlands plantings to die. If this occurs, they likely will be replaced by weedy, invasive species and the entire constructed wetlands complex will cease to function as designed. Therefore, an analysis of the water available throughout the year to keep the wetland functioning is probably the engineer's most important task when designing a constructed stormwater wetland.

In order to determine that the wetland will not dry out, the design engineer should analyze the water budget for the area to ensure that adequate water will be available throughout the year. There are many ways to calculate a water budget. Whatever method is chosen, the engineer should be careful to accurately model the following factors:

1. Inflow due to runoff and direct precipitation.
2. Groundwater flow into and out of the wetland.
3. Evapotranspiration.
4. Any loss of water due to irrigation (if the wetland pond serves in that capacity).
5. Surface flow out of the wetland.

The schematic below shows a simplified water budget.



Water Budget Schematic

Despite the appearance of the relatively simple schematic shown above, calculation of a water budget for a specific site can be fairly complex. The engineer has to be sure to adequately model all inflow and outflow parameters under a variety of conditions to ensure that sufficient water is available throughout the year. Remember, that no matter how well the wetland is designed and constructed it will not function properly if it dries up for an extended period of time. For this reason, the engineer should be careful to model the system not only for a year with average rainfall but for a dry year as well.

A brief description of a water budget calculation is provided below. This analysis is taken from the Michigan Department of Transportation (MDDOT) Drainage Manual. However, there are several other references regarding calculation of water budgets, and the design engineer should decide which model best fits his particular situation.

The MMDOT methodology will be discussed briefly below. In order to apply this method to a specific project, the engineer should refer to the detailed analysis included within the MMDOT Drainage Manual. The MDDOT methodology equates a water budget to a routing procedure using the following basic Water Budget Equation:

$I - O = dS/dt$,where:

I= Inflow per unit of time.

O= Outflow per unit of time.

dS/dt= The change in storage within the wetland per unit of time.

This can be related to the water depth by using the following equations:

$dV = Dt(I - O)$

$dD = dv / A$, where:

V= The volume of water in the wetland.

A= The surface area of the water.

D=The water depth.

T= time.

The following factors combine to make up the water budget equation:

1. Inflows:
   a. Direct precipitation.
   b. Surface inflows.
   c. Subsurface inflows.
2. Outflows:
   a. Surface outflows.
   b. Subsurface outflows.
   c. Evapotranspiration.

This gives rise to the following equation:

$P + SWI + GWI = ET + SWO + GWO + dV / dt$, where:

P= Precipitation.

SWI= Surface water inflow.

GWI= Groundwater inflow

ET= Evapotranspiration.

SWO= Surface water outflow.

GWO= Groundwater outflow.

dV/dt= Change in storage.

Note that all of the terms (except time) in this equation are in the units of depth of water in the wetlands.

The turnover rate of the water in the wetlands is sometimes of interest. The following equations address this issue:

$T = I / V$, where;

T is a specified time period.

I is the quantity of water during the time period (e.g. cubic feet per day).

R is the residence time within the wetland.

$R = 1/T = V / I$

A brief description of the parameters included in the water budget equations follows:

Precipitation: Precipitation data are generally available from the National Weather Service and other sources. Care should be taken to make sure that the data used is applicable to the site in question. In some areas rainfall can change greatly in a short distance due to lake effects, rain shadowing by mountains, elevation changes and other factors. In most cases, the direct precipitation on the wetland is combined with the surface inflow. Note that in the water budget schematic shown above there is no separate inflow due to precipitation. It is understood that this component is included with the surface inflow.

Surface water: Surface water is usually one of the main sources of water in wetlands. In modeling this component is important for the engineer to properly analyze the runoff. A variety of methodologies are available. These include the SCS Method, the Rational Method and others. Each of these methods is useful under a given set of conditions and the engineer should decide which one to use based on the specific conditions of the site in question. A detailed discussion of determining runoff is beyond the scope of this course.
Any impoundments within the watershed should be carefully analyzed when determining the surface water flow. Standard pond routing techniques should be used to decide if the upstream impoundment(s) will be overtopped during large storms. If this is the case, the emergency spillway of the constructed wetlands must be designed to safely pass the additional flow resulting from the overtopping of the upstream dam or dams.

Groundwater: In some situations groundwater can be a very significant part of the inflow to a constructed wetland. This is especially true in dry situations or on sloped sites. In other cases the groundwater flow out of the constructed wetland will be so significant that it will be very difficult or impossible to keep the wetland hydrated. In this case, the engineer should abandon the idea of a constructed wetland and use another method to provide stormwater quality control. Groundwater inflow and outflow rates are often more difficult to determine than surface water flow. In addition, the engineer should be aware that both the rate and the direction of groundwater flow can vary seasonally.

Evapotranspiration: Evapotranspiration includes both the surface evaporation of water and the transpiration through plants. This component can be somewhat difficult to analyze and depends on many factors including climate, season, vegetative cover, and others. There are several methodologies available to estimate evapotranspiration. The Thornthwaite-Mather Method uses the following equation:

$PET = 16(10T_a / I)^a$, where:

PET= Potential evapotranspiration in mm/month

Ta= Mean monthly temperature in ^{0}C

$a = 0.49 + 0.01791I - 0.0000771I^2 + 0.0000006751I^3$, where I is the monthly heat index and is computed over a 12 month interval by summing the value for each month. The monthly values are calculated by:

$I = (T_a / 5)^{1.5}$

The formula is based on a 30 days of sunlight per month and must be adjusted according to the table below:

Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
50^0N	0.71	0.84	0.98	1.14	1.28	1.36	1.33	1.21	1.06	0.90	0.76	0.68
40^0N	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
30^0N	0.87	0.93	1.00	1.07	1.14	1.17	1.16	1.11	1.03	0.96	0.89	0.85

The following example will illustrate how to calculate the evapotranspiration at a specific site.

Example: A water budget is to be calculated for an average year for a constructed wetland located in Somerset Count, NJ. The table below shows the monthly temperatures in ^{0}C for the year 2002 which was a fairly average year in New Jersey. This table is taken from the Rutgers University New Jersey State Climate website.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp	2.9	3.7	6.3	12.6	15.4	21.4	24.7	24.6	20.2	18.1	11.9	6.4

Solution: Using the equations presented above and the monthly temperatures presented in the table we will calculate the monthly evapotranspiration. New Jersey is located at approximately 40^0 N latitude.

The table below calculates the monthly I values based on the above equations:

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp	2.9	3.7	6.3	12.6	15.4	21.4	24.7	24.6	20.2	18.1	11.9	6.4
I	0.4	0.6	1.4	4.0	5.4	8.9	11.0	10.9	8.1	6.9	3.7	1.4

The total I value for the 12 months, based on the above data, is I=62.7

Using this value for I, find a=1.48

Using the equation above, the following monthly values are obtained for the Potential Evapotranspiration. ET is the monthly evapotranspiration after correcting for latitudinal effects.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PET (MM)	5.1	7.3	16.1	44.9	60.5	98.4	121.7	121.0	90.3	76.8	41.3	16.5
Adjustment	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
ET (MM)	4.1	6.5	15.9	49.4	72.6	123.0	149.7	139.2	93.9	71.4	34.3	12.9
ET (Inches)	0.2	0.3	0.6	1.9	2.9	4.8	5.9	5.5	3.7	2.8	1.4	0.5

Once again, recall that these monthly evapotranspiration values are just a part of the overall water budget equation.

Installation of the Constructed Wetlands:

The Installation of the constructed wetland is an integral part of the overall design. Because the design is predicated on several assumptions regarding the hydrologic regime that will be provided in the various zones of the wetland, these assumptions must be verified by field observations at the time of construction. If these assumptions are not met (e.g. some areas are wetter or drier than expected or have a different standing water depth than anticipated) then field changes must be made to the planting plan. Therefore, the design engineer should visit the site several during construction and have input on the final locations of specific plantings. Once again, it may be necessary to retain the services of a qualified horticulturist during the construction phase to ensure that the proper plantings are installed.

Several authorities recommend that the following seven step process be followed during construction of the wetland:

1. Preparation of the final grading plan for the wetland along with a detailed landscaping and pondscaping plan.
2. Excavation of the wetland and shaping the area to provide the major internal features (forebay, pool, safety ledges, inflow channel, emergency spillway, etc).
3. Adding the mulch or topsoil to the graded wetland to bring the entire system to the design elevations. Any areas that are above the permanent pool elevation should be stabilized by a temporary seeding or by other means.
4. Closing the pond drain and allowing the pond to fill to its design depth. At this point the constructed wetland should be left to stand for a period of at least six months. During this period the wetland should be closely monitored to determine the exact extent of inundation during rainfall events and the amount of drawdown during dry periods. This information is essential to determine if the proposed landscaping will thrive under actual field conditions and also to determine if the microtopography of the wetland will persist over time.

5. The stormwater depths should be measured during the six month period mentioned above. At the end of this period the pondscaping and landscaping plans should be re-evaluated in light of the field conditions observed and appropriate modifications should be made, if necessary.
6. It is absolutely essential that erosion control devices be applied during the filling and standing periods. All vegetated areas above the permanent pool should be permanently seeded. It is generally recommended that this be accomplished by hydro seeding.
7. After all of the above evaluations have taken place, the wetland should be landscaped. It is recommended that the pond be emptied some time before the wetland is landscaped because it is easier and more efficient to plant a dry area than a wet one.

Adaptations to Constructed Stormwater Wetlands to Meet Special Conditions:
Constructed stormwater wetlands sometimes are planned in unique or difficult conditions and special adaptations are required to ensure that they function properly. Some special cases are discussed in detail below. Much of the information contained in this section is taken from the Virginia Department of Conservation and Recreation (VDCR) Stormwater Design Specifications Manual.

I. Constructed Wetlands in Karst Topography: Karst topography is found in many areas throughout the United States and can present challenges for development in general and for constructed wetlands in particular. If karst formations are thought to be present, the design engineer must perform geotechnical investigations to determine the type of karst formation, the depth to rock, and most importantly, the potential for sinkholes. In some cases, the engineer will decide that constructed wetlands are not a viable option and other means must be employed. However, if a wetland is to be constructed in karst topography, the VDCR recommends the following safety measures be employed:

1. The bottom of the constructed wetland should be at least three above the underlying karst layer.
2. Shallow, linear wetlands are preferable to wetlands with deep pools. In fact, wetlands with deep permanent pools (i.e. pond type wetlands) are generally not suitable for areas with karst topography.
3. An impermeable liner should be used below the bottom of the wetland. The table below gives the specifications of this liner.

Constructed Wetland Situation	Liner Required
Not excavated to bedrock	24” of soil with a maximum conductivity of $1X10^{-5}$ cm/sec
Excavated to bedrock or to near bedrock	24” of clay with a maximum conductivity of $1X10^{-6}$ cm/sec
Excavated to bedrock within a wellhead protection area, in a recharge area for a domestic well, or in a known area of faults or folds.	24” of clay* with a maximum hydraulic conductivity of $1X10^{-7}$ cm/sec and a synthetic liner with a minimum thickness of 60ml.

*Clay shall have the following properties:

- Plasticity Index: Not less than 15% (ASTM D-423/424).
- Liquid Limit: Not less than 30% (ASTM D-2216)
- Clay Particles Passing: Not less than 30% (ASTM D-422)
- Clay Compaction: 95% of standard proctor density (ASTM D-2216)

II. Constructed Wetlands Within Coastal Plains: Because of the generally flat, low-lying terrain typical of coastal plains, constructed wetlands are often ideal in these areas. The following adaptations are applicable:

1. Shallow, linear constructed wetlands work better in coastal plain areas than wetlands consisting of deep permanent pools.
2. Excavation can be below the level of seasonal high water in these areas to help keep the wetland hydrated.
3. Plants selected for the wetlands should be somewhat salt-tolerant. Many coastal tree species are adapted to periodic inundation, so the engineer may be able to plant the wetland as a forest. Trees such as Atlantic White Cedar (*Chamaecyparis thyoides*), Bald Cypress (*Taxodium distichum*), and Swamp Tupelo (*Nyssa sylvatica*) are recommended in Virginia. In other areas around the country, other species may need to be substituted for these trees.

III. Constructed Wetlands and Steep Terrain: Generally constructed wetlands can not be used in steep terrain. The exception to his would be very small wetlands that are built into the hillside. However, an adjustment can be made that allow stormwater wetlands to be employed in these areas. The constructed wetlands can be terraced in a linear manner as with Regenerative

Conveyance Systems (RCS). These systems are open-channeled, sand seepage filtering systems that utilize a series of shallow aquatic pools, riffle weir grade controls, native vegetation and an underlying sand channel to treat and convey stormwater. They can also be used to recharge surface water back into the ground. In some ways, RCS systems combine the attributes of constructed wetlands, sand filters, and other stormwater control devices. They can be used not only in steep terrain but also work very well in coastal plains. As with conventional constructed stormwater wetlands, they must be designed to safely convey the runoff from large storms downstream without causing erosion.

IV. Constructed Wetlands in Cold Climates: Cold weather presents many challenges for constructed stormwater wetlands. Shallow wetland ponds and marshes often freeze over in winter which allows runoff to pass over the system without treatment. Conversely, winter storms and snowmelt often carry a high pollutant load, particularly in the form of salts and chlorides due to road maintenance activities. The following adaptations may help to alleviate these problems:

1. Provide a large forebay with a relatively small permanent pool to catch stormwater during winter storm events and to allow some of the pollutants to drop out of solution. This will also allow the forebay to withstand increased sediment loads due to sanding the roads in winter.
2. Do not submerge inlets pipes and keep a minimum pipe slope of 1% to prevent freezing.
3. Set the outlet pipe of permanent pools several inches below the expected ice level so that the pool can be de-watered in the case of an emergency.
4. Oversize the controlled outlet structure and angle any trash racks to ice formation and freezing pipes.
5. Plant salt tolerant vegetation.
6. In areas where winter stormwater treatment appears to be problematical, it may be necessary treat larger runoff volumes in the spring by adopting a seasonal operation of the permanent pool. If this option is chosen, it is imperative that the design engineer receive approval for the decision from the applicable reviewing agency before implementing the plan.

Maintenance:

As with any stormwater control feature maintenance of a constructed wetland is essential to its continuing functionality. The New York State Stormwater Management Design Manual includes a five page document entitled “Stormwater Pond/Wetland Operation, Maintenance and Management Inspection Checklist”. This checklist will be used to form the basis of the discussion below.

1. Embankments and emergency spillways should be inspected annually and after all major storms. Most importantly, the inspection should check for any signs of compromising of the structural integrity. These would include embankment erosion, animal burrows, cracking, bulging, or sliding of the dam, and seeps or leaks on the downstream side. In addition, the inspection should document that there is adequate ground cover and good vegetation growth in these areas.
2. The riser and principal spillway (or outlet structure) should be inspected on an annual basis. These areas are subject to the build-up of debris and the accumulation of excessive sediment. These should be cleaned whenever necessary. The condition of the riser structure, itself, and any outfall pipes should also be noted.
3. The permanent pool (if any) should be inspected more often; generally on a monthly basis.
4. The sediment forebay should be inspected incidentally when other inspections occur. If the sediment in the forebay reaches an excessive amount (i.e. >50% of the design depth) then it should be removed immediately. When removing sediment from the forebay it is generally desirable to dewater the area first.
5. The semi-wet zone (called "dry pond areas" by the NY State checklist) should also be inspected incidentally when other inspections are taking place. This area should be checked for adequate vegetative growth and for undesirable invasive species, which should be removed. This area should also be checked for standing water or wet spots and for the accumulation of excessive sediments.
6. The condition of any outfalls from the wetland should be inspected on an annual basis and after all major storms. These should be checked for structural damage, riprap failure, slope failure or other problems. Any of these problems should be remediated as soon as they are noted.
7. Miscellaneous inspections and remedial measures should be undertaken when any of the following have occurred:
    A. Complaints are received from neighbors.
    B. Any public health hazard is noted.
8. Wetlands vegetation should be inspected on an annual basis. The vegetation should be seen to be healthy and thriving and free from invasive species. If the plantings are not thriving or if they have suffered >50% loss or damage then replacement or reinforcement plantings will be required. Harvesting of emergent plantings may also be required if they have obtained excessive growth. Finally, the wetland area should be checked for excessive sediment and for appropriate water depth to support the plantings. If there is excessive sedimentation, it

should be removed when noted. If the water depth is not sufficient for the plantings, then it may be necessary to replace them with different species better adapted to the hydrologic regime.

Because maintenance of the constructed wetland is an integral part of the overall design, construction, and operation of the system the design engineer should build maintenance criteria into the design. This can be done in the following ways;

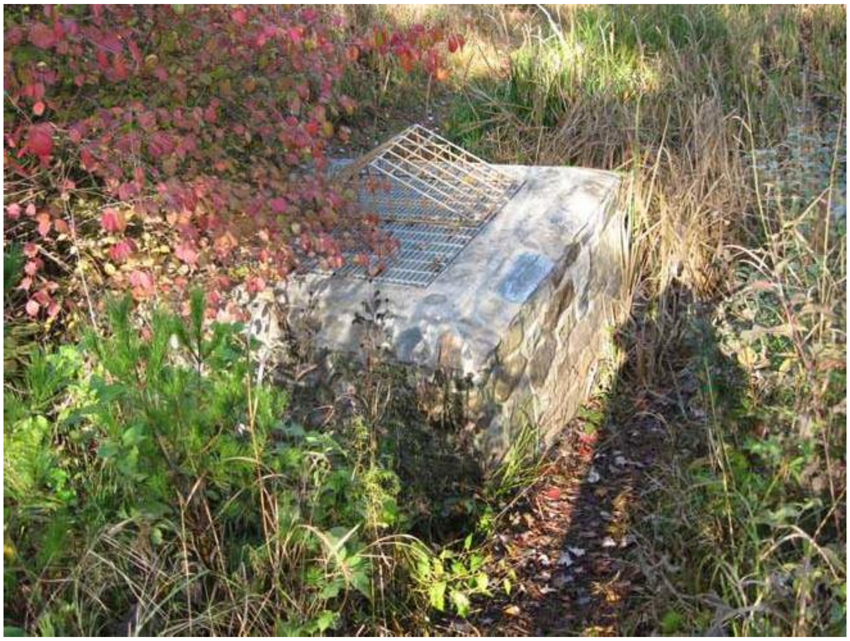
1. Providing for an access way to all of the parts of the wetland. In particular, dams, inlet headwalls, and outlet structures and pipes must be easily reached by maintenance personnel. Access roads along the embankment of a wetland should be constructed with a stabilized base so as to be passable in all weather conditions.
2. Keeping large trees and other woody plantings away from access roads is important. If this is not done then a lack of maintenance can become a cycle; if the trees are not trimmed, maintenance personnel cannot reach the rest of the basin for maintenance, etc.
3. A maintenance log should be provided so that the operator knows exactly what is expected. The "Stormwater Pond/Wetland Operation, Maintenance and Management Inspection Checklist" referenced above can be used as a guide in this regard. The engineer should modify this document, however, to meet the needs of the specific constructed wetland in question.
4. In many states there are state and local officials who have oversight responsibility for the individual wetlands maintenance. This is especially true if the wetland is part of a public or quasi-public project. In these cases, a copy of the wetlands maintenance report must be filed with the appropriate agency. At the time of final design, the engineer should identify who this agency is and provide contact information to the operator of the wetland.

When performing any maintenance on a constructed wetland it is important to keep any disturbance to a minimum. Often the emergent plants within the marsh zone or the plantings around the fringes of permanent pools are fragile and care should be taken not to disturb these plants when performing maintenance activities. Maintenance outside the permanent pools should generally be performed when the area is dry. If a significant number of plantings need to be replaced within the pool areas it is advisable to dewater these areas and wait a few days for drying to occur before replanting.

The constructed wetland shown in the photograph below is badly in need of maintenance. Note that the outlet structure is overgrown with vines and that litter has collected in the bottom of the basin.

The photograph above was taken in the late autumn after much of the foliage had fallen off the trees. However, it is easy to see how this outlet structure could become clogged by the vines during the growing season or by the litter in the bottom of the basin at any time of the year.

Conversely, the photograph below shows a well-maintained constructed wetland. The outlet structure is not overgrown (despite the fact that there is a significant vegetative cover around it) and there is no sign of sediment or debris build-up. Note also the angle of the top trash rack, which allows more area than the flat grate shown in the photograph above.



Concluding Remarks:

It has been demonstrated in this course that constructed stormwater wetlands have a great many benefits besides their ability to treat the quality of stormwater runoff. However, that is their main benefit and they do it very efficiently. In fact, the NJDEP gives them the highest rating in the removal of total suspended solids and also considers that they are quite effective at the removal of both phosphorous and nitrogen.

Constructed wetlands can be used in a variety of ways and in a number of different situations. The main constraint restricting their use is the amount of available water. If a water budget analysis indicates that there is not ample water to keep the wetland hydrated throughout the year, then an alternate method must be used.

Most of the references and examples of stormwater wetlands included in this course are taken from the Mid-Atlantic region. However, stormwater wetlands are used in many other regions and climates as well. They are used both throughout the United States and in many other countries.

The photograph below is taken from the College of Tropical Agriculture and Human Resources in Hawaii. It shows a constructed wetland swale designed to treat urban stormwater runoff.

Based on the facts presented in this course, however, it is apparent that this swale is not very efficient in treating the runoff. The photograph shows a fairly straight, somewhat poorly-vegetated swale flowing through an urban area. Several things could be done to increase its filtering capabilities. These include the following:

1. The swale could be re-laid with a more sinuous pathway which would increase both the time of concentration and the contact area.
2. The topography within the swale could be made more complex with small pools which would allow more of the solids to settle out of the stormwater runoff.

3. It could have a more complete vegetative cover both within the bottom area of the swale and along the banks. This would not only filter out more pollutants, but it would also reduce the potential for bank erosion.
4. It could be directed into a pond or marsh type wetland, where significantly more treatment would take place.