The Biofilter Wetland: Design and Construction of an Urban BMP to Treat Stormwater

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Introduction:

Constructed biofilter wetlands have become a well-accepted Best Management Practice (BMP) for treating stormwater (Ferlow, 1993; PA DEP, 1998; EPA, 1999). Unlike traditional stormwater detention basins that only provide stormwater storage and desynchronization of peak flows, properly designed stormwater treatment wetlands can provide significant water quality benefits (Ferlow, 1993; Kadlec and Knight, 1996). There are several documents that provide design guidance for constructing these wetlands (Moshiri, 1993; Kadlec and Knight, 1996; Pierce, 1993; EPA 1999; USDA, 1992). The key to improving water quality is to develop a design that allows for extended pooling or detention time within the wetland. This enables sediments with adsorbed pollutants to settle out, and allows the plants and micro-organisms within the wetland to take up the nutrients and biodegrade various pollutants, in addition to enabling certain chemical transformations.

In order to determine the proper wetland size relative to the drainage area, a hydrologic budget is prepared that accounts for historic average precipitation, evapotranspiration, and substrate seepage. This, along with a TR-55 (USDA, 1986) type analysis of expected runoff from various design storms (typically the 5-year storm), and an analysis of anticipated pollutant loads and desired removal efficiency enables determination of the wetland volume that will yield the desired detention time. In relatively flat areas in Pennsylvania and New Jersey, these calculations typically result in a desired wetland area on the order of 5% of the drainage area. This process is appropriate for developing a design for a wetland to treat runoff from a new development project where the designer is essentially working with a blank slate and has control over both the location and size of the BMP.

In urban areas, particularly in retrofit situations, space is often severely constrained and the designer has minimal control over the location and size of the BMP. Typically, the standard analyses will yield a desired volume or area that is impossible to achieve within the available space. In those situations, one must take a different tack. Given the available area, how large can the wetland be? Given the anticipated pollutant loads and minimum retention times to achieve a reasonable degree of treatment, how much flow can be treated? Can a water control structure be designed that will allow complete treatment of the small storms that account for 90% of the runoff in urban areas and the first flush of larger storms, while allowing larger flows to pass through untreated? Can performance be improved with a pre-treatment sedimentation chamber?

Another important consideration is aesthetics. In urban areas, waterbodies such as rivers and lakes that are receiving stormwater flows are typically publicly owned with parks along the shorelines, and attract numerous visitors on a daily basis. It is important that treatment wetlands in these areas not look like typical treatment wetlands. They should be as attractive as possible, using native plants and wildflowers. The design should be attractive to human visitors and native wildlife but unattractive to invasive
pests such as non-migratory Canada geese. Ideally, visitors should not suspect they are looking at a 'treatment wetland' unless they read the sign explaining what they are looking at and why.

**General Wetland Design Principles:**

There is no single wetland design that is optimal for all situations or locations. The design for a particular project needs to be developed based on desired goals for the project and site-specific considerations. Mitsch (1992) suggests the following broad guidelines for creating successful constructed wetlands:

- Keep the design simple-complex approaches invite failure.
- Design for minimal maintenance.
- Use natural energies such as gravity flow and nutrient influx from streams or runoff.
- Design the wetland with the landscape, not against it. Integrate the design with the natural topography of the site.
- Avoid over-engineering the site with rectangular basins, rigid structures, and channels and regular morphology. Mimic natural systems and forms.
- Give the system time. Wetlands do not become functional overnight.
- Design the system for function, not form.

In addition to these broad general guidelines, the wetland designer needs to have an understanding of how wetlands improve water quality. Long known as the “kidneys of the landscape” or “Mother Nature’s wastewater treatment plant,” wetlands are complex systems that improve water quality through a combination of physical, chemical, and biological processes. These processes include (USEPA 1999):

- Physical settling of suspended solids in accordance with Stoke’s Law.
- Filtration and chemical precipitation through contact of the water with the substrate and litter.
- Adsorption and ion exchange on the surfaces of plants, substrate, sediment, and litter with subsequent burial.
- Chemical transformation.
- Breakdown and transformation of pollutants by micro-organisms and plants.
- Uptake and transformation of nutrients by micro-organisms and plants.
- Predation and natural die-off of pathogens.

These natural processes are the result of complex interactions between the water flowing through the wetland and the macrophyte and unicellular plants, the macroinvertebrate assemblage, the litter and substrate, as well as micro-organisms such as bacteria that are present throughout the volume of the water and substrate, and attached to the plants and litter.

The linchpin of this complex biological system is the vegetation, which is the main difference between a treatment wetland and a simple wet pond detention system. While the plants can directly take up some pollutants such as nutrients or metals, they control the functioning of the wetland indirectly through the ability to produce organic carbon through photosynthesis (Tarutis and Unz, 1996). This plant biomass eventually degrades to become an organic litter layer at the top of the sediments, which subsequently undergoes burial and diagenesis. This litter layer acts as a trickling filter and adsorption bed for metals and other pollutants. Additionally, macrophyte plants serve to stabilize
the sediment layer, enhance sedimentation by reducing flows and capturing particles, diffuse oxygen into the sediments, induce advective flows towards the roots through evapotranspiration, and provide attachment sites for epiphytic algae and bacteria that help take up or reduce pollutants, especially metals. The root zone, or rhizosphere, provides a relatively oxic zone of biological activity, such as burrowing worms, which can influence the REDOX chemistry of the sediments through bioturbation and bioirrigation. Additionally, dead root biomass serves as an important source of organic carbon at depth, serving as a substrate for bacteria and fungi.

To take advantage of these various pollutant removal mechanisms and to facilitate routine maintenance, a good biofilter wetland design will try to incorporate some or all of the following features:

- A forebay area to allow settling of larger suspended sediments and facilitate subsequent removal of same periodically.
- A permanent deep water pooling area to enable a diverse community of aquatic organisms to become established.
- Heavily and diversely vegetated swales between ponding areas to slow flows, inhibit resuspension of sediments, and maximize contact between the water and the vegetation.
- Inlet and outlet structures that can control flow through the wetland so that very high flows don’t result in excessive erosion.
- Diverse native vegetation around the basin areas for both aesthetics and control of nuisance species such as non-migratory Canadian Geese.

Figure 1 depicts a plan view of a biofilter wetland at Strawbridge Lake in Moorestown, NJ, illustrating some of these features. Figures 2 and 3 are photographs of this wetland after 2 years of operation.

To ensure survival of the wetland vegetation, and sufficient water to keep ponds permanent, a detailed water budget needs to be prepared. A simple formulation for a wetland water budget is:

\[
\text{Inflows} - \text{Outflows} = \text{Change in Storage}
\]

For a stormwater treatment wetland, the inflows will be precipitation and stormwater runoff from the contributing watershed, the outflows will be seepage, evapotranspiration, and surface outflow. Since one of the keys to the success of your wetland is the ability to keep it permanently wet, it makes sense to keep track of cumulative water stored in the permanently ponded portion of the wetland, which cannot be greater than the volume of the permanent ponds. A spreadsheet can be constructed that accounts for runoff volume, evapotranspiration, and seepage.

To estimate the runoff from the contributing watershed, a TR-55 (USDA, 1986) type analysis should be performed to develop a composite curve number (CN) based on land use and underlying soil drainage group. In urban areas, this will be a fairly high curve number, typically something in the range of 80-90. Runoff can be estimated by using the SCS runoff equation:
\[ Q = \frac{(P-0.2S)^2}{(P+0.8S)} \]

where

- \( P \) = inches of rainfall,
- \( Q \) = resultant rainfall,
- \( S \) = potential maximum retention of the ground in inches, and
- \( S = \frac{1000}{CN} - 10 \).

For the water quality design storm of 1.25 inches of precipitation and a curve number of 85, the calculated runoff is 0.302 inches or roughly 24% of what falls. For a CN of 90, the runoff would be 0.494 inches or 40% of what falls. For smaller storms, the percentage of runoff would be somewhat less and for larger storms somewhat more. For average water budget calculations, this percentage runoff factor can be used along with the monthly average precipitation for a region (available from Northeast Regional Climate Center: [http://climod.nrcc.cornell.edu](http://climod.nrcc.cornell.edu)) to construct a spreadsheet that can be used to calculate total water volume for the wetland. The percentage runoff is multiplied by the contributing watershed area times the precipitation in feet to estimate runoff volume in acre-feet.

The evapotranspiration can be estimated from pan evaporation or calculated by Thornthwaite’s method (Thornthwaite and Mather, 1955). In New Jersey, the New Jersey State Climatologist ([http://climate.rutgers.edu/stateclim/clim.html](http://climate.rutgers.edu/stateclim/clim.html)) measures evapotranspiration at various sites around the State and can provide both evapotranspiration (ET) and average number of freeze days per month. Again, the ET is normally provided in inches/month and needs to be converted to acre-feet for the water budget calculations by multiplying the ET in feet by the total area of the wetland.

Seepage from the wetland can be estimated from infiltration rates available in the local soil survey. Seepage can be measured in the field by conducting a percolation test. If the seepage exceeds approximately 0.05 inches/hour (USDA Soil Groups A, B, C), it will be difficult to retain water in the wetland. If necessary, seepage can be reduced by lining the wetland with clay or mixing enough clay into the subsoil under the wetland.

Table I is a copy of a spreadsheet summarizing water budget calculations for a ¾-acre wetland with a permanent ponding volume of .35 acre-feet. The contributing watershed is 23 acres and the runoff coefficient estimated at 35%. The precipitation numbers are ten-year monthly averages, as are the evapotranspiration and freeze-day numbers. The calculations show that, on average, there will be sufficient water volume to maintain the ponded areas at full capacity in every month except November, when seepage exceeds inflows and the ponded volume is reduced to 0.25 acre-feet.

This type of spreadsheet is useful to conduct sensitivity analyses and sizing calculations for the wetland. The total volume outside the permanent ponding area should be sufficient to hold the runoff from a 1.5-inch storm for approximately 18-36 hours to ensure sufficient settling (Ferlow, 1993). The outflow structure can be designed to slowly release the overflow, ensuring extended detention time. From a water quality perspective, the longer retention times allow more time for the various pollutant removal mechanisms to take place. This is especially true where uptake by the plants is an important mechanism.
Limitations Caused by Urban Environment:

In new development situations, it is relatively straightforward to develop a design that will remain wet and contain sufficient volume to retain stormwater for the desired retention time. In urban areas, particularly in retrofit situations, space is often severely constrained and the designer has minimal control over the location and size of the BMP. Due to the high percentage of imperviousness and concomitant high runoff coefficient, urban runoff tends to be quite flashy, with rapid time of concentration and rapidly rising water levels. Typically, the standard analyses will yield a desired volume or area that is impossible to achieve within the available space. Additionally, the pollutant loads tend to be fairly high, especially the “first flush” that carries accumulated dust, metals, and oil and grease from the roadways (Taylor et. al., 1993). In those situations, one must take a different tack. Given the available area, how large can the wetland be? Given the anticipated pollutant loads and minimum retention times to achieve a reasonable degree of treatment, how much flow can be treated? Can a water control structure be designed that will allow complete treatment of the small storms that account for 90% of the runoff in urban areas and the first flush of larger storms, while allowing larger flows to pass through untreated? Can performance be improved with a pre-treatment sedimentation chamber?

In addition to space limitations, other factors can inhibit the wetland design in urban areas. For example, if the problem is to retrofit an existing stormwater sewer system, the designer has minimal control over changing existing pipe inverts and generally must design the wetland to fit the invert instead of the normal process of specifying an invert to go with the design.

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With the increasing spread of West Nile Fever in the Mid-Atlantic Region, mosquito control has gained in importance. There are two basic design approaches to controlling mosquito breeding in wetlands. One approach is to ensure that no water stands for longer than four days. This is appropriate for design of a wet meadow, bioretention basin, or other infiltration type BMP. The other approach is to ensure a permanently ponded (but not stagnant) area that encourages the development of a diverse community of macroinvertebrates (especially dragonfly larvae) as well as forage fish and amphibians that will control the mosquito population. In isolated wetlands, mosquitofish (Gambusia sp.) can be introduced, which are available in New Jersey from the local mosquito control commission. For wetlands contiguous to other water bodies, the green sunfish (Lepornis cyanellus) a hardy, native mosquito-eating fish can be stocked.
Engineering for Urban Situations:

In urban situations, the space is not typically available to build a treatment wetland that will capture and treat all the runoff from every rainfall event. Therefore, treatment wetlands are designed to capture and treat runoff from the smaller storm events. Since 90% of all storm events produce less than one-inch of rain, the key to reducing pollutant loads is to treat the runoff associated with the first one-inch of rain (Clayton & Schueler, 1996). By designing the wetland to capture and treat the runoff associated with one inch of rain, the wetland will also be capable of capturing and treating the first flush of the larger storms. The first flush carries the majority of the pollutants during each storm event.

Water control structures are required to divert the first flush into the treatment wetland. Typically, the storm water outfall that is being retrofitted with a treatment wetland consists of a series of catch basins on a road adjacent to a river or lake and a storm water pipe that carries flow from the catch basins directly to the waterway. This pipe is typically 24” to 36” in diameter and traverses a streamside buffer that usually consists of mowed grass. A diversion chamber is placed in this pipe near the road end of the pipe. This diversion chamber consists of a weir to divert the low flows to the treatment wetland and allows the larger flows to go over the weir and continue directly to the waterway (See Figure 4). Since the storm water outfall to be retrofitted is almost always designed for the 25-year storm or greater (over 5 inches of rainfall in 24 hours), a weir can be designed to divert the flow from the one-inch rainfall event without creating a backwater condition that will cause ponding at the roadway near the catch basins.

A potential problem with the diversion chamber can be the build up of sediment in front of the weir. If the diversion chamber is not regularly cleaned, this sediment build up can eventually hinder flow from entering the treatment wetland. Storm water runoff that contains high concentrations of sediment can also result in sedimentation of the constructed treatment wetland. Typically, treatment wetlands contain a forebay that can easily be cleaned to trap sediment. Where space is limited, a manufactured pre-treatment system can be installed to trap sediment prior to the runoff entering the constructed wetland. The StormCeptor and Vortech system are two such pre-treatment systems that are available as an attractive alternative to a forebay. Once again, these systems require regular maintenance but can dramatically extend the life of a constructed treatment wetland.

Equally important to properly designing the inlet structure (i.e., diversion chamber) for the treatment wetland is the design of the outlet structure. Since the treatment wetland is adjacent to a river or lake, the interaction of the water surface elevation of the receiving water with the treatment wetland must be considered. The outlet control structure for the treatment wetland is designed to retain the runoff from the water quality design storm (1.25 inches of rain over two hours). This structure is designed by performing a standard reservoir routing calculation assuming the wetland discharges to a free environment. The water surface elevation of the receiving water is then calculated for the design storm. Reservoir routing calculation are then performed on the wetland by altering the outlet based on the backwater effects due to the rise in the elevation of the receiving water. These calculations are then performed for the larger design storms to predict how the wetland will react under higher flows. Typically, the wetland will become flooded by the adjacent waterway during these larger storm events.
Aesthetics and Landscaping:

Plant material is an integral component to the design and function of the biofilter wetland. Recommended materials should be native species selected for their ability to withstand periodic flooding and drier/droughty conditions. Where possible and where information is available, species should be selected for their pollutant tolerance and pollutant removal capabilities.

The planting arrangement is flexible but should remain in a random or "natural plant layout". While flexible, it is important to establish distinct and diverse layers of overstory trees, understory trees, shrubs and herbaceous materials. The intent is to establish a diverse, dense vegetative cover to treat stormwater runoff and withstand stresses from insect and disease infestations, drought, temperature, wind and exposure. From an aesthetic perspective, choosing plants that flower at different times throughout the year, can ensure a visually-pleasing wetland that is attractive to beneficial insects and other wildlife. The “Native Species Planting Guide for New York City and Vicinity” (City of New York, 1993) is a good reference for these type of considerations. Other useful native plant references are Thunhorst (1993) and Hightshoe (1988).

The plant material takes up some nutrients and other pollutants, and available water through evapotranspiration. The use of native plant material, combined with minimum planting area size provides cover for wildlife and creates a micro-environment within the landscape. The conditions of a biofilter wetland mimic natural wetland and floodplain areas. Typical species found in these areas should be obtained from local native plant nurseries and installed per standard specifications. Material should be selected at the nursery by a qualified individual who will visually inspect trees and shrubs either at place of growth or at site before planting for compliance with requirements for genus, species, variety, size and quality. During the first year after planting of the basin, it may be necessary to protect plant material from goose predation with perimeter fencing. Plantings along the edge of water areas that are at least two feet tall (taller than a goose) will tend to discourage Canadian geese and reduce pollutant loadings from these nuisance birds.

While much less than manicured landscapes, some maintenance of vegetation is necessary. During the critical first two years of establishment, regular inspections every three to six months should be done. Regular inspections should note any plant mortality and the need for vegetation replacement. The vegetation planted should achieve between 80-100% coverage within a two-year period. Apart from the removal of invasive vegetation, regular maintenance of herbaceous vegetation is not required and herbaceous areas should not be mowed more than once a year. Proper maintenance is important for most trees and shrubs and will result in beautiful plants year after year. Typical maintenance considerations include watering thoroughly during the first year, if necessary, and occasional pruning if desired for aesthetic reasons or to remove dead stems.

If inspection by a qualified person deems that invasive vegetation has become established, removal of the invasive vegetation by hand weeding may be needed. Common invasive species include; Japanese knotweed, multiflora rose, purple loosestrife, phragmites, and tree-of-heaven. If a contiguous area of removal exceeds 100 square feet, the area should be reseeded/replanted with the original mix of vegetation, or with suitable substitutes if a particular species has a poor success rate.
A biofilter wetland offers opportunities for educating local residents about water quality improvements and, in particular, the role of wetlands in improving water quality. If located in a public park, educational trails and signage can provide visitors to these areas with the opportunity to explore the biofilter wetland area and learn about the need for treating stormwater before it enters lakes and streams. Descriptions of the native plants in the wetland and common wildlife will enable visitors to learn more about their local environment.

**Summary and Conclusions:**

In summary, urban areas place special constraints upon the design of stormwater treatment wetlands. However, by following certain basic design guidelines, effective, visually-pleasing stormwater BMPs can be designed that will improve water quality in these urban areas. These types of BMPs can often be incorporated into larger shoreline stabilization projects in urban waterways and can enhance the effectiveness of the stabilization by eliminating a major source of runoff. Additionally they can serve as focal points for educating residents about the functioning of the natural environment.
References:


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