Quantifying the Role of Wetlands in Achieving Nutrient and Sediment Reductions in Chesapeake Bay

Chesapeake Bay Program STAC Responsive Workshop
Sponsored by the Chesapeake Bay Program's
Land Growth and Stewardship, and Living Resources Subcommittees

November 2008
STAC Publication 08-006

Based on April 4, 2007 Workshop

About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program on measures to restore and protect the Chesapeake Bay. As an advisory committee, STAC reports periodically to the Implementation Committee and annually to the Executive Council. Since it's creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical conferences and workshops, and (5) service by STAC members on CBP subcommittees and workgroups. In addition, STAC has the mechanisms in place that will allow STAC to hold meetings, workshops, and reviews in rapid response to CBP subcommittee and workgroup requests for scientific and technical input. This will allow STAC to provide the CBP subcommittees and workgroups with information and support needed as specific issues arise while working towards meeting the goals outlined in the *Chesapeake 2000* agreement. STAC also acts proactively to bring the most recent scientific information to the Bay Program and its partners. For additional information about STAC, please visit the STAC website at www.chesapeake.org/stac.

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Appendices:

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Executive Summary:

Nine regional and national wetlands experts were invited to present recent research and findings to determine if there is a sufficient scientific foundation to quantify the benefits of wetlands restoration/enhancement for nutrient and sediment transport and processing. Based on their research, the presenters were able to provide recommendations for improving the development and implementation of wetland efficiencies into the Chesapeake Bay Watershed Model.

Highlights from the discussion moderated by Dr. Carl Hershner, Virginia Institute of Marine Science:

1. Current Knowledge Base for Refining Wetland Best Management Practices (BMP):

- Acreage area and geo-referenced location is presently used to determine where wetland restoration and creation projects are being implemented in Bay watershed States.
- Published work by Dr. John Day (Louisiana State University) and Dr. Bill Mitsch (Ohio State University) provides gross aerial estimates of phosphorus and sediment removal (per unit area wetland).
- Project managers working on wetland restoration/creation projects at the field level are familiar with the drainage area for a given project; however, drainage area data is not presently reported to the Chesapeake Bay Program or to the state regulatory agencies.
- Use of agricultural land ratios in the Chesapeake Bay watershed by hydrologic unit.

2. Chesapeake Bay Program Research Needs for Improving Efficiencies Calculations for Restored, Created, and Enhanced Wetland Systems:

- High resolution, up-to-date data on wetland acreage as a current land use
- Data on wetland age (which relates to phosphorus retention)
- Pre- and post-BMP wetland condition and monitoring data

Workshop Recommendations:

- Examine most recently released National Land Cover Data for existing wetland acreage.
- Investigate use of Digital Elevation Model (DEM) to determine drainage area of wetlands (works well in non-tidal areas, but not as well in tidal areas).
- Examine Elevation Derivatives for National Application (EDNA), a USGS product, for wetland age information.
- Target wetland BMPs for areas of known high Nitrate loading and prioritize wetlands based on drainage area.
- For targeted watersheds, work with State and Federal funding partner agencies to collect pre-BMP wetland condition data and require three years post-BMP monitoring data.
- Ask States to improve reporting of wetland project location to the Hydrologic Unit Code (HUC) 11 level; also ask that they begin to report drainage area associated with each project. [Note: Wetland drainage area was included as a field in water year 2007 data request form; no feedback was received in the first attempt]

- For Phase 5 of the model and beyond, consider an “extra credit” for wetlands associated with riparian forest buffers (places where both exist on landscape in combination). There needs to be additional discussion about how to incorporate wetlands that are riparian buffers into the model.
- Modify wetland efficiency based on drainage area as reported by states or using surrogate values as outlined in the following Wetland BMP proposal, subject to review.
- Seek additional sources to improve efficiency estimates for existing and enhanced wetlands.

Introduction:

The “Quantifying the Role of Wetlands in Achieving Nutrient and Sediment Reductions in Chesapeake Bay” workshop was designed to assemble the most current scientific information on the role of wetlands in reducing loads of nitrogen, phosphorus, and sediment in overland flow. The Chesapeake Bay Program’s (CBP) Watershed Model estimates the effects of various restoration efforts so that when the appropriate water quality levels are achieved, the Bay and its tidal tributaries can be removed from the impaired waters list. Environmental managers use different methods to improve water quality conditions, each known as a Best Management Practice (BMP). The effectiveness of a wetland BMP is determined by calculating or measuring the removal of nutrients and sediments associated with that BMP. Currently, removal efficiencies for created or restored wetlands used in the Chesapeake Bay Watershed Model are assumed to be the same as those for riparian buffers; efficiencies are not available for enhanced wetlands and are therefore not accounted for in the Model. This workshop facilitated discussions that lead to more accurate parameters included in the next version of the Watershed Model.

The Watershed Model regards wetlands as a BMP for water quality in two ways:

- Nutrient/sediment load reduction in both agricultural and mixed open (i.e. urban) areas (removal efficiency by wetlands is currently assumed to be equal to that of forest cover, which in Phase 4.3 of the Model is credited as 57% for Nitrogen and 70% for Phosphorus and sediment; the difference is that two acres area assumed to be treated by each acre of forest buffer, whereas four acres are assumed to be treated by each acre of wetland);
- Land use conversion (changing from another land use to wetland or vice versa).

Discussion Questions:

Each presenter at the workshop was asked to address the following questions:

1. What influence does scale (landscape vs. site specific) have on the efficiency of nutrient and sediment uptake (i.e. what controls nutrient and sediment processes within a wetland)?
2. Does focusing on certain geographic wetlands systems (piedmont vs. coastal) for restoration/enhancement projects merit a higher BMP credit in one system vs. another?
3. Noting that preserving/restoring forest buffers and stream corridors is important for maintaining high water quality, would the BMP credit be higher if wetland restoration/enhancement projects were done in conjunction with the forest buffer and stream restoration?
4. How efficient are created wetlands in nutrient and sediment removal in the urban storm water context?
5. How can your research relate the efficiency of nutrient and sediment uptake to certain species of wetland vegetation?
6. How does your research on wetland restoration/enhancement outline future management implications?

1. What influence does scale (landscape vs. site specific) have on the efficiency of nutrient and sediment uptake (i.e. what controls nutrient and sediment processes within a wetland)?

Detention Time

Scale affects a site's nutrient uptake ability by having a tremendous influence on the flow of water through the system. Wetlands that receive unregulated, non-point source inflows differ greatly in water detention time. According to first order kinetics, concentrations of removed materials should decline exponentially with time. Water detention time is roughly proportional to the ratio of wetland area to watershed area because watershed discharge and wetland volume increase with their respective areas. Simulation models predict that removal percentages increase as the proportion of wetland areas increases; however, published measurements show that much of the variance in removal percentages remains unexplained by the simple area relationship. Nevertheless, a non-linear regression model fit to measured phosphorus removal percentages suggests that the average proportion of inflowing phosphorus removed is 1-e-16.4a where *a* is the proportion of wetland in the watershed. By the same analysis, the average proportion of inflowing nitrogen removed is 1-e-7.9a. Removal efficiencies decrease with increased variability of water flow. Thus, a wetland with steady inflow rate would have higher removal efficiencies than a similarly-sized wetland with the same annual water flow concentrated during a few high flow events.

Water Velocity/ Flow Variability

In addition to detention time, research conducted on Kent Island, Maryland consisting of a wetland restoration project in an agricultural watershed showed the affects of water velocity on nutrient uptake. Water entering the wetland was slowed by a berm and then slowly drained by a standpipe. A v-notch weir was placed on the standpipe to accurately measure the velocity of water through the pipe. This project was monitored for two years with the first year being very dry with little surface flow out of the wetland and the second year being very wet. During the first year (dry), the wetland experienced a percentage of inflow removed by the wetland of 59 for total phosphorus, 38% for total nitrogen and -4.1% for total suspended solids. During the second year (wet) the results were not so compelling with removal of -11% for total phosphorus inflow, -8.4% for total nitrogen and 27% for total suspended solids. Combining the two years leads to a percentage of inflow removed by the wetland of 27% for total phosphorus, 14% for total nitrogen and 13% for total suspended solids. It was observed and measured that during the second year of monitoring, water moved through the system so fast that nutrients previously captured by the wetland began to leach out. A literature review comparing nitrogen and phosphorus removal among wetlands receiving unregulated inflows confirmed the Kent Island observations.

When predicting efficiency, the following assumptions must be made: the removal of nitrogen or phosphorus is exponential with time; water detention time equals wetland volume/flow which equals wetland area/watershed area; wetland receives watershed discharge; wetland area is less than the watershed area; and removal is equal to 0 if wetland area is equal to 0. When looking at the effects of detention time, the following rules apply: efficiency increases with increasing detention time and increasing wetland area and storage volume; efficiency decreases with increasing flow variability. Therefore, the conclusion can be made that wetlands receiving unregulated inflow are less efficient and wetlands become less efficient as impervious surface increase in the watershed. Also, the efficiency of wetlands increases with age in the first few years as vegetation and organic matter accumulate; however, the efficiency begins to decrease with age after the wetland begins to fill in. Efficiency cannot be assigned a single value because it is a function of wetland size relative to inflow and wetland age.

Sediment Distribution

Wetlands' ability to capture sediment is an important mechanism by which wetlands improve stream water quality, but sediment is not uniformly deposited throughout wetlands. Streams migration, abandoned channels, and the formation of streamside levees in natural wetlands alter the spatial patterns of new sediment deposition. Measured sedimentation and associated phosphorus deposition within several Midwestern wetlands was greatest within short distances (<20m) of tributary streams. Within-wetland geomorphic structure (riverbed, levee, backwater) exhibited different sedimentation rates: sedimentation was greater in marshy strips adjacent to the mainstem of the river than it was in backwater areas behind the natural river levee. Sediment deposition raises the level of the wetland surface, altering its inundation frequency and aeration, which in turn alters redox-associated processes. Sediment deposition also alters the texture and organic matter content of wetland soils, which can promote the growth of often undesirable plant species. In the Great Lakes' coastal wetlands, 90 of 169 plant species studied had a significant affinity for a particular soil type (sand, silt, clay, organic). The water quality benefits of using natural wetlands for sediment retention should be weighed against potential negative effects of sedimentation on biotic quality.

Sediment high in phosphorus, a pollutant in many aquatic ecosystems, can be damaging in and of itself. One of the benefits of sediment retention in wetlands is that it keeps phosphorus out of aquatic ecosystems. The downfall of sediment retention is that increased phosphorus loads in wetlands promote the growth of undesired plants; also wetlands only have a finite capacity for sediment retention.

There was a study of material retention at two study sites: 1) White Clay Lake and 2) Lake Superior tributaries. White Clay Lake showed greatest material retention in alluvial soils of natural levees. Material was also retained by enrichment of soil surface. The conclusion was that at White Clay Lake that there was an average soil alluvial soil accretion of 1.3 cm/yr; average sediment accumulation was 2.0 kg m^{-2} yr^{-1}; average phosphorus accumulation was 2.6 g m^{-2} yr^{-1}; and the average nitrogen accumulation was 12.8 g m^{-2} yr^{-1}. At site 2, Lake Superior tributaries, soil texture and water depth varied in their sedimentation rates along the tributaries with different flow rates. Material flux, measured at the riverbed, backwater and back marsh at several sub-sites, was mostly found to be higher in the riverbed and lower in the back marsh, with the backwater flux being in the middle.

Sedimentation is an important material retention mechanism in wetlands along streams of all sizes however sediment (and associated phosphorus) retention is localized in certain geomorphic structures: natural levees, marsh strips on the river side of levees, and sparsely vegetated backwater sloughs. Although wetlands are able to retain sediments and nutrients, they are not a panacea for poor water quality. BMPs must be implemented to keep sediment on the land.

Hydraulic Loading Rate

The effectiveness of wetlands in nitrate reduction is largely a function of hydraulic loading rate, hydraulic efficiency, nitrate concentrations, temperature, and wetland condition. Hydraulic loading rate and nitrate concentration are especially important for wetlands intercepting nonpoint source loads. Hydrologic and nitrate loading patterns vary considerably for different landscape positions and different geographic regions. In addition to spatial variation in land use and precipitation, there is considerable temporal variation in precipitation. As a result, loading rates to wetlands receiving non-point source loads can be expected to vary by more than an order of magnitude, and will to a large extent determine nitrate loss rates for individual wetlands. Much of the variability in mass nitrate removal among wetlands can be accounted for by explicitly considering the effect of hydraulic loading rate and nitrate concentration. Analysis of 34 "wetland years" of mass balance data (12 wetlands with 1-9 years of data each) for sites in Ohio, Illinois, and Iowa demonstrates that the performance of wetlands representing a broad range of loading and loss rates can be reconciled by a model explicitly incorporating hydraulic loading rate and nitrate concentration. The model explains 94% of the variability in mass removal rates for these wetlands.

After studying water quality benefits of wetland restoration, specifically looking at nitrate removal efficiency and mass nitrate load reduction by emergent marshes in agricultural watersheds, the following must be taken into account when restoring wetlands as nitrogen sinks in agricultural watersheds.

- Nitrogen sources and loads in agricultural watersheds
- Nitrogen transformation in wetlands
- Mass balance analysis and modeling of wetland performance
- Predicting watershed scale nitrogen loading and load reductions by restored wetlands.

The following are primary factors controlling non-point source (NPS) nitrate loss in wetlands:

- Bioactive surface area
- Organic carbon supply
- Nitrate transport rate
- Temperature
- Dissolved oxygen
- Nitrate concentration and residence time

Mass nitrate removal by wetlands is inversely related to the hydraulic load rate as measured in meters/year (primary determinant in ability of wetland to act as nitrogen sink). Only if nitrate concentrations are low enough then wetlands could potentially act as source of nitrogen (otherwise, they act as a net sink for nitrogen). To optimize nitrogen removal by wetlands, first determine where nitrate concentrations are highest, then target restoration/protection of those wetlands that drain the size watershed(s) that produce the hydraulic load rate (m/yr) you want to receive.

2. Does focusing on certain geographic wetlands systems (piedmont vs. coastal) for restoration/enhancement projects merit a higher BMP credit in one system vs. another?

Sediment and nutrient removal

One of the most important functions wetlands offer is the storage of sediment and the reduction of suspended solids. Natural and constructed wetlands have variable and temporal states of disturbance that affect sedimentation rates and services. Published studies indicate that ranges of sediment entrapment are available for only a few types of natural wetlands and that insufficient sediment entrapment studies have been conducted. However, by compiling information from studies across the country we can produce ranges of sediment sequestration potential based on simple classes of wetland ecosystems, such as condition, sediment loading potential, vegetation, hydrology and geomorphology. Existing BMPs may be used for preventing sediment from entering wetlands, and new BMPs may be produced for sustainably sequestering sediment and prevent re-suspension.

Wetlands offer many methods to retain sediment: settling due to a decrease in velocity or turbulence; settling due to flocculation; and adsorption onto plants and soil particles. Factors that affect the variability of these sedimentation rates are 1) intrinsic factors which include wetland geomorphology and hydrology; exposure/anchoring of sediment; and vegetation types and ground cover (i.e. fine leaf grasses, broad-leaf forbs, tree trunks, brush stems, bare ground with annual vegetation, and litter). 2) Extrinsic factors include dynamic changes in watershed over time (i.e. changes in stream or water body character; varying water velocity and quantity, and varying type and supply of sediment to wetland); direct human disturbance; and catastrophic events. The differences in wetland geomorphology and hydrology also play a role in the sediment retention. Wetland characteristics of closed depressions, lacustrine and pond, and flats play an important role. For example, lacustrine and pond areas that are several feet deep, isolated, and have inflow will have high retention of inputs – steady retention from flowthrough waters if the wetland is vegetated. Riverine systems (overbank) will have sandy soil retention at the natural levee as well as at the backswamp. As for tidal (estuarine and freshwater) wetlands, the entrapment is dependent on wave energy and vegetation type. These are very dynamic systems and storms can have catastrophic effects. Factors that affect tidal marsh entrapment and erosion are vegetation type and density, sediment supply, fetch, exposure to currents and boat wakes, difference in high and low tide, exposure to storm tides, hurricanes and tsunamis.

Also, published studies indicate that ranges of sediment entrapment are available for only a few types of natural wetlands and that insufficient sediment entrapment studies have been conducted. Many studies do not include sufficient information about the watershed characteristics of the normality of rainfall events, or the amount of human alteration of the watershed hydrology.

Few quantitative estimates exist for the percent retention of annual river loads of nitrogen, phosphorus, and suspended sediment by wetlands. Measurements were collected for depositional fluxes of nutrients and suspended sediment onto floodplain soil surfaces (g m^{-2} yr^{-1}; 1-6 yrs of accumulation) over a sampling network that included the Coastal Plain portion of five rivers in the Chesapeake Bay watershed. For each river, the average nitrogen, phosphorus, and sediment depositional flux rates were multiplied by an estimate of floodplain area to calculate floodplain trapping rates (kg yr^{-1}), and then compared to average river loads. Average material retention among the rivers was 27% of nitrogen (range 6-70%), 38% of phosphorus (15-82%), and 69% of suspended sediment (5-95%). Uncertainty in these estimates of retention derive from several assumptions related to adequacy of sampling network, permanency of the sink of deposited nutrients and sediment, and relative importance of the rivers as the source of deposited material. Coastal plain floodplains in the Chesapeake Bay watershed likely function as an important long-term sink for material transported by rivers, greatly reducing loading rates to the Bay. Restoration activities that increase floodplain area or the hydraulic connectivity between floodplains and river channels most likely would enhance nutrient and sediment retention.

Floodplains are important for retaining nutrient and suspended sediment in the Chesapeake Bay watershed because they represent the last location to retain materials, in which case, it is ideal to restore the system and let the water return to the floodplain. The floodplain acts as a speed bump for water, slowing it down and giving it time to spread across the plain and filter out its nutrients and sediments. The role of coastal plain floodplains in the Chesapeake Bay watershed is three-fold: 1) Sediment, phosphorus and nitrogen load retention rates are potentially very high (Sediment>P>N) 2) Load retention is a function of floodplain area [sink] and upstream land use [source] and 3) the permanence and sources of deposited material still needs to be studied in further detail.

Wetlands can transform reactive nitrogen into inert gaseous forms (N_2) through microbial activity. Sedimentation, soil adsorption, and plant uptake are important mechanisms for phosphorus uptake in wetlands. While water quality improvements of wetland mitigation have been well documented, trade-offs due to trace gas emissions from restored wetlands have not received as much attention. Denitrification in wetland soils can improve surface water quality, yet this and other microbial processes are also major sources of trace gases. Emissions of nitrous oxide and methane have been well documented in wetland environments, such as rice paddies and constructed wetlands. There is research and literature, some written by attendees of the workshop, to quantify multiple ecosystems costs and benefits of wetlands. There is currently an investigation of the effects of North Carolina’s largest (400 ha) wetland mitigation project to date in: a) altering nutrient export; b) sequestering carbon in plant biomass; and c) altering the forms and quantity of trace gas emissions. Hydrologic reconnection of the site in the winter of 2007 inundated nearly 80 hectares of the site, mobilized soil P, and altered denitrification potential and emission of N_20. Better understanding of the role of wetlands in achieving nutrient reductions and their net global warming potential will aid future management practices.

North Carolina’s largest mitigation bank, the Great Dismal Swamp, is located on the coastal plains of North Carolina. These plains were once forested with pond pine and white cedar. However, wildfires and ditching and draining of these plains for agriculture purposes have led to the degradation of the coastal plains ability to adequately filter nutrients. The mitigation itself included the movement of land, the planting of 750,000 trees and channels to reconnect its hydrology. There were stop pumps and flap gates installed throughout the area to reconnect the area with water and to form a wetland forest. The site performed quite well and it was found that when P was mobilized, there was an increased retention and mobilization of N and emissions of trace gases decreased. The potential long-term retention of nutrients can be linked to 1) biomass; 2) soil and sediments; and 3) atmosphere. Two points that became evident from this study are that flooding leads to P mobilization and that there is special heterogeneity in nutrient transformations. It is hard to maximize both N and P “retention” in wetland ecosystems.

Comparing Wetland Types

A literature survey evaluated the role of landscape position, hydrologic connectivity, loading rate and wetland age on nitrogen (N) and phosphorus (P) removal by freshwater wetlands. N and P removal is three times greater in connected (floodplain, fringe) wetlands than in depressional wetlands. In floodplain wetlands, 8-15 MT N/km^2 and 1-3 MT P/km^2 are sequestered annually in soil as compared to 3 MT N/km^2/yr under low nitrate loadings. Nitrogen removal is stimulated by increased nutrient loading, mostly through greater denitrification, and, in highly loaded wetlands, N removal may exceed 10-50 MT/km^2 wetland/yr. Increased nutrient loading also boosts P removal though P removal (1-5 MT/km^2/yr) is an order of magnitude less than N. And P removal declines with time as sedimentation reduces water storage capacity and sorption sites become saturated. Creation, restoration and enhancement of wetlands for nutrient and sediment removal must recognize that (1) not all wetlands are equal when it comes to nutrient removal, (2) N removal is greater than P removal and (3) effective N removal is sustainable over time but P removal declines as wetlands age. Phosphorus in wetlands is retained by, 1) accumulation with soil organic matter, 2) sedimentation of particulate P (PP), and 3) sorption and precipitation. Nitrogen retention and removal occurs by 1) accumulation with soil organic matter (SOM), and 2) denitrification. Denitrification is then controlled by, 1) soil moisture/wetness, 2) nitrate concentration, 3) soil organic carbon, and 4) retention time.

The literature survey revealed that floodplain wetlands can remove around 200 kg N ha^{-1} annually, and up to 600 kg ha^{-1} yr under high nitrate loading rates and therefore offer the best opportunities for nutrient removal and Total Maximum Daily Load (TMDL) compliance. There are three caveats to these findings: 1) legacy effects (long-term fertilization, drainage, soil oxidation) of re-flooding agricultural lands may initially release P and possibly N; 2) nutrient removal is not consistent throughout the year; and 3) phosphorus retention is high at first but decreases with time as sorption sites become saturated and sedimentation reduces wetland water storage capacity.

3. Noting that preserving/restoring forest buffers and stream corridors is important for maintaining high water quality, would the BMP credit be higher if wetland restoration/enhancement projects were done in conjunction with the forest buffer and stream restoration?

The position of the wetland or buffer system on the landscape usually defines its function. Wetlands usually located in depressional areas and prominent along shorelines in coastal areas will tolerate the hydrologic inundation better than forest buffers. Forest buffers found from headwater areas to confluences of streams and along shorelines are not as tolerant of constant hydrologic inundation. Many times in a coastal situation forest buffers line wetland borders, often the forested wetland is the natural riparian buffer. Wetlands in piedmont areas drain toward streams that have a riparian forest buffer. *Note: Forested wetlands are often the natural riparian forest buffer and are common in headwater areas.*

Herbaceous wetland and forest floodplain buffer systems have similar functions yet have subtle differences in how they function. Some of the similarities include:

- Hydrologic inundation: both experience tidal and non-tidal hydrology and surface flow (runoff)
- Pollutant reduction: both intercept and reduce non-point source pollution from multiple land uses, alone and in sequence of each other.
- Vegetation: serves as the nutrient processing units structural sediment traps
- Accumulate detritus: as nitrogen and carbon sinks
- Atmospheric deposition: interception and processing of air borne nutrients.

Herbaceous wetland and forest floodplain buffer systems also have subtle differences in function:

- Forested floodplain buffer systems have a winter nutrient processing activity, this activity for herbaceous wetlands is negligible.
- By definition wetland soils are saturated by surface or groundwater at a frequency to support hydrophytic vegetation. Floodplain forest buffer soils generally have lower water tables and inundation is a result of overbank flooding several times a year. It should be noted that some constructed wetlands rely on active manipulation of water control structures and do not have the consistent inundation of natural wetlands.
- Floodplain forests buffer systems provide large woody debris as a carbon source and as habitat diversity that is not found in herbaceous wetlands.

These similarities and differences can be applied to the Bay Program Model by: 1) consider crediting each by their efficiency performance; and 2) consider each in a landscape combination giving higher credit to the combination.

4. How efficient are created wetlands in nutrient and sediment removal in the urban storm water context?

The same principles and factors that affect sedimentation in natural systems apply to constructed systems; loading rates may be higher and storm events more frequent or turbulent meaning design and construction are critical. There are large differences among cropland stormwater ponds, surface flow wetlands, and subsurface flow wetlands, yet few studies can compare rates because it is similar to comparing apples to oranges – they need to be studied and monitored on a case by case basis but seldom matched with a reference wetland. The two most important watershed parameters are: 1) incoming sediment load which is dependent on the land use, soil type, vegetation type, litter cover, runoff and erosion and 2) water velocity and turbulence, which is determined by wetland type, amount and type of vegetation cover, precipitation events, antecedent conditions, morphology of water body, currents or tidal influences, construction and human activity.

Removal efficiencies may improve the first few years after wetland restoration due to establishment of vegetation, which helps trap particulate matter, and due to the production of organic matter, which supports denitrification. Removal efficiencies should later decline with age as the wetland fills in with trapped sediment and accumulated organic matter. Eventually, it may be necessary to excavate wetlands to renew their nutrient removal capacity. *Note: Excavation should never be done in wetlands that are supposed to be forested, only in a facility specifically designed for periodic maintenance.*

5. How can your research relate the efficiency of nutrient and sediment uptake to certain species of wetland vegetation?

In the Florida Everglades, tree islands are conspicuous as heterogeneous elements of the wetland landscape. Dr. Tiffany Troxler-Gann and fellow researchers at Florida International University characterized biogeochemical interactions among tree islands and the marsh landscape matrix, specifically examining hydrologic flows of nitrogen (N) and N retention capacity. Combined estimates of tree island ecosystem N standing stocks and fluxes, soil and litter N transformation rates, and hydrologic inputs of N were used to quantify the net sequestration of N by a seasonally flooded tree island. Results showed that hydrologic sources of N were dominated by surface water loads of NO_3^- and NH_4^+. Nitrate immobilization associated with soils and surficial leaf litter was on important soil N transformation promoting the net loss of surface water DIN. This study showed net inorganic N retention up to 37 g m^{-2} wet season $^{-1}$. This value exceeds that for wetland systems, but is a typical value for hyporethic zones of riparian systems. A second tree island study was developed to examine both Phosphorus (P) sources and N transformation processes in a tree island of the Water Conservation Area 3A. Results of both tree island studies were compared.

Dr. Troxler-Gann presented research that she and her team conducted on tree islands in the everglades at the Florida Coastal Everglades (LTER). Tree islands occur in tropical and sub-tropical landscapes. Their structure and root system is developed on a substrate of limestone and do experience nutrient transfers. Tree islands that occur in the southern everglades have soils that are carbonate derived, have low ammonia concentrations and low P and dissolved organic Carbon. There are many problems with tree islands and the everglades. Tree islands were once important to nutrient storage of the everglade system. They have been lost throughout the years by the degradation of the Florida everglades. Once they are restored, they may have the same importance as they once did at reducing outputs. The everglades themselves have problems as well. The extent has been reduced by half from drainage and conversion for agricultural and urban expansion; sugarcane farming produces effluent enriched phosphorus; and current water management activities direct water out to sea instead of through wetlands to recharge aquifers, which are the primary sources of drinking water for south Florida. Mechanisms of nitrogen sequestration and potential nitrogen sources in tree islands of southern Everglades include: tree islands as important sites of nitrogen biogeochemical flux; important structural component of the pre-drainage Everglades landscape and contain large quantities of nutrients in standing biomass and soil; significant tree island loss over the last 50 years; and a comprehensive metric for assessment of hydrologic change

Specifically, Dr. Troxler-Gann's research hypothesis focused on tree islands as contributors to N sequestration in the southern Everglades landscape. Her approach was to combine estimates of tree island ecosystem N standing stocks and fluxes, N soil and litter transformation rates, and hydrologic inputs of N to quantify net N sequestration. The litter and soil N standing stocks were found in plants, surficial littler, island surface water, soil pools, and in soil water. N fluxes occurred in litterfall, readily labile N, recalcitrant N, N accumulated in soil and N recycled by plants. A nitrogen budget was produced to see what pools and uptakes were active in the tree islands. She presented her conclusions as follows:

- Results show that hydrologic sources of N were dominated by surface water loads of NO_3^- and NH_4^+. Nitrate immobilization associated with soils and surficial leaf litter was an important soil N transformation promoting the net loss of surface water DIN.
- When upstream loads (62.7 g m-2 wet season-1) are compared with downstream loads (24.3 g m-2 wet season-1), this DIN immobilization value (based on Input-Storage=Output) appears realistic, assuming no other fixation in the marsh system. However, this is highly unlikely since we know that periphyton fixes N despite availability of N in marsh surface water.
- This value of net inorganic N retention exceeds that for other wetland systems, but is a typical value for highly biogeochemically-active hyporheic zones of riparian systems.

- N pool dilution experiments probably provide a better indication of *potential* immobilization depending on the enrichment level. More work is needed to insure no artifact of N enrichment on microbial consumption of NO_3^-.

Workshop Conclusions:

Mass nitrate removal by wetlands is inversely related to the hydraulic load rate as measured in meters/year (primary determinant in ability of wetland to act as N sink). To optimize N removal by wetlands, first determine where nitrate concentrations are highest, then target restoration/protection of those wetlands that drain the size watershed(s) that produce the desired hydraulic load rate (m/yr) you want to receive. While a range for wetland efficiencies could be provided, it would be subject to error given the areal extent of and variability due to hydrology, soil, parent material, and vegetation structure. Site specific assessment of nutrient efficiencies is important. Values for N removal in floodplain and riparian forests range from less than 1 to 35 g m-2 yr-1 (Walbridge and Lockaby 1994); removal mechanisms cited sediment/particulate deposition, denitrification, NH_4^+ adsorption, microbial immobilization, and plant uptake. These mechanisms and their removal efficiencies will vary by wetland type. To ensure accurate efficiency assessments, rates could be verified with additional mass balance parameters.

Workshop Recommendations:

- Examine most recently released National Land Cover Data for existing wetland acreage to more accurately account for the amount of wetland's affecting water quality.
- Investigate use of Digital Elevation Model (DEM) to determine drainage area of wetlands (works well in non-tidal areas, but not as well in tidal areas).
- Examine Elevation Derivatives for National Application (EDNA), a USGS product for wetland age information.
- Target wetland BMPs for areas of known high Nitrate loading, and prioritize wetlands based on drainage area.
- Design future wetland restoration sites to reduce flow variability, plan to cope with the problem of filling in (unless designed to be a forested wetland), link assessment with implementation, and, incorporate size effects in models.
- For targeted watersheds, collect pre-BMP wetland condition data, and work with State and Federal funding partner agencies to require three years post-BMP monitoring data.
- Ask States to improve reporting of wetland project location to the Hydrologic Unit Code (HUC)11 level; also ask that they begin to report drainage area associated with each project. [Note: Wetland drainage area was included as a field in water year 2007 data request form; no feedback was received in the first attempt]
- For Phase 5 of the model and beyond, consider "extra credit" for wetlands associated with riparian forest buffers (places where both exist on landscape in combination).
- Modify wetland efficiency based on drainage area as reported by States or using surrogate values as outlined in the following Wetlands as BMP proposal, subject to review.

Appendices

Appendix A: Workshop Presenters, Presentations, and Contact Information

(Listed in presentation order)

Tom Jordan ~ Smithsonian Environmental Research Center:
Nutrient Removal by Restored Wetlands in Agricultural Watersheds
CONTACT INFORMATION: Thomas E. Jordan and Donald E. Weller, Smithsonian Environmental Research Center, Edgewater, MD 21037, Phone (443) 482-2209, Email: jordanth@si.edu

Tiffany Troxler-Gann ~ Florida International University
The Wet Season Nitrogen Budget of an Everglades Tree Island: Potential Role in Wetland Landscape Biogeochemical Fluxes
CONTACT INFORMATION: T. Troxler-Gann, Florida International University, Southeast Environmental Research Center and Department of Biological Sciences, OE 167, University Park, Miami, FL, 33199, USA, Phone (305) 348-1453, Fax (305) 348-4096, Email: troxlert@fiu.edu

John Galbraith ~ Virginia Tech.
Sedimentation Sequestration Potential in Wetlands
CONTACT INFORMATION: John Galbraith, Department of Crop and Soil Environmental Science, Virginia Tech, 239 Smyth Hall (0404), Blacksburg, VA 24061. Phone (540) 231-9784, Fax (540) 231-7630, Email: john.galbraith@vt.edu

Greg Noe ~ U.S. Geological Survey
Retention of Riverine Nutrient and Sediment Loads by Floodplains in the Chesapeake Bay Watershed
CONTACT INFORMATION: Gregory B. Noe, U.S. Geological Survey, 430 National Center, Reston, VA 20192 USA, Phone (703) 648-5826, Fax (703) 648-5484, Email: gnoe@usgs.gov

Carol A. Johnston ~ South Dakota State University
Where Does Sediment Go in Wetlands (and What Does it Do to Them)?
CONTACT INFORMATION: Carol A. Johnston, Department of Biology and Microbiology, South Dakota State University, Brookings, SD, USA.

William G. Crumpton ~ Iowa State University
Predicting Water Quality Performance of Wetlands Receiving Nonpoint Source Loads: Nitrate Removal Efficiency and Mass Load Reduction by Emergent Marshes
CONTACT INFORMATION: William G. Crumpton, Department of Ecology, Evolution, and Organismal Biology, Iowa State University, Ames, IA, USA, Phone (515) 294-4752, Email: crumpton@iastate.edu

Chris Craft ~ Indiana State University
Hydrogeomorphic Control of Nutrient and Sediment Removal by Freshwater Wetlands
CONTACT INFORMATION: Christopher Craft, School of Public and Environmental Affairs, Indiana University, Bloomington, IN 47405, USA, Phone (812) 855-5971, Fax (812) 855-7802, Email: ccraft@indiana.edu

Judy Okay ~ U.S. Forest Service / Chesapeake Bay Program
Wetlands and Riparian Buffers: How are They Different?
CONTACT INFORMATION: Dr. Judy Okay, Chesapeake Bay Program, 410 Severn Avenue, Suite 109, Annapolis, MD 21403. Phone: 410-295-1311.

Marcelo Ardon (Duke University)
How Do We Quantify Trade-offs Between Various Wetland Ecosystem Costs and Benefits?
CONTACT INFORMATION: Marcel Ardon, Department of Biology, Duke University, PO Box 90338, Durham, NC 27708, USA, Phone (919) 660-7262, Fax (919) 660-7425, Email: mla5@duke.edu

Appendix B: LRSC Recommendations on Draft Wetland BMP Proposal

Chesapeake Bay Program
A Watershed Partnership

TO: Tom Simpson, Chair, Nutrient Subcommittee
Sarah Weammert, UMD / MAWQP

VIA: Kelly Shenk, Tributary Strategy Workgroup

FROM: Matt Fleming, Chair, Living Resources Subcommittee

DATE: August 1, 2007

RE: LRSC Recommendations on Wetland BMP Proposal

In response to the request from the Nutrient Subcommittee for input into the re-evaluation of various BMPs, I submit the recommendations and comments on behalf of the Living Resources Subcommittee regarding the University of Maryland Mid-Atlantic Water Quality Program's proposal for wetlands on agricultural lands.

Overall, LRSC agrees with the approach of weighting wetland efficiency based on percent drainage area of the watershed. However, members continue to express concern over the validity of the drainage area percentages in the proposal, including documentation in the scientific literature, how these percentages will be applied, and the inability of this approach to capture other important factors that impact wetland efficiency in N/P/S uptake and retention, such as seasonal variation, hydraulic load rate, and wetland aging. These concerns are detailed below.

We recommend that the final report on this particular BMP to the Water Quality Steering Committee provide a strengthened background/introductory section on how the model currently treats wetlands in agricultural areas, the rationale for change, and clear articulation of how the wetland drainage area percentages in the proposal will be applied in the model. Toward that end, LRSC offers the following specific comments on the definitions and efficiencies, with suggestions for future refinements and scientific references to strengthen validity of the model.

Recommendation on Definitions Section

Based on findings of the Chesapeake Bay Program's 2005 Wetland Evaluation, the Implementation Committee in September 2005 agreed to adopt standard tracking definitions* for purposes of tracking progress of the partnership toward wetland-related commitments. These official definitions were then referenced in subsequent guidance from the Principals' Steering Committee to the partnership, along with corresponding "common" terms. For consistency, LRSC strongly recommends that the NSC use the following wetland project definitions:

Re-establishment ("restore") – Manipulation of the physical, chemical, or biological characteristics of a site with the goal of returning natural/historic functions to a *former* wetland. Results in a gain in wetland acres.

Establishment ("create") – Manipulation of the physical, chemical, or biological characteristics present to develop a wetland that did not previously exist on an upland or deepwater site. Results in a gain in wetland acres.

Rehabilitation (“improve”) - Manipulation of the physical, chemical, or biological characteristics of a site with the goal of returning natural/historic functions to a *degraded* wetland. Results in gain in wetland function, not acres.

Enhancement (“enhance”) - Manipulation of the physical, chemical, or biological characteristics of an existing wetland (undisturbed or degraded) site to heighten, intensify, or improve specific function(s) or for a purpose such as water quality improvement, flood water retention, or wildlife habitat. Results in gain in function, not acres.

Protection (“protect”) – Removal of a threat to, or preventing the decline of, wetland conditions by an action in or near a wetland. Includes purchase of land or easements of 30 years minimum duration. Does not result in a gain of wetland acres or function.
**As identified in 2000 by the White House Wetlands Working Group, Federal Geographic Data Committee, and reiterated by the President’s Council on Environmental Quality in 2004.*

Recommendations on Efficiency Section

- Currently, the watershed model assumes that each acre of restored wetland removes a proportion of the nutrients discharged from four acres watershed. Thus, if the efficiency is 25%, it is assumed that each acre of wetland removes 25% of the nutrients released from four acres of watershed. Clearly, the functional efficiency of the wetlands currently depends on the assumed ratio of wetland: watershed area. The rationale for the 1:4 ratio is unclear. LRSC urges the TSWG and NSC to clarify this rationale.

- If the new efficiency estimates will be used with the assumption that each acre of wetland treats four acres of upland, then the seemingly arbitrary selection of the 1:4 ratio essentially sets the functional efficiency of the wetlands. With the 1:4 area ratio assumption, the new efficiencies will predict the same amount of nutrient removal by wetlands in the Coastal Plain as predicted in the current model, but half as much nutrient removal in the Piedmont and one forth as much in the Appalachian Province.

- Different predictions of nutrient removal will be obtained if the new efficiency estimates will be applied according to the assumed (or known) percentages of wetland area in the watersheds. For example, to estimate efficiency it is assumed that Coastal Plain wetlands make up 4% of the watershed area. Thus, it follows that each acre of wetland would treat the discharge from 24 acres of watershed. Therefore, the predicted amount of nutrient removal would be six times higher than is predicted by the current model using the same removal efficiency but assuming a 1:4 ratio of wetland area: watershed area. By similar reasoning the predicted amount of nutrient removed in the Piedmont and Appalachian Provinces would be 6-7 times that predicted by the current model. The percentage of wetlands in a watershed, by physiographic region, should be further investigated. Maryland Department of the Environment estimates are higher, particularly for the Coastal Plain.

- If nutrient removal is calculated using the assumed percentages of wetland in each province, then the calculation is not sensitive to the selection of the percentage of wetland area. This is because the efficiency roughly doubles as the area of watershed draining to the wetland is halved, so the amount of nutrient uptake would stay the same regardless of the estimated area percentage, assuming that the calculation of the amount of nutrient uptake uses the same area percentages as those used to estimate efficiency.

Recommendations for Future Refinements

LRSC members feel strongly that the model should be further refined at the earliest opportunity to reflect the following:

1. Seasonal correction factor – while the proposal does note that there is seasonal variability in rates of retention/uptake/transformation, it only addresses it by using average rates. Further work on seasonal variability and periods of nutrient discharge is needed to refine the model.
2. Hydraulic loading rate – during high flow periods, retention time in wetlands is reduced, leading to decreased removal of nutrients and sediment
3. Wetland aging – as wetlands collect sediment over time, they begin to fill and reach a point where they are no longer able to serve as a sediment sink. LRSC notes the distinction between created "wet ponds" and wetlands that are voluntarily restored on agricultural land. While "maintenance" of stormwater facilities is well understood and necessary, excavation of voluntarily established forested wetlands to restore capacity is not desirable.
4. Reporting of wetland drainage area – LRSC will request that States begin to provide this information on a project-by-project basis, beginning with the 2007 reporting year. We will work with IMS to streamline collection of this information, and investigate use of USGS' "EDNA" tool for estimating drainage area in places where drainage is not reported.

It is LRSC's understanding that such refinements to the model, if not considered "significant", do not need to wait until the next calibration. LRSC will work with STAC to advocate for necessary funding, data collection, and reporting to the Chesapeake Bay Program to pursue these refinements using actual, long-term studies in a variety of wetland types, including restored, rehabilitated, and created wetlands, as well as the wide range of existing natural wetlands, should be conducted for future model refinements.

It should also be considered that many voluntarily restored/created wetlands are intended to resemble natural wetlands. The extensive literature regarding nutrients/sediment processes in natural wetlands should have been considered, both in the model for newly established areas, and for existing wetlands. There are far more existing natural wetlands than restored sites, and refinement of the model to more accurately account for natural wetlands should be pursued.

Recommendations for Scientific References

- We recognize that the wetland BMP was evaluated in two ways by two different PIs (wetlands restored on agricultural land and those created in urban areas). LRSC notes that most voluntarily restored wetlands are not designed primarily as treatment wetlands. As such, the literature search for the agricultural portion appears to have been too narrow, with too much emphasis placed on wetlands that are treatment stuctures. Studies on wetlands established for wildlife, mitigation wetlands, and natural wetlands should have been evaluated. The wetlands being voluntarily built are for wildlife, aesthetics, with some water quality benefits, but they are, for the most part, not designed like a stormwater facility nor intended to have the same maintenance as a stormwater facility. Specifically, it is disconcerting that none of the references is from the journal *Wetlands.*

- Dr. William Crumpton's study "Predicting Water Quality Performance of Wetlands Receiving Nonpoint Source Loads: Nitrate Removal Efficiency and Mass load Reduction by Emergent Marshes," was presented at the STAC/LRSC Wetland BMP workshop in April 2007. While from a different part of the country, these results may be most applicable for the Bay Program model in that the wetlands studied are most similar to the wetlands most commonly restored/created in Maryland (emergent wetlands located in agricultural watersheds.) An abstract for this work follows for reference by the NSC:

Predicting Water Quality Performance of Wetlands Receiving Nonpoint Source Loads: Nitrate Removal Efficiency and Mass Load Reduction by Emergent Marshes. William G. Crumpton**,** Department of Ecology, Evolution, and Organismal Biology, Iowa State University, Ames, IA, USA, Phone: 515-294-4752, email: crumpton@iastate.edu

The effectiveness of wetlands in nitrate reduction is largely a function of hydraulic loading rate, hydraulic efficiency, nitrate concentration, temperature, and wetland condition. Hydraulic loading rate and nitrate concentration are especially important for wetlands intercepting nonpoint source loads. Hydrologic and nitrate loading patterns vary considerably for different landscape positions and different geographic regions. In addition to spatial variation in land use and precipitation, there is considerable temporal variation in precipitation. As a result, loading rates to wetlands receiving nonpoint source loads can be expected to vary by more than an order of magnitude, and will to a large extent determine nitrate loss rates for individual wetlands. Much of the variability in mass nitrate removal among wetlands can be accounted for by explicitly considering the effect of hydraulic loading rate and nitrate concentration. Analysis of 34 "wetland years" of mass balance data (12 wetlands with 1-9 years of data each) for sites in Ohio, Illinois, and Iowa demonstrates that the **performance of wetlands representing a broad range of loading and loss rates can be reconciled by a model explicitly incorporating hydraulic loading rate and nitrate concentration. The model explains 94 % of the variability in mass removal rates for these wetlands.**

- The Conservation Effects Assessment Project (CEAP) sponsored by USDA will be collecting actual measurements from natural and established wetlands in the Coastal Plain. The information will be very useful for model refinements. An extensive bibliography for the project "Wetlands in Agricultural Landscapes: A Conservation Effects Assessment Project (CEAP) Bibliography" (National Agricultural Library Special Reference Briefs 2006-01) is available.

Appendix C: Wetland BMP Report

Wetland Restoration on Agricultural Land Practices
Wetland Creation Practices
Definition and Nutrient and Sediment Reduction Efficiencies
For use in calibration of the Phase 5.0 of the Chesapeake Bay Program Watershed Model

Prepared by

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Introduction

The Mid-Atlantic Water Program (MAWP) housed at the University Of Maryland (UMD) led a project during 2006-2007 to review and refine definition and effectiveness estimates for BMPs implemented and reported by the Chesapeake Bay watershed jurisdictions prior to 2003. The objective is to develop definitions and effectiveness estimates that reflect the average operational condition representative of the entire watershed. The Chesapeake Bay Program (CBP) historically assigned effectiveness estimates based on controlled research studies that are highly managed and maintained by a BMP expert. This approach is not reflective of the variability of effectiveness estimates in real-world conditions where farmers and county stormwater officials, not BMP scientists, are implementing and maintaining a BMP across wide spatial and temporal scales with various hydrologic flow regimes, soil conditions, climates, management intensities, vegetation, and BMP designs. By assigning effectiveness estimates that more closely align with operational, average conditions modeling scenarios and watershed plans will better reflect monitored data.

One important outcome of the project is the wealth of documentation compiled on the BMPs. Previously, BMP documentation was limited and the CBP has been criticized for this in the press and in governmental reviews. To provide precise documentation the UMD/MAWP designed a robust practice development and review process utilizing literature, data, and best current professional judgment. The initial step was a literature and knowledge synthesis. Available scientific data were compiled and analyzed for quality and applicability and included in a report that summarizes all decisions on how effectiveness estimates were developed. The process for incorporating both science and best professional judgment to estimate average operational effectiveness is also well documented.

Another objective of the project was to initiate an adaptive management approach for BMP effectiveness for the CBP. An adaptive management approach allows forward progress in implementation, management and policy, while acknowledging uncertainty and limits in knowledge. The adaptive management approach to BMP development incorporates the best applicable science along with best current professional judgment into definition and effectiveness estimate recommendations. With adaptive management it is necessary to include a schedule that allows for revisions as advances knowledge and experience becomes available. UMD/MAWP recommends continued monitoring of BMPs, with revision of definitions and effectiveness estimates scheduled for every three to five years to incorporate new data and knowledge.

Attached to this report is a full accounting of the Chesapeake Bay Program's discussions on this BMP, who was involved, and how these recommendations were developed, including data, literature, data analysis results, and discussions of how various issues were addressed. All meeting minutes are included in Appendix C.

Definition/Description

The Chesapeake Bay Program will utilize the following definitions to classify wetland restoration on agricultural land and wetland creation:

Re-establishment (restore) – Manipulation of the physical, chemical, or biological characteristics of a site with the goal of returning natural/historic functions to a *former* wetland. Results in a gain in wetland acres.

Establishment (create) – Manipulation of the physical, chemical, or biological characteristics present to develop a wetland that did not previously exists on an upland or deepwater site. Results in a gain in wetland acres.

This BMP report discusses the water quality benefits of wetland restoration and wetland creation. The literature search for this report captures the water quality benefits that wetlands provide and literature on the wildlife, mitigation wetlands, and natural wetlands is not discussed. In addition these systems are not designed to treat wastewater, as they are not designed like a stormwater facility, nor intended to have the same maintenance as a stormwater facility.

These wetland treatment system designs have an even flow distribution and adequate retention time. The temporal variability of water flow through wetlands also results in variability of water detention times, which in turn affects the removal efficiencies. The longer water is detained within a wetland the more material may be removed from the water within the wetland. As flow variability increases the effective water detention time decreases and therefore the removal efficiency decreases (Jordan et al. 2003). It is intuitively clear that a wetland with steady water flow is likely to have higher removal rate than a wetland with the same amount of annual flow concentrated during a few days of high flow. Understanding these temporal flow conditions is absolutely necessary to provide estimated effectiveness.

Practice components meet criteria standards under the USDA-NRCS National Handbook of Conservation Practices (NHCP) (http://www.nrcs.usda.gov/technical/standards/nhcp.html) and associated Field Office Technical Guides (http://www.nrcs.usda.gov/technical/efotg/) for each state. Components included in the Wetland Restoration Practices on Agricultural Land, and Wetland Creation, include, but are not limited to the following USDA-NRCS conservation practices:

- Constructed Wetland (656)
- Wetland Creation (658)
- Wetland Restoration (657)

Restored versus created wetlands

It is important to distinguish wetland restoration from wetland creation. Agricultural wetland restoration activities re-establish the natural hydraulic condition in a field that existed prior to the installation of subsurface or surface drainage. In contrast, “wetland creation” establishes a wetland in a place where none previously existed. Created wetlands may use artificial or highly engineered hydrology. Often created wetlands have regulated water inputs, with water being pumped or fed in at steady controlled rates. In contrast, restored wetlands generally have natural or unregulated water inputs, with water entering through surface or subsurface flows at variable uncontrolled rates.

Efficiency

Using guidelines for efficiency development (see Appendix B) and the report below, effectiveness estimates for wetland creation and wetland restoration will be determined utilizing the contributing drainage area and wetland area equation supplied by Dr. Tom Jordan, SERC.

Total Nitrogen and Phosphorous

The efficiency of removal of waterborne materials by wetlands is often expressed as the percentage of the inflowing material that was removed in the wetland. Absolute removal rates may also be given in units of mass per wetland area. For example, Mitsch et al. (2000) suggest that sustainable removal rates range from about 5 to 50 kg ha^{-1} yr^{-1} for P and 100 to 400 kg ha^{-1} yr^{-1} for N. Removal rates are generally thought to follow first order kinetics, where the rate of removal is proportional to the concentration of the substance in the water. Many studies have found evidence supporting first order kinetics, but it does not always apply. For example, Braskerud (2002) found that the rate of removal of suspended sediment increased with sediment concentration faster than would be predicted by first order kinetics. Also, there are upper limits to absolute rates of removal, which prevent removal rates from rising indefinitely with increases in concentration. However, the general tendency of removal to follow first order kinetics makes it very useful to express efficiency as the percentage of inflowing material removed because this percentage will be relatively constant with variation in concentration.

Effects of wetland size and water detention time on efficiency

Changes in factors relating to soil, vegetation, or hydrologic conditions may alter the effectiveness of wetlands for removal of suspended solids or nutrients. For example, longer detention times will in general tend to improve efficiency due to increased contact between water and soil or microbial surfaces and vegetation, as well as longer times for settling of particulates. Longer detention times can be created by increasing the area or volume of wetlands relative to drainage area entering the system, or conversely by reducing the volume of runoff entering the wetland. Efficiency can also be affected by the geomorphology of the unit; designs that maximize the area of contact between water and soil, vegetation, or microbial surfaces should in general increase efficiency (e.g., long, linear wetlands with shallow water depth are likely to be more effective than deep, concave basins of the same volume).

The efficiency of removal will vary as a function of the size of the wetland. For example, if a 1 ha wetland removes 50% of the total N it receives from agricultural runoff and if another similar 1 ha wetland is restored downstream to remove 50% of the total N it receives in discharge from the first wetland, then the combined 2 ha wetland system will remove 75% of the total N received from agricultural runoff. Also, a 1 ha wetland would likely remove a greater percentage of material from discharge of a 10 ha watershed than from discharge from a 100 ha watershed. The effect of size is related to the ratio of wetland area to watershed area and probably reflects the detention time of water within the wetland. The longer water is detained within a wetland the more material may be removed from the water within the wetland due to increased contact between water and soil or microbial surfaces and vegetation, as well as longer times for settling of particulates. The detention time is the water volume of the wetland divided by the rate of water inflow. This varies with the area of the watershed and the area of the wetland. Thus, we would expect to find relationships between the removal efficiency and the ratio of the wetland to watershed areas. Simple models have been developed to account for these size effects.

The processes that remove materials

Waterborne materials removed by wetlands are either stored within the wetland or converted to gaseous forms and released to the atmosphere. Since P has no important gaseous phase it can only be accumulated within the wetland. Usually, most of the P discharged from watersheds is bound to particulate matter. Therefore, sedimentation of particulate matter is an important process for P removal. Particulate N and organic C may also be trapped by sedimentation. N and P may be taken up by plants, algae, bacteria, and fungi, and, thus be converted to particulate organic forms, which may accrete in the wetland. However, dissolved inorganic N and P may be released from organic matter as it decomposes. Wetland vegetation can enhance sedimentation by slowing water velocity, reducing turbulence, and providing surfaces for particle adhesion (Braskerud 2001). N, organic C, and especially P can be held in wetland sediment by adsorption. However, sites of surface adsorption have a finite capacity and can eventually become saturated.

It is important to note that the capacity of a wetland to accumulate particulate material is limited because the trapped material will eventually fill the wetland to the extent that incoming waterborne particles will pass through without being trapped. Reservoirs similarly fill up with sediment eventually. As wetlands fill with sediment or accumulated organic matter, their holding capacity and detention time for water decreases gradually diminishing their capacity to remove particles from incoming water.

The microbial process of denitrification can convert nitrate N to nitrous oxide, nitric oxide, or nitrogen gases, which may be released to the atmosphere. Unlike accretion processes, denitrification can continue indefinitely. Denitrification requires organic matter and a lack of oxygen, conditions often found in the waterlogged soils of wetlands. Like N, organic C can be converted to gaseous forms (carbon dioxide and methane), which are released to the atmosphere rather than accumulating in the wetland. Rates of these biotically mediated processes generally increase with temperature.

Variability of removal efficiencies

Although restored wetlands have significant potential to remove waterborne materials such as nutrients and sediments from watershed discharges, the efficiency of removals is highly variable. For 29 annual measurements the average total N removal efficiency was 20%, with a standard error of 3.7, and a range of -12% to 52%. For 36 annual measurements, the average total P removal efficiency was 30%, with a standard error of 5 and a range of -54% to 88%.

Some of the variance in efficiencies is due to size differences. These effects would be best evaluated by comparing the water detention times among wetlands. However, data needed to calculate water detention times are seldom reported. The ratio of the area of the wetland to the area of the watershed is a possible surrogate for water detention time and is more often available. Tonderski et al. (2005) developed a simple model to account for variability in the ratio of areas. Their model predicts a nearly linear increase in removal efficiencies as the percentage of the watershed area occupied by wetlands increases (Fig. 1). This modeled relationship looks useful for predicting the effect of wetland restoration but actual measurements show much less predictability (Fig. 2).

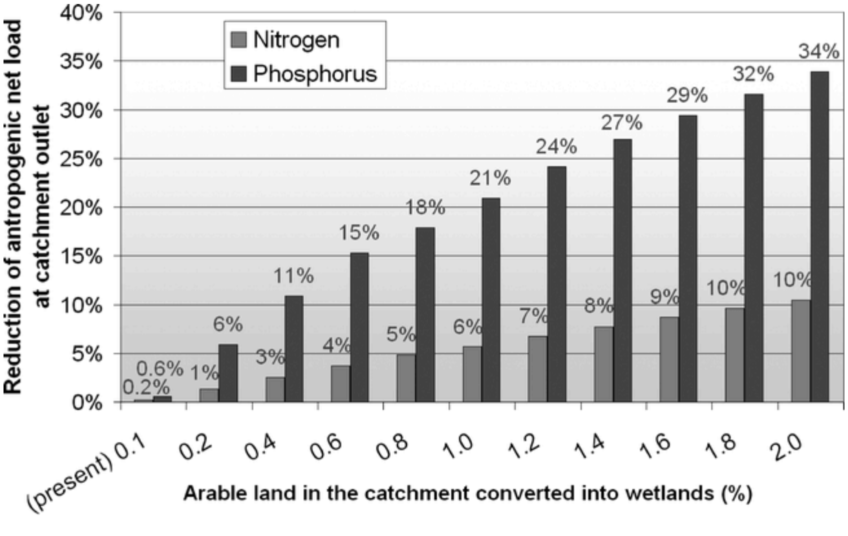


Fig. 1. Modeled effect of wetlands on anthropogenic net load at the catchment scale. Different proportions of catchment wetland areas were considered in the HBV-NP model (figure and caption from Tonderski et al. 2005).

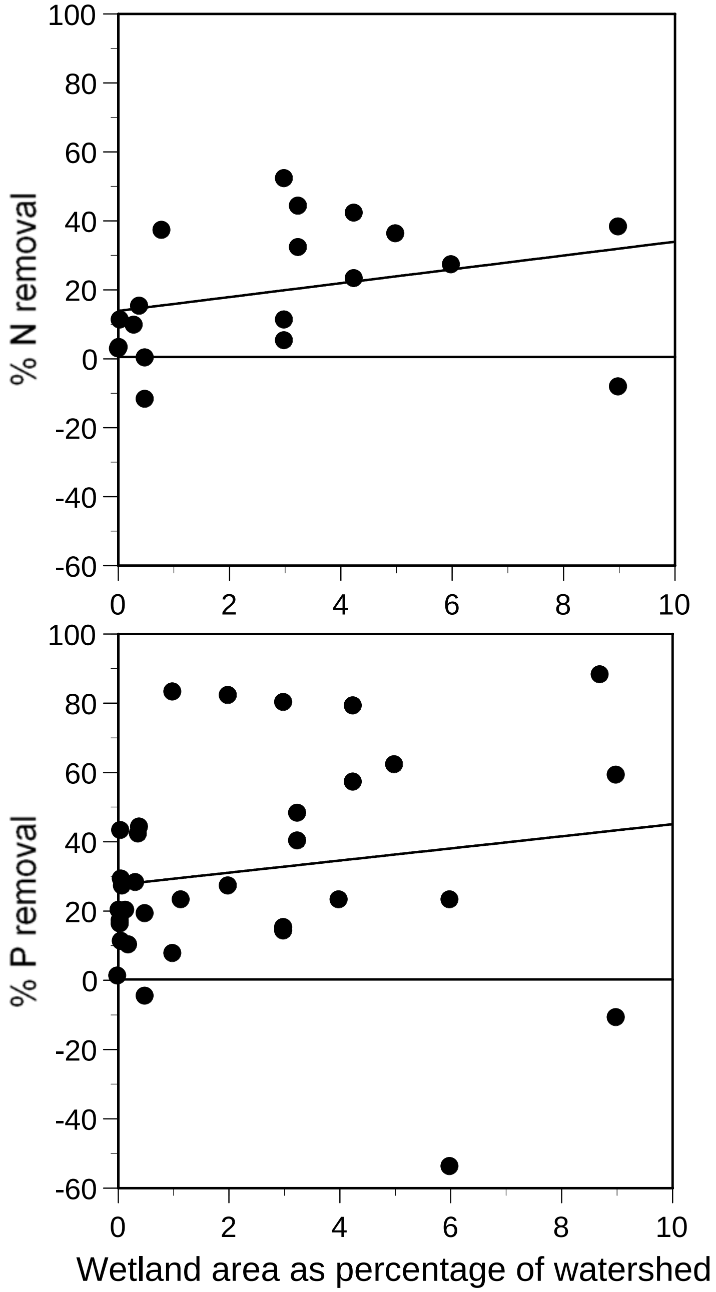


Fig. 2. Percentages of N or P removed annually versus the wetland area expressed as a percentage of the watershed area. Sloped lines are fit by linear regression. Most of the data points represent different wetlands but some are for different years for a given wetland. Data are from references marked with asterisks in the bibliography.

The temporal variability of water flow through wetlands also results in variability of water detention times, which in turn affects the removal efficiencies. As flow variability increases the effective water detention time decreases and therefore the removal efficiency decreases (Jordan et al. 2003). It is intuitively clear that a wetland with steady water flow is likely to have higher removal efficiencies than a wetland with the same amount annual flow concentrated during only a few days of high flow. The effect of flow variability is vividly illustrated by data from Reinhardt et al. (2005) (Fig. 3.) They found that efficiencies of dissolved reactive phosphorus removal (or retention) over two-day periods varied with water detention (or residence) time as well as with the concentration, and followed patterns consistent with a model they developed. Flow variability is influenced by rainfall patterns and increases with the proportion of impervious surface in a watershed. Restored or created wetlands receiving unregulated inflows may be equipped with flow control structures that decrease flow variability. For example, wetland drains may be designed to allow continued slow outflow after high flow events, thus creating capacity to hold water inputs from subsequent events.

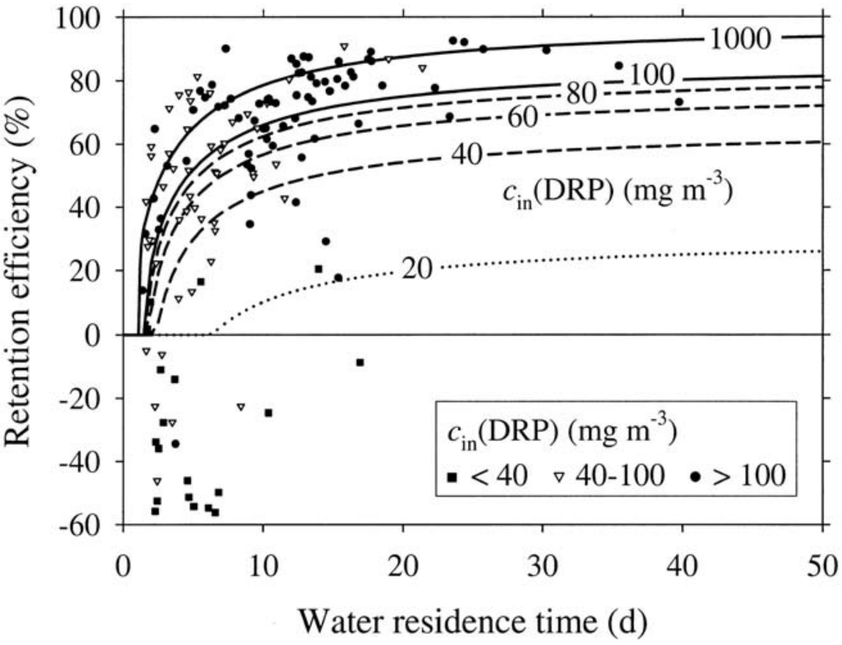


Fig. 3. Retention efficiency of dissolved reactive (bioavailable) phosphorus (DRP) predicted by the model (lines) and observed in Wetland Sonnhof in 2001 (symbols) as a function of water residence time and concentration of dissolved reactive phosphorus at the inlet c_{in}(DRP). Line styles and symbol types indicate DRP inlet concentration. Two-day retention efficiency was calculated according to Eq. [15]. Twenty-two data points ranging between –60 and –500% (τ: 1–6 d) are not shown (figure and caption from Reinhardt et al. 2005).

Effects of wetland age

Removal efficiencies are likely to vary with the age of the wetland although there are few data available to quantify this. When a wetland is first restored or created, it may lack vegetation. This would likely reduce removal efficiencies because vegetation can assimilate nutrients, enhance sediment trapping, and provide organic matter to support denitrification. Initial rapid increases in vegetation biomass may enhance accumulation of nutrients and organic matter. Later when the wetland vegetation is fully established, the rate of biomass increase will slow, thus reducing the accumulation of removed materials in biomass. As wetlands fill with sediment and biomass over time, their water holding capacity and water detention time decline, diminishing their ability to trap and accumulate new material. Although denitrification does not depend on accumulation of material in the wetland, the reduction of water detention time would also limit N removal by denitrification.

The likely effects of wetland age lead to two important conclusions. First, the effectiveness of a newly restored wetland may improve as vegetation becomes established and organic matter becomes available to support denitrification. It probably takes at least one year, possibly several, for a restored wetland to reach its full potential removal efficiency. Second, a wetland will eventually fill in and loose its capacity to remove waterborne materials. To restore this capacity the wetland would need to be excavated and the accumulated material removed. Periodic excavation would require a long-term commitment of effort and might also require special legal provisions.

Effects of improper maintenance

While no studies have specifically evaluated how BMP efficiencies should be adjusted to account for the impacts of improper maintenance on receiving waters, some general adverse effects to water quality are understood. If maintenance is neglected a BMP will become impaired, no longer providing its designed functions.

In addition sediment accumulation is one concern that if not addressed will adversely affect the BMPs effectiveness. As sediment accumulates it decreases storage volume and detention time, bypassing the intended functions of the BMP and increasing discharge of nutrient and sediment rich water (Livingston et al. 1997). Increased discharge will lead to decreased downstream channel stability, resulting in an increase of sediment loads and a reduction in available aquatic habitat. The consequences of increased discharges from sediment filled BMPs, are a reduction in the BMPs pollution removal efficiencies, and ultimately, increased ecological impairments. The uncertainty in how improper maintenance will adjust BMP efficiencies supports the recommendation to use a more conservative percent removal estimate.

Properly designed wetlands should require little or no maintenance for long-term treatment. However, periodic inspections should be performed to identify changes in hydrology, vegetation, or soils like those described above so that remedial measures can be taken in necessary. Particularly when systems are new, it is important to make sure water levels are suitable for the growth and persistence of wetland vegetation. Development of channels or other evidence of erosion should be dealt with expeditiously, for example by diverting some portion of the runoff, installing rock berms, or otherwise decreasing flow velocities in the BMP.

Effects of flow paths

Removal efficiencies may also be affected by the pathways of flow through the wetlands. For example, even dispersal of water flow over the entire wetland area maximizes removal efficiency by maximizing the area of the wetland’s microbes, soil, or vegetation that is interacting with the through-flowing water. If surface water flow follows a short cut from the wetland inlet to outlet while bypassing the main area of the wetland, the effective water detention time is reduced. Persson et al. (1999) discuss design features that improve the dispersal of water (hydrologic efficiency). Both surface- and groundwater flow can follow by passes. Velledis et al. (2003) noted that nitrate removal efficiency of a riparian wetland was reduced by groundwater flowing through limited preferential flow paths. Groundwater flow may be more effective than surface water flow in delivering nitrate for denitrification because groundwater can inject nitrate, which is formed in oxygenated environments, directly into anoxic water logged sediments where as nitrate entering a wetland in surface flow must diffuse slowly downward into anoxic sediments.

Effects of climate change

Climatic variables may also affect BMP performance over time, either positively or negatively. Periods of greater precipitation will likely result in shorter residence times, or even bypassing of the BMP due to high flow volumes, both of which will reduce performance. On the other hand, higher temperatures should increase metabolic rates, increasing growth of microbes and plants and facilitating greater transformation and uptake of nutrients. Global climate change may therefore affect performance by changing precipitation patterns and temperature in unpredictable ways. An additional factor is higher CO2 concentrations, which may result in shifts toward species competitively favored under high atmospheric CO2 levels. Changes in species composition may have some effect on performance, although effects are likely to be small unless there are large changes in stem density or biomass.

Predicting Removal Efficiency

Removal of total N and P by restored wetlands can be predicted from the relationship between the percentage of N or P removed and the percentage of the watershed occupied by wetland receiving discharge from the entire watershed. We assume that removal proceeds exponentially with detention time, as expected with first order kinetics. We also assume that detention time (wetland volume divided by water flow rate) is proportional to the percentage of watershed occupied by wetland. This follows if water discharge is proportional to watershed area and if different wetlands have similar average depths. Finally, we assume that there is no removal if there is no wetland area (i.e., the curve must go through the origin). Based on these assumptions:

$$\text{Removal} = 1 - e^{-k\,(\text{area})}$$

Where “removal” is the proportion (not percentage) of the input removed by the wetland, “area” is the proportion of the watershed area occupied by the wetland, and “k” is a fitted parameter. We used non-linear regression (SAS 2004) to fit this equation to data from studies reported in the literature.

Some studies reported negative removal values (i.e. a net export from the wetland) but negative values could not be used for our simple model. When negative removal occurred in particular years but not on the average (e.g. Kovacic et al. 2000, Jordan et al. 2003), we used the average removal percentage in fitting our model. In rare cases where only negative removal was observed, we omitted the observation from our analysis. Omission was only needed for total P removal by one of the wetlands studied by Kovacic et al. (2000) and total N removal by one of the wetlands studied by Koskiako et al. (2003).

While microbial removal processes that affect nitrogen removal are sustainable indefinitely under relative constant environmental conditions, soil surfaces may become phosphorus-saturated, and further phosphorus sorption is therefore not possible. Depending on the soil type and phosphorus loading rates, saturation may take many years, if it occurs at all. Phosphorus can also be sequestered in undecomposed plant material (i.e., peat) under certain waterlogged conditions in wetlands; however, if hydrology is altered, oxidation and decomposition of plant parts may release the phosphorus (and nitrogen) they contain. Capacity for sediment removal may also be impeded if high loading rates result in clogging or burial of vegetation. Additionally, high flow rates may lead to the formation of preferential flow pathways that reduce contact between water and microbes, soil, or vegetation. These and other variables may lead to changes in the efficiency of wetlands or wet ponds for stormwater quality improvement over time. Some processes may increase efficiency (e.g. peat formation) while other processes may simultaneously decrease efficiency (e.g. channel formation).

The non-linear regressions produced values of the k that can be used in the equation above to predict the proportion of total N or P removed based on the proportion of wetland area in the watershed. For total N, k=7.90 with lower and upper 95% confidence limits of 4.56 and 11.2. For total P, k=16.4 with lower and upper 95% confidence limits of 8.74 and 24.0. The proportion removed increases with the proportion of wetland area but the rate of increase declines as the proportion of wetland area increases (Fig. 4). Thus, the additional benefit of adding more wetland area gradually diminishes. The curves fit to the literature data are very similar to predictions of the more complex watershed scale models of Tonderski et al. (2005) (shown in Fig. 1 of the report for which this addendum applies).

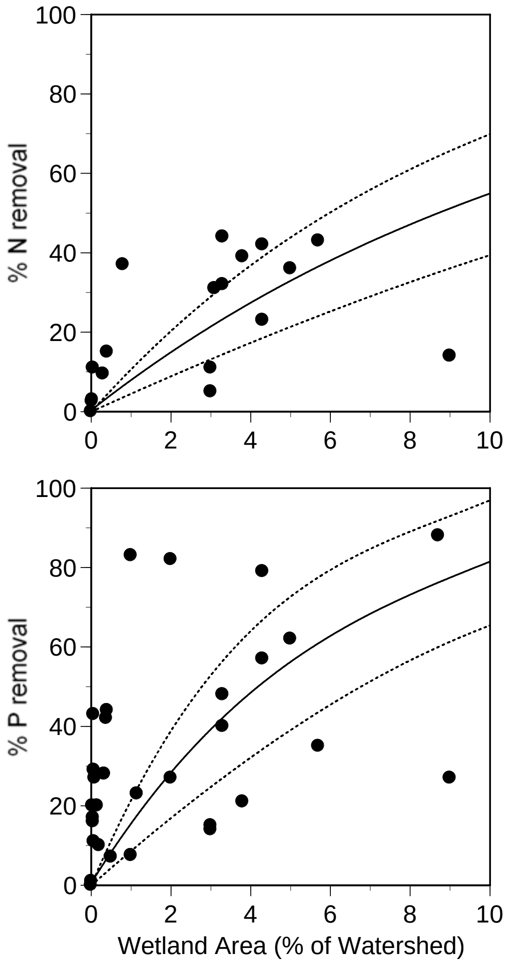


Fig. 4. The percentage of total N (top) or P (bottom) removed in wetlands versus the percentage of wetland area in the watershed. The curves are fit by non-linear regression to literature data on annual removal efficiencies after eliminating negative values of removal (see text). The dotted lines indicate the upper and lower 95% confidence interval. The data point at the origin is assumed by the model.

Reporting

In the event a jurisdiction does not report the area of the wetland or drainage area a one percent, two percent and four percent ratio of area of wetland to area of watershed will be used for the Appalachian, Piedmont and Valley, and Coastal Plain, respectively. Using the equation supplied by Jordan the effectiveness estimates for each geomorphic region are determined (Table 1).

Table 1. TN, TP and TSS removal efficiencies for wetlands broken down by geomorphic region.

Geomorphic Province	TN Removal Efficiency	TP Removal Efficiency

Appalachian	7%	12%
Piedmont and Valley	14%	26%
Coastal Plain	25%	50%

We assume wetland area increases moving from upland to lowland regions. The assigned wetland areas for each geomorphic area are based on natural hydrology and topography found in each region and is best professional judgment based on those natural conditions. As topography decreases, becomes flatter, wetland size increases. Surface and subsurface flow paths are clearly defined in upland regions, while these flow pathways interact to a greater degree with flatter terrain, providing more available area for larger wetland areas in coastal regions.

Total Suspended Solid

There are less data on removal of total suspended solids (TSS) then on removal of total N or P. The percentage of TSS removed averaged 21.6 (standard error 9.9) for five annual removal rates from Koskiaho et al. (2003) and two annual rates from Jordan et al. (2003). More data would be needed to determine the relationship between TSS removal and percentage of wetland area in the watershed.

The CBP approved effectiveness estimate for total suspended solid removal is 15%. This is calculating using the average from seven annual removal rates of 20%. Per our guidelines the average efficiency was adjusted because the research projects used to calculate the average do not always represent operational conditions (see Appendix B).

Other factors that adjust efficiencies not captured by the equation

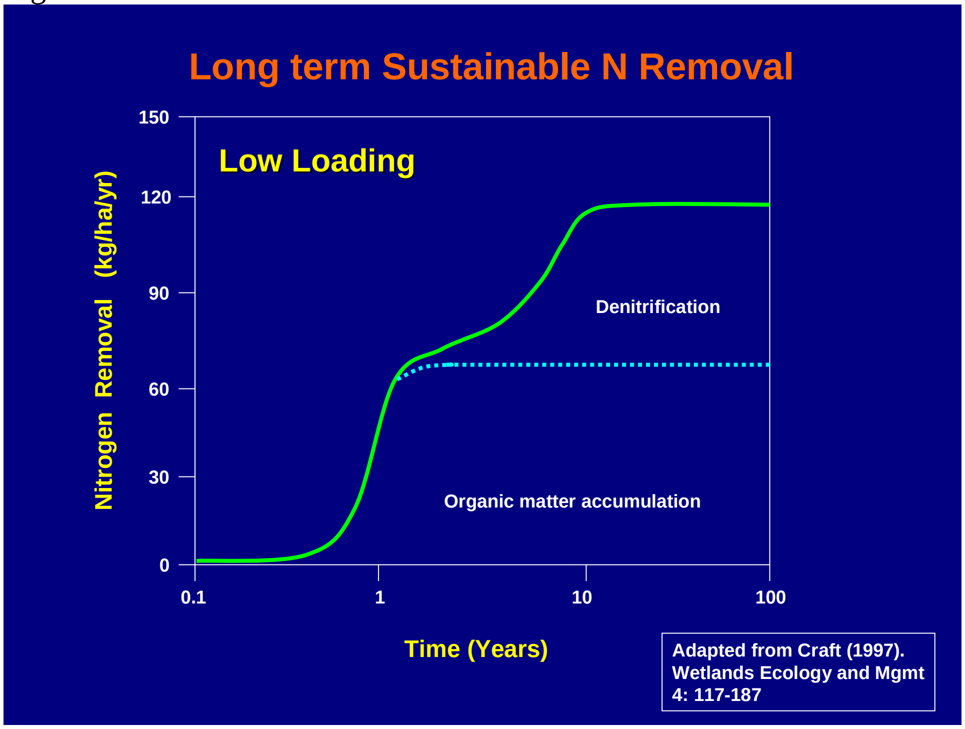
While the use of wetland area as a percentage of the watershed is a step in the right direction it does not address all factors that adjust efficiencies. Wetland age, seasonal variation, spatial and temporal variability of flow, landscape (position or type of wetland) will change residence time and loadings, consequences of land use conversions, and sediment accumulation is not addressed by the graph. Some studies have data that shows how efficiencies will be altered around these factors but no current method for calculating efficiencies for all these factors exists. To assist the CBP in future reviews that determine how to refine wetland creation efficiencies, the following studies are summarized.

Craft and Schubauer-Berigan (2007) surveyed the literature to evaluate the role of landscape position, hydrologic connectivity, loading rate and wetland age on nitrogen (N) and phosphorus (P) removal by freshwater wetlands. N and P removal is three times greater in connected (floodplain, fringe) wetlands than depressional wetlands. In floodplain wetlands, 8-15 MT N/km^2 and 1-3 MT P/km^2 are sequestered annually in soil as compared to 3 MT $N/km^2/yr$ and 0.5

MT P/km^2/yr for depressional wetlands. Denitrification removes an additional 3 to 15 MT of N/km^2/yr under low nitrate loadings. N removal is sustainable over the long-term (Fig. 5). Nitrogen removal is stimulated by increased nutrient loading, mostly through greater Denitrification, and, in highly loaded wetlands, N removal may exceed 10-50 MT/km^2/wetland/yr.

Nichols and Higgins (2000) determined that over an 18 year period nitrogen removal was consistent. However, phosphorous removal is variable. Increased nutrient loading also boosts P removal though P removal (1-5 MT/km^2/yr) is an order of magnitude less than N. Nichols and Higgins (2000) observed increasingly high phosphorous removal up to year 6, then removal drastically decreases around year 11 and finally remains consistently lower (Fig. 6). And P removal declines with time as sedimentation reduces water storage capacity and sorption sites become saturated. Floodplain wetlands can remove around 200 kg N ha annually and up to 600 kg ha yr under high nitrate loading rates. Creation, restoration and enhancement of wetlands for nutrient and sediment removal must recognize that (i) nutrient removal not consistent throughout the year (ii) P retention high at first but decreases with time as sorption sites become saturated and over a longer time scale sedimentation reduces wetland water storage capacity (iii) legacy effects (long term fertilization, drainage, soil oxidation) of re-flooding agricultural land may initially release P and possibly N, iv) not all wetlands are equal when it comes to nutrient removal, (v) N removal is greater than N removal, and (vi) effective N removal is sustainable over time but P removal declines as wetland age (Fig. 7).

Figure 5.



Adapted from Craft (1997). Wetlands Ecology and Mgmt 4: 117-187

Figure 6.

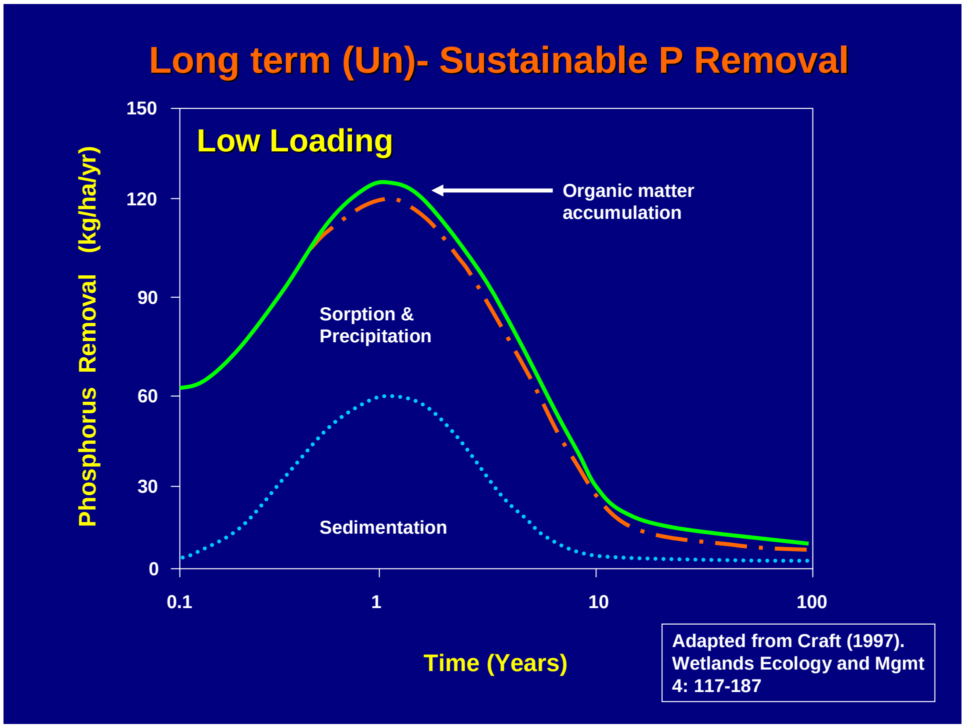
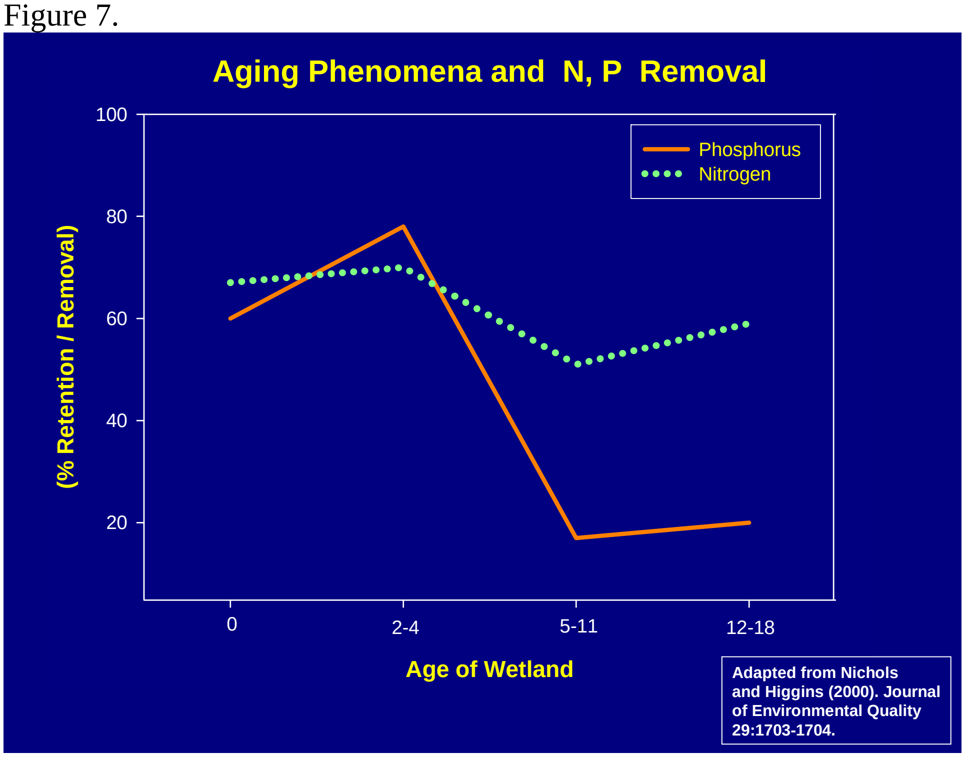


Figure 7.



Potential areas for wetland restoration

By definition wetland restoration areas are those where wetlands previously existed. Thus, the potential area for wetland restoration is most extensive in landscapes with extensive drainage ditches or drain tiles. The coastal plain is likely to have more area for wetland restoration than other physiographic provinces. However, the benefits of wetland restoration may also be extended to landscapes where wetlands may be created where none previously existed (e.g., Braskerud et al. 2005). In general, areas with flat topography and limited soil permeability are best for wetland restoration. Obviously, the wetlands must be positioned to receive drainage from areas that are the sources of materials that the wetlands are intended to remove. This positioning is assumed by the relationship between percent removal efficiency and the proportion of the watershed covered by wetland shown in Fig. 1. Natural wetlands are sometimes located at drainage divides (interfluves), high spots in the landscape. Restoring such wetlands may have other important benefits but will not contribute to intercepting materials released from uplands.

Because wetlands at the bottom of watersheds remove materials from emerging drainage water, the surface water quality benefits are immediate. In contrast, BMPs such as cover crops or special fertilizer application methods aimed at reducing loss of nutrients to groundwater may not affect surface water quality for several years because of the slow rate of groundwater flow to streams. Despite this time lag, it is still important to reduce nutrient losses at the source.

Future Research Needs

Variances in efficiencies due to size differences can be evaluated by comparing the water detention times among wetlands. However, data needed to calculate water detention times are seldom reported. The ratio of the area of the wetland to the area of the watershed is a possible surrogate for water detention time and is more often available, but incorporating water detention time into required procedures and methods would provide a more accurate picture of efficiencies.

As the effects of improper maintenance are not well known, it makes sense that we could try to account for improperly maintained wetlands by using conservative estimates of efficiencies. However, more research is needed to improve our understanding of how to properly maintain wetlands that are managed to remove nutrients and sediments. Also, we need to establish some protocol for evaluating wetland condition to determine if maintenance is needed. For example, there should be some way to assess whether a wetland is losing efficiency due to acretion.

Analyzing the potential negative benefits of using natural wetlands for sediment retention should be examined. This would include determining the potential negative effects of sedimentation on biotic quality that results when sediment deposition alters wetland soil texture and organic matter thus possibly promoting the growth of undesirable plan species. Carol Johnson, Department of Biology and Microbiology, South Dakota State University, Brookings, SD is investigating this issue.

In addition, net global warming potential due to greenhouse gas emissions from microbial process in restored wetlands should be examined. Marcelo Ardon, Department of Biology, Duke University, PO Box 90338, Durham, NC 27709, mla5@duke.edu should be contacted for more information on this topic.

And finally, as previously discussed, research is needed to determine how to calculate TSS removal efficiencies based on percent wetland area.

Recommendations for Future Refinements

1. Seasonal correction factor – while the proposal does note that there is seasonal variability in rates of retention/uptake/transformation, it only addresses it by using average rates. Further work on seasonal variability and periods of nutrient discharge is needed to refine the model.
2. Hydraulic loading rate - during high flow periods, retention time in wetlands is reduced, leading to decreased removal of nutrients and sediment
3. Wetland aging - as wetlands collect sediment over time, they begin to fill and reach a point where they are no longer able to serve as a sediment sink. The Living Resources Subcommittee (LRSC) of the Chesapeake Bay Program notes the distinction between created “wet ponds” and wetlands that are voluntarily restored on agricultural land. While “maintenance” of stormwater facilities is well understood and necessary, excavation of voluntarily established forested wetlands to restore capacity is not desirable.
4. Reporting on wetland drainage area - The percentage of wetlands in a watershed, by physiographic region, should be further investigated. LRSC will request that States begin to provide this information on a project-by-project basis, beginning with the 2007 reporting year. LRSC will work with IMS to streamline collection of this information, and investigate use of USGS’ “EDNA” tool for estimating drainage area in places where drainage is not reported.
5. Potential for dissolved P discharge from wetlands with high P content, due to past removal, under anaerobic conditions needs to be investigated.

How modeled

The equation outlined here replaces the modeling approach used by version 4.3 of the Chesapeake Bay Program’s Watershed Model that assumes each acre of restored or created wetland removes a proportion of the nutrients discharged from four watershed acres. This 1:4 ratio of wetland :watershed area will no longer be applied to wetland modeling. Also, effectiveness estimates in version 4.3 are assumed to be synonymous with riparian forest buffer estimates. As this report shows, extensive literature regarding nutrients/sediment processes is available to evaluate the effectiveness of wetlands and develop estimates of pollutant removal unique to wetland restoration and creation.

Conclusions

Efficiency of removal of N and P by restored wetlands can be approximately predicted from the ratio of wetland area to watershed area (Fig. 1) but actual efficiencies may be very variable. Implementation of wetland restoration BMPs should be linked with assessment of their effectiveness. Management of wetland BMPs should be adaptive, with provision for adjustment of expectations as more information on effectiveness becomes available.

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