AN ANALYSIS OF PALUSTRINE FORESTED WETLAND COMPENSATION EFFECTIVENESS IN VIRGINIA

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(ABSTRACT)

Plans to construct a wetland to replace wetland losses has become a common feature of permit requests. The purpose of this project is to suggest a methodology for quantifying the effectiveness of palustrine forested wetland construction in Virginia. Wetlands constructed by the Virginia Department of Transportation and the U.S. Army Corps of Engineers were surveyed and Wagner Road constructed wetland in Petersburg, Virginia was selected as the primary study site.

Chapter One of the present study suggests a method for early assessment of revegetation success utilizing weighted averages of colonizing vegetation. An adjacent reference site was chosen that was in close proximity to the constructed site and was used for comparison. Results from the Wagner Road site and the reference wetland indicated that colonizing vegetation weighted averages

provide a more sensitive measure of revegetation success than the methods described in the federal wetland delineation manual.

Chapter Two addresses the interaction of elevation, hydrology, and soil in order to (1) determine if constructed wetlands have the potential to perform those functions that are dependent upon anaerobic and/or reducing conditions, and (2) determine the relationship between hydrology, soil, and vegetation in order to suggest improvements in wetland construction techniques. Results at four study sites suggest that constructed wetland soils lack appropriate organic matter content to yield reducing conditions. Differences in carbon dioxide production within the Wagner Road constructed wetland suggested that elevation is also important.

In Chapter Three, a two-tiered method for assessing compensation effectiveness is presented. Tier one combines the early assessment methodology presented in Chapter One with permit compliance. Tier two is a research methodology to be conducted over the long term. An interpretation of the Wagner Road data was performed and the methodology was shown to (1) provide a comparison of constructed and reference wetland structure and function, (2) predict long-term functional performance, and (3) recommend improvements in construction techniques.

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General Introduction

Swamps, marshes, fens, and bogs have been grouped under the general term wetlands. Wetlands are considered to be transitional between terrestrial and aquatic systems where the water table is usually at or near the surface. The wetland definition most widely accepted, and used in this study, is that given in a wetland classification scheme proposed by the U.S. Fish and Wildlife Service (FWS) (Cowardin et al. 1979). That scheme typifies wetlands by three characteristics: (1) the land usually supports and is dominated by hydrophytes, (2) the substrate is predominantly undrained hydric soils, and (3) the substrate is saturated with water or covered by shallow water at some time during the growing season each year. Accordingly, vegetation, soil, and hydrology have been incorporated into the latest federal manual for delineating the border between wetlands and uplands (Federal Interagency Committee for Wetland Delineation 1989). The FWS classification scheme divides wetlands into five systems including: marine, estuarine, riverine, lacustrine, and palustrine. The palustrine system is considered in this study, and includes nontidal wetlands with salinity below 0.5 ppt. found in river floodplains. Palustrine wetlands are further classified by the dominant vegetation including emergent, scrub-shrub, and forested wetlands. Forested wetlands such as bottomland hardwood swamps are found along river floodplains throughout the Southeastern United States, and are the wetland type researched in this study.

<u>Wetland Values</u>

The value of wetlands to waterfowl habitat was noted by Shaw and Fredine (1956). Wetlands provide a refuge for displaced upland species and habitat diversity to other landscapes (Gill 1985). A disproportionately large percentage of rare and endangered species depend either directly or indirectly on wetlands. More than 50% of the endangered fishes and amphibians, 30% of the reptiles and birds, and 15% of the mammals of the United States depend on wetlands for survival (Williams and Dodd 1979). Both tidal and nontidal wetlands of the Chesapeake Bay help support numerous endangered and threatened animal species (White 1985).

Considerable research in wetlands has revealed many functions and values in addition to habitat. Sather and Smith (1984) divided wetland values among hydrology, water quality, food chain support, socio-economic, and habitat functions. Hydrologic values include flood control, groundwater recharge and discharge, and erosion buffer. Maltby (1987) describes a 60-65% reduction in flood peaks for a watershed composed of 15% wetlands and lakes.

Recharge and discharge of groundwater is poorly studied, but many wetlands can perform either, or at different times both groundwater discharge and recharge functions (Sather and Smith 1984). Root sediment holding potential and deflection of currents by plant stems help control shoreline erosion (Garbisch et al. 1975).

Water quality enhancement is a function most wetlands perform. Wetlands can act in several roles including transformers, filters, and sinks for a variety of chemicals and materials (Richardson 1988). Some functions result from the fact that wetlands are typically characterized by a narrow oxygenated layer directly above very reduced layers and are the primary reducing environment in the landscape (Gambrell and Patrick 1978). The position of wetlands between uplands and waterways creates an opportunity to ameliorate potentially negative impacts originating from either system.

Food chain values include primary production and export. Wetlands rank among the most productive ecosystems in the world (Smith 1980). Primary productivity yields a carbon source for many species, and exchange of biomass maintains linkages between adjacent systems (Wharton et al. 1982). Decline in wetland acreage and reduced fish harvests have occurred simultaneously in the Chesapeake Bay (Moore, pers. comm.).

As wetland values have become documented, the possibility for constructing wetlands to perform particular functions have been explored. Wetlands have been constructed for preventing shoreline erosion (Garbisch et al. 1975), wastewater treatment (Hammer 1989), water quality improvement from mined land runoff (Brooks et al. 1985), disposal of dredged material (Landin and Smith 1987), provision of habitat (Boyd 1982), control of shoreline erosion (Seneca 1980), stormwater control (Adams and Dove 1984), and replacement of damaged natural wetlands as part of the Clean Water Act of 1972 and 1977 (Garbisch 1985).

Legislation and Protection

Prior to this century, wetlands were considered to be wasteland and an impediment to development. Several swamp land acts (1849, 1850, and 1860) were designed to "reclaim" these areas for a variety of uses (Shaw and Fredine 1956). From 1950 to 1970, the United States lost 458,000 acres of its wetlands annually, and less than half of the nation's original wetland area remains. Most of the losses have occurred in palustrine forested wetlands (Tiner 1984a). The state of Virginia has lost 3,000 acres annually from 1956 to 1977, and inland wetland acreage losses, i.e., forested wetlands, were nearly ten times greater than coastal losses (Tiner 1984b).

Recent federal legislation has been enacted to protect wetlands. The Tax Reform Act of 1986 (P.L. 99-514) removed many tax incentives for converting wetlands to cropland. Executive Order 11990 requires that federal government activities avoid wetland impacts to the extent possible. The "Swampbuster" provision of the 1985 Farm Bill (Food Security Act of 1985, P.L. 99-198) denies federal price supports, payments, certain loans, and other benefits to farmers who convert wetlands for agricultural purposes.

The chief regulatory program for the protection of wetlands is Section 404 of the Federal Water Pollution Control Act of 1972 (33 U.S.C.A. 1344) and later amendments under the Clean Water Act of 1977 (U.S.C.A. 1251-1376) (Larsen 1985). Congress gave primacy to the U.S. Army Corps of Engineers (Corps), which controls permitting. The U.S. Environmental Protection Agency (EPA) has veto power over Corps permitting through Section 404(c). The FWS and the National Marine Fisheries Service (NMFS) serve merely in an advisory capacity with minimal regulatory responsibility. Several exemptions allowing negative impacts in wetlands are given under the Clean Water Act, including "general permits," which allow some highway construction to bypass parts of the permit and mitigation procedure (Salveson 1990 and Zaleha 1988).

Much confusion persists in the terminology of wetland construction. This study will follow the useage found in the National Environmental Policy Act of 1969 (C.F.R. Part 1508.20 (a-e)) regulations which define mitigation in five parts:

a) avoiding the impact by not taking a certain action or parts of an action;

b) minimizing impacts by limiting the degree or magnitude of the action and its implementation;

c) rectifying the impact by repairing, rehabilitating, or restoring the affected environment;

d) reducing or eliminating the impact over time by preservation and maintenance operations during the life of the actions; and,

e) compensation for the impact by replacing or providing substitute resources or environments.

Compensation measures considered by FHWA include preservation, restoration, enhancement, construction, and replacement (Isaacson 1988) and wetland construction is clearly the most controversial (Salveson 1990).

Wetlands may be constructed "on-site" or "off-site." Wetland construction is usually accomplished by (1) enlarging a natural wetland at one location to compensate for loss of an adjacent wetland (on-site replacement), or (2) construction of a replacement wetland at some other location (off-site replacement) (Larson 1987). Kusler (1988) suggested that "on-site" construction of wetlands would be more likely to replace wetland functions.

Wetlands may also be constructed "in-kind" or "out-of-kind." Structural replacement of a forested wetland with another forested wetland ("in-kind" replacement) has not been demonstrated due to the time needed for tree maturation (Clewell and Lea 1990). Brinson and Lee (1989) suggested that "in-kind" replacement held the greatest potential for functional replacement, and should be a goal for wetland compensation.

Wetlands have been constructed for a variety of purposes and studies can be found in conference proceedings (e.g., Hillsboro Community College 1974 to date, Swanson 1979, Larson and Neill 1987, Kusler et al. 1988, and Fisk 1989). An EPA-funded publication by Kusler and Kentula (1990) discussed wetland restoration and construction projects from around the United States. For most wetland construction projects, success has been defined as achieving the goals set for the project. Unfortunately, goals are seldom stated or sufficiently defined in wetland compensation projects (Quammen 1988, Garbisch 1990, and Gannett Fleming, Inc. 1991). Kusler (1990) found that stated goals ranged from replacement of vegetation to replacement of all natural wetland functions. Nontidal, freshwater wetland compensation in Pennsylvania was studied recently by Gannett Fleming, Inc. (1991). An extensive literature review in that study concluded that data concerning monitoring the results of wetland construction are sparse and that "functional success has rarely been documented."

Wetland construction for compensation is increasing but monitoring has been limited. Highways and wetlands are both linear aspects of the landscape and therefore frequently intersect. Permits for highway construction form the bulk of wetland fill permits in Virginia (Allen-Grimes, pers. comm.) and in the Southeastern United States (Deitz, pers. comm.). Recently, highway departments have embraced the concept of mitigation through wetland construction. Costs of constructing wetlands range from $250/acre to $6,000/acre (Office of Technology Assessment 1984), but federal agencies have conducted very few studies of compensation effectiveness. Roelle and Ellis (1988) suggested that monitoring by agencies (Corps, EPA, FWS, and NMFS) would lead to better recommendations in the future. No evaluation technique for constructed wetlands enjoys widespread approval, and there is a need for more monitoring of effectiveness (Race 1985, Butts 1988, LaRoe 1988, Larson 1988, and Kusler 1990). Several authors have addressed the need for a monitoring methodology, and noted that monitoring is uncommon for short-term evaluation, and even less for long-term evaluation (Clewell and Lea 1990 and Kusler and Kentula 1990). Forested wetland construction effectiveness may be the least studied of the major wetland types that are impacted (Kruczynski 1990).

Quammen (1988) distinguished between analysis of compliance with conditions of the permit (compliance monitoring) and analysis of construction success. Permit compliance monitoring addresses legal problems regarding permittee responsibilities over the short term (Quammen 1988 and Salveson 1990). In the long term, monitoring is also needed to demonstrate that fully functional wetland systems can be constructed (Kruczynski 1990). Predictive information is especially important in forested wetlands, since most forested wetland construction attempts are "too recent to predict their ultimate success" (Clewell and Lea 1990).

<u>Rationale for Chapter One</u>

Early monitoring is necessary for contractual issues (i.e., establishment period for vegetation planted by subcontractors) and for permit bonds that are typically for short periods (Kusler and Kentula 1990). Time considerations are of great significance in forested wetland construction, as it may take decades before structural or functional replacement is attained. Permittees and subcontractors are unlikely to remain responsible for effectiveness beyond the first few years (Clewell and Lea 1990).

In Chapter One, a method for analysis of colonizing vegetation is suggested as a component of compliance monitoring. Vegetation is planted in most forested wetland construction projects and permit conditions generally require some minimal level of revegetation success, which should be included in early assessment. Colonizing species may rapidly become established and may provide a useful indication of site conditions. Flooding frequency, timing, and duration affect development of the soil environment. Hydrology monitoring would provide useful data because of the controlling influence of hydrology on wetland ecology; however, the variability inherent in hydrologic measurements and high monitoring costs limit the usefulness of short-term hydrology data (Hollands 1986). Likewise, soil monitoring is of limited utility in the short term because of the uncertainty associated with the time needed for development of hydric soil characteristics (Federal Interagency Committee for Wetland Delineation 1989).

Colonizing vegetation characteristics may be a better predictor of effectiveness than planted vegetation success. Factors such as microsite limitations and quality of nursery stock may effect individual, planted species in ways that are independent of site conditions.

The species composition of colonizing vegetation is influenced by hydrology and soil conditions. Wetland soil conditions may stress vegetation in various ways including direct toxicity, bioavailability of nutrients (Gambrell and Patrick 1978), high concentrations of toxins (Armstrong 1975), and formation of inorganic-oxide layers around roots (Armstrong and Boatman 1967). Wetland plants, termed hydrophytes, possess morphological and/or physiological adaptations to these stresses, and upland species invasion is precluded. Plant adaptations and plant distribution occur along a gradient, and have been used to distinguish between uplands and wetlands (Federal Interagency Committee for Wetland Delineation 1989). Data on the hydrologic conditions that most native plant species are associated with has been collected by the FWS, and is available for Virginia. That system classifies species according to frequency of occurrence in wetlands (Reed 1988).

The method for estimating the vegetation parameter must not be too restrictive, but must be of sufficient sensitivity to evaluate site conditions. Similarity indices have been suggested for comparison of constructed wetland vegetation (planted or colonized) to an adjacent reference wetland. However, relatively pristine forested wetlands may differ greatly in species composition, and such a requirement or goal may be unrealistic and too restrictive (Clewell and Lea 1990). The federal wetlands delineation manual (Federal Interagency Committee for Wetland Delineation 1989) has recently been used to assess vegetation; however, this method would only indicate the presence of a wetland, without providing information on the similarity to the filled wetland. Chapter One investigates use of vegetation weighted averages (WA), which is a sensitive vegetative parameter that includes relative percent cover and wetland indicator status of each species, for early assessment of effectiveness. In that methodology, WA is calculated for the predisturbance wetland (or reference wetland if the former is unavailable) and used as a goal for the constructed wetland.

Rationale for Chapter Two

As the controlling influence on wetland ecology, hydrology determines many wetland soil characteristics (Mitsch and Gosselink 1986). When sufficient quantity and quality of organic matter are present in a flooded soil, oxygen rapidly becomes depleted and reducing conditions develop (Ponnamperuma 1972). Wetlands are the main reducing ecosystem on many landscapes, and some water quality functions and values frequently performed by wetlands are dependent upon these conditions.

Most forested wetland construction projects conducted by the Virginia Department of Transportation (VDOT) do not involve the application of organic matter (demucked soil or upland topsoil) over a site. The wetland construction process typically involves excavation to the water table depth and removal of the overlying soil (including the organic material of the O horizon). The resultant interaction between soil that is low in organic matter, hydrologic conditions, and the mosaic of elevations present at newly constructed wetlands affects the microbial activity and oxygen content of the soil environment.

Chapter Two is designed to (1) estimate potential performance of water quality functions and values dependent upon anaerobic and/or reducing conditions, (2) predict potential for long-term performance of water quality functions and values, and (3) to analyze the relationship between hydrology, soil, and vegetation in order to suggest improvements in wetland construction techniques. The Wagner Road constructed wetland site in

Petersburg, Virginia was selected because wetland type, construction techniques, and topography were representative of the 15 sites visited.

<u>Rationale for Chapter Three</u>

Very few studies are available at present that address forested wetland construction success, even though the practice of compensation through wetland construction is continuing to increase. Monitoring is essential if wetland construction techniques are to be improved (Roelle and Ellis 1988 and Kruczynski 1990). Several authors have called for both short-term and long-term monitoring to assess effectiveness, however no monitoring methodologies have widespread support (LaRoe 1988 and Kusler and Kentula 1990).

This study presents a two-tiered methodology that (1) evaluates compliance, and (2) addresses structural and functional replacement. Since permits routinely imply that wetland vegetation will become established, criteria for revegetation success should be required in order to determine compliance. Establishment of an equivalent aerial extent of appropriate vegetation communities using the methodology described in Chapter One is recommended for the first tier of monitoring, i.e., compliance.

In the second tier of monitoring, research on both a reference wetland and the constructed wetland addresses hydrology, soil, vegetation, fauna, and landscape ecological characteristics. The methodology recommends setup, monitoring, analysis, and interpretation procedures to address replacement of functions and values. Instead of restricting interpretation to known or anticipated functions and values of the original wetland, we recommend assessing all wetland functions and values as a means of avoiding replacement of degraded wetlands "in-kind" and increasing the wetland construction data base.

Funding for monitoring at the level of tier one (compliance) should be included in the budget for every permit that involves wetland construction. At the second tier level (research), funding should be in the form of competitive grants funded by those requesting permits and the regulatory agencies.

CHAPTER ONE

Use of Constructed Wetland Delineation and Weighted Averages as a Component of Assessment

Abstract

Forested wetland construction associated with Section 404 of the Clean Water Act is increasing dramatically thoughout the Mid-Atlantic region. However, few quantitative data are available regarding the effectiveness of past forested wetland construction efforts in this region, and no quantitative assessment techniques for evaluating success enjoy wide support. Though constructed wetlands may be lacking sufficient time for soil formation, colonizing vegetation and hydrology can be measured. Hydrology monitoring is expensive, time consuming, and highly variable over short periods of time (Gannett Fleming, Inc. 1991) and vegetation monitoring alone may be sufficient for early site assessment.

The purpose of this study was to develop a method for calculating percentage "wetland" and "upland" as an early monitoring tool. Calculations were made using the federal manual for wetland delineation, colonizing vegetation weighted averages (WA) and moisture estimates, and comparison with an adjacent reference wetland. Percentage "wetland" and "upland" estimates were similar whether vegetation alone or vegetation in combination with

hydrology were used in calculations. Vegetation colonizing the site responds to both soil and hydrology (Mitsch and Gosselink 1986) and may provide an accurate assessment of site conditions. The findings of this study suggest that calculating plot WA and comparison with pre-impact wetland vegetation (or an adjacent reference wetland) may be used as an early step in monitoring constructed wetlands.

Introduction

Section 404 of the 1972 Federal Water Pollution Control Act as amended requires a permit from the U.S. Army Corps of Engineers (Corps) for most activities involving placement of fill material in a wetland. Plans to construct a wetland to compensate for wetland losses have become a widely used component of permit applications. Forested wetland construction began in 1980 in Virginia and has rapidly become the preferred method of mitigation. Documentation is sparse, but 20 to 40 ha of forested wetlands have been constructed by Virginia Department of Transportation (VDOT), which has received the greatest number of permits issued to a single permitee by the Norfolk District of the Corps (Allen-Grimes, pers. comm.). A large number of major highway projects are anticipated within the coastal plain of Virginia.

Approximately three-fourths of the state's wetlands are located in this province, and over 400 ha of forested wetlands may be filled as a direct result of highway construction by 1995. In spite of this projected ten-fold increase in total forested wetland construction attempts, no quantitative monitoring study exists in Virginia.

Delineation of naturally occurring wetlands using the "federal manual" utilizes a three parameter method that includes soil, hydrology, and vegetation (Federal Interagency Committee for Wetland Delineation 1989). Freshwater wetland construction techniques usually involve grading of an upland site to ambient water table elevation, leaving the mineral soil without amendments, planting saplings, allowing natural colonization by herbaceous vegetation, and implying succession from emergent to forested wetland (Clewell and Lea 1990). Unless amended, constructed wetland soils are essentially upland mineral soils and may require years for transformation into wetland soil. The federal manual considers such areas "problem areas" and suggests that hydrology, vegetation, and professional judgment be used to delineate the wetland. Constructed wetland site inspections of hydrologic conditions in Virginia confirmed the presence of a range of freshwater, nontidal water regimes given by Cowardin et al. (1979); however, many areas within constructed wetlands are drier than the wetland water regimes listed. Such areas within constructed wetlands seldom exhibit standing water, are only moist at the surface following precipitation events, and fail to meet the hydrology criterion of the federal manual. A proposed scheme is presented here and includes wetland and upland hydrology modifiers (Table 1).

Wetland vegetation has colonized the 15 constructed forested wetlands surveyed in the current study, including the primary research site at Wagner Road, and forested wetlands studied by other researchers (e.g., Butts 1988 and Clewell and Lea 1990). However, based on the federal manual, the hydrology criterion was not met in several plots that narrowly met the vegetation criterion. To increase sensitivity of the vegetation parameter, a different technique utilizing all species found in plots was selected. For direct gradient analysis of vegetation along a single environmental gradient, such as moisture, weighted averages (WA) may be used (Whittaker 1951). Weighted averages have been described as useful for assessing wetland status of some vegetation types along a moisture gradient for wetland delineation under natural conditions (Carter et al. 1988, Wentworth et al. 1988, and Scott et al. 1989). In this study, WA of vegetation colonizing constructed wetlands was measured and compared

Table 1. Water regime modifiers for mean growing season surface moisture from Cowardin et al. (1979) and the proposed system.

Cowardin Modifiers	Proposed Moisture Modifiers: Modifier	Proposed Moisture Modifiers: Moisture Range
permanently flooded, intermittently exposed, permanently flooded, seasonally flooded	8	standing water >20 cm deep
	7	standing water 11-20 cm deep
	6	standing water 1-10 cm deep
saturated, intermittently flooded	5	very moist
temporarily flooded, intermittently flooded	4	moist
not wetland	3	dry to moist
	2	dry
	1	very dry

to the proposed moisture modifier system.

The purpose of this study was to compare the federal manual for wetland delineation, WA and moisture modifiers, and use of an adjacent reference wetland to provide a component of early assessment for constructed wetlands. Establishing the hydrology criterion in marginal cases is a time consuming, expensive effort, and may not be realistic for agencies considering the increased acreages involved. Likewise, soil may not be a useful parameter since soil transformation processes may require years. The current study seeks to analyze the response of colonizing vegetation to hydrology in constructed wetlands to determine the suitability of vegetation as a cost-effective means of site monitoring.

Site Description

Wagner Road constructed wetland site is located at 37° 11' 44" north latitude, 77° 20' 26" west longitude in Petersburg, Virginia (Figure 1). The 1.53-ha site was constructed in summer of 1987, and woody saplings (up to 2 m tall) and shrubs were planted in February 1989. The study area is in the upper coastal plain, between Old Wagner Road and its replacement, Route 795 (New Wagner Road). The site is within Blackwater Swamp headwaters, which has been recommended for state scenic river

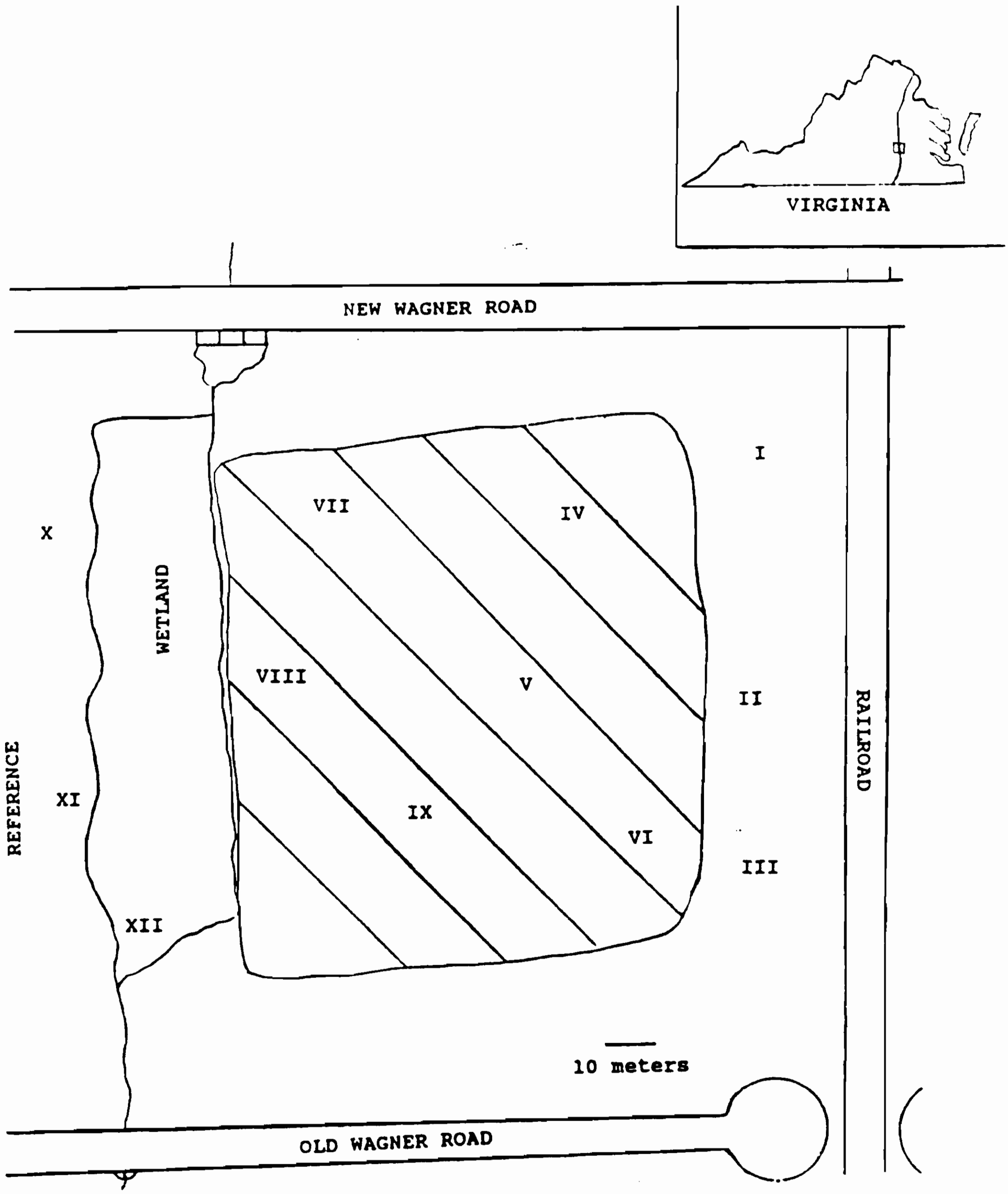

Figure 1. Location of the Wagner Road constructed wetland study site and reference wetland in Petersburg, Virginia. Roman numerals represent well locations.

designation. The previous early successional upland forest was graded to approximately ambient wetland elevations, 37.85 m above sea-level. Though permit conditions called for backfill of hydric soil to 30 cm above upland mineral soil, there is no evidence of hydric soil deposition. Surface percent organic matter content in the constructed wetland ranged from 1.3 to 3.3%, with an average of 1.87% (+/- 0.745). Organic matter at 0.1 m below surface ranged from 0.9 to 5.2%, with an average of 1.90% (+/- 1.63). An adjacent, natural forested wetland in Second Swamp, which is in the headwaters of the Blackwater River, was used as a reference site following selection criteria described in Abbruzzese et al. (1987). A middle-aged stand of *Fraxinus pennsylvanica*, *Nyssa sylvatica*, and *Taxodium distichum* formed the dominant canopy in the reference site. Subcanopy and herb strata were dominated primarily by obligate wetland species, though some dominants were facultative wetland species. No obligate upland or facultative upland species were found in the reference area. Few facultative species (3) were present, and no facultative species were dominants. Organic matter content at the surface and at 0.1 m below the surface of the reference site averaged 4.67% (+/- 0.923) and 2.40 (+/- 0.656), respectively. Water table readings in the constructed site and reference area were taken from nine 1.5-inch (3.81-cm) diameter pvc pipe wells arranged in a stratified random design. Constructed site (19.05 cm +/- 7.89) and reference site (21.40 cm +/- 7.60) depth to water table were not significantly different at the 0.05 level. However, three of six constructed wetland wells averaged significantly greater depth to water table than the mean for reference wetland wells. Mean standard deviation in depth to water table was greater within individual constructed wetland wells (+/- 19.23) than reference wetland wells (+/- 16.42). The water regime modifier for the reference wetland is "seasonally flooded" (Cowardin et al. 1979). None of the reference area became drier than "moist" (moisture modifier = 4, Table 1) during the 1989 growing season.

Materials and Methods

A modified plot sampling technique of the federal *manual* "comprehesive on-site determination method" was performed (Federal Interagency Committee for Wetland Delineation 1989). Permanent sampling locations were established using a stratified random sampling technique with 106 1-m^2 plots along seven parallel transects. Vegetation was sampled monthly from May through September, 1989 and again in September, 1990. Vegetation was identified using several vascular plant keys and nomenclature follows U.S. Department of Agriculture

(1982). Classification of species into indicator status categories was accomplished using the National List of Plant Species that Occur in Wetlands: Virginia (Reed 1988) (Table 2). The hydrophytic vegetation criterion was met when more than 50% of the dominant vegetation in the sample plot had an indicator status of obligate, facultative wetland, or facultative based on September, 1990 vegetation data (Federal Interagency Committee for Wetland Delineation 1989). Modified importance values for each species were calculated as the sum of relative cover and relative frequency (Daubenmire 1959), but only relative cover was used in WA calculations.

Relative cover estimates and indicator status of each species in each plot were used to calculate a WA for each plot (Wentworth et al. 1988), also termed community index (Scott et al. 1989), using the following formula (Jongman et al. 1987):

$$WA = (y_1u_1 + y_2u_2 + \ldots + y_mu_m)/100$$

where $y_1, y_2, \ldots, y_m$ are the relative cover estimates for each species in the plot, and $u_1, u_2, \ldots, u_m$ are the indicator values of each species.

Since indicator categories range from 1 to 5, plot indicator status does also. Thus, a plot composed of all

Table 2. Indicator categories, probability ranges, and indicator index values for vegetative species occurrence in wetlands (Reed 1988).

Indicator Category	Wetland Frequency	Indicator Index
Obligate wetland	>99%	1
Facultative wetland	67-99%	2
Facultative	34-66%	3
Facultative upland	1-33%	4
Obligate upland	<1%	5

obligate wetland species will have a status of 1; a plot of all obligate upland species would have a status of 5. The aerial extent of each constructed wetland that falls within each 0.5 WA status range was then calculated as a percentage of all plots in the constructed wetland (Table 3).

Determination of appropriate WA limit for "upland"/"wetland" boundary may require additional hydrologic data (Wentworth et al. 1988). A semi-quantitative range of moisture modifiers was produced and related to a list of nontidal wetland water regimes found in Cowardin et al. (1979) (Table 1). Qualitative estimates of surface moisture content were made at each quadrat for the five times vegetative cover estimates were made in 1989. Mean moisture content was calculated per plot. The 12 1.5-inch diameter pvc pipe wells were installed to a minimum depth of 1 m in April, 1989 and were sampled once per week through September, 1989. Well locations included three wells in the adjacent oak-hickory forest, three were in the reference wetland, and six were in the constructed wetland. Plot and well locations and elevations were recorded using a laser light level. Mean moisture content per plot was interpolated on maps in order to relate well data. Climatological data for 1989 and 1990 growing seasons were provided by the Virginia

Table 3. Mean weighted average, percent of all plots in the site, and mean moisture, for each weighted average range.

WA Range	WA		Percent	Moisture	
	Mean	SD	of Site	Mean	SD
unvegetated	-		1.89	2.30	0.10
>3.00	3.28	0.01	1.89	2.30	0.30
2.5-2.99	2.72	0.15	12.26	2.54	0.51
2.0-2.49	2.16	0.12	19.81	2.69	0.52
1.5-1.99	1.78	0.14	31.13	3.91	0.86
1.0-1.49	1.20	0.15	33.02	5.48	0.61

Climatology Office, Charlottesville, Virginia.

Soil samples (0.5 l) were collected at each of the 106 plots along the seven transects. Soil samples were weighed, dried, and reweighed for bulk density and volumetric water content estimates. Organic matter determinations were performed by taking ash free dry weight of subsamples. Field indicators of hydric soil, including gleization, mottling, low chroma, and dark vertical streaking, were missing in all constructed wetland and adjacent upland samples, but were present in all reference wetland samples. The federal manual (Federal Interagency Committee for Wetland Delineation 1989) section on "problem areas," which included newly constructed wetlands or "man-made wetlands," stated that these wetlands "will have indicators of wetland hydrology and hydrophytic vegetation. But the area may lack typical field characteristics of hydric soils..." Therefore, both hydrology and vegetation criteria were used to determine the status of each plot as either "wetland" or "upland."

Results

There were 33 species identified in the 106 plots at Wagner Road in 1989 compared to 57 species in 1990 (Table 4). However, immaturity and the presence of only vegetative organs may have limited identification of species during the second growing season in 1989. Maximum

Table 4. Indicator status (IS) and importance value (IV) for vascular plant species colonizing 106 1-m^2 plots within the Wagner constructed wetland as of September, 1990.

Species	IS	IV
Agalinis purpurea L. (Pennell)	2	8.01
Aneilema kaisak Hasskarl.	1	18.03
Ambrosia artemisifolia L.	4	12.02
Bidens polylepis Blake	2	56.65
B. frondosa L.	2	21.14
B. laevis (L.) B.S.P.	1	9.88
Campsis radicans (L.) Seemann	3	3.91
Carex scoparia Willd.	2	1.91
Cassia fasciculata Michx.	4	14.29
Cephalanthus occidentalis L.	1	1.89
Cyperus erythrorhizos Muhl.	2	2.87
C. esculentus L.	2	1.90
C. polystachyos Rottboel	2	1.90
C. pseudovegetus Steudel.	2	22.13
C. strigosus L.	2	7.73
Digitaria ischaemum (Schreber) Muhl.	3	11.61
Diodia teres Walter	5	22.39
D. virginiana L.	2	20.81
Echinochloa muricata (Beauvois) Fern.	2	86.59

Table 4, continued.

Species	IS	IV
Eclipta alba L. Hasskarl.	3	11.43
Eleocharis fallax Weatherby	1	66.03
E. obtusa (Willd.) Schultes.	1	58.06
Eupatorium hyssopifolium L.	5	1.97
Fimbristylis autumnalis (L.) R. & S.	2	10.49
Galium obtusum Bigelow.	2	10.50
Hypericum canadense L.	2	7.77
Juncus acuminatus Michx.	1	17.91
J. canadensis J. Gay ex La Harpe.	1	6.87
J. effusus L.	2	24.16
J. scirpoides Lam.	2	5.81
J. tenuis Willd.	3	7.75
Leersia oryzoides (L.) Swartz	1	20.74
Lespedeza stipulacea Maxim.	4	6.06
Lindernia dubia (L.) Pennell.	1	11.74
Lobelia cardinalis L.	2	2.87
Ludwigia alternifolia L.	2	14.89
L. linearis Walter.	1	6.04
L. palustris (L.) Ell.	1	32.63
Lycopus virginicus L.	1	2.85
Mikania scandens (L.) Willd.	2	3.95
Panicum dichotomiflorum Michx.	2	78.72
P. rigidulum Nees	2	10.11

Table 4, continued.

Species	IS	IV
P. scoparium Lam.	2	21.68
P. verrucosum Muhl.	2	75.22
Paspalum floridanum Michx.	2	2.98
P. laeve Michx.	3	34.32
P. dilatatum Poiret	3	3.96
Polygonum punctatum Ell.	1	29.50
Proserpinaca palustris L.	1	3.84
Rhexia mariana L.	1	5.71
Rhynchospora capitellata (Michx.) Vahl.	1	5.78
R. corniculata (Lam.) Gray	1	32.40
Rotala ramosior (L.) Koehne.	1	1.90
Scirpus atrovirens Willd.	1	1.90
S. cyperinus (L.) Kunth.	2	5.20
Typha latifolia L.	1	2.96
Vallisneria americana Michx.	1	5.22

vegetative cover attained by monthly sampling in 1989 occurred in August, and mean percent cover per plot was 25.33% (0-90.1%), but was not significantly different from September, 1989 mean percent cover of 23.44% (0-89.2%). Average raw cover per plot in September, 1990 was significantly greater, 66.09% (0-176.1%). Average number of species per plot (5.57 +/- 2.58) was the same for both months in 1989. Number of species per plot in September, 1990 was 8.33 (+/- 3.63). In 1989, obligate and facultative wetland categories had the highest number of species (13 each) and increased to 21 obligate wetland and 25 facultative wetland species in 1990. Facultative species increased from two in 1989 to six in 1990. Three facultative upland species were found in 1989 and two were found in 1990. Obligate upland species totaled two in 1989 and three in 1990. Species of highest importance values in 1990 were both facultative wetland species including _Echinochloa muricata_ (86.59) and _Panicum dichotomiflorum_ (78.82) (Table 4).

For within site comparison, Wagner constructed wetland vegetation was treated as two populations of plots, one "wetland" (68 plots) and one "upland" (36 plots). Nearly all obligate wetland species cover (98.8%) was contributed to the "wetland" portion of the constructed wetland. The dominant species in "wetland" plots were usually obligate wetland species, and included Eleocharis fallax (16 plots), E. obtusa (10 plots), and Ludwigia palustris (7 plots). Most obligate upland species cover (89.7%) was contributed by "upland" plots. Two obligate upland species were dominant in "upland" plots and included Ambrosia artemisifolia (1 plot) and Diodia teres (1 plot). The two obligate upland species were present in 21 of the 36 "upland" plots, and 7 of the 68 "wetland" plots. Of the three facultative upland species found at the Wagner constructed wetland site, 89.3% of their cover was in "upland" plots. Facultative upland species were present in 14 "upland" plots and four "wetland" plots. Facultative wetland species contributed roughly equal cover to both "upland" (42.2%) and "wetland" (57.8%) plots.

The federal delineation manual included constructed wetlands under the heading of "problem areas" since they lack one or more criteria necessary to perform a delineation, most often the soil criterion. Hydric soil indicators were absent at the end of three complete growing seasons (October, 1990); therefore, vegetation and hydrology were used to calculate the percent of the site that was "upland." Based on the federal manual, hydrology and/or vegetation criteria were not met in 27.9%, 32.7%, or 33.7% of the plots, using a water regime modifier of

3.0, 3.5, or 4.0. Of these "upland" plots, the hydrology criterion was not met in all but one plot (99.1%). Federal manual vegetation methods were less sensitive, and only five (4.7%) of the "upland" plots failed to meet the wetland vegetation criterion. Two plots (1.5%) were unvegetated and averaged "dry."

In order to meet the 1989 federal manual hydrology criterion, the depth to water table must be less than 15.24 cm (6 inches) for a duration of 1 week or more in somewhat poorly drained mineral soils. Three wells in the "upland" portion of the constructed wetland measured shallower than the 15.24-cm limit on two occasions (June 23 and July 14), and both times were within 24 hours of significant (at least 2.0 cm/24 hours) precipitation events. However, all three wells failed to meet the hydrology criterion for duration of flooding.

Precipitation totals for May through September, 1989 were 10.6% above normal, and 33.9% above normal for the same period in 1990. Moisture estimates indicated considerable variability in surface moisture in the constructed wetland at any given time. Some plots had standing water throughout the period, while others averaged "dry" to "very dry." Mean moisture estimate per plot for the period from June to September, 1989 was 3.42 (+/- 2.21), which is "dry/moist" to "moist." A moisture modifier of 3.5 was selected to delineate "upland" versus "wetland" hydrology based on the moisture modifier comparison to the Cowardin et al. (1979) system (Table 1), and also based on the driest mean moisture estimate for the reference wetland. Interpolation with a moisture modifier of 3.5 ("dry to moist" to "moist") defined an area that included only those wells failing to meet the federal manual hydrology criterion. The three wells that failed to meet the hydrology criterion were within the area defined as "uplands" based on either WA or a moisture modifier of 3.5 (Figure 2).

Percent "upland" based on WA and moisture modifier ranges was calculated. If both a WA of 2.0 and a moisture modifier of 3.5 are used, 32.7% of the Wagner site would be "upland," as compared with 34.6% if a WA of 2.0 is used alone (Table 5). Standard deviations were low for moisture modifiers in each WA range (Table 3). Weighted averages were correlated with the proposed moisture modifiers ($r^2 = 0.704$), and maps of the "upland" and "wetland" portions based on either moisture modifier of 3.5 or a WA of 2.0 are similar in location and aerial extent (Figure 2). While additional work at other constructed wetlands may be called for, the data suggests that WA alone may be used to delineate constructed wetland

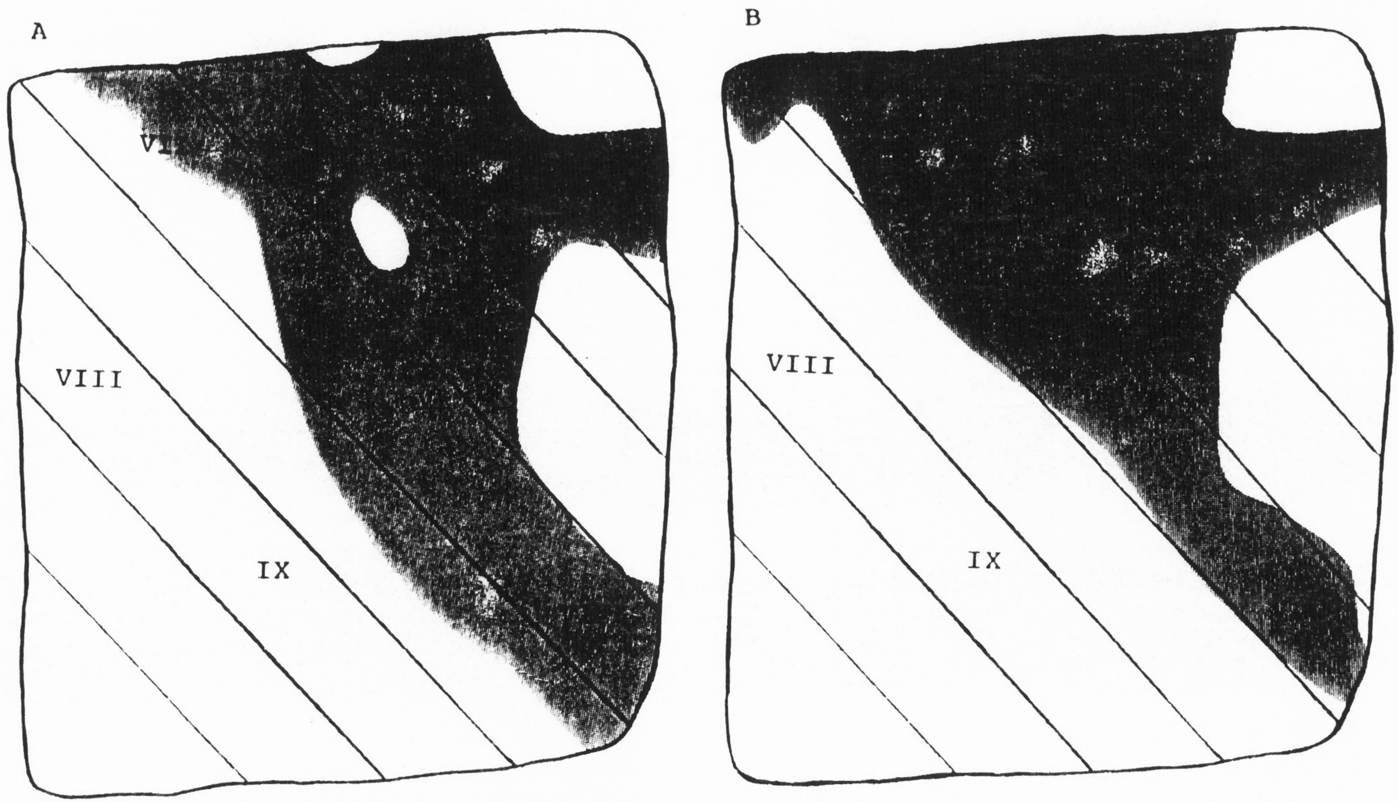

Figure 2. "Upland" and "wetland" portions of the Wagner Road constructed wetland study site in Petersburg, Virginia. (A) Shaded area represents "upland" portion of constructed wetland based on moisture modifier limit of 3.5. (B) Shaded area represents "upland" portion of constructed wetland based on weighted averages limit of 2.0.

Table 5. Percent of site delineated as upland based on moisture modifier and vegetation weighted averages (WA).

WA	Moisture Modifier				
	2.5 or drier	3.0 or drier	3.5 or drier	4.0 or drier	any moisture
all*	14.4	33.7	43.3	48.1	100.0
>=1.5	14.4	33.7	43.3	48.1	66.3
>=2.0	11.5	27.9	32.7**	33.7	34.6
>=2.5	6.7	12.5	13.5	14.4	14.4
>=3.0	1.0	1.9	1.9	1.9	1.9

*denotes entire WA range that includes all plots

**denotes percent upland using recommended WA and moisture modifier "upland"/"wetland" boundaries for early monitoring of revegetation success.

Discussion

Delineation of percent "wetland" and determination of revegetation success at the Wagner Road constructed wetland were assessed in three ways: (1) the recommended method from the federal manual problem areas section, (2) WA and moisture modifiers, and (3) comparison to an adjacent reference area.

(1) <u>Federal manual</u>

The federal delineation manual included constructed wetlands as "problem areas" that may lack one or more criteria for delineation, most often soils. Hydric soil indicators were absent at the end of three complete growing seasons (October, 1990); therefore, vegetation and hydrology were used to calculate the percent of the site that was "upland." Though the vegetation criterion was met by all but seven plots, hydrology was more limiting. Well data and moisture modifiers of 3.5 showed close agreement and indicated that hydrology criterion was not met in 27.9% to 33.7% of the plots.

(2) <u>WA and moisture</u>

Wentworth et al. (1988) suggested WA = 2.0 as a limit to the use of vegetation alone to delineate wetlands (i.e., without need of soil or hydrologic data). Use of

WA and a soil moisture estimate based on the driest mean moisture estimate of the reference wetland (moisture modifier = 3.5) would cause 32.7% of the site to be classified as "upland." However, WA and moisture estimates were correlated ($r^2 = 0.704$). Furthermore, percent "upland" based solely on use of a WA of 2.0 is 34.6%, compared to percent "upland" calculated using both WA = 2.0 and moisture modifier = 3.5 (32.7%). This close agreement in delineations between vegetation WA and hydrology suggests that WA alone may provide sufficient information for constructed wetland delineation. A WA limit of 2.0 may be selected based on reference site vegetation at Wagner Road. Alternative WA limits may be appropriate for constructed wetlands designed to replace other wetland types, e.g., those dominated by obligate wetland species (WA = 1-2) or facultative species (WA = 2-3).

(3) <u>Reference wetland</u>

The vegetative strata of the Wagner Road constructed wetland differed greatly from the reference site. Immature or dead plantings and colonizing vegetation yielded a dominant herbaceous strata in the constructed wetland, compared to a dominant forested strata in the reference wetland. Though similar in WA, constructed site "wetland" portions exhibited a higher number of species than the reference wetland. "Upland" portions of the constructed site differed from the reference site in both species composition and WA. Species compositional incongruencies among constructed site "wetland" portions and the reference wetland may be explained by successional sere differences.

Hydrology in the reference area differed greatly from the constructed wetland. Though often saturated to the surface and averaging "moist" to "very moist," reference area hydrology seldom exhibited standing water for more than 1 week. Constructed site hydrology was more variable, including 20 plots (18.9%) that averaged some standing water. All reference area moisture modifiers were at least "moist," but 33.7% of the constructed wetland plots were drier than "moist" (moisture modifier <4). Elevation, soil organic matter, and absence of climate moderating swamp canopy may have contributed to constructed site hydrologic variability.

<u>Additional considerations</u>

Prevalence of facultative wetland species (25 of 57 species in the constructed wetland), presence of three facultative upland species, and presence of two obligate upland species suggest that environmental factors were not severe enough to limit colonization of these species. Soil or hydrology characteristics are more than likely responsible. The correlation of vegetation and moisture modifiers seemed to emphasize the importance of hydrology in the system, but causality may also lie in part with soil organic matter content and high bulk density. Constructed wetland organic content was roughly half that of the reference wetland. If low organic content in the constructed wetland soil renders the substrate sterile, groundwater oxygen levels may not be depleted unless flooding persists. Frequently flooded areas within the constructed wetland were dominated by obligate wetland species, but conditions elsewhere within the site failed to exclude facultative upland and obligate upland species.

Any measure of percent "wetland" and constructed wetland success must be based on soil, hydrology, and/or vegetation. Scott et al. (1989) found vegetation WA highly correlated with soil conditions in natural wetlands. Soil regimes in constructed wetlands considered in this study were more similar to those of uplands than wetlands. Most of the constructed wetland was characterized by a chroma greater than 2, organic matter of approximately 3%, high bulk density, and low volumetric water content. Considerable time may be required for hydric soil indicators to develop, which limits the utility of soil in early delineation of constructed wetlands.

Like soil, hydrology may not be a suitable parameter for assessment. Hydrologic regimes of filled wetlands are usually not known, and adjacent reference wetland hydrology may be altered by either the highway or the construction of a wetland "on-site," which limits comparison with constructed wetlands. Further, hydrologic regimes are typically variable over weeks, seasons, and years and may be expensive to sample adequately (Gannett Fleming, Inc. 1991).

Vegetation assessment is not subject to the limitations associated with soil or hydrology monitoring. Vegetation typically colonizes constructed wetlands in the first growing season following excavation. Visits during peak growing season (July-September) may provide the necessary field data, however seasonal vegetation changes may necessitate monthly field visits. Vegetation may be less variable than hydrology, may respond to both soil and hydrologic conditions, and may provide agencies with a more feasible monitoring method than extensive soil and hydrology measurements. Complete replacement of impacted wetland functions and values will require soil development, appropriate hydrology, and similar vegetative characteristics, which may not occur for decades. Given the time needed for succession and time constraints for releasing most constructed forested wetland contracts, early vegetational characteristics may be the preferred means of quantifying percent "wetland" and determining revegetation success.

Several factors may affect successional direction in constructed wetlands. Factors suggesting a more xeric direction include soil and hydrology. Soil factors such as higher bulk density in constructed wetlands may limit slumping and cause accumulated mineral matter to exert a greater increase in elevation. Low organic matter accompanied by high oxygen levels may be a self-perpetuating problem, since high oxygen levels serve to expedite remobilization of organic matter that might otherwise accumulate in anoxic wetland ecosystems. Low organic matter may also contribute to low moisture estimates in the constructed wetland (Mitsch and Gosselink 1986). Factors tending to encourage development of a wetland community also include soil and hydrology. Constructed wetlands that are upstream from fill and box culverts (such as the Wagner Road site) may experience more flooding and sediment accumulation as a result of any damming effect by the fill. Such hydrologic alterations are likely to alter natural processes in adjacent wetlands, which may: (a) alter vegetation, especially herbaceous species composition and (b) render such areas unsuitable for reference sites. Vegetative factors such as propagule transport from adjacent and upstream wetlands during flood events may also encourage wetland community development.

Conclusions

Based on the federal manual, vegetation was marginal and hydrology was insufficient in one third of the Wagner constructed wetland site. Weighted averages have been described as useful for assessing wetland status of some vegetation types along a moisture gradient for wetland delineation under natural conditions (Wentworth et al. 1988, Scott et al. 1989, and Carter et al. 1988). Results of the current study suggest that WA may be useful in constructed wetland delineation. Calculation of an appropriate WA from pre-impact or reference wetland sites may provide a suitable parameter for comparison of vegetation.

This study was designed to test the hypothesis that one wetland parameter (vegetation) may be used to assess early compensation effectiveness. Though not designed to complete an assessment of compensation effectiveness at the Wagner Road site, some inferences can be made from the study. It appears likely that insufficient hydrology is present at one third of the site. Precipitation was 10.6% above normal for the period from May through September, 1989, yet nearly one third of the site averaged dry.

While we cannot be sure that constructed wetlands perform wetland functions and values, we can infer that uplands are unlikely to perform most wetland functions and values. Since much of the site lacked vegetative cover at the peak growing season and physiognomic differences may take decades to equilibrate, functions and values related to vegetation may not be performed for at least some time to come, if at all.

While it is tempting to suggest that 1.5:1 compensation ratio would be appropriate based on the results of this study, it would be unreasonable to do so. Even if two thirds of the Wagner site is determined to be wetlands, no measure of function is implied by this study. Monitoring of additional sites is needed to determine what compensation ratios are sufficient for structural replacement, and functional replacement needs to be addressed. Based on these uncertainties and the time required for even partial replacement, we recommend strict compliance with National Environmental Policy Act guidelines and use of compensation only as a last resort. When losses are unavoidable, construction techniques should incorporate valid experimental design so that continuous improvements can be made.

CHAPTER TWO

Constructed Wetland Potential for Performing Wetland Functions Dependent on Anaerobic Soil Conditions

Abstract

Replacement of vegetative structure was a primary goal of past wetland construction attempts; however, current goals include functional replacement as well. Wetlands are frequently located between areas of human activity and water supplies, and are the primary reducing environment on the landscape. Many water quality functions and values performed by wetlands are dependent upon anaerobic and/or reducing conditions that result from flooding and microbial activity.

Study sites were wetlands constructed as compensation for wetlands filled by VDOT. Carbon dioxide and methane production in flooded soils were measured in laboratory microcosms. Redox potential was monitored in a constructed wetland 24 h following a storm event. These data were compared to vegetation, organic matter, and elevation.

The results indicate that elevation, flooding duration, organic matter content, as well as microbial flora are related to development of anaerobic conditions. Wagner Road constructed wetland vegetation WA was correlated with microbial activity; however, reference

wetland microbial activity was significantly greater than that for constructed wetlands, regardless of vegetation WA. It appears likely that functions and values dependent upon anaerobic conditions may not be performed by recently constructed wetlands that were constructed using the same techniques as the sites in this study. Future construction techniques should include the spread of hydric soil over a site and careful attention should be given to elevation and hydrology.

Introduction

Wetlands were filled in the United States for many years with minimal regulation, and only a fraction of the original acreage remains (Dahl 1990). Most wetland protection is currently afforded by Section 404 of the 1977 Clean Water Act, which requires a permit for deposition of fill material in a wetland. The National Environmental Policy Act (CFR Part 1508.20 (1-5)) allows permits to call for substituting or replacing lost wetlands with constructed systems, when no alternatives are available. Mitigation by wetland construction is increasing in Virginia (Allen-Grimes, pers. comm.) and throughout the Southeastern United States (Deitz, pers. comm.).

Many wetland mitigation projects have had replacement of similar vegetative composition as the primary goal. However, the phrase "in-kind mitigation" has come to mean the replacement of functional, as well as structural, characteristics of the wetland that were lost, and concern over lost wetland functions are growing (e.g., Race and Christie 1982, Quammen 1988, and Brinson and Lee 1989).

Sather and Smith (1984) included water quality enhancement as one of five major wetland values. Brinson, Bradshaw, and Kane (1984) assessed nutrient assimilative capacity in an alluvial floodplain swamp and found considerable nitrate and ammonium removal. The bioavailability of most nutrients and toxicants are influenced by wetland soils conditions. Gambrell and Patrick (1978) suggested that wetlands may accumulate or degrade organic pesticides and accumulate heavy metals.

Wetlands are the primary reducing environment on the landscape, and many water quality functions depend on establishment of anaerobic and/or reducing conditions (Gambrell and Patrick 1978 and Sather and Smith 1984). Once flooded, diffusion of oxygen to the sediment slows dramatically. The microbial community consumes organic matter and oxygen, thereby altering both carbon dioxide concentrations and oxidation-reduction conditions (redox) in the soil (Pearsall 1938 and Ponnamperuma 1972). Water quality enhancement functions dependent upon anaerobic conditions may not be performed if carbon availability is not sufficient (Faulkner and Richardson 1989).

Anaerobic conditions develop over time and are partially dependent on hydrology (Wharton and Brinson 1978) and organic matter (Walker 1988). Elevation strongly effects timing, frequency, and duration of flooding, and organic matter content affects both microbial activity and redox potential under these conditions. Microbial decay and leaching by flood waters increases decomposition of organic matter at the surface of a wetland. Oxygen may be depleted at the surface of the O horizon if flooding persists. Deeper portions of the O horizon may remain anoxic under flooded or saturated conditions. Once anaerobic conditions become established, organic matter may accumulate and help maintain the reducing environment (Day 1989).

Establishment of anaerobic soil conditions may be precluded by conditions found in many constructed wetlands. Long dry periods can allow accumulated organic matter to decompose (Terry 1986). Frequent wet and dry cycles can also facilitate organic matter decomposition and dramatically limit organic matter accumulation (Reddy and Patrick 1975, Gambrell and Patrick 1978, and Kadlec 1989). Most of the 15 constructed freshwater wetlands visited in this study are characterized by a mosaic of elevations, including a range of elevations that are subject to either long dry periods or frequent wet and dry periods. These conditions may preclude or slow the formation of hydric soils in constructed wetlands.

This study was conducted to assess the potential for a constructed wetland to develop anaerobic soil conditions which are necessary in order to perform water quality enhancement functions and values. Factors that may effect development of wetland soil, hydrology, vegetation, and water quality functions and values over time are also addressed.

Site Descriptions

Study sites for experiment one included four VDOT compensation sites in the coastal plain of Virginia, including Route 106 in Charles City County, Fourmile Creek-Route 295 in Henrico County, Wagner Road in Petersburg, and Powhite Parkway in Richmond, Virginia. Adjacent, reference wetlands were nontidal forested wetlands dominated by obligate wetland species (species that occur in wetlands > 99% of the time). Adjacent uplands were mature hardwood forests of mixed composition and considerable organic matter in the O horizon. Experiments two and three utilized the Wagner Road constructed wetland described below.

Wagner Road constructed wetland site is located in Petersburg, Virginia at 37° 11' 44" north latitude and 77° 20' 26" west longitude (Figure 1). The 1.53 ha study site is located in the upper coastal plain and was constructed in the summer of 1987. An adjacent, forested wetland in Second Swamp of the Blackwater Swamp headwaters was used as a reference site. A recently completed wetland delineation of Wagner Road site indicated that 32.7% to 34.6% of the constructed wetland was actually upland, and hydrology was much more variable both spatially and temporally than the reference wetland. Vegetation in the constructed site is dominated by colonizing herbaceous species (57) that range from obligate wetland species to obligate upland species. A middle-aged stand of *Fraxinus pennsylvanica*, *Nyssa sylvatica*, and *Taxodium distichum* characterize the reference site vegetation and species are all obligate wetland to facultative species. Nine piezometers, six in the constructed wetland and three in the reference wetland, were installed and monitored in 1989 and 1991. The wetland hydrology criterion (Federal Interagency Committee for Wetland Delineation 1989) was met in half of the constructed wetland piezometers and all reference wetland piezometers, and the reference wetland is classified as "seasonally flooded" using the scheme set forth by Cowardin et al. (1979).

Methods

The study was composed of two laboratory and one field experiment. Field sampling locations corresponded with laboratory soil coring locations. Soil core locations were selected based on vegetation weighted averages (WA) that was calculated for each plot using the following formula (Jongman et al. 1987):

$$WA = (y_1u_1 + y_2u_2 + \ldots + y_mu_m)/100$$

where

$y_1, y_2, \ldots, y_m$ are the relative cover estimates for each species in the plot, and

$u_1, u_2, \ldots, u_m$ are the indicator values of each species.

Species indicator values range from one to five, therefore plot WA also range from one to five. Colonizing vegetation WA was used to distinguish "upland" (WA > 2) and "wetland" (WA < 2) portions of the constructed wetland. Reference wetland WA was consistently below 2. Moisture estimates were made monthly in summer, 1989 at each plot and converted to a proposed moisture modifier scheme (Table 1). The Student-Newman-Keuls test for significance was employed for statistical analyses (Zar 1984).

Experiment One

The effect of soil treatment on soil gas relations under short-term flooded conditions was quantified over a three-week period to predict the effect of wetland construction techniques. Study sites were four VDOT compensation sites in the coastal plain of Virginia, including Route 106 in Charles City County, Fourmile Creek-Route 295 in Henrico County, Wagner Road in Petersburg, and Powhite Parkway in Richmond, Virginia. Nine soil cores (0.30 l) were taken from upland and wetland areas adjacent to each site, including adjacent upland O horizons or topsoil (3), upland A horizons or mineral soils (3), and adjacent forested wetland O horizons (3).

Microcosms consisting of 1-l Mason jars received a soil core and sufficient water to leave 0.30 l of gas head space. The jars were sealed with a rubber stopper fitted with two sampling ports. After three weeks, gas samples were taken and injected into a thermal gas chromatograph fitted with a Supelco Hayesep Q 80/100 column, and carbon dioxide and methane concentrations were calculated. After gas sampling was completed, soil core organic matter content was calculated based on ash-free dry weights of subsamples.

Experiment Two

The effect of location within a constructed wetland on soil gas relations exposed to short-term flooded conditions was quantified over an eight-week period. Wagner Road was selected because the site had been constructed in 1987, four years prior to this study. Earlier work at the site indicated that both delineated "wetland" (65.4%) and delineated "upland" portions (34.6%) were present within this constructed wetland. Soil cores were placed in microcosms as in experiment one, however soil samples were taken from an adjacent upland O horizon (4), an adjacent reference wetland O horizon (4), and from specific areas within the constructed wetland (28). Soil samples from within the constructed wetland were based on vegetation WA and included "wetland" portions (14), a vegetated "upland" portion (10), and an unvegetated "upland" portion of the constructed wetland (4).

Elevations at the Wagner Road constructed wetland site were measured at 95 plots along seven transects using a laser light level. Mean moisture estimates were made monthly from April through September, 1989.

Experiment Three

The extent to which redox potential might be lowered throughout a constructed wetland and a reference wetland following a major precipitation event was assessed in the field. Platinum redox electrodes (40) were constructed following a modified welded redox electrode design (Faulkner et al. 1989). Redox probes were used to measure oxidation-reduction potentials 24 h after a major precipitation event at all locations sampled in experiment 2. Electrodes were inserted to a depth of 10 cm, were allowed to stabilize, and were read with a portable voltmeter after insertion of a calomel reference electrode. Mean redox potential of three replicates were analyzed for correlation with WA, moisture modifier estimate, and organic matter content for each plot.

Results

Experiment One

Soil biological activity was monitored during simulated flooding of upland mineral soils, upland topsoils, and adjacent wetland soils from four sites in the coastal plain of Virginia. Carbon dioxide production was significantly lower in upland mineral soils than in either upland topsoils or reference wetland soils. Carbon dioxide production was significantly lower in 3 of 4 upland top soils than in adjacent wetland soils (Figure 3). Methane production was detectible in 11 of 12 reference wetland microcosms, but no methane production was detected in upland topsoil or upland mineral soil microcosms.

Mean organic matter content was variable among reference wetland sites 21.39% (+/- 18.83), however, reference wetland organic matter was significantly higher than both upland topsoils and mineral soils for all four sites. Mean organic matter content in upland soil O horizon and A horizon was 14.39% (+/- 3.68) and 2.98% (+/- 2.13), respectively.

Experiment Two

Soil microbial activity under flooded conditions was monitored for soils taken from delineated "upland" and "wetland" portions of the Wagner Road constructed wetland, an adjacent reference wetland, and an adjacent upland area. Carbon dioxide production in the Wagner Road constructed wetland was significantly lower than that for the reference wetland at the 0.05 level for weeks two and three (Figure 4).

"Wetland" portions of the Wagner Road constructed wetland consistently produced more carbon dioxide than "upland" portions, but differences were generally not significant (Figure 4). Bare areas within the constructed wetland consistently produced the lowest amount of carbon dioxide, and were significantly different from carbon dioxide production in vegetated "wetland" portions of the constructed wetland. Adjacent upland soil carbon dioxide production was lower than that for the reference wetland each week, though usually not with statistical significance.

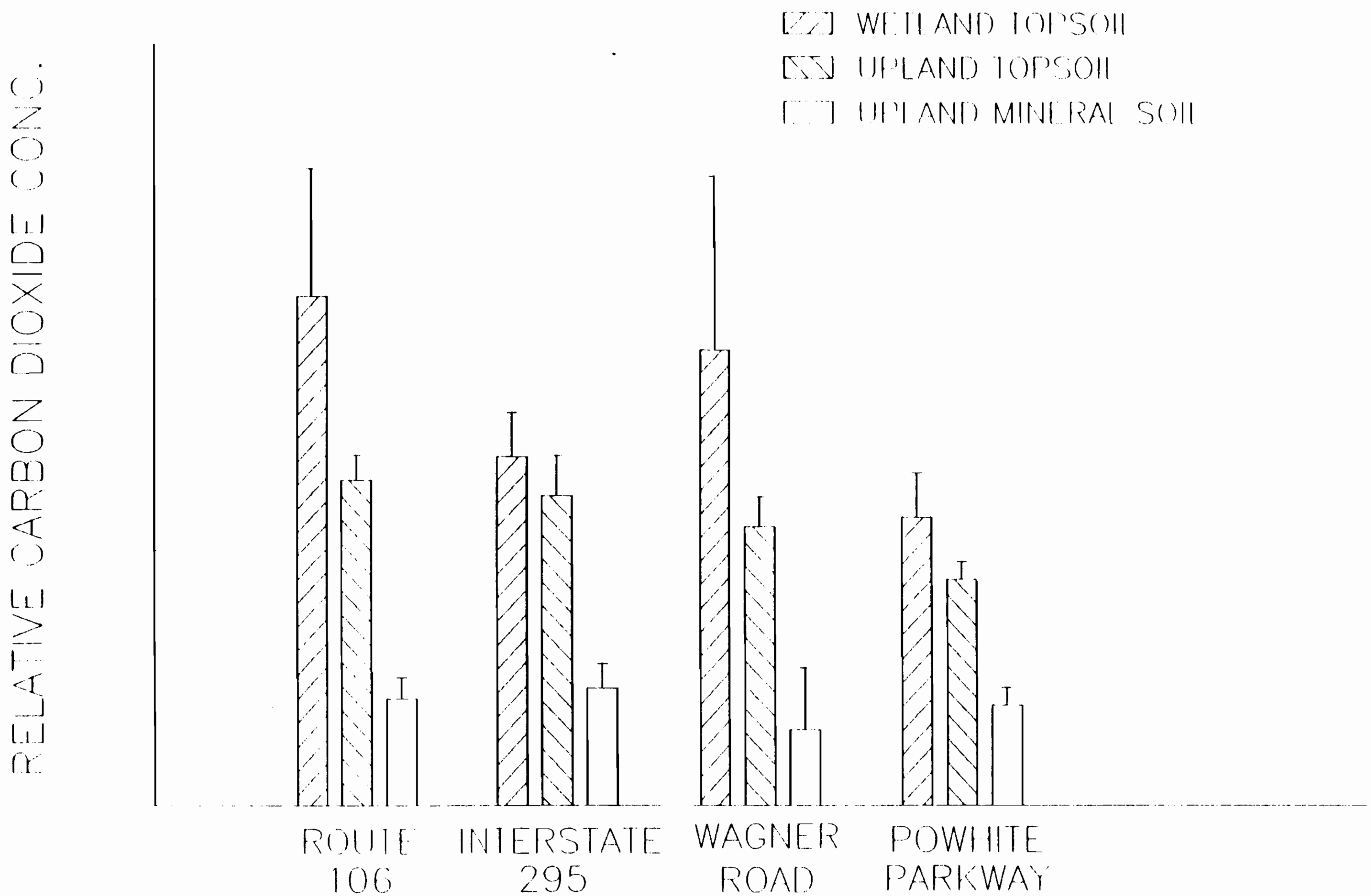

Figure 3. Relative carbon dioxide concentrations measured for three soil types collected from each of four constructed wetland study sites in Southeastern Virginia. (bars represent standard deviations)

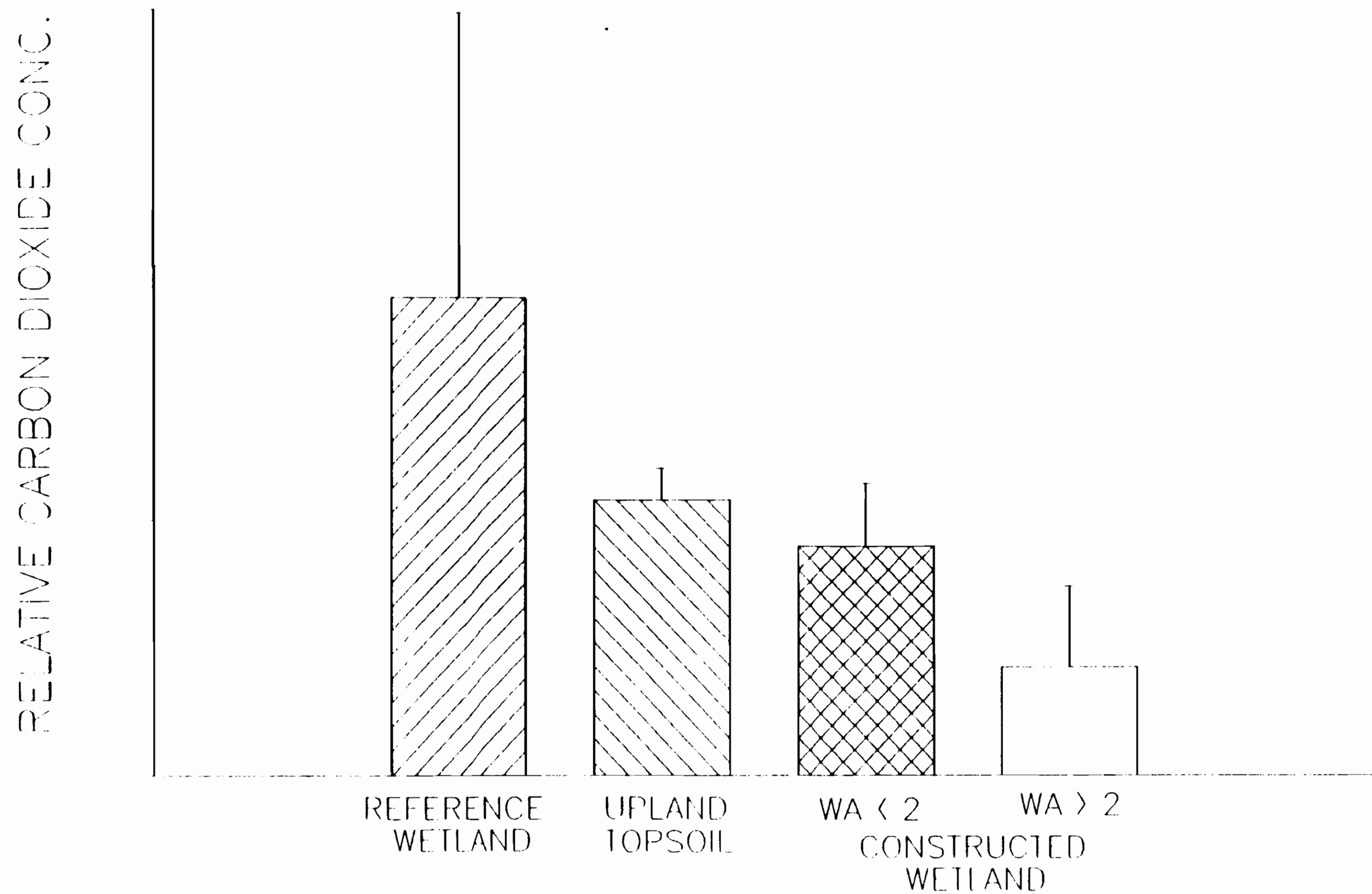

Figure 4. Relative carbon dioxide concentrations measured for soils taken from four locations at the Wagner Road study site in Petersburg, Virginia. (bars represent standard deviations)

Methane was only detected in reference wetland samples in week three, and methane production could not be quantified until weeks 6-8. Though only significant in week 7, methane production in the reference wetland and the upland topsoil was consistently greater than constructed wetland methane production during weeks 6-8. At no time during the experiment was methane detected in microcosms from either bare areas of the constructed wetland or in "wetland" portions of the constructed wetland that were located farther from the adjacent reference wetland.

There was significantly higher percent organic matter in the reference wetland than in all other locations in experiment two. Upland topsoil and constructed wetland percent organic matter content was not significantly different (Figure 5).

An elevational range of 0.631 meters was measured within the Wagner Road constructed wetland site. Standard deviation of elevation measurements was 0.126 (Figure 6). Mean moisture levels ranged from 1.6 ("very dry" to "dry") to 6.4 ("0-10 cm deep" to "11-20 cm deep). Mean moisture level was 3.91 ("dry to moist" to "very moist") and standard deviation was 1.37 (Table 1 and 3).

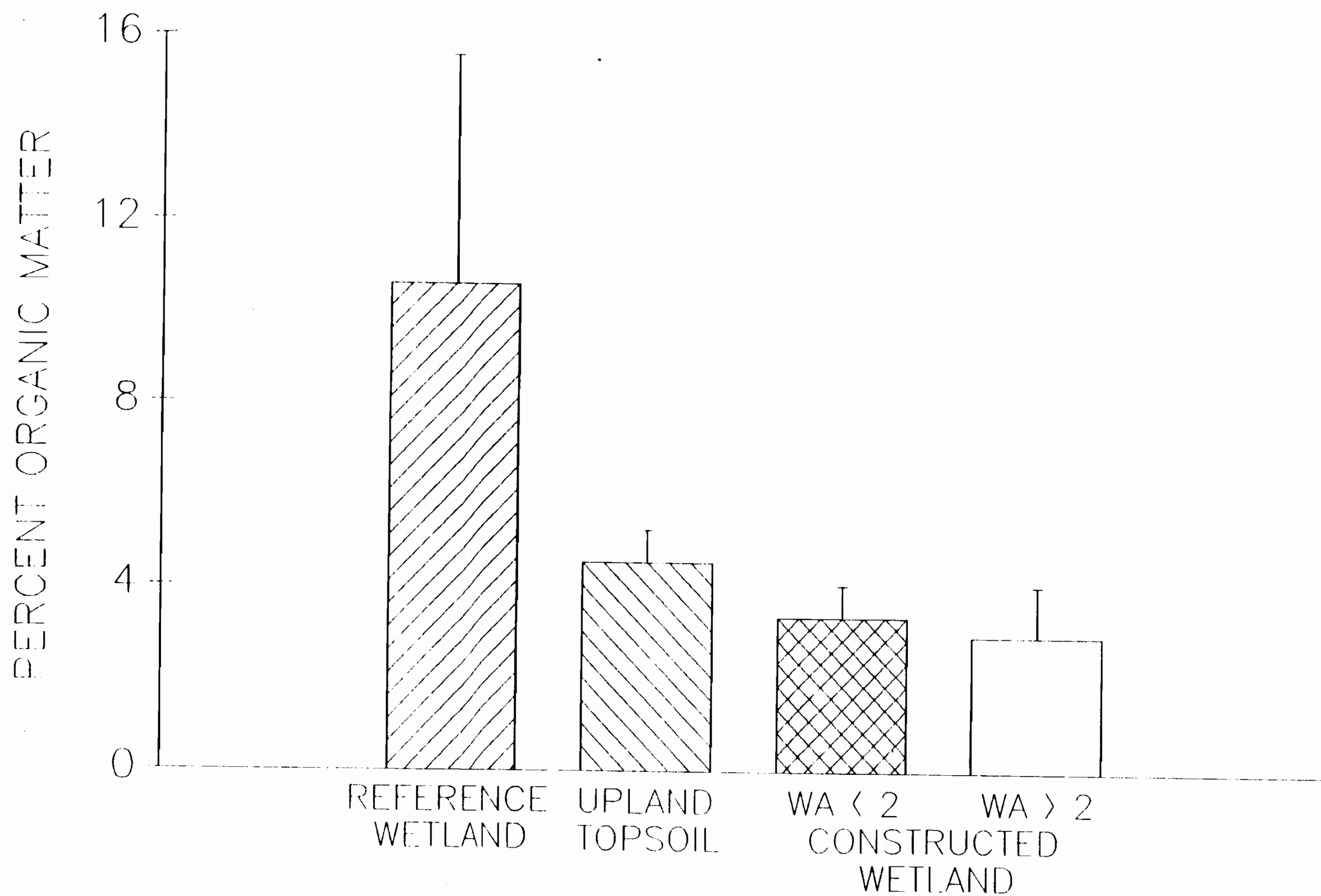

Figure 5. Percent organic matter measured for soils taken from four locations at the Wagner Road study site in Petersburg, Virginia. (bars represent standard deviations)

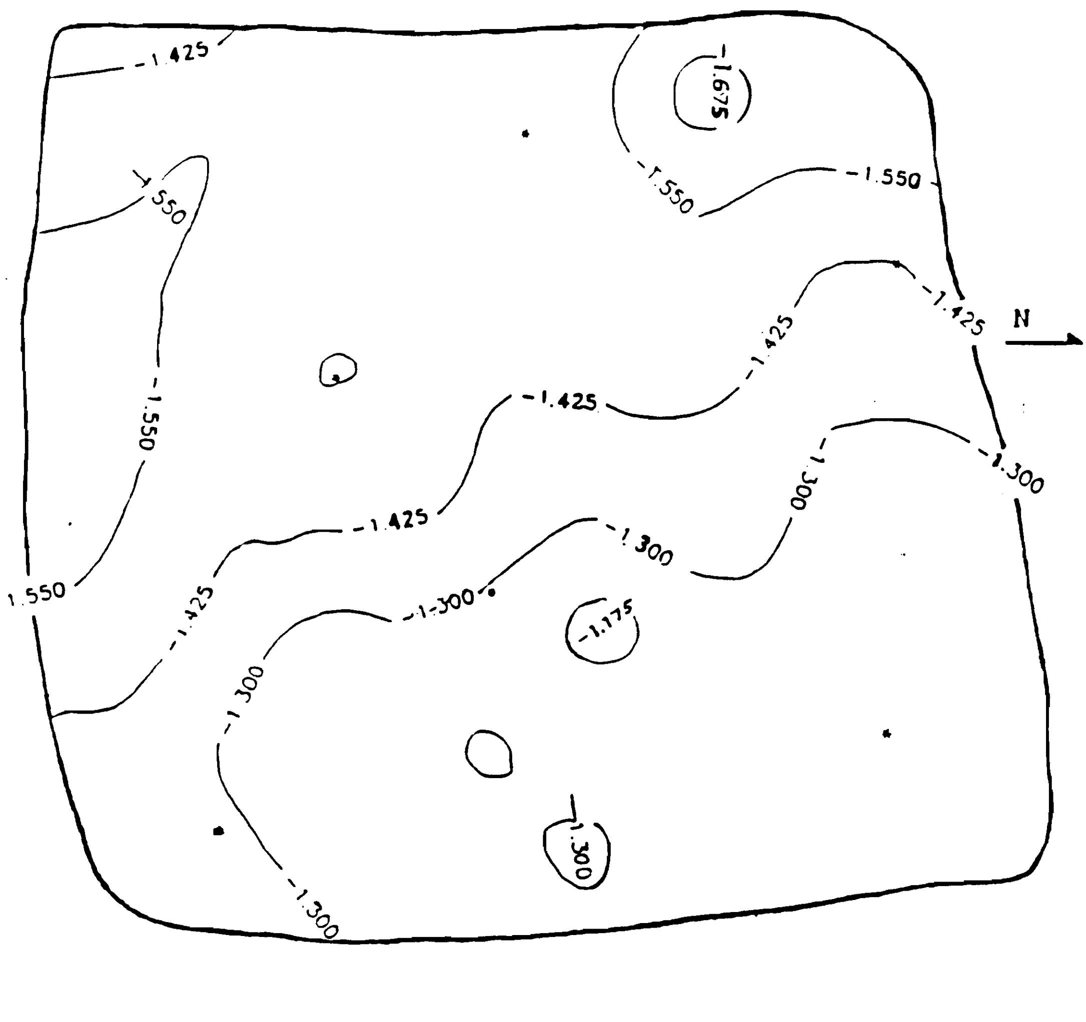

Figure 6. Topographic map of the Wagner Road constructed wetland in Petersburg, Virginia. (Readings are in meters below laser light level)

Experiment Three

Field redox measurements were taken in plots throughout the Wagner Road constructed wetland 24 h after a significant precipitation event. Redox potentials throughout most of the constructed wetland were significantly lower than redox potentials in the reference wetland and the typically flooded "wetland" portions of the constructed wetland. Redox potential measurements in the constructed wetland were positively correlated with vegetation WA ($r^2 = 0.906$) and negatively correlated with moisture modifier estimates ($r^2 = -0.869$). Redox potentials for unvegetated "upland" portions of the constructed wetland were indicative of oxygen content near saturation. Unfortunately, persistent drought conditions limited sampling to the one day following a heavy rain.

Discussion

The technique most frequently utilized by VDOT for freshwater wetland construction involves excavation to the approximate elevation of the water table and leaving the soil without amendments. There is an implicit assumption that appropriate hydrologic conditions will be established, functions may temporarily be forfeited, and wetland structure and function will eventually be replaced.

The results from experiment one suggest that if a mineral soil was left without amendments, then microbial activity would still be significantly lower than the reference wetland, regardless of flooding. The results suggest that microbial activity could be enhanced by spreading wetland soil over a site. Spreading of upland topsoil over a site may also lead to considerably more microbial activity than leaving an upland mineral soil unamended. However, methane production in experiment one was limited to the wetland soil, which indicated that a more negative oxidation-reduction system would be established if wetland soils were used instead of upland topsoil. Methane production may have eventually occurred in upland O horizon soils, but results of this study indicate that natural wetland soil becomes reduced more rapidly upon inundation.

In experiment two, within site sampling of Wagner Road constructed wetland four years following construction supports the findings of experiment one. The soil exhibited significantly lower microbial activity than the reference wetland soil. However, significant differences in microbial activities were also found within the constructed wetland (Figure 4).

Vegetation and hydrologic data in chapter one suggested that portions of the Wagner Road site may be, or may be becoming wetland, while other areas may remain upland. These "wetland" portions of the site occur at lower elevations, sustain longer periods of inundation, have more hydrophytic vegetation than "upland" portions of the constructed wetland, and demonstrated consistently greater microbial activity (Figure 4). However, organic matter content differences are not significant (Figure 5).

In experiment three, field redox potentials were taken at the same soil core locations sampled from experiment two. Experiments one and two characterized microbial activity under flooded conditions; therefore, experiment three was to be conducted following a heavy precipitation event. Drought conditions over much of the summer limited this portion of the study to one heavy rain. However after 24 h, reference wetland redox potential was significantly lower than redox potential in most of the Wagner Road constructed wetland. Redox potential seemed to reflect the frequency of saturation, since areas with wetter moisture modifiers exhibited lower redox potential ($r^2 = -0.869$).

Constructed wetland redox potentials were strongly correlated with both vegetation WA and moisture estimates. These results tend to support the assertion based on experiment two: that microbial activity differs among "wetland" and "upland" portions within the Wagner Road constructed wetland.

Conclusions

Elevation, hydrology, and soil organic matter were correlated with carbon dioxide production and redox potential in this study. Longer flooding periods may be required for lower redox potential in the constructed wetland than the adjacent reference wetland, perhaps resulting from lower organic matter content and lower microbial activity in the former. A large portion (34.6% of the Wagner Road constructed wetland) seldom exhibits saturated soil conditions. These and other portions of Wagner Road constructed wetland may lack the flooding duration necessary for development of strongly reducing conditions.

Soil amendments are suggested by the data from all three experiments. Demucked soils from the area receiving fill material should be spread over the constructed wetland. Organic matter content, a microbial community, and wetland vegetation propagules may be established by this procedure. While this procedure may increase the likelihood that some functions will be performed sooner, inappropriately high elevations may lead to rapid decomposition of organic matter and higher redox potentials. Kadlec (1989) stated that organic matter-rich peat may take millenia to decay, but exposure to the atmosphere would greatly accelerate the process.

It appears likely that functions dependent upon reducing conditions are not performed by most of the Wagner Road constructed wetland when compared to an adjacent, reference wetland. In time, anaerobic conditions may predominate in lower elevation, wetter portions of the constructed wetland that have been colonized by hydrophytic plant species. While organic matter may be expected to accumulate in these "wetland" portions, decompositional processes may outpace accumulation rates in portions of the constructed wetland site that are currently characterized as "upland". Such areas may not provide functions dependent upon wetland soil, hydrology, and vegetation in the forseeable future.

CHAPTER THREE

A Constructed Forested Wetland Effectiveness Assessment Methodology

Abstract

Forested wetland construction associated with Section 404 of the Clean Water Act of 1977 is increasing throughout the Southeastern United States. While wetland assessment in general has received attention in recent years, no constructed wetland effectiveness methodology has support from the scientific community. Most of the literature supports comparison of constructed wetlands with reference wetlands, and there is an interest in replacement of the functions, as well as the structure, of the filled wetland. Forested wetland construction generally yields emergent systems in the short term, and forest structure may take decades to develop.

In this chapter, a two-tiered constructed forested wetland methodology is presented that (1) addresses early concerns regarding project compliance, and (2) evaluates structure and functions in both the short and long term. Both tiers of the methodology include use of a reference wetland and are designed to generate improvements in wetland construction techniques.

Introduction

Very few studies are available at present that assess forested wetland construction effectiveness, even though the practice of compensation through wetland construction is continuing to increase (D'Avanzo 1987, Larson 1987, Kusler and Kentula 1990, and Gannett Fleming, Inc. 1991). Evaluations are essential if wetland construction techniques are to be improved (Roelle and Ellis 1988 and Kruczynski 1990). Several authors have called for both short-term and long-term monitoring to assess effectiveness, however no monitoring methodologies have widespread support (LaRoe 1988 and Kusler and Kentula 1990).

This study presents a two-tiered monitoring scheme that (1) evaluates compliance and (2) addresses functional replacement. Quammen (1988) distinguished between analysis of compliance with conditions of the permit (compliance monitoring) and analysis of construction success. However, most permits imply that wetland construction projects will replace wetland vegetation; therefore, some minimal criteria for revegetation success, in addition to following explicit permit conditions, should be required in order to determine compliance.

The extent to which structural and functional parameters are measured may determine the confidence level regarding success of replacement attempts. Clewell and Lea (1990) state that no forested wetland restoration [or construction] attempts are old enough to be determined successful, based on the generation time needed for trees; however, they suggest that if wetland form, i.e., wetland vegetation, is replaced, then one may expect some approximation of function. Cairns (1985) suggested that structural replacement by identical species might not be necessary to restore function, given establishment of equivalent species that were not exotics. Some minimum confidence level is the goal of tier one monitoring, and results would be used to evaluate compliance with permit conditions. A higher degree of confidence and more prescriptive results are the goal of tier two, research monitoring. Cairns (1985) suggested that wetland ecosystem structure may be an indicator of function, but that this is not necessarily the case and both structure and function should be assessed. Tier two monitoring involves measurement of both structure and function and provides more information than tier one monitoring.

Tier One Monitoring

Tier one monitoring (compliance) requires that conditions of the permit be followed and that appropriate vegetation be established. Permit conditions differ among projects and monitoring this portion of compliance would be on a case-by-case basis. For example, many permits require successful establishment of planted vegetation. A scheme for monitoring planted vegetation success was presented by Erwin (1990).

While several methods could be used to assess the revegetation portion of compliance, one method may achieve the optimal level of sensitivity. The federal manual for wetland delineation (Federal Interagency Committee for Wetland Delineation 1989) recommends the use of vegetation alone for constructed wetland delineation. Constructed wetland effectiveness studies have recently made evaluations based primarily on satisfaction of the vegetation criterion of the federal manual, e.g., Gannett Fleming, Inc. 1991. There are risks of such an approach. For example, a one-hectare constructed wetland dominated by facultative species could be considered a successful replacement of a one-hectare wetland dominated by obligate wetland species. Natural, pristine forested wetlands of similar hydrology may have very different species composition, therefore, requiring identical replacement may be an unneccessary extreme (Clewell and Lea 1990). Requiring that species composition be replaced could risk regrading and replanting of a successful site. Establishment of an equivalent aerial extent of vegetative communities having similar weighted average to the reference wetland was shown to be effective in Chapter One. The methodology described in detail in Chapter One should be used for the first tier of assessment, i.e., compliance.

Funding for monitoring at the level of tier one (compliance) should be included in the budget for every permit that involves wetland construction. Qualified wetland consultants or regulatory agency personnel should conduct this monitoring, and the study and bond period should last for three years.

Based on the results of tier one monitoring, if establishment of appropriate vegetation is not achieved, some aspect of constructed wetland hydrology or soil conditions may be inadequate. Since tier one analysis is conducted early in the development of the constructed wetland, permittees have time to correct site deficiencies, employing recommendations provided by the monitoring entity.

Tier Two Monitoring

Background Information

Several values have been described for wetlands since wildlife values were first recognized. Sather and Smith (1984) divided wetland values among hydrology, water quality, food chain, socio-economic, and habitat functions. Longer lists exist which are generally extrapolations of the five listed by Sather and Smith. Adamus et al. (1987) included groundwater recharge/discharge, flood flow alteration, sediment stabilization, sediment/toxicant retention, nutrient retention, shoreline anchoring, aquatic and wildlife diversity/abundance, production/export, uniqueness/heritage, and recreation. Others have grouped values within local, landscape, and global scales (e.g., Odum 1989 and Mitsch and Gosselink 1986).

Several studies of values have been performed and methods of value measurement have been produced. A "national wetland assessment" symposium was held at Portland, Maine in 1985 (Kusler and Riexinger 1986). The FWS has produced the Habitat Evaluation Procedure (HEP), and the Corps has produced the Habitat Evaluation System (HES). The Wetland Evaluation Technique (WET) assigns low, medium, and high ratings to 12 values (Adamus 1983 and Adamus et al. 1987).

The WET method has been suggested for constructed wetland assessment (Adamus 1988). A WET analysis of predisturbance values would be used for comparison with a WET analysis of values of the replacement wetland (op. cit.). In some cases wetlands perform specific values that may require specific monitoring strategies, and a WET analysis may identify those values. However, several factors may limit feasibility of this approach, for example, (1) many wetlands are currently designed and constructed with little preimpact site data, (2) once the wetland fill occurs there is no reference wetland area to compare community responses to periodic fluctuations, i.e., hydrologic variations, vegetation responses, etc., (3) the WET technique does not address community development over time and potential functions and values, and (4) use of the rating system alone would not provide diagnostic information for use in improving construction techniques.

Several authors have addressed the need for and strategies in selection of reference wetlands for comparison with constructed wetlands. Erwin (1990) noted a high degree of variability among different wetland systems but concluded that comparisons were necessary. Abbruzzese et al. (1987) and Brooks and Hughes (1988) recommended use of ecoregion wetland types for comparison. Kusler and Kentula (1990) suggested goal establishment based on an analysis of preimpact conditions of the wetland to be filled. Structure and functional characteristics of the wetland to be filled most closely represent the probable objective of most construction attempts; however, comparison data would be inaccessible if preimpact site data was not gathered. Furthermore, once filled, the original wetland would not be available for comparison of site conditions, i.e., response to seasonal and annual precipitation variability.

We recommend selection of a reference wetland that uses the best available data regarding structural and functional characteristics of the original wetland. A reference wetland of similar structure in the same watershed (preferably close to both the original and constructed wetland) should be selected for monitoring replacement of wetlands adjacent to a lotic system. Such a selection would facilitate comparison of wetland responses to hydrologic extremes such as droughts and floods. Care should be taken to avoid selection of an area that may be subject to alteration resulting from the wetland fill or the constructed wetland, i.e., hydrologic alteration, mudwaves, sedimentation, etc.

Constructed forested wetlands are generally planted with saplings and often exhibit emergent wetland physiognomy during the first several years following construction. Community development processes leading to forested wetland physiognomy are implicit in this process. Clewell and Lea (1990) express concern regarding comparison of mature forested reference wetlands with newly constructed systems, primarily because of physiognomic differences. The most ideal forested wetland replacement could fail to perform certain mature forested wetland functions to some degree during the early years following construction. Therefore, the potential for community development should also be assessed, e.g., potential for change from emergent wetland to forested wetland.

Wetland protection originated from recognition of derived anthropogenic services which are referred to as values. While values are distinct from ecological functions, performance of values arises from the ecological functioning of a wetland system (Mitsch and Gosselink 1986). A monitoring method should be based on parameters that affect wetland functions, since functions give rise to values and the goal of wetland protection legislation has been preservation of values.

Tier Two Monitoring

Tier two monitoring employs the study of hydrology, soils, vegetation, fauna, and landscape position. Wetlands are characterized and may be delineated by the analysis of hydrology, soils, and vegetation. Hydrologic conditions are characterized by the frequency, timing, and duration of flooding. Soils formed under wetland hydrologic conditions are termed hydric, and are the site of many chemical transformations in wetlands. Wetland vegetation, termed hydrophytes, are plant species that possess morphological and/or physiological adaptations to stresses inherent in wetland environments (Federal Interagency Committee for Wetland Delineation 1989). Wetland fauna contribute to ecosystem function, and in some cases affect community development, e.g., beaver or muskrat. Any analysis of wetland function will require thorough study of hydrology, soils, vegetation, and fauna.

Wetlands are typically one component of a mosaic of ecosystems on the landscape and its location is the fifth parameter of tier two monitoring. The juxtaposition of various systems may create conditions allowing performance of certain functions, including migration corridor and edge effect habitat functions. An analysis of the functions performed by the wetland to be filled (or already filled) and the constructed replacement wetland must consider the relative position of each in the landscape.

The tier two methodology proposes the use of structural and functional comparisons between constructed and reference wetlands. The data generated would be used to (1) assess the effectiveness of the compensation effort in structural and functional replacement, (2) assess the long-term potential for performance of functions and values, and (3) develop recommendations for wetland construction improvement.

Tier two monitoring is accomplished in four steps conducted at both constructed and reference wetlands. Steps include (1) setup, (2) monitoring, (3) analysis, and (4) interpretation. Functional assessment methods have not been developed to the extent needed for quantitative analysis of many wetland functions. Ongoing research in wetland assessment may yield improved methods, therefore few methods have been included. Rather, an outline is presented to facilitate qualitative comparisons between constructed and reference wetlands in order to assess effectiveness and generate recommendations for improvement.

Additional sources of information are available to supplement the methodology. Qualitative discussions of most functions can be found in WET (Adamus et al. 1987). Hydrologic monitoring suggestions are included in a wetland hydrology conference (Kusler and Brooks 1988) and discussion by Hollands and Magee (1986). Chapter One (this volume) provides the requisite vegetation sampling design, while Chapter Two describes a soil microbial monitoring method. Sampling of planted vegetation may be performed using methods described by Erwin (1990). Aerial photography has been used to monitor constructed wetlands (Erwin 1990). Black and white, color, and infrared film may be used. Faunal monitoring methods can be found for vertebrates (Brooks and Hughes 1988), invertebrates (Brooks and Hughes 1988), and microbial populations (Pratt et al. 1989). Methods for estimating importance of landscape position to wildlife were described by Keller (1986).

At the tier two level (research), funding should be in the form of competitive grants funded by permittees, i.e., VDOT, developers, federal agencies, and permiters, i.e., the Corps, EPA, FWS, NMFS, and any other public agency with regulatory oversite. Widespread adoption of a monitoring methodology such as that presented herein and computerization of results would facilitate incorporation of improved wetland construction techniques into compensation site planning, and aid regulatory agencies in policy and decision-making.

Setup

All information available from the U.S. Geological Survey (USGS), including stream data, climatological data, and topographic maps (see Carter and Baxter 1988), Soil Conservation Service (SCS) County Soil Surveys, and FWS National Wetland Inventory (NWI) maps should be accessed prior to setup. Setup should be conducted in the following order:

a. install piezometers to > 1.5 m depth,

b. install a stream gauge per channel,

c. establish transects perpendicular to observed elevational gradients at the site,

d. position > 1 m tall stakes at regular intervals along transects,

e. attach biodegradable plates (> 15 cm diameter) to tops of stakes as aerial targets, and photograph (from an altitude of 100 feet for every 20 meters of site diameter [500 foot minimum] and cross the site lengthwise along two parallel lines),

f. install animal traps if needed,

g. access data on local endangered species populations.

Note: Sample sizes will depend on site heterogeneity.

Monitoring

Monitoring should begin early in the first growing season (the portion of the year when soil temperatures are above biological zero (41°F)) from years 1-3, 5, 7, 10, and every five years thereafter. Statistical tests should be selected a priori. Steps in monitoring include:

a. record stream depth (weekly throughout growing season),

b. record depth to water table in piezometers each time stream gauges are read,

c. record elevation and location of plots, piezometers, and stream gauges with a level, and create a site topographic map,

d. estimate percent cover for each species in plots at each stake for each strata (monthly throughout growing season), and record species indicator status from FWS publication (Reed 1988),

e. estimate soil moisture per plot (Table 1) each time percent cover is estimated,

f. delineate communities within site and note adjacent land usage on maps using aerial photography (topographic and NWI maps may be of use),

g. collect soil samples and cores representative of delineated communities, and measure carbon dioxide production (see Chapter Two for methods),

h. note and record extent of exotic species populations, i.e., Phragmites communis,

i. collect animal presence data,

j. collect data on presence and status of endangered species populations.

Note: If original wetland has more than one class of wetland, i.e., forested wetland, scrub-shrub wetland, or emergent wetland (Cowardin et al. 1979), then each class may require separate setup, monitoring, analysis, and interpretation.

Analysis

Most analyses can be made as monitoring data is obtained. Monitoring steps (in parentheses) provide data to be used in the following reference and constructed wetland analyses:

a. correlation of stream depth and depth to water table (a,b),
b. variability within piezometers (b),
c. duration of surface saturation (b),
d. percent of site connected by surface hydrology to stream (a,b,c),
e. mean cover per plot (d),
f. plot weighted averages (WA) (d), as in tier one,
g. percent of site in each 0.5 WA range and considered "wetland" versus "upland" (d), as in tier one,
h. number of species present (d),
i. correlation of WA and mean moisture modifier per plot (d,e),
j. extent of bare area with mean moisture estimate <3.5 (upland) and bare area with mean moisture estimate >3.5 (open water or mud flat) (d,e),
k. soil characteristics per delineated community including bulk density, organic matter, macronutrients, and texture (f,g)

l. rate of carbon dioxide production per unit soil volume (g),

m. increase/decrease in aerial extent of exotic species (h),

n. edge effect based on adjacent land use (f),

o. loss/gain of corridor for safe migration (f,i),

p. aerial extent of constructed and of original wetland (f),

q. list of animal species observed per delineated community (i),

r. increase/decrease in endangered species populations (j).

Note: If original wetland has more than one class, calculate areal extent of each class.

Interpretation

The interpretation phase consists of (1) comparison of constructed and reference wetlands to assess functional performance potential based on the determinations, (2) prediction of community development over time and the potential for eventual functional performance, and (3) recommendations for improvements in wetland construction techniques.

Early hydrologic conditions may strongly effect vegetation establishment and functional performance in constructed wetlands (Hollands 1988). Constructed wetland assessments should take into consideration how current precipitation levels deviate from normal. Function and value assessment require information that has been produced in the preceding steps. Analysis steps are indicated in parentheses after each of the following wetland functions and values:

a. flood abatement potential (a,b,c,d,e),

b. low flow maintenance potential (a,b,c),

c. sediment trapping potential (d,e,l,j,o),

d. production/export (b,c,d,e,f,g,h,i,j),

e. water quality enhancement (b,c,d,e,n)

f. habitat and wildlife value (m,n,o),

g. risk of species extirpation (q),

Interpretation of Data for Wagner Road Compensation Site

The Wagner Road compensation site was constructed in spring of 1987 and four years is not sufficient time to draw conclusions. However, a qualitative interpretation of the data may provide useful information and is described below.

The degree to which precipitation deviated from the mean was assessed using data from the closest weather station. The NOAA-National Weather Service station at Robert E. Byrd Airport in Richmond, Virginia was the closest station to the Wagner Road site, and the Virginia

Climatological Office in Charlottesville, Virginia provided monthly summaries from the station. Precipitation totals for May through September, 1989 were 10.6% above normal, and 33.9% above normal for the same period in 1990. While the immediate effects of precipitation levels may be difficult to distinguish, over time such data may suggest a cause for many structural and functional trends.

An interpretation of the analyses was conducted for each functional value listed and is described below.

Flood abatement potential

The ability of most riparian wetlands to store and slowly release flood waters contributes to stream ecological processes and is often of value to downstream property (Maltby 1987). Surface area and elevation are primary considerations for determining flood abatement potential (L. Larson 1988). The conditions of the New Wagner Road permit granted to VDOT required that compensation be performed on a 2:1 ratio (i.e., two acres constructed for each acre filled). Elevations in the constructed wetland are similar to those in the reference wetland, which along with the increase in surface area, suggest that flood abatement potential may be high at the Wagner Road constructed wetland.

Other factors may effect flood abatement potential. Standard deviations within constructed wetland wells indicated rapid discharge of soil water. Soil physical characteristics including volumetric water content and percent organic matter may be causative factors in well fluctuations, and were not favorable for flood abatement at the Wagner Road site. Vegetative structure may deflect flood waters but this parameter has not been quantified (L. Larson 1988). The absence of mature tree species, fallen trees, and logs in the constructed wetland may reduce deflection of flood waters and limit flood abatement potential.

The long-term potential for flood abatement at the site may be enhanced by increased vegetative cover, tree and shrub growth, and some increase in percent organic matter. Flood abatement potential may be reduced by sedimentation from steep, poorly stabilized slopes on three sides (75%) of the constructed wetland.

Low flow maintenance potential

Many wetlands are capable of supplementing flow rates in streams by discharging during times of drought. Groundwater discharge was noted throughout the summers of 1989-1990 at two locations along the west-facing slope, at the upland/constructed wetland edge. A ridge across the site (Figure 6) prevented surface flow from reaching this area, however, subsurface flow may reach the adjacent creek (Second Swamp). As with flood abatement, slow discharge seems unlikely based on the extent of depth to water table fluctuation in the constructed wetland.

Long-term potential for low flow maintenance may increase if organic matter content increases. However, increased evapotransporational water loss following forest establishment may reduce this discharge.

Sediment trapping potential

Many wetlands located along creeks become inundated during periods of high flow, and sediments may be deposited as the current slows. Sediments transported by surface flow from adjacent uplands may also be deposited in wetlands. Factors at the Wagner Road site that may increase the probability of sediment trapping include the relatively large surface area that should reduce flow rate and the downstream location of the culvert that may have a damming effect.

Factors limiting sediment trapping potential at the Wagner Road constructed wetland include the absence of mature trees, fallen trees, and logs. The unvegetated areas of the steep slopes adjacent to the site have significant gully erosion and may have been the sediment source. Also, bare areas in the constructed wetland show minor erosion. Sediment export from the site has been observed during one heavy precipitation event in summer, 1990.

Long-term potential to trap sediment may be limited by several factors. Considerable sedimentation from the steep adjacent slopes may raise site elevations. Plans for land development upstream and the damming effect of the culvert during severe flooding could lead to extensive sediment deposition at Wagner Road constructed wetland. Natural wetland elevation is buffered by the low bulk density and potential for slumping; however, bulk densities in the constructed wetland were high, and slumping may not occur. Sediment trapping potential would eventually be reduced as sediments are deposited and elevations increase.

Production/Export

Wetlands are among the most productive ecosystems in the world (Smith 1980). Flushing of biomass from wetlands into adjacent waterways provides an additional carbon source (Wharton et al. 1982). Substantial physiognomic differences distinguish the constructed and reference wetlands. Based on the Cowardin et al. (1979) classification system, the constructed wetland vegetation most closely resembled a palustrine emergent wetland, while the reference wetland was classified as a forested wetland. Standing biomass was much lower in the constructed wetland than in most natural emergent wetlands and the reference wetland. However, a higher percentage of the biomass would be available to the adjacent creek in the constructed wetland than in the reference wetland. Biomass quality and decay characteristics may be as important as quantity (Chamie and Richardson 1978 and Odum and Heywood 1978). The type of organic matter produced in the constructed wetland may be inappropriate or too rapidly decomposed for local aquatic species assemblages.

The ridge at the center of the site may also effect this function (Figure 6). Conner and Day (1982) cited the energy subsidy associated with flooding and draw down cycles as the primary factor controlling riparian wetland productivity. Both the ridge and the disjointed portion of the constructed wetland were exposed to very infrequent flooding and productivity may be adversely effected. Vegetative cover was significantly higher in the "wetland" portion adjacent to the reference wetland than in either the "upland" portion or the disjointed "wetland" portion. Furthermore, export of organic material may have been limited by the effect of the ridge on surface water flow. Significantly lower species richness in the disjointed "wetland" portion than in the adjacent "wetland" portion may also have been a result of surface flow alteration caused by the ridge.

Long-term potential for production and export of carbon from the site depends on several factors. Establishment of wetland tree species in "wetland" delineated portions would improve the quality and seasonality of litter production. Extensive "upland" portions of the site may not be transformed into wetlands and may not contribute appropriate carbon forms. Long-term nutrient status is not known for constructed wetlands and may limit productivity. Erosion and sedimentation may alter site topography, limit productivity, and reduce surface water connections between the constructed wetland and the creek. Invasion of constructed wetlands by exotics and monocultures in general may lower the quality of exported material. Cattail, _Typha latifolia_, is present at the Wagner Road constructed wetland and is increasing annually.

Water quality enhancement

As the primary reducing environment on the landscape, wetlands are sites for the abatement of nutrients and toxicants (Gambrell and Patrick 1978). Water from either upstream or upslope may pass through wetlands, which may act as transformers, filters, or sinks, depending on the material involved. As a result of elevation, much of the Wagner Road constructed wetland was seldom inundated, while other portions are inundated for short periods.

Percent organic matter was significantly lower throughout the constructed wetland than in the reference wetland. These conditions were shown to limit microbial activity and the development of anaerobic conditions in Chapter Two. Water quality enhancement may be limited by infrequent anaerobic and/or reducing conditions.

Long-term potential for water quality enhancement depends on organic matter content, elevations, and inundation periods. Organic matter accumulation is limited by aerobic conditions (Terry 1986) and much of the constructed wetland may therefore fail to develop reducing conditions for some time to come. Inundation periods at the Wagner Road constructed wetland may actually become shorter if sediment deposition increases elevations at the site.

Habitat and wildlife values

Forested wetlands provide habitat for many wetland species and a refuge for many displaced upland species. In addition, many upland species exhibit a diurnal or seasonal dependence on wetlands. Many species require the unique hydrology, soil, and vegetation conditions of wetlands, however, even qualitative data regarding fauna reestablishment in constructed or restored sites is seldom available (Majer 1989).

Considerable faunal activity was recorded at the Wagner Road constructed wetland site from 1989 to 1991, and was generally associated with specific portions, either "wetland" or "upland." Muskrat sightings and signs were considerably more prevalent in the wettest part of the adjacent "wetland" portion of the constructed wetland than in either of the remaining portions of the constructed wetland or the reference wetland. Raccoon signs (tracks and scats) were noted for both "wetland" portions and the reference wetland. Crawfish "chimneys" were also found in delineated "wetland" portions and in the reference wetland.

Vegetative structure is critical for many avifaunal habitat requirements. The structural diversity of the reference wetland vegetation greatly increased the potential avifaunal habitat compared to the constructed wetland. Three heron species, wood ducks, and mallard ducks were sighted in the "wetland" portion near the reference wetland. Avifaunal species that are typically associated with uplands were limited to "upland" portions of the constructed wetland, and included doves, quail, sparrows, and killdeer.

Increased wildlife usage associated with interspersion of habitats is often referred to as the "edge effect." Edge effect in the constructed wetland was limited by steep sloped sides and adjacent land use, i.e., Old Wagner Road, New Wagner Road, and a railroad bordered three sides of the constructed wetland (Figure 1). Edge effect functions and values may have been limited to the side adjacent to the reference wetland.

Provision of a corridor for animal movements and plant and animal dispersal is an important function for many riparian wetlands. Based on aerial reconnaissance, Second Swamp may have performed corridor functions and values between undeveloped upland forest "islands" in Petersburg and Prince George County, Virginia. However, 6,670 cubic yards of fill, 74.7 meters wide, was placed in Second Swamp and the stream confined to a triple 9 x 6 foot culvert, 74.7 meters long. There was no evidence that any non-fish species passed through the culvert. Some animal species, i.e., deer and raccoon, appeared to cross at the train culvert beneath New Wagner Road (Figure 1). Most other species may have been precluded from accessing portions of Second Swamp.

Long-term habitat value may be improved if tree species become established in the constructed wetland, however, upland habitat of some value was forfeited by the compensation site selection. It seems unlikely that much of the site would develop into forested wetland, and landscape position precludes performance of edge effect functions and values. Corridor functions and values are not likely to be replaced due to the use of fill and box culverts instead of a column supported bridge.

Risk of species extirpation

Wetlands provide habitat for a disproportionately large percentage of endangered and threatened species (Williams and Dodd 1979). A population of an endangered species, pink turtleheads, Chelone cuthbertii Small, was found within the Second Swamp alignment by VDOT personnel. The population was relocated to the College of William and Mary in Williamsburg, Virginia by endangered species specialists. The species was not found in the vicinity of the Wagner Road site from 1989 to 1991.

There is a possibility that this or other endangered or threatened species may become established in the Wagner Road constructed wetland site over the long term. However, more aggressive wetland and upland species have already colonized much of the site, and access is further limited by the location of the constructed wetland site.

Other considerations

Many assessment methodologies include values such as "cultural heritage" and "recreation" for wetlands, and these values may be appropriate for some wetland assessments. The Wagner Road constructed wetland provides a possible example. Second Swamp is part of the Blackwater River headwaters, and has been proposed for scenic river designation by the state of Virginia.

In some cases, uplands that have considerable functions and values may be sacrificed for construction of a replacement wetland (Kruczynski 1990). Preconstruction photographs of the Wagner Road constructed wetland site indicate that the area may have provided upland habitat functions and values adjacent to Second Swamp.

Conclusions

Compensation through wetland construction is widely recommended by wetland consultants for clients who seek Section 404 permits to fill wetlands. The increasing frequency of wetland construction has not been followed by increasing evaluation of success. While wetland evaluation in general has progressed in recent years, no constructed forested wetland assessment methodologies have received widespread support from wetland scientists and regulators.

Based on the results of study at several constructed wetlands and review of the data at the Wagner Road constructed wetland, a two-tiered methodology is proposed. Tier one addresses compliance with both explicit permit conditions and the implied replacement of appropriate vegetation. Tier two generates and evaluates data to assess structural and functional replacement, causes for constructed wetland success and failure, and the potential for long-term success.

Tier one of the methodology is conducted during the first four years following wetland construction. Permanent transects are established at a constructed wetland, and weighted averages of colonizing vegetation are calculated based on species relative cover estimates and indicator status. An early indication of permit compliance is assessed and suggestions for site improvement may be made.

Tier two of the methodology involves four steps in logical sequence, including (1) setup, (2) monitoring, (3) analysis, and (4) interpretation. Results of a limited interpretation of data just four years following construction of the Wagner Road site in Petersburg, Virginia were presented. Qualitative interpretation of the data pertaining to seven wetland functions and values listed suggested a range of performance levels and the potential for long-term performance.

Possible inadequacies at the site became apparent in the interpretation and provided suggestions for future improvements in wetland construction techniques. Potential problems at the Wagner Road site included inappropriate compensation site selection, inappropriate grading over much of the site (elevations too high), the need for hydric soil backfill over the site, and inappropriately steep slopes on three sides of the constructed wetland. Column supported bridges would help maintain the wetland corridor, wetland hydrologic characteristics, and would reduce the total wetland acreage filled.

General Conclusions

Wetlands have been filled for many years in the absence of protective legislation. As the extensive loss of wetland acreage became apparent and wetland functions and values were illucidated, federal legislation protecting these systems was enacted. Several federal and state laws currently exist which afford some protection to wetlands, but Section 404 of the Federal Water Pollution Control Act of 1972 has had the most impact. The Act was interpreted through National Environmental Policy Act guidelines to allow wetland fills to be compensated for by construction of wetlands when (1) there are no alternatives, (2) impacts have been avoided as much as possible, and (3) impacts have been reduced as much as possible.

Forested wetlands occupy extensive areas of floodplains in the Southeastern United States, including Virginia. Like rivers, highways are linear aspects of the landscape, and intersects are unavoidable. Highway planners frequently decide not to bridge forested wetlands (which would substantially reduce the impact) and apply for Section 404 permits. As a result, highway departments have received the bulk of wetland fill permits and have attempted more forested wetland construction than any other single entity. The rate of construction is expected to increase dramatically in Virginia during the 1990's.

Monitoring of constructed wetland effectiveness has been sparse. The absence of a unified methodology for analyzing success has led to a range of methods for monitoring, a lack of agreement on criteria for evaluating success, minimal suggestions for improved construction techniques, and widely differing claims of success and failure.

Wetlands have been constructed for several other functions in recent years and many of these projects have been evaluated for the particular target function. Natural wetland assessment methods have also received attention and methods for evaluating wetland function are under development and testing. The current study borrowed from assessment parameters used for other purposes to develop a methodology for assessing constructed forested wetland success in replacing filled wetlands.

The Wagner Road constructed wetland site in Petersburg, Virginia was selected as the principal study site because wetland type, construction techniques, and topography were representative of the 15 sites visited. Replication of some experiments utilized other constructed wetlands, and all sites were within the Coastal Plain of Virginia.

Two types of monitoring are needed, compliance monitoring and effectiveness monitoring. In Chapter One, a technique was utilized that increased the sensitivity of the vegetation parameter. Vegetation was selected because of limitations of other parameters (in the recently constructed wetlands that would need compliance monitoring) and because vegetation establishment is frequently either stated or implied in permit conditions. Weighted averages of colonizing vegetation was quantified for the constructed wetland and was shown to be correlated with hydrology at the site. A comparison with an adjacent reference wetland determined that 34.6% of the constructed wetland failed to meet the revegetation criterion.

Forested wetlands that occur along a river, such as the Wagner Road site at Second Swamp, are well positioned to perform water quality functions. Chapter Two was designed to (1) estimate performance of water quality functions and values dependent upon anaerobic and/or reducing conditions, (2) predict potential for long-term performance of water quality functions and values, and (3) to analyze the relationship between hydrology, soil, and vegetation in order to suggest improvements in wetland construction techniques. Two laboratory studies of carbon dioxide and methane production were conducted using thermal gas chromatography. Significantly longer periods of time were required to develop anaerobic conditions in constructed wetland soils than in reference wetland soils. The elevations present at the Wagner Road constructed wetland and the duration of inundation periods that result are too brief for development of anaerobic conditions over much of the site. Therefore, the current potential for performing water quality functions dependent upon anaerobic and/or reducing conditions may be low at the Wagner Road site. Long-term performance of water quality functions are dependent upon many factors at the site. Organic matter accumulation without significant increase in elevation would afford the greatest potential, but appear unlikely for much of the site. Therefore, long-term potential for performance of water quality functions may improve over part of the "wetland" portion of the site, but may not be performed in the remaining portions. Improvements indicated by this study included grading to a lower elevation and spread of demucked soil over the site.

A two-tiered methodology for assessing constructed forested wetland effectiveness was presented in Chapter Three. Tier one utilized the methods described in Chapter One to evaluate compliance with both implicit and explicit conditions of a permit. A constructed wetland monitoring methodology for research purposes comprises tier two. Four steps including (1) setup, (2) monitoring, (3) analysis, and (4) interpretation were used to study vegetation, soil, hydrology, fauna, and landscape position characteristics. The interpretation provides an estimation of structural and functional replacement compared to a reference wetland, estimation of long-term potential for functional replacement, and generation of suggestions for improvements in wetland construction techniques. Though still very soon after wetland construction, interpretation of the Wagner Road site demonstrated that the assessment methodology could provide a qualitative measure of constructed wetland success. Refinements in the assessment methodology should be possible as older sites become available.

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Personal Data

Birth Date: January 30, 1962
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Education

Ph.D., Biology, expected 1991, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.
Major Professor: Dr. John Cairns, Jr.
Research Topic: An Analysis of Palustrine Forested Wetland Compensation Effectiveness in Virginia.

M.S., Biology, James Madison University, Harrisonburg, Virginia.
Major Professor: Dr. Norlyn Bodkin
Research Topic: Survey of the Vascular Wetland Plants of the Tidal Section of the James River.

B.S., Biology, 1984, James Madison University, Harrisonburg, Virginia.

Professional Employment

1988-1991 Graduate Research Assistant and Teaching Assistant, University Center for Environmental and Hazardous Materials Studies, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Wrote several grants proposals, conducted research, wrote journal articles, book chapters, abstracts, and book reviews. Supervised three undergraduate students and one technician in conducting soil and vegetation tests on created wetlands both in the field and in laboratory mesocosms. Taught General Biology laboratories for majors and nonmajors (three semesters) and developed several educational experiments.

1990 (summer) Graduate Research Fellowship/Summer Intern, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Conducted vegetation study of marshes along a salinity gradient from saline to freshwater in the York and Pamunkey Rivers, and assisted in research design and data analysis. The project is part of the National Estuarine Research Reserve System of NOAA.

1986-1988 Director of Marine Science, Christchurch School, Christchurch, Virginia.

Adminstrative/teaching position included establishment of a field-oriented marine science program at the high school junior-senior level. Designed curriculum for and taught both biology and marine science. Initiated and supervised a journal for student scientific research. Coproduced an interpretive video on wetlands. Wrote a grant proposal to DuPont Educational Foundation which was funded for $89,000.

1984-1986 Graduate Teaching Assistant, Department of Biology, James Madison University, Harrisonburg, Virginia.

Laboratory instructor for General Biology for four semesters.

Published Manuscripts

Atkinson, R.B., N.L. Bodkin, and J. Perry. New county records collected in tidal wetlands of four coastal plain counties along the James River. Castanea 55(1): 56-64.

Atkinson, R.B., J. Cairns, Jr., B. Wallace, and J. Perry. Ecological risk assessment for highways in the Chesapeake Bay watershed. p. 673-680 In (J. Mihurshy and A. Chaney eds.) New Perspectives in the Chesapeake System. Chesapeake Research Consortium, Solomons, Maryland.

Manuscripts Accepted for Publication

Atkinson, R.B. and J. Cairns, Jr. Ecological risks of highway construction. In J. Cairns, Jr., D.R. Orvos, and B.R. Niederlehner (eds.) Predicting Environmental Risk.

Manuscripts in Preparation

Atkinson, R.B., James E. Perry, E.P. Smith, and J. Cairns, Jr. Constructed wetland delineation as a component of assessment. Wetlands.

Atkinson, R.B. and J. Cairns, Jr. Status of a constructed freshwater wetland soil after four years.

Perry, J. and R.B. Atkinson. Plant distribution in tidal wetlands along a salinity gradient in the York River, Virginia.

Selected Abstracts / Presented Papers

Atkinson, R.B. and N.L. Bodkin. 1985. Preliminary results of a vascular flora on the tidal section of the James River. Virginia Journal of Science. 36 (2).

Atkinson, R.B. 1987. Establishment of field-oriented science program at the secondary level. Association of Southeastern Biologists Journal. 34 (2).

Atkinson, R.B. 1987. Inclusion of relevant field research in high school science courses. Virginia Journal of Science. 38 (2).

Atkinson, R.B. and J. Cairns, Jr. 1990. The effect of moisture on vegetative colonization of a man-made forested wetland in Virginia. Society of Wetland Scientists.

Atkinson, R.B. and J. Cairns, Jr. 1990. Early vegetative colonization of man-made forested wetlands in Virginia. Association of Southeastern Biologists.

Selected Presentations

Wetland workshop presentations. 1990-91. Ecology, regulation, wetland plant identification and advanced wetland plant identification. Workshops sponsored by Henricopolis Soil and Water Conservation District.

Wetland workshop presentations. 1991. Plant ecology, wetland delineation, and endangered plant species in strip mined regions. Virginia Council on the Environment and the U.S. Office of Surface Mining.

Education session chair at 50th Annual Meeting of Association of Southeastern Biologists, Charlotte, North Carolina, 1989.

Invited talk at training session on land use practices for Soil Conservation Service personnel, Virginia Tech, 1988.

Invited talk at training session on wetlands at Calvert Marine Museum, Solomons, Maryland, 1987.

Honors and Awards

1989-1991. Tuition waivers for 4 of 6 semesters from the VPI&SU Biology Department.

1990. Mark S. Maly Fellowship for Outstanding Biology Graduate Student, VPI&SU, Biology Department.

1989. Outstanding Graduate Teaching Award, VPI&SU, Graduate School.

1988. Midatlantic Marine Education Association Award for Meritorious Service.

1988. Christchurch School Award for Meritorious Service.

Selected Grant Proposals

DuPont Educational Foundation. Christchurch School Marine Science Program personnel grant. Funded $89,000.

Virginia Tech Biology Department. Competetive graduate student research grant. Funded $2,000.

Virginia Academy of Science. Seed Germination rates of various wetland plant species in artificial wetland soils. Funded $800.

Virginia Tech Graduate Student Assembly Research Development Project. Funded $300.

U.S. Army Corps of Engineers. An analysis of palustrine forested wetland compensation effectiveness and potential for improvement. $100,000 Rejected.

Virginia Department of Transportation. An analysis of palustrine forested wetland compensation effectiveness and potential for improvement. $100,000 Rejected.

Office of Surface Mining. Co-principal investigator. Evaluating the potential for constructed wetland establishment on restored surface mine sites. Funded $253,000.

Professional Societies

Society of Wetland Scientists
Association of Southeastern Biologists
Virginia Academy of Science
Midatlantic Marine Education Association

References

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