Environmental Management (2013) 51:1077–1091
DOI 10.1007/s00267-013-0027-7

ENVIRONMENTAL ASSESSMENT

Compensatory Stream and Wetland Mitigation in North Carolina: An Evaluation of Regulatory Success

Tammy Hill · Eric Kulz · Breda Munoz · John R. Dorney

Received: 4 October 2011 / Accepted: 26 February 2013 / Published online: 21 March 2013

Abstract Data from a probability sample were used to estimate wetland and stream mitigation success from 2007 to 2009 across North Carolina (NC). "Success" was defined as whether the mitigation site met regulatory requirements in place at the time of construction. Analytical results were weighted by both component counts and mitigation size. Overall mitigation success (including preservation) was estimated at 74 % (SE = 3 %) for wetlands and 75 % (SE = 4 %) for streams in NC. Compared to the results of previous studies, wetland mitigation success rates had increased since the mid-1990s. Differences between mitigation providers (mitigation banks, NC Ecosystem Enhancement Program's design-bid-build and full-delivery programs, NC Department of Transportation and private permittee-responsible mitigation) were generally not significant although permittee-responsible mitigation yielded higher success rates in certain circumstances. Both wetland and stream preservation showed high rates of success and the stream enhancement success rate was significantly higher than that of stream restoration. Additional statistically significant differences when mitigation size was considered included: (1) the Piedmont yielded a lower stream mitigation success rate than other areas of the state, and (2) recently constructed wetland mitigation projects demonstrated a lower success rate than those built prior to 2002. Opportunities for improvement exist in the areas of regulatory record-keeping, understanding the relationship between post-construction establishment and long-term ecological trajectories of stream and wetland restoration projects, incorporation of numeric ecological metrics into mitigation monitoring and success criteria, and adaptation of stream mitigation designs to achieve greater success in the Piedmont.

Keywords Wetland mitigation · Stream mitigation · Mitigation success

Introduction

Purpose of Study and Overview

Compensatory mitigation is a major component of stream and wetland permitting. Development projects impacting streams or wetlands in excess of established permitting thresholds usually require compensatory mitigation to offset impacts. The intent of compensatory mitigation is to replace functions and values unavoidably lost due to impacts, and support the goal of "no net loss" of aquatic resources of the United States. A number of States and U.S. Army Corps of Engineers (USACE) Districts have published regulatory success rates for their jurisdictions over the past decades (Allen and Feddema 1996 in southern CA; Balzano and others 2002 in NJ; Brown and Veneman 2001 in MA; Cole and Shafer 2002 in PA; Cruse 1991 in Broward County, FL; Fenner 1991 in San Diego County, CA; Hornyak and Halvorsen 2003 in the Upper Peninsula of MI; Kettlewell and others 2008 in OH; Matthews and

T. Hill (✉) · E. Kulz
Division of Water Quality, North Carolina Department of Environment and Natural Resources, 1650 Mail Service Center, Raleigh, NC 27699-1650, USA
e-mail: Tammy.L.Hill@ncdenr.gov

B. Munoz
RTI International, 221 Cox Building, 3040 Cornwallis Road, Research Triangle Park, NC 27709-2194, USA

J. R. Dorney
Atkins North America, 1616 East Millbrook Road, Suite 310, Raleigh, NC 27609-4968, USA

Endress 2008 in IL; Morgan and Roberts 2003 in TN; Redmond 1992 in FL; Robb 2000, 2002 in IN; Sudol and Ambrose 2002 in Orange County, CA) including more comprehensive reviews by Turner and others (2001) and Kihslinger (2008). These studies vary somewhat in their definition and scope. The reported regulatory success rates, based on acreage and not including preservation, range from 18 to 69 % and average about 48 %. The rate of regulatory success for stream mitigation has apparently not been previously analyzed or reported.

In North Carolina (NC), compensatory mitigation is a component of federal (USACE) and state (NC Division of Water Quality, NCDWQ) administration of Sections 404 and 401, respectively, of the Federal Clean Water Act, as well as the North Carolina Coastal Area Management Act (CAMA) and the coastal Dredge and Fill Law. Evaluation of permit applications under all of these acts follows the mitigation sequencing outlined in the 404(b)(1) guidelines (40 CFR 230), which require that once impacts have been avoided and minimized to the maximum extent practical, mitigation to compensate for the lost functions and values of the wetlands and/or streams impacted is often required.

The 401 Water Quality Certification Rules implemented in 1996 (15A NCAC 2H.0500) address activities that have the potential to degrade wetlands or surface waters. In discussing mitigation, these rules refer primarily to wetlands and mitigation of wetland acreage. As a result, mitigation in the 1990s generally involved restoration, creation or enhancement of wetland acreage, regardless of whether the impacted resources were wetlands or streams. In 1998, NCDWQ revised the General Water Quality Certifications to include a requirement for compensatory stream mitigation for impacts exceeding 150 linear feet of perennial streams (Cyndi Karoly, NCDWQ, personal communication, August 15, 2011). Since then, compensatory mitigation requirements have been extended to intermittent streams as well. Therefore since 1998, unavoidable impacts to streams and wetlands that required compensatory mitigation have generally required wetland mitigation for wetland impacts, and stream mitigation for stream impacts.

The purpose of this study was to evaluate compensatory mitigation efforts in NC to determine if mitigation required under Section 404 permits issued by the USACE and 401 Water Quality Certifications issued by the NCDWQ had met applicable regulatory success criteria in place at the time of project construction. The population of wetland mitigation projects included projects implemented as early as 1996, while the population of stream projects included projects designed as early as 1999 and constructed in 2000 or later. The scope of this project did not allow for direct comparison of permitted impacts versus required mitigation amounts (i.e., evaluation of net loss of aquatic resources); however, Hill and others (2012) reported wetland and riparian buffer mitigation kept up with permitted impacts during the study timeframe, while stream mitigation lagged behind, yielding an overall net stream loss in NC.

Performance Standards and Success Criteria

Review of mitigation plans as part of this study revealed that projects stated general goals (e.g., “replacement of lost functions and values,” “restoration of aquatic habitat,” “improvement of water quality”), but the performance standards in mitigation plans often fell short of quantifying whether or not projects were on track to meet or had achieved the mitigation plan goals. Specific aquatic functions can be difficult to measure directly; therefore, success criteria in mitigation plans dictate that mitigation monitoring efforts utilize surrogates as indicators of improved functions and values. As restoration science has developed, regulatory requirements for success criteria have changed over time.

For the earliest wetland projects (early 1990s), USACE required a 3-year monitoring period. Many projects established a hydrology success criterion for a minimum duration of saturation or inundation and a vegetation criterion of 260 trees per acre (TPA) surviving at the end of 3 years. In the late 1990s, projects began to require 5 years of monitoring, and criteria were added for some projects to examine vegetation diversity and/or appropriate hydroperiods for wetlands at different landscape positions. Circa 2000, hydrology success criteria began to include comparison with a reference ecosystem. Soil criteria have been infrequently utilized in NC, although a few projects in all timeframes required demonstration of hydric soil indicators (e.g., low chroma matrix, mottles, oxidized rhizospheres).

In this study, wetland components were evaluated on up to four categories of success, based upon criteria specified in the mitigation plan for each project:

Hydrology: A specified percentage of the growing season during which the project demonstrates continuous saturation within 12 inches of the soil surface or inundation. Criteria usually involve a minimum percentage (generally 5, 8, or 12.5 %) of the growing season based on the targeted wetland type and its expected minimum hydroperiod. Some criteria also establish a maximum hydroperiod (e.g., 75 % of the growing season) for projects in which long-term inundation is a potential concern.

Vegetation: Most criteria for forested wetlands involve a minimum planted woody stem density criterion (e.g., a requirement that vegetation plot monitoring demonstrate survival of 320 planted TPA at Year 3 post-planting, 290 TPA at Year 4 and 260 TPA at Year 5). Some projects set criteria for woody stem diversity, such as a minimum of five species characteristic of the wetland type. Success criteria for herbaceous wetlands, such as coastal marshes, usually involve a minimum percent cover, which may specify the targeted plant species (e.g., 80 % cover *Spartina alterniflora* and *S. patens*).

Soils: Although this is the third environmental diagnostic in wetland delineation, it is rarely a success criterion for mitigation projects in NC. Soils at restoration projects are usually disturbed before and/or during construction, and may involve previous agricultural activity or fill material. Development of a soil profile indicative of hydric conditions may take significantly longer than the typical monitoring period. A small number of projects in the random sample did have a requirement for development of at least one hydric soil indicator.

Protection: Mitigation projects are expected to be protected "in perpetuity" and plans must specify a long-term protection mechanism which defines limitations on use of the land such that the mitigation project is allowed to continue to develop naturally. Some mechanisms allow for long-term management, especially of vegetation, for specific permittee needs (e.g., airport visibility issues) or larger environmental efforts (e.g., forest management to support endangered species habitats).

Early stream projects (mainly those constructed before 1999) generally had success criteria that included stable channel cross-sections and some percentage of survival of planted vegetation. However, channel stability was often evaluated with a visual inspection and photo points only; quantitative measurements were usually not required. Some of the first specific quantitative stream monitoring requirements were presented in the Internal Technical Guide for Stream Work in North Carolina (NCDENR 2001). This guidance indicated that physical monitoring should include annual measurement of cross-sections at riffles and pools, longitudinal profile surveys and pebble counts. Monitoring of vegetation density was required, with a target success criterion of 320 planted TPA at the end of the monitoring period. Additional requirements for aquatic macrobenthos monitoring were included for some stream mitigation projects. The monitoring period was expected to be at least 5 years. However, no specific, measurable performance standards or success criteria beyond vegetative success were provided in the guidance.

In 2003, the Interagency Stream Mitigation Guidelines (USACE and others 2003) revised the monitoring criteria for evaluating NC stream mitigation projects. Geomorphic monitoring to evaluate channel stability included measurement of cross sections and longitudinal profiles annually for 5 years. Additional success criteria included consistency of pool/riffle spacing, minimal aggradation or degradation, and pebble counts showing a change in the size of the bed material toward a desired composition. Vegetation monitoring included evaluation of survival of planted stems. The targeted success criterion is 260 TPA after 5 years of monitoring. An additional requirement included in the 2003 guidelines is monitoring of at least two bankfull events in separate years during the 5-year monitoring period. The goals of many stream restoration projects include reconnection of the stream with its floodplain (or construction of a newer floodplain at a lower elevation). Therefore, bankfull events must be monitored using a crest or staff gauge during the monitoring period.

Review of Historical Mitigation Success in North Carolina

Despite limitations inherent in evaluating mitigation site success, particularly with limited guidance available and lack of clarity regarding goals and objectives of mitigation projects instituted during the 1990s, two reports attempted to evaluate the status of compensatory mitigation projects in NC (FHWA 1995; Pfeifer and Kaiser 1995). Both studies were completed in 1995, and involved evaluation of a variety of wetland mitigation sites throughout NC.

The Federal Highway Administration (FHWA) led a federal and state agency Process Review Team to evaluate the effectiveness of compensatory wetland mitigation projects associated with highway construction (FHWA 1995). The objective of this work was to evaluate compensatory mitigation projects associated with Section 404 permits issued to the NC Department of Transportation (NCDOT) for highway projects from 1986 to 1992. The Process Review Team selected a convenience sample of seven projects. The team reviewed permits and plans, and performed on-site inspections. The only available copy of the report included evaluation reports on five of the seven sites. Of the five projects for which data were available, only one (20 %) successfully produced the targeted wetland type. While the sample size was obviously very small, the results of the study highlighted the inadequacies of NC wetland mitigation in the early 1990s.

Pfeifer and Kaiser (1995) reviewed 59 permits which were issued between January 1, 1991 and December 31, 1993 and that required compensatory mitigation. These permits resulted in 82 separate compensatory mitigation projects having unique characteristics. Forty-one of the 82 mitigation projects were visited by the authors during the summer of 1994. Of the 24 projects for which current or probable achievement of correct wetland type and size could be determined, only 10 (42 %) were deemed successful. As noted in both reports, failure to achieve hydrology appropriate for the proposed wetland type was the most common factor for lack of success. Incorrect elevation was a contributing factor for seven of the eight completed projects with incorrect hydrology. Vegetative success was not discussed in this report.

Methods

Data Collection

In 2007, a tracking database was developed with the goal of cataloging all NC mitigation projects that were requirements of 401 Certifications. The NCDWQ's Basinwide Information Management System (BIMS) database was queried for lists of permitted stream and wetland mitigation and restoration projects, and for impact permits requiring mitigation that were issued by NCDWQ from 1990 through 2006. Paper files were referenced for these 401 Certifications, and the database was populated with information describing each mitigation project. Furthermore, each mitigation project was divided into mitigation "components" based on ecosystem type, mitigation type or other unique characteristics (e.g., "4 acres of riparian wetland enhancement," "1000 linear feet of perennial stream restoration"). Thus, a mitigation project could contain one or more components, which may or may not be physically connected. If present in the project's mitigation plan, success criteria were entered with each component. The mitigation tracking database did not include on-site and project-specific NCDOT mitigation projects, but did include larger off-site NCDOT mitigation projects.

Sample Selection

For the purposes of this study, the population of interest was defined as all projects in the mitigation database for which a 401 Certification application or final mitigation plan had been submitted to NCDWQ from 1996 through 2006. At the time of sample selection, there were 130 wetland projects and 193 stream projects in the population. The population was divided into categories by ecosystem type: wetland and stream. Ecosystem type categories were further classified into six strata based on mitigation provider: Ecosystem Enhancement Program (EEP) and its predecessor Wetland Restoration Program (WRP) design-bid-build (DBB) program, EEP Full-Delivery program, Mitigation Bank, NCDOT off-site mitigation, Private permittee-responsible mitigation, and Other (generally municipal or Department of Defense projects). The two types of EEP projects were evaluated separately because there has been significant debate within the NC mitigation community as to which method of project procurement and development yielded more successful mitigation projects.

A probability random sample was selected using a stratified cluster sampling design. USEPA's Environmental Results Program (ERP) Sample Planner (http://www.epa.gov/erp/toolsandresources.htm) with finite population adjustment was used to determine the sample size for each ecosystem type category (i.e., wetland and stream). ERP Sample Planner selection parameters were set at precision = 5 %, confidence = 95 % ($\alpha = 0.05$) and power = 80 % ($\beta = 0.20$). With these selection parameters, the ERP Sample Planner indicated a sample size of 98 wetland and 129 stream projects. The sample size was verified by the Yamane formula (Yamane 1967), which produced the same results. The sample size was allocated to each mitigation provider group using proportional allocation, such that mitigation provider groups with larger numbers of projects received a larger sample size. This type of allocation was used to ensure a sample with spatial and component coverage similar to the population. Projects were selected at random within each stratum and all components within selected projects were included in the sample.

Field and Office Evaluation Protocols

The goals of this research were to estimate population success rates for wetland and stream mitigation projects in North Carolina from a *regulatory* perspective instead of a strictly scientific evaluation, and to explore factors that may increase or decrease regulatory success rates. Each mitigation component was rated as successful or unsuccessful based on comparison of its present condition versus the regulatory success criteria approved in the project mitigation plan, rather than compared to an idealized ecological definition of its community type. The hope was that the outcomes of this study would highlight regulatory practices that were working, as well as opportunities for policy improvement, and ultimately contribute to greater success of compensatory mitigation within the state.

To facilitate and track project evaluations, data forms were developed and field tested for office and field use (Hill and others 2011). Once the forms were finalized, project evaluations began with file reviews for each selected project. Site visits were conducted for all of the projects that had been constructed. Project evaluation occurred statewide from 2007 to 2009, with the bulk of site visits performed during the 2009 growing season. All components selected for evaluation were walked by project staff, and observations were documented for later use in assigning ratings. Bias regarding the success of any specific mitigation provider was minimized in the following ways:

Table 1 Proportions of initial wetland and stream mitigation project populations, compared with the final datasets of evaluated projects, NCDWQ

Provider	Wetland projects (%)		Stream projects (%)	
	Population ($n = 130$)	Evaluated ($n = 82$)	Population ($n = 193$)	Evaluated ($n = 79$)
EEP/WRP (DBB)	33	18	54	42
Full-delivery (EEP)	10	16	13	15
Mitigation Bank	8	12	4	8
NCDOT	4	10	2	11
Other	7	5	7	3
Private	38	39	20	21

none of the NCDWQ project staff members were involved in the approval of mitigation plans for evaluated mitigation projects, nor was NCDWQ responsible for the construction or monitoring of any of the projects. Observations on stream sites included stream structures, flow, streambank stability, evidence of overbank flooding events, and riparian vegetation composition and condition. Wetland sites were evaluated for hydrology (evidence of inundation/saturation), soil development (creation sites), vegetation composition and condition, and open water areas. Each component was evaluated based on available monitoring data and observed site conditions, and given a rating of successful, unsuccessful or NA (for components that could not be evaluated).

The final numbers of projects evaluated using the office and field protocol developed for the study were 82 wetland and 79 stream projects (63 % of wetland and 41 % of stream projects in the population), consisting of 205 wetland and 136 stream individually-evaluated mitigation components, totaling over 8,000 wetland hectares and nearly 183,000 linear meters of stream. Sampling weights were adjusted to account for sampling frame imperfections such as overcoverage, undercoverage, and misclassification of projects in the wrong stratum. Post-stratification methods were used to adjust to population totals and to increase the precision of survey estimates. Comparisons of the original population frames and the final samples of evaluated wetland and stream mitigation projects are presented in Table 1.

Statistical and Exploratory Data Analyses

Statistical data analyses were performed using SUDAAN® (www.rti.org/sudaan), a software package developed at RTI International to handle complex study designs, such as the stratified cluster design and weighting adjustment in this study. Exploratory data analyses were conducted using Microsoft Excel and Access 2007 to further investigate factors that may influence mitigation success in NC.

Success rates were produced for each of the following subgroups or domains of the populations: mitigation provider, physiographic region, mitigation activity, age and size of the project, and in the case of wetland mitigation, ecosystem type. Mitigation providers were the same categories upon which the random sample was stratified: EEP/WRP design-bid-build, Full-Delivery (EEP), Mitigation Bank, NCDOT, Private and Other. The physiographic regions of North Carolina are, from west to east: Mountains, Piedmont and Coastal Plain. Mitigation activities were consolidated into four categories: Restoration, Enhancement, Creation, and Preservation, according to the definitions in the Interagency Stream Mitigation Guidelines (USACE and others 2003) for streams (Creation was substituted for Relocation of a stream outside of its natural valley) and North Carolina's Water Quality Certification Rules (15A NCAC 2H.0506(h)(4)(A-D)) for wetlands. Monitoring start date was utilized for the age of the project, and categorized into 4-year intervals for wetlands and 3-year intervals for streams to provide a roughly equal distribution of component counts within each age class. Project size was categorized similarly into 3 size classes for wetlands and 4 size classes for streams at natural breaks in wetland area and stream length. For wetlands, the ecosystem type domain included the categories Riparian (i.e., in a geomorphic floodplain), Non-riparian (i.e., not in a geomorphic floodplain) and Coastal (i.e., salt and brackish marshes), which consolidated the wetland types defined in the Dichotomous Key in the N.C. Wetland Assessment Method User Manual (NCWFAT 2008).

All response variables derived from the mitigation components were binary (Yes or No). Success rates were calculated for several domains and statistical testing was used to evaluate significant differences within domain success rates. Due to the unique characteristics of preservation, there was interest in both analyzing the entire dataset of evaluated components, and then removing preservation components from consideration to analyze the study data for restoration, enhancement, and creation components.

Weighted counts of successful and unsuccessful components were produced for all levels within each domain. Sampling weights were defined by the sampling design used to select the mitigation projects. Since a stratified sampling design was selected, standard formulas to calculate the weights for stratified designs were used (Lohr 2010). This involved determining the total number of mitigation projects (Nh) in each of the strata and the total sample size (nh) allocated to each of the strata. The sampling weights for a stratified sample design are defined as Nh/nh. It was determined during the project that some mitigation projects were wrongly classified and that a few others did not satisfy the criteria for inclusion in the population which resulted in the need to adjust the sampling weights. After the conflicting mitigation projects were removed or correctly classified, the sampling weights were adjusted so that the sum of the sampling weights of the mitigation projects within a given mitigation group added up to the total number of mitigation projects in that group (Nh). Successful and unsuccessful rates, as well as their 95 % confidence intervals, were calculated for each level. Analyses were conducted in an attempt to determine statistical differences for success rates within levels of each domain. Pair-wise t tests and their associated probability values were utilized to test null hypotheses of no significant difference in success rates between levels of each domain. Since the analyses involved multiple comparisons (i.e., each level was compared to every other level within the domain), a sequential Bonferroni correction (Holm 1979) was utilized to minimize the potential of falsely concluding a significant difference in the success rate between any two levels. Holm's method involves ordering the p values (low to high), then dividing the significance level ($\alpha = 0.05$) by the number of pair-wise tests remaining for comparison in the sequence. Analyses were conducted to compare success rates within all levels of each domain with and without inclusion of preservation components.

A primary concern in NC stream and wetland mitigation is not only the number of mitigation projects or components, but the size (i.e., hectares of wetlands, linear meters of stream) of mitigation that is successful. Therefore, success was examined based not only on the number of components that were meeting regulatory success criteria, but also on the size of those components. Analyses were repeated using component size (e.g., existing wetland area and stream length estimated based on monitoring data and site observations) as a way to compare the proportion of successful and unsuccessful hectares of wetlands and linear meters of stream within the levels of each domain. Again, analyses were repeated for the data set both with and without preservation components.

Results

Overall Success

Evaluation of wetland components estimated a success rate of 74 % (SE = 3 %) overall, and 70 % (SE = 3 %) when preservation was excluded. The proportion of successful wetland mitigation area was slightly lower at 70 % (SE = 3 %) and 64 % (SE = 4 %), with and without preservation, respectively. Evaluation of stream mitigation estimated a success rate of 75 % (SE = 4 %) for all components, and 74 % (SE = 4 %) when preservation was excluded. The proportion of successful stream mitigation length was estimated at 84 % (SE = 6 %) with preservation components and 75 % (SE = 6 %) when preservation was excluded (Fig. 1).

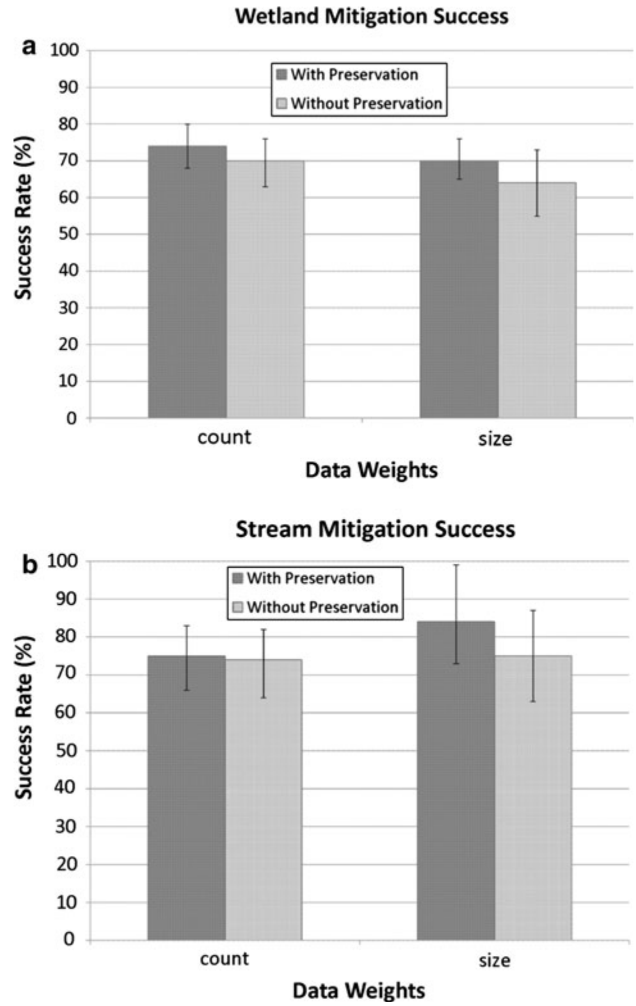

Fig. 1 Overall mitigation success rates, based on component counts and mitigation size (hectares of wetlands, linear meters of streams); error bars represent 95 % confidence limits

Mitigation Provider

The Other category was combined with Private for this analysis due to the small sample size and permittee-responsible nature of this category. Analysis of all evaluated wetland components, including preservation, yielded success rates of mitigation projects across mitigation providers ranging from 69 % (SE = 5 %) to 81 % (SE = 8 %), and successful total area estimates ranging from 63 % (SE = 4 %) to 79 % (SE = 9 %). Stream success rates ranged from 69 % (SE = 8 %) to 83 % (SE = 15 %) when looking at counts, and 67 %

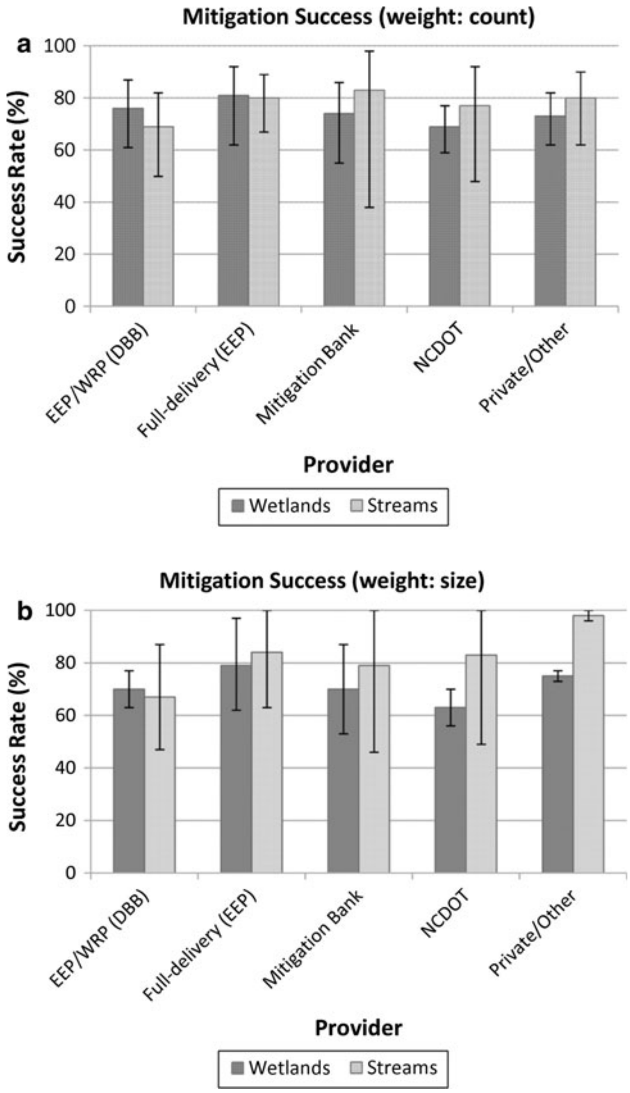

Fig. 2 Success rates based on component counts and weighted by wetland area and stream length for the mitigation provider categories; error bars represent 95 % confidence limits

(SE = 10 %) to 98 % (SE = 1 %) of the total length was successful. Results for the complete set of evaluated components, including preservation components, are displayed in Fig. 2. Preservation-excluded wetland success rates ranged from 59 % (SE = 5 %) to 78 % (SE = 8 %) when component counts were used, and from 53 % (SE = 3 %) to 76 % (SE = 9 %) when using component size. Preservation-excluded stream success rates ranged from 67 % (SE = 9 %) to 83 % (SE = 15 %) when weighted by component counts, and from 63 % (SE = 11 %) to 86 % (SE = 8 %) when using component size.

When comparing component success counts of the mitigation provider categories, statistically significant differences between providers were not found (Fig. 2). However when the proportion of successful size was considered, Private/Other permittee-responsible mitigation was found to have greater success rates (75 %, SE = 1 % and 71 %, SE = 3 %) than NCDOT off-site mitigation (63 %, SE = 4 % and 53 %, SE = 3 %) for wetlands only (with and without preservation components, respectively) and EEP/WRP design-bid-build mitigation for streams with preservation component inclusion only (67 %, SE = 10 %) compared to 98 % (SE = 1 %) for Private/Other.

Physiographic Region

Based on component counts, wetland mitigation showed weighted success rates of 81 % (SE = 14 %), 77 % (SE = 7 %), and 73 % (SE = 3 %) in the Mountains, Piedmont, and Coastal Plain, respectively. Statistical testing indicated that these rates were not statistically significantly different from one another. When success ratings factored in size, the values were 53 % (SE = 4 %), 81 % (SE = 7 %), and 70 % (SE = 3 %), respectively, resulting in a statistically significant difference at a 95 % confidence level between the Mountains and the other two regions (Fig. 3). Results were similar when preservation components were excluded from the analysis. Based on component counts, non-preservation wetland mitigation showed weighted success rates of 77 % (SE = 14 %), 74 % (SE = 7 %), and 68 % (SE = 4 %) in the Mountains, Piedmont, and Coastal Plain, respectively. The rates were not statistically significantly different from one another. When success ratings factored in size, success rates demonstrated a statistically significant difference between the Mountains (52 %, SE = 2 %) and the other two regions: 76 % (SE = 9 %) in the Piedmont and 64 % (SE = 5 %) in the Coastal Plain.

Stream results were similar to wetland results since statistically significant differences were not found based on component counts (81 %, SE = 8 %; 70 %, SE = 6 %; and 89 %, SE = 7 % in the Mountains, Piedmont, and Coastal Plain, respectively), but were found when the proportion of successful stream mitigation length was considered. Stream projects in the Piedmont physiographic region exhibited a statistically significant lower success rate (69 %, SE = 8 %) than the other two regions (98 %, SE = 1 % and 95 %, SE = 3 % in the Mountain and Coastal Plain regions, respectively) (Fig. 3). When preservation components were excluded from consideration, stream success results were nearly the same when looking at counts: 80 % (SE = 10 %), 69 % (SE = 6 %), and 88 % (SE = 7 %) in the Mountains, Piedmont, and Coastal Plain, respectively. When measuring success in terms of stream length, the results displayed a similar, but less dramatic trend. Size-weighted success rates were 86 %

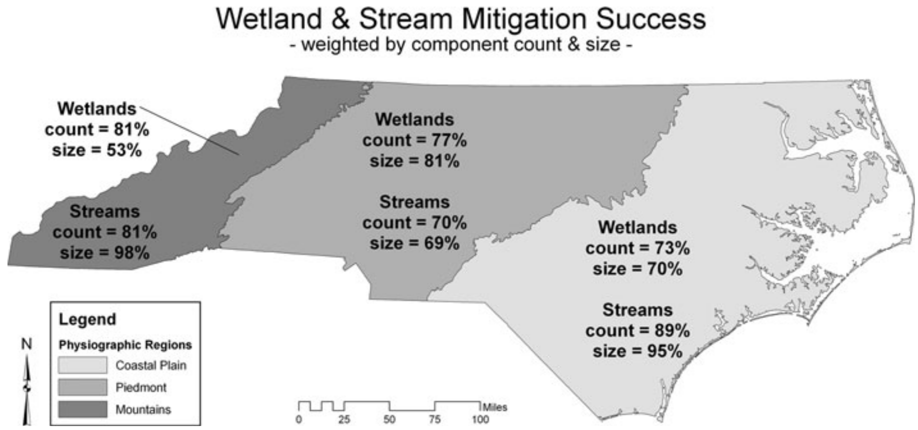

Fig. 3 Wetland and stream mitigation success rates in the physiographic regions based on all data (including preservation), weighted by both component count and size

(SE = 10 %), 67 % (SE = 8 %), and 94 % (SE = 4 %) in the Mountains, Piedmont, and Coastal Plain, respectively, and only the Coastal Plain and Piedmont regions were found to have a statistically significant difference in success rates.

Mitigation Activity

Preservation was the most successful mitigation activity for both wetlands and streams, with success rates of 97 % (SE = 3 %) and 100 %, respectively. No statistically significant difference was observed between the success rates of wetland restoration, creation and enhancement at 68 % (SE = 4 %), 71 % (SE = 6 %), and 75 % (SE = 7 %), respectively (Fig. 4). Creation accounted for the smallest part (2 %) of the mitigation area in the sample, restoration accounted for 73 %, and enhancement made up the remaining 25 % of evaluated non-preservation wetland mitigation area.

The stream restoration success rate (69 %, SE = 5 % based on component count or 72 %, SE = 7 % when the proportion of successful length was considered) was statistically significantly lower ($p = 0.0002$) than that for stream enhancement (92 %, SE = 5 % based on count; 99 %, SE = 1 % based on length) as well as preservation (100 % in both cases) (Fig. 4). Stream creation (i.e., relocation) appeared to have a high rate of success (100 %); however, the sample size of these 2 components was too small to deliver conclusive results.

Component Age

Stream components were grouped into three age classes based on their monitoring start date: pre-2003, 2003–2005, and 2006–2008. Success rates ranged from 66 % (SE = 9 %) to 89 % (SE = 8 %) across all age groups and no statistically significant differences were found between them. The ages of wetland components spanned a larger

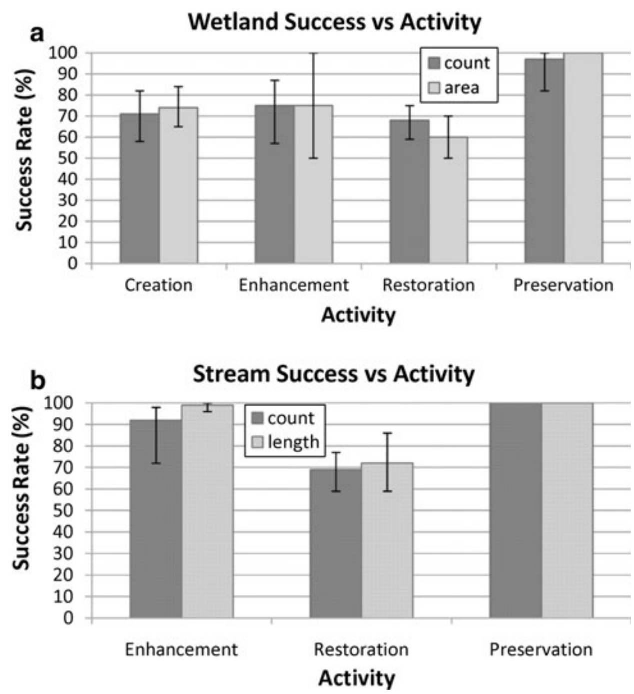

Fig. 4 Mitigation activity success rates, based on component counts and size; error bars represent 95 % confidence limits

range, and were grouped into four age classes: pre-1998, 1998–2001, 2002–2005, and 2006–2009. While component count analyses did not show a relationship between project age and success, consideration of successful wetland area revealed that wetlands first monitored prior to 2002 were rated as more successful than newer wetlands, especially those established during the most recent timeframe of 2006–2009. Preservation-included results were 78 % (SE = 3 %) for pre-1998 projects, 81 % (SE = 3 %) for 1998–2001 projects, and 63 % (SE = 4 %) for 2006–2009 projects. Preservation-excluded success rates were 76 % (SE = 1 %) for pre-1998 projects, 81 % (SE = 3 %) for 1998–2001 projects, 58 % (SE = 5 %) for 2002–2005 projects, and 50 % (SE = 1 %) for 2006–2009 projects (Fig. 5).

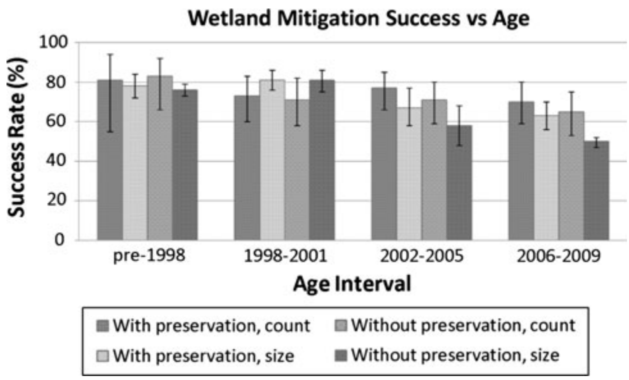

Fig. 5 Wetland component success rate by age group, with and without inclusion of preservation components, weighted by count and size; error bars represent 95 % confidence limits

Project Size

Stream components were grouped into four size classes based on total stream length of the mitigation project in which they existed: <762 meters, 762–1524 meters, 1525–3048 meters, and >3048 meters of stream mitigation. Wetland components were similarly grouped into three project size classes of <8.1, 8.1–81, and >81 hectares of wetland mitigation. No statistically significant differences in success rates were found for project size for either resource type.

Ecosystem Type (Wetlands)

Component wetland ecosystem types were analyzed to explore differences in the mitigation success rates of Coastal, Riparian, and Non-riparian wetlands. No statistically significant differences in success rates were found.

Discussion

Data Availability

A self-critique, as well as an external criticism (BenDor and others 2009; BenDor and Doyle 2010), of the regulatory agencies overseeing wetland and stream mitigation in NC involves the absence of an easily-accessible, complete listing of all existing mitigation projects in NC with up-to-date information regarding project location, quality, compliance and credit yield.

The USACE, Wilmington District has made great strides in this direction with the recent implementation of the OMBIL (Operations and Maintenance Business Information Link) Regulatory Module (ORM-2) for cataloging and analyzing information used in regulatory decision-making, including watershed characteristics, jurisdictional determinations, impact permits and mitigation requirements (Stetson and Soderberg 2009). The USACE, Wilmington District has also begun tracking mitigation bank activities (e.g., proposals, credit releases, bank debits) with the Regulatory In lieu fee and Bank Information Tracking System (RIBITS), and has long provided links to mitigation bank information and mapped locations from the mitigation page on its website (http://www.saw.usace.army.mil/Missions/RegulatoryPermitProgram/Mitigation.aspx).

The NCDWQ's BIMS database contains some mitigation-related information, but was not developed to track mitigation data. Developing queries to extract mitigation data has proven to be impossible due to the structure of the database and a lack of staffing and funding resources to implement large-scale changes within it. As part of this study, NCDWQ developed a separate database to catalog and track all NC mitigation projects when the information for projects can be located and entered. The study sample was drawn from this database, which contained an incomplete population of mitigation projects at the time. Populating the database is ongoing, and it has grown substantially since the random sample was selected for this study.

The NC Department of Environment and Natural Resources' non-regulatory mitigation provider, EEP, is continually working toward greater transparency, largely through development of data resources on the agency's website, http://portal.ncdenr.org/web/eep. Additions during the course of this study included a beta-tested version of maps that communicate geographic information about EEP projects and planning areas, and a spreadsheet linking to project documents (e.g., monitoring reports, mitigation plans).

Preservation as Mitigation

Preservation involves the long-term protection of property with high-quality wetlands and streams. However, preservation does not provide added net wetland acreage or stream length to replace functions and values lost through permitted impacts. While preservation does not directly support the goal of "no net loss", preservation is utilized to provide compensatory mitigation, usually in conjunction with other forms of mitigation activities. NC state wetland rules (15A NCAC 2H.0506(h)(6)) require compensatory mitigation for wetlands with a minimum 1:1 replacement of impacted acres through restoration or creation prior to utilizing enhancement or preservation. Current policy does not require this 1:1 replacement for streams; however, EEP utilizes this as a standard practice for stream mitigation.

Only one of the 36 wetland preservation components evaluated was shown to be unsuccessful and another was observed to be unsuccessful during the site visit, but the provider took immediate action to address the issue. Both sites were unsuccessful due to infringement or trespass. All of the seven stream preservation components evaluated were shown to be successful. The high rate of preservation success is attributed to the relatively small risk of failure of these sites. Generally, causes of failure of a preservation site are easement encroachment by adjacent landowners, illegal trespass for recreational purposes (e.g., off-road vehicles) and loss of vegetation due to mowing. On the other hand, if a solid plan for long-term stewardship is properly implemented by an entity capable of addressing such issues promptly, then preservation appears to provide a viable option for protection of existing wetland and stream resources.

Mitigation Activities (Other than Preservation)

Data analysis was expected to show higher success rates for wetlands than streams because of longer experience with wetland mitigation in NC and lower energy of water movement through wetland sites. However, success rates for restoration of the two resource types were similar. Wetland restoration success appears to have improved substantially since the 1995 FHWA and Pfeifer and Kaiser studies. To maximize the likelihood of success, care must be taken to provide an appropriate soil environment with minimal compaction during construction, surface elevation, and water budget for the targeted wetland type. Progress has also been made in some of the areas reported to reduce wetland restoration success in the 1995 studies, especially the use of hydrologic modeling prior to project implementation. In spite of this, wetland components that were rated unsuccessful were usually found to be too dry (i.e., did not achieve the hydroperiod specified in the mitigation plan) or too wet (i.e., long-term inundation was impacting survival of the targeted vegetative community).

A statistically significant difference was not found for wetland mitigation types, but stream enhancement demonstrated greater success than stream restoration. A possible explanation for the higher success rate of stream enhancement over stream restoration is that enhancement involves work on a stream that is generally in a more stable condition. Stream restoration (e.g., construction of a new channel) usually begins with a much more degraded channel, often a result of disturbance both along the proposed restoration reach and in the watershed above the project reach. The designer is required to use reference reach data and mathematical equations which have been developed to predict channel characteristics to design and construct a new channel that will function "naturally" within the existing site and watershed conditions. Errors in the design phase or construction phase, alterations in the watershed above the restoration reach and catastrophic natural events (e.g., excessive rain events or drought) are some of the possible reasons for lack of success of stream restoration projects. Enhancement projects usually involve relatively minor adjustments to stream dimension and profile, can be accomplished with less construction activity in the stream channel or adjacent floodplain than restoration projects, and most often include vegetative restoration and livestock exclusion. However, stream enhancement does not generally result in an increase in stream length while stream restoration usually does. Therefore the reduced success rate with restoration compared to enhancement may be partially offset with a gain in aquatic resources.

Physiographic Regions and Soils

The vast majority of NC wetlands (unimpacted, impacted, and mitigation) are located in the Coastal Plain physiographic region (NCDEM 1996). Of non-preservation wetland mitigation acreage in the random sample, 97 % was located in the Coastal Plain. Average project size in the Coastal Plain was significantly larger than that in other physiographic regions. In terms of wetland mitigation success, Coastal Plain projects appeared especially prone to ponding and long-term inundation issues, which in turn impacted the establishment of woody vegetation. Although hydrologic models can calculate optimal elevations, they cannot predict with absolute certainty the amount of water that will be present on a site after construction. Wetland mitigation projects in this physiographic region may require adjustment of elevation levels during the first years after construction in order to achieve the most favorable hydrologic conditions for wetland development; however, it can be difficult to know when to act to alter site elevations. As vegetation grows and soils loosen over time, a site's hydrology will change accordingly, so it is important to keep a long-term view in mind when considering additional earthwork at a mitigation project. If weather conditions are within normal ranges, but site hydrology is incorrect during the first 2 years, then it is probably time to consider additional grading activity. After that point, vegetation establishment may reach a point at which it is less desirable to disturb the plants than to adjust the hydrology. A benefit of recently extended mitigation monitoring timeframes in NC will be the opportunity to observe hydrology changes, in addition to vegetation growth and survival, over longer periods of time.

Although smaller and less numerous, wetlands in the Mountain physiographic region fill important ecological roles. Many mountain wetlands are unique, smaller systems (e.g., mountain bogs) that provide water quality benefits and ecological diversity to local areas and habitat for wetland-dependent organisms, such as bog turtles

(*Clemmys muhlenbergii*) and mountain pitcher plants (*Sarracenia rubra* ssp. *jonesii*). The sample size for evaluated components in the Mountains was small (one preservation and six non-preservation components). Most of the non-preservation wetland sites involved restoration or creation of small pockets of riparian wetlands that were generally placed in appropriate landscape positions and successfully met regulatory criteria. The one wetland that did not achieve success had become inundated due to beaver activity in the abutting stream, leading to low survival of woody vegetation. This wetland was relatively large in size (8.1 hectares) leading to the large shift in success rate when results were weighted by size. It does not appear that Mountain wetland mitigation is inherently less successful than that in other physiographic regions, and similar issues due to beaver activity were also observed in the Coastal Plain and Piedmont.

Stream mitigation success rates in the Coastal Plain and Mountains were higher than in the Piedmont physiographic region. While restoration success is dependent upon various site condition and design variables, the higher success rate observed in the Coastal Plain is partially attributable to the lower gradient of streams, which results in lower velocity flows and reduced shear stress on stream banks. In the Mountains, the higher success rate is attributed, in part, to the relative stability of materials (i.e., rocks) that make up the surrounding landscape and are appropriate for use in stream restoration projects.

Success rates for stream mitigation were lowest in the Piedmont, likely due in large part to issues stemming from the clayey, erodible soil types most frequently encountered. Establishing vegetation in these soils can be extremely challenging, especially when organic content is low and soils are compacted prior to or during construction. Piedmont stream projects often experience difficulties involving erosion at stress points, such as around structures and along the outside edges of meander bends. During this study, these issues were particularly evident on sites where a new stream channel was excavated and the channel and floodplain were constructed in subsoil. Once construction was completed and the site was exposed to hot, dry summer months, the ground surface was compacted, infiltration was low, and survival and growth of planted trees were inhibited. The same soils issues impacted some Piedmont wetland restoration components which demonstrated unsuccessful hydrology due to water either running off or perching on top of hardened, high-clay soils.

The lower rate of mitigation success in this region is especially troubling because several of the most rapidly developing urban areas in NC (e.g., Charlotte, Greensboro, Raleigh) are located in the Piedmont. Offsetting impacts related to urbanization requires successful mitigation projects, so it is important that mitigation attempted in the Piedmont focus on reducing soil compaction and taking other steps to facilitate both hydrologic and vegetative success. Use of soil amendments and inclusion of some larger trees in planting plans has been successful in some cases. The challenges to mitigation success in the Piedmont warrant further experimentation with these and other methods that could boost the establishment of mitigation projects, and continued investigation into appropriate design techniques for stream restoration in this physiographic region.

Vegetation and Hydrology

A review of wetland components rated unsuccessful during the study showed that falling short of vegetation density and/or diversity success criteria was the most frequent cause of failure, followed closely by hydrology. Most unsuccessful wetlands failed to meet multiple success criteria. The period of drought during the early part of the study inhibited the hydrologic success of many projects, and newly planted vegetation could not become established. However, a nearly equal number of wetlands held too much water, and tree survival was impacted by long-term inundation due to beavers, soil compaction and/or perched water tables. Further experimentation and pilot long-term planting studies, especially in combination with soil amendments, fertilizers, and herbaceous and woody vegetation management techniques are warranted. However, these studies and practices would increase the cost of mitigation project construction and time commitment by mitigation providers.

A less-frequent cause of vegetation failure was competition by aggressive and/or invasive vegetation in all strata (e.g., *Typha* spp., *Ligustrum sinense*, *Lonicera japonica*, *Liquidambar styraciflua*). Very few mitigation plans included success criteria related to invasive vegetation, although many discussed eradication or reduction of these species as project goals. Control of invasive vegetation can be difficult immediately post-construction as these species take advantage of disturbed conditions and bare soils. Especially when present in surrounding areas, removal of invasive vegetation may need to occur often during the early stages of vegetation growth to ensure that it does not threaten the long-term vegetative community composition at the mitigation site.

Mitigation Age

When weighted by size, wetland mitigation projects demonstrated decreasing success rates over time, with older mitigation sites appearing more successful than newly constructed projects. There are several possible reasons for this trend. Mitigation success criteria have continued to become more rigorous, specific, and measurable over time. Older projects, especially those in the pre-2002 age groups, generally had less stringent regulatory requirements than those permitted and constructed in the last several years. Recently constructed mitigation projects require time to allow for vegetation establishment and development of surface water and groundwater connections through, and interactions with, soil. However, the most likely cause was the weather during the evaluation phase of this study: a record-setting drought for the southeastern United States, including the entire state of NC (NCDWR 2007). Many wetland mitigation projects constructed during or just prior to this time period did not achieve compliance with regulatory success criteria approved in their mitigation plans. Older, established mitigation wetlands probably show greater resilience to drought due to deeper, more strongly rooted vegetation and more developed soil profiles which allow for more storage of groundwater.

After issuance of Compensatory Mitigation for Losses of Aquatic Resources: Final Rule (USACE and USEPA 2008), monitoring was extended to 7 years for forested wetland mitigation ecosystems in NC. The trend observed during this study supports that extension, and indicates that a timeframe greater than the original 5-year monitoring period may be necessary to fully apprise the success of a mitigation project and its long-term likelihood to perform the functions that will offset permitted losses of aquatic resources.

Stream mitigation success criteria have also become more fully developed over time, especially since the release of the Stream Mitigation Guidelines (USACE and others 2003). Projects constructed since that time were more likely to be evaluated using stricter standards than the pre-2003 projects. To an even greater degree than wetland mitigation, stream mitigation (especially restoration) projects take time to develop, depending largely on the establishment of woody riparian vegetation to provide stability to streambanks. Younger stream reaches without mature woody vegetation are susceptible to instability due to flashy flows, and newly planted vegetation is more susceptible to herbivory and drought impacts. Consideration of longer stream monitoring periods (e.g., 7–10 years) offset with less intensive monitoring and more frequent visual observation may be warranted to identify problems in the early stages of site development.

A recent study of riparian buffer age and its effects on stream aquatic function supports the hypothesis that restoration of a functional stream corridor may require significantly longer time periods to display restored ecological functions and values. Orzetti and others (2010) collected data on water quality, habitat, and macroinvertebrates from 30 Piedmont streams with buffers ranging from zero to greater than 50 years of age in the Chesapeake Bay watershed. Overall, buffer age was positively related to improved stream habitat, water quality, and a suite of macroinvertebrate metrics. The data collected showed marked improvements occurring within 5–10 years post-restoration, with conditions approaching those of streams with long established buffers within 10–15 years post-restoration. Few stream restoration projects exceeding 10 years old are present in North Carolina. Myriad opportunities to test the hypothesis that functional uplift at stream restoration sites cannot be realized until 10–15 years following restoration will be available as projects completed since 1999 mature.

Success Criteria

Post-restoration monitoring is utilized to demonstrate that a mitigation project is on a trajectory toward developing the environmental characteristics of the targeted resource type based on reference ecosystems. Restored wetlands and streams on subsoils with planted bare-root seedlings will begin developing the functions (e.g., nutrient transformation, shading) of mature vegetative communities and hydric or riparian soils, but full functionality is not generally expected to be achieved in 5–7 years. Success criteria (primarily channel stability and riparian zone vegetation reestablishment for streams, hydroperiod, and vegetation survival for wetlands) are surrogates for improvement of aquatic function. Direct measurements of aquatic function and ecological improvement can be difficult to accomplish and expensive to conduct. Results of such direct measurements (e.g., macrobenthic community monitoring) are greatly affected by climatic variation, especially in smaller streams that are most often the target of stream mitigation projects. Further, the monitoring timeline makes some analyses (e.g., aquatic chemistry) less meaningful than they would be for longer-term monitoring.

Success criteria used for this study were based on the criteria in the original restoration plans for each project. As discussed earlier, regulatory success criteria have changed over time, and therefore varied from project to project in the random sample. The present-day environmental conditions of components within each mitigation project were compared to the success criteria set for that specific project at the time of approval or construction.

The NC Interagency Review Team (IRT), which consists of federal and state agencies and is tasked with overseeing compensatory mitigation in NC, has ongoing discussions with the mitigation community about how to better monitor functional uplift on mitigation sites. Long-term (e.g., 10-year) intensive monitoring techniques such as collection of numerous water quality samples, placement of on-site monitoring devices and rigorous field evaluation techniques over time could be used to document improvements in water quality or aquatic function. However, the limitations of regulatory agency staff oversight, economics and political pressure preclude academic-level evaluations, and the goal for the IRT is to develop an improved set of metrics which can be easily documented and act as indicators that a mitigation site is on a trajectory toward a higher level of aquatic function.

The success ratings described the state of the project at the time of evaluation, but did not necessarily predict the future quality of the mitigation. While most projects with successful components were expected to continue to meet approved success criteria, an unsuccessful rating did not necessarily mean that a component would ultimately fail to provide successful wetland area or stream length. In many cases as a result of this research, remedial activities were implemented (e.g., replanting, repair of structures), resulting in a site being considered successful at project closeout (i.e., release from further required monitoring). Where portions of sites continue to fail to meet success criteria, credit adjustments are made by USACE and DWQ when such projects close out after the monitoring period ends.

Mitigation Provider

The relative success of area-weighted Private/Other permittee-responsible wetland mitigation was due, at least in part, to the tendency of permittees to attempt more on-site wetland mitigation area than required by the 401 Certification Conditions. For example, as part of the permitting for a project on Pope Air Force Base, mitigation requirements included 0.81 hectare of on-site wetland creation. The area amenable to wetland creation on the site was larger than the requirement, and 1.12 hectares of wetland creation were attempted. During a 2009 site visit, USACE-Wilmington and NCDWQ staff determined that although a portion (0.15 hectare) of the mitigation area did not meet the approved success criteria, the area that did successfully meet the criteria exceeded the 0.81 hectare amount required by the permit. Therefore, for the purposes of this study, the component was evaluated as successful. In the case of all other provider types, the evaluations considered the entire area of wetland mitigation because each hectare could end up being used to offset wetland impacts elsewhere.

Conclusions

The overall success rate for wetland mitigation in North Carolina found by this study (74 % SE = 3 %) has greatly improved in comparison with studies conducted in the mid-1990s (FHWA 1995; Pfeifer and Kaiser 1995), which estimated success rates at much less than 50 %. These earlier studies highlighted the importance of hydrologic modeling in developing construction plans for wetland mitigation projects. Since that time, use of hydrologic modeling has become standard, and regular application of this practice appears to have increased the frequency at which mitigation projects achieve appropriate hydrology. In spite of this, continued obstacles to wetland mitigation success include post-construction soils and ground surface elevations that hold too much or too little water on the site, thereby inhibiting the establishment of the targeted plant community and ecosystem type.

Overall success of stream projects evaluated during this study was 75 % (SE = 4 %) based on site conditions at the time of on-site evaluations. Rating of a particular stream component as unsuccessful does not mean that the component will ultimately not generate mitigation credit. In many cases, repairs to stream channels, replanting of riparian buffers and/or nuisance exotic vegetation control efforts will put the project back on track to meet regulatory success criteria.

In general, detailed evaluation of mitigation projects or components that are not achieving success criteria should be conducted to address the reasons for lack of success, rather than simply "treating the symptoms" and replanting or repairing problem areas. Identifying causative factors on problem sites is as important as documenting and highlighting successes in furthering the practices used in mitigation activities. Regulatory and non-regulatory agencies comprising the NC IRT are identifying evaluation criteria that can better demonstrate functional uplift of stream and wetland mitigation sites, as required in the federal mitigation rule (USACE and USEPA 2008).

An important significant finding of this study is that the physiographic region in which a project was located had a significant effect on the success of stream restoration. It is likely the lower stream mitigation success rate in the Piedmont is a result of soil characteristics prevalent on Piedmont sites, which appear to have an effect on both channel stability and vegetative success. Mitigation providers for stream projects in the Piedmont need to address potential problems associated with Piedmont soil characteristics such as erodibility, as well as low permeability, infiltration, soil nutrients, and organic matter. Further, the difference in success rates between stream restoration and enhancement indicates that greater emphasis should be placed on developing stream enhancement projects, especially in areas such as the Piedmont, where restoration is a high-risk endeavor.

While efforts continue on several fronts to provide greater transparency and completeness of available data, it is often difficult to readily find information related to aquatic resource impacts and associated mitigation projects in NC. The mitigation community would benefit from a coordinated effort between regulatory and non-regulatory agencies involved in mitigation to develop an easily-accessible data clearinghouse that shows linkages between impact and mitigation sites as well as locations and boundaries, service areas, released and potential credits, plans and other documents, and monitoring data for planned and existing mitigation projects. In addition, this clearinghouse could encourage the continued incorporation of the most recent scientific research into improved mitigation practices.

This study examined mitigation projects at one moment in time, based on the available data and environmental conditions of the projects at that moment. To make the results more meaningful, it would be beneficial to conduct a similar study periodically (e.g., every 5 years) using the most complete inventory of mitigation projects and the most current evaluation techniques available at that time. This repetition would allow for analysis of trends in the quality and compliance of wetland and stream mitigation in NC.

Acknowledgments This work was funded by an EPA Wetland Program Development Grant (WL 9643505-01) issued to the NC Division of Water Quality. The authors would like to thank the following agencies who assisted with site visits: various staff from the NC Ecosystem Enhancement Program, private mitigation providers and their consultants who accompanied us on site visits as well as staff from the US Army Corps of Engineers, US Fish and Wildlife Service, US Environmental Protection Agency, NC Division of Coastal Management and NC Wildlife Resources Commission.

References

(CAMA) NC Coastal Area Management Act. http://dcm2.enr.state.nc.us/rules/cama.htm

(FHWA) Federal Highway Administration, North Carolina Division (April 1995) Process review on: Compensatory wetland mitigation associated with highway construction in North Carolina. Raleigh, NC

(NCDEM) North Carolina Division of Environmental Management (1996) A field guide to North Carolina wetlands. Department of Environment, Health and Natural Resources. Raleigh, NC

(NCDENR) North Carolina Department of Environment and Natural Resources (2001) Internal technical guide for stream work in North Carolina

NC Dredge and Fill Law. http://dcm2.enr.state.nc.us/rules/dredgefill.htm

(NCDWR) North Carolina Division of Water Resources (2007) North Carolina Drought Management Advisory Council activities report, 2007

(NCWFAT) N.C. Wetland Functional Assessment Team (2008) N.C. Wetland Assessment Method (NC WAM) user manual, version 1.0

(USACE, USEPA) U.S. Army Corps of Engineers, U.S. Environmental Protection Agency (2008) 33 CFR 325 and 332, 40 CFR 230. Compensatory mitigation for losses of aquatic resources: Final rule

(USACE) U.S. Army Corps of Engineers (2011) Regional Internet Banking Information Tracking System (RIBITS). http://www.saw.usace.army.mil/Missions/RegulatoryPermitProgram/Mitigation.aspx

(USACE) U.S. Army Corps of Engineers Wilmington District, N.C. Division of Water Quality, U.S. Environmental Protection Agency Region IV, Natural Resources Conservation Service, N.C. Wildlife Resources Commission (2003) Stream mitigation guidelines. Wilmington, NC

Allen AO, Feddema JJ (1996) Wetland loss and substitution by the Section 404 Permit Program in Southern California, USA. Environ Manage 20:263–274

Balzano SA, Ertman SA, Brancheau L, Smejkal W, Greene AS, Kaplan M, Fanz D (2002) Creating indicators of wetland success (quantity and quality): Freshwater wetland mitigation in New Jersey. NJ Department of Environmental Protection, Division of Science, Research and Technology. http://www.state.nj.us/dep/dsr/wetlands/final.pdf

BenDor TK, Doyle MW (2010) Planning for ecosystem service markets. J Am Planning Assoc 76:59–72

BenDor T, Sholtes J, Doyle MW (2009) Landscape characteristics of a stream and wetland mitigation banking program. Ecol Appl 19:2078–2092

Brown SC, Veneman PLM (2001) Effectiveness of compensatory wetland mitigation in Massachusetts, USA. Wetlands 21: 508–518

Cole CA, Shafer D (2002) Section 404 wetland mitigation and permit success criteria in Pennsylvania, USA, 1986–1999. Environ Manage 30:508–515

Cruse VL (1991) An evaluation of the effectiveness of wetland mitigation in Broward County, Florida permitted by the Florida Department of Environmental Regulation. http://images.library.wisc.edu/EcoNatRes/EFacs/Wetlands/Wetlands20/reference/econatres.wetlands20.vcruse.pdf

Fenner T (1991) Cumulative impacts to San Diego County wetlands under federal and state regulatory programs 1985–1989. MA thesis, San Diego State University

Hill T, Kulz E, Munoz B, Dorney J (2011) Compensatory stream and wetland mitigation in North Carolina: an evaluation of regulatory success. NC Division of Water Quality, Raleigh

Hill T, Mueller A, Munoz B, Dorney J (2012) Aquatic resources in NC: an examination of the spatial relationship between approved impacts and compensatory mitigation. NC Division of Water Quality, Raleigh

Holm S (1979) In: Walsh B (ed) (2004) Multiple comparisons: Bonferroni corrections and false discovery rates. http://nitro.biosci.arizona.edu/courses/EEB581-2004/handouts/Multiple.pdf

Hornyak MM, Halvorsen KE (2003) Wetland mitigation compliance in the western Upper Peninsula of Michigan. Environ Manage 32:535–540

Kettlewell CI, Bouchard V, Proej D, Miccacchion M, Mack JJ, Whilet D, Fay L (2008) An assessment of wetland impacts and compensatory mitigation in the Cuyahoga River watershed, Ohio, USA. Wetlands 28:57–67

Kihslinger RL (2008) Success of wetland mitigation projects. Natl Wetl Newslett 30(2):14–16

Lohr SL (2010) Sampling: design and analysis, 2nd edn. Brooks/Cole Publishing Co, Pacific Grove

Matthews JW, Endress AG (2008) Performance criteria, compliance success and vegetation development in compensatory mitigation wetlands. Environ Manage 41:130–141

Morgan KL, Roberts TH (2003) Characterization of wetland mitigation projects in Tennessee, USA. Wetlands 23:65–69

Orzetti LL, Jones RC, Murphy RF (2010) Stream condition in Piedmont streams with restored riparian buffers in the Chesapeake Bay watershed. J Am Water Resour Assoc 46:473–485

Pfeifer CE, Kaiser EJ (1995) An evaluation of wetlands permitting and mitigation practices in North Carolina. University of North Carolina at Chapel Hill, funding from the Water Resources Research Institute, Project 50200

Redmond A (1992) How successful is mitigation? Natl Wetl Newslett 14(1):5–6

Robb JT (2000) Indiana wetland compensatory mitigation: Inventory. Final report, EPA Grant # CD985481-010-0

Robb JT (2002) Assessing wetland compensatory mitigation sites to aid in establishing mitigation ratios. Wetlands 22(2):435–440

Stetson L, Soderberg J (2009) Utilizing new technology and GIS to improve permitting programs. Wetland News, December 2009, Association of State Wetland Managers, Inc.

Sudol MF, Ambrose RF (2002) The US Clean Water Act and habitat replacement: evaluation of mitigation sites in Orange County, California, USA. Environ Manage 30(5):727–734

Turner RE, Redmond AM, Zedler JB (2001) Count it by acre or function: mitigation adds up to net loss of wetlands. Natl Wetl Newslett 23(6):5–16

Yamane T (1967) Statistics: an introductory analysis, 2nd edn. Harper and Row, New York