GEOMORPHOLOGY

ELSEVIER

Geomorphology 31 (1999) 355–371

Use of hydrogeomorphic concepts to design created wetlands in southeastern Virginia

G. Richard Whittecar [a,*], W. Lee Daniels [b]

[a] *Ocean, Earth and Atmospheric Sciences, Old Dominion University, Norfolk, VA 23529-0276, USA*
[b] *Crop and Soil Environmental Sciences, Virginia Tech, Blacksburg, VA, USA*

Received 25 October 1996; received in revised form 4 March 1997; accepted 1 May 1997

Abstract

Mitigation wetlands constructed in southeastern Virginia during the past decade have experienced problems with inappropriate water levels, excessive erosion and sedimentation, low levels of soil organic matter, overly compacted substrates, and sulfidic soils. Most of these problems can be recognized in the future with adequate planning that permits sufficient study of the geomorphic and hydrologic processes active at the mitigation site, and if greater attention is given to the history of geomorphic processes that created natural wetlands in that area. New procedures of assessing wetland functions that use the "hydrogeomorphic" (HGM) classification of wetlands require examination of both surface and subsurface processes. If these HGM concepts are expanded to include geomorphic evolution, they will greatly improve recent practices in the design and construction of mitigation wetlands. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: wetlands; erosion; planning; ecology; coastal areas

1. Introduction

Prior to the 1980s, the extent of wetlands in the United States declined to approximately half of the original total. Draining and filling of wetlands for agriculture, forestry, and construction of roads and housing was ignored or encouraged by government agencies (National Research Council, 1995). In recent decades studies by ecologists, wildlife managers, and many others demonstrated that many wetland functions are critical to the maintenance of healthy environmental conditions in waterways. Federal and state laws that now govern use of most streams and wetlands in the U.S., most notably Section 404 of the 1977 Clear Water Act, reflect a major switch in societal attitude and public policy about the perceived value of wetlands. Scientists in many U.S. federal agencies, including the Army Corps of Engineers (COE), U.S. Fish and Wildlife, the Natural Resources Conservation Service, and the Environmental Protection Agency, study wetland processes and functions and have contributed to the formation of policies, manuals and guidance documents that now direct wetland activities. The COE manages the permitting process based on Section 404 and may allow for the destruction of wetland areas (Kruczynski, 1989). For example, road construction, mining and other activities that impact

* Corresponding author.

0169-555X/99/$ - see front matter
PII: S0169-555X(99)00081-1

large areas often require wetland disturbance that is deemed "unavoidable." Commonly, permits will be granted to disturb a wetland only if a larger area of self-sustaining wetland with the same type of vegetation is created elsewhere. These compensatory mitigation projects can involve formation of new wetlands by grading non-wetland areas down to the level of neighboring wetlands, in effect creating new landscape features.

In this paper, we discuss the results of research on natural and mitigation non-tidal forested wetlands in southeastern Virginia and recommend improvements in the planning and construction processes for future wetlands. Because the geomorphological significance of these suggestions rests upon the evolution of certain threads of thought, we also review past use of some basic geomorphological concepts in wetlands science.

2. Characteristics of some non-tidal wetlands in Virginia

Since 1980, the Virginia Department of Transportation (VDOT) has constructed more than 105 non-tidal mitigation wetlands, the vast majority of which lie in eastern Virginia on the Atlantic Coastal Plain (Fig. 1A). Below, we summarize some of the results of three related research projects done for VDOT to improve the success of mitigation wetland construction. We conducted a state-wide survey to evaluate wetland construction practices, characterized paired sets of natural and mitigation wetlands in rival settings, and evaluated the potential for created wetlands around a highly acidified lake in an upland, pocosin setting (Daniels et al., 1994, 1996; Haering et al., 1994).

2.1. Survey of mitigation wetland sites

The objective of this survey was to document anc evaluate VDOT's non-tidal wetland mitigation prac tices throughout the state in order to develop long term research goals that met the department's need Haering et al. (1994) obtained information from the mitigation management list maintained in VDOT

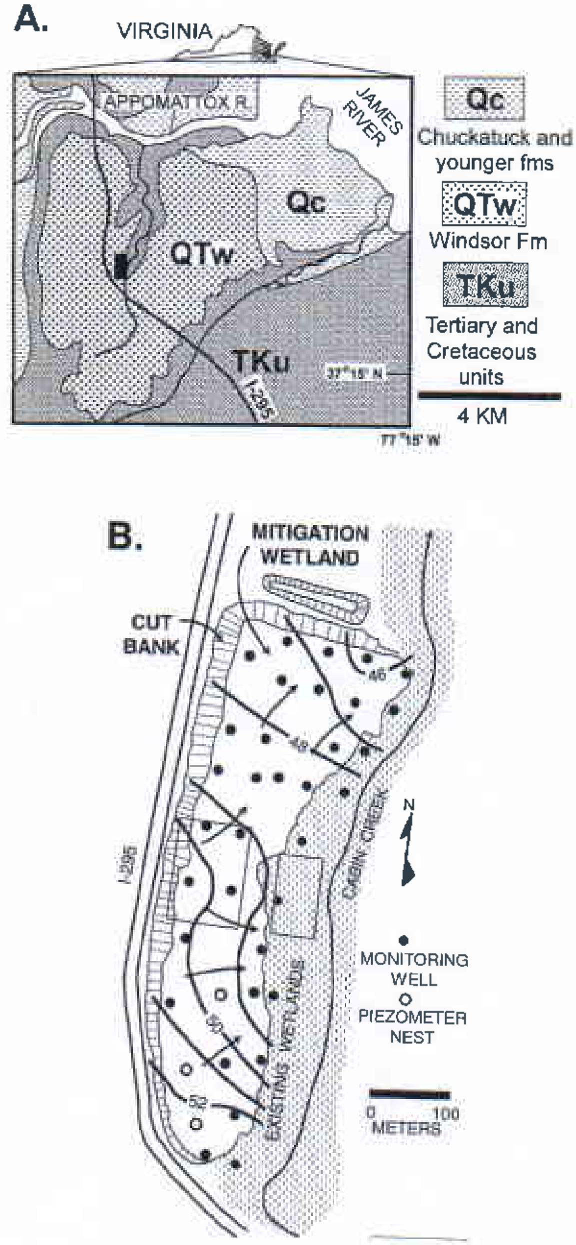


Fig. 1. (A) Location map and geologic setting of Fort Lee, VA, study site. Shading on index map represents the approximate extent of the Atlantic Coastal Plain in Virginia. (B) Map of the Fort Lee, VA, study area. Mitigation wetlands were formed by the excavation of hillslope strata to form a nearly level lowland adjacent to existing wetlands along Cabin Creek. Water table contours (grey; units in feet above local datum) and flowlines are based upon heads in shallow monitoring wells. Open circles denote piezometer nests; heads usually increase with depth at these sites. Open rectangles approximate the outline of surveyed grids used to assess microtopographic variations (see Fig. 2).

entral headquarters, from evaluation forms com-leted by environmental specialists in VDOT district ffices, and by visiting mitigation sites in districts hat manage all but six of VDOT's projects.

Analysis of the mitigation management list indi-ates that almost three-quarters of VDOT's non-tidal nitigation projects were larger than 500,000 ft^2 (4650 n^2, approx.). Only 3% of the projects were larger han 500,000 ft^2 (46,500 m^2, approx.) (Table 1). That list also indicates the wetland type replaced nost commonly was palustrine forested, either alone 54%) or mixed with palustrine emergent systems or palustrine scrub-shrub. Two riverine systems and one palustrine open water system were also the replace-ment goals for mitigation projects. All sites but one were constructed since 1987.

Compilation of information on the 43 evaluation forms returned by VDOT practitioners illuminated how baseline data were collected at pairs of impacted and mitigation sites, particularly the larger ones. Some type of hydrologic evaluation was made at 23 of the 43 impacted sites, mostly by visual evaluation or as part of a stream crossing report. At the mitigation sites, hydrologic data were gathered at 21 sites, largely by visual estimation or ad hoc observations of water levels in adjacent wetlands. No sites were known to have had readings taken at monitoring wells over a full year. Most mitigation sites relied upon two or more sources of water. ''Groundwater'' was the most commonly cited source (28 sites) with others being adjacent streams, swamps, lakes, or beaver ponds. Hydric soils or upland topsoil was added to 26 mitigation sites. Surfaces were rough-graded with a bulldozer, whether or not hydric soil was applied, but only five sites were disked or plowed to prepare a suitable seedbed.

Table 1
Characteristics of mitigation wetland projects of the VDOT

Project sizes	
> 500,000 ft^2 (> 4645 m^2)	3%
100,000–500,000 ft^2 (9290–4645 m^2)	12%
50,000–100,000 ft^2 (4645–9290 m^2)	13%
10,000–50,000 ft^2 (929–4645 m^2)	31%
5000–10,000 ft^2 (465–929 m^2)	13%
1000–5000 ft^2 (93–465 m^2)	18%
< 1000 ft^2 (< 93 m^2)	10%
Wetland type to be replaced	
(1) Palustrine forested	54%
(2) Palustrine forested and emergent, mixed	17%
(3) Palustrine emergent	10%
(4) Scrub-shrub mixed with 1–3	10%
(5) Riverine	3%
(6) ''Palustrine''	5%
(7) Palustrine open water	1%

After discussions with environmental specialists during visits to mitigation wetland sites, Haering et al. (1994) identified several important issues and questions related to current mitigation practices. Two of these are relevant to this paper.

2.1.1. *The degree of wetness desirable for long-term success is difficult to determine, to develop, and to maintain*

Many mitigation sites constructed by VDOT in eastern Virginia are ''too wet'' (21%) or ''too dry'' (21%), usually because of conservative water balance planning or insufficient information about potential sources of water. In particular, ground-water conditions are too poorly understood at most sites, especially the larger ones. Many authors report that establishing the proper hydrology is a major recurring problem in created wetlands, particularly those dominated by ground-water (e.g., Hollands, 1987; Pierce, 1993; Garbisch, 1994). Successful prediction of hydrologic conditions and processes at a newly created wetland landscape is always complex because of the large number of variables involved, some of which are time-consuming and expensive to evaluate. Unforeseeable complications, changing site conditions, economic and regulatory pressures, decreased funding and staffing in some agencies, and the lack of basic research into the best methods to use in evaluating wetland functions all combine to limit the development of a successful mature mitigation site. For example, mitigation sites may become drier with time because of the expected increase in evapotranspiration at a forested wetland due to tree growth and associated closure of the herbaceous understory canopy. One solution frequently mandated is to make the site wetter than a comparable natural forested wetland. However, typical forested wetland vegetation will not survive under permanently flooded conditions. It is therefore possible that vegetation in the new wetland will be significantly different than that in the one originally impacted. In order to ensure that created wetland achieve the goals set for them, both the owner and the regulatory agencies may need to commit to decades of hydrological and ecological monitoring and must have the flexibility designed into the site to adjust the hydrology if necessary.

2.1.2. Steeply sloping cut banks surround many mitigation sites

Long cut-banks at 4:1 and 5:1 slopes 5 m or more high form the margins of many mitigation wetlands. These wetland sites usually experience excessive ponding during wet periods, and account for the high number of sites (43%) that reported problems with erosion and sedimentation. Ecological transition zones are not built into these sites because regulatory agencies give no mitigation credit for transitional area. Combined with the need to minimize the disturbance footprint and land acquisition costs, this policy results in some wetland mitigation sites that more resemble bathtubs than natural upland/transitional/wetland landscapes. A change in policy to permit or require more gently sloping transitional areas would help to solve these problems.

2.2. Case study: riverine wetlands

From the statewide survey of VDOT mitigation wetlands, Daniels et al. (1996) selected five pairs of natural-and-mitigation wetlands for intensive monitoring. The initial goal of this on-going research was to document differences in critical topographic, soil and hydrologic properties between wetlands; after a few more years of sampling we hope to develop an estimate of the initial rates of change of properties in the created wetlands.

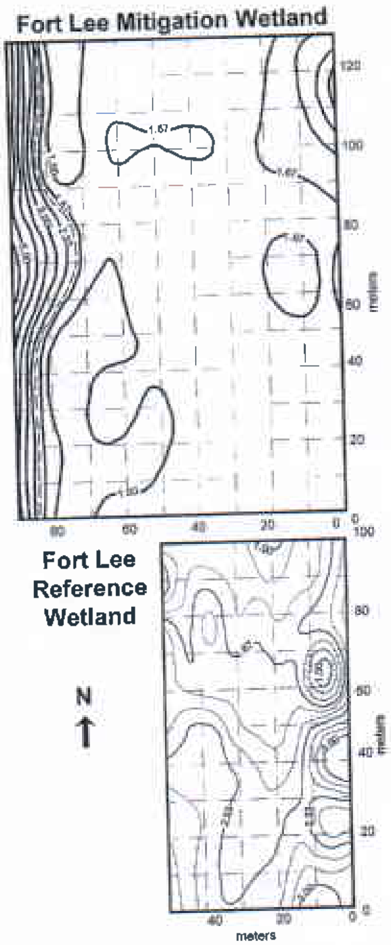
The pairs selected all consisted of reasonably comparable, adjacent wetlands of at least one acre (4050 m^2, approx.) and represented a variety of ages and hydrologic settings. At each reference and mitigation wetland, relative elevations were measured on a grid spaced at 10 m centers and contoured. Soils were collected at three locations chosen at random to represent high, median and low elevations within the wetland. Samples were collected at depths of 5–15, 40–50 and 90–100 cm. Three samples were collected from each depth and mixed to form a composite sample. Soils were analyzed for nutrient status, pH, organic carbon content, DCB extractable Fe and Mn, and particle size distribution. At selected sites, soil profiles were observed from auger cuttings for detailed description and characterization of soil morphology. Special emphasis was placed on rooting depth and distribution, redoximorphic features, and restrictive layers. Numerous shallow groundwater monitoring wells were constructed across each wetland. Most wells were approximately 1 m long with continuous screens and sand filter packs. At a few locations where upwelling occurred, monitoring wells were placed by pairs of peizometers approximately 0.3 and 1.0 m long with screens less than 10 cm long.

The five reference wetlands studied were either forested or emergent and were located along streams and ponds in the Piedmont or Coastal Plain with a variety of energy settings. Because the characteristics of the Fort Lee site illustrate many of the situations and problems common to the five sites studied, we describe it in detail below.

The reference forested wetland lies on the floodplain between the mitigation wetland and Cabin Creek, a second-order stream that occupies a broad valley carved into the Coastal Plain near Hopewell, VA (Fig. 1B). Beneath the valley sides lie Plio-Pleistocene estuarine-fill deposits including the Quaternary–Tertiary Windsor formation and Cretaceous fluvial and marine sediments (Mixon et al., 1989). The mitigation site was formed by excavating a steep-sided basin in the hillside adjacent to the floodplain and Interstate 295. Hydric soils were not returned to the site. The site was seeded in tall fescue.

Differences in elevations between the highest and lowest points in the wetland and in the degree of micro-relief are greater in the reference wetland than in the mitigation wetland (Fig. 2). Relatively flat surfaces cut by heavy machinery dominated the constructed sites. As at each of the five VDOT sites examined, the mitigation sites have much less micro-site variability for plant communities than do natural wetlands.

Soil profiles in the reference sites were poorly developed and often contained buried A horizons typical for floodplain pedons (Table 2). Low chroma A horizons usually had many and common roots to over a meter depth. Soils in the mitigation sites were



ig. 2. Microtopography of portions of the mitigation wetland and ie reference wetland at the Fort Lee, VA, site. Contours in meters bove arbitrary datum; contour interval 0.67 m. Supplemental ontours (grey) were used where wetland surfaces with gentle lopes were notably non-planar. Elevations surveyed on grid with 0 m centers. Outline of grid location shown in Fig. 1. Dashed ine marks approximate limit of wetland along western side.

Entisols with A–C horizons and very few roots; oxidized rhizospheres were the only active redoximorphic features observed.

As at each of the five mitigation wetlands studied, soils at the Fort Lee site were considerably more compacted with higher bulk densities than soils in companion reference wetlands. Excavation here exposed abundant quantities of sulfidic soil materials in the cut-bank above the wetland and in the fills in the road median draining into the site. Once oxidized, the materials become highly acidic and generate metalliferous and toxic leachate which can kill vegetation near seeps. The banks are being treated with high liming rates but will pose a continuing threat to water quality.

Average organic carbon content in the reference site soils was markedly higher at all levels sampled than in the mitigation site soils (Table 3). The TKN values were notably higher in the near surface samples of the reference site soils. The pH was on average higher in the mitigation site, with the upper materials having the lower values. The samples collected in the mitigation site were away from any influence of the acid sulfate leaching so the TKN and pH values differences may be a function of the organic matter contents.

Ground-water levels across the Fort Lee mitigation site decline gently towards the north and the river from a high in the southwest (Fig. 1). Three pairs of piezometers installed in the southwestern corner of the mitigation site indicate heads increase there with depth; the piezometers replaced monitoring wells that commonly showed very high heads. Although upwelling has been documented at this site only in this portion of the wetland, this phenomenon is a common occurrence near steep embankments in Coastal Plain valley-bottom wetlands.

Mitigation site soils have profoundly different physical and chemical properties than the natural wetland soils, an inevitable result of their youth and the construction practices employed at Fort Lee and other VDOT projects. The high bulk density and the low organic matter levels pose the greatest problems for the success of wetland vegetation plantings and the establishment of low redox conditions necessary for wetland microbial activity.

2.3. Case study: pocosin wetland

We were asked to perform a site evaluation study of an acidified gravel pit lake in Hampton, VA (Fig. 3) (Daniels et al., 1994). The site was excavated and abandoned in the 1970s when Interstate 64 was constructed, and now contains two lakes. The smaller lake is only slightly acidic ($pH = 5.8$) while the larger lake is markedly acidic ($pH < 3.7$), metallifer-

Table 2
Soil morphology in mitigation and reference wetlands at Fort Lee, VA, study area

Horizon	Depth (cm)	Color	Texture roots	Notes
A1	0–10	10YR3/2	loam	many fine and medium
A2	10–30	10YR4/1	loam	common fine and medium
AC	130–140	10YR4/1	loam	few fine and medium
AC	240–260	10YR5/2	sandy loam	few fine and medium
CA	60–80	2.5Y5/2	sandy loam	none
C	80–110 +	10YR8/1	v. gravelly coarse sand	none
Mitigation wetland				
Ap	1–13	10YR4/4	loam	many fine, few medium
C1	13–41	7.5YR5/6	sandy clay loam	few fine structureless, massive
C2	41–64	7.5YR5/6	sandy clay loam	few fine structureless, massive
C3	64–80 +	7.5YR5/6	sandy clay loam	few fine structureless, massive

ous, and virtually barren of life. VDOT believed some uplands and transitional areas surrounding the larger lake might be converted to mitigation wetlands if they were regraded to slope more gently into the lake. Additional mitigation wetland area might come from filling the acidified lake. We had four research objectives at this site: (1) to map and characterize the natural soils and disturbed sediments; (2) to characterize the acid-forming potential of sulfidic materials surrounding the larger lake and predict their response to liming, flooding, and regrading; (3) to monitor water table fluctuations and begin a long-term hydrologic evaluation; and (4) to develop strategies for creating appropriate hydric soil conditions to support several different types of non-tidal wetland vegetation communities.

Table 3
Soil chemical analyses for Fort Lee study area. OC = combustion method; N = Total Kjeldalh method

Depth (cm)	Organic carbon		Nitrogen		pH	
	Range (%)	Mean (%)	Range	Mean	Range	Mean
Reference wetland (n = 3)						
5–15	1.9–4.2	2.9	0.14–0.21	0.18	4.3–5.2	4.8
40–50	0.1–1.6	0.2	0.03–0.12	0.08	4.5–5.5	4.9
90–100	< 0.1–0.4	0.2	0.02–0.06	0.05	4.9–5.8	5.3
Mitigation wetland (n = 3)						
5–15	0.5–1.1	0.8	0.05–0.08	0.07	5.0–5.5	5.3
40–50	< 0.1–0.3	0.1	0.02–0.06	0.04	5.0–5.7	5.3
90–100	< 0.1–0.2	0.1	0.02–0.06	0.04	5.0–5.7	5.4

The terraced surface of the York–James Peninsula consists of a series of Pleistocene marine surfaces and intervening scarps formed by several transgressions–regressions (Peebles et al., 1984; Johnson et al., 1987; Mixon et al., 1989). Significant relief exists near large streams and near modern and relict estuaries, especially on relatively old terrace surfaces. The study site lies on a relatively young terrace surface with little dissection. A forested wetland once covered much of this surface; native Americans called these areas ''pocosins'' (swamps-on-a-hill) (Daniel, 1981). Many large natural swales through these swamps now contain steep-sided

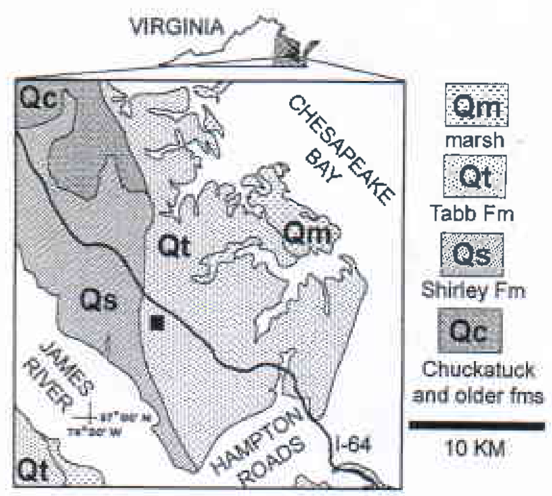


Fig. 3. Location map and geologic setting of Hampton, VA, study site. Shading on index map represents the approximate extent of the Atlantic Coastal Plain in Virginia.