

ANNOTATED BIBLIOGRAPHY

COASTAL PRAIRIE FRESHWATER WETLANDS and WETLAND FUNCTIONAL ASSESSMENT

Freshwater Wetland Functional Assessment Study Contract No. 582-7-77820



Photo courtesy of Marty Underwood

October 2007

An ANNOTATED BIBLIOGRAPHY OF
COASTAL PRAIRIES FRESHWATER WETLANDS
and
WETLAND FUNCTIONAL ASSESSMENT

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ANNOTATED BIBLIOGRAPHY

COASTAL PRAIRIES FRESHWATER WETLANDS

Grace, J. B., L. Allain, and C. Allen. 2000. Factors associated with plant species richness in a coastal tallgrass prairie. *Journal of Vegetation Science* 11: 443-452.

This study evaluates species richness correlates using the data generated from 107 plots in a coastal tallgrass prairie site in Louisiana. Structural equation modelling was used to examine the relationship between site variables and species richness. Estimates of site variables included micro-elevation, above-ground biomass, soil characteristics, evidence of recent disturbance, and light penetration. Species richness was primarily correlated with soil organic matter and elevation.

Grace, J. B., L. Allain, and C. Allen. 2000. Vegetation associations in a rare community type – coastal tallgrass prairie. *Plant Ecology* 147: 105-115.

This paper examined plant species, elevation, soil, disturbance, above-ground biomass, and light penetration at 107 plots in a coastal tallgrass prairie site in Louisiana. Coastal prairie extends for more than 800 km from south-central Louisiana to south Texas and is bordered on the south by coastal wetlands. Very few studies have characterized the coastal prairie community and approximately 99% of the original grassland community has been lost to agricultural and urban development. Elevation and variables associated with soil organic content were found to be best correlated to species composition. Elevation is, therefore, an important consideration for conservation and restoration efforts.

Grace, J. B., L. K. Allain, H. Q. Baldwin, A. G. Billock, W. R. Eddleman, A. M. Given, C. W. Jeske, and R. Moss. 2005. Effects of prescribed fire in the coastal prairies of Texas. USGS Open file report 2005-1287.

This report documents the effects of experimental fires on the flora and fauna of selected sites within the Texas mid-coast National Wildlife Refuge System, including many sites in Brazoria, Big Boggy, and San Bernard National Wildlife Refuges. The report focuses on how fire functioned historically to maintain dominance of grasses in the ecosystem and how lack of fire promotes spread of the native shrub *Baccharis hamifolia* and the exotic Chinese tallow. They also assess the effects of fire on selected fauna (prairie grassland birds and rails). There are thorough descriptions of the present flora of coastal prairie grasslands as well as historical descriptions of the system, which lacked *Baccharis* but had abundant grasses and canes.

Gutenspergen, G. R. and B. A. Vairin. 1998. Vulnerability of coastal wetlands in southeastern United States: Climate change research results, 1992-1997. USGS/BRD/BSR 1998-0002. 101 pp.

The USGS National Wetlands Research Center and several Universities attempt to describe the current state and vulnerability of coastal wetland ecosystems and develop an understanding of the processes that underlie change in response to climate change. They focus on species, community and landscape-level processes related to hydroperiod, sea level rise, subsidence, and disturbance events. The report focuses on submersed aquatic vegetation ecosystems (both salt and freshwater) and forested wetlands. Sea level rise has been about 1 – 2 mm per year in the past couple of centuries, but is projected to increase by a factor of 2 to 3. It is doubtful whether sediment accretion rates can keep pace with sea level rise. The potential inundation of these coastal marshes will be exacerbated by land subsidence. In freshwater submersed aquatic ecosystems, it was found that increased concentrations of dissolved carbon dioxide favored phytoplankton over macrophytes, caused increases in below-ground versus above-ground biomass, and the authors concluded that species that are strong competitors would dominate. One study site was located in Galveston Bay. Although the report contains excellent information, much is site specific and probably should not be extrapolated to CPFWs in the Galveston Bay area.

Jacob, J. S. and R. Lopez. 2005. Freshwater, non-tidal wetland loss, lower Galveston Bay watershed 1992-2002: A rapid assessment method using GIS and aerial photography. Texas Coastal Watershed Program, GBEP 582-3-53336.

This report concludes that 3.1% of natural freshwater wetlands in the Galveston Bay watershed disappeared between 1992 and 2002, with the highest loss (13%) occurring in Harris County. Similar rapid losses due to urbanization are projected for adjacent Ft. Bend, Galveston, and Brazoria Counties. The authors state that NWI maps are the only regional maps showing wetlands, but that due to scale issues, they have considerable error (as much as 30-70%) and consistently underestimate the true amount of freshwater wetlands. Comparing two NWIs to determine wetland losses cannot be valid because these high error levels preclude quantitative comparisons. On the other hand, NWIs rarely misidentify wetlands (i.e. few false positives). However, as no other mapped wetland resources exist, the authors overlaid the 1992 NWI maps with 2002 NWI maps to assess wetland losses. The category of land use to which the wetland was converted was included in the analyses. Several tables and figures delineate wetland losses and conversion by Cowardin system-class and by county. Considerable detail is provided regarding the approach and data utilized in this study.

Lopez, R. D. 2004. A landscape ecology approach to identifying ecological vulnerability in geographically isolated wetlands. Poster presented at “Monitoring Science and Technology Symposium”, Denver, CO, September 20-24th, 2004. Online abstract at USEPA EIMS Metadata Report – Document ID 86038.

This poster shows ongoing research that includes sites along the Texas coast. The work is being done by U.S. EPA’s Office of Research and Development in order to assist regulatory decision making by assessing the potential impact of SWANCC on “isolated” wetlands. The researchers combined remote sensing with a landscape approach to assess the potential for hydrologic connectivity and disturbance of geographically isolated wetlands in selected regions of the US. The initial study areas are in the Midwest, Texas coastal, and California coastal regions. The study approach integrates remote-sensing, GIS, existing field data, and prior knowledge of geographically isolated wetlands to estimate extent, connectivity, and ecological/hydrologic function. The approach will quantify the cumulative area of geographically isolated wetlands and model ecological/hydrologic/societal wetland function.

Lopez, R. D., L. Mata, E. J. Evanson, L. A. Bice, L. R. Tinney, T. D. Sajwaj, and D. R. Williams. 2006. An inventory and assessment of geographically isolated wetlands in the Texas coastal region: Initial mapping and accuracy assessment. Internal Report. U.S. Environmental Protection Agency, Office of Research and Development, Las Vegas, NV. EPA/600/X-06/018.

This research is an extension of the previous reference (Lopez 2004). It uses landscape scale imagery to identify palustrine wetlands in the coastal region (Montgomery, Harris, Fort Bend, Brazoria, and Galveston Counties) of Texas. The study also explores map accuracy. Palustrine wetland acreages within 100-yr floodplain boundaries, within 100-500-year floodplain boundaries, and outside of these boundaries, are presented by county. Accuracy was checked using 18 stereo pairs of aerial photographs of Landsat ETM+ satellite data. Wetlands were classified into open water, emergent, scrub-shrub, and forested palustrine ecological types, according to the Cowardin classification. The authors argue that understanding the location of palustrine wetlands and their ecological subclasses is the first step toward understanding their hydrological and ecologic functions at a broad scale. The five Texas counties contain a large number of relatively small palustrine wetlands comprising hundreds of thousands of hectares. The report suggests that hydrologic connectivity can be inferred by evaluating wetlands that occur in both the 100-yr and 500-yr floodplains in conjunctions with FEMA floodplain data. However the introduction includes a disclaimer regarding drawing conclusions about hydrologic connectivity.

Moulton, D. W. and J. S. Jacob. 2000. Texas coastal wetlands guidebook. www.texaswetlands.org. Texas SeaGrant Publication TAMU-SG-00-605. 66 pp.

This online booklet gives an illustrated description of geomorphology and ecology of various coastal wetland types in Texas. It is followed by a list of public land sites where various types of coastal wetlands can be seen. The following summary focuses on descriptions of

prairie potholes/marshes and barrier island interior wetlands. Prairie potholes and marshes refers to any isolated freshwater depression; and these occur primarily between Galveston and the Rio Grande. On the upper coast, potholes and marshes occur in complexes with pimple mounds (small hummocks 1-2 ft tall) and intermound flats. The patterns of uplands and wetlands is often very intricate. These formed thousands of years ago from ancient rivers and bayous that were modified through time and climatic (particularly wind) as well as biotic forces. Due to land leveling for agriculture and development, there are few intact complexes left with the full range of relief from high pimple mounds to deep potholes. The most extensive prairie potholes and marshes are found on the Lissie and Beaumont Geological Formations, which arose from river floodplain and delta sediment deposits but have been modified by wind. The Katy Prairie west of Houston is one of the more well known prairies on the Lissie Formation with abundant pothole wetlands. The soil, an alkaline sandy clay loam, is ponded for periods ranging from a few weeks to several months in the winter and early spring.

Prairie potholes and marshes receive direct precipitation and runoff from surrounding flats. Groundwater may be a factor in many potholes, particularly those on the Ingleside Sand, but its role is not well understood. Hydrology in pothole complexes is very diverse, and may be locally variable. Deeper potholes can remain saturated for more than 6 months a year (especially along the upper coast), with adjacent pimple mounds that are nearly semi-arid, resulting in high habitat and biological diversity. Hydrology also becomes drier moving down the coast.

Vegetation consists typically of concentric zones or belts of plants adapted to elevation and resulting inundation patterns. More permanent potholes may have floating and submerged plants in the open water zone; with cattails, bulrushes, arrowheads and common reed in the emergent zone; and willow, *Baccharis*, and Chinese tallow in the higher woody zone. Wildlife is diverse and tends to concentrate near permanent potholes during drought.

Agriculture has been replaced by urban sprawl as the greatest cause of wetland loss. Many coastal prairie wetlands have been converted to rice fields, which are by far, at about 1.5 million total acres, the most abundant type of wetlands on the Texas coast. They retain some wetland functions, especially when flooded as they provide habitat for migrating waterfowl and invertebrates. Even rice farming is threatened however, due to loss of subsidies and urban sprawl.

Moulton, D. W., T. E. Dahl, and D. M. Dall. 1997. Texas coastal wetlands, status and trends, mid-1950s to early 1990s. U.S. Fish and Wildlife Service, Southwestern Region Albuquerque, New Mexico. 32 pp.

This booklet describes the changes in wetland land areas in coastal Texas since the mid 1950s. Palustrine emergent wetlands have decreased more than any other wetland type (235,100 ac). Reasons for loss included conversion to agriculture, conversion to scrub-shrub resulting from invasion by Chinese tallow-tree and reservoir construction. The area around Houston once had a relatively high proportion of this wetland type but has also been the area

where losses are most pronounced. The methods used were based on changes in aerial photos of wetlands at least 3 acres in size, followed by 10% field verification (754 plots).

NatureServe Explorer, An Online Encyclopedia of Life. www.natureserve.org/explorer/, accessed June 2007.

According to the International Terrestrial Ecological Systems Classification (ITESC), the Texas-Louisiana Coastal Prairie (CES203.541) encompasses non-saline tallgrass prairie vegetation ranging along the coast of Louisiana and Texas. Soil types are dominated by Vertisols and Alfisols which developed over Pleistocene terraces flanking the Gulf coast. Ridge-and-swale or mound-and-intermound microtopography encompasses both upland and wetland communities. Wetland dominants in undisturbed areas include *Panicum virgatum* and *Tripsacum dactyloides* as well as *Andropogon glomeratus* (bushy bluestem). In the absence of regular fire, this system will be invaded by woody shrubs and trees. *Eleocharis wolfii* (Wolf's Spikerush) is listed as an "At-Risk Species" for this ecological system.

Rosen D. J. 2004. Noteworthy collections of *Cyperus drummondii* (Cyperaceae) from Texas. *Sida* 21:495-497.

The author collected the plant species referenced in the title, which has not been well-documented in Texas. The populations were found in poorly-drained prairie depressions in the Nash Prairie remnant in Brazoria County, Texas.

Rosen, D. J. 2007. The vascular flora of Nash Prairie: A coastal prairie remnant in Brazoria County, Texas. *Journal of Botany Research Institute, Texas* 1:679-692.

The author conducted an intensive floristic survey of a 120-hectare coastal prairie remnant 35 km south of Houston, from August 2003 to September 2006. Of the 311 species of vascular plants that were collected, about 91 of these were denoted as wetland plants (wetlands were present on the site). Some rare plants were collected, and the major conclusion of the work is that previous estimates of species richness for climax Coastal Prairie in Texas are low and that historic and potential losses of botanical diversity are greater than previously thought.

Rosen, D. J. and B. J. Christoffersen. 2004. Rediscovery of *Cyperus cephalanthus* (Cyperaceae) in Texas. *Phytologia* 86:107-109.

The only populations known in Texas of the plant referenced in the title were destroyed sometime between 2002 and 2004. However, the authors of this paper found a population comprising over 50 individuals while working in the Nash Prairie remnant in Brazoria County. It was found in the seasonally wet fringes of a prairie depression wetland and it is considered a reliable indicator of relatively undisturbed prairie remnants in Texas and Louisiana, although it may possibly be naturalized rather than native.

Sipocz, A. 2005. "The Galveston Bay Wetland Crisis". National Wetlands Newsletter 27(4). 5 pp. Environmental Law Institute. <http://www.eli.org/nww>.

This article discusses the U.S. Army Corps of Engineers Galveston District's approach to regulating Coastal Prairie wetlands in the Galveston area. These wetlands are typically poorly drained and below 250 ft elevation. According to the author, the wetlands have surface water connections and may be contiguous to navigable stream or bays, but the Galveston District Corps of Engineers either does not recognize such connections or does not consider them sufficient to extend for jurisdictional status.

The Coastal Prairie area has been described as a "clay plain" that is characterized by a lack of incised drainage. Wetlands occur in mud-filled relic river channels, wind eroded circular depressions, and areas where relic-channel meander ridges lead to sumps. Most of these wetlands were leveled and drained for rice farming during the World War II era. Geomorphically, the wetland are most similar to California vernal pools, however surface connections in the coastal plain result in fish access. One-third of the freshwater entering Galveston Bay is locally generated from surface flows from the clay plain. Each acre of undeveloped land in the Houston area produces about an acre-foot of runoff each year. Pulsed surface flow exits sites such as those at Armand Bayou with flows exceeding 500 cfs. The Corps, however, does not recognize surface runoff as jurisdictional unless it arrives via defined channels with mean high water marks.

Sipocz, A. 2002. Southeast Texas isolated wetlands and their role in maintaining estuarine water quality. Paper presented at "The Coastal Society 2002 Conference: Converging Currents: Science, Culture, and Policy at the Coast", Galveston, Texas.

This paper discusses the potential for freshwater isolated wetlands to positively affect water quality by documenting their role in the surface hydrology of southeast Texas estuarine watersheds. Three study sites (Stringfellow Wildlife Management Area, Armand Bayou, and Addicks Reservoir) located on relatively undisturbed mosaics of isolated wetlands and uplands typical of the region. Runoff volumes were estimated using a coastal plain stream model. Watersheds were delineated using USGS 7.5-minute quads and direct observation of flow during runoff events. Digital orthoquads (DOQQs) illustrated even slight elevation differences associated with soil moisture and vegetation gradients. Wetland boundaries were delineated using DOQQs and the overlap of delineations and drainage ways were used to calculate the average annual runoff that passed through the wetlands.

The sites were underlain with clays with extremely slow infiltration rates, resulting in 24% of the annual precipitation leaving the sites as runoff. Isolated wetlands found within drainageways collected runoff from surrounding uplands. They emptied stair-step fashion into nearby lower-elevation wetlands. These "chains of wetlands" produced a few outfall points into interstate waters, and high precipitation rates led to large average annual outfall volumes.

Some isolated wetlands originate as ancient river channel scars reworked by aeolian erosion, with watersheds 4 to 5 times their size. Others result from the vertic action of clay soils. These “gilgai” wetlands had smaller watersheds. Two of the three sites (Stringfellow and Armand) were formed by backswamp deposits, and received surface runoff before discharging directly into tidal waters. Surface runoff was conveyed by broad shallow drainages (interbasin flats or sloughs) that, although visible on DOQQs, were too small to be shown on USGS topographic maps, which causes the Corps to not consider these wetlands “hydrologically connected”. The authors concluded that (1) ground water inputs are small, (2) most stream flow is derived from rainfall, and (3) aerial deposition of nitrogen pollutants to Galveston Bay is ~ 15% of the total N load. The author states that: “Freshwater wetlands within the study area are abundant and well positioned within the hydrologic pathway to provide substantial attenuation of runoff pollution destined for these estuaries.”

The author also points out that in the SWANCC 2001 ruling, the court did not dispute the ability of wetlands to positively affect the quality of this Nation’s waters, but rather wanted proof of this ability. The Galveston District has decided that freshwater wetlands lying outside of the 100-year floodplain of rivers and streams are isolated from interstate waters and thus no longer protected by the Clean Water Act (CWA). They assume that these wetlands are not part of the surface hydrologic system, but rather runoff sinks. There are approximately 3.3 million acres of freshwater wetlands on the Texas coastal plain. Of these, most flatwoods, farmed wetlands, prairie potholes and sloughs are no longer regulated by the CWA.

Smeins, F. E., D. D. Diamond, and C. W. Hanselka. 1992. “Coastal Prairie”, Chapter 13, Ecosystems of the World 8A Natural Grasslands, pp 269-290. Elsevier Publishers, New York.

This chapter provides a basic description of the coastal prairie ecosystem. The Coastal Prairie region encompasses about 38,000 km² along the Gulf of Mexico. It is a low, featureless plain of generally poor drainage, with mid- to tall-grass vegetation and many rivers and streams. The geology and soils are described in detail. Vertisols and Alfisols, the major soil orders within upland areas, are poorly drained and tend to be waterlogged in winter and after storms. During summer periods without rainfall, soils can dry and crack. The large clay component (~72%) in Vertisols (Beaumont, Lake Charles and Victoria series) accounts for the shrink-swell nature of the soils. They also exhibit a unique micro-depression or micro-knoll relief known as “gilgais”. Beaumont and Lake Charles soils are both acidic (pH 5.0-5.5). and organic matter in all three Vertisols is 2~ 4%. Surface layers of Alfisols are acidic sandy or sandy-loam with clayey subsoils. Alfisols have circular sandy mounds (“mima” or “pimple mounds”) which cover as much as 25% of the landscape in some areas. Explanations for the origin of the mounds have not been completely worked out, however they tend to follow drainage divides and be associated with past coastal forces of wind and wave. They have an important influence on patterns of plant distribution and abundance.

Climate in the coercion varies from semi-arid in the south to humid in the east. Tropical storms and hurricanes can bring large amounts of rainfall in very short periods of time,

coupled with strong winds. The Galveston Bay area is located in the “upper coastal prairie” portion of the coercion, which is the more humid portion that typically lacks a summer drought.

A very significant aspect of the ecology of this region is the change brought about by European settlement. The historical record indicates that woody vegetation has increased considerably due to increased grazing and fire suppression. Extensive areas of cane (“Great Prairie Cane-brakes”) were also commented on by early explorers. These are presumed to have been *Arundinaria macrosperma* (=gigantea) although *Phragmites australis* may also have been present. Fire suppression and ungulate intensity, artificial drainage and damming of rivers, urbanization, and cultivations are listed as major contributors to ecological changes in the region. Tables of dominant vegetation, details regarding soil properties, and maps of ecoclines are also provided. The coastal marshes include fresh and saline species ranging from *Spartina alterniflora* to *Tamarix gallica*.

U. S. Geological Survey. 2000. Coastal prairie. FS-019-00 National Wetlands Research Center, Lafayette, LA. 2 pp.

This short article provides a brief ecological description of Coastal Prairie ecosystem type, that once covered ~ 3.8 million ha along the coastal region of Texas and Louisiana. As much as 99% of this land has been converted to agriculture, range and urban use, leaving only about 100,000 ha intact in Texas. Located at the southern tip of the tallgrass prairie, vegetation overlaps include bluestems, coneflowers, and blazing stars, mingled with species native to the coastal wetlands. This ecosystem is currently listed as “imperiled globally” by the Nature Conservancy and the Texas Natural Heritage Program. The Louisiana Natural Heritage Program lists it as “critically imperiled”. A dozen plant species, including orchids and sedges, are regarded as “state-rare”, and two additional species are listed as “critically imperiled”. Exotic species such as Chinese tallow also threaten native habitats. Coastal prairie receives nearly twice the annual rainfall (142 cm) as Midwestern grasslands (71 cm) which would typically result in forest rather than grasslands. However scientists believe that the Coastal Prairie developed because of the hard clay layer underneath the topsoil, which inhibited root formation of larger species. Natural fires may also have played a role in checking the growth of trees and shrubs. According to the US Fish and Wildlife Service (USFWS), restoration of Coastal Prairie is a top priority for the region. Several USFWS national wildlife refuges are located in the ecosystem including Anahuac, Aransas, Atwater, San Bernard, Big Boggy, and Brazoria in Texas. Coastal Prairie management and restoration are the two primary mission goals of the USGS’s Wetland Research Center. The Center conducts research on plantings of native grasses and effects of prescribed fire.

White, W.A., T.A. Tremblay, E.G. Wermund, Jr. and L.R. Handley. 1993. Trends and status of wetland and aquatic habitats in the Galveston Bay system, Texas. Galveston Bay National Estuary Program GBNEP-31, 144 pp.

This report examined 30 quadrangle maps around Galveston Bay for the presence of a variety of wetland types. Aerial photographs (1950s, 1979, 1989) were interpreted with stereoscopic procedures developed for the USFW's NWI program. Field reconnaissance was also performed. Palustrine wetlands are defined according to the Cowardin 1979 descriptions. In the study area, palustrine wetlands are fresh marshes that include naturally occurring ponds or depressions. Semi-permanently flooded emergent wetlands (PEM1F) are low fresh marshes; seasonally flooded (PEM1C) and temporarily flooded (PEM1A) palustrine emergent wetlands are high fresh marshes. Vegetation typically associated with these include *Scirpus californicus*, *Typha* spp., *Alternanthera philoxeroides*, *Cyperus articulatus*, *Spartina patens* (in higher areas), *Scirpus americanus*, *Polygonum hydropiperoides*, *Bacopa monnieri*, *Phragmites australis*, *Eleocharis* spp. *Zizaniopsis miliacea*, and others. Less frequently flooded emergent wetlands (PEM1C and PEM1A) include *Cyperus* spp., *Scirpus americanus*, *Eleocharis* spp., *Sesbania drummondii*, *Typha* spp. *Spartina patens*, and *Polygonum hydropiperoides*, to name a few. Field observations revealed the existence of small depressions or mounds with plant communities and moisture regimes that were not easily characterized from photographs and for which elevation was not measured.

According to the map analyses, 22,211 acres of palustrine emergent wetland were identified in the Galveston Bay Area whereas only 85 acres of palustrine aquatic bed were delineated. This palustrine emergent wetland type are distributed in inland areas along the Trinity River alluvial valley in the Anahuac and Cove quads, inland of Christmas Bay and West Bay (Oyster Creek and Hoskins Mound quads) and inland of East Bay (Frozen Point and High Island quads). Cove, Oyster Creek, and Anahuac have the largest areas of palustrine emergent wetlands, accounting for about 4,389, 3,600 and 3,360 acres respectively.

WETLAND FUNCTIONAL ASSESSMENT

Adamus, P. R. and C. T. Stockwell. 1983. A method for wetland function assessment, volume I: Critical view and evaluation concepts. United States Federal Highway Administration. FHWA-IP-82-23.

This report is one of the earliest comprehensive reviews of wetland functions and is the prelude to the widely used Wetland Evaluation Technique (WET 2.0). It describes eight wetland functions and examines the validity, interactions, and possible significance for the functions, as well as documenting their underlying processes. The report contains extensive literature citations organized by function. Wetland characteristics that lead to high functional capacity are provided, followed by illustrations of hypothetical examples of wetlands that have a high probability of performing each function. The rationale for each characteristic is explained and cited. Finally, the interactions of each function with other wetland functions is discussed. For flood storage and desynchronization, palustrine, lacustrine and riverine wetland high in the watershed are considered to have greater effectiveness. Several studies are referenced which demonstrate or estimate the importance of wetlands for decreasing flood peaks in various watersheds. The major factors or processes affecting the function are listed (e.g. magnitude and duration of storms, upslope runoff, above ground basin storage capacity, frictional resistance, below-ground basin storage capacity, and position of the wetland basin in the watershed).

The report lists 75 predictors of wetland functional value such as shape of basin, water depth, dissolved oxygen, etc. Each predictor is described and its origin and importance to each function is discussed. There is also a discussion of the certainty of each predictors validity, as many of the predictors are arbitrary (e.g. basin size importance to habitat). There is a discussion of the uncertainty that arises from the extreme variability in wetland types. Sample worksheets are provided that illustrate the characterization of the wetland site and the use of the method. Many of the fundamental factors that influence function have changed little from this original effort.

Adamus, P. R., E. Clairain, R. D. Smith and R. Young. 1987. Wetland evaluation technique (WET), volume II: Methodology. United States Federal Highway Administration. FHWA-IP-88-29.

This volume (WET 2.0) is a revision of the original "Adamus" method. WET 2.0 is designed primarily for conducting initial rapid assessments of wetland functions and values. The method evaluates eleven functions and values with respect to their social significance, effectiveness, and opportunity. WET 2.0 relies on predictors which are analyzed in a series of interpretation keys. The result is a qualitative probability rating of high, moderate or low. WET 2.0 also assesses habitat suitability for several groups, guilds, or species of wildlife. The report emphasizes that the results are an estimate of the probability that a function or value will exist or occur at the wetland, not a measure of the magnitude of a wetland function, nor should numerical values be applied to these measures of probability.

Two important components of WET 2.0 that are not included in HGM are opportunity and social significance. Opportunity is defined as the likelihood that the wetland will perform the function based on its position in the watershed and the characteristics of the watershed. Social significance is defined as the probability that a wetland is of value to society. Although this method has limits and is no longer in favor among federal agencies, it is still widely used and has been the template for many state wetland assessment methods. Furthermore, much of the information embodied in the WET approach has been incorporated into regional functional assessment models.

Bartoldus, C. C. 1994. EPW: A procedure for the functional assessment of planned wetlands. *Water, Air and Soil Pollution* 77: 533-541.

The author describes the Evaluation for Planned Wetlands (EPW) procedure which assesses six functions: shoreline erosion control, sediment stabilization, water quality, wildlife, fish, and uniqueness/heritage. Wetland functional differences are expressed in terms of wetland characteristics, Functional Capacity Indices (FCI) and Functional Capacity Units (FCU). What is unique about this approach is that it allows the calculation of the size of the wetland that would be necessary to replace the lost function. The FCI is indexed between 0.0 and 1.0. The FCU is simply the FCI multiplied by the total wetland area.

Bradshaw, J. G. 1991. A technique for the functional assessment of nontidal wetlands in the coastal plain of Virginia. Special Report No. 315. Virginia Institute of Marine Science, College of William and Mary, Virginia.

This assessment method combines effectiveness and opportunity and ignores groundwater interactions. It uses quantitative and qualitative assessment, but results in a qualitative rating of high, moderate or low for each factor. The factors are then used to determine a rating of high, moderate, or low for each function.

For flood storage and storm flow modification, effectiveness is enhanced by wetlands that:

1. Have large wetland:watershed ratios
2. Are not permanently flooded
3. Have constricted or no outlet
4. Have high channel sinuosity
5. Have dense vegetation (#stems/acre)
6. Have wetland plants with rigid stems

This technique includes a discussion of the Simon method (Simon et al. 1987) which determines flood storage capacity. The Simon method is quantitative but rapid and calculates the volume of runoff from the watershed, based on a 2-year, 24-hour rainfall, and the land use characteristics and soil hydrologic group classification of the watershed soils. This runoff volume is adjusted depending on whether additional wetlands are located upgradient but within the watershed. The holding capacity of the wetland is calculated by multiplying wetland area by wetland flood storage depth. Flood storage depth is defined as the elevation

range within wetland multiplied by 0.5. The elevation range is the difference in elevation between the open water/wetland boundary and the wetland/upland boundary, as determined by a hand held level and stadia rod to the nearest tenth of a foot. Wetlands which can store more than 25% of the runoff delivered from the watershed perform a significant flood storage function.

Nutrient retention and transformation function (inorganic P and nitrate) is defined as both storage (e.g. sediment accretion) and transformation (e.g. denitrification). Opportunity is linked to the flood storage function. Effectiveness is increased by detention time, organic matter in soil (denitrification) watershed slope, nutrient sources, sediment sources, land use, watershed:wetland area ratio, wetland type bordering watercourse, water impoundment within wetland, flood storage in inches or runoff. Effectiveness is high if the wetland is large relative to its watershed and is not permanently flooded, or if soils are effective at adsorbing P or removing N. The Virginia model relies on sources of excess nutrients, runoff delivering nutrients to the wetland, and water retention time (longer is better). Sediment and toxicant (e.g. pesticides) trapping opportunity is based on sources from the watershed and delivery (same as nutrient retention) with no factors that address effectiveness.

Brinson, M. 1996. "Assessing Wetland Functions using HGM". National Wetlands Newsletter, January-February 1996. pp 10-16.

The authors states that HGM provides a much-needed tool for accurately measuring the net change in function resulting from both degradation and restoration, and therefore should be an essential tool for management decisions and to measure progress toward national wetland goals. Geomorphic setting (where the wetland is positioned in the landscape) and other factors lead to natural variation in key wetland properties, and an approach must be able to distinguish between natural cycles and changes due to impacts by human activities. In HGM, the reference wetland, therefore, serves as a control. The HGM approach is also designed to be rapid once the models are developed (based on literature) and field work has been conducted for calibration.

The editor argues that HGM is an improvement over previous functional assessment methods because it eliminates confusion regarding societal issues (social significance and valuation), and is tailored to the proper geomorphic setting and hydrologic regime. The author also states that HGM has an exposed architecture, that is, regardless of how much is known about the particular type of wetland, the model may be easily examined. Several examples of functional models are provided. The author stresses that "care must be taken not to fall into the opportunity trap, whereby degraded uplands and pollution inputs cause wetlands to appear to function at higher but unsustainable levels". The article includes a discussion regarding how HGM should be used in mitigation, review, and monitoring of Section 404 permits.

Brinson, M. M. and R. Rheinhardt. 1996. The role of reference wetlands in functional assessment and mitigation. *Ecological Applications* 6: 69-76.

The authors argue that use of a reference wetland to evaluate success or failure of compensatory mitigation is desirable because it makes the goals explicit to reference standards that typify sustainable conditions in a region. It also provides a template for designing restored and created wetlands. It also establishes a baseline whereby a decline in functions from impacts can be documented. An example from a North Carolina coastal plain pine flat is provided. The purpose of reference wetlands are to encompass the known variation of a group or class of wetlands, including both natural and disturbance-mediated variation. The reference standards are then determined using information obtained on the least degraded members of the class.

Carletti, A., G. A. De Leo, and I. Ferrari. 2004. A critical review of representative wetland rapid assessment methods in North America. *Aquatic Conservation: Marine Freshwater Ecosystems* 14: S103-S113.

The authors are European and they evaluate and compare 17 rapid assessment methods for tidal and nontidal North American wetlands. Thirteen of the 17 methods were developed for land planning purposes, the remaining for wetland area management, inventory, or environmental impact assessment. The 17 methods have been applied in a total of 1264 case studies. Most methods involve completion of a simple data form or questionnaire that can be accomplished in an office. Only three methods adopted a reference-based system (comparing wetlands to minimally impacted sites that presumably have intact functionality). Ten of the methods result in a score on a quantitative scale, in 3 methods it is in terms of functional level and in one in terms of probability. Many of these approaches assess wetland condition rather than function. The authors conclude that the 17 approaches require very different levels of expertise, time, and resources. They favor the Massachusetts approach for adaptation to Mediterranean wetlands.

Cowardin, L. M., V. Carter, F. C. Golet and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U. S. Fish and Wildlife Service, FWS/OBS 79-31. 47 pp.

This document presents the widely used classification scheme for developing inventories of wetlands and deepwater habitats in the U. S. The system uses five major classes (marine, estuarine, riverine, lacustrine, and palustrine) followed by subsystems under each class. Within the subsystems, further divisions are based on substrate material and flooding regime, or on vegetative life form. There are five classes based on vegetative form (aquatic bed, moss-lichen, emergent, herbaceous angiosperms, scrub-shrub and forested). Modifying terms are also included where possible. These may refer to water regime (e.g. intermittently exposed, irregularly exposed, etc.), salinity, and hydrological alterations (diked, impounded, excavated, partly drained, farmed, and artificial). Most of the document contains detailed definitions and examples of the different classifications and modifiers. This document is the

foundation for much subsequent classification and mapping work. It also is the basis, through NWI maps, for most comparisons of landscape-level changes in wetland acreages.

Cedfeldt, P. T., M. C. Watzin, and B. D. Richardson. 2000. Using GIS to identify functionally significant wetlands in the Northeastern United States. *Environmental Management* 26: 13-24.

This functional assessment approach uses spatial predictors for assessing three wetland functions in Northeastern U.S. wetlands: flood flow alteration, surface water quality improvement, and wildlife habitat. Predictors were taken from the literature on wetland structure and function, and from several wetland assessment techniques (Primarily WET, HGM and two from the region), and then automated using GIS. Eight Arc Macro Language programs were developed that use remote sensing land use information and digital elevation models. The results were tested on four wetlands in Vermont.

Flood flow alteration was modeled with four opportunity and three effectiveness predictors. Opportunity predictors included: (1) upslope wetlands comprise less than 5% of the wetland's watershed; (2) wetland area is less than 20% of watershed area; (3) the majority (>50%) of the wetland watershed is made up of impervious surfaces; and (4) most of the soils (>80%) in the wetland's watershed have a very slow infiltration rate (<1.5 mm/hour). Effectiveness predictors included: (1) wetland located near an intermittent or first-order stream (i.e. wetland is located high in the watershed); (2) wetland area is larger than 81 hectares; and (3) wetland is not connected to the surface water network (i.e. has no permanent outlet).

The water quality function was modeled by four opportunity and two effectiveness predictors. The opportunity predictors were: (1) wetland's watershed contains potential sources of pollutants; (2) all of the following are true: majority of watershed is not forested or scrub shrub, wetland is less than 5% of watershed area, and upslope wetlands don't comprise less than 5% of watershed; (3) average slope of wetland's watershed is greater than 10%; and (4) wetland type is riparian. The effectiveness predictors were: (1) soil type under wetland is either histosol or frequently flooded mineral soil with both high clay and high organic matter content and (2) wetland is located near an intermittent or first order stream (landscape position is high in the watershed). The authors concluded that the method has important application for land managers in identifying wetlands with high potential for functionality.

Eckles, S. D., A. Ammann, S. J. Brady, S. H. Davis, J. C. Hamilton, J. Hawkins, D. Johnson, N. Melvin, R. O'Clair, R. Schiffner, R. Warren. 2002. Assessing wetland functional condition change in agricultural landscapes. Natural Resource Conservation Service, Wetland Technical Note No. 1.

The purpose of this assessment effort by NRCS was to determine whether wetland function on restored agricultural lands was increasing or decreasing. Three regions were selected for the pilot sampling: northern prairie pothole region, central and lower Mississippi valley, and

the high plains. The workgroup used an HGM type approach and classified wetlands according to water source and geomorphic location, and determined the functional capacity of restored wetlands relative to reference wetlands. The authors then compared restoration sites with reference sites to evaluate the success or failure of restoration. They concluded that there was a modest relative increase in mean functional capacity for wetland restoration sites on restored agricultural lands within the three geographic regions sampled. However, relative condition of restoration sites was not at the highest sustainable functional capacity.

Fennessy, M. S., A. D. Jacobs and M. E. Kentula. 2004. Review of rapid methods for assessing wetland condition. EPA/620/R-04/009. U.S. Environmental Protection Agency, Washington, DC. 75 pp.

This report evaluates over 16 methods for assessing wetland condition. Most methods were developed by state and tribal programs for use in regulatory and management programs. The report focuses on rapid assessment methods, rather than intensive monitoring efforts and distinguishes between methods that evaluate condition and those that evaluate function. Of the 16 assessment methods reviewed, only five specifically address wetland functional assessment: Maryland, Minnesota, Virginia, Oregon and Wisconsin. A criticism of rapid functional assessment methods is that they assign qualitative scores (high medium or low) to each function, which makes comparisons between sites difficult. Furthermore, these qualitative rankings are ineffective at rating the condition of the resource as a whole. High functional ratings do not necessarily equate with high ecological condition particularly since maximizing one function may cause a reduction in other functions (e.g. good storm water wetland may have poor wildlife habitat).

The report further discusses methods for scoring, using value added metrics, and validation with comprehensive ecological data. An appendix includes a list of indicators for each wetland characteristic. For example, hydroperiod indicators include ratio of wetland area to watershed area, microrelief of wetland surface, water marks or silt rings on trees, drift line deposition, etc. Flood storage potential is indicated by FEMA maps or USGS data, water-vegetation interspersions, degree of channelization, enclosed basin, and ratio of wetland to watershed area. Appendix C contains an overview of methods, where each of the 16 methods is cited and a list of functions and stressors and general conclusions provided.

Gilbert, M. C., P. M. Whited, E. J. Clairain, Jr. and R. D. Smith. 2006. A regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of prairie potholes. ERDC/EL TR-06-5.

Prairie potholes are primarily closed basins that receive water from precipitation, runoff, and groundwater. This HGM report models the following functions for prairie potholes: storing water, recharging groundwater, retaining particulates, biochemical processes, plant community resilience and carbon cycling, and providing faunal habitat. The water storage, particulate retention, and biogeochemical processes functions are reviewed in detail.

A potential independent quantitative measure of the water storage function is the amount (volume) of water stored in the wetland per a given time (e.g. hectare-m/yr). The model variables are: wetland surface outlet, wetland subsurface outlet, wetland sediment accumulation (indicates loss of storage volume), source of water inputs, and upland land use. The outlet variables are multiplicative so that the function will be assessed as zero if the outlet value is 0 (i.e. the wetland has been drained).

The particulate retention function can be independently measured by the quantity of particulates retained per unit area per unit time ($\text{g m}^{-2}\text{yr}^{-1}$). The model is based on two types of factors: sources and mechanisms by which particulates are transported to the wetland, and processes that immobilize particulates within the wetland. The model factors are: upland land use, grass continuity, grass width, vegetation composition (reduces water velocity), wetland surface outlet, wetland subsurface outlet, sedimentation (zero if no storage capacity remains). The structure of the model allows sedimentation to drive the index to zero, the other variables are averaged.

The biogeochemical cycling function (“remove, convert, and sequester dissolved substances”) is defined similarly to other HGM models, and covers nutrients, pesticides, organics, and other non-particulate materials. A potential independent measure of this function is the amount of one or more imported elements and compounds removed or retained per unit area during a specified period of time (e.g. $\text{g m}^{-2} \text{yr}^{-1}$). Variables used to model this function include: grass width, grass continuity, source of water input, upland land use, sedimentation of wetland, vegetative composition, soil organic matter, wetland outlet (minimum of surface and subsurface). All of these variables are averaged arithmetically with the exception of wetland outlet; if the wetland is completely drained (wetland outlet = 0), the function is completely lost.

Hauer, F. R., B. J. Cook, M. C. Gilbert, E. J. Clairain, Jr., and R. D. Smith. 2002. A regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of intermontane prairie pothole wetlands in the northern Rocky Mountain. ERDC/EL TR-02-7.

This HGM report addresses prairie potholes of the intermontane area of the northern Rocky Mountains. The Rocky Mountain potholes have highly variable soil types, but are generally located within unconsolidated glacial till, and therefore have significant interaction with groundwater. The presence or absence of fine glacial till, the geomorphic origin of intermontane potholes, their degree of interception with the groundwater, soil hydrologic conductivities, and human activities are all proposed as having an effect on surface water storage.

The report includes functional models for surface water storage, nutrient cycling, and retention of elements, compounds, and particulates (water quality). Water storage model variables include upland land use, land use at wetland edge, land use in wetland, soil pore space, hydrologic modification, duration of wetland flooding, and geomorphic modification (tilling, dredging, excavating, ditching, etc.).

Decomposition of organic matter indicates long-term storage of nutrients and decomposer community. If greater than the reference wetland, this indicates too great a nutrient load, or decomposition rates that are too slow and thus the function level is not sustainable. The soil A horizon (surface mineral soil characterized by accumulation of humus), has the greatest ability to hold nutrients. Thus the depth and color of the A horizon are indexes of the ability of the soil to store nutrients relative to the reference wetland. The resulting functional capacity index for nutrient cycling combines land use (overall and edge of wetland) with sediment load (RUSLE) and soil characteristics (O and A horizon and pore space). Model variables also include land use in the wetlands (a table of land uses and their scores are provided). This variable is based on general land use within all zones of the wetland over an extended period of time (10-20 years). They also include a variable for land use at the wetland edge, (low prairie zone) with a similar table.

The “retention of elements, compounds and particulates” function is defined as the ability of the pothole wetland to remove permanently and/or sequester elements, compounds, and particulates that are imported to the wetland from adjacent upland and atmospheric sources. This function is controlled by (1) the source and mechanisms of transport into the wetland, (2) the basin morphology and landscape position, (3) vegetation structure, and (4) wetland soils. The authors argue that wetland soils provide the best available indicators of the average long-term biogeochemical processes and groundwater flow patterns for depressional wetlands. In the prairie pothole region, groundwater recharge wetlands are temporary to seasonal with very low electrical conductivities, groundwater discharge wetlands are semipermanent to permanent wetlands with highest electrical conductivities, and flow-through wetlands vary from seasonal to permanent are intermediate in electrical conductivity, etc. Wetland morphology influences surface runoff and hydrologic connectivity during wet periods. Larger catchments have a greater source area and thus greater inputs. Steeper slopes also contribute to runoff volume (reduces infiltration). A doubling of overland flow velocity enables transport of particulates 64 times larger. Surface water connections between palustrine wetlands may occur during flood events and wetland drainage can increase watershed discharges and flooding. Drained wetlands are presumed to export pollutants rather than retaining them in the wetland and therefore would have reduced function. Dense vegetation in adjacent uplands reduces surface water velocities and thus enhances infiltration, filtration, and reduces erosion.

Hruby, T., S. Stanley, T. Granger, T. Duebendorfer, R. Friesz, B. Lang, B. Leonard, K. March, and A. Wald. 2000. Methods for assessing wetland functions, volume II: Depressional wetlands in the Columbia Basin of Eastern Washington. Washington State Department of Ecology. Ecology Publication # 00-06-47.

This State of Washington method was developed for freshwater, long-duration, depressional wetlands in the Columbia River basin. It assesses 13 functions including sediment removal, phosphorus removal, nitrogen removal, heavy metal and toxic organics removal, decreasing downstream erosion and flooding, and others. Predictors are derived from literature demonstrations and from WET. For example, sediment removal potential is higher in

wetlands with constricted or no outlets, with high storage, vegetative cover, good vegetative buffer width and condition, slope and sediment sources. The function is rated separately for potential (effectiveness) and opportunity in an HGM-type approach (e.g. arithmetic averages of predictors).

Jordan, T. E., M. P. Andrews, R. P Szuch, D. F. Whigham, D. E. Weller, and A. D. Jacobs. 2007 Comparing functional assessments of wetlands to measurements of soil characteristics and nitrogen processing. *Wetlands* 27: 479-497.

This publication compares actual N removal, measured as N₂O emissions or denitrification enzyme activity (DEA); to corresponding HGM model scores for biogeochemistry developed for Delaware and Maryland riverine and flats wetlands. To our knowledge, this is the first attempt to compare HGM model results to an independent and objective measure of the function. Scores did not correlate with N₂O emissions or DEA except in summer when DEA in flats increased with increasing score. Wetland alterations that increased soil moisture relative to the reference standard yielded lower HGM scores, but DEA levels were observed to increase. DEA levels were found to be a better correlate to potential denitrification than N₂O emission. In addition DEA levels were correlated to percent water-filled pore space, pH, ammonium concentration, and the percentages of N and organic carbon DEA also decreased with increases in oxidation-reduction potential (E_h) and water-table depth.

Lin, J. P. 2006. A regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of depressional wetlands in the Upper Des Plaines River Basin. ERDC/EL TR-06-4.

This HGM report developed several functional assessment models, including water storage and water quality. The hydrology function (“maintain characteristic hydrologic regime”) is defined as the capacity to maintain variations in depth and duration of surface and subsurface water levels, as well as volume, frequency and timing of water inputs and outputs similar to conditions found in reference wetlands. Alteration of the hydrologic regime is predicted to reduce this function. Independent measurements are long-term monitoring of the water table, and comparison of hydrograph results between impacted and reference wetlands. Main source of water is direct precipitation and associated runoff from the wetland catchment. This document includes floodplain depressions, however our review is limited to non-floodplain wetlands.

The ability of the wetland to store surface and subsurface water is affected by climate and landscape scale geomorphic features. On-site factors include the relative size and volume of the wetland, soil sorption capabilities, and the amount of biomass present for evapotranspiration. The following variables are used for assessing maintenance of isolated depressions: presence of hydrologic alteration, ratio of wetland area to catchment area, ground vegetation cover, land use of catchment area, soil structure, and Floristic Quality Assessment. The variables are differentially weighted. Catchment features, in particular land use, also affect the timing and volume of runoff and thus influence water storage and flood

attenuation functions. The presence of herbaceous vegetation can greatly increase evapotranspiration. For example, broadleaf cattail can in some cases have double or triple the evapotranspiration rate compared to unvegetated areas.

The water quality function is termed maintenance of biogeochemical processes, and is defined as the capacity of a wetland to maintain the rate, magnitude, and timing of various biogeochemical processes compared to the reference condition. Direct measurement of this function may include estimates of net annual primary productivity, annual rates of organic matter decomposition, or denitrification rates. This function is assessed using the following variables: wetland buffer, vegetation cover, land use of catchment area, thickness of surface O horizon, soil structure. The model is based on the average of the amount of living and dead biomass at the site and the buffer vegetation; this average is then averaged again with the soil structure, and the land use in the catchment area.

Lopez, R. D. and M. S. Fennessy. 2002. Testing the floristic quality assessment index as an indicator of wetland condition. *Ecological Applications* 12: 487-497.

This work was conducted in depressional wetlands and it uses an assessment tool that ranks wetlands along a disturbance gradient. The predictor variables are also used in various functional assessment models. For example, wetland condition (ranks) were found to be correlated to surrounding land covers, vegetated buffer characteristics, and extent of human-induced hydrologic alteration at the wetland site. The authors found that the floristic quality index was negatively correlated with disturbance rank (e.g. surrounded by agricultural land) and with distance to neighboring wetlands.

Lopez, R. D., C. B. Davis and M. S. Fennessy. 2002. Ecological relationships between landscape change and plant guilds in depressional wetlands. *Landscape Ecology* 17: 43-56.

The authors examined the relationship between changes in plant guilds and landscape changes around 31 depressional wetlands in central Ohio. They found that changes in land uses, distances between wetlands, and wetland size (area) were correlated to taxa richness. The area of open water in the local landscape and the area of the wetland site itself were positively correlated to richness. Other predictors such as submersed herbaceous plant perennial-to-annual-ratio were found to be important.

Magee, D. W. and G. G. Hollands. 1998. A rapid procedure for assessing wetland functional capacity based on hydrogeomorphic (HGM) classification. Normandeau Associates Inc. and ENSR. 190 pp.

This document combines the HGM approach with ideas and concepts from other sources such as the Hollands-Magee wetlands assessment method. One purpose of the document is to serve as a template for the development of assessment procedures for different regions of the

country. When combined with reference wetland data, this template can also be used to build regional HGM models. The document also includes a fully developed procedure for assessing wetland function in the glaciated northeast and midwest.

Definitions, hypothetical examples, and plan and cross-sectional drawings of HGM classes (depressional, slope, lacustrine, peatlands, flats, and riverine) are provided. Definitions and sketches illustrating wetland functions are also included. The suite of functions is then explained in the context of each HGM class. For example, “storm and flood water storage” in depressional wetlands is described and the impact of various wetland characteristics on this function is discussed. This document is a good primer for understanding the basic factors influencing wetland functions in different classes of wetlands.

Minnesota Board of Water and Soil Resources. 1998. Minnesota routine assessment method for evaluating wetland functions (MNRAM) Draft version 2.0. Minnesota Board of Water and Soil Resources, St. Paul, MN. 39 pp.

This assessment approach resembles WET 2.0 and results in low, medium, high, and exceptional functional ratings for nine functions: vegetation diversity/integrity; maintenance of hydrologic regime; flood/storm water attenuation; water quality protection; shoreline protection, wildlife habitat; fishery habitat; aesthetics/recreation/education/cultural; and commercial uses. Users review existing data sources, visit the area, and answers questions that indicate the presence of factors important for each function. There are no models. The answers to questions and explanations in the user guidance sections are used as a guide in rating the capability of a wetland to provide a function compared to a reference wetland in the same wetland comparison domain.

For storm water storage/flood attenuation, wetland characteristics which affect ability to store or attenuate storm water include soil condition, vegetation, channel connectivity, and most importantly outlet configuration. Higher rated wetlands will have a restricted outlet, dense emergent vegetation without channels. Opportunity variables for wetlands with a high rating include a high proportion of impervious surfaces in the catchment, large runoff volumes, clayey upland soils, and few wetlands present within the catchment.

For water quality, variables include vegetative diversity/integrity, dominant upland land use, storm water runoff pretreatment and detention, upland buffer width, upland buffer vegetative cover, upland buffer slope, sediment delivery, and nutrient loading. Variables are weighted and averaged. These indices were derived from a combination of sources including HGM, WEM, WET, and experiences of the project team.

Miller, R. E. and B. E. Gunsalus. 1997. Wetland Rapid Assessment Procedure (WRAP) Technical Publication REG-001. South Florida Water Management District, Natural Resource Management Division, West Palm Beach, Florida.

WRAP is a rapid assessment technique that relies on observable variables (scale 0.0 – 3.0) to obtain an index between 0-1.0. It was developed for use in a regulatory context to evaluate mitigation, restoration, and other wetland projects. WRAP utilizes six variables, including adjacent land use, vegetation overstory, wetland vegetation, wildlife use, wetland hydrology, and water quality input and treatment to evaluate or compare sites with the same geomorphology (e.g. variable scores for wet prairie should not be mixed with cypress domes). Detailed methodologies are provided for assigning values to each variable. This approach is based on the Habitat Assessment Procedure developed by US Fish and Wildlife Services, and resembles WET 2.0 more than HGM. Although it mentions functional assessment, it actually ranks the condition of the wetland using observations of functions (which they call variables but they are actually functions).

Natural Resources Conservation Service. 1999. Interim functional assessment model for playa region revised draft. Garden City, Kansas.
<http://www.pwrc.usgs.gov/wlistates/playas2.htm>

This HGM report does not appear to be fully developed, if is not in the same format as the published HGMs. Modeled functions include elemental cycling and maintenance of hydrologic regime. The models and their variables are similar to those with other depressional wetlands that lack substantial groundwater exchange. Some of the functions have separate models for wetlands with flow through and those without flow-through.

Noble, C. V., R. Evans, M. McGuire, K. Trott, M. Davis, and E. J. Clairain, Jr. 2004. A regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of depressional wetlands in peninsular Florida. ERDC/EL TR-04-3.

This HGM report contains models for surface water storage, subsurface water storage, and cycling of nutrients. These geographically isolated wetlands rely primarily on precipitation and groundwater for inputs and outputs. Sandy soils contribute to groundwater playing a significant role in the water cycle in these wetlands. The surface water storage function is defined as storage above the soil surface. The variables in this model include wetland volume, change in catchment size, upland land use, surface outlet, cypress canopy (greater coverage enhances function). The model uses wetland volume as a multiplier, thus if wetland volume has been substantially altered, even by excavation, the function is lost. The remaining variables are averaged and thus have more or less similar contribution to the function.

The water quality function titled “cycle nutrients” is defined as the ability of wetlands to transform biotic essential elements and materials, primarily in light of support to food web and habitat processes. The variables influencing these processes include change in catchment size, upland land use, surface outlet, macrophytic vegetation cover, understory vegetation

biomass, tree basal area, surface soil texture. The model for cypress dome depressional wetlands is the same except macrophytic vegetation cover is replaced with variables for herbaceous vegetation. Appendices provide model summaries and details on collecting/measuring data for variables.

Roth, R., R. Olsen, P. Snow and R. Sumner. 1996. The Oregon freshwater wetland assessment methodology. Wetland Program, Oregon Division of State Lands. 106 pp.

The Oregon Method is based on WET 2.0. Assessments are organized by functions and values and based on answers to multiple choice questions. The resulting ratings are either “intact”, “degraded” or “lost/not present”. Water quality (pollutant removal) assessment is divided into sediment trapping and nutrient attenuation. Water level fluctuation is deemed important because impounded or standing water acts as sediment trap by slowing water and giving solids time to settle out. Longer retention time and the extent of coverage by wetland vegetation enhance nutrient uptake and suspended solids removal. Wetlands with larger surface areas or connected clusters of smaller wetlands have a greater capacity to improve water quality.

Hydrologic control (flood control and water supply) are defined as the ability to reduce peak flood flows and ability to slowly release long-term stored water (flow conservation). Assessment is based on location within the 100-year floodplain (leads to greater opportunity to store water from flooding), evidence of flooding or ponding (indicates fluctuations in water level and thus water storage), wetland size (increases ability to store water), and lack of outlet increases flood storage potential and slower release of water. dense, tall (>6 ft) woody vegetation (slows the velocity of flood flows), location in the watershed (if upstream from developed areas, its ability to control floods becomes more important). Finally, if the dominant land use is urban or agricultural, increased runoff occurs and the opportunity for flood storage is considered higher.

Smith, R., D. A. Ammann, C. Bartoldus, and M. M. Brinson. 1995. An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands, and functional indices. US Army Corps of Engineers Wetlands Research Program Tech Report WRP-DE-9.

This document is the official guide for developing and applying the hydrogeomorphic (HGM) assessment approach to a regional class of wetlands. The HGM approach to functional assessment was developed for use within the context of the Clean Water Act Section 404 Regulatory Program. It seeks to improve on a variety of functional assessment methods that have failed to achieve widespread use for various reasons. In general, the HGM approach is similar to Habitat Evaluation Procedure (USFWS 1980), the Index of Biological Integrity (Karr et al. 1986) and other indices. Wetlands are highly variable, thus the classification of wetland types according to their HGM characteristics focuses the functional assessment process and narrows the range of values used to calibrate the functional indices. Brinson (1993) developed the HGM classification system to identify groups of wetlands that

function similarly. To date, HGM models have been developed for several ecosystems, such as the Northern Gulf of Mexico Salt Marsh, and Nebraska Rainwater Depressional Wetlands ecosystems. However models for many ecosystems have not been completed. There is presently no HGM model for Coastal Prairie wetlands in the Northern Gulf of Mexico.

The approach consists of a development phase and an application phase. The development phase classifies wetlands into regional subclasses based on hydrogeomorphic factors followed by a description of the wetland including the functions that are most likely to be performed. The characteristics of the wetland that influence how those functions are performed are included and reference wetlands are selected to represent the range of variability exhibited by the regional subclass. Assessment models are constructed and calibrated by an interdisciplinary team based on reference standards and data from reference wetlands. Reference standards are the conditions exhibited by the undisturbed, or least disturbed, wetlands and landscapes in the reference domain. The functional indices resulting from the assessment models provide a measure of the capacity of a wetland to perform functions relative to other wetlands in the regional subclass.

The application phase, which may be performed by a consultant, regulatory staff, or other end user, includes the characterization of the wetland, assessment of its functions, analyzing the results of the assessment, and applying them to a specific project (e.g. impact of fill and resulting mitigation). The main uses of the assessment results have been to compare project alternatives, determine impacts of a proposed project, avoid and minimize impacts, determine mitigation requirements or success, and other applications.

The general order of activities involved in developing an HGM model is as follows:

1. Classify the wetland according to hydrogeomorphic characteristics
2. Develop a functional profile
3. Identify reference wetlands
4. Develop assessment models with indices for each function
5. Calibrate models using reference wetlands

The HGM classification is based on geomorphic setting, water source, and hydrodynamics. Geomorphic refers to the landform of a wetland, its geologic evolution, and its topographic position in the landscape (e.g. depressional landform in top of watershed). Water source refers to the location of water just prior to entry into the wetland (e.g. precipitation, groundwater, surface runoff, river flow). Hydrodynamics refers to the energy level of moving water, and the direction that surface and near-surface water moves in the wetland (e.g. floodplain high energy, movement from upstream to downstream, isolated wetlands have less energy).

Wetland functions are defined as the normal or characteristic activities that take place in wetland ecosystems or simply the things that wetlands do. Wetland function can be viewed as simple to complex (e.g. ecological integrity->biogeochemical cycling -> nutrient cycling ->nitrogen cycling ->denitrification). Not all wetlands perform all functions to the same

degree or magnitude, if at all. The regional HGM classification should result in an appropriate list of functions that the wetlands are likely to perform.

The functional indices provides an objective, documented method for comparing changes in a wetlands capacity to perform a specific function. Functional capacity is defined as the degree to which an area of wetland performs a specific function. It can be quantitatively or qualitatively measured. For example, the functional capacity of a wetland area to store floodwater on an annual basis can be measured in terms of cubic or acre feet per year or estimated to be high or low. The functional capacity is determined by characteristics of the system such as hydrologic regime, plant species composition, and soil type, the nature of the larger systems that surround the wetland, and regional factors such as climate and geology. Because the purpose of the HGM approach is to predict or measure change in wetland functional capacity, the reference standard serves as the optimal condition. The reference standards are the conditions under which the highest, sustainable functional capacity occurs across the suite of functions that are naturally performed by a wetland ecosystem. It is assumed that the highest function is achieved in systems and landscapes that have not been subject to long-term anthropogenic disturbance.

Assessment models are simple representation of the relationship between attributes of the wetland ecosystem and the surrounding landscape, and the functional capacity of the wetland. Variables in the assessment model are assigned a sub index value from 0.0 to 1.0 according to their similarity to the reference standard. As the condition deviates from the reference standard, it is assigned a progressively lower sub index that reflects the decrease in functional capacity. Variables values may be based on quantitative or qualitative scale data. When direct data are not available, it may be possible to assign a sub index based on an indicator. For example, if flood frequency is the variable, and data are not available, indicators may be evidence of recent flooding such as fresh piles of wrack, silt on litterfall, bryophte-lichen patterns, etc. The interaction between variables is defined using an aggregation function or logical rules. The result is a functional capacity index (FCI), which is the ratio of the FC under existing conditions to the FC under reference standards. For example, wetlands with a FCI of 1.0 exhibit conditions similar to reference standards, whereas a FCI of 0.1 perform functions at a minimal level, but retain the potential for recovery. An FCI of 0.0 indicates a permanent loss of function. The actual development of assessment models is accomplished by multidisciplinary teams using literature, their expertise and experience, and information from reference wetlands. The models may be adaptations of generic assessment models from national guidebooks for other classes (e.g. riverine, depressional, etc.), which should be considered templates for developing regional subclass models.

Calibration of assessment models uses information from reference wetlands to establish reference standards and calibrate assessment model. There are a variety of approaches to calibration, from best professional judgment to multivariate techniques.

Solomon, R. C. and N. R. Sexton. *Methods for Evaluating Wetland Functions*. WRP Technical Note WG-EV-2-2. May 1994. 17 pp.

This technical note reviewed 17 methods for evaluating wetland function such as Habitat Evaluation Procedure, Habitat Assessment Technique, WET, and Ontario Method. Wetland functions were grouped into four broad categories: hydrology/water quality; landscape integrity; fish and wildlife habitat, and recreation. All 17 methods used 82 variables to assess hydrology/water quality and these are listed in a table. However many of these are not truly variables, but rather descriptions of function (e.g. “contribute to groundwater quality” or “erosion control”). Actual variables should be observable or measurable attributes of the individual wetland (e.g. flooding duration, nutrient levels, water depth, vegetation cover type, size of wetland, proximity to other wetlands, position within watershed, etc.). WET used the greatest number of variables for hydrology/water quality (28) and several used 12 variables. The hydrology/water quality function had 18 variables that were common to at least three methods. A suggested reading list is included.

Stutheit, M. C. Gilbert, P. M. Whited, and K. L. Lawrence. 2004. A regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of rainwater basin depressional wetlands in Nebraska. ERDC/EL TR-04-4.

This HGM model assesses water storage and water quality functions for rainwater basin depressions in Nebraska. These are semi-permanent, perched wetlands not normally connected to groundwater and are typically dry in summer. The water storage function is defined as the capacity of the wetland to store water primarily from precipitation and snow-melt. Water losses are through evapotranspiration and seepage. Characteristics that influence the function include wetland outlet, hydrologic modification, source of runoff, sedimentation inputs, upland land use, soil pores and structure. The first three variables are multiplicative and thus have the ability to drive the index to zero.

The nutrient cycling model, referring to the annual turnover or release of nutrients, suggests the following independent quantitative measures for validating the index: standing stock of living and dead biomass (g m^{-2}), net annual primary productivity (g m^{-2}), annual accumulation of organic matter (g m^{-2}) and annual decomposition of organic matter (g m^{-2}). The model variables are vegetation composition, wetland land use, soil pores and structure, and wetland outlet. The second water quality function addressed is the removal, conversion or sequestration of elements, compounds, and particulates. This model includes nitrogen and other nutrients, so is different than nutrient cycling, which stresses the dependence of energy flow and food web support on nutrient cycling. Thus this function more closely addresses the pollution remediation aspect of water quality function. Six equally weighted variables influencing this function are: grassland width, upland land use, wetland land use, sediment, wetland outlet, source area of flow, soil pores and structure. The model has two categories of characteristics and processes that influence this capacity: transport of the elements to the wetland and structural components. They are averaged because they are considered to be interdependent and equally important. The arithmetic average allows for some variables to drop to zero without resulting in complete loss of function. Appendix B in the document provides methods and guidelines for collecting data and information relating to all variables in these models.

Thiesing, M. A. An evaluation of wetland assessment techniques and their applications to decision making. U.S. Environmental Protection Agency Region 2. New York. 9 pp.

This unpublished paper argues that most “early” assessment methods focus on a single site and thus ignore macro-scale, landscape and system-level processes which are critical for conservation of biodiversity. By contrast, more recent methods seek to protect whole watersheds and thus evaluate populations of wetlands against reference wetlands in that landscape. The author compares the most commonly used wetland assessment procedures and classifies them into four general types: inventory and classification, rapid assessment protocols, data-driven assessment methods, and indices of biotic integrity. The inventory technique relies on GIS, aerial photography, etc. Data-driven methods are typically model-based and have a higher degree of reproducibility and predictive value. The author provides recommendations for improving the way that we incorporate wetland assessment into decision-making, including setting clear goals, always having reference sites, and recognizing what elements will not be identified by the chosen method.

Tiner, R. W. 2003. Correlating enhanced National Wetlands Inventory data with wetland functions for watershed assessments: A rationale for Northeastern U.S. wetlands. U.S. Fish and Wildlife Service, National Wetland Inventory Program, Region 5, Hadley, MA 26 pp.

This document addresses the need to expand the Cowardin-based wetland classification data attached to National Wetland Inventory databases so as to include information relevant to Brinson’s HGM approach. The proposed method is called “Watershed-based Preliminary Assessment of Wetland Functions” (W-PAWF) and it simplifies the relationships between wetlands and various functions into a set of practical criteria or observable characteristics. W-PAWF does not typically include opportunity to provide function, or condition of adjacent upland or runoff. Ten functions may be evaluated with W-PAWF including surface water detention, coastal storm surge detention, nutrient transformation, and sediment and other particulate retention. As an example, surface water storage function was rated according to wetland type (e.g. lotic basin, lotic floodplain, lentic fringe, etc.), rather than wetlands with specific soils, watersheds, vegetation, or other characteristics.

Preliminary projects to develop indicators for wetland landscape position, landform and water flow path were undertaken in several eastern watersheds. Correlations were developed between wetland characteristics recorded in the NWI database and wetland functions. The correlations reflect the authors’ best approximation of what types of wetlands are likely to perform certain functions at significant levels based on the information included in the wetland database. On the watershed scale, where individual field visits are impractical, they propose a preliminary assessment based on remotely sensed information. This does not, however, replace the need for field evaluations, the ultimate assessment of the function for individual wetlands. The more generalized assessment (level 1) is worthwhile for targeting wetlands that may provide certain functions, especially those dependent on landscape position, landform, hydrologic processes, and vegetative life form.

Zahina, J. G., Saari, K., Woodruff, D. A. 2001. Functional assessment of South Florida freshwater wetlands and models for estimates of runoff and pollution loading. South Florida Water Management District, Tech. Publ. WS-9.

This work addressed the need to identify important landscape functions of South Florida's wetlands and to describe methods for evaluating how well these functions could be met under different planning strategies. The approach uses GIS and is based on landscape ecology concepts, and is a synthesis of HGM and WET 2.0 and GIS approaches. The document also has an excellent review of water quality and water storage processes in wetlands. The report has separate methodologies for wetland assessment, pollution risk analysis, and basin runoff and pollution loading estimates. The functional capacity assessment is based on the inherent capacity to mitigate a pollution type. The pollution risk method is based on the risk of receiving that pollutant, respectively. Both provide a qualitative rank (low, medium, high), whereas the runoff model is quantitative.

The inherent capacity to improve water quality is a function of the physical biological and chemical characteristics of the wetland and it is separate from the pollution risk, which is a function of surrounding landscape, land uses, and other anthropogenic activities. The combination of functional capacity and pollution risk provide a functional analysis that allows water managers to evaluate where water quality problems are most or least likely to occur and why. Qualitative ratings are derived for each function and pollutant.

The potential runoff and pollution loading methods consider land use type, rainfall volume, soil type, and the presence or lack of on-site treatment systems, to estimate the runoff volume. The period of time for which runoff is calculated can be varied.

Pollution mitigation models addressed major pollution mitigating mechanisms (e.g. denitrification, sorption, settling) and the following pollutants: N, P, micronutrients, heavy metals, suspended solids, pathogens, and pesticides. Models are based on extensive literature reviews that identify the major mechanisms that reduce pollutants in wetlands. Databases were GIS tables of values derived from ground-based and remotely sensed observations or analysis such as USDA's National Soil Survey Handbook 1993). Runoff and leaching characteristics for soils were taken from NRCS and wetlands were delineated using NWI GIS Images.

Nitrogen is the most mobile nutrient and subject to the greatest loss from wetlands through processes such as denitrification, volatilization, ammonium fixing, and leaching. Although nitrogen is stored in living and dead plant tissue, denitrification and ammonium fixing provide the greatest mechanism for nitrogen losses. Denitrification is mediated by soil organic matter and soil microbes under anaerobic conditions. Denitrification rates are related to soil pH, available nitrate, the presence of organic matter, and temperature (optimal 25 C, if too cold rates low). The denitrification model assigns a high potential N removal rating to nonacidic soils (denitrifying bacteria are sensitive to low pH) with moderate to high soil depth (process occurs in soil column), some organic matter present (carbon source), low to moderate leaching potential (loss of nitrate to groundwater), and low to moderate soil runoff potential. A table is provided that summarizes these conditions. Ammonium fixing to soil

particles occurs in soils depending on the soils: clay content (enhances), organic content (interferes with), cation exchange capacity (CEC), hydrology (regular wet dry cycles best) and pH (nonacidic best). Soils with high potassium are not efficient ammonium fixing soils. The ammonium fixing model assigns a high potential to nonacidic soils with high amounts of clay (with high CEC), low organic matter content, moderate to high active zone depth, low to moderate runoff potential, and a wet-dry hydrology.

Phosphate has a strong tendency to adsorb on colloidal surfaces and will readily form insoluble complexes with divalent and trivalent cations. P can be readily immobilized as calcium, iron, or aluminum phosphates. P has been shown to adsorb strongly on calcium carbonate and this is believed to be why calcium and carbonate-rich sediments contain generally low concentrations of dissolved phosphate in their pore waters. Under low pH soil conditions with high Al or Fe, P binding is enhanced by fluctuating oxic-anoxic conditions (wet-dry cycles). Thus the presence of a spodic layer in porous acidic soils, and the formation of apatite in alkaline soils offer the greatest P removal potential. Although soil organic matter does not sorb P well, it indicates P storage in undecayed plant material. A high rating is assigned to wetlands with alkaline soil, and low to moderate runoff potential and a low rating to wetlands with acidic nonspodic or thin soils.

The micronutrient model addresses iron, zinc, manganese, copper and boron. Major removal mechanisms include binding to sediment or particulates, incorporating precipitated insoluble complexes. Uptake and long-term storage by the plant community is also an important mechanism. Binding to soils occurs via cation exchange or chelation (divalent and trivalent bonds with humic substances). Solubilities of metals are pH-controlled (most soluble when slightly acidic = 5.0-6.5). Media pH greater than 7.0 can result in limiting conditions, primarily due to the formation of insoluble complexes, while media pH below 4.5 can lead to toxicity. Wetlands with nonacidic soils and high organic matter or clay contents with high CEC, and low to mod runoff potential were assigned a high rating. A low rating was assigned to wetlands that had acidic conditions, little to no soil, or soils low in organic matter or clay.

Heavy metals (e.g. mercury, cadmium, lead) may also be complexed in high pH soils with clay and organic matter (highly insoluble carbonates, sulfates, phosphates). A high rating is assigned to wetlands with nonacidic soils with high organic matter or clay contents, and low to moderate runoff potential. A low rating is assigned to those with acidic conditions, little to no soil, or low in organic matter or clay.

Long-term uptake and storage of nutrients in wetland plants varies significantly as a function of the community species composition. Most nutrient uptake is from the soil, although some species absorb directly from the water column. Floating plants (e.g. water hyacinth) wetland have rapid uptake rates. Emergent-dominated wetlands have high nutrient removal potentials and productivity that can be affected by nutrient loading. The accretion rates of organic matter (a mechanism of nutrient storage) can be substantial and is often the result of prolonged hydroperiod which promotes anoxia and thus retards decomposition at the soil-surface water interface. Wetlands dominated by woody vegetation have slower uptake rates but greater potential for total long-term storage.

The results from these analyses are available online, in electronic format, with the ability to generate maps or GIS coverages. The authors advise that their approach was one of synthesis of available information and accuracy of results is only as accurate as the original data sets. Also, should be used as a landscape-level analytical tool. Also, this is only one of several wetland functional assessment approaches.