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A Hydrogeomorphic Classification for Wetlands

by Mark M. Brinson

August 1993 – Final Report

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	Task		Task
CP	Critical Processes	RE	Restoration & Establishment
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Wetlands Research Program

Technical Report WRP-DE-4
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A Hydrogeomorphic Classification for Wetlands

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Final report

Prepared for U.S. Army Corps of Engineers
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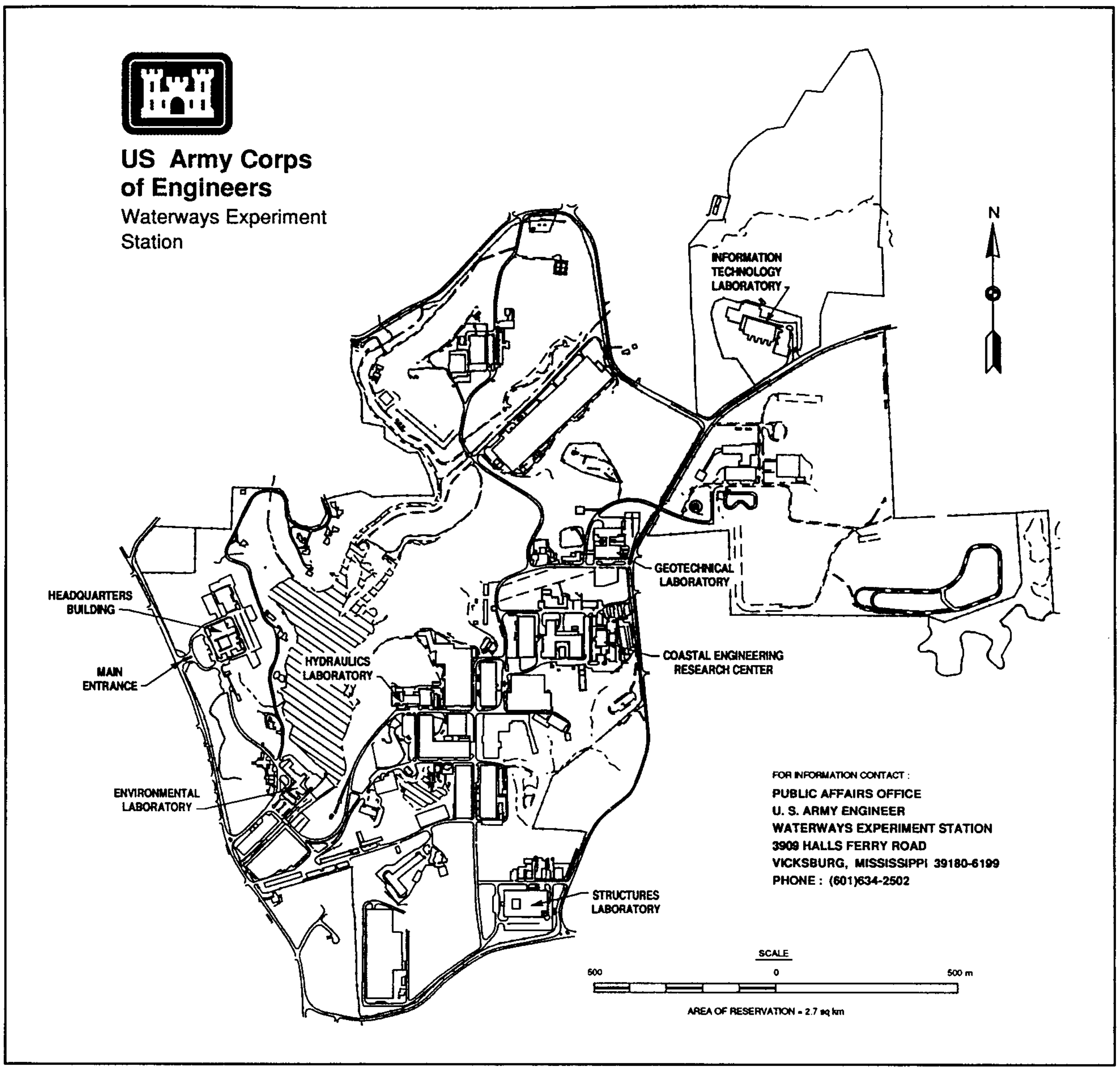

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Wetland Functions

A Hydrogeomorphic Classification for Wetlands (TR WRP-DE-4)

ISSUE:

Under the Corps 404 Regulatory Program, the permit review process requires assessing the effect of a project on wetland functions. Many of the currently available methods fail to address critical technical and programmatic requirements.

RESEARCH:

The hydrogeomorphic classification of wetlands is intended to lay a foundation for and support ongoing efforts to develop methods for assessing the physical, chemical, and biological functions of wetlands. Strengths of the classification include its ability to clarify the relationship between hydrology and geomorphology and wetland function, and its open structure, which allows adaptation in various types of wetlands and geographic regions of the country.

SUMMARY:

This report outlines a classification of wetlands based on the wetland hydrogeomorphic properties of geomorphic setting, water source, and hydrodynamics. Indicators of function are discussed as derivatives of the three basic properties, along with the ecological significance of each of the properties. Development of "profiles" that reveal the functions that wetlands are likely to perform is discussed.

AVAILABILITY OF REPORT:

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About the Author:

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Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Delineation and Evaluation Task Area of the Wetlands Research Program (WRP). The work was performed under Work Unit 32756, for which Mr. R. Daniel Smith was Principal Investigator. Mr. John Bellinger (CECW-PO) was the WRP Technical Monitor for this work.

Mr. Jesse A. Pfeiffer, Jr. (CERD-C), was the WRP Coordinator at the Directorate of Research and Development, HQUSACE; Mr. William L. Klesch (CECW-PO) served as the WRP Technical Monitor's Representative; Dr. Russell F. Theriot was the Wetlands Program Manager. Mr. Ellis J. Clairain, Jr., was the Task Area Manager.

This work was performed by Dr. Mark Brinson at East Carolina University, North Carolina. Mr. R. Daniel Smith, Wetlands Branch, Environmental Laboratory (EL), was the Project Manager under the general supervision of Mr. E. Carl Brown, Chief, Wetlands Branch, EL; Dr. Conrad Kirby, Chief, Ecological Research Division, EL; Dr. John Keeley, Assistant Director, EL; and Dr. John Harrison, Director, EL.

The hydrogeomorphic classification of wetlands described in this report was intended to lay a foundation for ongoing efforts to develop methods for assessing the physical, chemical, and biological functions of wetlands. Strengths of the classification include clarification of the relationship between hydrology, geomorphology and wetland function, as well as the open structure, which allows adaptation in various types of wetlands and geographic regions of the country. The classification is not intended to replace or displace other wetland classifications such as the U.S. Fish and Wildlife Service's Classification of Wetlands and Deepwater Habitats, which are well suited for the purposes for that they were designed.

Much of the credit for the hydrogeomorphic classification can be attributed to the many pioneers who have demonstrated the relationship between ecosystem structure and function. Dr. J. Henry Sather saw the critical need to further develop functional assessments, and was instrumental in initiating the development of a hydrogeomorphic procedure. The manuscript benefited from the detailed written comments of Mr. Garrett Hollands and Drs. Frank Golet, Katherine Ewel, Daniel Hubbard, and more recently, Dr. Robert

Beschta and Ms. Sydney Bacchas. Earlier work with Drs. Ariel E. Lugo and Sandra Brown helped to solidify the author's perspective on hydrogeomorphic classification. Credit goes to Dr. Robert Christian for providing alternative viewpoints and for suggesting the paper by Slobodkin et al. (1980) for consideration.

Participants of the Stone Mountain Workshop, who discussed the classification and the emerging assessment procedure, were as follows: Dr. Alan Amman, Dr. Candy Bartoldus, Dr. Virginia Carter, Mr. Ellis J.Clairain, Jr., Dr. David Cooper, Dr. Lewis Cowardin, Mr. Charles DesJardins, Dr. Katherine C. Ewel, Mr. Lloyd Fanter, Dr. Frank Golet, Dr. Jan Hoover, Dr. Courtney Hackney, Mr. Garrett Hollands, Dr. Dan Hubbard, Dr. Roy Johnson, Mr. Jack Killgore, Ms. Barbara Kleiss, Ms. Kathy Kunz, Dr. Joseph Larson, Dr. Lyndon Lee, Dr. Edward Maltby, Mr. Thomas A. Muir, Mr. Richard Novitzki, Dr. Jean O'Neil, Mr. Bruce Pruitt, Dr. J. Henry Sather, Mr. Rick Schroeder, Dr. Paul Shuldiner, Mr. Bill Sipple, Mr. R. Daniel Smith, Dr. Arnold van der Valk, and Dr. William Wilen. Norman Van Horne prepared some of the figures, and Eileen Nordlie edited several drafts of this report at East Carolina University.

At the time of publication of this report, the Director of WES was Dr. Robert W. Whalin. The Commander was COL Bruce K. Howard, EN.

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1 Introduction

Purpose

This manuscript introduces a classification approach for wetlands[1] that places emphasis on the hydrologic and geomorphic controls. These controls are apparently responsible for maintaining many of the functional aspects of wetland ecosystems. The approach places emphasis on the importance of abiotic features of wetlands for such functions as the chemical characteristics of water, habitat maintenance, and water storage and transport. An attempt has been made to keep it robust enough to accommodate all wetland types. It is hoped that it also is flexible enough to accommodate the continua that exist among wetland types, between wetlands and uplands, and between wetlands and deepwater ecosystems. An effort has been made to keep the classification simple enough so that the user can learn it quickly, and, in the process, progressively can gain insight into the functioning of wetland ecosystems through practice. The approach is completely open to revision and correction as additional information becomes available.

The focus on abiotic features of wetlands is not meant to ignore or trivialize the importance that organisms play in the structure and function of wetland ecosystems. In contrast, it is hoped that by using the approach, it will lead to a better understanding of the relationship between organisms and the environment. Other classifications, for very good reason, have placed great emphasis on the structure and species composition of the plant community. For example, the Fish and Wildlife Service's Wetland Classification system (Cowardin et al. 1979) relies largely on vegetative cover because the type of plant cover (or the lack of it) is the kind of information that can be reliably interpreted from aerial photographs. This allowed the classification to meet one of its major goals of providing the basis for tracking changes in the surface area of wetlands over time through the National Wetland Inventory. However, the present goal is to place emphasis on features of wetlands that are relatively independent of the biogeographic distribution of species. Species composition of plant communities,

[1] A glossary of terms is presented in Appendix A.

in theory, should be irrelevant to this classification because it relies almost exclusively on geomorphic, physical, and chemical descriptors. In practice, however, vegetation often provides important clues of hydrogeomorphic forces at work in an ecosystem. Also, vegetation structure, especially the distinction between forested wetlands and marshes, may play a fundamental role in the capacity of the wetland to serve as habitat for birds, mammals, and other groups. Hence, familiarity with the adaptations and tolerance limits of plant and animal species is a necessary skill for successful classification within a given biogeographic region.

Ideally, this classification should interface logically with existing regional classifications that place emphasis on hydrogeomorphic descriptors. If such regional classifications do not exist, it is hoped that this approach can provide a convenient template upon which to build a locally or regionally useful system. Once those tools are developed, the biotic components should be drawn into the classification process.

The classification is limited to aggregating wetlands with similar functions. It is not intended to be a "valuation" procedure that ranks one wetland relative to another for specific functions. While there may be some merit to using this classification as a starting point for ranking functions, assessment procedures are beyond the scope of this report. Chapter 5 discusses how the transition can be made from classification to assessment procedures. Neither does the classification rank wetlands according to their capacity to provide a service of value to society. This does not mean that functions of wetlands are "value free," but that ecosystem function is based only on factors essential to the maintenance of the wetland itself and its associated ecosystems. Factors that contribute to the well-being of society are omitted in part because such values are prone to vary over time and geographic region (Lugo and Brinson 1979).

As presented here, the classification lacks the resolution to distinguish among the many types of wetlands that commonly are recognized within a geographic region (i.e., bald cypress versus water tupelo swamps; red maple versus buttonbush; willows versus balsam poplar). This is intentional for two reasons: (a) hydrogeomorphic classifications by their very nature are not designed to be sensitive to species composition of vegetation, and (b) this report describes a generic approach to classification and not a specific one to be used in practice. Rather, the approach is described so that an array of existing wetlands in a geographic region can be assigned hydrogeomorphic classes that will reveal better their ecosystem functions.

Unlike classifications that depend solely on information that can be collected within the wetland, this classification requires that factors external to the wetland be recognized. One cannot classify, for example, a hectare of seasonally flooded bottomland without at least implicitly recognizing that it is part of a larger floodplain and watershed complex. The attributes of a particular hectare of wetland, such as the source of the water for a site, are intrinsic properties of that hectare even though they are derived from a much larger geographic area.

One of the distinguishing properties of the classification is the emphasis on what might be considered "first principles" of wetland function. While it has become trite to say that hydrology is the most important variable that distinguishes wetlands from other ecosystems and wetlands from each other, there has been insufficient quantitative work to reveal why and how hydrology influences wetland type. One of the tools that can be developed during the process of classification is a "functional profile" that is derived from the ecological significance of the functions determined during the classification process. This concept will be described more fully in the section "Profile Development."

Meaning of Ecosystem Function

In the literature on the assessment of wetlands, it is common to refer to "functions and values." The implication is that wetlands are functioning in a way that society perceives as valuable, so there is no effort to make a distinction between the two terms. In addition, "values" has been used to indicate that certain functions are "valuable" to wildlife, whereas the terms "essential" or "beneficial" are more neutral and appropriate terms. Taylor, Cardamore, and Mitsch (1990) draw a distinction between functions and values by pointing out that values are the goods and services that emanate from functions. The present classification stops short of discussing values because the intent is to classify wetlands according to their hydrogeomorphic properties, not their potential value to society. By limiting the analysis to science, issues can be avoided that deal with which value is more important than others. As it turns out, however, most of the functions that are attributable to wetlands also have a corresponding societal value. It is possible that the bias invoked in placing emphasis on the better understood functions may cloud the capacity to see and understand more fundamental functions that have yet to be articulated.

An example of the difference between functions and values is the removal of nitrate from surface and groundwater by wetlands. It is common that nonpoint sources of nitrate are intercepted from agricultural and urban landscapes by wetlands (Kuenzler 1989). The societal service is improved water quality because of lower nitrate concentrations. Clean water is perceived to have societal value as recognized in legislation such as the Clean Water Act. The ecosystem function is the removal of nitrogen by denitrification. Denitrification (as well as other attendant microbial and nonmicrobial processes) is the critical mechanism that allows this to occur.

Another way to distinguish among mechanisms, functions, values, and related properties is to recognize that functions exist in the absence of society and are normally part of the self-sustaining properties of an ecosystem. The relationship among these properties is illustrated in Figure 1.

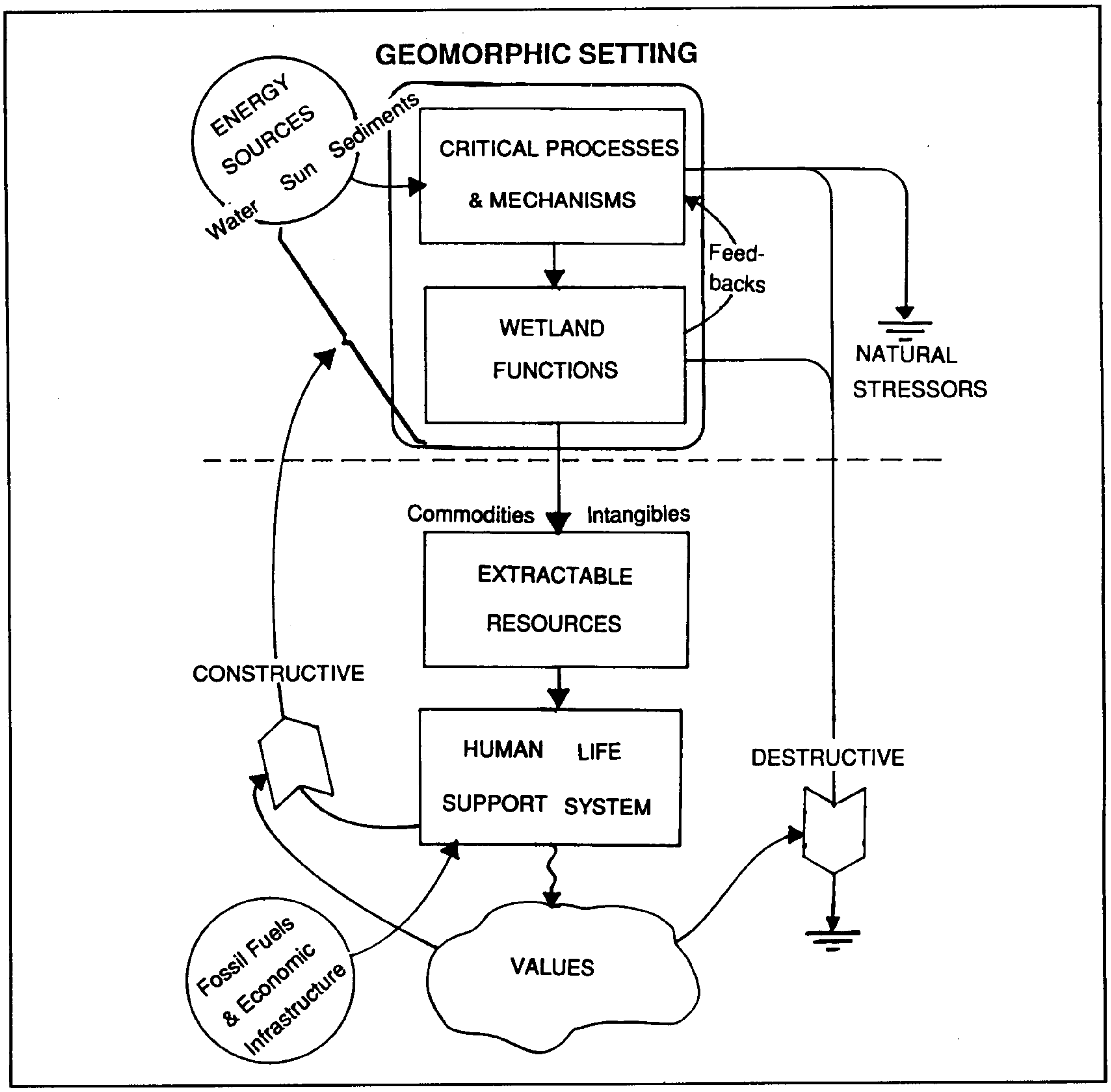

Figure 1. Diagram that conceptualizes the relationship between wetland functions and wetland values. The dashed line separates the geomorphic setting, which contains wetland functions, from societal interaction with wetlands. Items above the dashed line can continue in the absence of society; those below show the "uses" of wetlands by society. Critical processes and mechanisms (e.g., photosynthesis, microbial activity, and decomposition) and ecosystems functions (e.g., primary productivity, biomass accumulation, and nutrient cycling and retention) may become resources for human life support. The term extractable resources is meant to include intangibles, commodities, and all other goods and services that contribute to the human life support system. Note that human life support relies both on wetlands in their geomorphic settings and fossil fuels. Feedbacks initiated by societal values can be either constructive or destructive. While values are merely perceptions, they establish how the life support system interacts with the wetland resource. Adapted and modified from Twilley (personal communication, 1990, University of Southwestern Louisiana, Lafayette, LA), Taylor, Cardamore, and Mitsch (1990), E. Maltby (personal communication, 1990, University of Exeter, Exeter, U.K.), and Whigham and Brinson (1990)

However, others argue that human uses should be incorporated into classifications.[1] While this has much merit given the dependence of some societies on wetland functions, especially those in the tropics (Welcomme 1979), the approach would be better reserved for classifications designed to distinguish different types of human uses rather than hydrogeomorphic classes, the goal sought by the present document. Regardless of the functions and whether they are perceived as having utility during a given decade or by a particular culture, an anthropocentric goal of management for ecosystems worldwide should be to maintain ecological processes, preserve the genetic diversity, and utilize species, populations, and ecosystems in a sustained way (Lubchenco et al. 1991).

Classifications with Hydrogeomorphic Approaches

A number of wetland classification systems use hydrology and geomorphology as the basis for differentiating types of wetlands. Some of these will be reviewed briefly below. One classification of lakes and one of rivers are included because they possess many of the features that are useful to functional classifications of wetlands. The examples given below are not exhaustive, but they provide an overview of past efforts to deal with a large variety of wetland types. Mader (1991) has reviewed the literature on classifications for forested wetlands.

Wetlands

Most classifications of wetlands are designed for use with a restricted range of types or restricted geographic coverage. The approach of Gosselink and Turner (1978), however, can be characterized as geographically neutral. They argue that the hydrologic characteristics of wetlands influence four ecosystem attributes: species composition of the plant community, primary productivity, organic deposition and flux, and nutrient cycling. The major "hydrodynamic characteristics" that they propose are water inputs, water outputs, type of water flow, and hydropulses (i.e., seasonality) (Table 1).

The "hydrogeologic" evaluation of O'Brien and Motts (1980) was designed for wetlands of New England and the glaciated northeastern United States. The geologic factors are the composition and thickness of surficial material and the composition of bedrock. Hydrologic factors are hydrologic position (perched, water table, or artesian), permeability of organic layer, depth of surface water, transmissivity of underlying aquifers, groundwater outflow, and water quality. Topographic factors are position within

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[1] Personal Communication, 1990, E. Maltby, University of Exeter, U.K.

Table 1
Major Hydrodynamic Characteristics of Freshwater Marshes[1]

	Raised-Convex	Meadow	Sunken-Convex	Lotic	Tidal	Lentic
Water Inputs						
Capillary	+	+				
Precipitation	+	+	+	+	+	+
Upstream		Little	+	+	+	+
Downstream					+	
Type of Water Flow						
Capillary	+					
Subsurface	+	+	+	+	+	+
Surface			Slow	+	+	+
Overbank				+	+	+
Water Outputs						
Percolation	+	+				
Evapotranspiration	+	+	+	+	+	+
Downstream		Little		+	+	+
Hydropulses	Seasonal	Seasonal	Seasonal	Seasonal	Tidal	Variable

[1] From Gosselink and Turner (1978).

a drainage, absolute size, and size relative to the drainage basin. Various combinations of these factors can be synthesized into major geologic types common to the New England area. The authors present two such geologic types that combine hydrologic and topographic positions to yield a relatively small number of classes. They suggest that further efforts may ultimately allow mapping of hydrologic types.

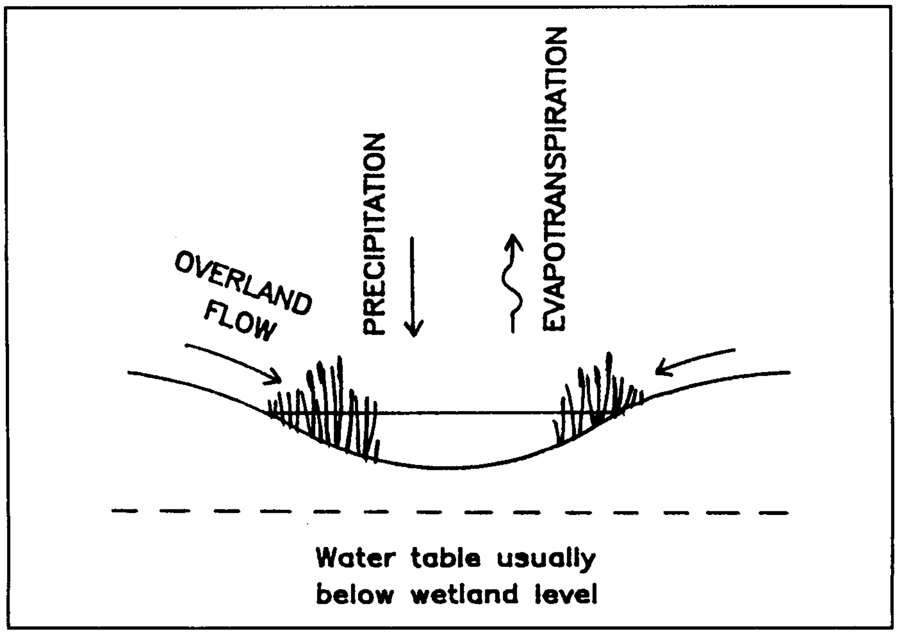
Another classification, applicable also to glaciated regions, is outlined by Hollands (1987) who stated that "In reality, the wetland [vegetation] is only a green fuzz that grows on top of and as a result of this hydrogeologic setting." He identifies (a) six dominant or combined hydrologic types: open water, vegetated without cranberries, active cranberry bog, inactive cranberry bog, perennial stream, ephemeral stream; (b) four surface inflow-outflow situations: inflowing stream only, outflowing stream only, inflowing and outflowing streams, no streams; and (c) three groundwater characteristics: discharge dominated, recharge dominated, and both recharge and discharge. Combinations of these types and situations are described as located within a surficial geologic setting. Hollands also provides a methodology that can be used to acquire the information needed to apply the classification to other geographic regions.

Novitzki (1979) described the hydrologic characteristics of Wisconsin's wetlands with regard to water source and landform. He recognized four: surface water depression, groundwater depression, surface water slope, and groundwater slope (Figure 2). Surface water depressions receive precipitation and overland flow. Losses are through evapotranspiration (ET) and downward seepage into a surficial aquifer. Groundwater depression wetlands, in contrast, intercept the water table, so they receive groundwater in addition to direct precipitation and overland flow. Groundwater slope wetlands differ from the groundwater depressions by having an outlet and also tending to occur on slopes where groundwater has stronger flow than would normally be encountered in depressions. The size of these wetlands corresponds to the quantity of groundwater discharge. Surface water slope wetlands receive water from lake or river flooding, and the water can readily drain back into lake or river as the stages fall. They may be flooded infrequently, as in the cases of floodplains, or permanently, as in the case of lakeside wetlands.

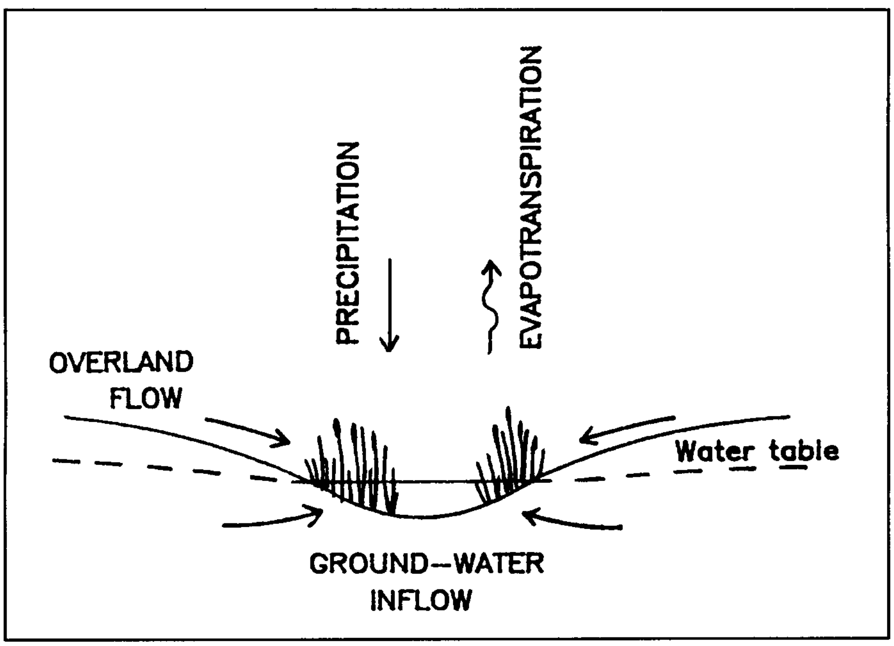
A system has been developed for the hydrologic characteristics of the East Anglian fens (Gilvear et al. 1989). Seven major classes are distinguished based on the relative contribution of water source (Figure 3): (a) surface water runoff and riverine flooding (two subclasses), (b) leaky aquifer with some surface water inputs, (c) surficial aquifer sequences with some surface inflow, (d) both surficial and aquifer sources, (e) leaky main aquifer although some surface water input, (f) groundwater inputs from an unconfined main aquifer, and (g) sources totally from the surficial aquifer. In addition to identifying the water sources, characteristics are given for the surficial stratigraphy, water chemistry, catchment size, and vegetation.

The wetlands of Amazon inundation forests have been classified by Prance (1979) based on water quality and flooding regime (Table 2). River types are divided into white water, a term that encompasses turbid waters that receive their high-suspended sediment load from eroding lands in the steep headwaters of the basin, and either clear water or black water which originate in the lower Amazon basin. The black waters differ from clear waters by having high humic content and low-ion concentrations. Within each of two categories, the flooding regime can be annual (the higher order streams), daily (tidally influenced reaches near the mouth), and irregular (smaller catchment areas that respond to more localized rainfall than the annual regime).

The Canadian system (National Wetlands Working Group 1987) presents five commonly recognized wetland classes (bog, fen, marsh, swamp, and shallow water) and further divides these on the basis of form, of which 70 are identified using surface morphology, surface pattern, water type, and morphology of underlying mineral soil. The lowest level uses the physiognomy of the vegetation.

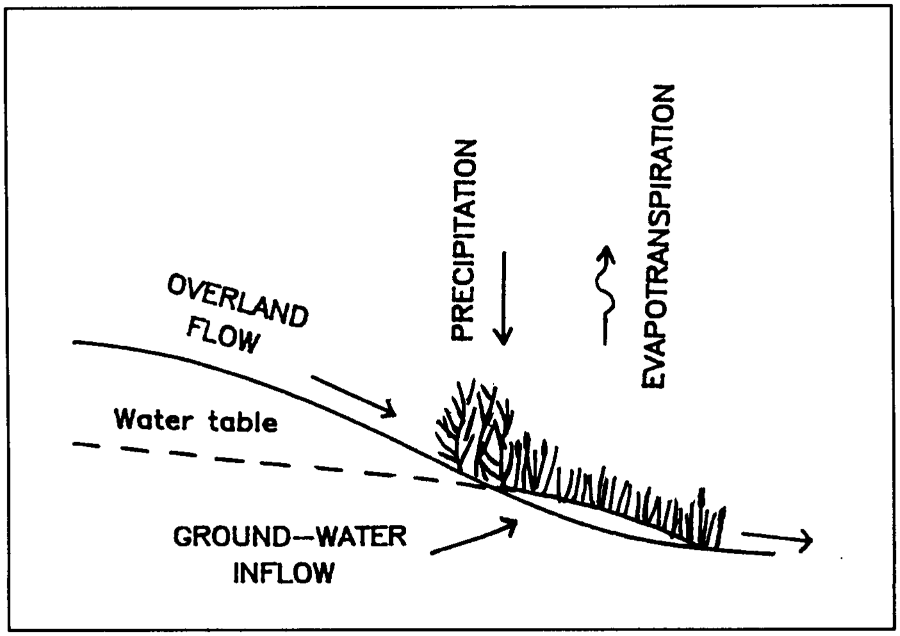


a. Surface water depression

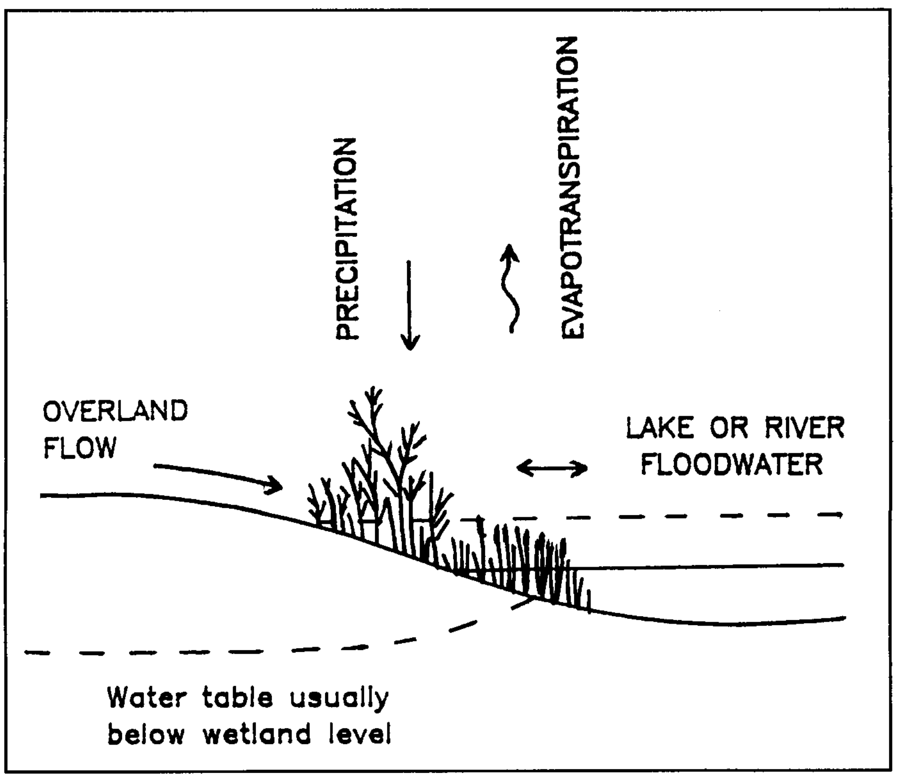


b. Groundwater depression

Figure 2. Four major hydrologic types of wetland types in Wisconsin (Continued)



c. Groundwater slope



d. Surface water slope

Figure 2. (Concluded)

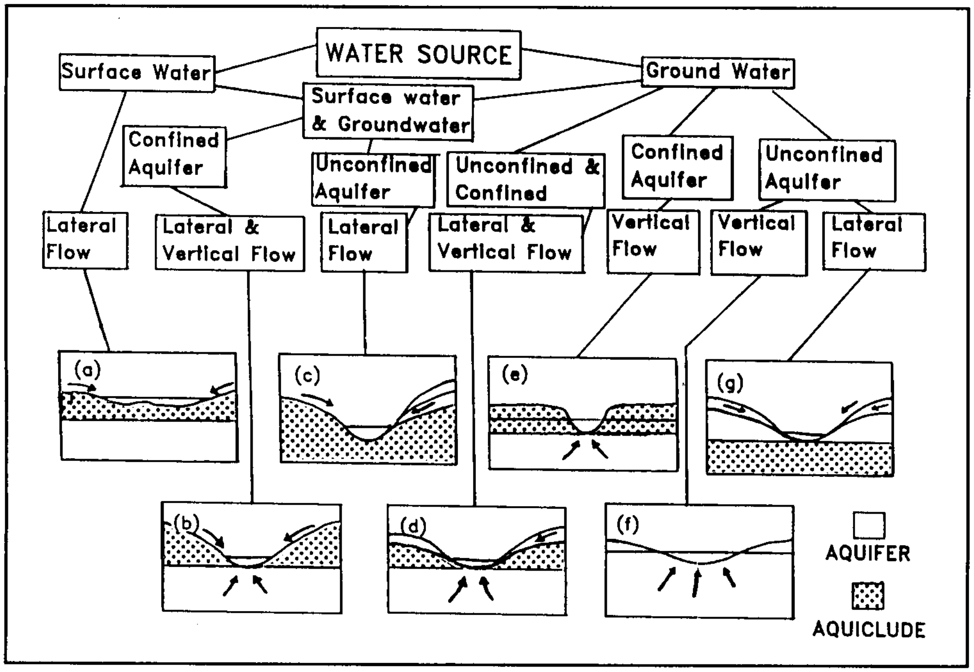


Figure 3. Hydrogeologic classification of Gilvear et al. (1989) for East Anglian fens. Description of wetland classes are as follows: (a) those fed by surface water runoff and wetlands that receive river flooding, (b) those receiving aquifer discharge in addition to some surface water, (c) those fed by surficial groundwater in addition to some surface water, (d) those receiving both surficial groundwater and aquifer discharge, (e) those fed predominately by aquifer discharge with minor surface water input, (f) those fed by unconfined main aquifer, and (g) those receiving total surficial groundwater. Precipitation inputs are assumed similar in all examples

Table 2
Classification of Amazon Inundation Forests[1]

	River and Forest Type	
Flooding Regime	**White Water Várzea Forest**	**Clear or Black Water Igapó Forest**
Annual	Seasonal várzea	Seasonal igapó
Daily	Tidal várzea	Tidal igapó
Irregular	Floodplain várzea	Floodplain igapó

[1] Adapted from Prance (1979).

Tidal wetlands can be divided into those that receive mostly fresh water and those that are exposed to brackish water. In a typical salt marsh, zonation of vegetation appears to correspond to differences in flooding frequency (i.e., tall-form *Spartina alterniflora* in the regularly flooded brackish zone; short-form *S. alterniflora* in the irregularly flooded zone; and other halophytes listed below in the higher elevations that are infrequently flooded by tides). The short-form *S. alterniflora* sites often develop hypersaline pore waters in summer. This additional stressor partially explains the growth form. Where flooding from tides becomes extremely rare, low-salinity marshes develop that are composed of a mixture of species depending in part on geographic location (*Juncus gerardi, J. roemerianus, S. patens, Distichlis spicata,* and *S. cynosuroides*). Tidal freshwater wetlands can range from marshes (Odum et al. 1984) to forested wetlands. Because of a somewhat unique environmental setting in the sounds of North Carolina, Brinson (1989) developed a classification for sea-level controlled wetlands that first differentiated tidal from nontidal, and then freshwater from saltwater (Figure 4). This allowed recognition of hydrologically distinct marshes—ones in tidal regimes (described above) and others in nontidal regimes—both of which were colonized by similar assemblages of halophytes.

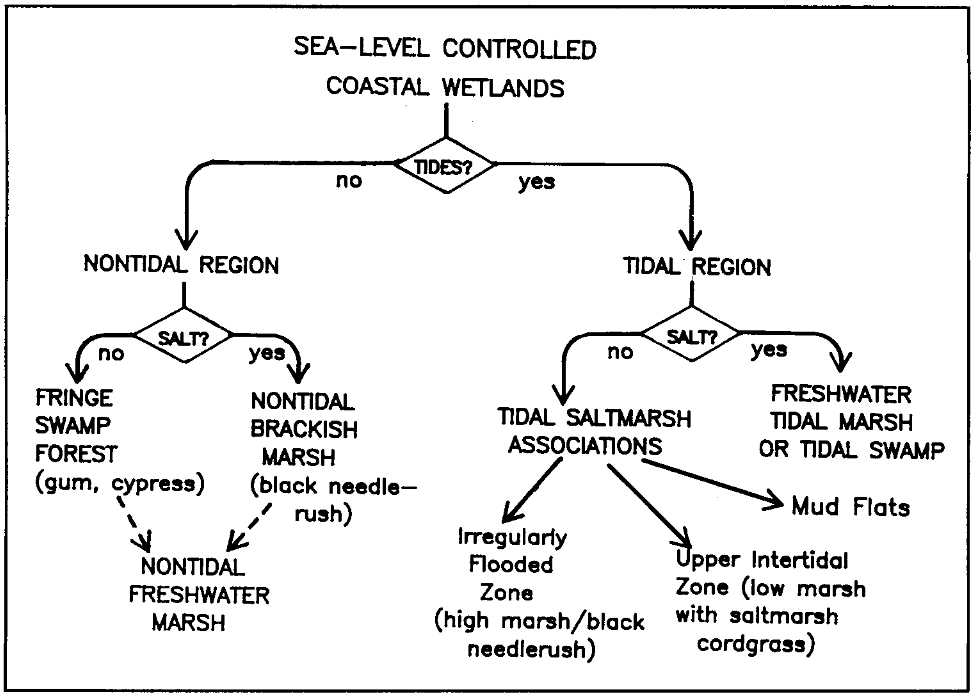


Figure 4. Factors controlling expression of plant community physiognomy and species composition of sea-level controlled wetlands in North Carolina. From Brinson (1989)

Lakes and Streams

As indicated above, classification of lakes from a hydrologic perspective might provide some insight to the differentiation of wetlands. The classical temperature-mixing classes (Hutchinson 1957) are of little use because they rely on thermal stratification of the water column, a property of little significance in the shallow waters typical of wetlands. However, Winter's (1977) classification of hydrologic settings in the north-central United States uses parameters that would apply also to wetlands. These include regional slope, regional position, local relief, ratio of drainage basin to lake area, presence of inlets and outlets, substrate composition, water quality, and the precipitation-evaporation balance. His analysis by principal components methods showed that many of the variables mentioned above had an important influence on classification.

Stream classifications based on morphological characteristics are particularly relevant when they give insight into wetlands in floodplains and riparian zones. Leopold, Wolman, and Miller (1964) still stands as a useful reference for floodplain and stream channel processes. One of the more recent syntheses of stream classification is that of Rosgen (1985). He identifies 25 stream types based on continua within six factors: gradient, sinuosity, width/depth, dominant particle size in channel, channel entrenchment and valley confinement, and landform that includes soil characteristics and descriptors of stability. Additional types are identified for estuarine streams (i.e., deltas—four of them) and glacial streams (two). Stream subtypes require further description of organic debris (10 descriptors), channel width (13 sizes), depositional features (8 bar types), riparian vegetation (10 or more if mixtures occur), flow regime (4 general and 5 specific categories), and meander patterns (8 types). Naiman et al. (1992) provides a historical synthesis on principles of stream classification.

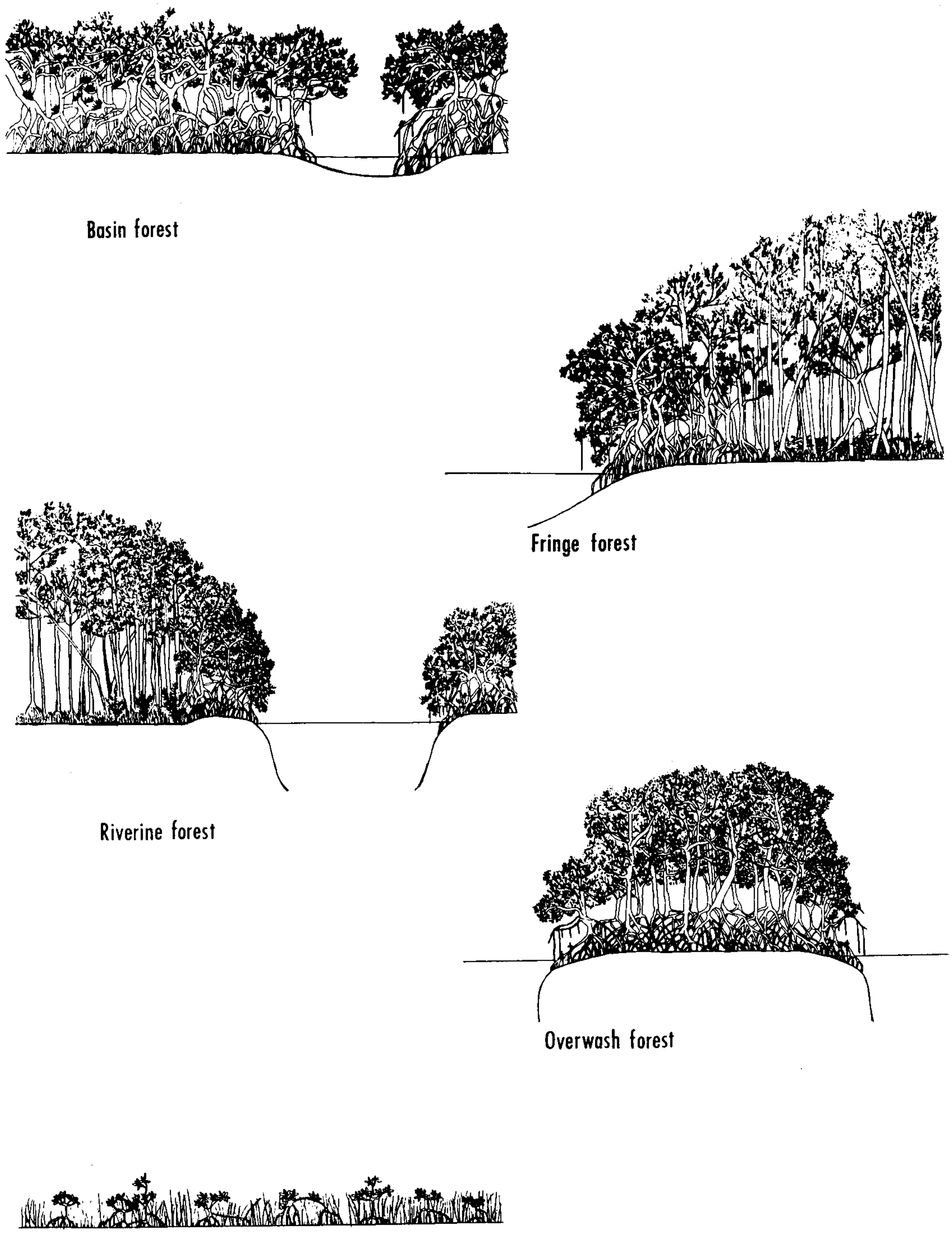
Ontogeny of the Present Classification

Early explorers such as Humboldt and Darwin were very much aware, as illustrated in their writings, of the strong effect of climate on vegetation form and pattern. Merriam (1894) was among the first in the United States to illustrate the parallel properties that gradients in altitude and latitude had on the distribution of plants and animals. Continental maps produced for soils and natural vegetation illustrate at a glance patterns of temperature and moisture (Küchler 1964). Both Holdridge et al. (1971) and Walter (1973) developed elegantly simple approaches to the classification of terrestrial ecosystems based on temperature, precipitation, and derivatives of the two. All of these efforts had one thing in common: they virtually ignored wetlands that are subject to edaphic control rather than climatic control.

The need for functionally based classifications of wetlands is twofold. The first is to simplify our concept of wetlands, recognizing that while each one may be unique, each can be placed into categories in which similar wetlands share functional properties. The exercise of reducing the apparent complexity of an array of ecosystems that change rapidly over time and space should not be taken lightly. The result of this simplification should be improved communication among researchers and managers, and perhaps even with the public, by focusing on processes that are fundamental to the sustained existence of these ecosystems. The other need for functionally based classifications is to foster the development and the redevelopment of paradigms that clarify the relationship between ecosystem structure and function. For example, the Environmental Monitoring and Assessment Program (EMAP)-Wetlands program, which is to follow the "health" of the nation's wetland resources over time, needs to have indicators that are sensitive to the condition of specific wetlands. To what extent do qualitative or quantitative changes in hydroperiod cause wetlands to change and in what way? Are the tools and procedures available to predict the long-term effects of changing the nutrient regime of a wetland? What are the thresholds of the factors that are likely to create a change in state from one wetland type to another? These are all legitimate questions that could be answered from recognizing a set of common denominators to which wetlands respond.

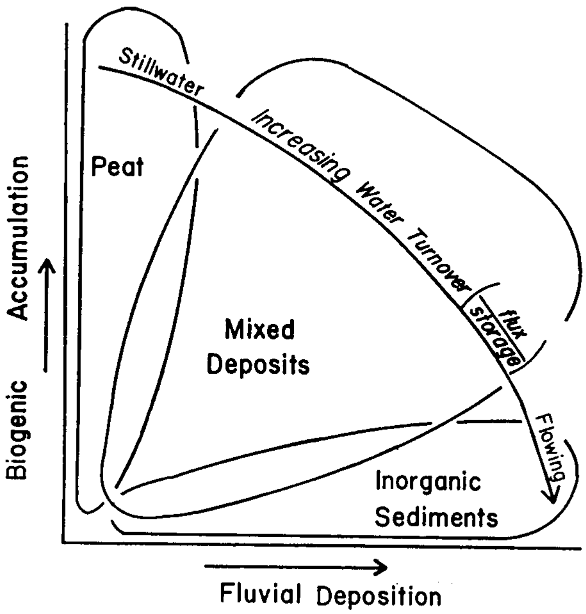
The progenitor of the current classification is the one developed by Odum, Copeland, and McMahan (1974) for coastal ecosystems. They proposed a classification "according to the most prominent processes dominating the functional activity of the system." It was based on a theory of classification "that includes biological, geological, chemical, and physical classification factors, energy being a common denominator." Within each of the six major categories, up to 18 types were identified along with their characteristic energy or source of stress. The major categories (with some examples of representative types) are as follows: (a) naturally stressed systems of wide latitudinal range (high energy beaches and sedimentary deltas), (b) natural tropical ecosystems of high diversity (coral reefs and tropical seagrass beds), (c) natural temperate ecosystems with seasonal programming (marshes and bird and mammal islands), (d) natural Arctic ecosystems with ice stress (sea ice and ice-stressed coasts and glacial fjords), (e) emerging new systems associated with man (sewage waste and pulp mill wastes), and (f) migrating subsystems that organize areas. The monumental task of organizing this document has not been updated for coastal systems in over 20 years. (The work was actually conducted in 1968 and 1969. The description and literature synthesis of each type of ecosystem was written by one or more authors.)

While "Coastal Ecological Systems of the United States" covered much more than just wetlands, a mangrove-specific classification emerged from studies on the hydrologic, structural, and other properties of mangrove swamps in Florida (Lugo and Snedaker 1974). They proposed five groupings of mangroves based on source and quality of water, the mechanism of flow through the system, and the zonation of vegetation (Figure 5a). Somewhat later, Brown, Brinson, and Lugo (1979) illustrated that freshwater forested wetlands appeared to differ according to the amount of water flow. Structural indices, primary production rates, and sediment properties were different between flowing-water wetlands and still-water wetlands (Figure 5b). These efforts led to the possibility that three core factors—hydroperiod, hydrologic energy, and nutrient level—were responsible for much of the variation occurring in wetlands (Figure 5d), at least for forested ones (Lugo, Brinson, and Brown 1990b). Three hydrogeomorphic types resulted by subsuming two of the five types for mangroves within other

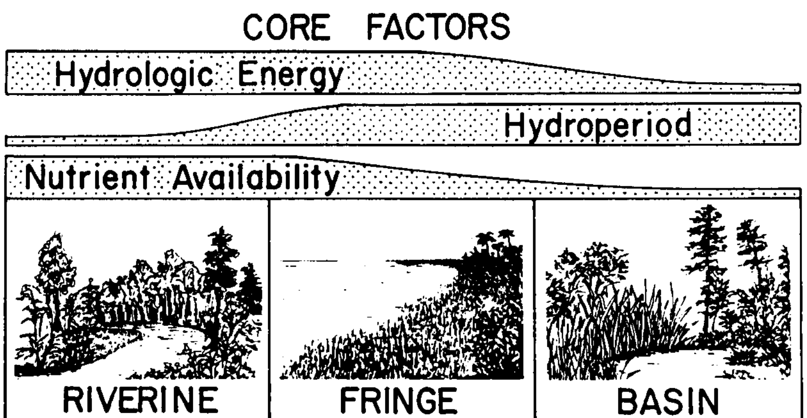


a. Five types proposed for mangroves in Florida by Lugo and Snedaker (1974) as illustrated in Wharton et al. (1977)

Figure 5. Classifications of wetlands based on their functional properties (Sheet 1 of 4)



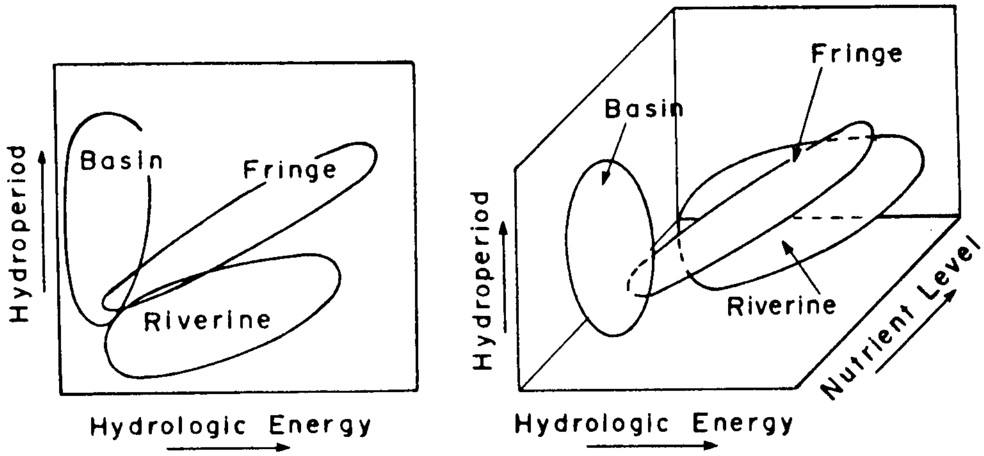
b. Flowing versus still-water proposed by Brown, Brinson, and Lugo (1979) for forested wetlands



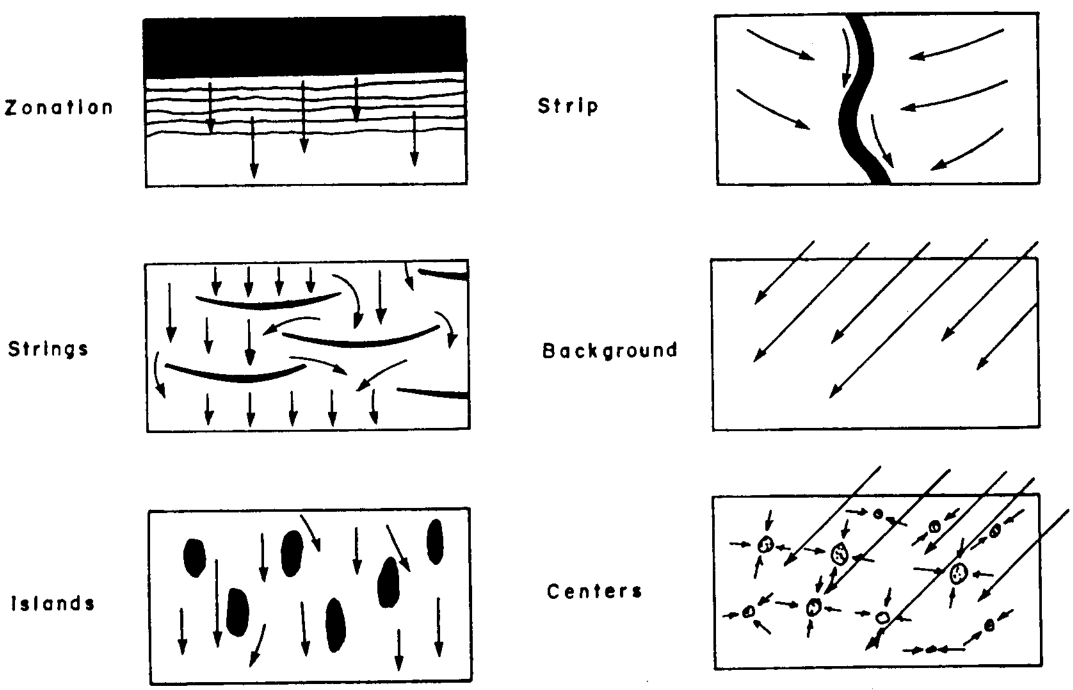
Modulating Factors	RIVERINE		FRINGE		BASIN	
TEMPERATURE	MOD	LOW	HIGH	MOD	LOW	MOD
SALINITY	LOW	LOW	MOD	MOD	LOW	LOW
FIRE FREQUENCY	LOW	HIGH	LOW	MOD	LOW	HIGH
HERBIVORY	LOW	HIGH	LOW	LOW	LOW	LOW
	BOTTOMLAND HARDWOOD FOREST	NORTHERN RIVERINE MARSH	MANGROVE FOREST	TEMPERATE SALTMARSH	BOG-MUSKEG	POCOSIN

c. The use of modulating factors to characterize specific types of wetlands beyond the core factors (Brinson and Lee 1989)

Figure 5. (Sheet 2 of 4)

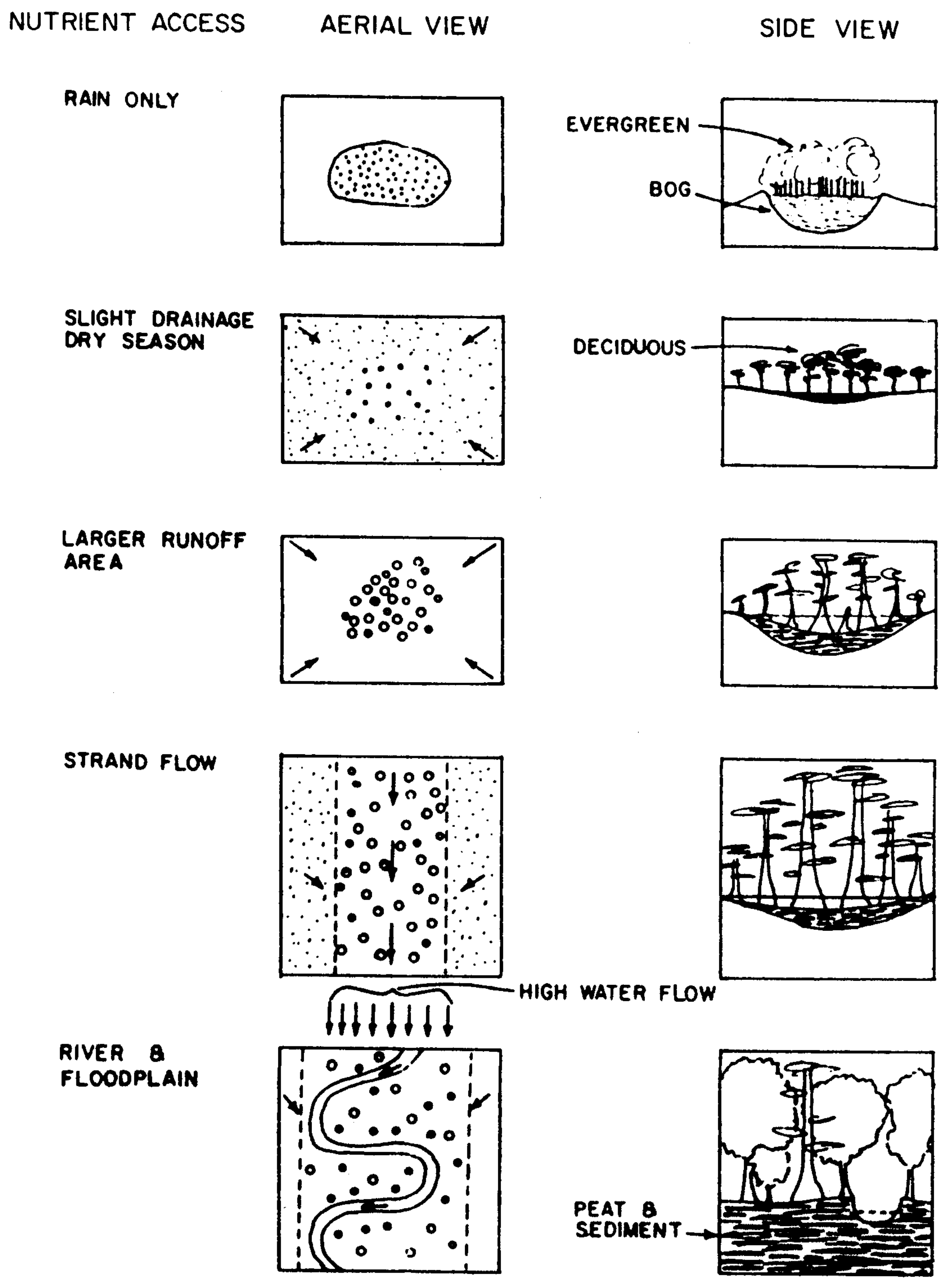


d. Riverine, basin, and fringe arranged around three core factors proposed by Lugo, Brinson, and Brown (1990b)



e. Six generic landform patterns that have equivalents for wetlands (Kangas 1990)

Figure 5. (Sheet 3 of 4)



f. Cypress wetlands of Florida arranged along increasing water and nutrient flows

Figure 5. (Sheet 4 of 4)

categories. The concept of only three primary controls did not, of course, explain more than the most gross aspects of the variation among all wetlands. Modulating factors like fire, herbivory, frost, and other variables were necessary to further characterize specific wetlands and their vegetation (Figure 5c).

During this same period, other classifications emerged that have been discussed in the previous section. However, one developed by Kangas (1990) stands out as embodying landscape properties that could be extended beyond wetlands. This system recognizes four spatial distributions of energy (sheet, point, front, and line) and combines them with six basic ecosystem forms. The resulting patterns are represented by the following ecosystem types (Figure 5e): zones (tidal salt marshes), string (string bogs), islands (perpendicular to strings), strip (streams and floodplains), background (large bogs, which may have other types embedded within them), and center (cypress domes in Florida). These are similar to the pattern recognized for cypress wetlands of Florida (Odum 1984), which are arranged in order of increasing water and nutrient flows (Figure 5f). Fire could be added as a factor that controls vegetation structure and resets succession.

2 Description

The core of the classification has three components: (a) geomorphic setting, (b) water source and its transport, and (c) hydrodynamics. Geomorphic setting is the topographic location of the wetland within the surrounding landscape. The types of water sources can be simplified to three—precipitation, surface or near-surface flow, and groundwater discharge. Hydrodynamics refers to the direction of flow and strength of water movement within the wetland. While the three components are treated separately, it is apparent that there is considerable interdependency. Such redundancy may be useful if it serves to reduce errors of interpretation and to reinforce the underlying principles that explain wetland functions.

Geomorphic Setting

Implicit in the hydrology of a particular wetland is its landscape position, or "geomorphic setting," which will accommodate the flows and storages of water. From a broad and long-term geomorphic perspective, water flows and wetland position are inextricably linked. Consequently, it is difficult to describe geomorphic setting without also discussing hydrology. However, water source and hydrodynamics will be discussed in detail in separate sections.

Background

The geomorphic settings listed in Table 3 (column 1) are elaborations of the depressional, riverine, and fringe categories developed originally for mangroves by Lugo and Snedaker (1974). They have been simplified from the original report by Lugo and Snedaker in descriptions by Brinson (1988) and Lugo, Brinson, and Brown (1990a). Each category tends to have a distinctive combination of hydroperiod, dominant direction of water flow, and zonation of vegetation. Extensive peatlands have been added here as a separate category because of the strong feedback between biogenic accretion and hydrology.

Table 3
Examples of Geomorphic Setting as a Property of Hydrogeomorphic Classification

Examples of Geomorphic Setting[1]	Qualitative Evidence[2]	Quantitative Evidence[3]	Functions[4]	Ecological Significance[5]
		Depressional Wetlands[6]		
No apparent inlet or outlet.	Topographically isolated from other surface water bodies.	Drydowns frequent; water table significantly below wetland much of the time.	Retains inflow; loss primarily by evapotranspiration (ET) or infiltration.	Inaccessible to aquatic organisms dependent on streams. Endemism likely.[7]
Positioned on local topographic high. Surface outlet only.	Outlet may be defined by contours or intermittent stream symbol.	Drydowns frequent and water table significantly below wetland much of the time.	Temporary flood storage; outlet may overflow during high water (surface-water dominated) or flow continuously (groundwater supported). Outlet controls maximum depth.	System open to upstream immigration and downstream emigration of aquatic organisms. Potential for recolonization by aquatic organisms if drydowns cause local extinctions.
Located in marginally dry climate (e.g., prairie pothole region). Variable inlets and outlets.	Inlets and outlets may be defined by contours or intermittent stream symbol.	If water has low conductivity, wetland is recharging underlying aquifer. If high conductivity, groundwater is discharging to wetland (Sloan 1972).	Retains inflow; loss primarily by ET or infiltration. May be subject to wide fluctuation in water depth.	Geographic location critical to migrating waterfowl as flyway position indicates. Changes in vegetation create varied waterfowl habitat. May be vulnerable to eutrophication and toxin accumulation because of long residence time of water. Probable import and export of detritus.

(Sheet 1 of 4)

[1] Array of geomophic settings is derived from the fringe-riverine-basin/depressional categories of Lugo, Brinson, and Brown (1990b). Extensive peatlands were originally not a separate category.
[2] Normally assessed by direct observation.
[3] Normally requires records of discharge and stage height to illustrate seasonal and interannual variation. Reliable indicators may be used also.
[4] Mechanisms for maintaining ecological significance.
[5] Other ecologically significant functions may be present; only examples are given.
[6] If wetland contains open water, waterfowl habitat may be inferred. For prairie pothole region, soil properties provide excellent indicators of hydrology (Hubbard 1988). Playa lakes of the southern High Plains reviewed by Bolen, Smith, and Schramm (1989).
[7] Zedler (1987).

Table 3 (Continued)

Examples of Geomorphic Setting	Qualitative Evidence	Quantitative Evidence	Functions	Ecological Significance
Depressional Wetlands (Continued)				
Both surface inlet and outlet; large catchment sustains marginal riverine features.	Inlets and outlets may be defined by contours or intermittent stream symbol.	Water budget dominated by lateral surface flows or strong groundwater discharge.	Temporary flood storage; drainage back to stream shortly after flooding (surface-water supported) or continuous saturation (groundwater supported).	Potential for fish population recruitment through migration. Probable import and export of detritus.
Located on break in slope.	Soil saturated most of time.	Chemistry indicative of groundwater; discharge from slope base or face. Piezometric confirmation.	Inflow steady and continuous; loss by ET seasonal. Renewal of pore waters maintains higher redox than typical for constant saturation. Low-surface storage capacity.	Provides surface moisture during dry periods; contributes to beta diversity of landscape.
Extensive Peatland				
Ombrotrophic bog.	Peat substrate; saturated most of time. Plant species indicate ombrotrophic bog; surface flows negligible.	Peat confirmed by organic content and thickness. Ombrotrophy evident from low pH and low-ion content.	Surface storage may facilitate storm runoff; groundwater conservation occurs when water table is below surface. Peat deposits control topography and geomorphic surface.	Wetland-upland interactions minor relative to wetland-atmospheric exchanges.[8] Upland habitats scarce. Species composition unique to bog conditions.
Rich fen.	Peat substrate; saturated most of time. Graminoid species indicative of groundwater supply.	Peat confirmed by organic content and thickness. Minerotrophy evident from circumneutral pH and high-ion content.	Subsurface water supply maintains saturation to surface and hydraulic gradient to maintain flow.	Represents conduit for lateral water movement without channelized flow. Moderate levels of primary production and organic matter export.

(Sheet 2 of 4)

[8] Brinson (1991).

Table 3 (Continued)

Examples of Geomorphic Setting	Qualitative Evidence	Quantitative Evidence	Functions	Ecological Significance
Riverine Wetlands (floodplain, not channel)				
Streamside zones of intermittent streams.	Headwater position; first order stream.	Flows not continuous; flow lacks headwater flooding and overbank flow properties.	Interface of landscape where groundwater and surface water sources change phases to fluvial environment.	Riparian zone critical to maintaining buffer between upland and stream flow.
High-gradient: downcutting portions[9]	Bedrock-controlled channel.	Substrate lacks alluvium (soil maps). Flow may be continuous but likely flashy.	Scour precludes extensive wetland development. Unvegetated reaches allow light penetration to support aquatic production.	May impede wildlife movement and cover if corridor too narrow. Maintains important in-stream riffle habitat.
aggrading portions	Substrate controlled by fluvial processes.	Stratigraphy shows interbedding and coarse particle size (gravel and larger).	Wetland on coarse substrate maintained by upslope groundwater source.[10]	Unstable substrate in high-energy environment colonized by pioneer species. Streamside vegetation contributes to allochthonous organic supply.
Middle-gradient landform.	Channelized flow, evidence of oxbows, meander scrolls, etc., consistent with fluvial processes.	Flow likely continuous with moderate- to high-base flows.	Channel processes establish variation in topography, hydroperiod, and habitat interspersion on a floodplain.	Alluvium is renewed by surface accretion and point bar deposition; interspersion of plant communities contributes to beta diversity.[11]
Low-gradient alluvial. Floodplain of bottomland hardwood.	As above, but in low-gradient landform.	Flow continuous with cool season flooding. High-suspended sediments in stream.	Flood storage; conserves groundwater discharge.	Major habitat for wildlife and biodiversity; strong biogeochemical activity and nutrient retention.

(Sheet 3 of 4)

[9] Geomorphic processes and their ecological significance in riparian ecosystems are reviewed by Gregory et al. (1991).
[10] Major water supply to streamside wetlands is provided from upslope by groundwater discharge (Ruddy and Williams 1991).
[11] Metzler and Damman (1985) describes dependence of understory herbaceous vegetation on annual flood regime.

Table 3 (Concluded)

Examples of Geomorphic Setting	Qualitative Evidence	Quantitative Evidence	Functions	Ecological Significance
Riverine Wetlands (floodplain, not channel) (Continued)				
Low-gradient nonalluvial (i.e., low in suspended sediments): Florida cypress strands and sloughs, peat water tracks).	Flows not channelized or channels shallow; if peatland, flow limited to acrotelm (upper 20 to 30 cm) (Clymo 1983, 1984).	Manning coefficient normally high.[12] Vegetation and sediment redox differ from surroundings if peatland.	Conduit for drainage in otherwise precipitation-dominated wetland. Flow facilitates nutrient availability.	Wetland possesses both depressional and riverine attributes because of weak lateral flows.
Fringe Wetlands				
Shoreline of large lake (i.e., lacustrine).	Subjected to seiches. Lake level controls position.	Amplitude and frequency of wind-generated fluctuations. Year-to-year trends in zonation follow climatic cycles.	Lake serves as water supply for wetland and establishes hydroperiod gradient for wetland zonation.	Provides shoreline stabilization under moderate wave action; transition habitat utilized by both aquatic and terrestrial organisms.
Coastal sea-level location (i.e., estuarine).	Subjected to astronomic tides; sea-level controlled.	Elevation relative to tides and changing sea level.	Wetland responsive to tides and changing sea level.	Barrier to saltwater encroachment; accommodates sediment deposition; open to estuarine organisms for feeding and recruitment.

(Sheet 4 of 4)

[12] Arcement and Schneider (1989).

Depressional wetlands include such landforms as kettles, potholes, vernal pools, and Carolina bays. Because they frequently occur high in drainages, they are typically more dependent on atmospheric exchanges than other wetland types. In dry climates, depressions are either dry much of the time, as in vernal pools (Zedler 1987), or they are dependent on groundwater sources. In more moist climates, they may accumulate sufficient peat to develop a domed topographic relief, or a tertiary mire. Such wetlands necessarily receive their water from precipitation. Ombrotrophy can result in strong seasonal fluctuations in water table because of the seasonality of the ratio of precipitation to potential evapotranspiration (PET). Where landscapes have undergone widespread paludification, the depressional category no longer applies because wetland surface features become decoupled from the topography of the underlying landscape. Such wetlands would fall under the next category, extensive peatlands.

Extensive peatlands cover large areas of land such that the peat substrate dominates the movement and storage of water, the mineral nutrition of the plants, and patterns in the landscape itself (Moore and Bellamy 1974). Blanket bogs and tussock tundra are examples of extensive peatlands. Once tertiary mire formation radiates by paludification across the landscape, surface patterns develop that are independent of underlying topography. The connections of bogs in higher topographic positions may occur through surface unchannelized flow paths and subsurface pathways to peatlands lower in the landscape or drainage basin (Ingram 1967). Hence, there is a gradient from the truly headwater ombrotrophic wetlands with diffuse outlets only to ones further downstream with distinct inlets and outlets with fen-like characteristics (Siegel and Glaser 1987).

Riverine wetlands form as linear strips throughout the landscape. They have predominately unidirectional flow. Hydroperiod ranges from short and flashy in headwater streams to long and steady in higher order streams. Their slope controls whether a given section of stream is predominately erosional or depositional.

Fringe wetlands occur in estuaries where tidal forces dominate or in lakes where water moves in and out of the wetland from the effects of wind, waves, and seiches. Consequently, bidirectional flow, largely across the surface, dominates and the hydroperiod is long as a result of the cumulative frequency of many flooding events, especially for wetlands that receive semidiurnal astronomic tides. Lakes that are too small to develop frequent seiches would not support fringe wetlands; such lakeside wetlands would fall into the depressional category described above.

The processes that maintain wetlands at this coarse level of resolution are often so large in scale that they define the very nature of the wetland itself. Hence, it may be problematic to classify in isolation a distinct wetland on a small scale (ha) if it is part of a larger wetland complex of tens of hectares. This is especially true if one or several of the wetland functions is size-dependent or a result of its strategic position in the landscape (Brinson 1988, 1991). Also, a given wetland may have characteristics of more than one of the three categories. An oxbow lake, for example, may behave more like a depressional wetland when it is hydrologically isolated from overbank flow than the greater riverine system that was responsible for its genesis. It is also apparent that the three categories intergrade such that continua form among them. Column 2 on qualitative evidence (Table 3) suggests indicators that are characteristic of the geomorphic wetland type. Additional quantitative estimates (column 3) that would characterize these wetlands relate to the amplitude and frequency of water turnover or flushing (Miller and McPherson 1991), water chemistry, substrate composition, stream power estimates (Richards 1982), and water budgets, the latter being useful for depressional wetlands.[1]

The functions in column 4 are derived from the descriptions in the first three columns (Table 3). To the extent that functions are the result of geomorphic settings, they should vary in response to different settings. Ecological significance (column 5) is one interpretation of the functions that goes beyond the physical and chemical aspects of wetlands and includes the biotic portions. Ecological significance is highly variable and could be greatly expanded to capture the special features of regionally important wetland types. For example, high-gradient streams in Alaska could be further characterized by estimates of vegetation cover, primary production, and food web transfer coefficients, which Duncan, Brusven, and Bjornn (1989) has done for estimating salmonid production.

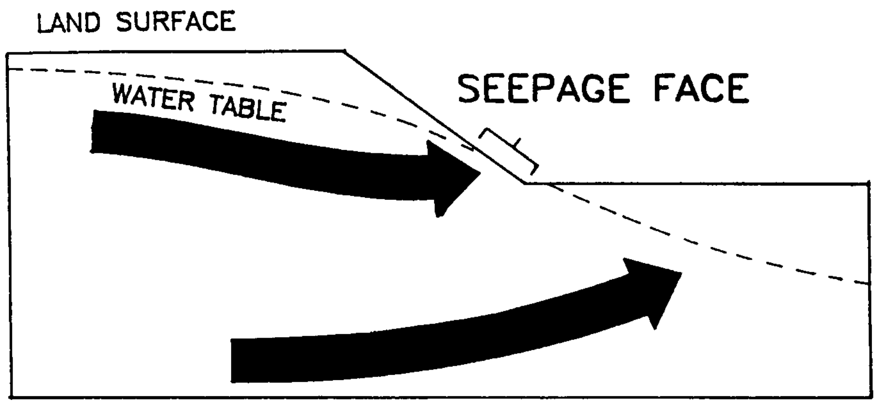
Examples of geomorphic settings

Six commonly recognized wetland types are examined—one depressional, one extensive peatland, two riverine, and two fringe (tidal) wetlands. This is done to illustrate a higher resolution than the four basic settings by using subsets of these broad categories for which the functioning is reasonably well understood. (Note: In each case in Table 3, the reader is referred to one of four "settings" (e.g., depressional, extensive peatland, riverine, and fringe), and then directed to a specific row by indicating its order (first row, second row, etc.).

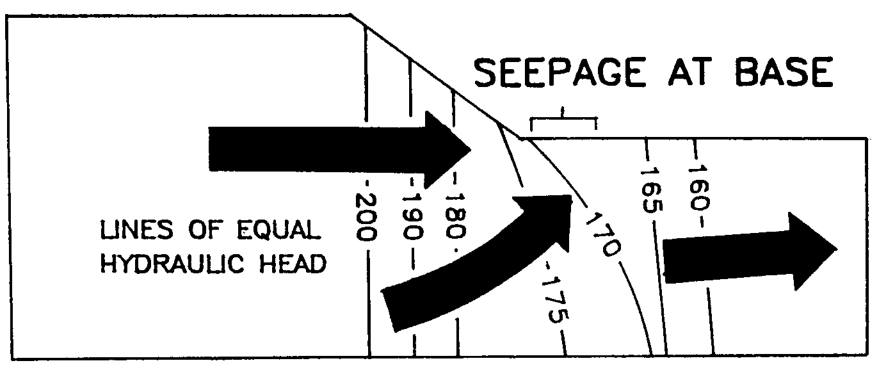
Groundwater slope wetland. Groundwater slope wetlands occur where there are breaks in slopes (Table 3, Depressional Wetlands, fifth (last) row). In terms of water source, they are the groundwater slope wetlands of Novitzki (1979), except they are not necessarily associated with stream flow (Figure 2c). Two conditions can exist: those with a seepage

[1] The reader is reminded that this report is meant only to provide an overview of the logic of a methodology that relates certain hydrologic and geomorphic characteristics through a process of interpretation, and finally to the ultimate description of ecological significance. A full, field-tested method for actual use by persons to classify would include a larger array of options. For depressional wetlands, if there are surface inflows and no surface outflows in a moist climate, the wetland is likely recharging a groundwater aquifer. Information on the hydraulic conductance of sediments underlying the wetland might corroborate with this inference. Data on water table position and piezometric surfaces could confirm or exclude this possibility.

face caused by groundwater flow intersecting a land surface (Figure 6a) and those with seepage at the base where the upward movement of groundwater occurs in the lower slope segment of the break (Figure 6b) (Winter 1988). A third condition in glaciated regions is where till deposits are arranged with more permeable layers overlying less permeable ones, thus creating a shallow perched aquifer. Erosion through the discontinuity can cause exposure of the aquifer and seepage at the surface.[1]



a. Seepage face where groundwater flow intersects the land surface



b. Seepage in the lower slope portion of the break

Figure 6. Interaction of breaks in slope with groundwater flow as a source of water for wetlands. Adapted from Winter (1988)

[1] Personal Communication, 1991, Frank Golet, University of Rhode Island, Kingston, RI.

Figure 3 shows additional examples of depressional wetlands with varying degrees of groundwater seepage. Some tend to have relatively constant water tables if the aquifer responsible for the water source is large and quickly recharged, thus being relatively immune to seasonal demands by evapotranspiration. Depending on the composition of the aquifer matrix, groundwater slope wetlands may receive well-buffered, nutrient-rich water, or be relatively poor in nutrients. Sediment loads are negligible, and most cannot flood deeply because they have a sloped surface. If the seep is fed by a shallow and perched aquifer, the wetland soils will likely undergo desaturation during the growing season as vegetation intercepts groundwater supplies to the seepage area.

Ombrotrophic peat bog. The interdependency of geomorphology and hydrology is no better expressed than in extensive peatlands where the accumulation of organic matter as peat controls topographic relief (Table 3, Extensive Peat-land, first row). This can be perceived as a special case in which a gas, carbon dioxide, is deposited as organic carbon through the process of photosynthesis. As such, accretion occurs in low-energy environments through biogenic processes, rather than being limited to inorganic sediment accretion or allochthonous organic matter deposits, processes that require hydraulic energy for sediment transport (Gosselink and Turner 1978; Brown, Brinson, and Lugo 1979).

Ombrotrophic peat bogs are usually the terminal condition of peat accumulation in depressions, subsequent radiating paludification, and finally a domed landscape where the highest elevation receives precipitation as the sole water source and generally is the most nutrient poor environment. The connections of bogs with downstream ecosystems could be through distinct outlets or unchannelized flow. Peatlands lower in the landscape or drainage basin may also have inlets. Hence, there is a gradient from the truly headwater ombrotrophic wetlands with outlets only, to fens further downslope with either diffuse surface inlets and outlets or primarily groundwater discharge (Table 3, Extensive Peatland, second row). This is clearly a shift in peatlands from ombrotrophic toward fen-like conditions with a minerotrophic water supply. Patterned peatlands may contain both ombrotrophic bogs and minerotrophic fens. Sites with woody vegetation act as recharge areas, and force groundwater to pass through inorganic soil. When this water, now enriched in minerals, discharges to the surface, the fen-like portion of the pattern is maintained (Siegel and Glaser 1987).

The terminology and literature describing hydrologic and water chemistry continua of peat-based wetlands has a long and rich history of development (Gorham 1956; Moore and Bellamy 1974; Clymo 1983, 1984). The range of wetlands found in Europe is summarized in Figure 7. Climate and original landform combine to produce both topographic and drainage patterns in the peatlands. This interaction has received much attention, particularly in boreal peatlands (Ingram 1967, 1983; Ivanov 1981).

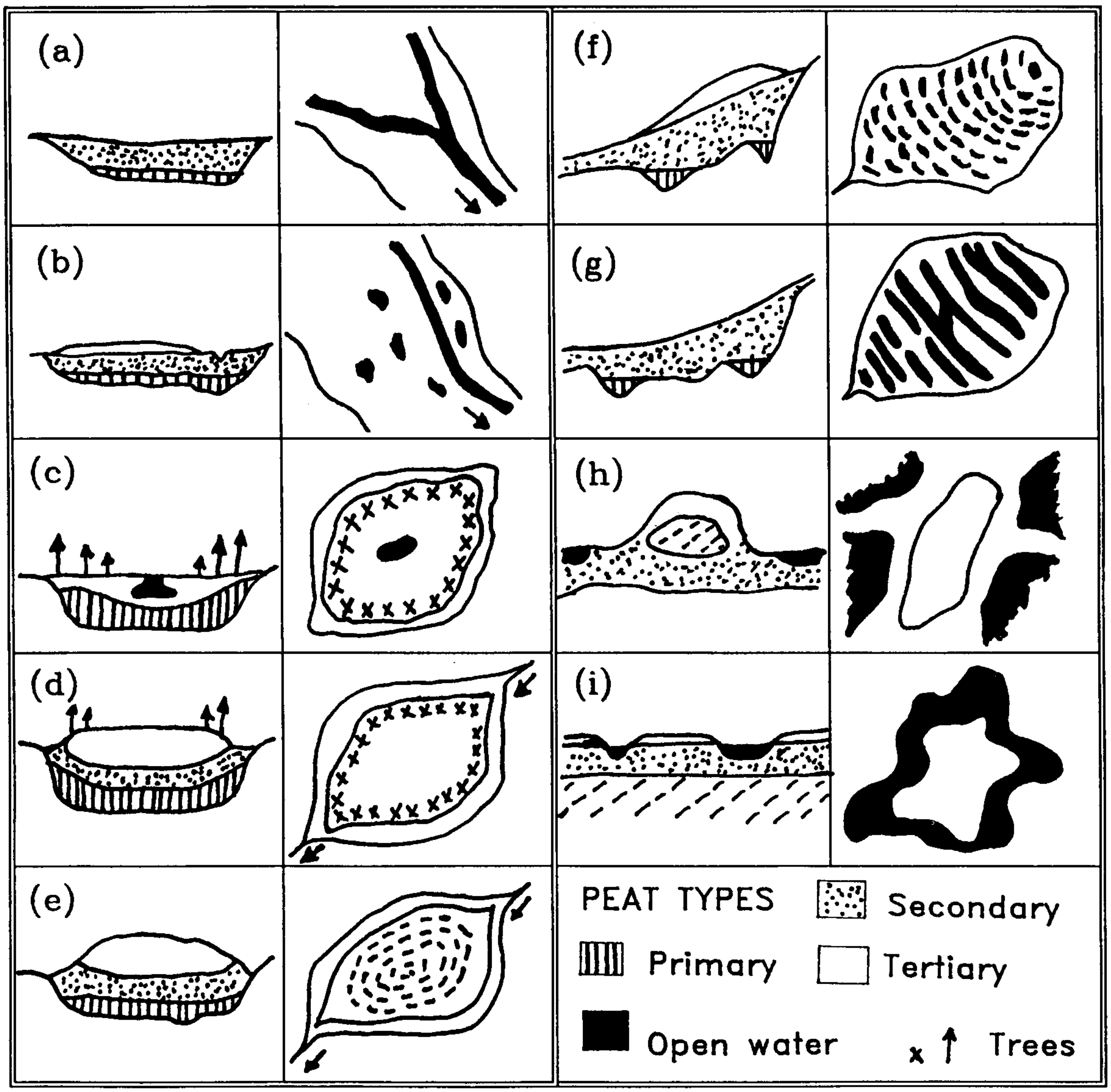


Figure 7. Major types of wetlands found in Europe. Cross-sectional and plan view in each panel: (a) mires with primary and secondary peats only (floodplains), (b) flat tertiary mires in open basins (deltas), (c) flat tertiary mires in closed basins, (d) plateau mires without concentric pattern of hummocks and hollows, (e) concentric domed mires, (f) eccentric domed mires, (g) aapamires (as "f" but no tertiary peat), (h) palsamires (diaganol dashes represent permafrost), and (i) arctic mires underlain by permafrost. From Moore and Bellamy (1974)

High-gradient riparian. High-gradient riverine wetlands occur in a regime of erosion and net downcutting of the stream channel (Table 3, Riverine Wetlands, second row). Streams that have steep gradients overall frequently have shorter reaches that alternate between accretion on point bars and erosion of cutbanks. The process of sediment trading (Leopold, Wolman, and Miller 1964) maintains areas of active deposition where the floodplain wetlands are located. In high rainfall regions, woody debris and debris dams may be dominant structural channel and floodplain features

(Triska and Cromack 1980; Gregory et al. 1991; Sedell and Beschta 1991). Lane's (1955) simple relationship is useful for explaining observations of the effects of changing slope on grain size of bedload.

$$QS = Q_s D_{50}$$

where

Q = water discharge

S = slope of the channel bed

Q_s = the bed material discharge

D_{50} = a measure of the average diameter of grain size of the channel bed material

If all other factors remained constant, a decrease in slope (S on the left side of the equation) would be accompanied by a decrease in diameter of grain size (D_{50} on the right). Overall, the wetlands of high-gradient streams would tend to have sediments that are coarse (cobble, boulders), have high hydraulic conductivity, and maintain a strong coupling between groundwater of the floodplain and surface water of the stream (Stanford and Ward 1988). In other cases, however, large woody debris and riparian vegetation contribute greatly to the control of channel characteristics (Sedell and Beschta 1991).

In arid climates where precipitation is not only lower but more variable from year to year, wetlands may be dependent on relatively large catchment areas for providing sufficient supplies of water to maintain their integrity. In other areas, spring snowmelt at higher altitudes may account for most of the water supply to wetlands. Many of these streams and associated riparian zones in the American West (United States and Canada) have had dramatic changes in function because of flow modification (Rood and Mahoney 1990).

Low-gradient nonalluvial riverine. Low-gradient riverine landforms are represented by near-headwater drainages where surface flow is strong enough to be recognized, but not strong enough to create distinct stream channels (Table 3, Riverine Wetlands, last (fifth) row). This condition would be transitional between the depressional landforms that lack flow or have negligible flow, and the high-gradient riparian wetlands just described. Where channelized flow is present and there is sufficient hydraulic energy to carry sediments and create streamside natural levees, the landform may be designated as either middle-gradient or low-gradient alluvial (Table 3, Riverine Wetlands, third and fourth rows). In unglaciated regions where drainage patterns have had a long time to develop, low-gradient riverine wetlands are limited to regions with very low slope, such as parts of the coastal plain of the Southeast (Kuenzler 1989) and Florida (Duever, Meeder, and Duever 1984), where they are variously known as cypress strands, stream-swamps, and sloughs. In glaciated areas, the inherited landscape may continue to have major control on drainage patterns, thus leading to complex and variable hydrogeologic processes (Hollands 1987). Forested wetlands of the Northeast commonly have mixed riverine and depressional characteristics for this very reason.

As indicated by the arrangement of the riverine wetlands in Table 3, decreasing slope shifts the classification from high-gradient riparian wetlands to those with reduced slopes, to the near absence of surface flow, and finally to the depressional category. Where the drainage of a depressional wetland has both surface inlet and outlet, a large enough catchment can sustain marginal riverine features (Table 3, Depressional Wetlands, fourth row). As slopes become reduced, so does the capacity of water to carry sediment and directly influence geomorphology through accretion, erosion, and transport. In such cases, hydrology and vegetation interact on a geomorphic surface to further modify the substrate through the process of biotic deposition of organic sediments. This modified substrate in turn becomes the geomorphic platform for another series of feedbacks (Gosselink and Turner 1978).

Tidal salt marsh and tidal freshwater marsh. Both tidal salt marsh and tidal freshwater marshes have the fringe geomorphic setting as a result of their position in relationship to sea level and the influence of tides (Table 3, Fringe Wetlands, second row). Salinity of the adjacent estuary determines whether salt marsh or freshwater marsh prevails. Tides represent frequent and predictable hydroperiod events in these wetlands, especially for the regularly inundated portions. In the irregularly flooded portions of tidal salt marshes, spring tides and storms are responsible for inundation patterns. Because of the reduced frequency of estuarine forces in the irregularly flooded zones, precipitation becomes of greater significance in contributing to hydroperiod and in influencing salinity (Brinson, Hook, and Bryant 1991). While the very highest of "high marshes" would still be located in a fringe geomorphic setting, they acquire characteristics of depressional wetlands because precipitation often becomes the most important source of water for short-term water balance.

Depending on the local conditions of land subsidence or emergence, the relationship of these wetlands to sea level will define their landscape role. A relative rise in sea level normally results in overland migration with the irregularly flooded portion of the fringe wetland invading upland ecosystems. Several combinations of sea-level change and marsh development processes are illustrated in Figure 8. Vertical accretion by deposition of allochthonous mineral sediment or in situ accumulation of organic substrate are local manifestations of processes that allow these wetlands to maintain their geomorphic setting. In tidal marshes that become progressively isolated from their inorganic sediment source, deterioration appears to take place within the marsh rather than preferentially at the edges (Stevenson, Kearney, and Pendleton 1985; Hackney and Cleary 1987). This illustrates the vulnerability of fringe marshes to sediment balance.

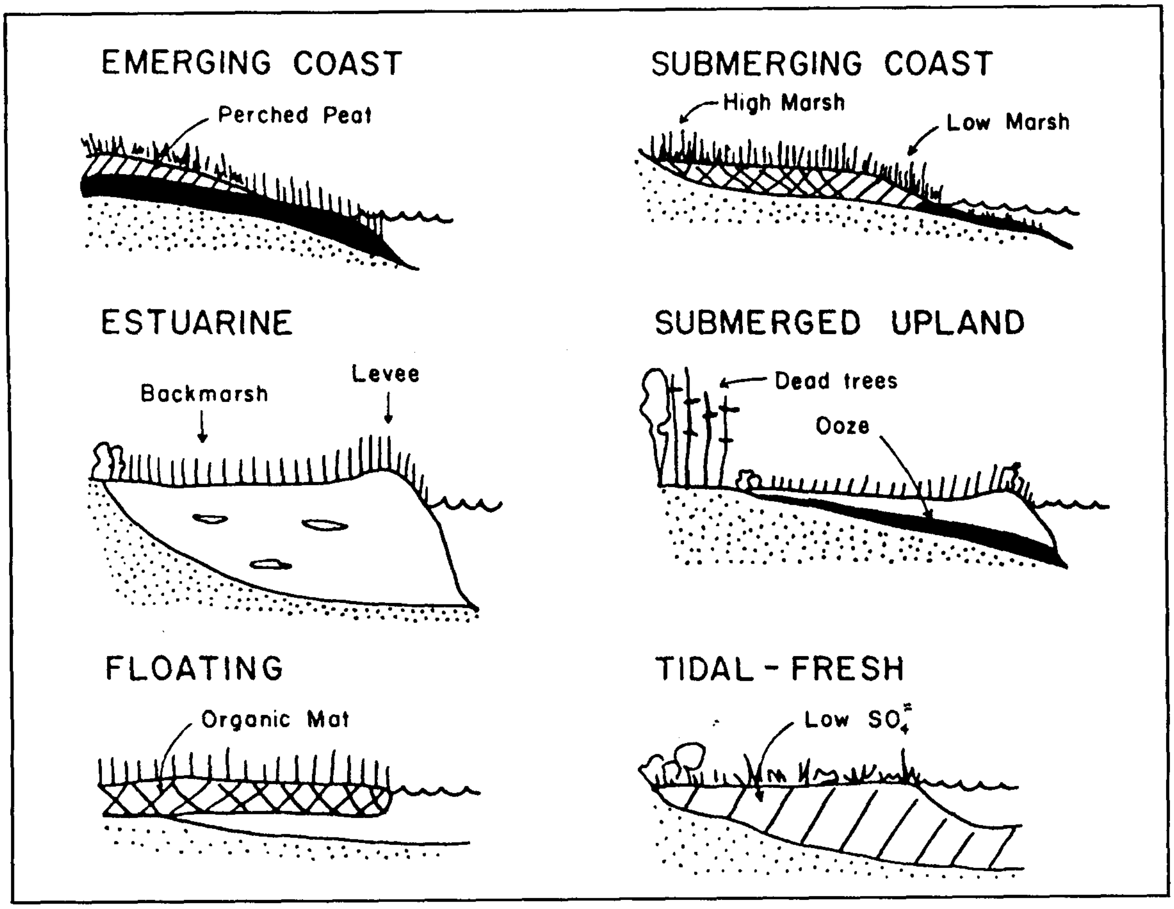


Figure 8. Six major types of fringe wetlands and their position relative to changing sea level and vertical movement of coastal marshes. From Stevenson, Ward, and Kearney (1986)

Water Sources

One of the more difficult phenomena to observe in wetlands is the source of water, particularly when the observed water at the surface is derived from groundwater. In glaciated regions where landscapes are relatively "immature" and drainage patterns have not had time to fully develop, the relationship between surface water and groundwater is often complex.

Background

Most treatments of hydrology in wetlands begin with the components of a water budget whereby inputs and outputs of water are defined and itemized[1] (LaBaugh 1986). The sum of all inputs and all outputs tend to cancel one another over periods of 1 to several years. From this standpoint, a hydrologic budget of a wetland does not differ from any other ecosystem except for the specific cases of tidal exchange and the prevalence of surface inflows and outflows. Without further qualifying information, a water budget, no matter how detailed and accurate, may not provide information that is critical in evaluating how the storage term influences ecosystem processes and sets wetlands apart from other ecosystems. Adaptations of plants, animals, and protists are insensitive to the water budget per se. Rather such factors as water depth, flood duration, flow velocity, and water source either act as selective factors for the adaptations of organisms or are capable of performing work in the system.

For purposes of this discussion, hydrologic inputs will be simplified to three water sources: (a) precipitation, (b) groundwater discharge (inflow, usually into and through wetland sediments), and (c) surface or near-surface inflow (i.e., depending on the wetland, this could include flooding from tides, overbank flow from stream channels, and interflow or overland flow from higher potentiometric surfaces in the wetland). The movement of sources to a location within a wetland is illustrated in Figure 9. The quantity of water that each source contributes to the hydroperiod annually could be expressed as an average if a detailed water budget were developed. Even if such detailed data were not available, it may be possible to rank the relative importance of the sources to the total site water balance. Consideration should be given to interannual variation.

A less quantitative approach could utilize the interpretation of hydrographs to determine the dominant sources of water. Figure 10 illustrates hypothetical hydrographs in four wetlands on the east coast and four stream channel hydrographs on the west coast and Rocky Mountain region. For the east coast wetlands (Figure 10a-d), two are on floodplains adjacent to streams (stream-swamp and alluvial swamp), one is precipitation driven (pocosin), and another is affected by sea level combined with irregular flooding from wind events rather than astronomic tides (sea-level controlled swamp or marsh). For floodplains of higher order streams and especially streams with steep gradients (Figure 10 e-h), most water table

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1 The components of a water budget can be reduced to the following:

$$dS = PR + S_i + GW_i + NC_i - ET - S_o - GW_o - NC_o$$

where dS = the change in storage in the wetland; PR = net precipitation reaching the soil surface; S_i = stream inflows such as overbank flooding; GW_i = groundwater inflow; NC_i = unchannelized surface water inflow; ET = evapotranspiration; S_o = stream outflows; GW_o = groundwater outflows or discharge to another hydrologic unit; and NC_o = unchannelized water outflow. When dS = zero, inflows are equal to outflows.

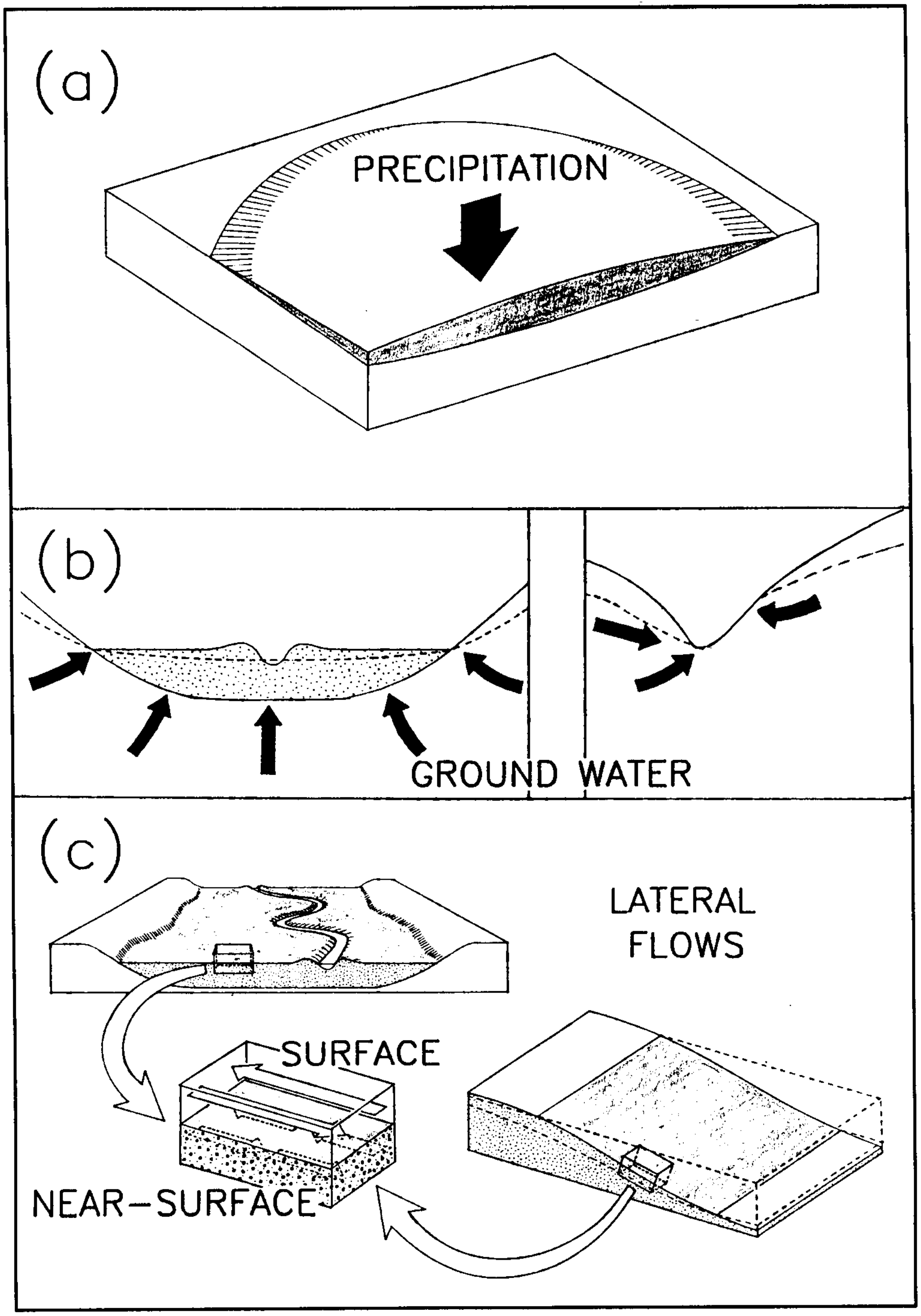

Figure 9. Principal sources of water

fluctuations above the surface are derived from overbank flows when stream discharge exceeds channel capacity. Under natural conditions, lateral flows tend to be negligible in precipitation-driven wetlands except with major rainfall events when radial flow from the center may occur from raised peatlands.

Evapotranspiration can result in extreme drawdowns because of sole dependence on precipitation as a water source. In the sea-level controlled wetland, estuarine water is delivered to the wetland surface during infrequent wind events. Although the amount and distribution of precipitation could be the same for all four east coast wetlands in Figure 10 (a-d), the influence that rainfall has on the hydrographic signature would depend primarily on the relative contribution of other water sources (i.e., groundwater discharge and delivery from upstream sources), whether the sediments were flooded or unsaturated prior to the rainfall event, and the physical properties of the sediments (storativity of unsaturated sediments and the hydraulic conductivity).

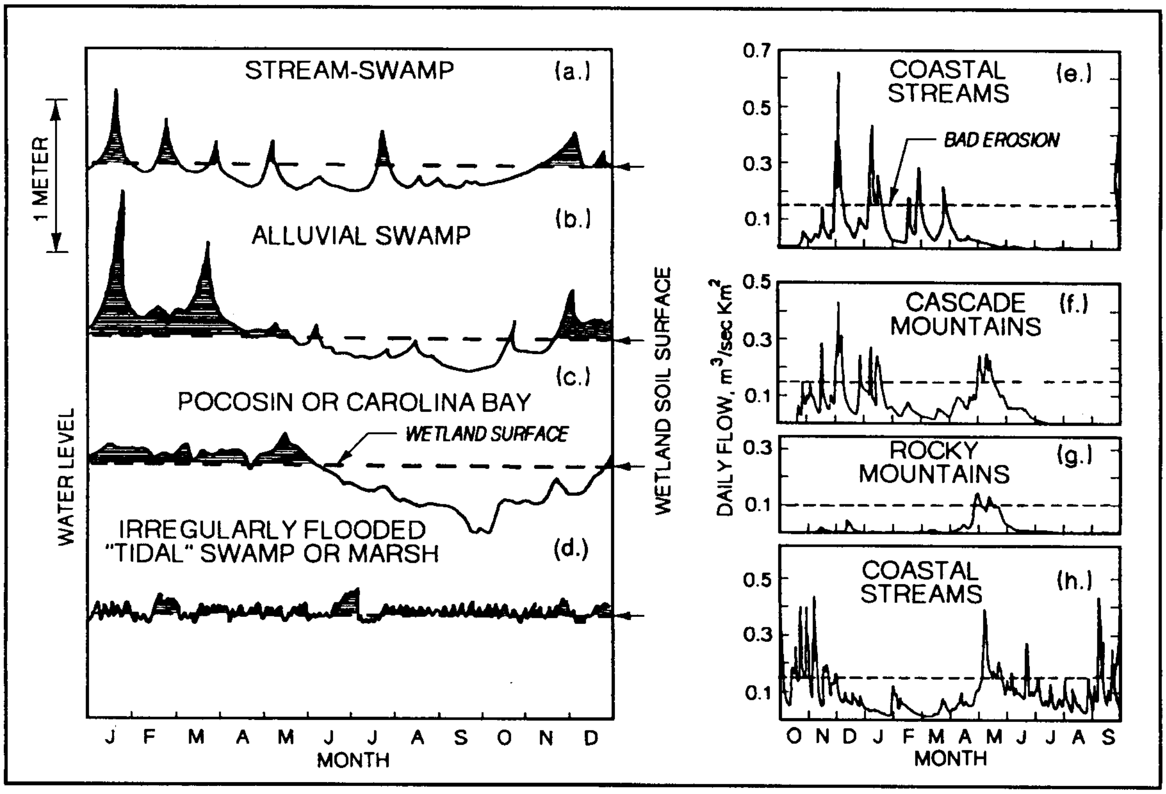

Figure 10. Hydrographs of wetlands and streams associated with wetlands. Left panel: Idealized hydrographs of water levels within four wetlands in the eastern United States. The horizontal line is the wetland surface. The first two (a and b) represent the riverine type that has flood peaks principally because of overbank flooding. The hydrograph for the depressional wetland (c) is dominated by precipitation and evapotranspiration. The fringe marsh hydrograph (d) is subject to sea-level control, and thus does not show strong seasonal fluctuations. From Brinson (1985). Right panel: Hydrographs from streams in riverine wetlands in the western United States and Canada: (e) N. California, Oregon, Washington, and British Columbia, (f) Oregon and Washington, (g) Rocky Mountain states and provinces, and (h) British Columbia and Alaska. Horizontal dotted line is the discharge at which significant bedload transport and overbank flooding are expected to occur. From Everest et al. (1987)

Groundwater discharge from slopes or in the wetland itself may be derived from perched sources or from regional groundwater systems. A perched source can occur where a downcutting of a stream through glacial till intersects a stratum of relatively lower permeability than the strata above or below it.[1] Consequently, water that would normally continue downward seepage as gravity flow is diverted laterally by an aquitard to the edge of a slope. The groundwater above the aquitard is described as "perched" when sediments below the aquitard are not fully saturated. Alternatively, regional groundwater systems may discharge directly into a wetland. The origin of such water may be a groundwater recharge area many kilometers removed from the wetland itself. All that is required for significant flow to occur is for the potentiometric surface of the groundwater slope toward the wetland to be steep enough and for the permeability of the shallow aquifer to be high enough.

Regardless if groundwater is discharged into a depression (Figure 2b) or a slope (Figure 2c), the saturated conditions are derived from water that has been in contact with the mineral content of the aquifer or soil. Depending on the time of contact and the composition of the lithology, such water normally has much higher plant nutrient content than water derived directly from precipitation. Consequently, plant communities in wetlands that receive groundwater discharge tend to be more productive than ombrotrophic bogs.

One of the challenges of comparing the relative importance of the three water sources is finding appropriate and comparable measurements and units that allow hydroperiod to be quantified. Several approaches to the problem have been proposed and are mentioned briefly below. The cumulative frequency distribution of flooding duration and dry periods has been used for tidal marshes (Swenson and Turner 1987), but the source of the water is not revealed (Figure 11a). Twilley (1985) used cumulative tidal amplitudes to scale the capacity of mangroves to export organic carbon (Figure 11b). Hook (1991) used total water table drawdown below the surface in an attempt to express the potential for sediment aeration in experimental treatments. Brinson, Hook, and Bryant (1991) explored the use of cumulative rise in water table, which is the sum of all increases in water table over a specified time. In this example, water table rises in coastal marshes are separated into those responding to precipitation and those responding to flooding by surface flow from an adjacent water body. The values of the two vary with distance from the shoreward margin of the wetland (Figure 11c). Over sufficiently long periods of time, cumulative rises and drawdowns cancel. Finally, the flow duration curves for streams draining a groundwater bog (i.e., groundwater-fed fen) and a perched bog (i.e., ombrotrophic peatland) illustrate both the effects of differing water sources and the differences in range of water table fluctuation (Figure 11d).

1 Personal Communication, 1991, Frank Golet, University of Rhode Island, Kingston, RI.

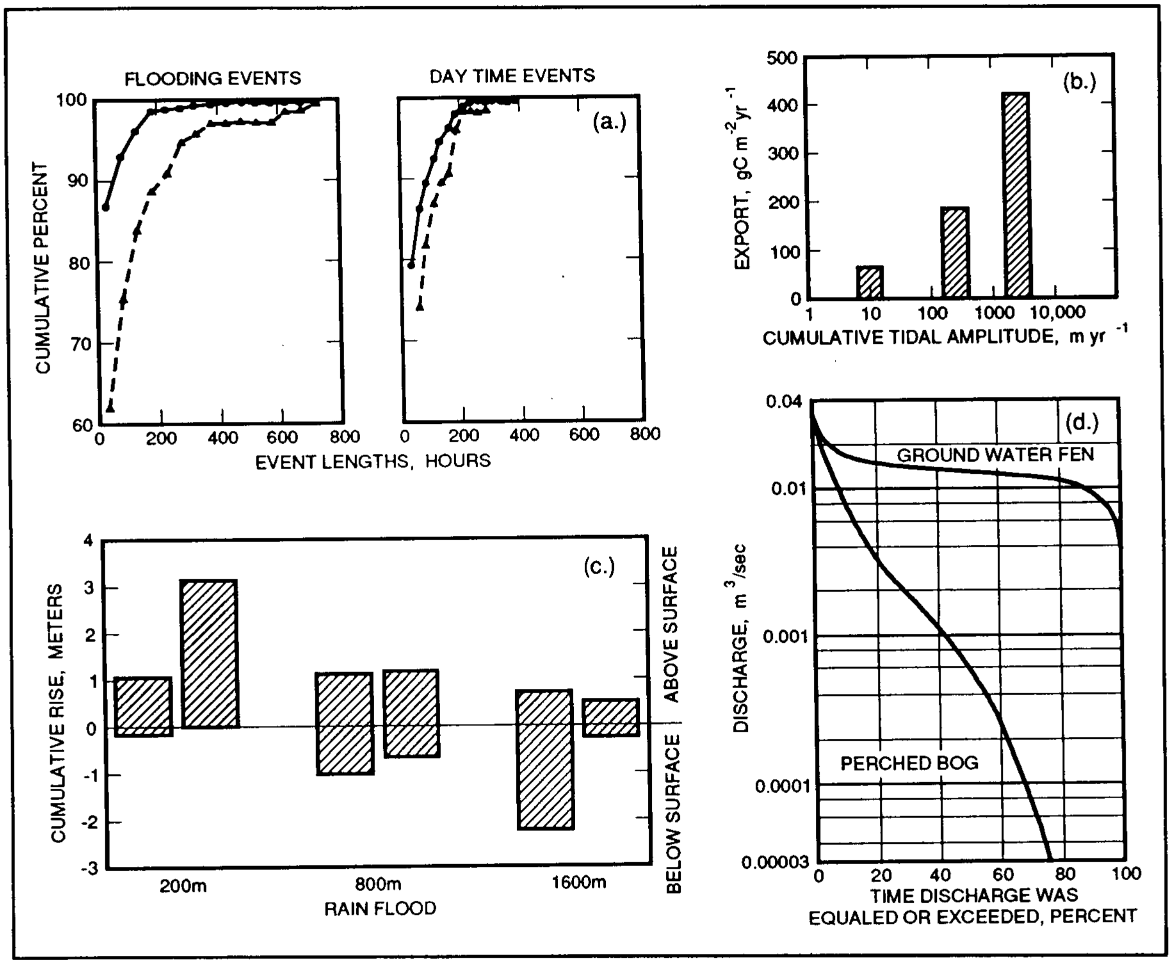

Figure 11. Several approaches for quantifying hydroperiod in wetlands that reveal the dynamics of flooding: (a) Distribution of flooding and dry time intervals expressed as cumulative percent of occurrence for a tidal marsh (solid line) and partially impounded marsh (broken line) (Swenson and Turner 1987), (b) Cumulative tidal amplitude in m yr^{-1} shown as the independent variable for net export of organic carbon from mangrove forests (Twilley 1985), (c) Cumulative drawdown (Hook 1991) or cumulative rise (Brinson, Hook, and Bryant 1991) of water table, (d) Flow duration curves for ombrotrophic peatland (perched bog) and fen (groundwater bog) (Boelter 1977)

Once the relative importance of the three sources of water is established, the sources can be illustrated graphically as in Figure 12. Hypothesized positions of several wetland types are shown in the triangle. The scale in percent could represent any one of the indices of water quantity just discussed. Wetlands that have only two sources of water could be illustrated as easily on Cartesian coordinates. In arid climates, for example, precipitation may be negligible relative to groundwater sources and inflows from upstream. If groundwater discharge were the principal source, the wetland would likely be a groundwater slope or depressional wetland. If water from a stream channel dominated flows through delivery of surface flow (by overbank flooding or flood tides), the wetland would have riverine or

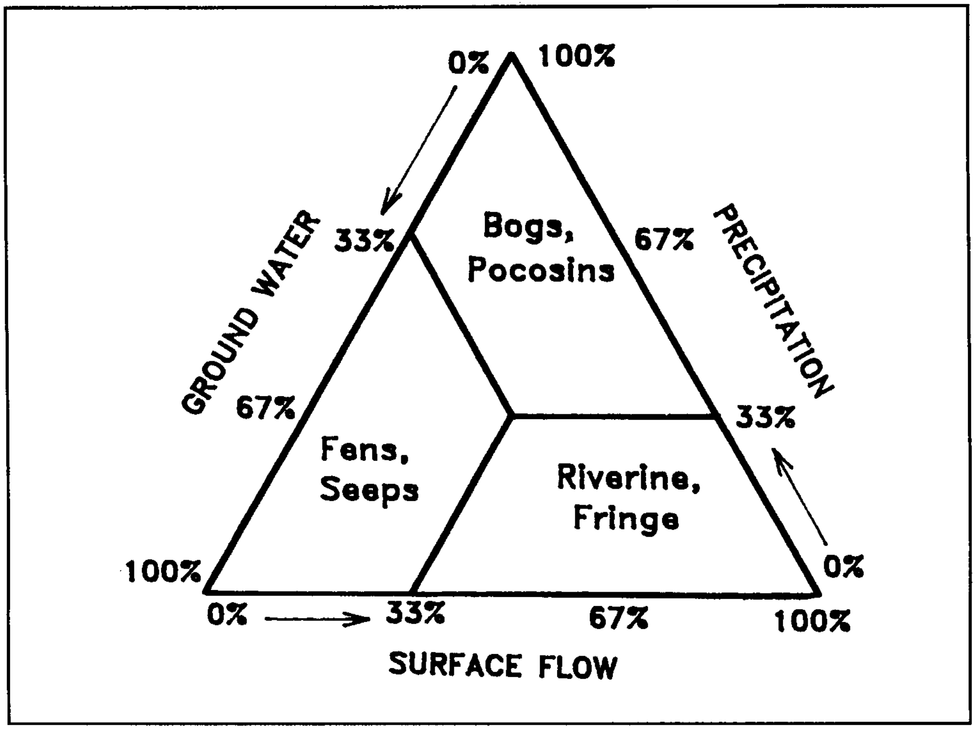

Figure 12. Diagram that allows expression of the relative contribution of three water sources—precipitation, groundwater discharge, and lateral surface flow—to a wetland; location of major wetland types (bog, riverine, etc.) within the triangle show the relative importance of water sources (Brinson 1987)

fringe characteristics. In contrast, ombrotrophic bogs would lack the groundwater and upstream inflow component. A similar diagram was prepared for Wisconsin wetlands (Zimmerman 1987).

It could be argued that quantifying the fates (sinks) of water might be more useful than quantifying the sources. Fates include evapotranspiration, groundwater infiltration to underlying aquifers, and export by surface flow or interflow. The main difference is that emphasis would be shifted to the behavior of water after it affects the wetland rather than before. As such, it would not encompass potential influences of differing water quality being delivered to the wetland under evaluation. Information on the fates of water nevertheless would be influential when assessing effects on adjacent ecosystems. For the immediate purposes of classifying wetlands, both inflows and outflows were treated in the geomorphic setting component of the classification (Table 3) where combinations of inlets and outlets are considered. Information on the destination of water may, however, be very useful in evaluating the implications of hydrologic modification.

Examples of water sources

Knowledge of the source of water often reveals its chemical make-up. The source may also reveal something about flow paths and the energy required to transport the water to the wetland surface. However, hydrodynamics, covered below, deals more explicitly with the mechanism of delivery. Here we will examine what functional characteristics tend to covary with water source.

Precipitation is a source of water for virtually all wetlands and, because it varies with climate, it is essential for comparisons of wetlands among climatic regimes. Even within a given climatic regime, however, the relative importance of precipitation is a function of presence and dominance of the other two sources. Table 4 provides examples of five combinations of water sources, discussed next, while other examples are described later in this section. Dominant water sources and the climatic setting in which each of the five examples occurs are listed in column 1 of Table 4. The first one receives precipitation exclusively and is necessarily located in a moist climate. The second wetland receives surface transport or near-surface transport from overbank flows, but groundwater sources cannot be excluded without the availability of appropriate data. The remaining three wetlands receive substantial groundwater discharge; the first of these three is in a mesic climate, and the other two are in more arid climates. Obviously, more combinations than these five examples exist in nature. Next, a qualitative scale given in column 2 provides some assessment of the relative dominance of the principal water sources relative to others. In column 3, these water sources are described in more quantifiable terms (e.g., seasonality of flooding, cumulative rise or drawdown in water table, duration and frequency of flooding). The fourth column explains how the water sources function to interact with each other, create anaerobic conditions or flush sediment pore-waters, and transport nutrients and sediments. Further elaboration would be possible based on site-specific studies. Finally, the ecological significance of the functions is explained in the last column of Table 4. Ecological significance in some cases is little more than an interpretation of function based on hydrologic common sense or professional opinion. While hydrologic measurements are time-consuming and expensive, others could be estimated by extrapolating from studies that have been conducted in similar ecosystems.

To further illustrate the importance of climate, and, by inference, the importance of recognizing the environmental setting in which a functional classification is conducted, six common wetland types are examined to see how different atmospheric moisture regimes might interact with other sources of water to result in a characteristic, composite group of water sources. Each wetland is examined to consider the hypothetical effects of two climatic conditions: a warm arid climate and a climate characterized as cool and moist. (A shorthand approach is expressed quantitatively as PET ratio. An arid climate would have less precipitation than PET (PET ratio <1), while a cool, moist climate would have greater precipitation

Table 4
Examples of Water Source as a Property of Hydrogeomorphic Classification

Examples of Water Source[1] (and climatic setting)	Qualitative Scale[2]	Quantitative Estimate[3]	Functions[4]	Ecological Significance or Characters Maintained[5]
Precipitation (moist climate).	Precipitation dominates site-water balance and water supply to plant community.[6]	Precipitation > PET during growing season.	Rarity of water table drawdown promotes organic matter accumulation, which further retards drainage; paludification is promoted.	Biogenic landscape isolates mineral soil from access by plants; low primary production eventually results.
Lateral surface or near-surface transport from overbank flow (mesic climate).	Discharge commonly exceeds bankfull-channel capacity.	Duration and frequency of overbank flow to floodplain can be inferred from hydrographs and floodplain elevation.	Overbank flow contributes to both flashy hydroperiod and vertical accretion of sediments. This creates rapid biogeochemical cycling and supplies nutrients.	Conditions maintained for high primary productivity and complex habitat structure.
Groundwater (GW) discharge to wetland (mesic climate).	Seeps occur at bases of hillslopes or below breaks in slope, and along edges of streams and lakes.	Hydraulic gradient of groundwater increases with distance from wetland. Substrate permeable enough to allow flows.	GW supplies nutrients, renews water, and flushes potential plant growth inhibitors.	Conditions conducive for stable plant community of high productivity. Peat accumulation possible.
Both GW discharge and, during flood flows, lateral surface transport from upstream (arid climate).	Nonatmospheric sources greatly exceed supply from precipitation.	Precipitation << PET during growing season.	High water tables are maintained by catchment supplies from upstream and from GW sources.	Water supplies support vegetative complexity and habitat structure not found in uplands because of water stress in arid climate.
All 3 sources, but precipitation is minor (subhumid to semiarid).	Alternate drought and wet periods produce decade-long cycles of water table fluctuations.	Precipitation < PET.	High water levels induced by precipitation; GW discharge prevents extreme drawdowns; wetland may recharge GW when water table is high; conserves/ reduces GW discharge when water levels are normal.	High primary production occurs when water is abundant; decomposition is rapid enough during dry periods to prevent peat accumulation.

[1] Five simple examples with three climatic settings are represented by dominance of one type (first three) or mixtures of several sources of water illustrated in Figure 9: precipitation, groundwater, and lateral surface or near-surface flow. In floodplains, groundwater is normally transported subterraneanly from the upland to the wetland. Surface water may be delivered by overbank flow from the stream channel or from channelized or nonchannelized flow by riparian transport.
[2] Climate and source of water are combined to illustrate four different types of wetland. Roughly speaking, the mesic climate has precipitation approximately equivalent to PET, the humid climate has precipitation > PET, and the arid climate has precipitation << PET.
[3] Climatic records allow calculation of potential evapotranspiration (PET), which can be determined from the empirical formula of Holdridge et al. (1971): mean annual biotemperature $\times$ 58.93 = PET in millimeters, where mean annual biotemperature is the average of all values > 0 $^{\circ}$C. Where precipitation falls short of PET, sources of water other than precipitation reduce site-water deficits. Supplies from groundwater and inflows from upstream are necessary to maintain wetland conditions in all but moist climates.
[4] This column describes mechanisms by which hydrology contributes to and maintains wetland conditions.
[5] Other ecologically significant functions may exist; those listed serve only as examples.
[6] High amounts of orographic rainfall are necessary to maintain waterlogged conditions on sloped landscapes (Lugo, Brinson, and Brown 1990b).

than PET (PET >1).) The six ecosystems are prairie pothole marsh, ombrotrophic peat bog, high-gradient riverine forest, low-gradient riverine forest, tidal freshwater marsh, and tidal saltmarsh.

- **Prairie pothole marsh.** (May also apply to kettles, Carolina bays, playa lakes, and other depressional wetlands with limited catchment area.)

  - **Arid climate.** Under climatic conditions of the northern prairie (central Iowa and northward), wetlands have a negative atmospheric water balance (precipitation minus PET) ranging from -10 to -75 cm (Winter 1988). Depressional storage during each year is a function of previous runoff and climatic conditions. Groundwater interaction with wetlands occurs through a nested set of local to regional flow systems in which recharge occurs at water table highs and discharges at water table lows. Both recharge and discharge can occur in depressions containing wetlands; it is common for a wetland to receive groundwater discharge in one part and recharge in another and for seasonal reversals to occur. The variation of both atmospheric and groundwater interaction induces fluctuations in water quality (LaBaugh 1989) and wet-dry cycles (ephemeral wetlands) characteristic of multiyear successional cycles in prairie pothole marshes (Weller and Fredrickson 1974).

  - **Cool, moist climate.** Conditions probably are not conducive to maintain the depressional configuration of prairie potholes or the marsh vegetation associated with them. Instead, peat-forming wetlands are likely to develop in depressions, and paludification may propagate more poorly drained conditions across the landscape (Heinselman 1970). Where depressions may have occurred in the landscape at one time, potentially inherited topographic features have been obliterated by paludification and replaced with new topographic features. If domed peatlands develop, characteristics described below (ombrotrophic peat bogs) apply. Deep kettle lakes that are oligotrophic may remain as open water rather than undergoing hydrarch succession as typified in many ecology textbooks.

- **Ombrotrophic peat bogs.**

  - **Arid climate.** Conditions are antithetical to development of this ecosystem.

  - **Cool, moist climate.** This wetland type is dependent upon precipitation exceeding PET. Where climatic conditions are marginally conducive for peat accumulation, restricted drainage is likely required to initiate peat accumulation.

- **High-gradient riverine.**

  - **Arid climate.** Small catchment areas with intermittent flow seldom support wetlands. In such climates, wetlands are dependent primarily on groundwater seeps, or, in larger drainage basins, inflows from upstream. Both V-shaped and U-shaped bedrock valleys in the Sierra Nevada region of California tend to be barren of riparian vegetation in comparison to valleys containing glacial till (Harris 1988).

  - **Cool, moist climate.** As with the low-gradient floodplain described below, water may play a major role as a geomorphic agent for transporting sediments, nutrients, and organic matter. In the smaller streams, woody debris can be considered a geomorphic agent that is supplied through biologic processes (Triska and Cromack 1980, Sedell and Beschta 1991). Where present, beaver result in further modification of the geomorphology (Naiman, Johnston, and Kelley 1988).

- **Low-gradient alluvial floodplain wetland.**

  - **Arid climate.** In arid regions, wetlands and streams on alluvium of a floodplain, when adequately saturated with water during moist periods, may act as a source of recharge to water tables in the vicinity. Flows from upstream are often critical to riparian plant communities because of little local rainfall at low elevations (Zimmerman 1969), as exemplified in regions where flow diminution occurs with decreasing elevation (i.e., losing streams). In such situations, riparian vegetation becomes increasingly dependent on water supplied from upstream. Detention of water in reservoirs on tributary streams places additional stress on riparian vegetation downstream.

  - **Cool, moist climate.** Unlike the situation described for arid climates, only protracted droughts are likely to create extreme drawdown of water tables under natural conditions. In fact, water may be more important either as a geomorphic agent or as a stressor because of waterlogging rather than having an effect on water storage. Physical disturbance from ice floes may abrade the vegetation in colder regions (Bliss and Cantlon 1957). Such flooding may result in accretion of sediments on the floodplain in some areas and scouring in others (Hardin and Wistendahl 1983). It appears that as floodwaters become less limiting in supplementing site water balance, they become more important as a medium for transporting nutrients and sediment. For floodplain wetlands assembled along a gradient from low to high order streams, the ratio decreases between groundwater and run-on sources and overbank flooding.

- **Tidal freshwater marsh.**

  - **Arid climate.** Conditions would not be conducive for this type of marsh because sustained sources of freshwater runoff are lacking.

  - **Cool, moist climate.** The freshwater source from stream discharge and the opposing tidal wedge contribute to gradients of salinity in the estuary on the large scale. Within this gradient, tides provide the energy to flood these areas, and consequently are the immediate regulating force on hydroperiod of the wetland (W. E. Odum 1988, Odum et al. 1984, Simpson et al. 1983).

- **Tidal saltmarsh.**

  - **Arid climate.** In arid regions where estuaries receive minimal dilution from freshwater inputs, tidal flushing is the principal mechanism to mitigate hypersaline conditions in estuaries and to prevent porewater salinities from exceeding the tolerance limits of marsh vegetation (Beare and Zedler 1987). Fresh water, when it is episodically delivered, becomes the driving force for species change, sediment supply, and relief from osmotic stress created by hypersaline pore waters. Hence, the ecosystem is controlled by a frequently repeated (usually twice daily) signal from the tides on one hand and infrequent freshwater pulses on the other.

  - **Cool, moist climate.** Where PET is less than precipitation, salt marshes develop in estuaries with ranges in salinity from oligohaline to euhaline. Salt marshes in these moist climates may develop a broad zone of brackish wetland, normally without an interior zone of hypersaline pore waters like Ewing and Kershaw (1986) describe in James Bay coastal marshes. Lower evapotranspiration in colder climates, such as the marshes of the Atlantic Coast of Canada (Roberts and Robertson 1986), the Pacific Northwest of the United States (Ewing 1983), British Columbia, and Alaska, would not subject plants to extreme water stress and may account for the higher species diversity in the marshes of cooler climates (Vince and Snow 1984) as well as the declining importance with increasing latitude of species with C-4 metabolic pathways (Thompson 1991).

Hydrodynamics

Background

The term hydrodynamics, as used here, refers to the motion of water and the capacity of that water to do work (i.e., transport sediments, flush hypersaline water from sediments, transport nutrients to root surfaces). For example, as water loses velocity when it moves across the surface of a floodplain after overbank flow, it also loses its capacity to maintain sediment particles in suspension. The kinetic energy of such floodflows is recorded in the sediments as a progressive decrease in mean particle size from the streamside levee toward the floodplain interior. Ideally the kinetic energy of water could be quantified in terms of its capacity to do work in the ecosystem. Additional examples of such work include surface erosion (Leopold, Wolman, and Miller 1964) and rafting of litter (Hardin and Wistendahl 1983); aeration of sediments; and dispersal of seeds and other propagules to more favorable microsites (Huenneke and Sharitz 1986; Schneider and Sharitz 1986). Because of the stochastic nature of most of these processes, the capacity or opportunity for performing work is seldom quantified. Hence, we are constrained to making inferences about hydrodynamics based on velocity of flow, rate of water table fluctuations, particle size distribution of bedload sediments, and the capacity to replace soil moisture deficits created by evapotranspiration.

Figure 13 portrays three qualitative categories of hydrodynamics: (a) vertical fluctuations of the water table that result from evapotranspiration and subsequent replacement by precipitation or groundwater discharge into the wetland, (b) unidirectional flows that range from strong channel-contained currents to sluggish sheet flow across a floodplain, and (c) bidirectional, surface or near-surface flows resulting from tides or seiches. These prevalent directions of water movement correspond, respectively, to the geomorphic setting categories (i.e., depressional, riverine, and fringe) covered previously. The rate of water level fluctuations of the hydrographs in Figure 13 are somewhat indicative of hydrodynamic conditions.

Examples of hydrodynamic settings

Table 5 provides elaboration of the three categories of hydrodynamics. Each of these is more fully described below.

Vertical fluctuations. Although the hydrodynamics of all wetlands exhibit a vertical fluctuation component, it occurs in its simplest form in depressional wetlands. Two of the major variables affecting vertical fluctuation are the rate of evapotranspiration and the frequency at which water deficits are replaced by groundwater transport and surface flow. An unlimited number of scenarios could be developed matching duration and intensity of evapotranspiration with the frequency and intensity of water delivery to the wetland site. In arid climates where drawdown can be extreme and prolonged,

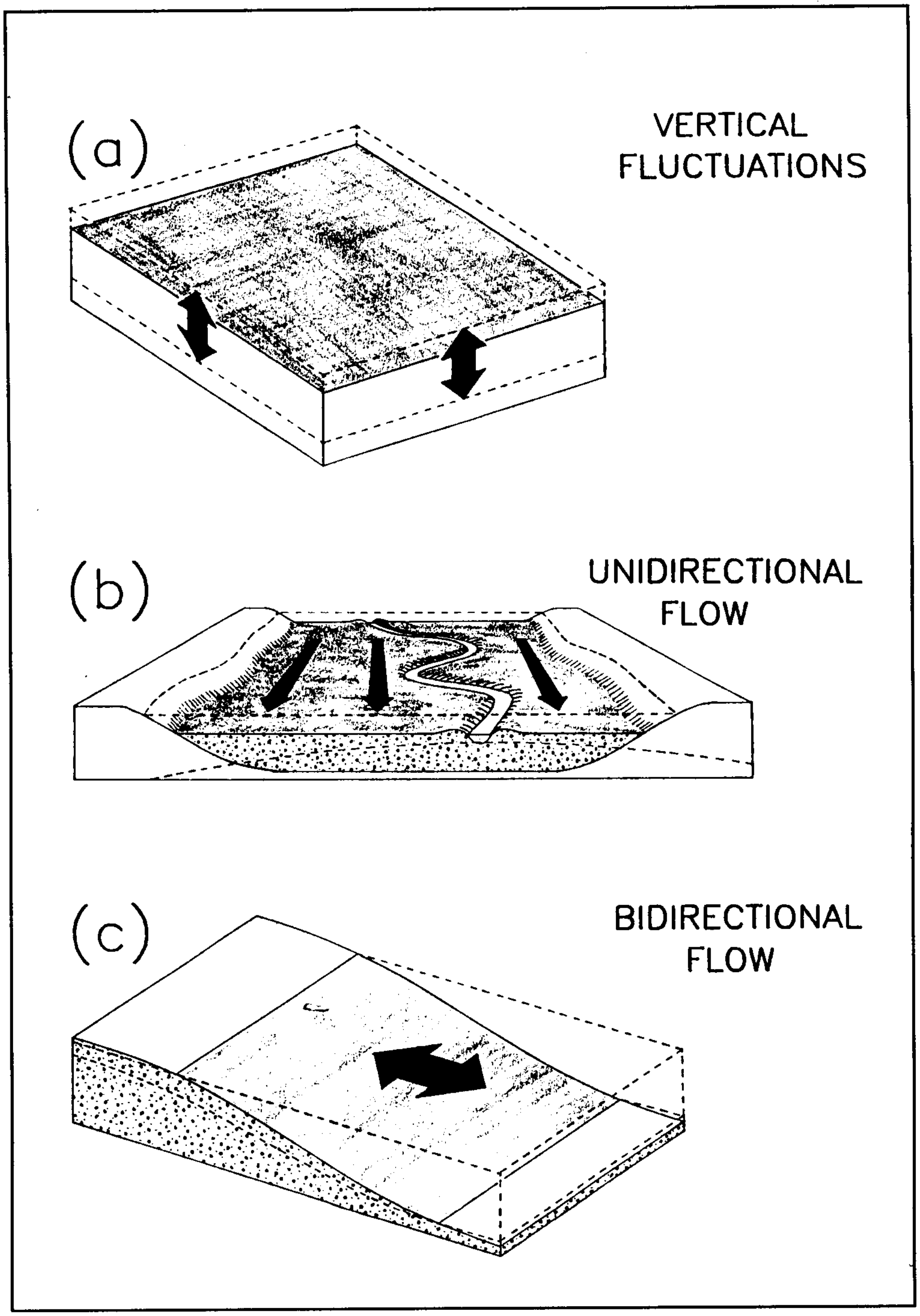

Figure 13. Categories of hydrodynamics based on dominant flow pattern: (a) vertical fluctuations normally are caused by evapotranspiration and precipitation, (b) unidirectional flows are horizontal surface and subsurface, and (c) bidirectional flows are horizontal across the surface

Table 5
Examples of Hydrodynamic Properties of Hydrogeomorphic Classification

Examples of Hydrodynamics[1]	Qualitative Evidence[2]	Quantitative Evidence[3]	Functions[4]	Ecological Significance[5]
Vertical Fluctuation of Water Table[6]				
Seasonal fluctuations nested within multiyear cycles.	Prairie pothole region. Soils diagnostic of dominant water sources.[7]	Aerial photos show variable year-to-year extent of flooding. Hydrographs of water table confirm both short- and long-term fluctuations.	Landscape a mosaic of ponds varying in depth at a single point in time. Floodwaters retained by depressions.	Flyway and breeding sites for waterfowl. Retention of water results in aquatic/moist habitat in otherwise semiarid conditions.
Drawdowns of WT interspersed between frequent rain events that fully saturate sediments.	High ET, but supply by rain in poorly drained landscape of impervious sediments creates wetland conditions.	Hydrographs confirm that water table fluctuates widely.	Precipitation and ET dominate site-water balance. Floodwaters retained by depressions.	Fluctuating WT conducive to rapid biogeochemical cycling; strong atmospheric exchanges.
Drawdown extreme during course of growing season; periods of flooding brief.	Arid climate or sources of recharge minimal.	Hydrographs confirm that water table is low during long periods.	Frequent deficits in site-water balance result in ephemeral aquatic ecosystems because of temporary floodwater storage.	Support of rare plant and aquatic communities such as vernal pools.[8]
Alternating recharge and discharge varying with stream stage.[9]	Wetland narrow and adjacent to channel; sediment texture coarse.	Water table hydrograph proportional to and coincident with stream hydrograph.	High exchange between channel and groundwater. Temporarily stores floodwaters; conserves/ reduces GW discharge.	Substrate well aerated and flushed; hydrophytic vegetation may occur in well-aerated soils.

(Sheet 1 of 3)

Note: ET = evapotranspiration; WT = water table; GW = groundwater.

[1] Hydrodynamics is a measure of the kinetic energy of water that takes into account velocity, turbulence, and rate of change of water table position. Because velocity changes so much temporally, sediment particle size can be useful for integrating hydrodynamics.

[2] Potentially useful indices that require little or no laboratory analysis. Usually observable in field.

[3] Velocities can be measured with sensitive current meters; water table fluctuations can be measured within the wetland with continuous stage recorders or frequently monitored wells without instrumentation.

[4] Processes or conditions that contribute to ecological significance.

[5] Other ecologically significant functions may be present; those provided are only examples.

[6] Not mutually exclusive with horizontal unidirectional and bidirectional flows listed below.

[7] Hubbard (1988).

[8] Zedler (1987).

[9] Stanford and Ward (1988).

Table 5 (Continued)

Examples of Hydrodynamics	Qualitative Evidence	Quantitative Evidence	Functions	Ecological Significance
Vertical Fluctuation of Water Table (Continued)				
Nearly constant water table at or near surface.	Relatively constant WT position suggests low ET because of cool, moist climate; if ET is high, strong groundwater discharge required.	Water table hydrographs have little fluctuation and are at or near surface. A cool, moist climate may suggest low ET; otherwise, strong GW discharge must be assumed.	Stable WT encourages peat accumulation. Where ET is low, ombrotrophic conditions promote bog formation. Strong ground-water sources encourage development of fens or maintain seepage slopes.	Landscape patterns dominated by biogenic process of peat accumulation that is vulnerable to changes in drainage and climate. For seepage slopes, species composition reflects waterlogged soils that are nevertheless well flushed and not strongly reduced.
Unidirectional Flow				
Flow velocities correspond with high-gradient landforms.	Coarse sands and cobble sediments; pool and riffle bedform. Evidence of flooding is transient (e.g., debris lines, tree damage).	Currents strong enough to export fines; particle sizes confirm high fluvial energy.	Strong currents ensure active geomorphic landform. Wetland well flushed because of high turnover rate of water.	Strong downstream transport processes. Well-aerated water supports coldwater fish populations.
Flow velocities correspond with middle-gradient landforms.	Fine to coarse sediments (silts and sands); easily observable flow; point bars develop. Evidence of flooding is persistent (e.g., sediments, disturbance-dependent plant communities).	Measurements of flow velocities and sediment particle size confirm middle-gradient condition.	Interspersion between well-flushed and stagnant areas on floodplain. During flooding, strong transport of particulate matter occurs.	Interspersion of low- and high-energy environments supports complex food webs. Possesses capacity to import nutrients or export toxins.
Flow velocities correspond with low-gradient landforms.	Fine sediments (silt-clay and high-organic content); barely perceptible flow during flooding.	Slope, flows, and particle size distribution all confirm low-energy system.	Residence time of water allows long contact between water and sediment; low-suspended load allows light penetration.	Good conditions for trapping sediment and altering water quality. As nutrient trap, food web support is strong. Reducing conditions favor strongly obligate wetland species.

(Sheet 2 of 3)

Table 5 (Concluded)

Examples of Hydrodynamics	Qualitative Evidence	Quantitative Evidence	Functions	Ecological Significance
Bidirectional Flow				
Astronomic tides: Regular flooding (low marsh or fringe mangrove).	Adjacent to estuary; frequent flooding.	Sea-level controlled; daily to twice-daily tides.	Very active region for biogeochemical process and estuarine food web support.	Many known attributes of intertidal wetlands.
Irregular flooding (high marsh or basin mangroves).	Landscape position landward of low marsh or fringe mangroves.	Flooding during extreme tides and during storms.	Infrequent events transport salt and maintain distinctive ecotone between halophytes and upland.	Leading edge of landward wetland migration responding to rising sea level. Transition establishes barrier to saline water and unique habitat.
Wind-generated water level fluctuations from seiches of large lakes.	Wetland is adjacent to lake: Strongly influenced by lake if at lake level.	Hydrographs show strong evidence of coupling between wetland water table and wetland surface.	Shallow water and vegetation contribute to habitat complexity and food production.	Contributes to food web support and habitat maintenance for aquatic and amphibious species in region of otherwise featureless lake bottom and shoreline.
	Likely GW-supported if on slope above lake level; minimal lake input in most years.	Hydrograph of wetland WT proportional to lake level, but consistently above it (except in extreme GW drawdown/drought).		

(Sheet 3 of 3)

phreatic water must be available to sustain some species of vegetation (Gatewood et al. 1950). At the other extreme, the short and cool growing season of Arctic tundra wetlands or the continual water source from a groundwater seep provides little opportunity for vertical fluctuations of the water table. Five examples of vertical fluctuations are given in Table 5 (Vertical Fluctuation of Water Table; five rows). They range from seasonal fluctuations within multiyear cycles of wet and dry to nearly constant water table at the soil surface. As in Tables 3 and 4, the logic is developed for deriving functions and ecological significance. These range from the reduction of physiological stress by the flushing and displacement sediment porewaters at microenvironmental scales to the maintenance of waterfowl populations along flyways at intercontinental scales (Table 5).

Once the sediments are saturated and gas diffusion to belowground processes is restricted, deeper flooding in itself probably has little influence on most ecosystem processes. There are exceptions, however, such as surface flows, which are largely responsible for transport of suspended sediments. Except for small seedlings that may become completely submerged and die, most tree species can tolerate at least temporarily flooded conditions. However, unseasonably deep floods during the growing season may result in physiological stress to trees (Bacchus 1992). Fluctuations below the wetland surface can have important consequences for root aeration and microbial activity. Alternating reduced and oxidized conditions facilitate interdependent biogeochemical processes that otherwise would become spatially isolated under static conditions. For example, it is well established that denitrification, an anaerobic process, requires nitrification (NH_4^+ to NO_3^-), an aerobic process, before the sometimes high ammonium concentrations in pore waters can be depleted (Patrick and Tusneem 1972).

Examples of quantitative expressions of vertical fluctuations are presented in Figure 11 (a-c). The functions resulting from these fluctuations can be translated into ecological significance. Whether the direction is vertical, horizontal and unidirectional, or horizontal and bidirectional, water movement represents an important factor in characterizing a wetland. Suboptimal plant performance and selection for only the most flood-tolerant species occur under stagnant conditions when water currents are too weak to supply nutrients, flush toxins from sediments, and transport sediments to the wetland surface.

Unidirectional horizontal flow. Unidirectional flow of water can range from barely perceptible surface and near-surface movement to strong, channel-contained erosive currents. Dominance by surface transport is a feature that distinguishes most wetlands from uplands. In terms of sediment transport, the supply for deposition and the loss by erosion governs whether the sediment balance for a site is positive or negative. This in turn is controlled largely by the capacity of a stream to supply sediment. It is axiomatic that wetlands undergoing erosion will have a very short life expectancy or have a very limited surface area. While the transport of water, nutrients, and organic matter from wetlands to downstream ecosystems may be considered a positive attribute of some wetlands, excessive export obviously jeopardizes the self-sustaining properties of wetlands.

The three velocities of unidirectional flow listed in Table 5 span the extremes normally found in wetlands. More discrete categories could be developed to span the continuum between these extremes. The low end member (Table 5, Unidirectional Flow, third row) might be characteristic of the surface flow in a fen portion of a wetland complex in northern Minnesota where the spatial arrangement of groundwater recharge and discharge alters water chemistry in such a way that bogs and fens are interspersed (Siegel and Glaser 1987). The high energy end member (i.e., "... high gradient landforms") might be represented by Arctic streams subjected to strong currents and damage to vegetation by ice floes (Bliss and Cantlon 1957).

The three velocity or energy regimes represented in Table 5 under unidirectional flow are accompanied by a range in qualitative descriptors, but quantitative values (i.e., $m^3 s^{-1}$) are not given. Presumably, quantitative scales would best be developed for geographic regions where similar patterns of landform allow resolution of high and low energy regimes. Within the function column, documentation is provided where available. The ecological significance column of these functions is highly speculative, but there is some documentation for specific geographic regions. Regardless, the proposed qualitative changes that occur when water flow and landform gradient interact create relatively sharp differences among ecosystem functions. The reasons for such changes in "state" are due to the concomitant changes in many interdependent variables. This is why a classification for wetlands cannot be fragmented into a series of independent variables that can be later reassembled into an unrestricted number of combinations.

Bidirectional flow. Current velocities of bidirectional tidal flows on the wetland surface tend to be low, on the order of 1.5 cm s^{-1} or less for South Carolina salt marshes (Wolaver et al. 1985). Inorganic suspended sediments in flood tides between a tidal creek and marsh ranged between 6.0 and 68.4 mg L^{-1} (Wolaver et al. 1988). While any given tidal cycle is unlikely to have much influence on net sediment transport, nutrient exchange, and detritus movement, the cumulative effects of nearly two tides per day becomes a dominant force in these ecosystems. The variation in water transport and water chemistry among tidal cycles makes difficult the development of reliable seasonal and annual water budgets. However, progress has been made in dealing with the error associated with variations in concentrations over space, the asymmetry associated with tidal events (Reed 1987), and the seasonal changes that must be dealt with to develop a water budget (Whiting et al. 1985). In fact, Chalmers, Wiegert, and Wolf (1985) have suggested that precipitation on exposed sediment during ebb tides may be responsible for most of the particulate organic matter export from salt marshes. For estuarine food webs, however, access for fish and other nekton to the food-rich surface of the marsh during inundation is a major factor in contributing to trophic support.

Bidirectional flows can be generated by astronomic tides and by wind. Both regular and irregular flooding occurs within the astronomic tidal group (Table 5, Bidirectional Flow, first row). Regular flooding ranges from semidiurnal tides on the Atlantic and Pacific coasts, to diurnal tides on the Gulf coast. Landward and upslope of the regularly flooded portion of a tidal marsh is the irregularly flooding portion. Functions of regularly flooded marshes include high rates of primary production, nurseries for finfish and shellfish, habitat for wading birds, intense biogeochemical cycling, and others (Teal 1986). As many of these functions have been shown to diminish with tidal amplitude, it follows that irregularly flooded portions of the same marsh are likely to have both a reduction in these specific functions and a qualitative change in functions. As an example of a qualitative change, the landscape role of "high marshes" may be of fundamental importance in initiating landward migration in a regime of rising sea level (Stevenson, Ward, and Kearney 1986; Brinson 1991), in maintaining the pattern of groundwater salinity, and in providing habitat for marsh residents not adapted to the deeper and regular flooding.

Water level fluctuations forced by winds are most apparent in lakes and nontidal or microtidal estuaries (Table 5, Bidirectional Flow, row 2). The latter occur in North Carolina because the narrow inlets of the Outer Banks attenuate tides. Sustained wind "set-up" can create floods up to and exceeding 1 m in depth on marsh surfaces (Brinson, Hook, and Bryant 1991). In the fresher portions of these estuaries, forested wetlands occupy the eroding shorelines (Brinson 1989). Eustatic rise in sea level forces these wetlands to vertically accrete so that plants do not become subjected to excessive flooding. For lakeside wetlands, seiches are the source of water level fluctuations. These wetlands dissipate wave energy, provide areas of refuge for small fish, and provide waterfowl habitat. Herdendorf, Raphael, and Jaworski (1986) describes some of the fringe wetlands in the Great Lakes region, but points out that many of these have been impounded, and thus isolated from flooding by seiches. The Black Swamp region of the Ohio shoreline of western Lake Erie was a vast area of forested wetlands that extended far beyond the fringe marshes (Kaatz 1955). Studies on freshwater fringe wetlands are not abundant (Prince and D'Itri 1985), especially in comparison with saltwater ones (Lugo 1990).

3 Indicators of Functioning

In the foregoing sections, Tables 3, 4, and 5 provided the logic of connecting fundamental wetland properties with ecological significance. It was assumed that with sufficient information on geomorphic setting, water source, and water movement, it should be possible to make reasonable judgments on how these physical properties can be translated into wetland functions. This is an inductive approach and should remain open to testing and further development. What is missing from this sequence for a practitioner who classifies and determines functions is a methodology for estimating or quantifying these properties for a particular wetland. This requires a deductive approach. In practice indicatives of functions are need rather than the functions themselves.

Indicators can be observed in the field (high-water marks, species composition, soil texture, etc.) or can be derived from other data sources (maps, water quality data, etc.). They can be used both to aid in classification of a wetland and to predict whether a wetland has a particular function. In other words, they are surrogates for function rather than function itself. There would be little gained in using indicators for groundwater discharge or overbank flooding if one could depend upon observing these directly on any given field visit. To illustrate indicators and how they can be interpreted to reveal water source and associated habitat features, three examples are given.

a. **Prairie potholes**. The salinity of water in prairie potholes provides insight into both the water source and fate. Seepage conditions range from potholes with outflow only (Figure 14c) to ones with seepage inflow only (Figure 14b). These two extremes correspond to fresh and saline end points shown in Figure 14a. A balance between inflow and outflow results in intermediate salinity (Figure 14d). From such information, inferences can be made about the source of water and to some extent hydrodynamics.

b. **Brackish marsh salinity**. If a coastal brackish marsh contains water of 17 ppt salinity, one can normally assume that about half of the water was derived from sea water (35 ppt) and the other half from a combination of freshwater runoff and precipitation (<0.5 ppt). Consequently, rather than salinity being a hydrogeomorphic factor

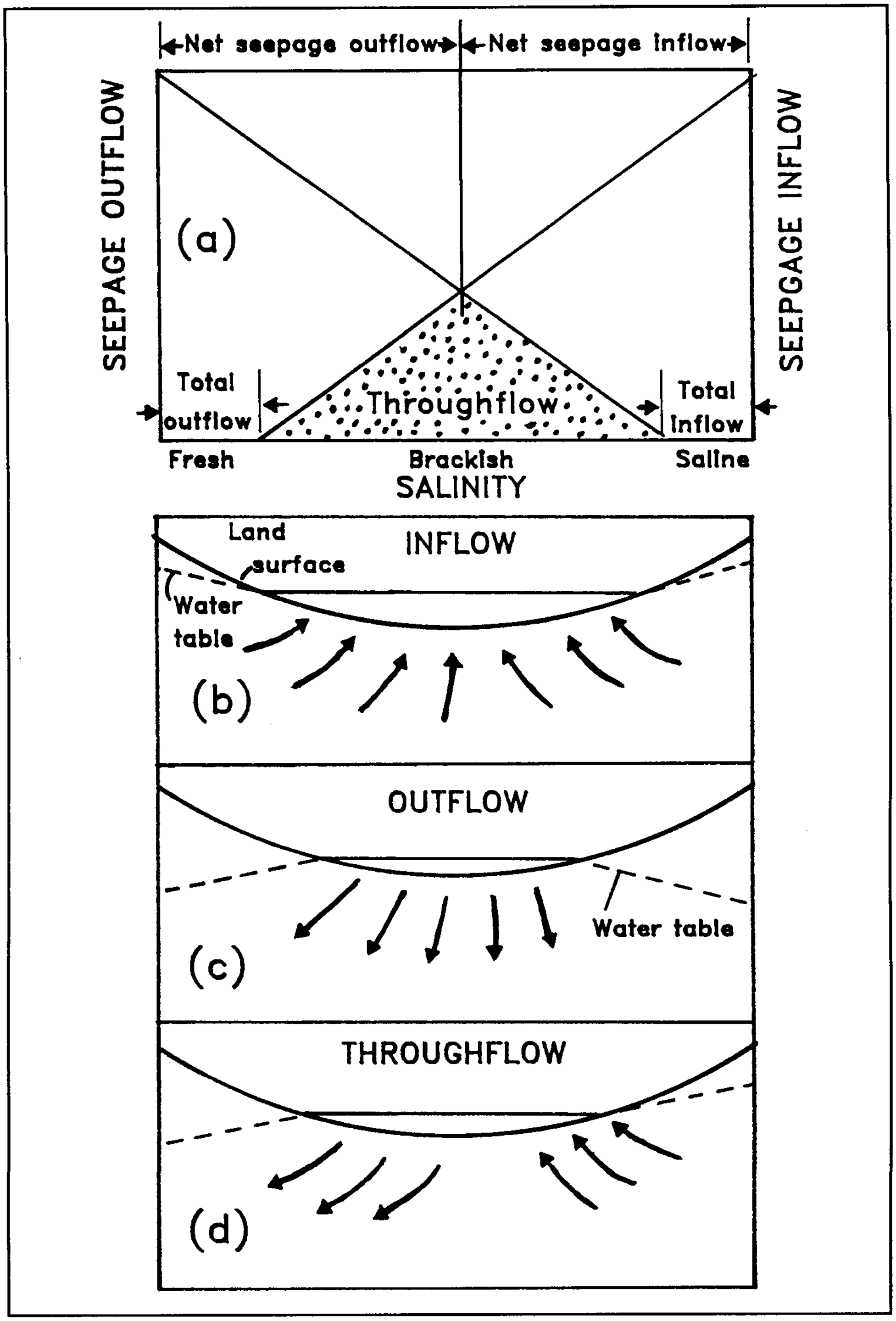

Figure 14. The relationship between seepage conditions (groundwater flow) and water salinity in prairie potholes. (a) Left-hand side of graph is fresh with net seepage outflow. Right-hand side of graph is saline because all the water that flows into the wetlands is evaporated. Diagrams b, c, and d illustrate cross-sectional profiles and direction of water flows. From Sloan (1972)

itself, it is an indicator of the sources of water, the geomorphic setting (near or at sea level), and, less reliably, hydrodynamics (probably tidal).

c. **Hydrographs of flooding**. Hydrographs can be used as indicators to determine water source and hydrodynamics. This was illustrated in Figure 10. Such hydrographs often can be interpreted to show when wetlands are flooded, how deeply they flood, and the thresholds of discharge for associated streams that are likely to transport bedload. Duration and depth of flooding might be interpreted further to indicate a function of supporting fish populations, for example. Welcomme (1979) demonstrated the positive relationship between flooding duration and fisheries yield in African floodplain-river systems. In addition to floods providing access for fish to the floodplain surface, the topographic complexity of floodplains that result from hydraulic energy contributes to fish habitat (Leitman, Darst, and Nordhaus 1991).

Characteristics of both the water and soils or sediments of a wetland tend to roughly correspond with the three major hydrogeomorphic characteristics and, thereby, the functioning of the wetland itself (Table 6). Organic

Table 6
Examples of Indicators for Water and Soil Often Associated with Hydrogeomorphic Characteristics

	Hydrogeomorphic characteristics		
Indicator	**Geomorphic setting**	**Water source**	**Hydrodynamics**
Water Characteristics			
Suspended sediments[1]			
Low	Depressional	Precipitation, groundwater	Mostly vertical
High	Riverine or fringe	Lateral surface	Bidirectional or unidirectional
Organically stained	Depressional or riverine	Surficial groundwater[2]	Vertical, unidirectional
Salinity	Fringe	Lateral surface	Bidirectional
High pH in moist climate	Fen or fringe	Groundwater, marine origin	Unidirectional, bidirectional
Soil or Sediment Characteristics			
Organic	Not in fringe if strongly tidal	Precipitation, groundwater	Vertical, unidirectional
Fine-grained mineral	Not in high-gradient riverine	Headwater floods	Overbank flow
Cobble-sized mineral	Riverine	Headwater floods	Unidirectional

Note: Geographic variation of the characteristics will vary widely. Consequently, they should be developed for local wetland types. It is unlikely that one or two indicators would reliably characterize a wetland.
[1] If standing water is subjected to wind mixing, resuspended sediments may be high in any category.
[2] Groundwater derived from sandy soils that are not wetlands often have high concentrations of humic and fulvic compounds as indicated by water color.

soils (Table 6, column 1) normally develop in environments that have low hydrodynamic energy. Some indicators are better at eliminating several possibilities than at choosing a specific one. For example, organic soils do not develop in strongly tidal creeks of fringe wetlands. (However, tidal creeks may incise previously developed organic sediments by headward erosion.) Organic soils, of course, typify ombrotrophic bogs in low-energy environments where precipitation and evapotranspiration control vertical fluctuations rather than lateral displacement of water. Because the source of bog water is precipitation, both the water characteristics (low-ion content) and the sediment (peat) are indicators of the source of water, the hydrodynamic environment, and, by extrapolation, the geomorphic setting (i.e., poorly drained, generally flat, and elevated above the nearby landscape).

Each of these generalizations has obvious limitations. One might find many exceptions where indicators are not reliable, especially if their use is not restricted to a fairly homogeneous group of wetland types or to a uniform climatic regime. Indicators are not intended to replace general knowledge about hydrology, biogeochemistry, and geomorphology, but, rather, to provide shortcuts to predicting functions. Their reliability in doing so requires verification through testing.

Table 7 proposes a list of parameters that could be used as indicators. Indicators may be either qualitative or quantitative. Some tentative suggestions are given for their ecological significance. In contrast to "water quality," which has overtones of societal use and values, "water characteristics" are interpreted in terms of what they reveal about ecosystem function. For example, low concentrations of suspended sediments allow light penetration in the water column. Adequate light potentially could support aquatic primary production by phytoplankton and epibenthic algae (Minshall 1978). In contrast, high-suspended sediments represent a resource of nutrients that may contribute to the fertility of a soil, while accumulation of sediments may provide a mechanism for geomorphic adjustment of the wetland surface to a changing hydrology such as rising sea level.

Water Characteristics as Indicators

Salinity is a strong selective agent of plant life form in nontropical zones because it determines whether the wetland will be dominated by graminoids and herbs (i.e., marshes) rather than woody plants (i.e., shrub wetlands and swamps). Salinities below that of sea water indicate that terrigenous or atmospheric water sources are present; hypersaline conditions provide additional information on local water balance. Where saline soils develop inland, some of the same halophytic genera (*Distichlis, Salicornia, Salicornia, Suaeda*) proliferate as those found in coastal marshes (Stewart and Kantrud 1972). Halophytes can be roughly ranked according to their salinity tolerance range, although many factors such as hydroperiod often vary in parallel with salinity and thus make it difficult to independently

Table 7
Interpretation of Potentially Useful Indicators of Ecological Significance

Parameter (units)	Range	Ecological significance
Water Characteristics		
Suspended sediments, mg/L		
Low	<20	Low suspended sediment indicates either weak sediment source or weak hydrodynamics. Light transmission may facilitate establishment of SAVs and macro algae.
High	>50	Abundant sediment source reduces light transmission; hydrodynamics sufficiently strong to transport sediment.
Salinity, parts per thousand		
Slightly brackish	<2-3	Terrigenous sources dominate water source; sediments potentially abundant.
Estuarine	3-30	Favorable for salt marsh and mangrove ecosystems.
Sea water	ca. 35	Lacking terrigenous sources; likely nutrient-limited growth.
Hypersaline	>40	Arid climate; wetland processes limited by salinity stress.
Inland salinities (i.e., prairie potholes)	Variable	Potential evapotranspiration exceeds precipitation.
Color (platinum units)		
Clear	Low absorbance	Source predominantly groundwater in contact with soils finer than sand. Allows light penetration if suspended sediments are low (see above).
Black	High color	Source in contact with organic sediments or derived from sandy soils. Complex organics may chelate and mobilize metals.
pH		
Acid	<5	Favors *Sphagnum* domination, restricts denitrification.
Circumneutral	>5	Water sources other than precipitation are likely (i.e., groundwater and estuarine sources).
Nutrient Status		
Low	Oligotrophic	Lack of contact with mineral soil.
Medium	Mesotrophic	Not distinctive.
High	Eutrophic	Potentially high primary and secondary production.
Soil or Sediment Characteristics		
Mineral	Sand, silts, and clays	Thorough flushing; water table dries down during growing season to facilitate decomposition of soil organic matter.
Organic sediments (peat)	High percent loss on ignition	Long hydroperiod; low decomposition rates.

Note: Indicators may not be useful in all wetland types (e.g., salinity).

evaluate the influence of either. Animal communities are often distributed within relatively narrow ranges of salinity (Remane and Schlieper 1971).

In freshwater wetlands, adaptations to the range of conditions are a bit more subtle than adaptations to salinity. However, the often autocorrelated factors of pH, conductivity, hardness, and alkalinity have been useful in the classification of peatlands (Moore and Bellamy 1974). Concentrations of these factors and availability of plant nutrients commonly correspond to whether the wetland is classified as a bog, a rich fen, or a poor fen, for example. On a broader scale of freshwater wetland types, water chemistry has been used only marginally. Turbidity and darkly stained waters tend to be mutually exclusive in the coastal plain of the Southeast. "Blackwater streams" originate in the coastal plain and tend to be sediment and nutrient poor while "alluvial rivers" are sediment rich and originate in the more highly erodible mountains and piedmont.

Water color is sometimes diagnostic of the history of groundwater before it discharges to the surface. For example, streams flowing through clayey soils may be either clear or turbid, but their water is not normally stained by humic and fulvic compounds. In contrast, water discharging from sandy aquifers often retain whatever organic content they may have acquired before becoming part of the surficial groundwater. Similarly, acidic pH may be reflective of a low-ionic content, and hence weak buffering capacity, or may have sufficient concentration of organic acids to maintain low pH. Circumneutral conditions are favored where groundwater has had extensive contact with mineral soils, particularly carbonate lithology.

Nutrient status is seldom a definitive indicator of function, but may have important implications for rates of primary production and food web support. For example, water chemistry and algal species composition have been used extensively as an indicator of the trophic states of lakes (Rawson 1956). Similarly, the water chemistry of peatlands has been related to site productivity and species composition of vegetation (Moore and Bellamy 1974). In fact, when the rate of nutrient delivery to oligotrophic wetlands is increased substantially, changes in species composition usually occur. The most common species replacement is by *Typha* spp., which can invade shrub bogs when wastewater is discharged into them (Guntenspergen and Stearns 1985). Extended hydroperiod and deeper flooding, presumably without enhanced nutrient supplies, also favor dominance by cattails (Wilcox, Apfelbaum, and Hiebert 1985).

In contrast to some of the gross physical features discussed in preceding sections, water characteristics, such as elemental composition, provide quantifiable tests that can be used to compare one water source with another. Because of the overlap that may occur between water chemistry and geomorphic features, the characteristics in Table 7 are meant to provide additional dimensions to the classification rather than proliferate the number of wetland types.

Other Indicators of Functioning

Indicators have been used in other classifications. For example, the Fish and Wildlife Service classification (Cowardin et al. 1979) uses several "modifiers" of water, pH, soil material, and salinity regimes. Their usefulness for resolving wetland types is due, in part, to the fact that they are a consequence of ecosystem processes and function. Indicators have also been used extensively in assessing the opportunity of a wetland to fulfill a particular function (Adamus et al. 1987).

Topographic maps and remote sensing information can yield indicators that are useful in interpreting geomorphic settings of a wetlands. Topographic maps can provide clues on the likelihood of groundwater discharge, overbank flooding, and other similar processes. Wetlands bordering estuaries in tidal regimes will have characteristics of fringe wetlands. The hydroperiod of those located next to a large lake will be determined by the larger body of water and perhaps intermittent flushing from storms. Small, isolated water bodies (i.e., no inlets or outlets) are depressional, while linear features that are wetlands and are located adjacent to streams, undoubtedly have characteristics of riverine wetlands. The use of remote sensing and maps, however, should not be substituted for field visits when classifying wetlands.

Classification of wetlands into functional groups is no more precise than the ability of the observer to record and interpret indicators and other surrogates of ecosystem function. Indicators can help not only in determining the hydrogeomorphic type of wetland, but their interpretation can lead directly to ecological significance (Table 7). Society often places value on the ecological significance (Figure 1), but the relationship between the two is beyond the scope of the classification or this report.

Finally, it has been argued that developing a species list of an ecosystem is the cheapest and most useful approach for answering questions about function (Slobodkin et al. 1980). The rationale is that the life-history requirements of a species provide information on environmental conditions (i.e., ecosystem type) to which the species is adapted. The emphasis on physical factors rather than organisms in the hydrogeomorphic approach is partially a choice of the scale around which one wishes to focus. By choosing major forcing functions, the classification moves beyond the details of biogeographic variation in species composition and beyond the boundaries of the wetland where the forcing functions generally originate. However, once the classification is applied to a specific geographic region of the country, it is appropriate to depend upon the adaptation of species as indicators of environmental conditions. Wetland indicator status of plants is an excellent example of this application (Tiner 1991).

4 Profile Development and Reference Wetlands

Recognizing that wetlands represent a continuum between aquatic and terrestrial ecosystems, it could be argued that there are no discrete categories of wetlands from the standpoint of hydrology and associated properties (Figure 12). The process of interpreting ecological significance from the geomorphic setting, water source, and hydrodynamics illustrates how one can arrive at a description of a wetland's function without actually placing it into a discrete category. This contrasts with most classifications where a finite number of categories is chosen a priori, and each wetland is evaluated to determine which category is the best match. (This open-ended approach used here is intentional because different "classes" of wetlands will emerge as the procedure is developed for different physiographic regions of the country.)

The ecological significance column of Tables 3-5 and 7 can be used to develop a "profile" for a wetland. Profiles are the hydrogeomorphic descriptions of wetland ecosystems resulting from the information developed during a site visit or more detailed study. They can be narrative descriptions or appear in tabular form as quantitative data. Profiles are the end point of the classification as presented in this document. For a particular region of the country, one could develop an array of profiles to describe the existing wetland types. (This process of profile development is addressed below.) Gebhardt et al. (1989) suggests the use of narrative descriptions to describe the "state" of riparian systems to reveal dominant hydrologic processes such as substrates and soils, discharge and channel capacity, and flow regime. By preparing such narratives, one is forced to recognize the processes that are responsible when an ecosystem changes from one state to another.

Closely tied to profile development is the establishment of reference wetlands. These wetlands represent benchmarks against which other wetlands can be compared for various purposes including assessment, training, and mitigation. The process of developing profiles is intended to result in a population of reference wetlands. Those involved in assessment can utilize this documentation as standards against which to compare wetlands being assessed in the future.

Profile Development

A narrative form has been used below to illustrate the development of profiles for three very different wetlands. (These are not actual sites, but are prepared to illustrate the process.) To do this, information from the ecological significance columns are abstracted and modified from Tables 3, 4, and 5. Within each table, the categories and row numbers are identified (first, second, etc.). ("Table 5, second row" under Unidirectional Flow indicates that the information was taken from within the Unidirectional Flow heading in Table 5, and represents the second entry below the heading.)

Examples of profiles are developed below for an ombrotrophic bog, an arid riparian ecosystem, and a groundwater seepage wetland. Each of the items listed can be more thoroughly documented by research results from similar wetlands. The Community Profiles of the U.S. Fish and Wildlife Service are essentially extensive, composite profiles developed from many studies and numerous localities. Other synthesis efforts and original research from the primary literature can be assembled to develop composite profiles.

Ombrotrophic bog profile

Table 3, first row under Extensive Peatland. The wetland site and much of the surrounding landscape is occupied by peatlands similar to that described by Glaser et al. (1981) in northern Minnesota. Upland areas are scarce. Consequently, wetland-upland interactions are minor relative to atmospheric exchanges of gases such as carbon dioxide (Armentano and Menges 1986) and methane (Matthews 1987) and interception of precipitation and dryfall.

Table 4, first row (Precipitation). As a consequence of peat accumulation, plants are dependent exclusively on "new" nutrient sources from precipitation and recycling from organic matter. Low primary productivity is a consequence of these conditions as well as the lack of access to nutrients from weathering in mineral soils.

Table 5, last row under Vertical Fluctuation of Water Table. Because of nearly constant water table and low-flow velocities, accumulation of peat is encouraged; weak lateral flows minimize export of particulate organic matter. Of the dissolved organic matter that is exported, most consists of humic and fulvic compounds capable of transporting heavy metals (Saar and Weber 1982). Existing landscape is vulnerable to changes in drainage because of strong coupling between landform and hydrology and to changes in climate because of climatic control of water balance.

Arid riparian profile (middle-gradient stream floodplain in an arid region.)

Table 3, third row under Riverine Wetlands. Wetland in this middle-gradient landform differs from surrounding landscape by displaying a preponderance of woody vegetation and high structural complexity (Brinson et al. 1981; Brinson 1990). Such corridors of forest provide habitat for many songbirds and other wildlife (Johnson and Haight, In preparation; Knopf 1986). Active geomorphology assures interspersion of plant communities, thus contributing to beta diversity.

Table 4, fourth row. Water supply supports vegetative complexity and habitat structure in contrast to poorly developed vegetation in arid uplands. Floodplain topographic features are varied and complex, providing the template for interspersion of several plant communities ranging from early successional, shade-intolerant species to those occupying more stable sites (Campbell and Dick-Peddie 1964). Sediments consist of allochthonous mineral sediments.

Table 5, second row under Unidirectional Flow. Interspersion of low- and high-energy environments supports complex food webs. Because they are relatively well flushed during flood events and aerated near surface, accumulation of organic matter is prevented. Consequently, they possess a high capacity to import nutrients and export toxins.

Groundwater seep profile

Table 3, last row under Depressional Wetlands. Groundwater flow provides abundant water when regional water tables are sufficiently high. When these drop, evapotranspiration in the wetland may deplete storage in pore waters and desaturate sediments. In cases where groundwater discharge occurs at the face of a slope (Figure 6), flows may maintain saturated conditions year-round, resulting in shallow but predictably stable water-table flooding. Availability of this water source during dry periods may contribute to beta diversity of the landscape.

Table 4, third row. Seepage wetlands tend to have high nutrient supplies from groundwater sources. Resources are abundant and the environment is predictable, making conditions conducive to relatively high primary production and biomass accumulation.

Table 5, fifth row under Vertical Fluctuations. The water table is stabilized by groundwater flow. Such water replacement may maintain high redox levels relative to stagnant saturated soils, thus allowing the establishment of plant species that are not restricted to strongly reducing environments.

Reference Wetlands

Reference wetlands are a product of profile development. They can represent a particular site for which a profile has been developed, or they can represent a population of sites that exhibit a range of variation within a particular functional type. Reference wetlands should be sites where indicators have been tested, measured, and related to corresponding ecosystem functions. Depending on the state of knowledge, it may be necessary to conduct research in these areas to facilitate the development of better or new indicators, and even unforeseen ecosystem functions. The most crucial criterion for reference wetlands is that they include representatives of natural or quasi-natural wetlands that either occur presently in the region or occurred there at one time. This array of different wetlands needs to be established and protected so they can represent "types" similar to type specimens in herbaria, type localities for geologic formations, and type series of soils.

The array of reference wetlands should include those that have been degraded or disturbed. Profiles of degraded wetlands, however, should document the nature and history of the disturbance. The extent to which they differ from relatively undisturbed references may provide insight into the relationship between function, structure, and the nature of the disturbance. Disturbed wetlands may actually perform some functions better than their natural counterparts. They may be useful in training because they force one to identify the source of the disturbance and its effect on function, positive or negative. When dealing with disturbed wetlands, one should keep in mind that there are both qualitative and intensity components to disturbance. For example, harvest of timber may have the effect of altering wildlife usage (a specific quality), but the effect may be short-lived if the forest regenerates adequately (low intensity). Irreversible disturbances should be distinguished from reversible ones.

Reference wetlands could also be used to standardize EMAP sites (Liebowitz, Squires, and Baker 1991) and should serve as the reference for goal-oriented wetland construction (Kentula et al. 1992). Areas in which there is some level of protection and in which research is normally conducted include the National Estuarine Research Reserves, National Research Parks, and the National Science Foundation's (NSF) Long Term Ecological Research (LTER) sites. The NSF LTER sites could serve as a model for reference wetland sites. In fact, LTER sites that have wetlands should be reviewed first as potential sites. However, it is unlikely that LTER sites offer the full range of wetland types that are needed for a comprehensive coverage, especially ones that have been disturbed.

5 Toward Functional Assessments

This manuscript is not an assessment tool, but rather a tool that can be used to develop an assessment methodology. For a particular group of wetlands, the development of profiles will begin to reveal both the major functions of the wetland types and the hydrogeomorphic basis for the functions. The evaluation of the functioning of wetlands is envisioned as a major outgrowth of this classification scheme (Smith 1992). By studying in detail the functioning of various reference wetland types, one should be able to extrapolate to other similar wetlands on the assumption that wetlands with similar landscape position and shape (i.e., geomorphic setting), similar location with respect to water sources, and similar slope and catchment area (i.e., hydrodynamics) will also have similar functions. The confidence that one can place in such comparisons depends on how well the reference wetlands span the range of conditions being assessed and how sensitive the methodology and indicators are for resolving differences.

In the 404 review process,[1] an applicant for a dredge and fill permit could be required to identify the functional type of wetland in the application, and within reason, identify which reference wetland it most resembles in the same physiographic region. Presumably, the reference wetland (or a population of them) will have had their functions assessed previously and will be supported by a fairly comprehensive profile (or group of profiles), possibly including data from research and monitoring efforts. The regulatory team, having been trained locally or regionally in the functioning of each wetland class, will be prepared to assess the similarity between the one described in the permit application and the reference wetland population for which a body of knowledge exists. It would be incumbent upon the applicant, if conditions warrant, to illustrate which functions do or do not exist relative to the reference wetland both before and after the

[1] The details of the regulatory process are not discussed because they are beyond the scope of this report and because they become obsolete as regulations change. The permit review sequence is outlined in the Corps of Engineers Regulatory Program Regulations (33 CFR Parts 320-330), Environmental Protection Agency 404(b)(1) Guidelines (40 CFR Part 230), and several Memoranda of Agreement between the Corps and EPA.

project. The burden of proof would then rest with the applicant to demonstrate the presence or lack of similarity.

Each population of wetland types or classes would be identified with a unique list of functions and associated indicators. (If the list is not unique in some way for the wetland type, then it is probably not adequate for assessment. In other words, the classification was not specific enough and the functional profile was not adequately prepared.) For example, a workshop in early 1992 identified the functions listed in Table 8 for alluvial floodplain swamps of the Georgia Piedmont. Note that discharge of a

Table 8
Four Major Groups of Functions Identified in the Assessment of Alluvial Floodplain Swamps of the Georgia Piedmont

Hydrology	Biogeochemistry	Plant Community	Food Web/Habitat

Flood-peak attenuation
Base-flow augmentation
Wave celerity
Sediment retention
Surface water storage
  detention storage
  retention storage
	Nutrient and contaminant retention from:
	  precipitation
	  overbank transport
	  riparian transport
	Biogeochemical maintenance of water
		Basal area and stocking
		Balanced species composition
		Reproductive and gap processes
			Balanced faunal species composition
			Interspersion of plant communities and of plant communities and open water
			Complex vertical stratification
			Detritus stocks intact

Note: All characteristics were present in the relatively unmodified reference wetland. Indicators for each characteristic have not been fully developed. A glossary of terms is needed to define critical terms. The list was developed by L. C. Lee, M. M. Brinson, W. Nutter, R. D. Smith, and D. Whigham.

deep groundwater aquifer to the alluvium does not appear on the list. This is because the alluvium of Piedmont floodplains is bedrock confined and, consequently, insufficiently permeable to provide water flow to the alluvium. Also, the functions based on vegetative structure would need to be different if one were assessing the habitat variables in depressional wetlands such as prairie pothole marshes. This is in stark contrast with the Wetland Evaluation Technique (Adamus et al. 1987), which is used as a tool to determine the probability that a wetland will perform a particular function. In the hydrogeomorphic approach, the functions for the wetland category are established first in the process of developing profiles and accumulating a population of reference wetlands. It is not until one or several reference wetlands have been assembled that an assessment is actually attempted. The reason for this is that reference wetlands provide scalars against which a particular "project" wetland can be assessed.

Just as reference wetlands will serve as examples of types that are identified in the classification, the classification system itself must undergo change as new data become available and the hydrogeomorphic controls become better understood. As structure and species composition of vegetation become part of the description, regional classifications should be tailored to fit important quality, hydrologic, and habitat features that are representative of a particular region. For example, certain fringe wetlands contribute little toward maintaining the water quality of estuaries as indicated by the fact that exports and imports of sediments and nutrients are often in balance, or at least similar enough so they do not consistently represent either a large net import or export (Wolaver et al. 1988). Such tidal marshes would be better assessed for other functions, such as their contribution to maintaining estuarine fish populations.

The example just given illustrates a distinction that should be made between the assessment of wetland functions and the estimation of wetland values. In a functional assessment, tidal marshes should be evaluated for their capacity to maintain fish populations and not fisheries. The distinction is that the maintenance of fish populations is a property of the ecosystem, not the human population that may or may not happen to use it (Figure 1). The manner in which fish populations are utilized by a given human society changes with the economy, among cultures, and throughout history. Likewise, floodplains in Ohio and in Louisiana may function similarly in terms of biogeochemical cycling and hydrology. Such attributes would be "useful" or "valuable" for wetland rice farming in Louisiana but not in Ohio. Similarly, prairie potholes in the upper plains states may be important habitat for waterfowl (a function) in the Mississippi Flyway, but also have societal value (i.e., be useful and valuable to hunters). Depressional wetlands in the Carolinas (i.e., Carolina bays) may function similarly by providing habitat for endangered species of vascular plants or amphibians (i.e., a function of the wetland and a biodiversity value for humans).

No assessment technique on wetland function is likely to be robust enough to first evaluate the level of a particular function and then further distinguish whether the function is part of a human-based value system. Functional assessment should be grounded squarely in the natural sciences. Resource use and values should be handled by the appropriate disciplines of economics, sociology/anthropology, and resource management. Each of these disciplines has its own techniques, but they usually focus on one or several commodities of wetlands and are not sensitive to the forces that are responsible for the self-maintaining properties of the ecosystem itself. One of the main differences between a functional assessment and an economic assessment is that they use totally different indicators. A potential pitfall of any assessment system, whether functional or otherwise, is the confusion that develops when trying to handle too many disciplines with a single set of indicators.[1] One of reasons for presenting the functional clas-

1 Energy analysis is an example that uses a fundamental, thermodynamically grounded set of techniques and indicators. However, energy analysis, as it is now developed, is too time-consuming and conceptually rigorous to be appropriate for the applications discussed here for wetlands. See H. T. Odum (1988) and Costanza (1980) for explanations and examples. More recently, attention has been focused on the shortcomings of standardized economic assessment procedures. Specifically, the United Nations System of National Accounts (SNA) does not depreciate natural resources such as forests and soils when they are removed or irreversibly damaged. Instead, the SNA ignores assets such as forests and soils, but further treats their destruction as an increase in income rather than a loss of wealth (Solorzano et al. 1991).

classification in this manuscript, without an assessment component, is that the classification is the logical first step that is needed to clear the path for a manageable assessment procedure.

The array of key wetland types that emerge as reference wetlands can be used not only for the purposes of characterizing and quantifying various aspects of wetland function, but also as standards to evaluate wetland construction and restoration projects. In this sense they become the standards of success in contrast to relying on endless lists of design criteria and performance standards. One of the most valuable uses may be in the training of wetland scientists who will be involved in work on permit review, assessment of functions, construction of new wetlands, and restoration of degraded ones.

Highly modified wetlands may require an additional level of classification. Because the hydrogeomorphic approach is to be driven by function, it may be useful to classify according to existing, modified functions, rather than attempting to reconstruct whatever original functions might have existed. Because there is a finite number of functions that can be supported by a given wetland type, and this constraint limits the intensity at which functions can operate, management toward a specific function (like agricultural crop production) will necessarily compromise other functions (e.g., the dictim that only one thing at a time can be maximized). Nevertheless, examples abound where management is oriented toward multiple uses. In river floodplains of some regions of Africa, dry-season cattle grazing on floodplains is compatible with wet season fish utilization (Welcomme 1979). Usually when a wetland is managed for a particular commodity or value, the capacity to maintain competing uses is reduced. In the cases of the floodplain systems described by Welcomme, there may be complementary or even synergistic uses. If future options are to remain open, however, modification of the wetland should not be irreversible. In this regard, it is worthwhile to remember such long-term goals as the sustainable utilization of species and ecosystems.

For a classification to undergo change and improvement, its structure must not be so rigid or complex that it cannot be modified by its users. It should be clear at this point that the classification, as presented above, is not intended for a user to take it to the field for the purpose of matching indicators with functions. Rather, the report is intended to show how some fundamental knowledge about water flows and sources can be interpreted to illustrate ecological functioning. This purpose is lost if one bypasses the development of profiles and the establishment of reference wetlands. It is considered essential to understand the basic underpinnings of wetland function. Much of the hyperbole surrounding the protection of wetlands attributes multiple functions to wetlands that have not been rigorously documented. Until such carelessness is corrected, little progress can be made beyond the current state of understanding.

Local adaptations of this classification, and ultimately assessments, are anticipated to incorporate the use of either locally recognized wetland names or a modification of cover types with modifiers from the Fish and Wildlife Service's classification (Cowardin et al. 1979). A greater number of specific categories may be advantageous to some geographic regions (Table 9). However, unless the logic is followed that reveals the functions and ecological significance of those functions, then the basis for function has not been well articulated and probably not understood. Conducting rigorous assessments of poorly understood functions or doing a poor job assessing well-understood functions is not in the best interest of wetland science and resource management.

Table 9
Categories of Geomorphic Setting, Water Source, and Generalized Functional Types

Geomorphic Setting	Functional Types
Blanket bog/raised	Blanket bog
Depressional	Raised bog
neither inlet nor outlet	Surface-water depression
surface inlet only	Groundwater depression
surface outlet only	Groundwater slope
surface inlet and outlet	High-gradient channel
Slope	Low-gradient channel
Channel	Stream floodplain
Floodplain	Lake floodplain
Fringe	Channel fringe
	Lake fringe
Water Source	
Precipitation	
Upslope runoff	
Groundwater (regional or perched)	
Channel flow (perennial and intermittent)	
Overbank flow (stream or lake)	
Tides (astronomical and wind)	

Note: Presented by Frank Golet, University of New Hampshire, at the Stone Mountain Workshop.

It could be argued that one of the problems with classification and assessment procedures is the shortage of qualified people to do them. Resources usually are not available to support assessments by professionally trained teams of hydrologists, ecologists, and geomorphologists. Likewise, it is probably futile to expect a classification or assessment technique to substitute for such expert opinion. Most routine needs for assessment probably do not justify what might be construed as "overkill." Consequently, what is needed is a reliable and defensible approach that utilizes as much as possible the body of information that is currently available on wetlands. Thus, professionals who are conducting the assessments must either be trained or train themselves to learn the fundamentals of hydrology, geomorphology, plant and animal ecology, biogeochemistry, etc., and apply these disciplines to interpreting information that is available on wetlands. There is no substitute for applying knowledge about wetlands in reaching valid assessment conclusions. The use of reference wetlands as training vehicles should facilitate the learning process for the following reasons: (a) The number of wetland types that need to be mastered in a given locality is probably less than five or six. Thus, one does not have to deal with an infinite array of wetlands to adequately assess a few types. (b) Reference wetlands create mental images that can be carried from one site to another. Although observable structure alone might be misleading in terms of functional interpretation,[1] visual acuity may be as reliable as lists of individual indicators. Mental images, although powerful, are not defensible scientifically and should not substitute for narrative descriptions in functional profiles and, if possible, quantitative data. (c) The environmental setting of reference sites in agricultural, urban, and other disturbed locations makes one aware of the effects of modifications on wetlands, especially alterations of hydrology and how the history of human activity may account for their current functional condition.

While there is little new in the hydrogeomorphic classification that has not been demonstrated previously, it does require a synthesis of information and a fairly rigorous interpretation of information to reveal functions. There are essentially no limits to the amount of information that could be brought to bear in functional classification. Consequently, there is much to be done in constructing profiles, generating and testing indicator lists, and establishing reference wetland populations. The process is completely open to new information and modification. However, we are still poorly positioned to have definitive answers in all aspects of wetland functioning. One of the challenges that makes this an exciting endeavor is the potential to discover new functions and reveal their ecological significance.

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[1] Personal Communication, 1991, Dennis Whigham, Plant Ecologist, Smithsonian Environmental Research Center, Edgewater, MD.

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Appendix A Glossary

Some of the terms are defined specifically for wetlands or this classification. Consequently, definitions may differ from those more broadly applied. If so, they are marked with an asterisk (*). Definitions marked with a † were taken from Fetter (1988).[1]

Abiotic—Not living. Deposition of suspended sediments on floodplains is an abiotic process.

Accretion—Vertical accumulation of sediments or organic matter. If organic matter is accumulating as a result of photosynthesis, the process is biotic and may result in biogenic landscapes such as peat bogs.

Aerobic—Occurring in the presence of free molecular oxygen. Obligate aerobic bacteria cannot be active in the absence of oxygen.

Alkalinity—The capacity of water to buffer changes in pH. The carbonate buffering system is the most common. See buffered water and hardness.

Allochthonous organic matter—Organic matter that is transported to a site rather than being produced by photosynthesis at the site.

Alluvial—Pertaining to alluvium, or material transported by flowing water.

Alluvial swamp—A forested floodplain wetland with soils consisting generally of fine-grained sediments that have been deposited by overbank transport of sediments from a stream.

Ammonium—A reduced inorganic form of nitrogen in a monovalent cation form (NH_4^+). Ammonia (NH_3) is a gas.

[1] References cited in this appendix are included in the References at the end of the main text.

Aquifer, confined—An aquifer that is overlain by an aquiclude or aquitard, and thus does not have a water surface in direct contact with the atmosphere.

Aquifer, perched†—A region in the unsaturated zone where the soil may be locally saturated because it overlies a low-permeability unit.

Aquifer, phreatic—The zone that contains unfrozen fresh water.

Aquifer, surficial—The uppermost region of the aquifer that is near the land surface.

Aquifer, unconfined—An aquifer that is in direct vertical contact with the atmosphere through open pores. Synonymous with water-table aquifer.

Artesian—The condition of water flowing freely from uncapped wells because it originates from a confined or semiconfined aquifer for which the potentiometric surface is above the ground surface.

Basin wetland—See depressional wetland.

Bedload, sediment—Sediments that move along the bottom of a stream channel.

Bedrock-confined channel—A stream channel that has as its bottom the bedrock that is normally undergoing erosive downcutting.

Beta diversity—Variety of organisms occurring in different habitats of a region in contrast to alpha diversity, the variety of organisms within a small, homogeneous area.

Biogenic—Derived or originating from living material, as peat.

Biogeochemical—The interaction and integration of biological and geochemical cycles.

Biogeographic—Refers to the distribution of species on the surface of Earth.

Biotic—Refers to living processes or entities.

Blackwater streams—Streams common in the southeastern United States that have high concentrations of dissolved organic carbon and humic compounds, resulting in a darkly stained water.

Bog—A peatland that is nutrient poor because it lacks access to substantial quantities of mineral-rich water.

Bottomland—General term that refers to floodplain wetlands.

Brackish—Water containing salt. Normally a mixture of fresh water and sea water.

Buffered water—Water that is resistant to changes in pH. See alkalinity and hardness.

C-4 plants—Vascular spermatophytes that are usually monocots, and possess anatomy and physiology that allow high water use efficiency and rates of photosynthesis that tend not to saturate in full sunlight.

Capillarity—The phenomenon of adhesive forces between water and solids that results in matrix potential in soil-water systems.

Capillary fringe—The saturated zone in soils above the water table as a result of capillarity.

Carolina bays—Depressional wetlands of the Carolinas and nearby states to the north and the south. They normally have a sandy rim, the long axis is oriented northwest to southeast, and they may be filled with open water or completely vegetated. Sediments range from sands to clays which can be overlain by peat or organic-rich soils.

Catchment—A term similar to watershed, which consists of all of the land upstream from a point where rainfall may potentially flow.

Channel capacity—The discharge of a stream just prior to overbank flow.

Channelized flow—Flow that is confined to a channel in contrast to unchannelized (nonchannelized) flow or overland flow.

Chelate—A reversible complexation of an organic molecule normally with an ionic form of a metal.

Circumneutral—Water with a pH of around 7.

Conductivity—The capacity of water to conduct electrical current. Conductivity is proportional to the ionic content of the water. Units are normally micromhos per centimeter, which is equivalent to the SI units of microSiemens.

Cumulative rise in water table*—The sum of increases in water table over a specified period of time, normally as a consequence of influxes of water because of precipitation and lateral surface transport.

Cutbank—The outside meander of a stream channel that is undergoing erosion by lateral migration of the channel.

Cypress strands—Shallow drainages dominated by cypress trees. Channels are poorly defined such that overbank flow is quickly exceeded with minor increases in discharge.

Denitrification—The microbially mediated heterotrophic process of converting nitrate or nitrite to either nitrous oxide or dinitrogen gas.

Depressional wetland*—A wetland located in a depression in the landscape so that the catchment area for surface runoff is generally small.

Depressional*—A wetland geomorphic setting that occurs in depressions, but usually at the headwaters of a local drainage. Consequently, surface flows are restricted.

Detritus—Organic matter undergoing decomposition, with the attendant protists, protozoans, and other organisms that serve as food for detritus feeders.

Discharge—The volume of flow per unit time, such as m^3/sec.

Distichlis spicata—Salt grass.

Drawdown of water table*—The phenomenon of a natural decrease in water table usually as a result of evapotranspiration, or unnatural decrease as a result of consumptive withdrawal of groundwater.

Edaphic (control)—The controls on plant-species distribution or function as a result of conditions in the soil in contrast to atmospheric controls.

EMAP—Environmental Monitoring and Assessment Program is an Environmental Protection Agency program to assess long-term changes in ecosystem performance or "health." EMAP-Wetlands is the component limited to wetland ecosystems.

Epibenthic algae—Algae that live on the bottom or benthos of an aquatic ecosystem.

Euhaline—Approximately the salinity of sea water, or about 35 ppt.

Evapotranspiration—The combination of evaporation and transpiration expressed in the same units as precipitation.

Fen—A peatland that is fed by groundwater. Poor fen—A peatland that receives groundwater flow and achieves productivity intermediate between that of a rich fen and an ombrotrophic bog. Rich fen—A highly productive peatland often dominated by grasses or trees in contrast with shrubs and mosses.

Floodplain—The land beside a river that receives overbank flooding when discharge exceeds channel capacity.

Flow, groundwater—Water that flows below the land surface through a porous medium normally under saturated conditions.

Flow, near-surface*—Flow that occurs just below the surface of a wetland in a layer that is often more permeable than the more consolidated sediments just below.

Flow, surface—Nonchannelized flow (unchannelized) that occurs above the surface. Overland flow.

Fringe wetland*—A wetland that is located near a large body of water, most typically the ocean, and receives frequent and regular two-way flow from astronomic tides or wind-driven water-level fluctuations.

Function (ecosystem)*—Processes that are necessary for the self-maintenance of an ecosystem such as primary production, nutrient cycling, decomposition, etc. The term is used primarily as a distinction from values. The term "values" is associated with society's perception of ecosystem functions. Functions occur in ecosystems regardless of whether or not they have values.

Functional profile*—Narrative or quantitative information on a wetland being assessed that describes the ecological significance of properties of water source, hydrodynamics, etc.

Geomorphic—A term that refers to the shape of the land surface.

Geomorphic setting*—The location in a landscape, such as stream headwater locations, valley bottom depression, and coastal position.

Geomorphology—The study of Earth's surface and its development.

Graminoid—A grass or grass-like plant, such as sedges and rushes.

Gravity flow—Flow of water controlled by gravity instead of strictly piezometric head differences.

Groundwater discharge—Flow originating from an aquifer that flows to the surface.

Groundwater inflows*—Flow of water received by a wetland or some other area as a result of groundwater discharge via lateral seepage or upward movement.

Groundwater recharge—Flow of water from an area that contributes to an aquifer. Most upland areas contribute to groundwater recharge.

Halophytes—Plants that are tolerant of salty water.

Hardness—A property of water that is roughly proportional to the ion concentration. Water from calcareous aquifers is often hard because of the calcium carbonate content. Such waters are very resistant to fluctuations in pH.

Hydrarch succession—The sequence of community changes that occurs as an aquatic ecosystem fills with sediment and eventually, through mostly extrinsic factors, develops into a terrestrial ecosystem.

Hydraulic conductivity†—A coefficient describing the rate at which water can move through a permeable medium.

Hydraulic gradient†—The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.

Hydrodynamics*—The motion of water that generally corresponds to its capacity to do work such as transport sediments, erode soils, flush pore waters in sediments, fluctuate vertically, etc. Velocities can vary within each of three flow types: primarily vertical, primarily bidirectional and horizontal, and primarily unidirectional and horizontal. Vertical fluxes are driven by evapotranspiration and precipitation. Bidirectional flows are driven by astronomic tides and wind-driven seiches. Unidirectional flows are downslope movement that occurs from seepage slopes and on floodplains.

Hydrologic—Dealing with the field of hydrology or the distribution and movement of water.

Hydroperiod*—The depth, duration, seasonality, and frequency of flooding.

Hydrostatic head—Piezometric head. A position of higher water-table stand relative to a lower one. Water flows toward decreasing hydrostatic heads, and not necessarily to lower elevations. See hydraulic gradient.

Hypersaline—Generally values well above sea water, i.e., greater than 40 ppt.

Ice floes—Floating masses of ice usually associated with spring breakup on lakes and rivers.

Igapó—Refers to the portion of the Amazon Basin not derived from the foothills of the Andes where suspended sediments arise. In contrast, these waters tend to be clear albeit somewhat stained.

Indicators (of function)*—Water chemistry, species composition, soil characteristics, or some other feature that allows one to infer or predict certain ecosystem functions or other conditions.

Inundation—The condition of water occurring above the surface, i.e., flooding.

Juncus gerardi—A species of *Juncus* (a true rush) that occupies high or irregularly flooded portions of salt marshes from the mid-Atlantic to the north.

Juncus roemerianus—The ecological equivalent of *J. gerardi* that is distributed in warmer climates from the mid-Atlantic southward including Florida and the Gulf coast.

Kettles—Deep depressions in glaciated areas that resulted from the melting of an ice block that had been buried previously by glacial outwash. These small lakes may undergo hydrarch succession and fill with peat and become forested wetlands.

Kinetic energy—Energy of motion in contrast to stored or potential energy.

Landscape—Gross features of the land surface, including but not limited to slope, aspect, topographic variation, and position relative to other land forms.

Life form, plant—The general morphologic category of plants, such as tree, shrub, herb, etc.

Lithology—Refers to the composition of Earth's crust. The consequences of weathering of this parent material may carry over to properties of the soils that develop.

Mangrove—A general term for several of halophytic woody species that occupy fringe wetlands. They tend to be restricted to climates that have little or no frost.

Marsh—A wetland with emergent, herbaceous vegetation.

National Wetland Inventory—A program of the Fish and Wildlife Service that maps and categorizes wetlands of the United States. The categories used are those developed in the "Classification of Wetlands and Deep Water Habitats of the United States."

Near-surface flow—Flow that is not visible just below the surface. It often occurs in the rhizosphere where hydraulic permeability is high. See Seepage.

Nitrate—The most oxidized form of nitrogen that can be used as an alternate electron acceptor in anaerobic respiration.

Nitrification—The microbial transformation from ammonium to nitrite and from nitrite to nitrate. It is an energy-yielding aerobic process.

Nonchannelized flow—Normally reserved for surface flow that is diffuse and thus not confined to a channel. Also unchannelized and overland flow.

Nonpoint source—Diffuse sources of nutrients or contaminants, often from agricultural and urbanized landscapes. They are in contrast to point sources, which are discharged from a pipe.

Nurseries, fin fish and shellfish—Normally used to designate habitat critical for young stages of fish or shellfish.

Overbank flooding*—Refers to excess flow to a floodplain when discharge of a stream exceeds channel capacity.

Overbank, transport*—Movement of water from the channel to the floodplain surface.

Ombrotrophic bog—A peatland that receives precipitation as the sole source of water. Generally peat has accumulated enough to isolate the plants from acquiring nutrients from the underlying mineral strata. The elevated surface is indicative of tertiary mires.

Overland flow—Water movement parallel with the soil surface.

Paludification—The landscape phenomenon of organic-matter accumulation on mineral soil thus forming a histosol.

Palustrine—Nontidal wetlands where the salinity from ocean-derived salts is less than 5 ppt. Further modifiers are used by the National Wetland Inventory.

Parts per thousand—See ppt.

Perched—Describes an aquifer that is underlain by an unsaturated zone.

Permeability—See hydraulic conductivity.

pH—The negative log of the hydrogen (hydronium) ion concentration.

Phreatic flow—The movement of water that occurs in an unconfined aquifer.

Physiognomy—The gross structure of a plant community resulting from the dominance of life forms such as trees, shrubs, graminoids, etc.

Phytoplankton—Algae that are carried with water currents in contrast to the relatively immobile and attached epibenthic algae.

Piedmont—The steeper, rolling physiographic province formed at the base of mountains. Locally it is west of the Atlantic coastal plain and east of the mountains.

Pipe flow—Flow of groundwater that results from secondary porosity (macropores) often formed by decayed root channels or animal burrows.

Plant-life form—The general morphologic category of plants, such as tree, shrub, herb, etc.

Playa lakes—Shallow depressions similar to prairie potholes, but abundant on the Southern High Plains on a tableland south of the Canadian River in Texas and New Mexico. They undergo annual and multiyear cycles of drydown and filling.

Playa wetlands—See playa lakes.

Pocosin—Evergreen shrub bogs and fens of the southeastern United States that frequently burn.

Pore water—Water that fills the interstices of soil or sediment.

Potential evapotranspiration (PET)—The amount of water that would be lost by evapotranspiration from natural vegetation in a particular climate if water were never limiting during the year.

Potential evapotranspiration ratio (PET ratio)*—The ratio between evapotranspiration and actual precipitation. Values greater than 1.0 represent water deficits. Wetlands in such climates must be supplemented by other sources of water.

PET—See potential evapotranspiration.

Potentiometric surface—The elevation to which the water table of an aquifer would raise if there were no confining layer. The potentiometric surface of an unconfined aquifer is the water table.

ppt—Parts per thousand, units generally used for expressing salinity.

Prairie pothole—Depressional wetlands in the upper Midwestern States and the plains provinces of Canada.

Primary production—The conversion of solar energy into organic matter by photosynthesis.

Principal-components analysis—A multivariate statistical analysis that distributes data in two-dimensional space along gradients that represent variables that appear to be independent.

Profile, wetland*—A qualitative or quantitative descriptive depiction of a wetland that, in the case of the hydrogeomorphic classification, emphasizes the physical characteristics such as geomorphic setting, water source, and hydrodynamics. Profiles also may include the biotic components.

Propagules—Reproductive structures, as the seeds or cuttings from plants.

Recharge, groundwater—Addition to the storage component of an aquifer.

Redox—The potential difference, usually expressed in millivolts, between a platinum electrode and a reference electrode in a solution. The scale is especially useful for sediments that are devoid of oxygen because it allows an expression of reducing conditions beyond the scale of oxygen.

Reference wetland*—A wetland or one of a group of wetlands within a relatively homogeneous biogeographical region that represents typical, representative, or common examples of a particular hydrogeomorphic wetland type, or examples of altered states.

Reference wetland population*—A group of wetlands of the same hydrogeomorphic type that represents the variation that occurs within the type because of natural or society-influenced causes.

Riparian*—Pertaining to the boundary between water and land. Normally represents the streamside zone and the zone of influence of the stream toward the upland.

Riparian transport*—Movement of water from upland regions to floodplains either by groundwater discharge at the slope face or toe, and by direct precipitation and overland flow.

Salicornia—Pickle weed, a salt-marsh plant.

Saturated—In reference to soils, the condition in which all pore spaces are filled with water to the exclusion of a gaseous phase.

Seasonal programming—The genetically controlled behavior or activities of organisms.

Seepage†—A site where groundwater of a surficial aquifer discharges to the surface, often at the toe of a slope.

Seiche—Harmonic water level fluctuations in large lakes resulting from wind relaxation after a period of set-up.

Setting, geomorphic*—See geomorphic setting.

Set-up—The increase in water surface elevation downwind of a large body of water because of sustained winds.

Shade intolerant—Normally refers to tree species that require full sunlight to survive the early stages of growth.

Source, nonpoint—See nonpoint source.

Spartina alterniflora—Salt-marsh cordgrass. A true grass that dominates regularly flooded portions of salt marshes.

***Spartina cynosuroides*—**Giant cordgrass. A true grass that is most common in the fresher portions of salt marshes, especially in the high marsh or the marsh-upland transition zone.

***Spartina patens*—**Salt-meadow hay. A true grass that is common in the irregularly flooded zones of tidal salt marshes.

Stratigraphy—The vertical layering of sediments or other materials often as a consequence of the chronological sequence in which they were deposited.

Stochastic—A phenomenon that varies over time, usually in an irregular or unpredictable pattern.

Storage, specific†—In hydrology, it is the amount of water released from or taken into storage per unit volume of porous medium per unit change in head.

Storativity (storage coefficient)†—The volume of water released from or taken into storage per unit surface area of aquifer per unit change in head. In an unconfined aquifer, the storativity is equivalent to the specific yield.

Stress—The condition of diverting potentially useful energy from an ecosystem or an organism.

Stressor—The factor or group of conditions that cause the stress.

Succession—The predictable and orderly change in species composition over time at a particular location. Succession is sometimes called ecosystem development which places additional emphasis on abiotic components of change.

Swamp—An emergent wetland in which the uppermost stratum of vegetation is composed primarily of trees.

Swamp-stream*—Tentative: A headwater swamp containing a shallowly incised and intermittently braided channel. As a consequence of low-channel capacity, increases in discharge tend to be dissipated across the entire floodplain. In Florida, they are called strands or sloughs.

Terrigenous—Of or deriving from terrestrial or land.

Tidal amplitude—The elevational difference between high and low tide.

Tidal marshes, irregularly flooded—Marshes located in a tidal region, but too isolated to be inundated by all tides.

Tidal marshes, regularly flooded—Marshes located in a tidal regime with elevations low enough to be flooded by nearly all tides.

Topographic—A term referring to the slope and elevation of land.

Transmissivity—The capacity of a porous medium to conduct water. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.

Transport, overbank*—Movement of water from the channel to the floodplain surface.

Riparian transport*—Movement of water from upland regions to floodplains either by groundwater discharge at the slope face or toe or by surface-water (overland) transport.

Turbidity—Low water clarity principally because of suspended sediments.

Typha—The genus of cattail.

Unchannelized flow—Normally reserved for surface flow that is diffuse and thus not confined to a channel. Also nonchannelized flow.

Upland—The land upslope from a wetland that lacks wetland characteristics.

Valuation—The process of ascribing values.

Values—The rules that determine what people consider important. It can be measured by what motivates people into activity.

Várzea—Lakes in the floodplain of the main Amazon basin where water high in suspended sediments occurs.

Water quality—Descriptive or quantitative conditions of water, usually in reference to the physical, chemical, and biological properties, and usually from the perspective of society's use.

Water stress—A water-deficit condition of plants that develops because plants are losing water by transpiration faster than they can take up water through their roots.

Water table—The surface of an unconfined water mass where the piezometric head equals atmospheric pressure.

Water table, rebound*—The night-time phenomenon of an increase in water table after evapotranspirational drawdown during the day. The cause may be due to redistribution of water among pore spaces toward an equilibrium state or the adjustment toward hydrostatic equilibrium with controlling piezometric gradients.

Wetland—Those areas that are inundated or saturated at a frequency to support, and which normally do support, plants adapted to saturated and/or inundated conditions. They normally include swamps, bogs, marshes, and peatlands.

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13. ABSTRACT *(Maximum 200 words)*

Wetlands can be classified by methods that range from the use of commonly recognized vegetation or cover types, to systems based on hydrology, geomorphology, or some combination of the two. The classification presented here is based on the hydrogeomorphic functions of wetlands. There are three basic properties that are used to provide insight into wetland functions:

1. Geomorphic setting—The three categories are depressional, riverine, and fringe. Extensive peatlands constitute a separate category because of their unique topographic and hydrologic conditions. Depressional wetlands can be open or closed to surface flows, and can be tightly or loosely connected to groundwater flows. Riverine wetlands range from those associated with steep to low gradient streams and are represented by floodplains. Fringe wetlands are sea level or lake level controlled. Peat lands normally initiate their development in depressions. If peat lands develop beyond the original depression, they can create their own unique geomorphic settings. Each of these four types roughly corresponds with limited combinations of water sources and hydrodynamic conditions.

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2. Water source—The three sources are precipitation, lateral flows from upstream or upslope, and ground water. Respectively these correspond to transport from the atmosphere, transport by surface or near-surface flows, and subsurface transport by flow of groundwater from unconfined aquifers. Each of these sources tends to have different water chemistry. This influences how the wetland functions. If precipitation is the sole source, evapotranspiration must necessarily be low enough to maintain water storage. Transport by surface flows allows sediment to be delivered to the wetland surface, as in floodplains. Groundwater sources are often rich in minerals. The flushing common in groundwater flows often counterbalances stressful conditions otherwise expected under waterlogged conditions.

3. Hydrodynamics—Velocities can vary within each of three flow types: primarily vertical, primarily unidirectional and horizontal, and primarily bidirectional and horizontal. Vertical movements are due to evapotranspiration and precipitation, unidirectional flows are downslope movement that occurs from seeps and on floodplains, and bidirectional are astronomic tides or wind driven seiches. Where the vertical flow type dominates, the wetland has characteristicly low hydraulic energy. Sediment accretion in such low energy environments is necessarily restricted to peat accumulation. Where flows are primarily unidirectional and horizontal, they may range from erosive, as occurs during the cutoff process in meandering streams, to depositional, as occurs in most floodplain environments. The bidirectional movement of tidal regimes creates predictable flooding and cumulatively long hydroperiods which are conducive habitat conditions for many estuarine organisms.

Indicators of function are discussed also, but they are considered derivatives of the three basic properties. Indicators range between short-term and ephemeral to long-term and stable. Short term indicators are high water marks, the annual plants, debris piles, etc. Long term indicators are geomorphic structure, forest canopy species composition, and geomorphic features that can be determined from topographic maps and aerial photographs.

The ecological significance of each of the properties is quantified, if possible, from published studies on similar ecosystems, or the significance is developed through logic. For the properties possessed by a particular wetland, a "profile" is developed that reveals probable functions carried out by the wetland, both within the wetland and as a landscape entity. Profiles are the end point of this classification. It is recommended that a number of wetland profiles be developed in a geographic region which will constitute a reference wetland population. Reference wetlands should typify the functions of a given type as well as the probable variations of these functions within a wetland type. Such reference wetlands represent the basis of comparison for any assessment procedures. Reference sites or types may also be established to recursively validate or correct the classification and to serve as benchmarks for additional functional studies.

The classification can be adapted to any geographic region and is easy to modify as additional information becomes available. The present manuscript is not appropriate for direct use, but can serve as the basis for developing a classification within a distinct biogeographic region.

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Classifications of wetlands
Geomorphic setting
Hydrodynamics
Hydrogeomorphics
Indicators of ecosystem functioning
Reference wetlands
Water source