Hydrology of Wetlands

4

Hydrologic conditions are extremely important for the maintenance of a wetland's structure and function, although simple cause and effect relationships are difficult to establish. Hydrologic conditions affect many abiotic factors, including soil anaerobiosis, nutrient availability, and in coastal wetlands, salinity. These, in turn, determine the flora and fauna that develop in a wetland. Finally, completing the cycle, biotic components are active in altering the wetland hydrology. The hydroperiod, or hydrologic signature of a wetland, is the result of the balance between inflows and outflows of water (called the water budget), the soil contours in the wetland, and the subsurface conditions. The hydroperiod can have dramatic seasonal and year-to-year variations, yet it remains the major determinant of wetland function. Major hydrologic inflows include precipitation, flooding rivers, surface flows, groundwater, and tides in coastal wetlands. Simple hydrologic measurements, a water budget approach, and concepts such as turnover time in wetland studies can contribute to a better understanding of specific wetlands. Hydrology affects the species composition and richness, primary productivity, organic accumulation, and nutrient cycling in wetlands. Generally, productivity is highest in wetlands that have highest flow-through of water and nutrients or in wetlands with pulsing hydroperiods. Decomposition in wetlands is slower in anaerobic standing water than it is under dry conditions. Although many wetlands are organic exporters, this cannot be generalized even within one wetland type. Nutrient cycling is enhanced by hydrology-mediated inputs, and nutrient availability is often increased by reduced conditions in wetland substrates.

The hydrology of a wetland creates the unique physiochemical conditions that make such an ecosystem different from both well-drained terrestrial systems and deepwater aquatic systems. Hydrologic pathways such as precipitation, surface runoff, groundwater, tides, and flooding rivers transport energy and nutrients to and from wetlands. Water depth, flow patterns, and duration and frequency of flooding, which are the result of all of the hydrologic inputs and outputs, influence the biochemistry of the soils and are major factors in the ultimate selection of the biota of wetlands. Biota ranging from microbial communities to vegetation to waterfowl are all constrained or enhanced by hydrologic conditions. An important point about wetlands—one that is often missed by ecologists who begin to study these systems, is this: *Hydrology is probably the single most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes.* An understanding of rudimentary hydrology should be in the repertoire of any wetland scientist.

THE IMPORTANCE OF HYDROLOGY IN WETLANDS

Ecological Processes and Hydrology

Wetlands are transitional between terrestrial and open-water aquatic ecosystems (see Chapter 1). They are transitional in terms of spatial arrangement, for they are usually found between uplands and aquatic systems. They are also transitional in the amount of water they store and process. Wetlands represent the aquatic edge of many terrestrial (emergent) plants and animals; they also represent the terrestrial edge of many aquatic (submersed) plants and animals. Hence small changes in hydrology can result in significant biotic changes. A conceptual model of the role of hydrology in wetlands is shown in Figure 4–1. Hydrologic conditions can directly modify or change chemical and physical properties such as nutrient availability, degree of substrate anoxia, soil salinity, sediment properties, and pH. Except in nutrient-poor bogs, water inputs are the major source of nutrients to wetlands; water outflows often remove biotic and abiotic material from wetlands as well. These modifications of the physiochemical environment, in turn, have a direct impact on the biotic response in the wetland (Gosselink and Turner, 1978). When hydrologic conditions in wetlands change even slightly, the biota may respond with massive changes in species composition and richness and in ecosystem productivity. When the hydrologic pattern remains similar from year to year, a wetland's structural and functional integrity may persist for many years.

Biotic Control of Wetland Hydrology

Just as many other ecosystems exert feedback (cybernetic) control of their physical environments, wetland ecosystems are not simply passive to their hydrolog-

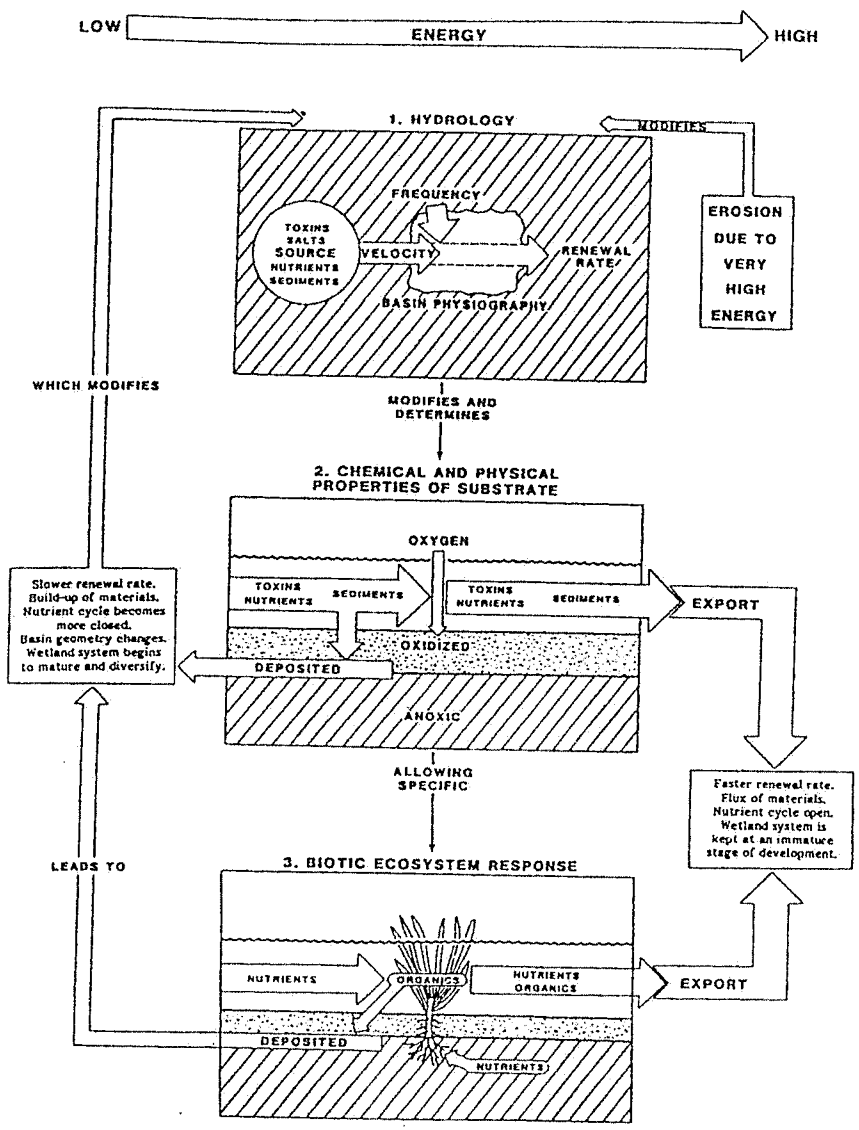


Figure 4–1. Conceptual model showing the direct and indirect effects of hydrology on wetlands. *(From Wicker et al., 1982, after Gosselink and Turner, 1978)*

wetlands, mainly vegetation, can control their water conditions through a variety of mechanisms, including peat building, sediment trapping, nutrient retention, water shading, and transpiration. Many marshes and some riparian wetlands and frequency with which they are flooded. Wetland vegetation influences hydrologic conditions by binding sediments to reduce erosion, by trapping sediment, by interrupting water flows, and by building peat deposits (Gosselink, 1984). Bogs build peat to the point at which they are no longer influenced at the surface by the inflow of mineral waters. Some trees in some southern swamps save water by their deciduous nature, their seasonal shading, and their relatively slow rates of transpiration.

Animals contribute to hydrologic modifications and subsequent changes in wetlands (Fig. 4–2; see for example Naiman, 1988). The exploits of beavers (*Castor canadensis*) in much of North America in both creating and destroying wetland habitats are well known. They build dams on streams, backing up water across great expanses, creating wetlands where none existed before, and possibly even altering global carbon biogeochemistry (Naiman et al., 1991). American alligators (*Alligator mississippiensis*) are known for their role in the Florida Everglades in constructing "gator holes" that serve as oases for fish, turtles, snails, and other aquatic animals during the dry season. In all of these cases, the biota of the ecosystem have contributed to their own survival by influencing the ecosystem's hydrology.

Studies of Wetland Hydrology

Until recently, the importance of hydrology in wetland function contrasted markedly with the paucity of published research on the subject. Most early wetland investigations that dealt with hydrology explored the relationships between hydrologic variables (usually water depth) and wetland productivity (e.g., Conner and Day, 1976; Mitsch and Ewel, 1979) or species composition (e.g., Heinselman, 1963, 1970; McKnight et al. 1981; Huffman and Forsythe, 1981). There have been several review papers on various aspects of the hydrology of wetlands, but many of them were published only recently (e.g., Linacre, 1976; Gosselink and Turner, 1978; Carter et al., 1979; Bedinger, 1981; Ingram, 1983; Carter, 1986; Carter and Novitzki, 1988; Winter, 1988; Siegel, 1988a; O'Brien, 1988; Duever, 1988, 1990; Kadlec, 1989; Winter and Llamas, 1993); few comprehensive studies have described in detail the hydrologic characteristics within specific wetland types. An exception to this has been the study of northern peatlands, for which a wealth of literature exists, including work in the former Soviet Union (e.g., Romanov, 1968; Ivanov, 1981), in the British Isles (Ingram et al., 1974; Ingram, 1982; Gilman, 1982), and in North America (e.g., Bay, 1967, 1969; Boelter and Verry, 1977; Verry and Boelter, 1979; Wilcox et al., 1986; Siegel, 1988b). Some of the more notable hydrology studies for other types of wetlands in the United States have included salt marshes (Hemond and Burke, 1981; Hemond and Fifield, 1982), cypress swamps (R. C. Smith, 1975; Heimburg, 1984), and large-scale wetland complexes (Rykiel, 1977, 1984; Hyatt and Brown, 1984)

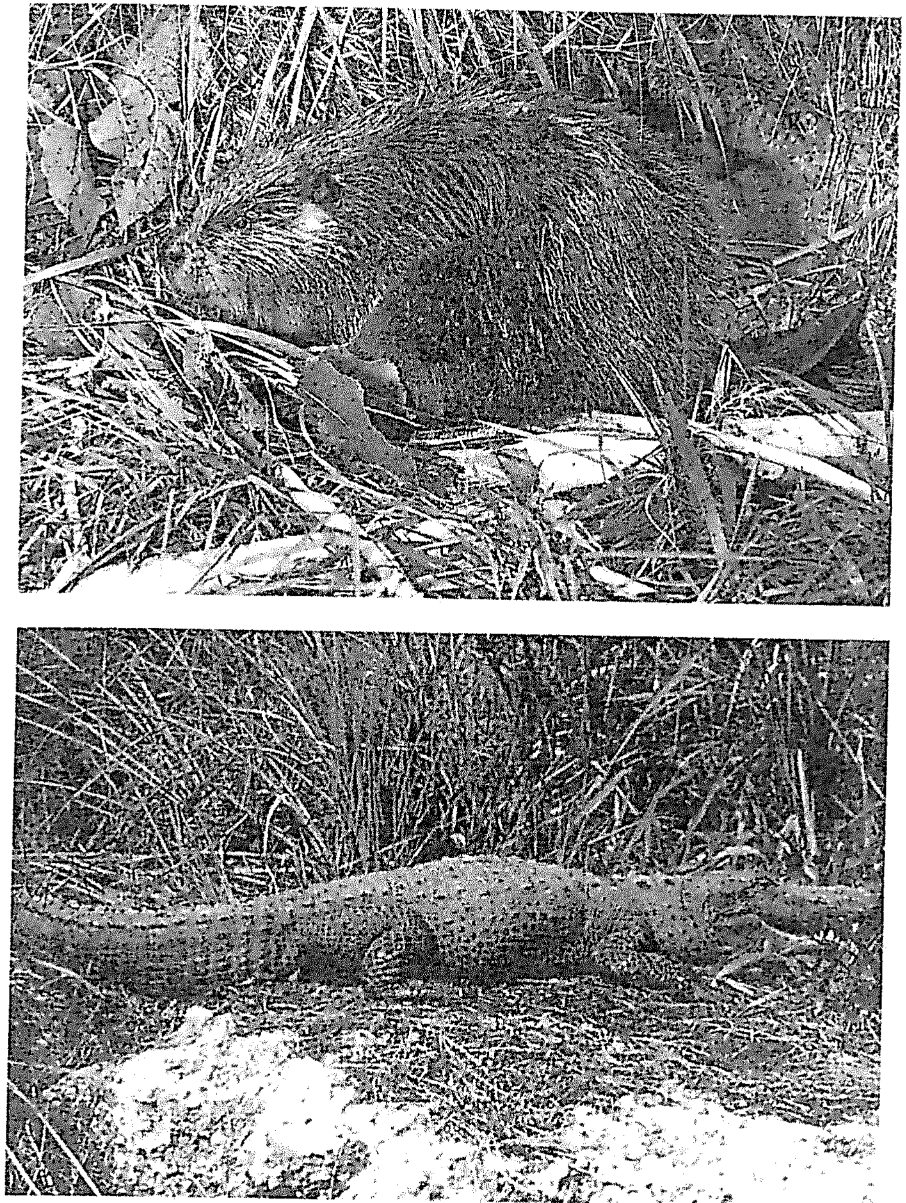


Figure 4–2. Two animals, beaver (*top*) and alligator (*bottom*), that can significantly modify hydrology and subsequent chemical and physical properties of wetlands. (*Top photo copyright © 1980 by Alvin E. Staffen, reprinted with permission. Bottom photo copyright © 1991 by David M. Dennis, reprinted with permission.*)

WETLAND HYDROPERIOD

The *hydroperiod* is the seasonal pattern of the water level of a wetland and is like a hydrologic signature of each wetland type. It defines the rise and fall of a wetland's surface and subsurface water. It characterizes each type of wetland, and the constancy of its pattern from year to year ensures a reasonable stability for that wetland. The hydroperiod is an integration of all inflows and outflows of water, but it is also influenced by physical features of the terrain and by proximity to other bodies of water. Many terms are used to describe qualitatively a wetland's hydroperiod. Table 4–1 gives several definitions that have been suggested by the U.S. Fish and Wildlife Service. For wetlands that are not subtidal or permanently flooded, the amount of time that wetland is in standing water is called the *flood duration*, and the average number of times that a wetland is flooded in a given period is known as the *flood frequency*. Both terms are used to describe periodically flooded wetlands such as coastal salt marshes and riparian wetlands.

Some typical hydroperiods for very different wetlands are shown in Fig. 4–3. For a cypress dome in north-central Florida (Fig. 4–3a), the ecosystem has standing water during the wet summer season and dry periods in the late autumn and early spring. A coastal salt marsh has a hydroperiod of semidiurnal flooding and dewatering superimposed on a twice-monthly pattern of spring and ebb tides (Fig. 4–3b). There are also hydroperiods that have less pronounced seasonal

Table 4–1. Definitions of Wetland Hydroperiods

Tidal Wetlands

- Subtidal—permanently flooded with tidal water
- Irregularly Exposed—surface exposed by tides less often than daily
- Regularly Flooded—alternately flooded and exposed at least once daily
- Irregularly Flooded—flooded less often than daily

Nontidal Wetlands

- Permanently Flooded—flooded throughout the year in all years
- Intermittently Exposed—flooded throughout the year except in years of extreme drought
- Semipermanently Flooded—flooded in the growing season in most years
- Seasonally Flooded—flooded for extended periods during the growing season, but usually no surface water by end of growing season
- Saturated—substrate is saturated for extended periods in the growing season, but standing water is rarely present
- Temporarily Flooded—flooded for brief periods in the growing season, but water table is otherwise well below surface
- Intermittently Flooded—surface is usually exposed with surface water present for variable periods without detectable seasonal pattern.

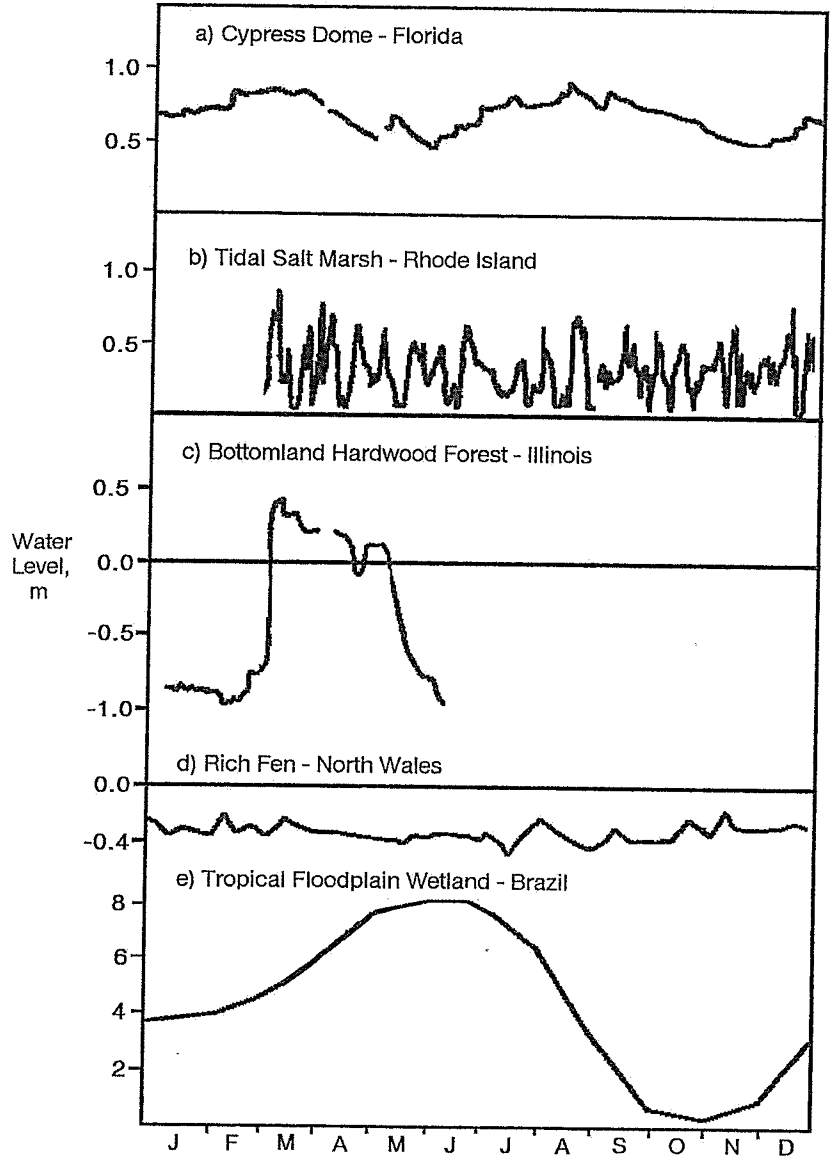


Figure 4–3. Hydroperiods for several different wetlands: *a.* cypress dome in northcentral Florida; *b.* New England salt marsh (*after Nixon and Oviatt, 1973*); *c.* bottomland hardwood forest along Kankakee River in northeastern Illinois (*from Mitsch et al., 1979b*); *d.* peatland (fen) in northern Wales (*from Gilman, 1982*); *e.* Amazon floodplain forested wetland at confluence of Amazon and Negro Rivers, Manaus, Brazil (*from Junk, 1982*). Vertical scale indicates water

fluctuations, as in the below-ground water level of many bogs and fens (Fig. 4–3d). Low-order riverine wetlands respond sharply to local rainfall events rather than to general seasonal patterns. For example, the hydroperiod of many bottomland hardwood forests (Fig. 4–3c) on low-order streams is sudden and relatively short seasonal flooding due to local precipitation and thawing conditions followed by a rapid drop of the water level. On the other hand, a high-order river is more influenced by seasonal patterns of precipitation throughout a large watershed rather than local precipitation (Junk et al., 1989). The annual fluctuation of water in the tropical floodplain forest near Manaus, Brazil, at the confluence of the Rio Negro and Rio Amazon is a more predictable seasonal pattern that includes a tremendous seasonal fluctuation of almost 8 m because of the flooding rivers (Fig. 4–3e).

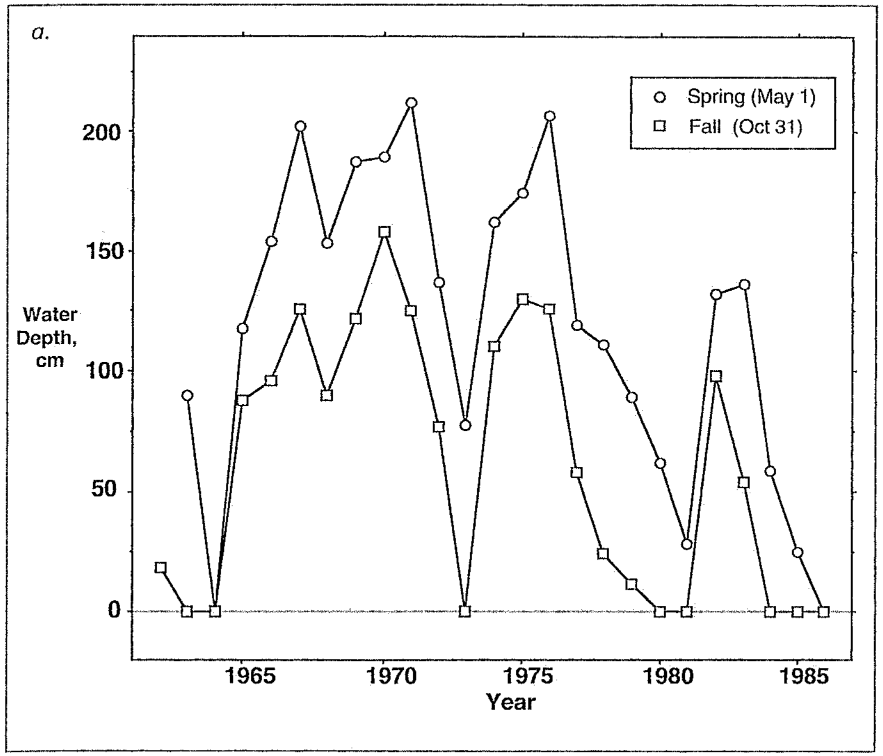
Year-to-Year Fluctuations

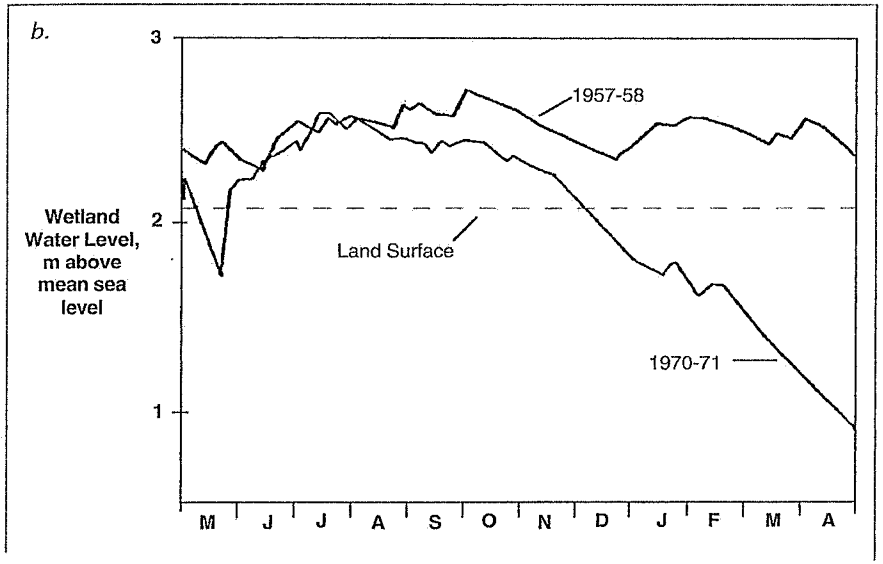
The hydroperiod, of course, is not the same each year but varies statistically according to climate and antecedent conditions. Great variability can be seen from year to year for some wetlands, as illustrated in Figure 4–4 for a prairie pothole regional wetland in Canada and the Big Cypress Swamp/Everglades region of south Florida. In the pothole region, a wet-dry cycle of 10 to 20 years is seen; spring is almost always wetter than fall but depths vary significantly from year to year (Fig. 4–4a). Figure 4–4b illustrates cases of an even seasonal rainfall pattern for the Everglades in 1957–1958, which caused a fairly stable hydroperiod through the year, and a significant dry season in 1970–1971, which caused the hydroperiod to vary about 1.5 m between high and low water.

Pulsing Water Levels

Water levels in most wetlands (all of the hydroperiods shown in Figure 4–3 except for the rich fen) are generally not stable but fluctuate seasonally (high-order riparian wetlands) daily or semi-daily (types of tidal wetlands) or unpredictably (wetlands in low-order streams and coastal wetlands with wind-driven tides). In fact, wetland hydroperiods that show the greatest differences between

Figure 4–4 (*opposite page*). Year-to-year fluctuations in wetland hydroperiod: *a.* spring (May 1) and fall (October 31) water depths for 1962–86 for shallow open-water wetland in prairie pothole region of southwestern Saskatchewan, Canada, and *b.* wet and dry season hydrographs for Big Cypress Swamp region near the Everglades, Florida. (a. *from Kantrud et al., 1989, as adapted from J. B. Millar, 1971, redrawn with permission of J. B. Millar; b. from Freiberger, 1972 as cited in Duever, 1988; copyright © 1988 by Elsevier Science Publishers, Amsterdam,*





high and low water levels such as those seen in riverine wetlands are often caused by flooding "pulses" that occur seasonally or periodically (Junk et al., 1989; see Fig. 4–3c, e). These pulses nourish the riverine wetland with additional nutrients and carry away detritus and waste products. Pulse-fed wetlands are often the most productive wetlands and are the most favorable for exporting materials, energy, and biota to adjacent ecosystems (see Specific Effects of Hydrology on Wetlands in this chapter). Despite that obvious fact, many wetland managers, especially those who manage wetlands for waterfowl, often manage for stable water levels. Fredrickson and Reid (1990) stated that "Because the goal of many [wetland] management scenarios is to counteract the effects of seasonal and long-term droughts, a general tendency is to restrict water level fluctuations in managed wetlands. This misconception is based on the fact that most wetland wildlife requires water for most stages in their life cycles." Kushlan (1989) suggested that because the avian fauna that use wetlands often possess adaptations to fluctuating water levels, the active manipulation of water levels may be appropriate in artificially managed wetlands. A seasonally fluctuating water level, then, is the rule, not the exception, in most wetlands.

THE OVERALL WETLAND WATER BUDGET

The hydroperiod, or hydrologic state of a given wetland, can be summarized as being a result of the following factors:

1. the balance between the inflows and outflows of water
2. the surface contours of the landscape
3. subsurface soil, geology, and groundwater conditions

The first condition defines the water budget of the wetland, whereas the second and the third define the capacity of the wetland to store water. The general balance between water storage and inflows and outflows, illustrated in Figure 4–5, is expressed as

$$\Delta V/\Delta t = P_n + S_i + G_i - ET - S_o - G_o \pm T \qquad (4.1)$$

where

V = volume of water storage in wetlands

$\Delta V/\Delta t$ = change in volume of water storage in wetland per unit time, t

P_n = net precipitation

S_i = surface inflows, including flooding streams

G_i = groundwater inflows

ET = evapotranspiration

S_o = surface outflows

G_o = groundwater outflows

T = tidal inflow (+) or outflow (-)

The average water depth $\bar{d}$, at any one time, can further be described as

$$\bar{d} = V/A \qquad (4.2)$$

where A = wetland surface area.

Thus each of the terms in Equation 4.1 can be expressed in terms of depth, per unit time, e.g., cm/yr, or in terms of volume per unit time, e.g., m^3/day.

Examples of Water Budgets

Equation 4.1 serves as a useful summary of the major hydrologic components of any wetland water budget. Examples of hydrologic budgets for several wetlands are shown in Figure 4–6. The terms in the equation, however, vary in importance according to the type of wetland observed; furthermore, not all terms in

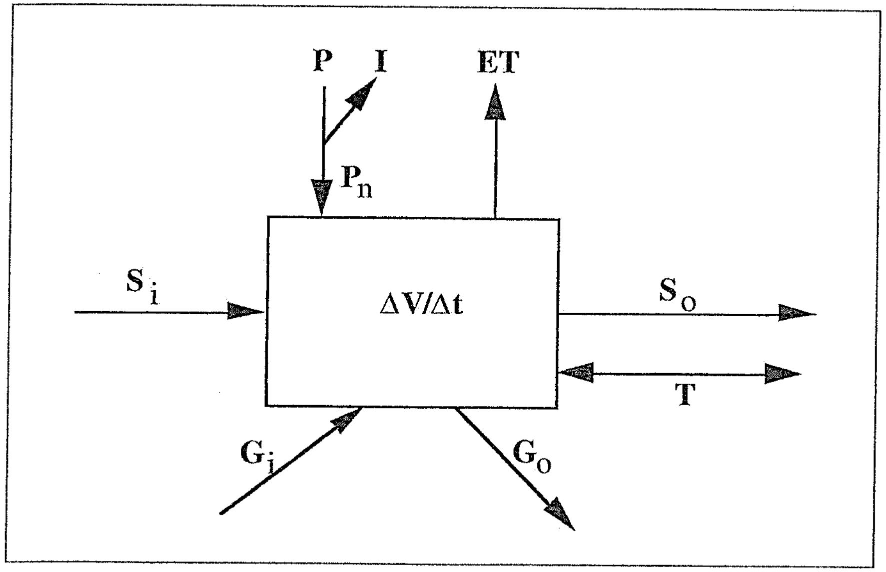


Figure 4–5. Generalized water budget for a wetland corresponding to terms in Equation 4.1. P = precipitation, ET = evapotranspiration, I = interception, P_n = net precipitation, S_i = surface inflow, S_o = surface outflow, G_i = groundwater inflow, G_o = groundwater outflow, $\Delta V/\Delta t$ = change in storage per unit time, T = tide or seiche

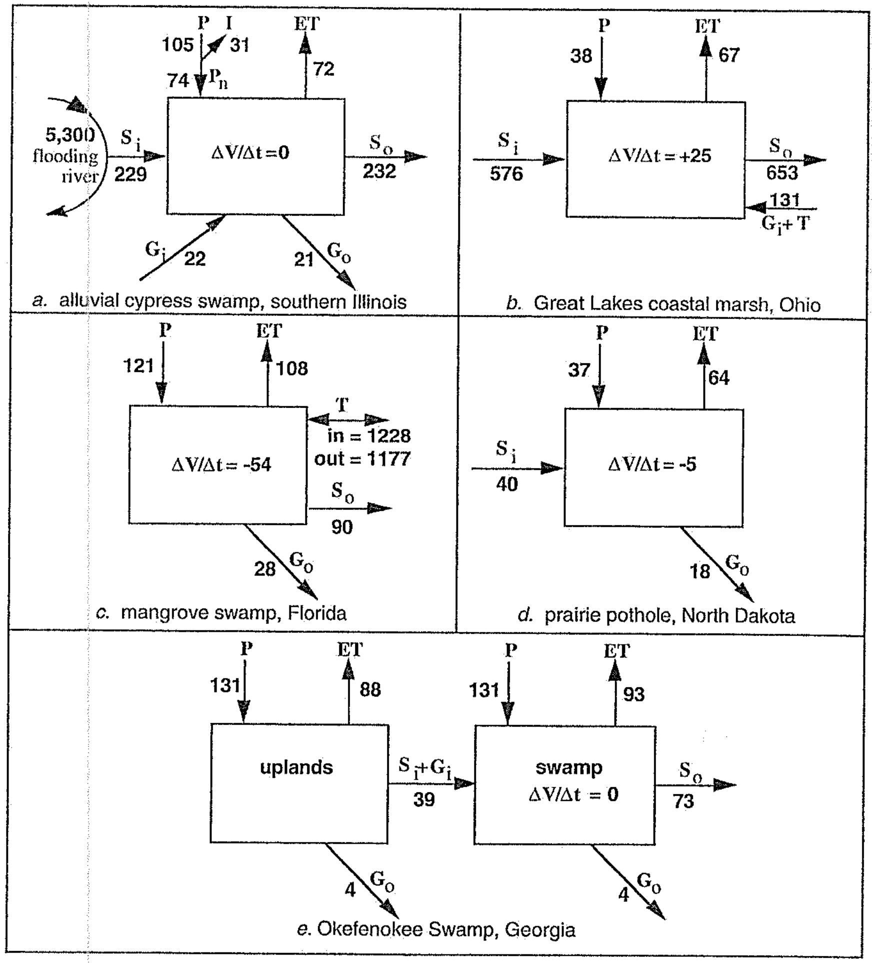
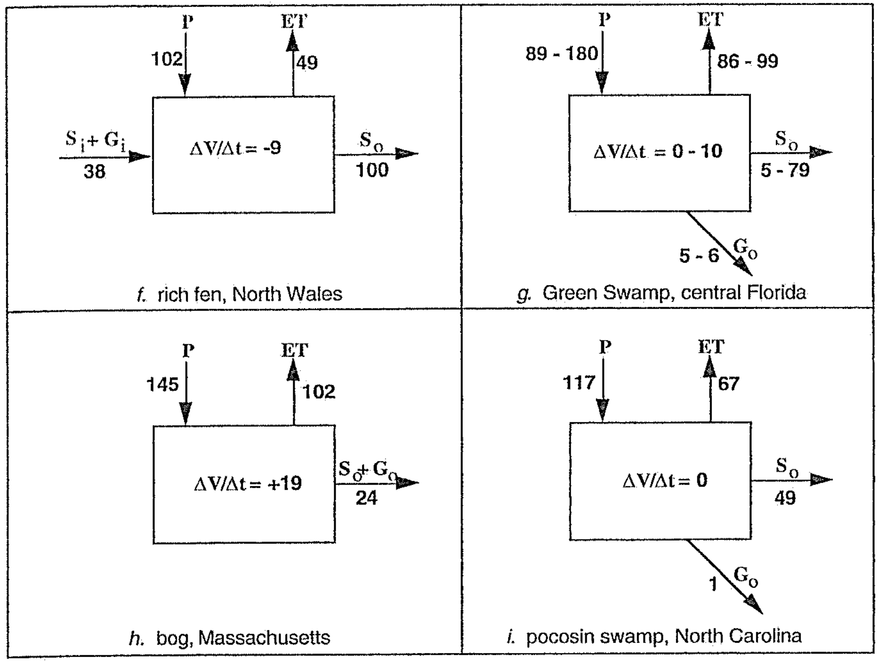


Figure 4–6. Annual water budget for several wetlands including (*above*) *a.* an alluvial cypress swamp in southern Illinois (*after Mitsch, 1979*); *b.* a Lake Erie coastal marsh in northern Ohio (March through September, 1988 only, during a drought year; *after Mitsch and Reeder, 1992*); *c.* a black mangrove swamp in southwestern Florida (*after Twilley, 1982, as cited in S. Brown, 1990*); *d.* prairie pothole marshes in North Dakota (average of 10 wetlands; after Shjeflo, 1968, *as cited in Winter, 1989*); *e.* the Okefenokee Swamp watershed in Georgia (*after Rykiel, 1984*); and (*opposite page*) *f.* a rich fen in northern Wales (*after Gilman, 1982*); *g.* the Green Swamp region of central Florida (*after Pride et al., 1966 as cited in Carter et al., 1979*); *h.* Thoreau's Bog, Concord, Massachusetts (*after Hemond, 1980, as cited in Brown, 1990*); *i.* a pocosin swamp (*average of 3 years; after Richardson, 1983 as cited in Brown, 1990*). All values are expressed in cm/yr unless otherwise noted. See Figure 4–5 for symbol definitions.



the hydrologic budget apply to all wetlands (Table 4–2). There is a great variability in certain flows, particularly in surface inflows and outflows, depending on the openness of the wetlands. An alluvial cypress swamp in southern Illinois received a gross inflow of floodwater from one flood that was more than 50 times the gross precipitation for the entire year (Fig. 4–6a). Even the net surface inflow from that flood (the water left behind after the flooding river receded) was three times the precipitation input for the entire year. Surface and groundwater inflows to a coastal Lake Erie marsh in Ohio were estimated to be almost 20 times the precipitation for a major part of a drought year (Fig. 4–6b), and tides contributed 10 times the precipitation to a black mangrove swamp in Florida (Fig. 4–6c). In contrast to these inflow-dominated wetlands, surface inflow is approximately equal to the precipitation inflow in the prairie pothole marshes of North Dakota (Fig. 4–6d), considerably less than precipitation for the Okefenokee Swamp in Georgia (Fig. 4–6e) and a rich fen in North Wales (Fig. 4–6f) and essentially nonexistent in the upland Green Swamp of central Florida (Fig. 4–6g), a bog in Massachusetts (Fig. 4–6h), and a pocosin wetland of North Carolina (Fig. 4–6i). In most of these examples, the change in storage is small or zero, indicating that the water level at the end of the study period (usually an annual cycle) is close to where it was at the beginning of the study period.

Table 4–2. Major Components of Hydrologic Budgets for Wetlands

Component	*Pattern*	*Wetlands Affected*
Precipitation	Varies with climate although many regions have distinct wet and dry seasons	All
Surface Inflows and Outflows	Seasonally, often matched with precipitation pattern or spring thaw; can be channelized as streamflow or nonchannelized as runoff; includes river flooding of alluvial wetlands	Potentially all wetlands except ombrotrophic bogs; riparian wetlands, including bottomland hardwood forests and other alluvial wetlands, are particularly affected by river flooding
Groundwater	Less seasonal than surface inflows and not always present	Potentially all wetlands except ombrotrophic bogs and other perched wetlands
Evapotranspiration	Seasonal with peaks in summer and low rates in winter. Dependent on meterorological, physical, and biological conditions in wetlands	All
Tides	One to two tidal periods per day; flooding frequency varies with elevation	Tidal freshwater and salt marshes; mangrove swamps

Residence Time

A generally useful concept of wetland hydrology is that of the *renewal rate* or *turnover rate* of water, defined as the ratio of throughput to average volume within the system:

$$t^{-1} = Q_t/V \qquad (4.3)$$

where

t^{-1} = renewal rate (1/time)

Q_t = total inflow rate

V = average volume of water storage in wetland

Few measurements of renewal rates have been made in wetlands, although it is a frequently used parameter in limnological studies. Chemical and biotic properties are often determined by the openness of the system, and the renewal rate is an index of this since it indicates how rapidly the water in the system is replaced. The reciprocal of the renewal rate is the *residence time* (t), (sometimes called *retention time* by engineers, for constructed wetlands; see Chapter 17) which is a measure of the average time that water remains in the wetland. Recent evidence, however, suggests that the theoretical residence time, as calculated by Equation 4.3, is often much longer than the actual residence time as water flows through a wetland because of non-uniform mixing. Because there are often parts of a wetland where waters are not well mixed, the theoretical residence time (t) estimate should be used with caution when estimating the hydrodynamics of wetlands.

PRECIPITATION

Wetlands occur most extensively in regions where *precipitation,* a term that includes rainfall and snowfall, is in excess of losses such as evapotranspiration and surface runoff. Exceptions to this generality occur where surface inflows are seasonally abundant or tides are prevalent such as coastal salt marshes or in arid regions such as the western United States, where riparian wetlands depend more on river flow and less on local precipitation. Precipitation generally has well-defined yearly patterns, although variations among years may be great. An almost uniform pattern of precipitation exists for eastern North America because of the heavy influence of both cold and warm fronts and summer convective storms. The northern Great Plains experience a summer peak in precipitation. Relatively less precipitation occurs in the winter because of the cold continental high pressure that recedes northward in the summer. By contrast, parts of the West Coast have a Mediterranean-type climate characterized by wet winters and pronounced dry summers. The northern extremes of Canada show more uniform patterns of precipitation, but overall amounts are small. The precipitation pattern in Florida shows a decidedly wet season in summer caused by the almost daily convective storms.

The fate of precipitation that falls on wetlands with forested, shrub or emergent vegetation is shown in Figure 4–7. When some of the precipitation is retained by the vegetation cover, particularly in forested wetlands, the amount that actually passes through the vegetation to the water or substrate below is called *throughfall.* The amount of precipitation that is retained in the overlying vegetation canopy is called *interception.* Interception depends on several factors, including the total amount of precipitation, the intensity of the precipitation, and the character of the vegetation, including the stage of vegetation development, the type of vegetation, e.g., deciduous or evergreen, and the strata of the vegetation, e.g., tree, shrub, or emergent macrophyte. The percent of precipitation that is intercepted in forests varies between 8 and 35 percent. One review cites a median value of 13 percent for several studies of deciduous forests and 28 percent for coniferous forests (Dunne and Leopold, 1978). The water budget in

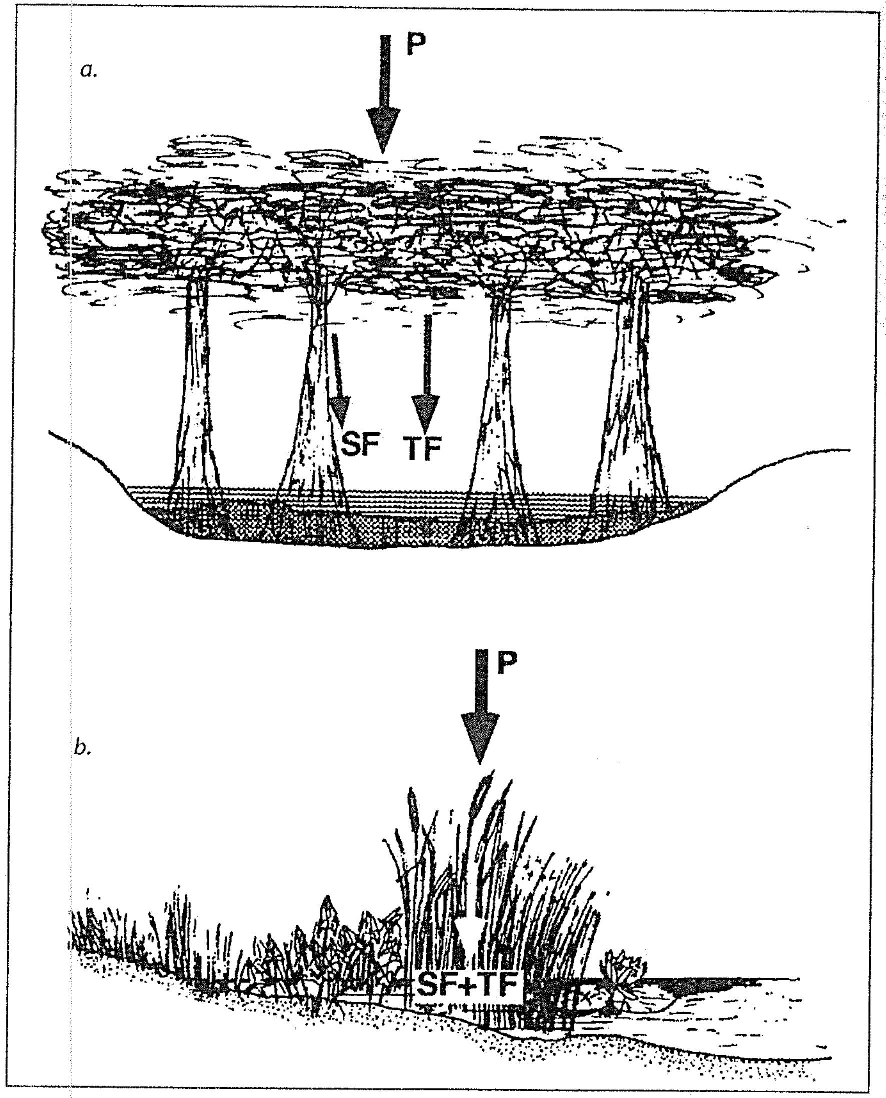


Figure 4–7. Fate of precipitation in *a.* a forested wetland and *b.* a marsh. P = precipitation; TF = throughfall; SF = stemflow.

Figure 4–6a illustrates that 29 percent of precipitation in a forested wetland was intercepted by a canopy dominated by *Taxodium distichum*, a deciduous conifer.

Little is known about the interception of precipitation by emergent macrophytes, but it probably is similar to that measured in grasslands or croplands. Essentially, in those systems, interception at maximum growth can be as high as that in a forest (10–35 percent of gross precipitation). On an annual basis the

percent intercepted would be expected to be much less in nonforested wetlands than in forested wetlands because of the dormancy of herbaceous plants (macrophytes in emergent wetlands) in winter. It follows that replacing one wetland type with another (e.g., a marsh for a forested wetland) may not completely replace the former wetland's hydrologic function. On the other hand, an interesting hypothesis about interception and the subsequent evaporation of water from leaf surfaces is that, because the same amount of energy is required whether water evaporates from the surface of a leaf or is transpired by the plant, the evaporation of intercepted water is not "lost" because it may reduce the amount of transpiration loss that occurs (Dunne and Leopold, 1978). This argues that wetlands with high and low interception may be similar in overall water loss to the atmosphere.

Another term related to precipitation, *stemflow,* refers to water that passes down the stems of the vegetation (Fig. 4–7). This flow is generally a minor component of the water budget of a wetland. For example, Heimburg (1984) found that stemflow was, at maximum, 3 percent of throughfall in cypress dome wetlands in north-central Florida.

These terms are related in a simple water balance as follows:

$$P = I + TF + SF \qquad (4.4)$$

where

P = total precipitation

I = interception

TF = throughfall

SF = stemflow

The total amount of precipitation that actually reaches the water surface or substrate of a wetland is called the net precipitation (P_n) and is defined as

$$P_n = P - I \qquad (4.5)$$

Combining Equations 4.4 and 4.5 yields the most commonly used form for estimating net precipitation in wetlands

$$P_n = TF + SF \qquad (4.6)$$

SURFACE FLOWS

Wetlands can be receiving systems for surface water flows (inflows), or surface water streams can originate in wetlands to feed downstream systems (outflows). Surface outflows are found in many wetlands that are in the upstream reaches of

Table 4–3. Description and Hydrologic Response Coefficients for Estimating Direct Runoff from Forested Watersheds in Eastern United States

	Watershed Area, A_w (ha)	*Mean Elevation (m)*	*Mean Slope (%)*	*Soil texture*[a]	*Forest Type*[b]	*Hydrologic Response Coefficient R_p*
Coweeta 2, N.C.	13	850	30	SL	OH	0.04
Coweeta 18, N.C.	13	820	32	SL	OH	0.05
Coweeta 14, N.C.	62	880	21	SL	OH	0.05
Coweeta 21, N.C.	24	990	34	SL	OH	0.06
Bent Ck 7, N.C.	297	940	22	SL	OH	0.06
Coweeta 8, N.C.	760	950	22	SL	MH	0.07
Union 3, S.C.	9	170	7	SC	P	0.08
Coweeta 28, N.C.	146	1,200	33	SL	MH	0.10
Copper Basin 2, Tenn.	36	580	27	SL	OH	0.10
Leading Ridge 1, Pa.	123	370	19	TL	MH	0.11
Dilldown Ck, Pa.	619	580	4	SL	SO	0.12
Fernow 4, W.Va.	39	820	18	TL	MH	0.14
Coweeta 36, N.C.	46	1,300	47	SL	MH	0.15
Burlington Bk, Conn.	1,067	270	3	SS	NH	0.17
Hubbard Brook 4, N.H.	36	600	26	NL	NH	0.18

[a]SL, sandy loam; SC, sandy clay; TL, silt loam; SS, stony sand; NL, stony loam.
[b]OH, oak hickory; MH, mixed hardwoods; NH, northern hardwoods; SO, scrub oak; P, pine
Source: From R. Lee, 1980, after Hewlett and Hibbert, 1967

a watershed. Often these wetlands are important water flow regulators for downstream rivers. Some wetlands have surface outflows that develop only when their water stages exceed certain levels.

Surface Inflows

Wetlands are subjected to surface inflows of several types. *Overland flow* is nonchannelized sheet flow that usually occurs during and immediately following rainfall or a spring thaw or as tides rise in coastal wetlands. If a wetland is influenced by a drainage basin, channelized *streamflow* may enter the wetland during most or all of the year. Often wetlands are an integrated part of a stream or river; for example, as instream freshwater marshes. Wetlands that form in wide shallow expanses of river channels are greatly influenced by the seasonal streamflow patterns of the river. Coastal saline and brackish wetlands are also significantly influenced by freshwater runoff and streamflow that contribute nutrients and energy to the wetland and often ameliorate the effects of soil salinity and anoxia. Wetlands can also receive surface inflow from seasonal or episodic pulses of flood flow from adjacent streams and rivers that may otherwise not be connected hydrologically with the wetland.

Surface runoff from a drainage basin into a wetland is usually difficult to estimate without a great deal of data. Nevertheless, it is often one of the most important sources of water in a wetland's hydrologic budget. The direct runoff component of streamflow refers to rainfall during a storm that causes an immediate increase in streamflow. An estimate of the amount of precipitation that results in direct runoff, or *quickflow*, from an individual storm can be determined from the following equation:

$$S_i = R_p \cdot P \cdot A_w \tag{4.7}$$

where

S_i = direct surface runoff to wetland, m^3 per storm event
R_p = hydrologic response coefficient
P = average precipitation in watershed, m
A_w = area of watershed draining into wetland, m^2

This equation states that the flow is proportional to the volume of precipitation ($P \times A_w$) on the watershed feeding the wetland in question. The values of R_p, which represent the fraction of precipitation in the watershed that becomes direct surface runoff, range from 4 percent to 18 percent for small watersheds in the eastern United States (R. Lee, 1980); a summary of values for certain conditions of slope, soil, and forest type are shown in Table 4–3.

While Equation 4.7 predicts the entire direct runoff caused by a storm event, in some cases wetland scientists and managers might be interested in calculating the peak runoff (*flood peak*) into a wetland caused by a specific rainfall event. Although this is generally a difficult calculation for large watersheds, a formula with the unlikely name of the *rational runoff method* is a widely accepted and useful way to predict peak runoff for watersheds of less than 80 hectares (200 acres). The equation is given by

$$S_{i(pk)} = 0.278\ CIA_w \quad (4.8)$$

where

$S_{i(pk)}$ = peak runoff into wetland (m^3/sec)

Table 4–4. Values of the Rational Runoff Coefficicient, C, Used to Calculate Peak Runoff

	C
Urban Areas	
Business areas: high-value districts	0.75–0.95
neighborhood districts	0.50–0.70
Residential areas: single-family dwellings	0.30–0.50
multiple-family dwellings	0.40–0.75
suburban	0.25–0.40
Industrial areas: light	0.50–0.80
heavy	0.60–0.90
Parks and cemeteries	0.10–0.25
Playgrounds	0.20–0.35
Unimproved land	0.10–0.30
Rural Areas	
Sandy and gravelly soils: cultivated	0.20
pasture	0.15
woodland	0.10
Loams and similar soils: cultivated	0.40
pasture	0.35
woodland	0.30
Heavy clay soils; shallow soils over bedrock:	
cultivated	0.50
pasture	0.45
woodland	0.40

Source: From Dunne and Leopold, 1978

C = rational runoff coefficient (see Table 4–4)

I = rainfall intensity (mm/hr)

A_w = area of watershed draining into wetland, km^2

The coefficient C, which ranges between 0 and 1 (Table 4–4), depends on the upstream land use. Concentrated urban areas have a coefficient ranging from 0.5 to 0.95, and rural areas have lower coefficients that greatly depend on soil types, with sandy soils lowest ($C = 0.1$–0.2) and clay soils highest ($C = 0.4$–0.5).

Channelized streamflow into and out of wetlands is described simply as the product of the cross-sectional area of the stream (A) and the average velocity (V) and can be determined through stream velocity measurements in the field:

$$S_i \text{ or } S_o = A_x \cdot V \quad (4.9)$$

where

S_i, S_o = surface channelized flow into or out of wetland m^3/sec

A_x = cross sectional area of the stream, m^2

V = average velocity, m/sec

The velocity can be determined in a number of ways, ranging from velocity meters that are hand-held at various locations in the stream cross section to the floating orange technique, where the velocity of a floating orange or similar fruit (which is 90 percent or more water and therefore floats but just beneath the water surface) is timed as it goes downstream. If a continuous or daily record of stream-

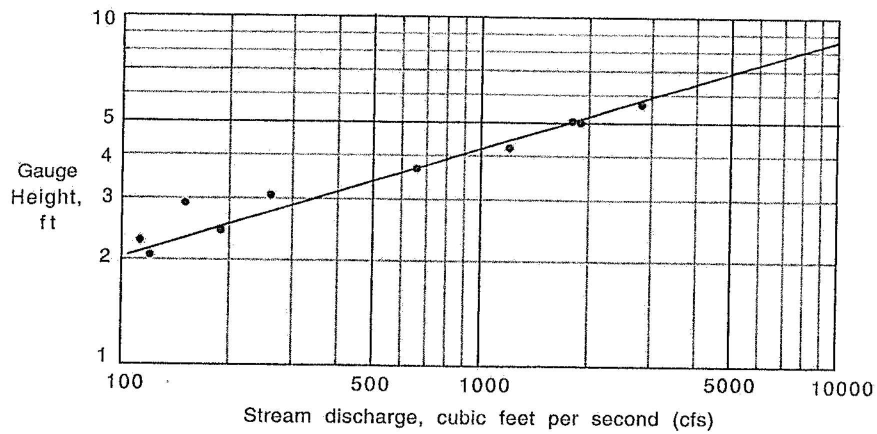


Figure 4–8. Rating curve for streamflow determination as a function of stream stage. This example is from New Fork River at Boulder, Wyoming *(redrawn from Dunne and Leopold, 1978; copyright © W.H. Freeman and Company, redrawn with permission)*. 100 cfs = 2.832 m^3/sec.

flow is needed, then a *rating curve* (Fig. 4–8), a plot of instantaneous streamflow as measured with Equation 4.9 versus stream elevation or stage, is useful. If this type of rating curve is developed for a stream (the basis of most hydrologic streamflow gauging stations operated by the United States Geological Survey), then a simple measurement of the stage in the stream can be used to determine the streamflow. Caution should be taken in using this approach for streams flowing into wetlands to ensure that no "backwater effect" of the wetland's water level will affect the stream stage at the point of measurement.

When an estimate of surface flow into or out of a riverine wetland is needed and no stream velocity measurements are available, the *Manning Equation* can often be used if the slope of the stream and a description of the surface roughness are known:

$$S_i \text{ or } S_o = \frac{A_x\ R^{2/3}\ s^{1/2}}{n} \quad (4.10)$$

where

n = roughness coefficient (Manning coefficient) (see Table 4–5)

R = hydraulic radius, m (cross-sectional area divided by wetted perimeter)

s = channel slope, dimensionless

Examples of roughness coefficients are given in Table 4–5. Although these coefficients have not generally been determined as part of wetland studies, they can often be applied to streamflow in and out of wetlands. The relationship is particularly useful for estimating streamflow where velocities are too low to measure directly and to estimate flood peaks from high-water marks on ungauged streams (Lee, 1980). These circumstances are common in wetland studies.

Floods and Riparian Wetlands

A special case of surface inflow occurs in wetlands that are in floodplains adjacent to rivers or streams and are occasionally flooded by those rivers or streams. These ecosystems are often called *riparian wetlands* (Chap. 14). The flooding of

Table 4–5. Roughness Coefficients (n) for Manning Equation Used to Determine Streamflow in Natural Streams and Channels

Stream Conditions	*Manning Coefficient, n*
Straightened earth canals	0.02
Winding natural streams with some plant growth	0.035
Mountain streams with rocky streambed	0.040-0.050
Winding natural streams with high plant growth	0.042-0.052
Sluggish streams with high plant growth	0.065
Very sluggish streams with high plant growth	0.112

Source: After Chow, 1964, and R. Lee, 1980.

these wetlands varies in intensity, duration, and number of floods from year to year, although the probability of flooding is fairly predictable. In the eastern and midwestern United States and in much of Canada, a pattern of winter or spring flooding caused by rains and sudden snowmelt is often observed (Fig. 4–9). When river flow begins to overflow onto the floodplain, the streamflow is referred to as *bankfull discharge*. A hydrograph of a stream that flooded its

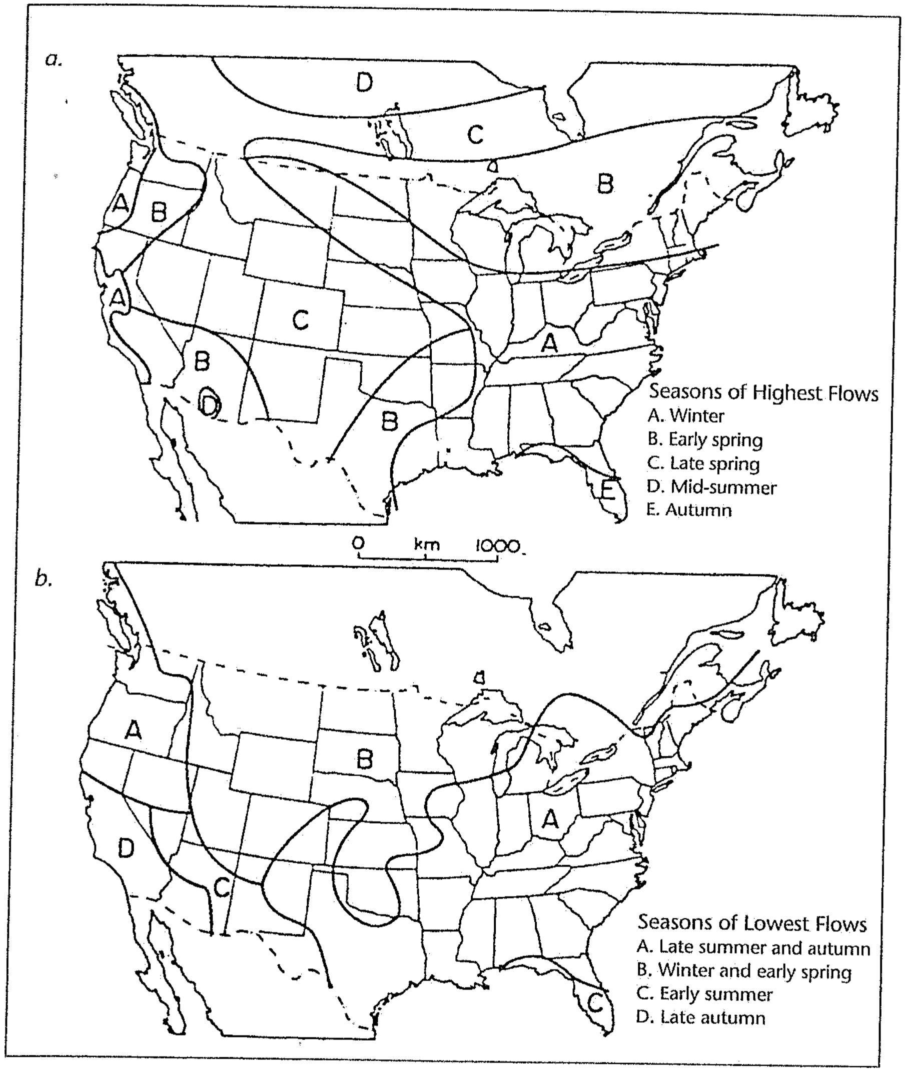


Figure 4–9. Periods of *a.* maximum and *b.* minimum streamflow in North America. *(From Beaumont, 1975; copyright © Blackwell Scientific Publications, reprinted with permission)*

riparian wetlands above bankfull discharge is shown in Figure 4–10. Riparian floodplains in many parts of the United States have recurrence intervals between 1 and 2 years for bankfull discharge, with an average of approximately 1.5 years (Fig. 4–11) (Leopold et al., 1964). The *recurrence interval* is the average interval between the recurrence of floods at a given level or greater flood (Linsley and Franzini, 1979). The inverse of the recurrence interval is the average probability of flooding in any one year. Figure 4–11 indicates that a stream will overflow its banks onto the adjacent riparian forest with a probability of 1/1.5, or 67 percent; this means that these rivers, on the average, overflow their banks in two of three years. Figure 4–11 also demonstrates that twice bankfull discharge occurs at recurrence intervals of between five and ten years; this flow, however, results in only a 30 percent greater depth over bankfull depth on the floodplain.

Surface Outflow

When it is confined to a channel, surface outflow from wetlands can be determined with the general equations for surface flow (see Equations 4.9 and 4.10 above). When a continuous record is desirable, a rating curve related to stream stage, as described above, can be developed. The outflow can also be estimated to be a function of the water level in the wetland itself according to the equation:

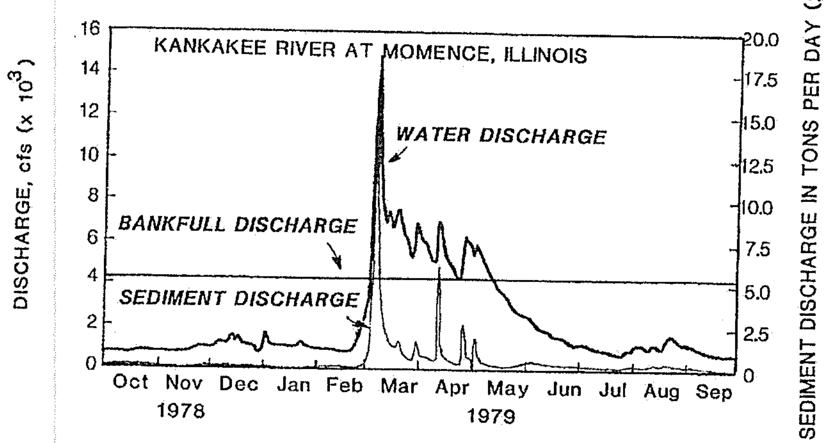


Figure 4–10. River hydrograph from northeastern Illinois, indicating bankfull discharge when riparian wetland is flooded, and sediment load of river. 1000 cfs = 28.32 m^3/sec. *(After Bhowmik et al., 1980)*

$$S_o = x\,L^y \quad (4.11)$$

where

S_o = surface outflow

L = wetland water level (cm above a control structure such as weir)

x,y = calibration coefficients

If a control structure such as a rectangular or V-notched weir is used to measure the outflow from a wetland, standard equations of the form of Equation 4.11 can be obtained from water measurement manuals (e.g., U.S. Department of Interior, 1984).

GROUNDWATER

Recharge-Discharge Wetlands

Groundwater can heavily influence some wetlands, whereas in others it may have hardly any effect at all (Carter, 1986; Carter and Novitzki, 1988). The recharge-discharge function of wetlands on groundwater resources has often

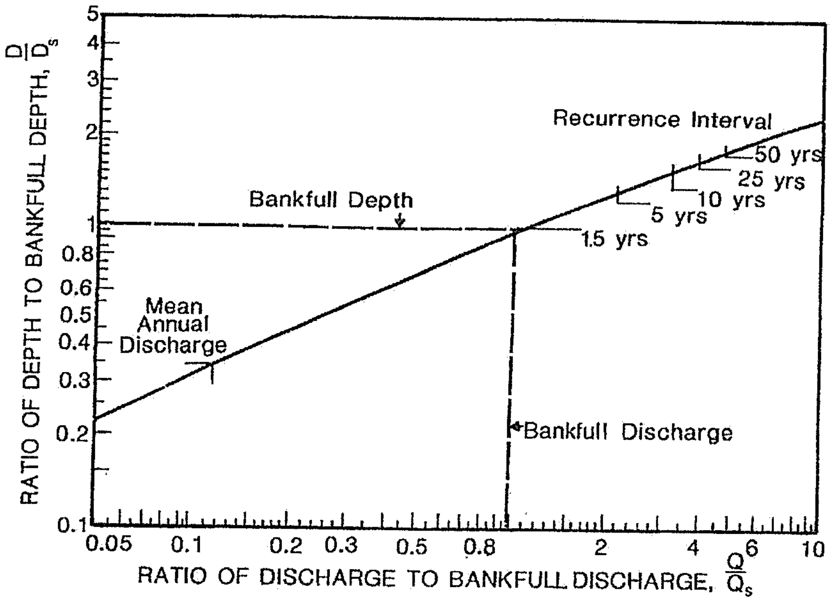


Figure 4–11. Relationships among streamflow (discharge), stream depth, and recurrence interval for streams in midwestern and southern United States. *(After Leopold et al., 1964)*

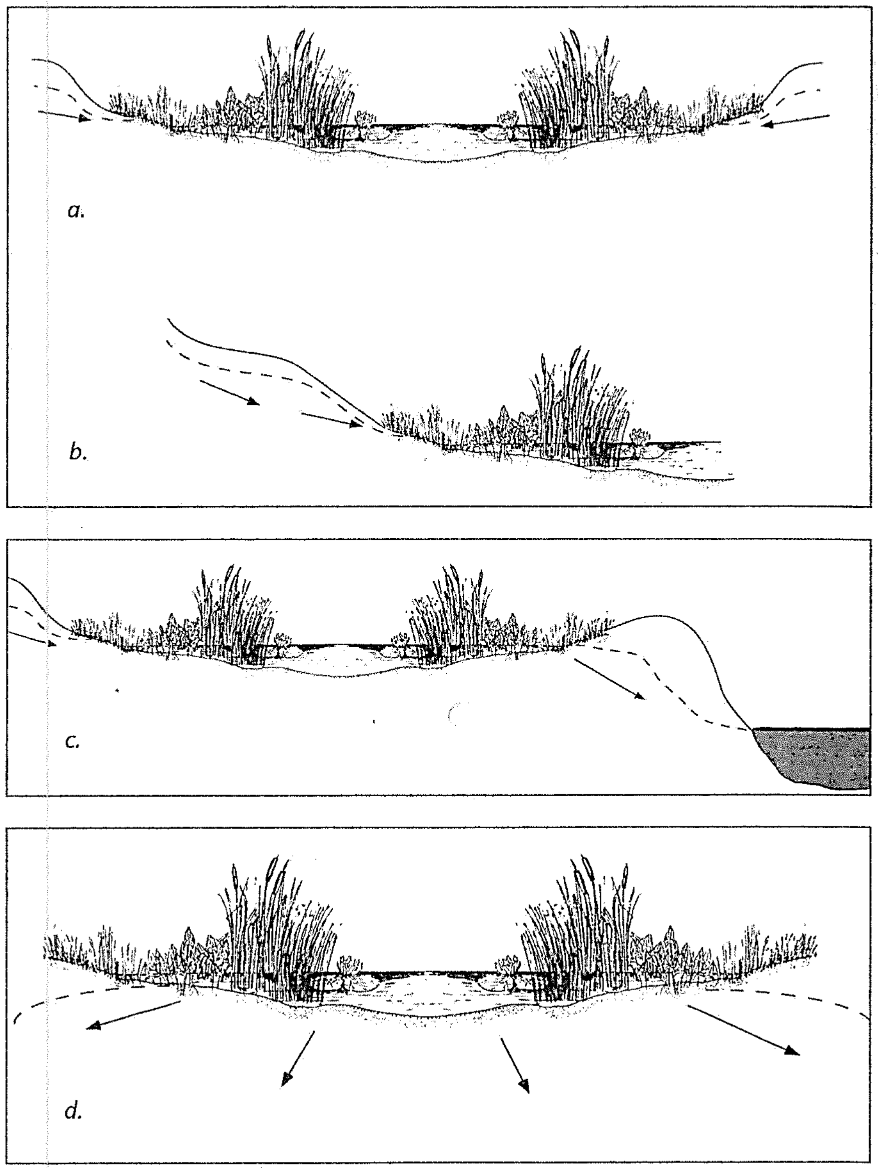
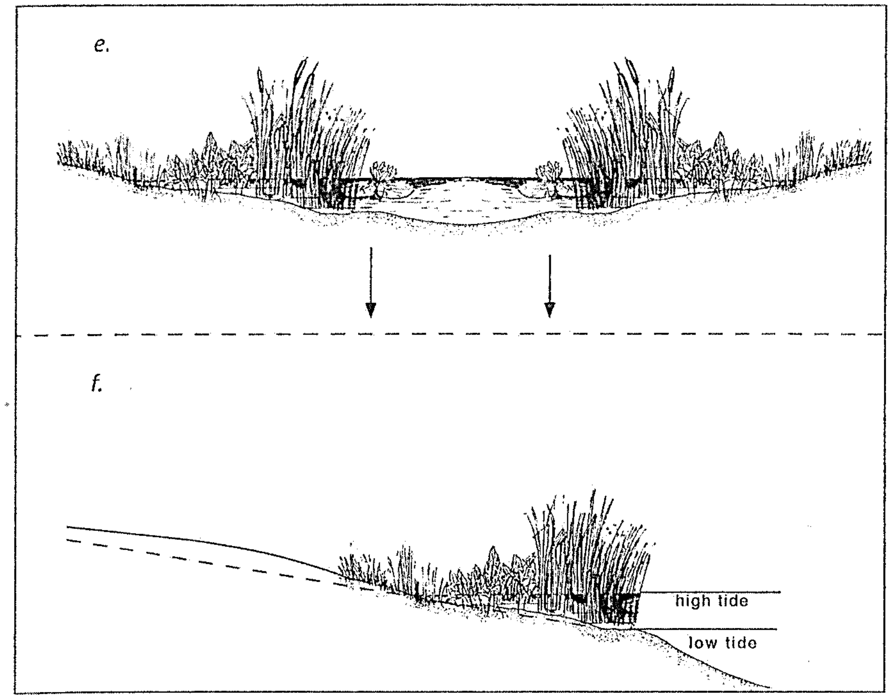


Figure 4–12. Possible wetland discharge-recharge interchanges with wetlands, including (*above*) *a.* marsh as groundwater depression wetland or "discharge" wetland; *b.* groundwater "spring" or "seep" wetland or groundwater slope wetland at base of steep slope; *c.* floodplain wetland fed by groundwater; *d.* groundwater "recharge" wetland; (*opposite page*) *e.* perched wetland or surface water depression wetland; *f.* groundwater flow through tidal wetland. *(Some terminolo-*



been cited as one of the most important attributes of wetlands, but it does not hold for all wetland types; nor is there sufficient experience with site specific studies to make many generalizations (Siegel, 1988a). Groundwater inflows result when the surface water (or groundwater) level of a wetland is lower hydrologically than the water table of the surrounding land (called a *discharge wetland* by geologists who generally view their water budget from a groundwater, not a wetland, perspective). Wetlands can intercept the water table in such a way that they have only inflows and no outflows, as shown for a prairie marsh in Figure 4–12a. Another type of discharge wetland is called a *spring* or *seep* wetland and is often found at the base of steep slopes where the groundwater surface intersects with the land surface (Fig. 4–12b). This type of wetland often discharges excess water downstream, usually as surface water (Novitzki, 1979; Winter, 1988). A wetland can have both inflows and outflows of groundwater, as shown in the riparian wetland in Figure 4–12c.

When the water level in a wetland is higher than the water table of its surroundings, groundwater will flow out of the wetland (called a *recharge wetland* Fig. 4–12d). When a wetland is well above the groundwater of the area, the wetland is referred to as being perched (Fig. 4–12e). This type of wetland, also referred to as a "surface water depression wetland" by Novitzki (1979), loses water only through infiltration into the ground and through evapotranspiration.

Table 4–6. Typical Hydraulic Conductivity for Wetland Soils Compared with Other Soil Materials

Wetland or Soil Type	*Hydraulic Conductivity cm/sec x 10^{-5}*	*Reference*
Northern Peatlands		
Highly Humified Blanket Bog, U.K.	0.02-0.006	Ingram, 1967
Fen, U.S.S.R.		
slightly decomposed	500	Romanov, 1968
moderately decomposed	80	
highly decomposed	1	
Carex fen, U.S.S.R.		
0-50 cm deep	310	Romanov, 1968
100-150 cm deep	6	
North American Peatlands (general)		
fibric	>150	Verry and Boelter, 1979
hemic	1.2-150	
sapric	<1.2	
Coastal Salt Marsh		
Great Sippewissett Marsh, Mass. (vertical conductivity)		Hemond and Fifield, 1982
0-30 cm deep	1.8	
high permeability zone	2,600	
sand-peat transition zone	9.4	
Non-Peat Wetland Soils		
Cypress Dome, Florida		
clay with minor sand	0.02-0.1	Smith, 1975
sand	30	
Okefenokee Swamp Watershed, Georgia	2.8-834	Hyatt and Brook, 1984
Mineral Soils (general)		
Clay	0.05	Linsley and Franzini, 1979
Limestone	5.0	
Sand	5000	

Source: Partially after Rycroft et al., 1975

reduce soil salinity and keep the wetland soil wet even during low tide (Fig. 4–12f).

A final type of wetland, one that is fairly common, is very little influenced by or influences groundwater. Because wetlands often occur where soils have poor permeability, the major source of water can be restricted to surface water runoff,

flooding (e.g., some prairie potholes, Fig. 4–4a), and standing water is dependent on seasonal surface inflows. If, on the other hand, such a wetland were to be influenced by groundwater, its water level would be better buffered against dramatic seasonal changes or at least it will be semipermanently flooded (Winter, 1988).

Darcy's Law

The flow of groundwater into, through, and out of a wetland is often described by *Darcy's Law*, an equation familiar to groundwater hydrologists. This law states that the flow of groundwater is proportional to (1) the slope of the piezometric surface, or the hydraulic gradient, and (2) the hydraulic conductivity, or *permeability*, the capacity of the soil to conduct water flow. In equation form, Darcy's Law is given as

$$G = k \cdot a \cdot s \tag{4.12}$$

where

G = flow rate of groundwater (volume per unit time)

k = hydraulic conductivity or permeability (length per unit time)

a = groundwater cross-sectional area perpendicular to the direction of flow

s = hydraulic gradient (slope of water table or piezometric surface)

Despite the importance of groundwater flows in the budgets of many wetlands, there is a poor understanding of groundwater hydraulics in wetlands, particularly in those that have organic soils. Table 4–6 gives some typical values of hydraulic conductivity from wetland studies, while Figure 4–13 shows the normal range of hydraulic conductivity for wetland peat as a function of fiber content. The hydraulic conductivity can be predicted for some peatland soils from their bulk density or fiber content, both of which can easily be measured. In general, the conductivity of organic peat decreases as the fiber content decreases through the process of decomposition. Water can pass through fibric, or poorly decomposed, peats a thousand times faster than it can through more decomposed sapric peats (Verry and Boelter, 1979). The type of plant material that makes up the peat is also important. Peat composed of the remains of grasses and sedges such as *Phragmites* and *Carex,* for example, is more permeable than the remains of most mosses, including sphagnum (Ingram, 1983). Rycroft et al. (1975) properly note that hydraulic conductivity of peat can vary over 9 to 10 orders of magnitude, between 10^{-8} and 10^{2} cm/sec. They also note that there has been disagreement over methods for measuring hydraulic conductivity and about whether Darcy's Law applies to flow through organic peat (Hemond and Goldman, 1985; Kadlec, 1989).

When groundwater flows into wetlands, it can often be an important source of

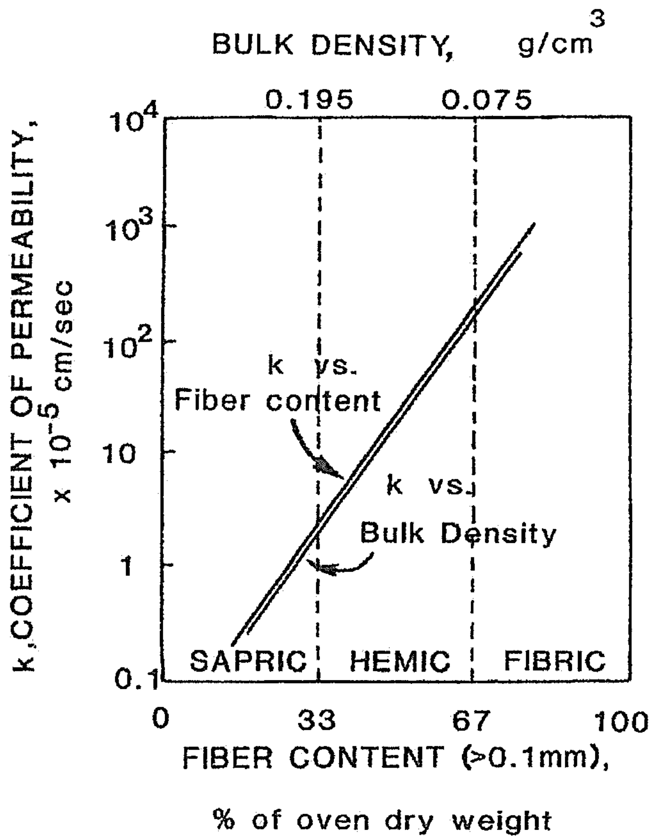


Figure 4–13. Permeability of peatland soil as a function of fiber content and bulk density. (*After Verry and Boelter, 1979; copyright © 1979 American Water Resources Association, reprinted with permission*)

nutrients and dissolved minerals. This is particularly true in the early stages of peatland development and in many coastal marshes. Fresh groundwater can influence coastal wetlands by lowering salinity, particularly at the inland edges of the wetland.

EVAPOTRANSPIRATION

The water that vaporizes from water or soil in a wetland (evaporation), together with moisture that passes through vascular plants to the atmosphere (transpiration), is called *evapotranspiration*. The meteorological factors that affect evaporation and transpiration are similar as long as there is adequate moisture, a condition that almost always exists in most wetlands. The rate of evapotranspira-

tion is proportional to the difference between the vapor pressure at the water surface (or at the leaf surface) and the vapor pressure in the overlying air. This is described in a version of *Dalton's Law*:

$$E = c\,f(u)\,(e_w - e_a) \qquad (4.13)$$

where

E = rate of evaporation

c = mass transfer coefficient

$f(u)$ = function of windspeed, u

e_w = vapor pressure at surface, or saturation vapor pressure at wet surface

e_a = vapor pressure in surrounding air

Evaporation and transpiration are enhanced by meteorological conditions such as solar radiation or surface temperature that increase the value of the vapor pressure at the evaporation surface or by factors such as decreased humidity or increased wind speed that decrease the vapor pressure of the surrounding air. This equation assumes an adequate supply of water for capillary movement in the soil or for access by rooted plants. When the water supply is limited (not a frequent occurrence in wetlands), evapotranspiration is limited as well. Transpiration can also be physiologically limited by certain plants through the closing of leaf stomata despite adequate moisture during periods of stress such as anoxia.

Empirical Estimates of Wetland Evapotranspiration

Evapotranspiration can be determined with any number of empirical equations that use easily measured meteorological variables or by various direct measures. One of the most frequently used empirical equations for evapotranspiration from terrestrial ecosystems, which has been applied with some success to wetlands, is the *Thornthwaite Equation* for potential evapotranspiration (Chow, 1964):

$$ET_i = 16\,(10T_i/I)^a \qquad (4.14)$$

where

ET_i = potential evapotranspiration for month i, mm/mo

T_i = mean monthly temperature, °C

I = local heat index $= \sum_{i=1}^{12} (T_i/5)^{1.514}$

$a = (0.675 \times I^3 - 77.1 \times I^2 + 17{,}920 \times I + 492{,}390) \times 10^{-6}$

This equation was used to determine evapotranspiration from the Okefenokee Swamp in Georgia by Rykiel (1977, 1984). For a 26-year period examined in that study, average evapotranspiration ranged from 21 mm/mo in December to 179 mm/mo in July. Kadlec et al. (1988) tested the Thornthwaite Equation on wetland evapotranspiration in Michigan and Nevada and found it to underpredict actual evapotranspiration, especially in the arid Nevada site.

A second empirical relationship that has had many applications in hydrologic and agricultural studies but relatively few in wetlands is the *Penman Equation* (Penman, 1948; Chow, 1964). This equation, based on both Dalton's Law and the energy budget approach, is given as

$$ET = \frac{\Delta H + 0.27 E_a}{\Delta + 0.27} \qquad (4.15)$$

where

ET = evapotranspiration, mm/day

Δ = slope of curve of saturation vapor pressure *vs.* mean air temperature, mm Hg/°C

H = net radiation, cal/cm^2-day

$= R_t (1 - a) - R_b$

R_t = total shortwave radiation

a = albedo of wetland surface

R_b = effective outgoing longwave radiation = $f(T^4)$

E_a = term describing the contribution of mass-transfer to evaporation

$= 0.35 (0.5 + 0.00625\, u)(e_w - e_a)$

u = wind speed 2 m above ground, km/day

e_w = saturation vapor pressure of water surface at mean air temperature, mm Hg

e_a = vapor pressure in surrounding air, mm Hg

The Penman Equation was compared with the pan evaporation (multiplied by 0.8 factor) and other methods at natural enriched fens in Michigan and constructed wetlands in Nevada by Kadlec et al. (1988). They found that the Penman Equation, like the Thornthwaite Equation, generally underpredicted evapotranspiration from the Michigan wetland (Fig. 4–14) but agreed within a few percent with other measurement techniques for the Nevada wetlands.

Another empirical relationship for describing summer evapotranspiration was developed by Scheffe (1978) and was described by Hammer and Kadlec (1983). The equation, which was used individually for sedges, willow, leatherleaf, and cattail vegetation covers, is

$$ET = \alpha + \beta B + \delta C + \gamma D + \lambda E \qquad (4.16)$$

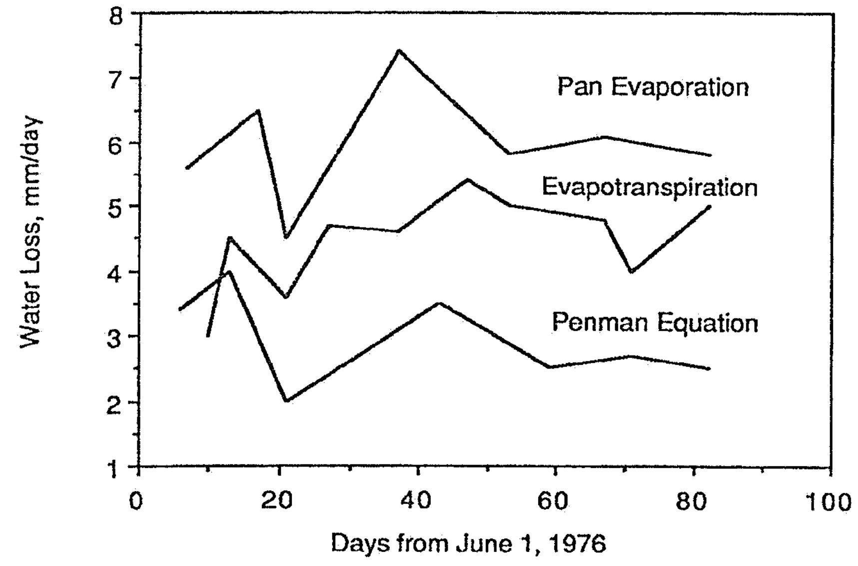


Figure 4–14. Comparison of evapotranspiration measured by diurnal change in water level with pan evaporation measurements and calculations from Penman equation for Houghton Lake, Michigan, enriched fen (sedge site) in summer 1976. (*From Kadlec et al., 1988; copyright © by Donald D. Hook, reprinted with permission*)

where

$\alpha, \beta, \delta, \gamma, \lambda$ = correlation coefficients

B = incident radiation (measured by pyranograph)

C = air temperature

D = relative humidity

E = wind speed

The equation gives estimates that are better than some more frequently used evapotranspiration relationships, although when the results of using this model were compared to actual measurements, the radiation term was shown to dominate (Hammer and Kadlec, 1983).

Because of the many meteorological and biological factors that affect evapotranspiration, none of the many empirical relationships, including the Thornthwaite, Penman, and Hammer and Kadlec Equations, is entirely satisfactory for estimating wetland evapotranspiration. Lee (1980) cautions that there is "no reliable method of estimating evapotranspiration rates based on simple weather-element data or potential evapotranspiration." Nevertheless, these equations of potential evapotranspiration offer the most cost-effective first approximations for estimating water loss. Furthermore, when applied to wetlands, which are only rarely devoid of an adequate water supply, they may be more reliable than their applications to upland terrain, where evapotranspiration can be limited by a lack of soil water.

Direct Measurement of Wetland Evapotranspiration

Several direct measurement techniques can be used in wetlands to determine evapotranspiration. Over fairly uniform areas, it is possible to determine evapotranspiration from heat and water balances through the plant canopy (Hsu et al., 1972). Evapotranspiration from wetlands has also been calculated from measurements of the increase in water vapor in air flowing through vegetation chambers (S. L. Brown, 1981) and from observing the diurnal cycles of groundwater or surface water in wetlands (Mitsch et al., 1977; Heimburg, 1984; Ewel and Smith, 1992). This latter method, described in Figure 4–15, can be calculated as follows:

$$ET = S_y\,(24\,h \pm s) \qquad (4.17)$$

where

ET = evapotranspiration, mm/day

S_y = specific yield of aquifer (unitless)

= 1.0 for standing water wetlands

< 1.0 for groundwater wetlands

h = hourly rise in water level from midnight to 4:00 A.M., mm/hr

s = net fall (+) or rise (-) of water table or water surface in one day

The pattern assumes active "pumping" of water by vegetation during the day and a constant rate of recharge equal to the midnight-to-4:00-A.M. rate. This method also assumes that evapotranspiration is negligible around midnight and that the water table around this time approximates the daily mean. The water level is usually at or near the root zone in many wetlands, a necessary condition for this method to measure evapotranspiration accurately (Todd, 1964).

Effects of Vegetation on Wetland Evapotranspiration

A question about evapotranspiration from wetlands, which does not elicit a uniform answer in the literature, is, "Does the presence of wetland vegetation increase or decrease the loss of water over that which would occur from an open body of

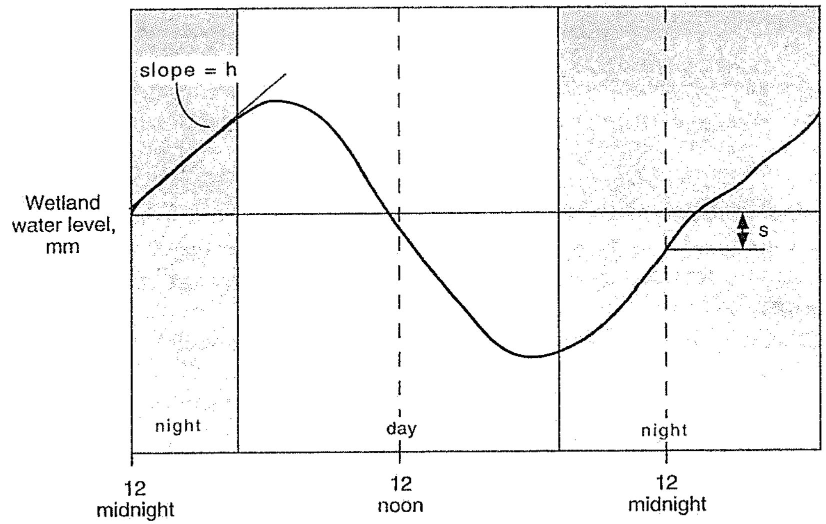


Figure 4–15. Diurnal water fluctuation in some wetlands as it is used to calculate evapotranspiration with Equation 4.17. *(After Todd, 1964)*

water?" Data from individual studies are conflicting. Obviously, the presence of vegetation retards evaporation from the water surface, but the question is whether the transpiration of water through the plants equals or exceeds the difference (Kadlec et al., 1988; Kadlec, 1989). Eggelsmann (1963) found evaporation from bogs in Germany to be generally less than that from open water except during wet summer months. In studies of evapotranspiration from small bogs in northern Minnesota, Bay (1967) found it to be 88 percent to 121 percent of open-water evaporation. Eisenlohr (1976) found 10 percent lower evapotranspiration from vegetated prairie potholes than from nonvegetated potholes in North Dakota. Hall et al. (1972), through a series of measurements and calculations, estimated that a stand of vegetation in a small New Hampshire wetland lost 80 percent more water than did the open water in the wetland. In a forested pond cypress dome in north-central Florida, Heimburg (1984) found that swamp evapotranspiration was about 80 percent of pan evaporation during the dry season (spring and fall) and as low as 60 percent of pan evaporation during the wet season (summer). S. L. Brown (1981) found that transpiration losses from pond cypress wetlands were lower than evaporation from an open water surface even with adequate standing water.

In the arid West, it has been a long-standing practice to conserve water for irrigation and other uses by clearing riparian vegetation from streams. In this environment where groundwater is often well below the surface but within the rooting zone of deep-rooted plants, trees "pump" water to the leaf surface and actively transpire even when little evaporation occurs at the soil surface.

The conflicting measurements and the difficulty of measuring evaporation and evapotranspiration led Linacre (1976) to conclude that neither the presence of wetland vegetation nor the type of vegetation had major influences on evaporation rates, at least during the active growing season. Bernatowicz et al. (1976) also found little difference in evapotranspiration among several species of vegetation. This general unimportance of vegetation-species variation on overall wetland water loss is probably a reasonable conclusion for most wetlands, although it is clear that the type of wetland ecosystem and the season are important considerations. Ingram (1983), for example, found that fens have about 40 percent more evapotranspiration than do treeless bogs and that evaporation from the bogs is less than potential evapotranspiration in the summer and greater than potential evapotranspiration in the winter. Furthermore, H. T. Odum (1984) concluded that the draining of Florida cypress swamps and their "replacement with either open water or other kinds of vegetation may decrease available water, increasing frequency of drought, raising microclimate temperatures in summer, and reducing productivity of natural and agricultural ecosystems."

TIDES

The periodic and predictable tidal inundation of coastal salt marshes, mangroves, and freshwater tidal marshes is a major hydrologic feature of these wetlands. The tide acts as a stress by causing submergence, saline soils, and soil anaerobiosis; it acts as a subsidy by removing excess salts, reestablishing aerobic conditions, and providing nutrients. Tides also shift and alter the sediment patterns in coastal wetlands, causing a uniform surface to develop.

Typical tidal patterns for several coastal areas in the Atlantic and Gulf coasts of the United States are shown in Figure 4–16a. Seasonal as well as diurnal patterns exist in the tidal rhythms. Annual variations of mean monthly sea level are as great as 25 cm (Fig. 4–16b). Tides also have significant bimonthly patterns because they are generated by the gravitational pull of the moon and, to a lesser extent, the sun. When the sun and the moon are in line and pull together, which occurs almost every two weeks, *spring tides,* or tides of the greatest amplitude, develop. When the sun and the moon are at right angles, *neap tides,* or tides of least amplitude, occur. Spring tides occur roughly at full and new moons, whereas neap tides occur during the first and third quarters.

Tides vary more locally than regionally. The primary determinant is the coastline configuration. In North America, tidal amplitudes vary from less than 1 meter along the Texas Gulf Coast to several meters in the Bay of Fundy in Nova Scotia. Tidal amplitude can actually increase as one progresses inland in some funnel-shaped estuaries (W. E. Odum et al., 1984).

Typically on a rising tide, water flows up tidal creek channels until the channels are bankfull. It overflows first at the upstream end, where tidal creeks break up into small creeklets that lack natural levees. The overflowing water spreads back downstream over the marsh surface. On falling tides the flows are reversed. At low tides water continues to drain through the natural levee sediments into adjacent creeks because these sediments tend to be relatively coarse; in the marsh interior, where sediments are finer, drainage is poor and water is often impounded in small depressions in the marsh.

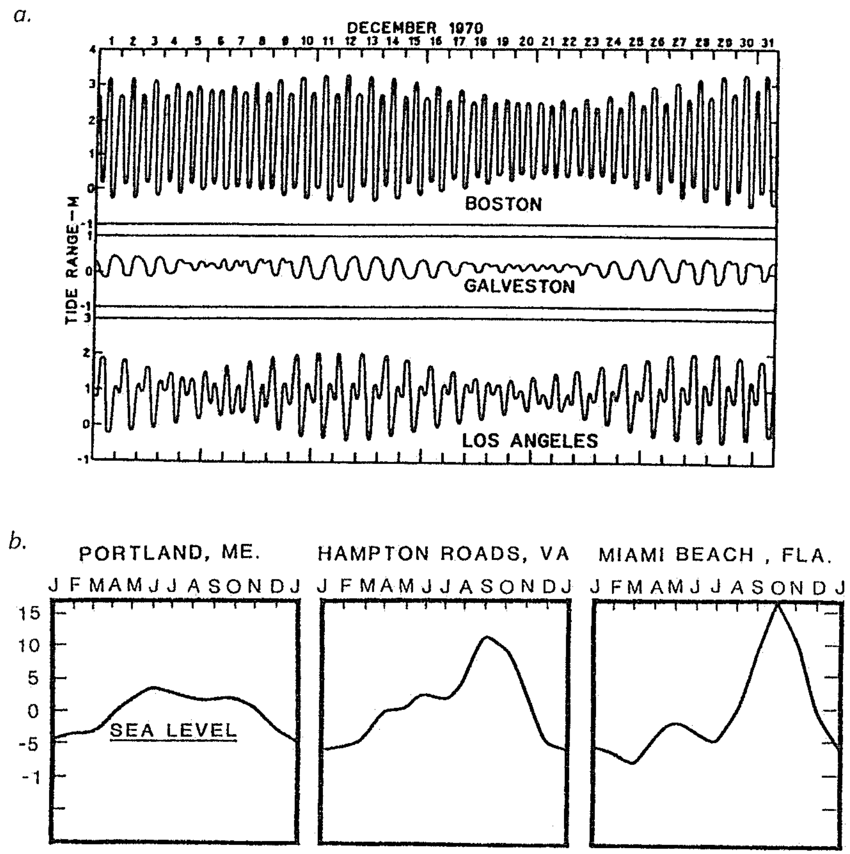


Figure 4–16. *a.* Daily pattern of tides, and *b.* seasonal changes in mean monthly sea level for several locations in North America. *(After Emery and Uchupi, 1972)*

SPECIFIC EFFECTS OF HYDROLOGY ON WETLANDS

The effects of hydrology on wetland structure and function can be described with a complicated series of cause and effect relationships. A conceptual model that shows the general effects of hydrology in wetland ecosystems was shown in

Figure 4–1. The effects are shown to be primarily on the chemical and physical aspects of the wetlands, which, in turn, affect the biotic components of the ecosystem. The biotic components, in turn, have a feedback effect on hydrology. Several principles underscoring the importance of hydrology in wetlands can be elucidated from the studies that have been conducted to date. These principles, discussed below, are as follows:

1. Hydrology leads to a unique vegetation composition but can limit or enhance species richness.
2. Primary productivity and other ecosystem functions in wetlands are often enhanced by flowing conditions and a pulsing hydroperiod and are often depressed by stagnant conditions.
3. Accumulation of organic material in wetlands is controlled by hydrology through its influence on primary productivity, decomposition, and export of particulate organic matter.
4. Nutrient cycling and nutrient availability are both significantly influenced by hydrologic conditions.

Species Composition and Diversity

Hydrology is a two-edged sword for species composition and diversity in wetlands. It acts as a limit or a stimulus to species richness, depending on the hydroperiod and physical energies. At a minimum, the hydrology acts to select water-tolerant vegetation in both freshwater and saltwater conditions. Of the thousands of vascular plants that are on Earth, relatively few have adapted to waterlogged soils. (These adaptations are discussed in more detail in Chapter 6.) Although it is difficult to generalize, many wetlands that sustain long flooding durations have lower species richness in vegetation than do less frequently flooded areas. Waterlogged soils and the subsequent changes in oxygen content and other chemical conditions significantly limit the number and the types of rooted plants that can survive in this environment. McKnight et al. (1981), in describing the effects of water on species composition in a riparian wetland, stated that "In general, as one goes from the hydric [wet] to the more mesic [dry] bottomland sites, the possible combinations or mixtures of species increases." Bedinger (1979), in reviewing the literature of flooding effects on tree species, attributes the effects to the following factors:

1. Different species have different physiological responses to flooding.
2. Large trees show greater tolerance to flooding than do seedlings.
3. Plant establishment depends on the tolerance of the seeds to flooding.
4. Plant succession depends on the geomorphic evolution of the floodplain such as by sediment deposition or stream downcutting.

Heinselman (1970) found a change in vegetation richness for seven different hydrologically defined conditions of northern peatlands. He noted an increase in diversity, as measured by the number of species, as the flowthrough conditions increased (Table 4–7). In this case, the flowing water can be thought of as a stimulus to diversity, probably caused by its ability to renew minerals and reduce anaerobic conditions.

Hydrology also stimulates diversity when the action of water and transported sediments creates spatial heterogeneity, opening up additional ecological niches (Gosselink and Turner, 1978). When rivers flood riparian wetlands or when tides rise and fall on coastal marshes, erosion, scouring, and sediment deposition sometimes create niches that allow diverse habitats to develop. On the other hand, flowing water can also create a very uniform surface that might cause monospecific stands of *Typha* or *Phragmites* to dominate a freshwater marsh or *Spartina* to dominate a coastal marsh. Keddy (1992) likens water level fluctuations in wetlands to fires in forests. They eliminate one growth form of vegetation (e.g., woody plants) in favor of another (e.g., herbaceous species) and allow regeneration of species from buried seeds (see Chapter 7).

Primary Productivity

In general, the "openness" of a wetland to hydrological fluxes is probably one of the most important determinants of potential primary productivity. For example, peatlands that have flow-through conditions (fens) have long been known to be more productive than stagnant raised bogs (Moore and Bellamy, 1974; see Chapter 12). A number of studies have found that wetlands in stagnant (nonflowing) or continuously deep water have low productivities, whereas wetlands that are in slowly flowing strands or are open to flooding rivers have high productivities. Brinson et al. (1981a) summarized the results of many of these studies by describing the net biomass production of forested freshwater wetlands in order of greatest to least productivity:

flowing water swamps > sluggish flow swamps > stillwater swamps

The relationship between hydrology and ecosystem primary productivity has been investigated most extensively for forested wetlands (e.g., Conner and Day, 1976; Mitsch and Ewel, 1979; S. L. Brown, 1981). A general relationship was developed by Mitsch and Ewel (1979) for cypress productivity as a function of hydrology in Florida. That study concluded that

> Cypress-hardwood associations, found primarily in riverine and flowing strand systems, have the most productive cypress trees. The short hydroperiod favors both root aeration during the long dry periods and elimination of water-intolerant species during the short wet periods. The

Table 4–7. The Relationship Between the Hydrologic Regime and Species Richness in Northern Minnesota Peatlands

	Species Present						
	Tree	*Shrub*	*Field herbs*	*Grasses and ferns*	*Ground layer*	*Total*	*Flow Conditions*
1. Rich swamp forest	6	16	28	11	10	71	Good surface flow; minerotrophic
2. Poor swamp forest	3	14	17	12	5	51	Downstream from 1; not adapted to strong water flow
3. Cedar string bog and fen	3	10	10	12	4	39	Better drainage than 2
4. Larch string bog and fen	3	9	9	12	4	37	Similar to 3; sheet flow
5. Black spruce feather moss forest	2	9	2	2	10	25	Gentle water flow on semiconvex template
6. Sphagnum bog	2	8	2	1	7	20	Isolated; little standing water
7. Sphagnum heath	2	6	2	2	5	17	Wet, soggy, and on convex template

Source: After Gosselink and Turner, 1978, and Heinselman, 1970.

continual supply of nutrients with the flooding river system conditions may be a second important factor in maintaining these high productivities.

Productivity was found to be low under both continually flooded conditions and drained conditions. S. L. Brown (1981) found that much of the variation in biomass productivity of cypress wetlands in Florida could be explained by the variation in nutrient inflow, as measured by phosphorus. Productivity is lowest there when nutrients are brought into the system solely by precipitation and is highest when large amounts of nutrients are passed through the wetlands by flooding rivers. Brown suggested that rather than there being a simple relationship between wetland productivity and hydrology, there is a more complex relationship among hydrology, nutrient inputs, and wetland productivity, decomposition, export, and nutrient cycling. Hydrology, then, also influences wetland productivity by being the main pathway through which nutrients are transported to many wetlands.

The influence of hydrologic conditions on freshwater marsh productivity is less certain. If peak biomass or similar measures are used as indicators of marsh productivity, studies can easily indicate a higher macrophyte productivity in sheltered, non-flowing marshes than in wetlands open to flowing conditions or coastal influences. For example, Robb (1989), as described by Mitsch (1992b), measured consistently higher macrophyte biomass in wetlands isolated from surface fluxes with artifical dikes than in wetlands open to coastal fluxes along Lake Erie (Table 4–8). Several explanations are possible: (1) the coastal fluxes may also be serving as a stress as well as a subsidy on the macrophytes; (2) the open marshes may be exporting a significant amount of their productivity; and (3) the diked wetlands have more predictable hydroperiods. A study of the influence of flow-through conditions on water column primary productivity of constructed marshes found that after two years of experimentation, productivity was higher in high-flow wetlands than in low-flow wetlands (Fig. 4–17). It appears that while the macrophyte productivity may take many years to respond to the difference in hydrology, the water column pro-

Table 4–8. Selected Macrophyte Measurements at Peak Biomass from Diked and Undiked Wetlands of Ohio's Coastal Lake Erie

Measure of Vegetation Structure	Average ± std error	
	Diked (impounded) Wetlands (n=6)	*Undiked (open to Lake Erie) Wetlands (n=4)*
Biomass g dry wt/m^2	897 ± 277	473 ± 149
# species/plot[a]	1.7 ± 0.3	1.4 ± 0.3
# stems/m^2	597 ± 211	241 ± 59

[a]Only species > 10% by weight per plot. Plots were 0.5 m^2 randomly placed in each wetland (3 to 6 per wetland).

Source: From Mitsch, 1992b, based on data from Robb 1989

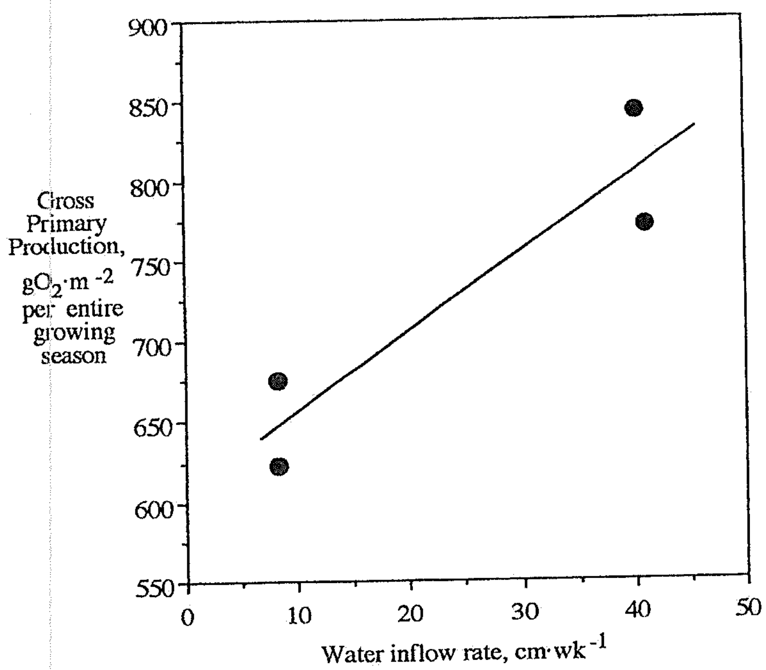


Figure 4–17. Aquatic gross primary productivity per growing season for two years versus average flow-through conditions of constructed freshwater marshes at Des Plaines River Wetland Demonstration Project in Northeastern Illinois. (*From Cronk and Mitsch, unpub. manuscript*)

ductivity, which is mainly due to attached and planktonic algae, responds relatively quickly to different hydrologic conditions.

Saltwater tidal wetlands subject to frequent tidal action are generally more productive than those that are only occasionally inundated. For example, Steever et al. (1976) showed a direct relationship between tidal range (as a measure of water flux) and end-of-season peak biomass of *Spartina alterniflora* (Fig. 4–18). They attributed the relationship to a nutrient subsidy and a flushing of toxic materials such as salt with vigorous tidal fluxes. Whigham et al. (1978) further suggested that freshwater tidal wetlands may be even more productive than saline tidal wetlands because they receive the energy and nutrient subsidy of tidal flushing while avoiding the stress of saline soils.

Despite the overwhelming evidence of the influence of hydrology on wetlands, some investigators have cautioned against always ascribing a direct linkage between hydrologic variables and wetland productivity. Richardson (1979) states that "a definitive statement about the influence of water levels on net primary productivity for all wetland types is impossible, since responses of individual species to water fluctuations vary." Water level fluctuations, however, are not necessarily related to the volume of flow-through of water and the associated nutrients and allochthonous energy. Furthermore, although individual species vary in their responses to water levels and hydrology, ecosystem-level responses may be more consistent.

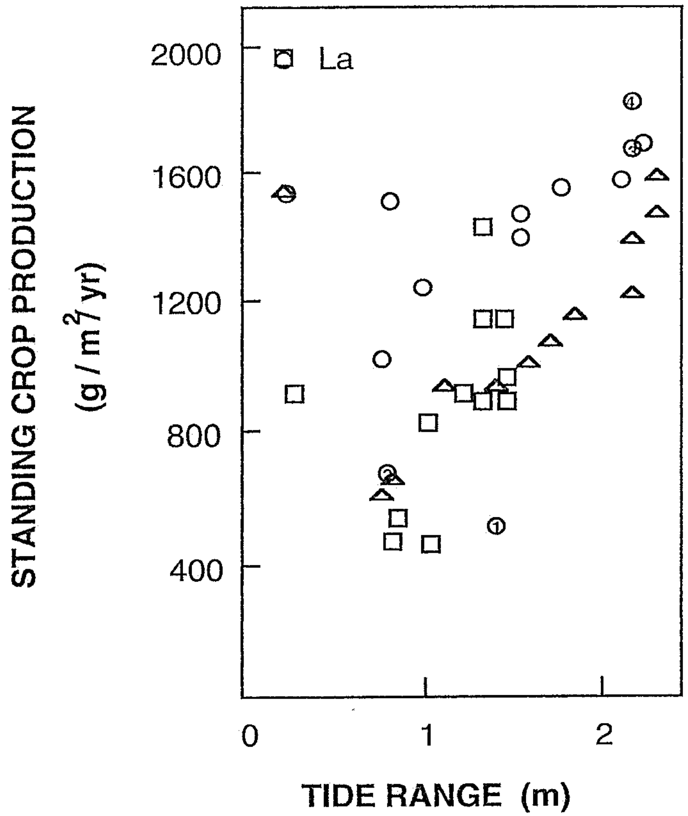


Figure 4–18. Production of *Spartina alterniflora* versus mean tidal range for several Atlantic coastal salt marshes. Different symbols indicate different data sources. La refers to Mississippi River delta marshes. (*After Steever et al., 1976*)

Organic Accumulation and Export

Wetlands can accumulate excess organic matter either as a result of increased primary productivity (as described above) or decreased decomposition and export. Notwithstanding the discrepancies from short-term litter decomposition studies, peat accumulates to some degree in all wetlands as a result of these processes. The effects of hydrology on decomposition pathways are even less clear than the effects on primary productivity discussed above. Brinson et al. (1981a) concluded that it cannot be assumed that increased frequency or duration of flooding will necessarily increase or decrease decomposition rates. They suggested, however, that alternating wet and dry conditions may lead to optimum litter decomposition rates, whereas completely anaerobic conditions caused by constant flooding are the least favorable conditions for decomposition.

Although litter decomposition rates have been measured in several wetlands, field results do not consistently supporting this view. Brinson (1977), in a study of an alluvial tupelo swamp in North Carolina, found that the decomposition of litter was most rapid in the river, slower on the wet swamp floor, and slowest on a dry levee. W. E. Odum and Heywood (1978) found that leaves of freshwater tidal marsh plants decomposed more rapidly when permanently submerged than when periodically or irregularly flooded. They suggest that this may be due to (1) better access to detritivores in the water, (2) a more constant physical environment for decomposer bacteria and fungi, (3) a greater availability of dissolved nutrients, and (4) a more suitable environment for leaching. Chamie and Richardson (1978), on the other hand, stated that "periodic or even constant flooding of a soil's surface, characteristic of wetlands, leads to an overall decrease in the activity of soil fauna" and causes slow anaerobic decomposition to dominate. Deghi et al., (1980), in a study of decomposition in cypress wetlands in Florida, found that the decomposition of cypress needles occurred more rapidly in wet areas than in dry ones but that there was no difference in decomposition rates between deep and shallow sites. Van der Valk et al. (1991) demonstrated at the Delta Marsh in south-central Manitoba that litter from several emergent plants decayed at a slightly faster rate in wetlands that were flooded approximately 1 m above normal water levels. They suggest that "when litter is not inundated [as was apparently the case in the normal water level sites], it rapidly dries out, and this adversely affects microbial populations."

The importance of hydrology for organic export is obvious. A generally higher rate of export is to be expected from wetlands that are open to the flowthrough of water. Riparian wetlands often contribute large amounts of organic detritus to streams, including macro-detritus such as whole trees. For many years salt marshes and mangrove swamps were considered major exporters of their production (for example, 45 percent estimated by Teal (1962) for a salt marsh; 28 percent measured by Heald (1969) for a mangrove swamp), but the generality of this concept is not accepted by coastal ecologists (Nixon, 1980; see Chap. 5). Hydrologically isolated wetlands such as northern peatlands have much lower organic export. For example, Bazilevich and Tishkov (1982) found that only 6 percent of the net productivity of a fen in Russia was exported by surface and subsurface flows.

Nutrient Cycling

Nutrients are carried into wetlands by hydrologic inputs of precipitation, river flooding, tides, and surface and groundwater inflows. Outflows of nutrients are controlled primarily by the outflow of waters. These hydrologic/nutrient flows are also important determinants of wetland productivity and decomposition (see previous sections). Intrasystem nutrient cycling is generally, in turn, tied to pathways such as primary productivity and decomposition. When productivity and decomposition rates are high, as in flowing water or pulsing hydroperiod wetlands, nutrient cycling is rapid. When productivity and decomposition processes are slow, as in isolated ombrotrophic bogs, nutrient cycling is also slow.

The hydroperiod of a wetland has a significant effect on nutrient transformations and on the availability of nutrients to vegetation (see Chap. 5). Nitrogen availability is affected in wetlands by the reduced conditions that result from waterlogged soil. Typically, a narrow oxidized surface layer develops over the anaerobic zone in wetland soils, causing a combination of reactions in the nitrogen cycle—nitrification and denitrification—that may result in substantial losses of nitrogen to the atmosphere. Ammonium nitrogen often accumulates in wetland soils since the anaerobic environment favors the reduced ionic form over the nitrate common in agricultural soils.

The flooding of wetland soils by altering both the pH and the redox potential of the soil, influences the availability of other nutrients as well. The pH of both acid and alkaline soils tends to converge on a pH of 7 when they are flooded (see Chapter 5). The redox potential, a measure of the intensity of oxidation or reduction of a chemical or biological system, indicates the state of oxidation (and hence availability) of several nutrients. Phosphorus is known to be more soluble under anaerobic conditions. Several studies have documented higher concentrations of soluble phosphorus in poorly drained soils than in oxidized conditions (e.g., Redman and Patrick, 1965; Patrick and Khalid, 1974). This is partially caused by the hydrolysis and reduction of ferric and aluminum phosphates to more soluble compounds. The availability of major ions such as potassium and magnesium and several trace nutrients such as iron, manganese, and sulfur is also affected by hydrologic conditions in the wetlands (Gambrell and Patrick, 1978; Mohanty and Dash, 1982). Chemical transformations in wetlands are discussed in more detail in the next chapter.

WETLAND HYDROLOGY STUDIES

Measurement of Wetland Hydrology

It is curious that so little attention has been paid to hydrologic measurements in wetland studies, despite the importance of hydrology in ecosystem function. A

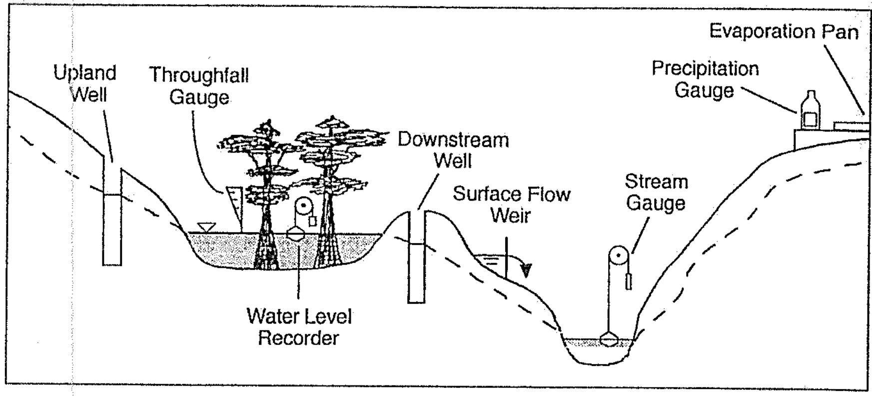


Figure 4–19. Placement of typical measuring equipment for monitoring a water budget of an alluvial wetland.

great deal of information can be obtained with only a modest investment in supplies and equipment. A diagram summarizing many of the hydrology measurements typical for developing a wetland's water budget is given in Figure 4–19. Water levels can be recorded continuously with a water level recorder or during site visits with a staff gauge. With records of water level, all of the following hydrologic parameters can be determined: hydroperiod, frequency of flooding, duration of flooding, and water depth (Gosselink and Turner, 1978). Water level recorders can also be used to determine the change in storage in a water budget, as in Equation 4.1.

Evapotranspiration measurements are more difficult to obtain, but there are several empirical relationships such as the Thornthwaite Equation that can use meteorological variables (Chow, 1964). Evaporation pans can also be used to estimate total evapotranspiration from wetlands, although pan coefficients are highly variable (Linsley and Franzini, 1979). Evapotranspiration of continuously flooded non-tidal wetlands can also be determined by monitoring the diurnal water level fluctuation as described in Figure 4–15.

Precipitation or throughfall or both can be measured by placing a statistically adequate number of rain gauges in random locations throughout the wetland or by utilizing weather station data. Surface runoff to wetlands can usually be determined as the increase in water level in the wetland during and immediately following a storm after throughfall and stemflow have been subtracted. Weirs can be constructed on more permanent streams to monitor surface water inputs and outputs.

Groundwater flows are usually the most difficult hydrologic flows to measure accurately. In some cases, a few shallow wells placed around a wetland will help indicate the direction of groundwater flow. Estimates of permeability are required to quantify the flows. In other cases, groundwater input or loss can be determined as the residual of the water budget, although this method has limited accuracy (Carter et al., 1979).

Hydrology and Wetland Classification

Hydrologic conditions are so important in defining wetlands that they are often used by scientists to classify these ecosystems. It is no coincidence that classification and mapping of wetlands based on biotic features (dominant vegetation) often matches the hydrologic conditions of the different wetlands very well. For example, peatlands have been classified according to whether they have water flow from surrounding mineral soils or if they are in flow-isolated basins. Salt marshes and salt marsh vegetation are defined and subdivided according to the frequency and depth of tidal inundation. Bottomland forests are zoned according to flooding frequency, and certain deep swamps are classified according to stillness or movement of water. Some of the classifications for particular wetland types are described in Chapters 8–14. Overall wetland classifications, which are based in whole or in part on hydrologic conditions, are described in Chapter 18.

Research Needs

There are several needs and shortcomings in wetland hydrology studies. Some of these, originally were listed by Carter et al. (1979), are still valid today:

1. the need for improving, refining, and perhaps simplifying existing techniques for hydrologic measurements;
2. the need for making accurate measurements of all the hydrologic inputs and outputs to representative wetland types and estimating the errors inherent in various measurement techniques;
3. the need to quantify the soil-water-vegetation relationships of wetlands and to improve our basic understanding of these relationships
4. the need to make in-depth, long-term studies of different wetland types under different environmental conditions; and
5. the need to continue developing models based on hydrologic data so that we can develop better analyses and predictive capability.

Wetland researchers and managers should recognize the importance of hydrologic studies and research to augment the more frequently studied biological components of wetlands. These two aspects are closely related.