Chapter 4

Wetland Hydrology

Hydrologic conditions are extremely important for the maintenance of a wetland's structure and function. They affect many abiotic factors, including soil anaerobiosis, nutrient availability, and, in coastal wetlands, salinity. These, in turn, determine the biota that develops in a wetland. Finally, completing the cycle, biotic components are active in altering the wetland hydrology and other physicochemical features. 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 wetland basin geomorphology, and subsurface conditions. The hydroperiod can have dramatic seasonal and year-to-year variations, yet it remains the major determinant of wetland processes. The major components of a wetland's water budget include precipitation, evapotranspiration, surface inflows and outflows including overbank flooding into riparian wetlands, groundwater fluxes, and tides or seiches in coastal wetlands. Simple determinations of the hydroperiod, water budget, and turnover time in wetland studies can contribute to a better understanding of wetland function. Hydrology affects species composition and richness, primary productivity, organic accumulation, and nutrient cycling in wetlands.

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.

Importance of Hydrology in Wetlands

Wetlands are transitional between terrestrial and open-water aquatic ecosystems. They are transitional in terms of spatial arrangement, for they usually are found between uplands and aquatic systems (see Fig. 2.1a). They are also transitional in the amount of water they store and process and in other ecological processes that result from the water regime. Wetlands form the aquatic boundary of the habitats of many terrestrial plants and animals; they also form the terrestrial edge for many aquatic plants and animals. Hence, small changes in hydrology can result in significant biotic changes.

The starting point for the *hydrology* of a wetland is the climate and basin geomorphology (Fig. 4.1). All things being equal, wetlands are more prevalent in cool or wet climates than in hot or dry climates. Cool climates have less water loss from the land via evapotranspiration, whereas wet climates have excess precipitation. The second important factor is the geomorphology of the landscape and basin. Steep terrain tends to have fewer wetlands than flat or gently sloping landscapes. Isolated basins have different potential for wetlands than do tidal-fed or river-fed environments. When climate, basin geomorphology, and hydrology are considered as one unit, it is referred to as a wetland's *hydrogeomorphology*. Figure 4.1 illustrates that the hydrology of a wetland directly modifies and changes its *physiochemical environment* (chemical and physical properties), particularly oxygen availability and related chemistry, such as nutrient availability, pH, and toxicity (e.g., the production of hydrogen sulfide). Hydrology also transports sediments, nutrients, and even toxic materials into wetlands, thereby further influencing the physiochemical environment. Except in nutrient-poor wetlands such as bogs, water inputs are the major source of nutrients to wetlands. Hydrology also causes water outflows from wetlands that often remove biotic and abiotic material, such as dissolved organic carbon, excessive salinity, toxins, and excess sediments and detritus. Some modifications in the physicochemical environment, such as the buildup of sediments, can modify the hydrology by changing the basin geometry or affecting the hydrologic inflows or outflows (pathway A in Fig. 4.1).

Modifications of the physiochemical environment, in turn, have a direct impact on the biota in the wetland. When hydrologic conditions in wetlands change even slightly, the biota may respond with massive changes in species composition and richness and in ecosystem productivity. Biota such as emergent aquatic plants adapt to the anoxia in the sediments, although the anoxia excludes most vascular plant species. The level of nutrients in the sediments determines productivity and which species will dominate. Animals adapted to shallow water and this vegetation cover will flourish. Microbes able to metabolize in anoxic conditions dominate the reduced sediments, while aerobic microorganisms survive in a thin layer of oxidized sediments and in the water column

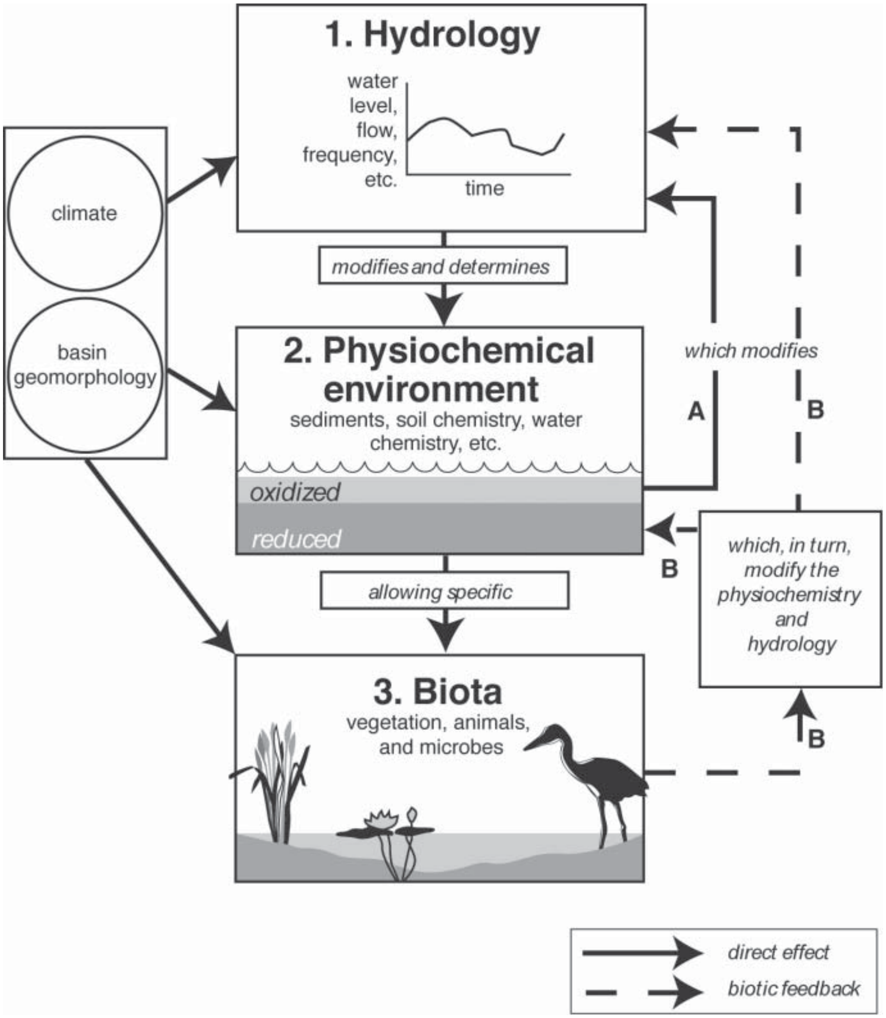

Figure 4.1 Conceptual diagram illustrating the effects of hydrology on wetland function and the biotic feedbacks that affect wetland hydrology. Pathways A and B are feedbacks to the hydrology and physiochemistry of the wetland.

if oxygen is present there. When hydrologic patterns remain similar from year to year, a wetland's biotic 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 biota are not passive to their hydrologic conditions. Pathway B in Figure 4.1 shows that the biotic components of wetlands can control the hydrology

Mitsch, William J., and James G. Gosselink. <i>Wetlands</i>, John Wiley & Sons, Incorporated, 2015. ProQuest Ebook Central, http://ebookcentral.proquest.com/lib/bu/detail.action?docID=1895927.

and chemistry of their environment through a variety of mechanisms. Microbes, in particular, catalyze virtually all chemical changes in wetland soils and thus control nutrient availability to plants and even the production of phytotoxins, such as sulfides. Plants, animals, and microbes that use these essential biological feedback mechanisms were formally recognized in the ecological literature as *ecosystem engineers.* Plants cause changes in their physical environment through processes such as peat building, sediment trapping, nutrient retention, water shading, and transpiration. Wetland vegetation influences the hydrologic conditions of the physicochemical environment by binding sediments to reduce erosion, by trapping sediments, by interrupting water flows, and by building peat. Accumulated sediments and organic matter, in turn, interrupt water flows and can eventually decrease the duration and frequency by which the wetlands are flooded. 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. In more temperate climates, trees that invade shallow marshes and vernal pools can decrease water levels during the growing season by increasing transpiration, thus allowing even more woody plants to take over. Removal of these trees in what appears to be a dry forest sometimes surprisingly causes standing water and marsh vegetation to reappear.

Several animals are particularly noted for their contributions to hydrologic modifications and subsequent changes in wetlands. 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 and creating wetlands where none existed before. In colonial times, beaver populations covered the entire American continent north of Mexico, before fur trappers drastically reduced them. Beavers have been an important causal force in the creation of the Great Dismal Swamp of Virginia and North Carolina. Hey and Philippi (1995) estimated that a population of 40 million beavers could have accounted for 207,000 km^2 of beaver ponds (wetlands) in the upper Mississippi and Missouri River basins before European trappers entered the region and that, with the demise of the beaver, only 1 percent of those beaver ponds exist today.

Muskrats (*Ondatra zibethicus*) burrow through wetlands, changing flow patterns and sometimes water levels directly. They harvest large amounts of emergent vegetation for their food and to build winter lodges, thereby opening up large areas of marshes. Geese, especially Canada geese (*Branta canadensis*) and several varieties of snow geese (*Chen* spp.), cause *eat-outs*, or major wetland vegetation removal by herbivory, in many parts of the world. Newly planted wetlands are particularly susceptible to Canada geese eat-outs in North America. By removing vegetation cover, these herbivores reset the successional status of the wetlands and thus have a major impact on wetland hydrology.

The American alligator (*Alligator mississippiensis*) is known for its 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, to the survival of other species, and to the elimination of others by influencing the ecosystem's hydrology and other physical characteristics.

Wetland Hydroperiod

The *hydroperiod* is the seasonal pattern of the water level of a wetland and is the wetland's hydrologic signature. It characterizes each type of wetland, and the constancy of its pattern from year to year ensures a reasonable stability for that wetland. It defines the rise and fall of a wetland's surface and subsurface water by integrating all of the inflows and outflows. The hydroperiod 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). These terms such as *seasonally flooded* or *intermittently flooded* are specific in their meaning and should be used with care and with sufficient data in describing a wetland's hydroperiod. For wetlands that are not subtidal or permanently flooded, the amount of time that a wetland is in standing water is called the *flood duration*. 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.

Typical hydroperiods for a diverse set of wetlands are shown in Figure 4.2. A coastal salt marsh has a hydroperiod of semidiurnal flooding and dewatering superimposed on a twice-monthly pattern of spring and ebb tides (Fig. 4.2a). Wetlands along coastlines often show some of this same spring-and-ebb pulsing (Fig. 4.2b), whereas others reflect seasonal water-level changes of freshwater inflows and the water levels

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 during 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 during the growing season, but standing water is rarely present
Temporarily flooded—flooded for brief periods during 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

Source: After Cowardin et al. (1979)

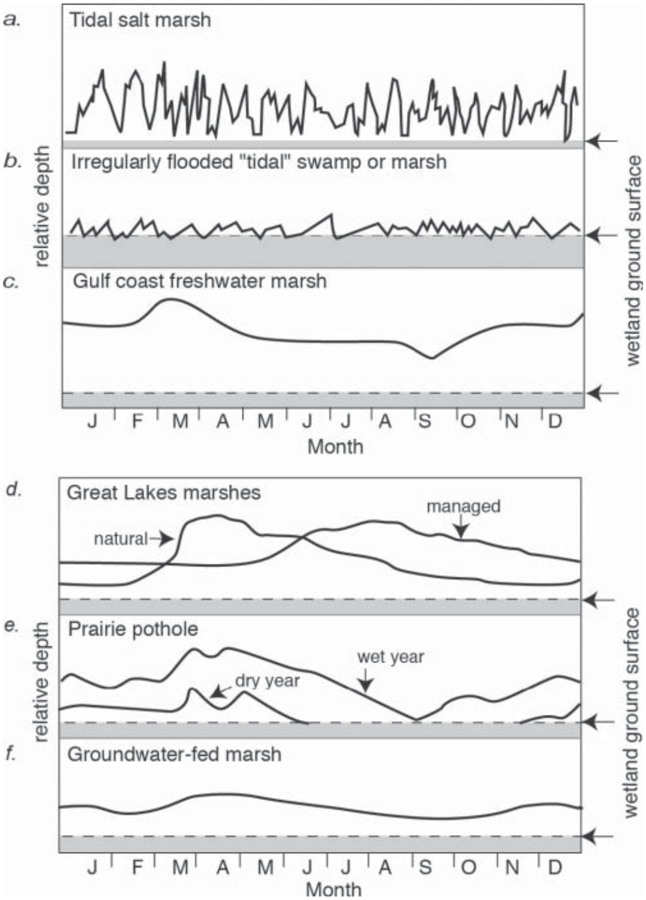

Figure 4.2 Hydroperiods for several different wetlands, presented in approximately the same relative scale: (a) tidal salt marsh, Rhode Island; (b) irregularly flooded "tidal" swamp or marsh; (c) Gulf Coast freshwater marsh, Louisiana; (d) Great Lakes marshes, northern Ohio (natural and managed); (e) prairie pothole marsh with little groundwater flow (dry and wet years); (f) groundwater-fed prairie pothole marsh; (g) vernal pool, California; (h) subtropical cypress dome, Florida; (i) alluvial swamp, North Carolina; (j) bottomland hardwood forest, northern Illinois; (k) mineral soil swamp, Ontario, Canada; (l) rich fen, North Wales; (m) pocosin or Carolina Bay, North Carolina; (n) tropical floodplain forest, Amazon River, Manaus, Brazil. (Data from Nixon and Oviatt, 1973; Mitsch et al., 1979; Gilman, 1982; Junk, 1982; P.H. Zedler, 1987; Mitsch, 1989; van der Valk, 1989; Brinson, 1993; Woo and Winter, 1993)

of the ocean itself (Fig. 4.2c). Hydroperiods of coastal lacustrine wetlands along the Laurentian Great Lakes in the United States and Canada vary considerably, depending on whether pumps and water management are used or whether the marshes are open to the seasonal patterns of river flows and lake levels (Fig. 4.2d). In fact, the hydroperiods of these wetlands, when used as hunting clubs for waterfowl production, actually are managed to be dry when the normal season calls for wet and wet when the seasonal

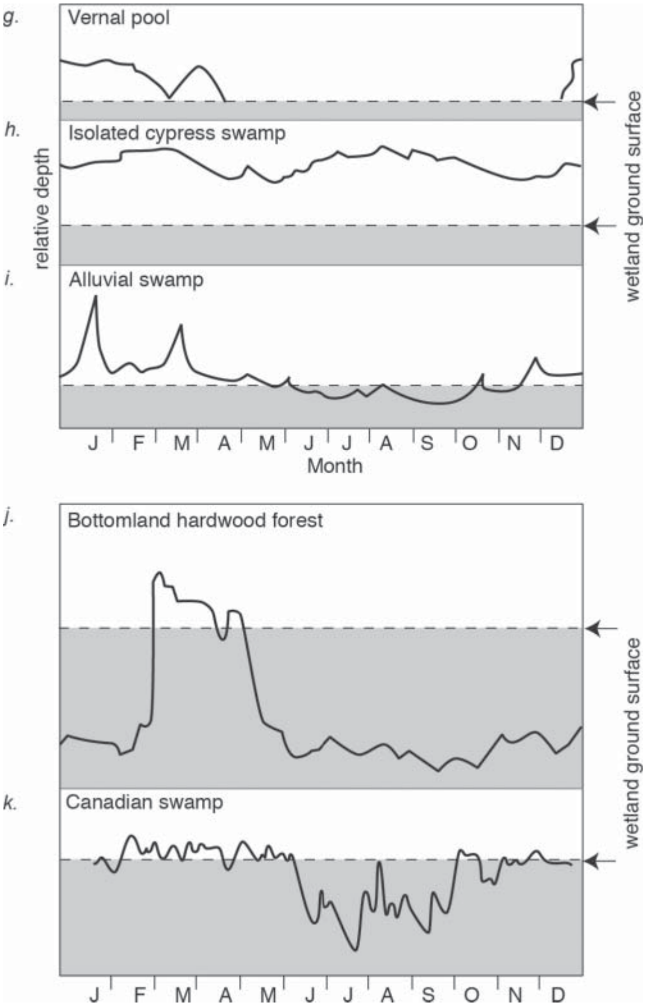

Figure 4.2 (***Continued***)

pattern calls for dry conditions. Water levels for interior wetlands, such as the prairie potholes of North America, vary considerably from year to year (see the next section), with differences depending on climate variability (Fig. 4.2e). Wetlands affected by groundwater tend to have water levels that are less seasonally variable (Fig. 4.2f).

Some of the most seasonally variable wetlands are the vernal pools of central California, where surface water essentially disappears in this Mediterranean-type climate for all but four or five months (Fig. 4.2g). Cypress domes in central Florida have standing water during the wet summer season and dry periods in the late autumn and early spring (Fig. 4.2h). Low-order riverine wetlands, such as the alluvial swamps in the southeastern United States, respond sharply to local rainfall events rather than to

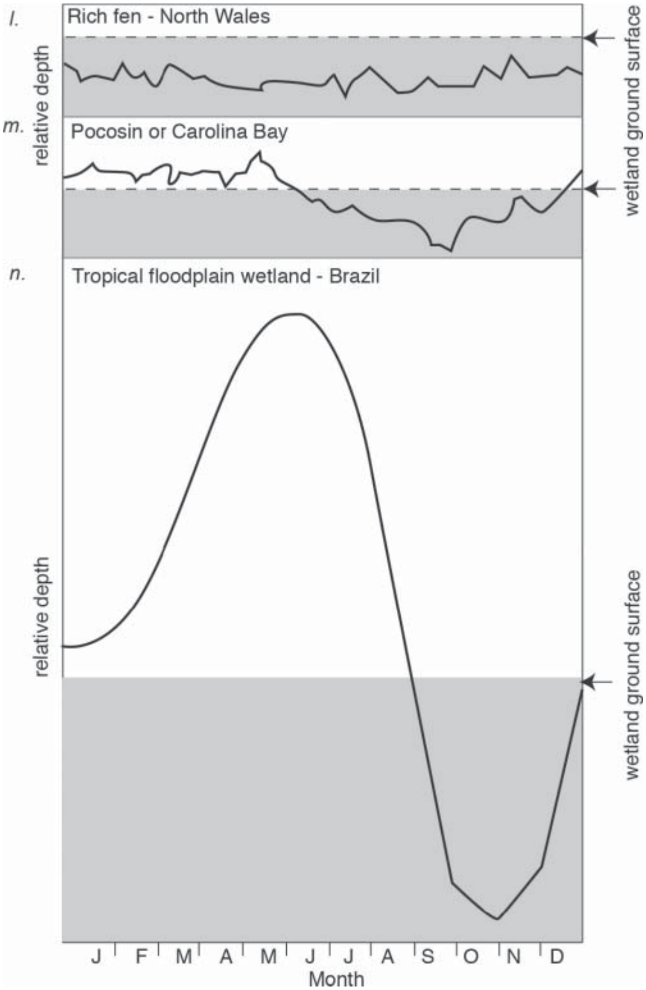

Figure 4.2 (***Continued***)

general seasonal patterns (Fig. 4.2i). The hydroperiods of many bottomland hardwood forests and swamps in colder climates have distinct periods of surface flooding in the winter and early spring due to snow and ice conditions followed by spring floods but otherwise have a water table that can be a meter or more below the surface (Fig. 4.2j and k).

Peatlands in cooler climates can have hydroperiods with little pronounced seasonal fluctuation, as in the fen from North Wales (Fig. 4.2l). If peatlands such as the pocosins of North Carolina are located in regions of warm summers, significant patterns of seasonal water-level change will occur (Fig. 4.2m). The most dramatic hydroperiods result from high-order rivers that are more influenced by seasonal patterns of precipitation throughout a large watershed than by local precipitation, leading to a more predictable and seasonally distinct hydroperiod. For example, the annual fluctuation of water in the tropical floodplain forests along the Amazon River is a predictable seasonal pattern that can include a seasonal fluctuation in water level of 5 to 10 m caused by flooding of upstream rivers (Fig. 4.2n).

Year-to-Year Fluctuations

The hydroperiod is not the same each year but varies according to climate and antecedent conditions. Great variability can be seen from year to year for some wetlands, as illustrated in Figure 4.3 for a prairie pothole regional wetland in Canada and for the Big Cypress Swamp 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. 4.3a). Figure 4.3b illustrates cases of an even seasonal rainfall pattern for the Big Cypress Swamp in Florida between a fairly stable hydroperiod and a year with a significant dry season, which caused the hydroperiod to vary about 1.5 m between high and low water. A three-year study of groundwater levels in a red maple swamp shows dramatically different growing season water levels from year to year (Fig. 4.4). Water is near or at the surface during high precipitation periods (last half of first year and entire second year) while dry low-water conditions are mainly driven by seasonal evapotranspiration in the swamp accelerated by groundwater loss during tree transpiration.

Pulsing Water Levels

Water levels in most wetlands are generally not stable but fluctuate seasonally (riparian wetlands), daily or semidaily (types of tidal wetlands), or unpredictably (wetlands in low-order streams and coastal wetlands with wind-driven tides). Flooding “pulses” that occur seasonally or periodically especially in riverine wetlands nourish the wetlands 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. Despite this obvious fact, many wetland managers, especially those who manage wetlands for waterfowl, often attempt to control water levels by isolating formerly open wetlands with levees meant to restrict flooding. A seasonally fluctuating water level, then, is the rule, not the exception, in most wetlands.

Wetland Water Budget

The hydroperiod, or hydrologic state of a given wetland, can be summarized as being a result of these three 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

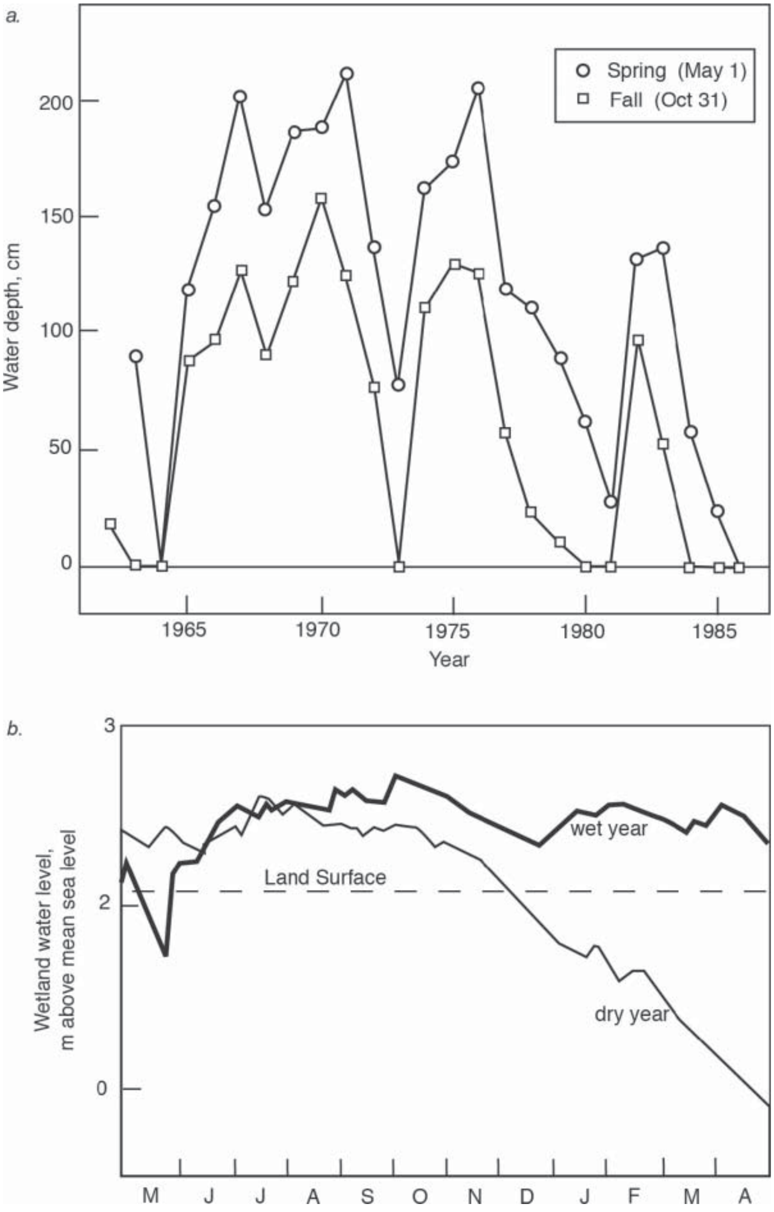

Figure 4.3 Year-to-year fluctuations in wetland water levels in two regions: (a) spring and fall water depths for 25 years in shallow open-water wetlands in the prairie pothole region of southwestern Saskatchewan, Canada; and (b) wet and dry year hydrographs for the Big Cypress Swamp region of the Everglades, southwestern Florida. ((a) After Kantrud et al., 1989 and Millar, 1971; (b) after Freiberger, 1972 and Duever, 1988)

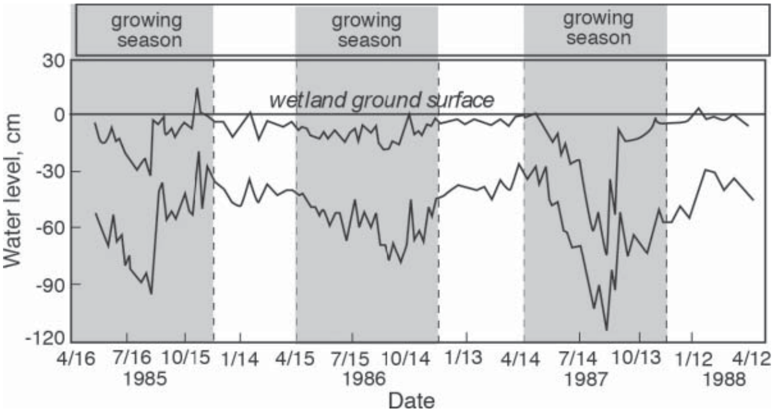

Figure 4.4 Relative water levels in two seasonally saturated red maple swamps in Rhode Island, United States, for 1985 to 1987. Growing season precipitation amounts for 1985, 1986, and 1987 were 104, 76, and 59 cm, respectively. (After Golet et al., 1993)

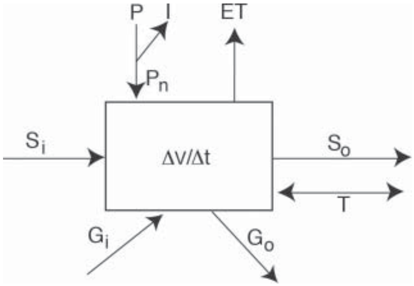

Figure 4.5 Generalized water budget for a wetland with corresponding terms as in Equation 4.1. P = precipitation; ET = evapotranspiration; I = interception; P_n = net precipitation; S_i = surface inflow; S_o = surface outflow; G_i = groundwater inflow; G_o = groundwater outflow; T = tide or seiche; $\Delta V/\Delta t$ = change in storage per unit time.

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

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

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, *d*, at any one time, can further be described as

$$d = \left(\frac{V}{A}\right) \tag{4.2}$$

where

A = wetland surface area

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/yr).

Examples of Water Budgets

Equation 4.1 and Figure 4.5 serves as useful summaries of the major hydrologic components of any wetland water budget. Examples of hydrologic budgets for several wetlands are illustrated in Figure 4.6. The terms in the equation vary in importance according to the type of wetland observed; furthermore, not all terms in the hydrologic budget apply to all wetlands (Table 4.2). There is a large variability in certain flows, particularly in surface inflows and outflows, depending on the openness of the

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 meteorological, 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

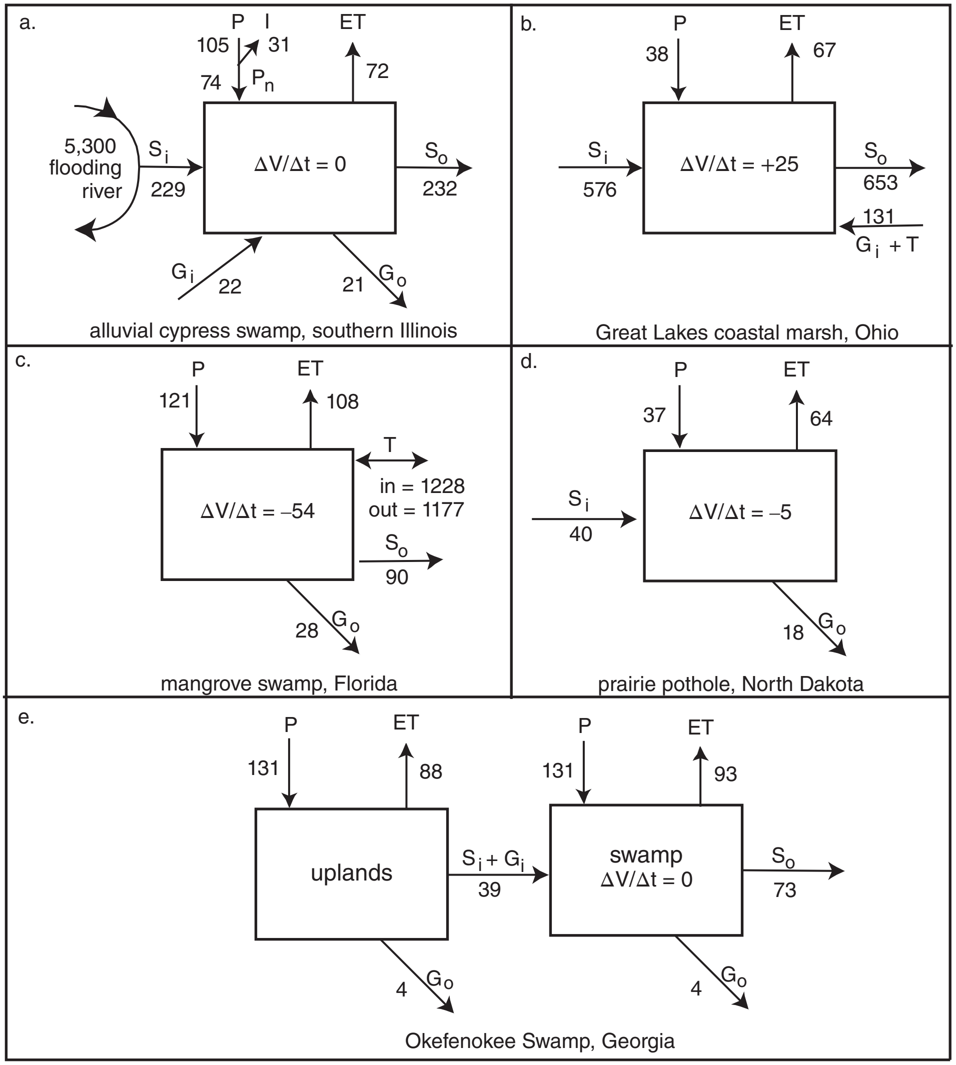

Figure 4.6 Annual water budgets for several wetlands. See Figure 4.5 for symbol definitions. All values are expressed in centimeters per year (cm/yr) except (b), which is March–September only. (Data from Pride et al., 1966; Shjeflo, 1968; Mitsch, 1979; Hemond, 1980; Gilman, 1982; Twilley, 1982; Richardson, 1983; Mitsch and Reeder, 1992; Mitsch et al., 2010)

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 northern

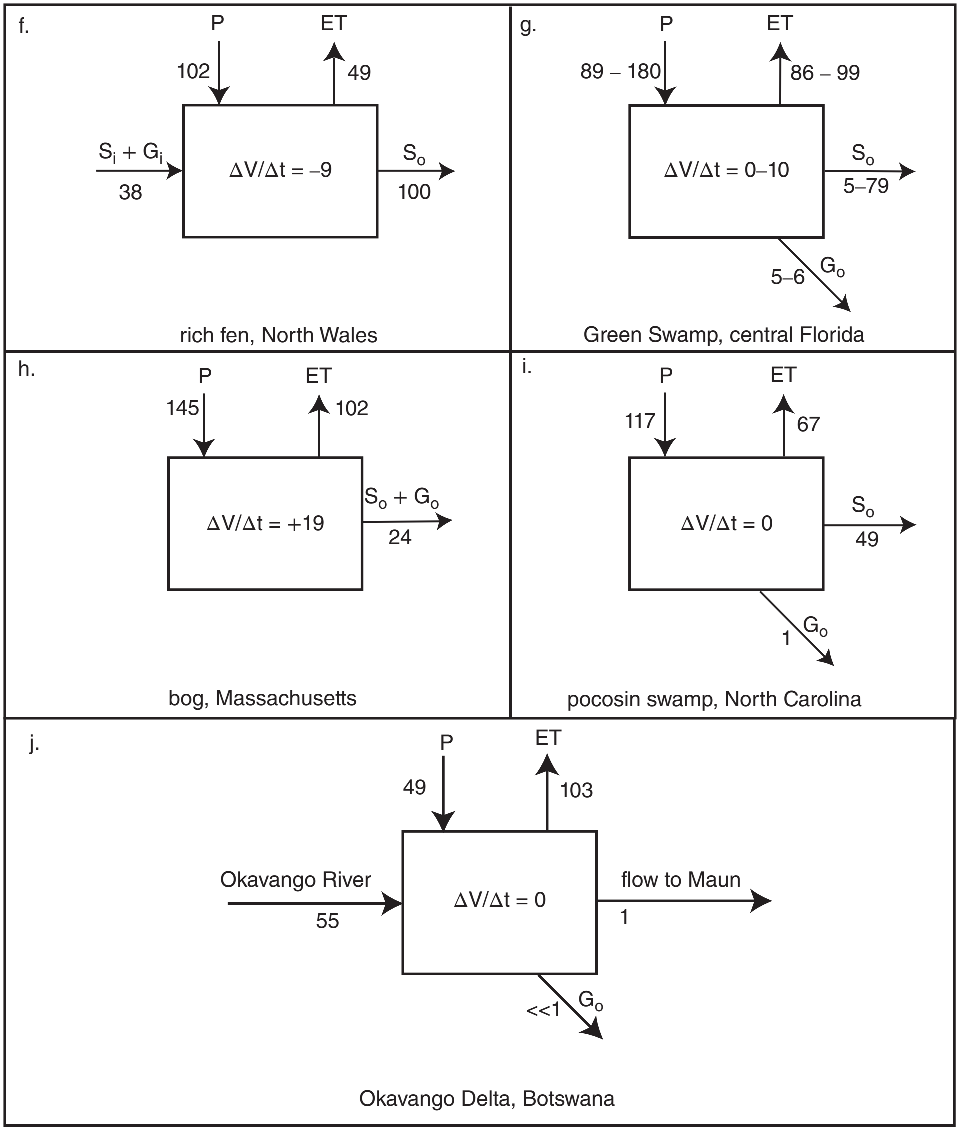

Figure 4.6 (***Continued***)

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 the 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.

The water budget for the tropical Okavango Delta in southern Africa (Botswana) has been investigated for many years. Figure 4.6j represents the average conditions for the past 36 years. The data show that the Okavango River input, when averaged over the entire delta, is about equivalent to the rainfall over this vast area. Furthermore, the budget shows that essentially all of the inputs are balanced by a loss of evapotranspiration in this semiarid climate, and only about 1 percent of the water now leaves the wetland region to the downstream village of Maun.

Residence Time—How Long Does Water Stay in a Wetland?

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:

$$t^{-1} = \left(\frac{Q_t}{V}\right) \tag{4.3}$$

where

t^{-1} = renewal rate (time^{-1})
Q_t = total inflow rate (volume/time)
V = average volume of water storage in wetland

Few measurements of renewal rates have been made in wetlands, although the renewal rate 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 because it indicates how rapidly the water in the system is replaced. The reciprocal of the renewal rate is the *turnover time* or *residence time* (t, sometimes called *detention time* by engineers for constructed wetlands), which is a measure of the average time that water remains in the wetland. The theoretical residence time, as calculated as the reciprocal of Equation 4.3, is often much longer than the actual residence time of water flowing through a wetland, because of nonuniform mixing. Because there are often parts of wetland where waters are stagnant and 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. The fate of precipitation that falls on a wetland 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

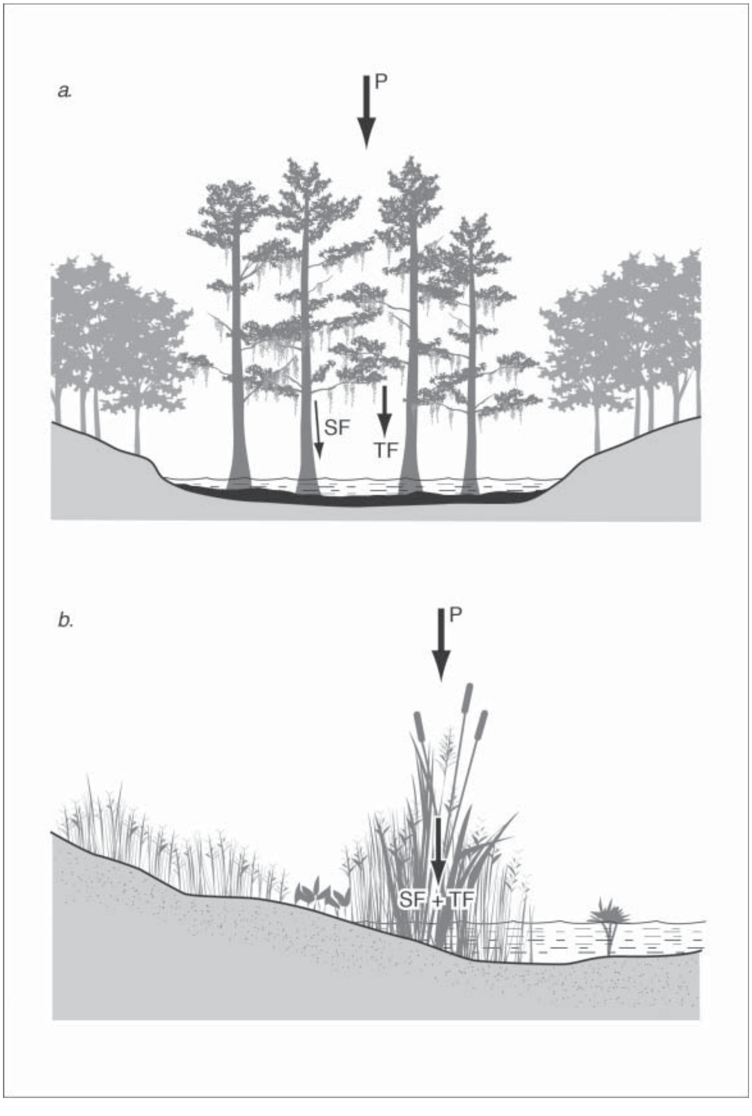

Figure 4.7 Fate of precipitation in (a) a forested wetland and (b) a marsh. *P* = precipitation; *TF* = throughfall; *SF* = stemflow.

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, such as 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 percentage of precipitation that is intercepted in forests varies between 8 and 35 percent. The water budget in Figure 4.6a, for example, illustrates that 29 percent of precipitation in a forested wetland was intercepted by a canopy dominated by the deciduous conifer *Taxodium distichum*.

Little is known about the interception of precipitation by emergent herbaceous 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 to 35 percent of gross precipitation). 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. This suggests that wetlands with either high or low interception may have similar 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:

$$P = I + TF + SF \tag{4.4}$$

where

P = total precipitation
I = interception
TF = throughfall
SF = stemflow

The total amount of precipitation that actually reaches the water’s surface or substrate of a wetland is called the net precipitation (P_{n}) and is defined as

$$P_{\text{n}} = P - I \tag{4.5}$$

Surface Flow

Watersheds and Runoff

The percentage of precipitation that becomes surface flow depends on several variables, with climate being the most important. Humid cool regions such as the Pacific Northwest, western British Columbia, and the northeastern Canadian provinces have 60 to 80 percent of precipitation converted to runoff. In the arid southwestern United States, less than 10 percent of the already low precipitation becomes runoff. This difference is related, in large part, to the higher temperatures in the arid Southwest, which translate into higher evapotranspiration rates, greater soil moisture deficits, and higher soil infiltration rates than in the Pacific Northwest. Even though runoff in arid regions is small relative to that in humid areas, it does contribute *streamflow*, which is an important part of a riparian wetland's water budget. 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 located in the upstream reaches of a watershed. These wetlands are often important water flow regulators for downstream rivers. Some wetlands have surface outflows that develop only when their water stages exceed a critical level.

Wetlands are subjected to surface inflows of several types. *Overland flow* is non-channelized sheet flow that usually occurs during and immediately following rainfall or a spring thaw, or as tides rise in coastal wetlands. A wetland influenced by a drainage basin may receive channelized streamflow during most or all of the year. Wetlands are often an integrated part of a stream or river, for example, as instream freshwater marshes or riparian bottomland forests. Wetlands that form in wide, shallow expanses of river channels or floodplains adjacent to them are greatly influenced by the seasonal streamflow patterns of the river. 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. Coastal saline and brackish wetlands are also significantly influenced by freshwater runoff and streamflow (in addition to tides) that contribute nutrients and energy to the wetland and often ameliorate the effects of soil salinity and anoxia.

Surface inflow 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:

$$S_i = R_p P A_w \tag{4.6}$$

where

S_i = direct surface runoff into 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. R_p, which represents the fraction of precipitation in the watershed that becomes direct surface runoff, ranges from 4 to 18 percent for small watersheds in the eastern North America and generally increases with latitude. Slope and type of vegetation appear to have little influence on R_p in a watershed with a mature forest cover. As the following paragraph suggests, land use and soil type can strongly influence runoff.

While Equation 4.6 predicts the volume of 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 less than 80 ha in size. The equation is given by

$$S_{i(pk)} = 0.278 C I A_w \tag{4.7}$$

where

$S_{i(pk)}$ = peak (pk) runoff into wetland ($\mathrm{m^3/s}$)
C = rational runoff coefficient (see Table 4.3)
I = rainfall intensity (mm/h)
A_w = area of watershed draining into wetland ($\mathrm{km^2}$)

The coefficient C, which ranges from 0 to 1 (Table 4.3), depends on the upstream land use. Concentrated urban areas have a coefficient ranging from 0.5 to 0.95, and

Table 4.3 Values of the rational runoff coefficient *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

rural areas have lower coefficients that greatly depend on soil type, with sandy soils lowest ($C = 0.1\text{–}0.2$) and clay soils highest ($C = 0.4\text{–}0.5$).

Channelized Streamflow

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

$$S_i \text{ or } S_o = A_x v \tag{4.8}$$

where

S_i, S_o = surface channelized flow into or out of wetland (m^3/s)
A_x = cross-sectional area of stream (m^2)
v = average velocity (m/s)

The velocity can be determined in several ways, ranging from handheld velocity meter readings taken 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 streamflow is needed, then a *rating curve* (Fig. 4.8), a plot of instantaneous streamflow (as estimated using Equation 4.8) 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 U.S. Geological Survey), then a simple measurement of the stage in the stream can be used to determine the streamflow. Because hydrographs generally assume a constant water gradient, 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.

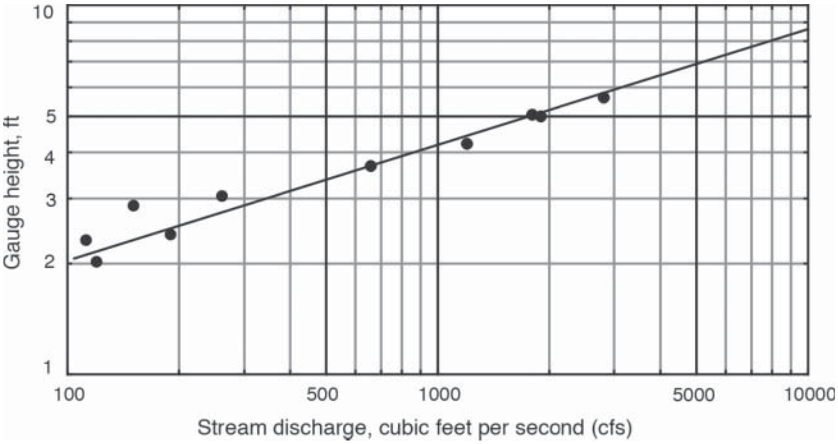

Figure 4.8 Rating curve for streamflow determination as a function of stream stage. 100 cfs = 2.832 m^3/s. (After Dunne and Leopold, 1978)

Measuring Streamflow with Weirs

When a weir or other control structure is used at the outflow of a wetland (Fig. 4.9), the outflow of a wetland can be estimated to be a function of the water level in the wetland itself according to the equation:

$$S_o = xL^y \tag{4.9}$$

where

S_o = surface outflow
L = wetland water level above a control structure crest (level at which flow just begins)
x, y = calibration coefficients

Figure 4.9 Control structures such as the V-notched weir shown here can be used for measuring surface water flow in small streams into or out of wetlands. (Photo by W. J. Mitsch)

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 4.9 can be obtained from water measurement manuals (e.g., U.S. Department of Interior, 2001). Care should be taken to calibrate standard weir equations with actual measurements of streamflow and water level.

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* often can be used if the slope of the stream and a description of the surface roughness are known:

$$S_i \text{ or } S_o = \frac{A_x R^{2/3} s^{0.5}}{n} \tag{4.10}$$

where

n = roughness coefficient (Manning coefficient; see Table 4.4)
R = hydraulic radius (m) (cross-sectional area divided by the wetted perimeter; this is an estimate of the relative portion of the stream cross section and hence flow volume, in contact with the streambed)
s = channel slope (dimensionless)

The equation states that flow is proportional to stream cross-section, as modified by the roughness of the streambed and the proportion of flow in contact with that bed. Although the potential exists for their use in wetland studies, the roughness coefficients given in Table 4.4 and the Manning equation (Eq. 4.10) have not been used very often. The relationship is particularly useful for estimating streamflow where velocities are too slow to measure directly and to estimate flood peaks from high-water marks on ungauged streams. These circumstances are common in wetland studies.

Floods and Riparian Wetlands

A special case of surface flow occurs in wetlands that are in floodplains adjacent to rivers or streams and are occasionally flooded by those rivers or streams. These ecosystems

Table 4.4 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

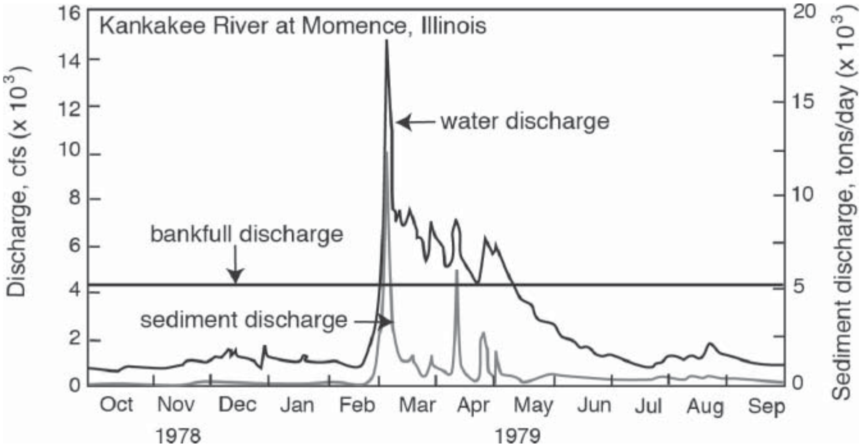

Figure 4.10 River hydrograph from northeastern Illinois, showing discharge and sediment load of the river and discharge at which a riparian wetland is flooded (bankfull discharge). 1,000 cfs = 28.32 m^3/s. (After Bhowmik et al., 1980)

are often called *riparian wetlands*. The flooding of 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. 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 riparian wetlands above bankfull discharge for several months in the spring is shown in Figure 4.10. There is a remarkable consistency in the hydrographs of rivers in the midwestern United States, in that they tend to overflow their banks (bankfull discharge) at intervals between one and two years or on the average two years out of three (see the next box).

Recurrence Interval

The *recurrence interval* is the average interval between the occurrences of floods at a given or greater stage (depth). The inverse of the recurrence interval is the average probability of flooding in any one year. Figure 4.11 suggests that streams in the midwestern and southern United States will overflow their banks onto the adjacent riparian forest with an average recurrence interval of 1.5 years (or a probability of 1/1.5, or 67 percent, of overbank flooding in any one year). Stated another way, these rivers, on average, overflow their banks in two out of every three years. Figure 4.11 also illustrates that flow that is twice that of bankfull discharge occurs at recurrence intervals of approximately five years; this flow, however, results in only a 40 percent greater river depth over bankfull depth on the floodplain. This predictable relationship suggests that in natural stream systems, the size of a stream channel is related to the hydraulic energy that scours the streambed.

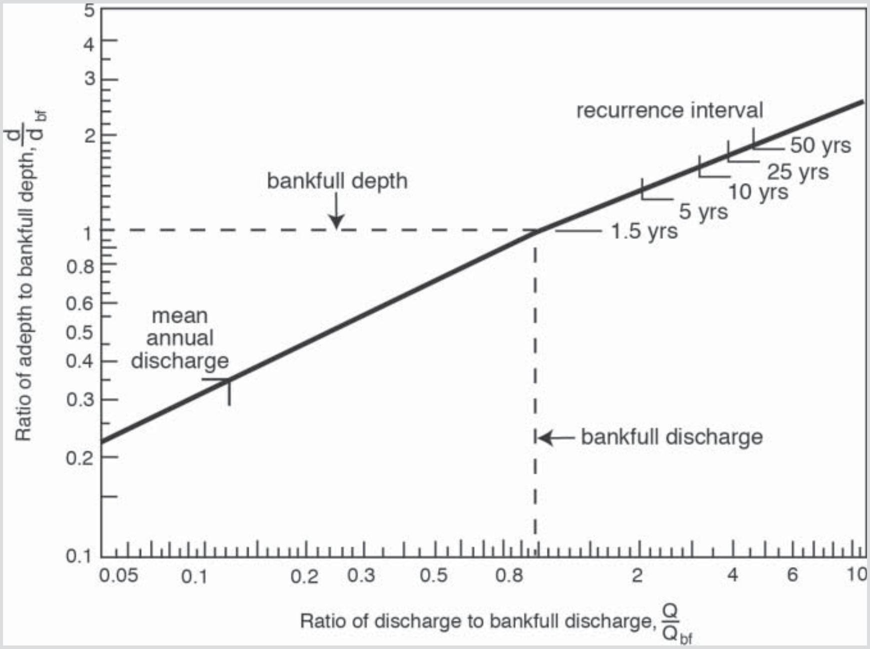

Figure 4.11 Relationships among streamflow (discharge), stream depth, and recurrence interval for streams and rivers in the midwestern and southern United States. Q = stream discharge; Q_{df} = bankfull discharge; d = stream depth; d_{df} = bankfull depth (depth of river with floodplain is initially flooded). (After Leopold et al., 1964)

Groundwater

Recharge and Discharge Wetlands

Groundwater can heavily influence some wetlands, whereas in others it may have hardly any effect at all. The influence of wetland recharge and discharge on groundwater resources has often 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. Groundwater inflow results 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 from a wetland, perspective). Wetlands can intercept the water table in such a way that they have only inflows and

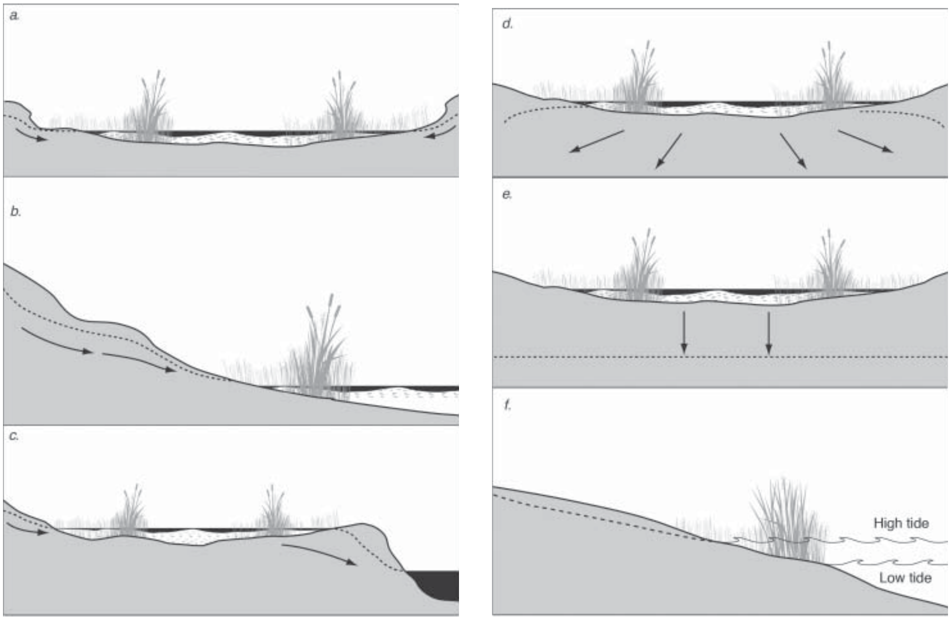

Figure 4.12 Possible discharge–recharge interchanges between wetlands and groundwater systems including (a) marsh as a depression receiving groundwater flow (discharge wetland); (b) groundwater spring or seep wetland or groundwater slope wetland at the base of a steep slope; (c) floodplain wetland fed by groundwater; (d) marsh as a recharge wetland adding water to groundwater; (e) perched wetland or surface water depression wetland; (f) groundwater flow through a tidal wetland. Dashed lines indicate groundwater level.

no outflows, as shown for a prairie marsh in Figure 4.12a. Another type of discharge wetland, called a *spring* or *seep* wetland, is often found at the base of steep slopes where the groundwater surface intersects the land surface (Fig. 4.12b). This type of wetland can be an isolated low point in the landscape; more often, it discharges excess water downstream as surface water or as 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*, loses water only through infiltration into the ground and through evapotranspiration. Tidally influenced wetlands often have significant groundwater inflows that can influence 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 little influenced by groundwater inflows. Because wetlands often occur where soils have poor permeability, the major source of water can be restricted to surface water runoff, with losses occurring through evapotranspiration and other outflows. This type of wetland often has fluctuating hydroperiods and intermittent flooding (e.g., prairie potholes [Fig. 4.12e] and vernal pools [Fig. 4.12d], with standing water dependent on seasonal precipitation and surface inflows. If, however, such a wetland were to be influenced by groundwater, its water level would be better buffered against dramatic seasonal changes (see Fig. 4.12a, c).

Nomenclature for the four types of groundwater hydrologic settings for freshwater wetlands are illustrated in Figure 4.13 and summarized here:

1. *Surface water depression wetland* (Fig. 4.13a). This type of wetland is dominated by surface runoff and precipitation, with little groundwater outflow due to a layer of low-permeability soils. This is similar to the perched wetland type described in Figure 4.12e, where the wetland is separated from the water table by an unsaturated zone.
2. *Surface water slope wetland* (Fig. 4.13b). This type of wetland is generally found in alluvial soil adjacent to a lake or stream and is fed, to some degree, by precipitation and surface runoff but, more important, by overbank

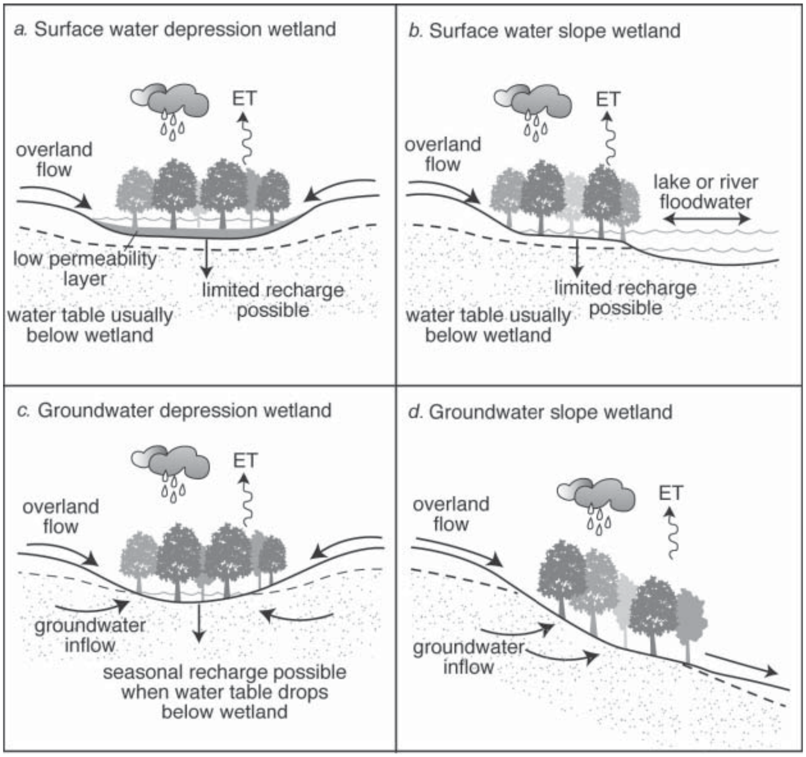

Figure 4.13 Novitski groundwater flow patterns for wetlands: (a) surface water depression, (b) surface water slope, (c) groundwater depression, and (d) groundwater slope. Dashed lines indicate groundwater level. (After Golet et al., 1993)

flooding from the adjacent stream, river, or lake. Hydroperiods of these wetlands match the seasonal patterns of the adjacent bodies of water, with relatively rapid wetting and drying. Some groundwater recharge is possible, but that groundwater soon discharges back to the stream, river, or lake.

3. *Groundwater depression wetland* (Fig. 4.13c). This is the groundwater discharge wetland described previously (Fig. 4.12a), where the wetland is in a depression low enough to intercept the local groundwater table. These kinds of wetlands can occur in coarse-textured glaciofluvial deposits, where the interchange between groundwater and surface water is enhanced by relatively coarse soil material. Water-level fluctuations in these types of wetlands are less dramatic than fluctuations in surface flow wetlands because of the relative stability of the groundwater levels.
4. *Groundwater slope wetland* (Fig. 4.13d). Wetlands often develop on slopes or hillsides where groundwater discharges to the surface as springs and seeps. Groundwater flow into these wetlands can be continuous or seasonal, depending on the local geohydrology and on the evapotranspiration rates of the wetland and adjacent uplands.

Darcy's Law

Darcy's law, an equation familiar to groundwater hydrologists, often describes the flow of groundwater into and out of a wetland. This law states that the flow of groundwater is proportional to (1) the slope of the piezometric surface (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

$$G = kA_x s \tag{4.11}$$

where

G = flow rate of groundwater (volume per unit time)
k = hydraulic conductivity or permeability (length per unit time)
A_x = 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 poor understanding of groundwater hydraulics in wetlands, particularly in those that have organic soils. The hydraulic conductivity of both organic and inorganic wetland soils is discussed in more detail in Chapter 5: "Wetland Soils."

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 evapotranspiration 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*:

$$E = cf(u)(e_w - e_a) \tag{4.12}$$

where

E = rate of evaporation
c = mass transfer coefficient
$f(u)$ = function of wind speed, 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 the same meteorological conditions, such as solar radiation or surface temperature, that increase the value of the vapor pressure at the evaporating surface and 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 in plants through the closing of leaf stomata despite adequate moisture during periods of stress such as anoxia.

Direct Measurement of Wetland Evapotranspiration

Several direct measurement techniques can be used in wetlands to determine evapotranspiration. The classical reference method is the measurement of evaporation from a water-filled pan, usually by measuring the weight loss, by measuring the volume required to replace lost water over a period of time, or by measuring the drop in water level. This is generally considered a measurement of potential evaporation, since the evaporating surface is saturated. The method is tedious and the results often poorly correlated with actual evaporation from vegetated surfaces, because the transpiration, unsaturated soils, winds, and shading effects of the plant canopy all influence the rate, often in unknown ways. However, pan evaporation provides a reference evaporation rate for comparison with other techniques. Furthermore, because wetland soils tend to be saturated most of the time, the pan method may be more accurate for wetlands than for terrestrial environments.

Wetland evapotranspiration can also be estimated by measuring the change in water level of the water in the wetland itself. This method, illustrated in Figure 4.14, can be calculated as follows:

$$ET = S_y(24h \pm s) \tag{4.13}$$

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

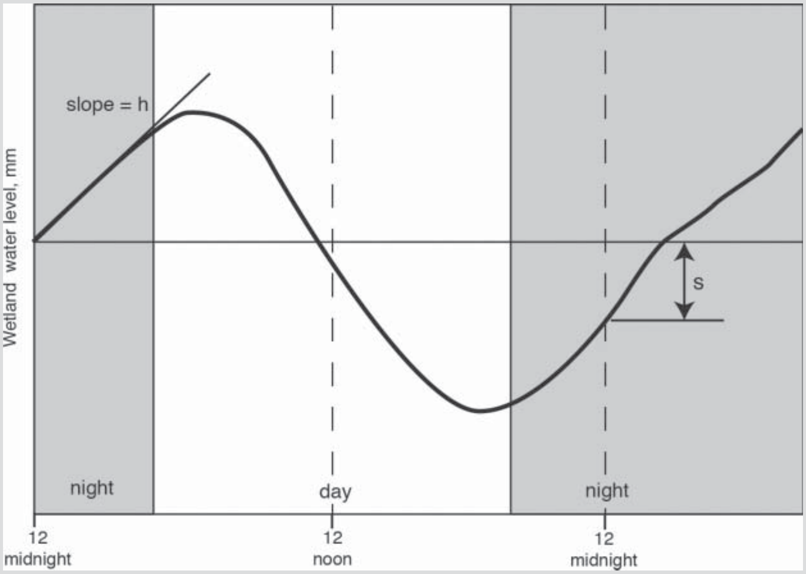

Figure 4.14 Diurnal water fluctuation in some wetlands can be used to estimate evapotranspiration as in Equation 4.13.

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.

Empirical Estimates of Wetland Evapotranspiration

Thornthwaite Equation

Evapotranspiration can be determined with any number of empirical equations that use easily measured meteorological variables. One of the most frequently used empirical

Mitsch, William J., and James G. Gosselink. <i>Wetlands</i>, John Wiley & Sons, Incorporated, 2015. ProQuest Ebook Central,
http://ebookcentral.proquest.com/lib/bu/detail.action?docID=1895927.

equations for evapotranspiration from terrestrial ecosystems, which has been applied with some success to wetlands, is the *Thornthwaite equation* for potential evapotranspiration:

$$ET_i = 16(10T_i/I)^a \tag{4.14}$$

where

ET_i = potential evapotranspiration for month i (mm/month)
T_i = mean monthly temperature (°C)
$I = \text{local heat index} \sum_{i=1}^{12} (T_i/5)^{1.514}$
$a = (0.675 \times I^3 - 77.1 \times I^2 + 17{,}920 \times I + 492{,}390) \times 10^{-6}$

Penman Equation

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

$$ET = \left(\frac{\Delta H + 0.27E_a}{\Delta + 0.27}\right) \tag{4.15}$$

where

ET = evapotranspiration (mm/day)
Δ = slope of curve of saturation vapor pressure versus mean air temperature (mmHg/°C)
H = net radiation (cal/cm^2-day)
$= R_t (1 - a) - Rb$
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
$= 0.35\ (0.5 + 0.00625u)(e_w - e_a)$
u = wind speed 2m above ground (km/day)
e_w = saturation vapor pressure of water surface at mean air temperature (mmHg)
e_a = vapor pressure in surrounding air (mmHg)

The Penman equation was compared with the pan evaporation (multiplied by a factor of 0.8) and other methods at natural enriched fens in Michigan and constructed wetlands in Nevada. The Penman equation, like the Thornthwaite equation, generally underpredicted evapotranspiration from the humid Michigan wetland but agreed within a few percentage points with other measurement techniques for the arid Nevada wetlands.

Because of the many meteorological and biological factors that affect evapotranspiration, none of the many empirical relationships is entirely satisfactory for estimating wetland evapotranspiration. Several comparisons of approaches to measuring evapotranspiration have been attempted (Lott and Hunt, 2001; Rosenberry et al., 2004). One finding has been that empirical estimates of potential evapotranspiration (PET), such as those determined from the Penman equation, generally underestimate true wetland evapotranspiration during the growing season, possibly due to limitation of the equation for describing surface roughness. A comparison of an energy budget method for estimating evapotranspiration at a wetland in North Dakota with 12 empirical evapotranspiration equations found that most of the empirical methods gave reasonable approximations of evapotranspiration (Rosenberry et al., 2004).

The Thornthwaite equation, the simplest method investigated as it only requires air temperature, worked relatively well and may provide the most accurate measurement per instrument cost. It remains one of the more commonly uses empirical equations for estimating wetland evapotranspiration, but it only gives monthly estimates, not daily or hourly rates.

Effects of Vegetation on Wetland Evapotranspiration

A question about evapotranspiration from wetlands that does not elicit a uniform answer in the literature is: "Does the presence of wetland vegetation increase or decrease the loss of water compared to that which would occur from an open body of 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. 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) reported 10 percent lower evapotranspiration from vegetated prairie potholes than from nonvegetated potholes in North Dakota. Hall et al. (1972) 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. The general unimportance of plant 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.

In some cases, the type of vegetation in the wetland does matter. When trees are removed from some forested swamps where the soil is hydric but there is little surface flooding, standing water may return and, with it, herbaceous marsh vegetation. This resets a hydrologic succession; woody plants are able to reinvade the marsh during dry years and reestablish the site back to a forested wetland.

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 of the United States are shown in Figure 4.15a. 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. 4.15b). 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 m along the Texas Gulf Coast to several meters in the Bay of Fundy in Canada. Tidal amplitude can actually increase as one progresses inland in some funnel-shaped estuaries. 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 creeks 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.

Seiches

While inland wetlands are nontidal by definition, periodic water-level fluctuations in wetlands adjacent to large freshwater lakes do occur as a result of short-term

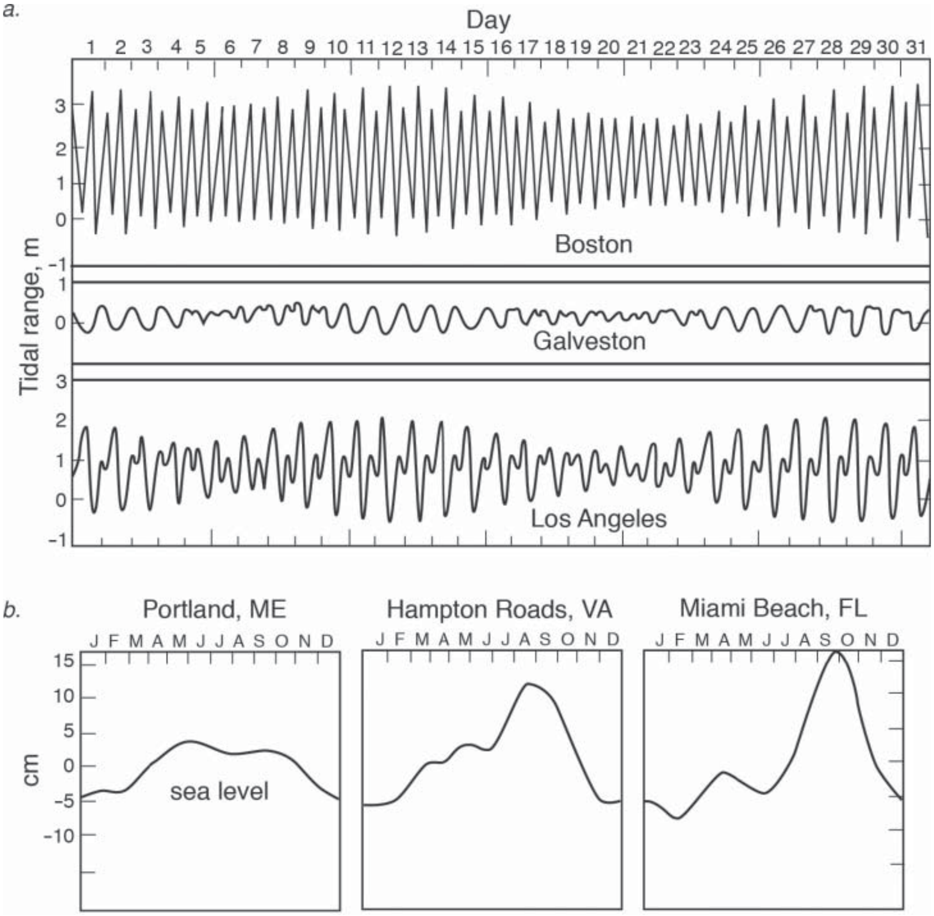

Figure 4.15 Patterns of tides: (a) daily tides for a month and (b) seasonal changes in mean monthly sea level for several locations in North America. (After Emery and Uchupi, 1972)

water-level seiches, or "wind tides." These are a common occurrence in wetlands adjacent to large lakes, such as the Laurentian Great Lakes in the United States and Canada (Fig. 4.16). When wind has a persistent direction, particularly in a long fetch across a lake, water "piles up" on the downwind side of the lake, causing high-water events for wetlands in that location. When the wind shifts or dies down, the high water is released and flows to the opposite shoreline, causing a secondary wind-relaxation seiche there and lower-than-normal water in the original high-water location.

Effects of Hydrology on Wetland Function

The effects of hydrology on wetland structure and function can be described with a complicated series of cause-and-effect relationships. A conceptual model of the general

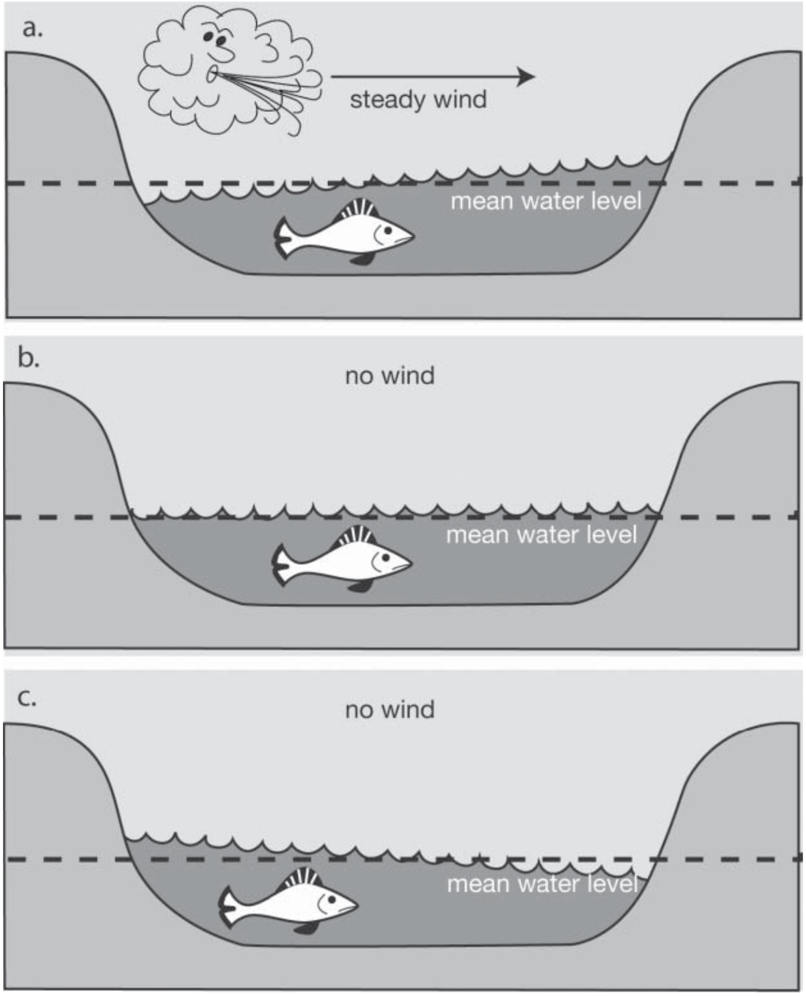

Figure 4.16 Concept of a seiche: a wind-relaxation seiche caused by (a) a steady wind that (b) relaxes or shifts directions from initial wind set and (c) results in an oppositely directed tilt; (d) water levels in Ohio (Toledo and Cleveland) and New York (Buffalo) coastlines of Lake Erie during an April 1979 storm and subsequent wind-relaxation seiche. (After Korgen, 1995)

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, influence the biotic components of the ecosystem. The biotic components then have a feedback effect on hydrology. Four principles underscoring the importance of hydrology in wetlands can be elucidated from studies that have been conducted to date. These principles are described next.

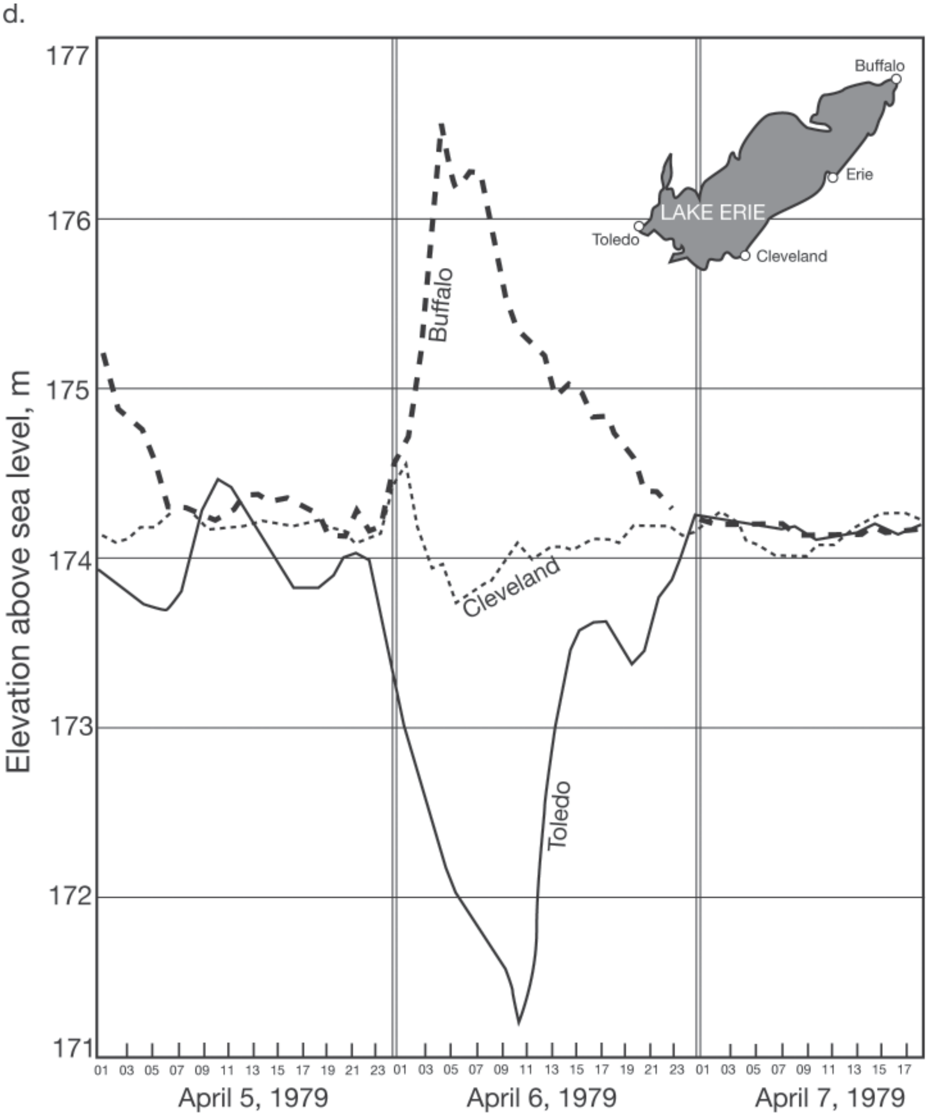

Figure 4.16 (***Continued***)

1. Hydrology leads to a unique vegetation composition but can limit or enhance species richness.

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 and to exclude flood-intolerant species. Of the thousands of vascular plants on Earth, relatively few have adapted to waterlogged soils. Although it is difficult to generalize, many wetlands that sustain long flooding durations have lower species richness in vegetation than do less frequently flooded or pulsing 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.

In general, species richness, at least in the vegetation community, increases as flow-through or pulsing hydrology increases. 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. When rivers flood riparian wetlands or when tides rise and fall in coastal marshes, erosion, scouring, and sediment deposition sometimes create niches that allow diverse habitats to develop. However, flowing water can also create a relatively uniform surface that might allow monospecific stands of *Typha* or *Phragmites* to dominate a freshwater marsh or *Spartina* to dominate a coastal marsh. Keddy (1992) likened 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.

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.

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. Some 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.

This relationship between hydrology and ecosystem primary productivity has been investigated most extensively for forested wetlands. Figure 4.17 shows a set of similar typical "Shelford-type" limitation curves that have been suggested in separate studies to explain the importance of hydrology on forested wetland productivity. All of the curves in Figure 4.17 suggest that the highest productivity occurs in systems that are neither very wet nor too dry but that have either average hydrologic conditions or seasonal hydrologic pulsing.

The subsidy-stress model of H. T. Odum (1971) and E. P. Odum (1979), later refined as the *pulse stability* concept by all three Odums (W. E. Odum et al., 1995), includes concepts that potentially apply well to the effects of hydrology on

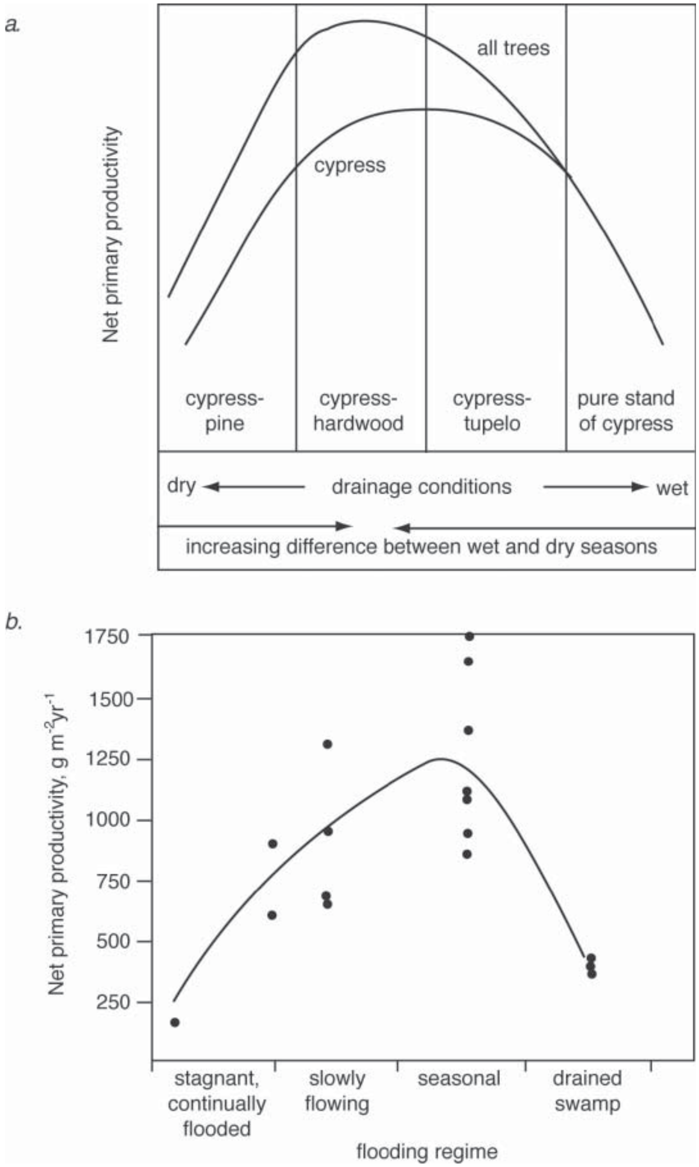

Figure 4.17 Relationships between swamp productivity and hydrologic conditions: (a) for cypress (*Taxodium*) swamps in north-central Florida, (b) between flooding regime and net primary productivity of Louisiana swamps, and (c) between radial growth of red maple (*Acer rubrum*) and annual water level for six Rhode Island red maple swamps over six years. ((a) after Mitsch and Ewel, 1979; (b) after Conner and Day, 1982; (c) after Golet et al., 1993)

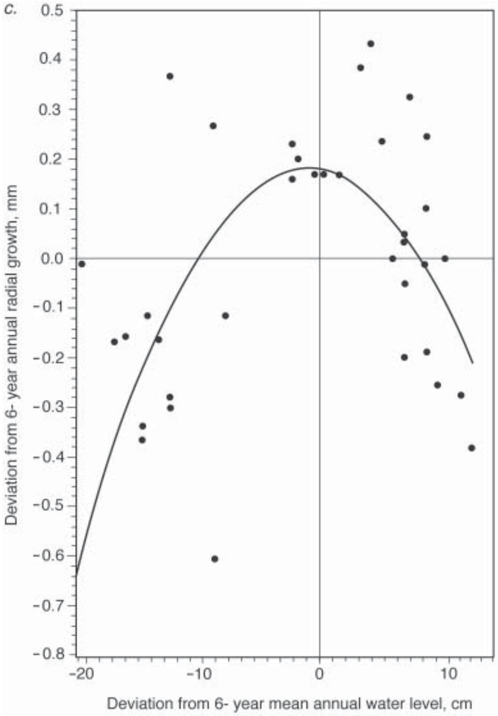

Figure 4.17 (***Continued***)

wetland productivity. Seasonal pulsing of floodwater can be both a subsidy and a stress, whether the wetland is a salt marsh or mangrove swamp subject to twice-per-day flooding or a riparian wetland subject to seasonal river pulses. Pulsing is frequent in nature, and ecosystems such as bottomland forests and salt marshes appear to be well adapted to taking advantage of this subsidy. Despite this clear theoretical basis for understanding the effects of hydrology on productivity, it has been difficult to confirm or deny these theories in practice.

The model shown in Figure 4.18 may explain the difficulty in ascribing a direct relationship between vascular plant productivity and hydrologic conditions. While flood intensity increases available moisture and nutrients, longer flood durations increase stresses caused by an anaerobic root zone and can actually decrease the length of the growing season. In effect, "subsidies and stresses may occur simultaneously and cancel one another" (Megonigal et al., 1997). In this Mitsch-Rust model, flood intensity and duration affect moisture, available nutrients, anaerobiosis, and even length of growing season in a complex and nonlinear "push-pull" arrangement.

The influence of hydrologic conditions on freshwater marsh productivity is less certain. If peak biomass or similar measures are used as indicators of marsh

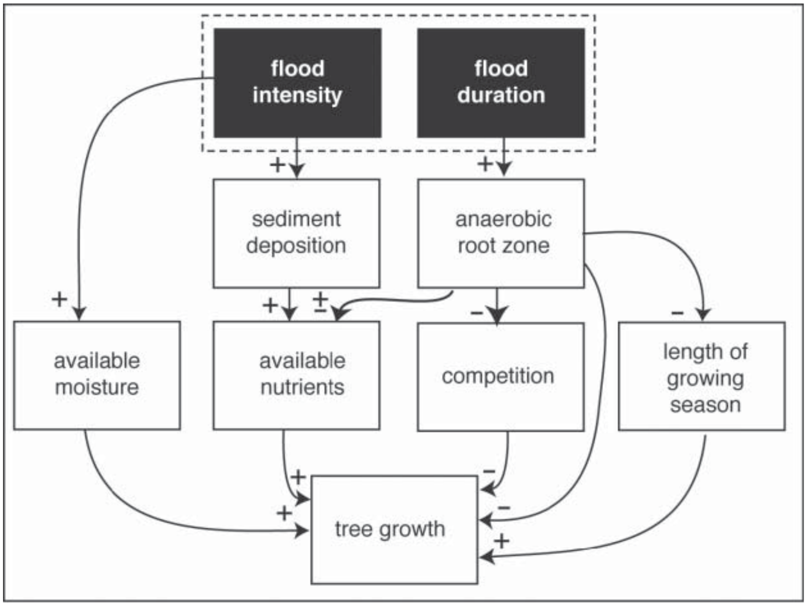

Figure 4.18 Causal model that describes the major causes for increases and decreases in individual tree growth in riparian floodplain forests. Plus (+) sign indicates a positive effect; minus sign (−) indicates a negative effect. (After Mitsch and Rust, 1984)

productivity, some studies have shown the classical stimulation of vegetation along the water's edge, whereas other studies have indicated a higher macrophyte productivity in sheltered, nonflowing marshes than in wetlands that are open to flowing conditions or coastal influences. For example, consistently higher macrophyte biomass was found in wetlands isolated from surface fluxes with artificial dikes than in wetlands that were open to coastal fluxes along Lake Erie. 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.

Similar results were found in a hydrologic pulsing experiment in central Ohio, where simulated river floods caused a decrease in macrophyte and water column primary productivity but led to changes in greenhouse gas emissions because of a flushing effect (Mitsch et al., 2005; Altor and Mitsch, 2006, 2008; Hernandez and Mitsch, 2006, 2007; Tuttle et al., 2008; Fig. 4.19a) Conversely, an earlier study in Illinois of the influence of flow-through conditions on water column primary productivity of constructed marshes found that, after two years of experimentation, water column (phytoplankton and submerged aquatics) productivity was higher in high-flow wetlands compared to low-flow wetlands (Fig. 4.19b). While macrophyte productivity may take many years to respond to the difference

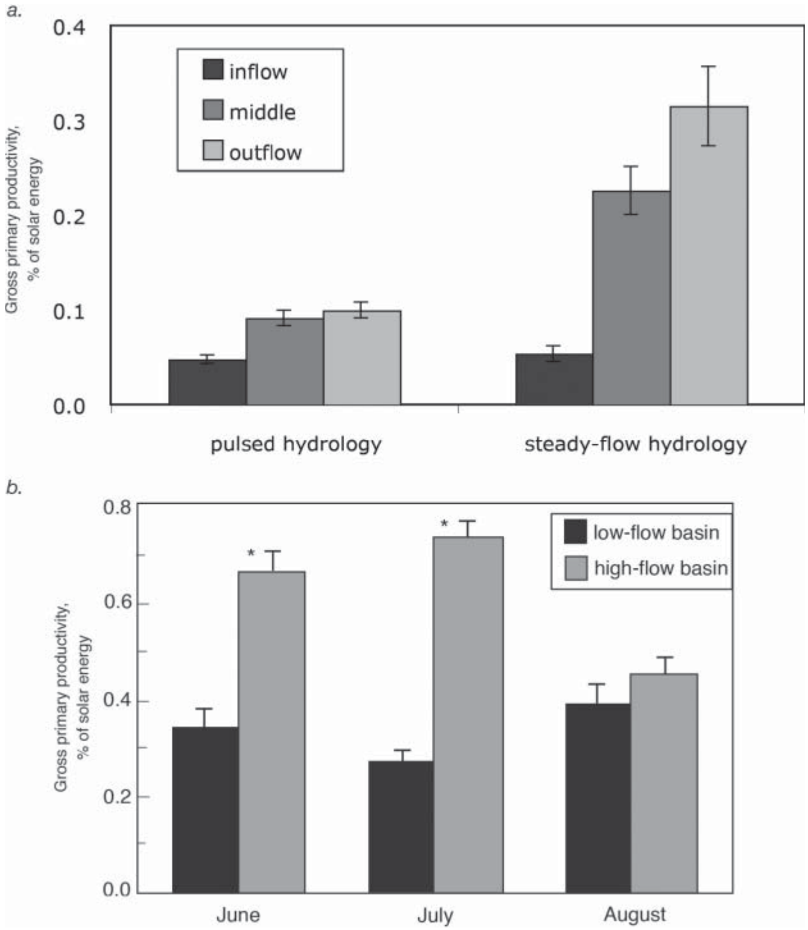

Figure 4.19 Aquatic primary productivity in freshwater marshes as a function of hydrologic conditions: (a) pulsed flooding versus steady-flow hydrology at the Olentangy River Wetland Research Park, central Ohio; (b) high-flow and low-flow conditions at the Des Plaines Wetland Demonstration Project, northeastern Illinois. * indicates statistical differences (0.05_ between low-flow and high-flow conditions. ((a) After Tuttle et al., 2008; (b) after Cronk and Mitsch, 1994)

in hydrology, water column productivity, which is often caused by attached and planktonic algae, responds relatively quickly to changing hydrologic conditions.

Coastal wetlands subject to frequent tidal action are generally more productive than those that are only occasionally inundated. A comparison of several Atlantic Coast salt marshes, for example, showed a direct relationship between tidal range (as a measure of water flux) and end-of-season peak biomass of *Spartina alterniflora* (Fig. 4.20). Apparently, vigorous tides increase the nutrient subsidy and cause a flushing of toxic materials, such as salt. Freshwater tidal

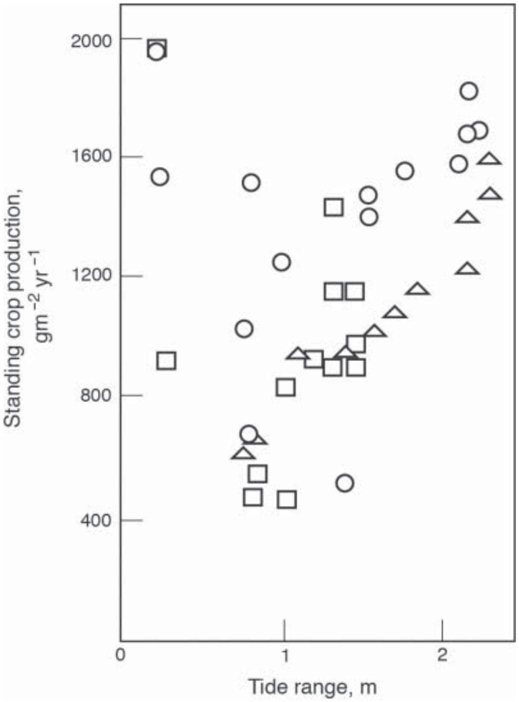

Figure 4.20 Production of *Spartina alterniflora* versus mean tidal range for several Atlantic Coast salt marshes. Different symbols indicate different data sources. (After Steever et al., 1976)

wetlands are 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.

3. Accumulation of organic material in wetlands is controlled by hydrology through its influence on primary productivity, decomposition, and export of particulate organic matter.

Wetlands can accumulate excess organic matter as a result of either increased primary productivity (as described previously) 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 previously. Probably the lack of agreement among the many studies published on the subject results from the complexity of the decomposition process. In general, decomposition of organic detritus requires electron donors (usually oxygen, but alternate chemicals such as sulfate or nitrate may be effective under anoxic conditions), moisture, inorganic nutrients, and microorganisms capable of metabolizing in the specific environment concerned. The observed rate of organic decomposition is also influenced by the ambient temperature and by the activity of macrodetritivores that shred the plant remains and/or repackage it as bacterially inoculated fecal pellets. Hydrology modifies many of these variables; for example, moisture depends on the flooding regime, flowing water carries oxygen and nutrients, while in stagnant water oxygen is rapidly depleted and nutrients are transformed to more or less available forms. Given this complexity, it is not surprising that the results of short-term *in situ* decomposition studies often disagree.

The importance of hydrology for organic carbon 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 macrodetritus such as whole trees. There is also considerable evidence that watersheds that drain wetland regions export more organic material but retain more nutrients than do watersheds that do not have wetlands (Fig. 4.21). For example, the slope of the line in Figure 4.21 for wetland-dominated watersheds is much steeper than that for upland watersheds,

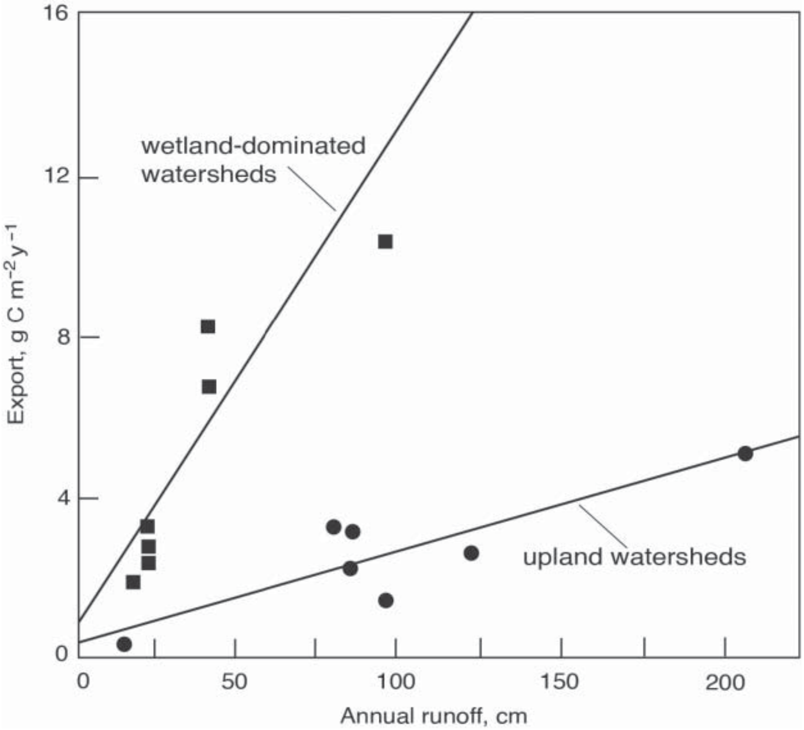

Figure 4.21 Organic carbon export from wetland-dominated watersheds compared with non-wetland watersheds. (From Mulholland and Kuenzler, 1979)

indicating a much greater organic carbon concentration in runoff as well as greater export for a given runoff from the wetland-dominated watersheds. Salt marshes and mangrove swamps are also considered major exporters of their productivity by most, but the generality of this concept is not fully accepted by coastal ecologists. Hydrologically isolated wetlands, such as northern peatlands, have much lower organic export.

4. Nutrient cycling and nutrient availability are both significantly influenced by hydrologic conditions.

Nutrients are carried into wetlands by the hydrologic inputs of precipitation, river flooding, tides, and surface and groundwater inflows. Outflows of nutrients are controlled primarily by the outflow of water. 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, on the availability of nutrients to vegetation, and on loss from wetland soils of nutrients that have gaseous forms. Thus, nitrogen availability and loss are 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 dinitrogen gas to the atmosphere. Furthermore, ammonium nitrogen is usually the form of nitrogen most available to plants in wetland soils, because the anaerobic environment favors the reduced ionic form over the nitrate common in agricultural soils.

Flooding of wetland soil, by altering both the pH and the redox potential of the soil, influences the availability of other nutrients. The pH of both acid and alkaline soils tends to converge on a pH of 7 when they are flooded. The redox potential, a measure of the intensity 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, partly because of 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.

Techniques for Wetland Hydrology Studies

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 great

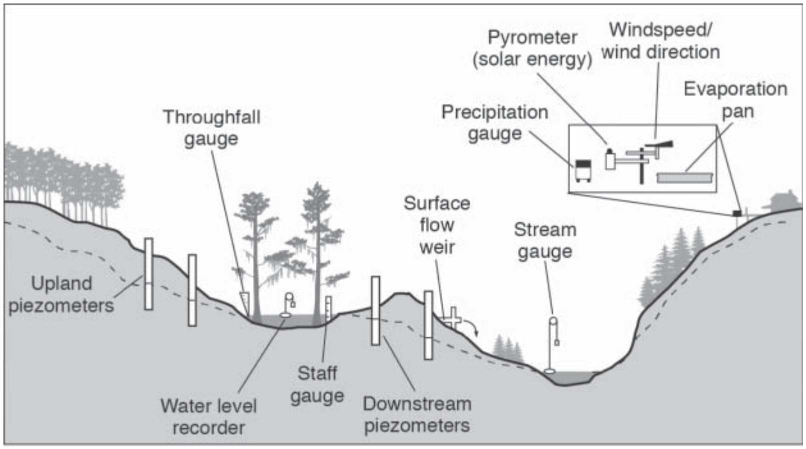

Figure 4.22 Placement of hydrology instruments in the landscape to estimate a water budget for a floodplain wetland.

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 4.22. Water levels can be recorded continuously with water-level recorders or data loggers 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. 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 several empirical relationships, such as the Thornthwaite equation, use meteorological variables. Evaporation pans can also be used to estimate total evapotranspiration from wetlands, although pan coefficients are highly variable. Evapotranspiration of continuously flooded nontidal wetlands can also be determined by monitoring the diurnal water-level fluctuation.

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 net precipitation has been subtracted. Weirs can be constructed on more permanent streams to monitor surface water inputs and outputs.

Groundwater flows are usually the most difficult and most costly hydrologic flows to measure accurately. In some cases, clusters of shallow monitoring wells, placed around a wetland, will help indicate the direction of groundwater flow and the slope of the water or hydraulic gradient as required in Equation 4.11. The wells are called *piezometers* when they are only partially screened, and thus measure the piezometric head of an isolated part of the groundwater rather than being screened through the entire length of the well and thus measuring the surface water aquifer. Piezometers can be installed by professional well-drilling companies or, for low-budget installations, generally can be installed with augers or as well points. Estimates of permeability or hydraulic conductivity are then required to quantify the flows. Permeability can be estimated through *in situ* pump tests using the wells or through laboratory analysis of intact soil cores. The variability of results among different hydraulic conductivity measuring techniques suggests that caution should be used in taking these numbers.

If a wetland is a perched or a recharge wetland, seepage can be estimated either through a water budget approach (e.g., subtracting evapotranspiration losses from water-level decreases when there are no other inflows or outflows) or by using half-barrel seepage meters. Other methods available to measure groundwater flows in wetlands include the use of stable isotopes, generally $^{18}O/^{16}O$ or $^{2}H/^{1}H$, because of the propensity of the lighter isotope in each case to evaporate more readily, allowing water to be "tagged" according to its source (Hunt et al., 1996). Groundwater flow models have also been used to estimate the flow of groundwater into and out of wetlands with some success (Hunt et al., 1996; Koreny et al., 1999).

The uncertainty in the scientific literature concerning many wetland processes (e.g., the rates of organic matter decomposition discussed earlier) is often closely related to unquantified hydrologic parameters. Thus, careful attention to quantification of pertinent hydrologic parameters in wetland research studies is virtually certain to improve our understanding of the ecological processes that control wetlands.

Recommended Readings

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