2

WETLAND GEOMORPHOLOGY, SOILS, AND FORMATIVE PROCESSES

Randy K. Kolka and James A. Thompson

The soil is where many of the hydrologic and biogeochemical processes that influence wetland function and ecology occur. A complete understanding of wetland formation, wetland ecology, and wetland management requires a basic understanding of soils, including soil properties, soil processes, and soil variability. In this chapter, we will discuss how soils and landscapes influence the local hydrologic cycle to lead to the development of wetland hydrology. We then will examine some fundamental soil properties and how they lead to and respond to the development of wetland hydrology. Finally, we will consider specific types of wetland ecosystems and discuss their general distribution, origin, hydrology, soil, and vegetation.

WETLAND GEOMORPHOLOGY AND WETLAND SOILS

Landscape geomorphology influences how water moves over or through the soil, and thus hillslope hydrology and local hydrologic budgets affect soil properties and determine the formation of wetland soils. Surface topography is a particularly important factor controlling surface and subsurface water flow and accumulation. While many landscapes are complex and irregular, there exist distinct and repeating patterns of hillslope elements, which occur in most geomorphic settings. A typical hillslope profile (Fig. 2.1) can be segmented into summit, shoulder, backslope, footslope, and toeslope landscape positions. The summit is the relatively flat area at the top of the slope. The shoulder is the steeply convex portion at the top of the slope. This surface shape favors the shedding of water and relatively drier soil conditions. The backslope is

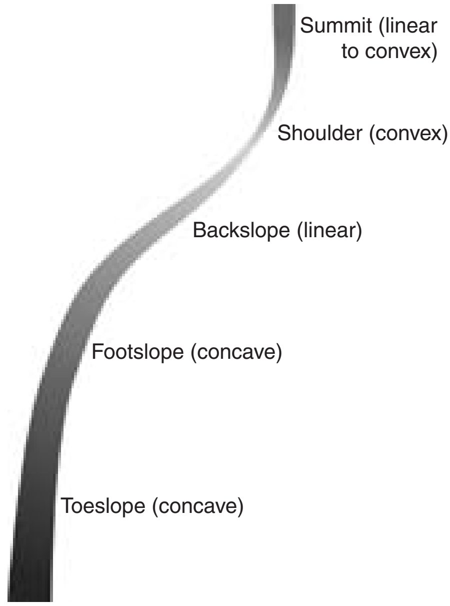

FIGURE 2.1
Typical hillslope cross section illustrating landscape positions of summit, shoulder, backslope, footslope, and toeslope.

a linear portion of the slope and is not present in all hillslopes. At the bottom of the slope are the more concave footslope and toeslope positions, with the footslope being more steeply sloping than the toeslope. On such a typical hillslope, the quantity of water stored in the soils increases with proximity to the base of the hillslope in response to the accumulation of surface and subsurface flow from upslope positions. The cross-slope geometry of the land also influences water redistribution and accumulation at the hillslope scale (Fig. 2.2). Concave contours promote convergent water flow, focusing surface and subsurface runoff to lower hillslope positions. Conversely, convex contours lead to divergent water flow. Across the landscape, we can identify various landforms that represent different combinations of profile and contour curvatures (Fig. 2.2), each of which affects the redistribution and storage of water. This, in turn, influences soil properties and wetland functions. Hillslope hydrologic processes and wetland water budgets are discussed in greater detail in Chapter 3.

SOIL PROPERTIES

Soils represent the zone of biogeochemical activity where plants, animals, and microorganisms interact with the hydrologic cycle and other elemental cycles. A typical soil contains both mineral and organic materials as well as the adjacent water-filled and air-filled pore space. The physical and chemical properties of a soil may influence the processes that lead to wetland formation and function. Furthermore, wetland formation and function may influence some of the physical and chemical properties of soils, especially soil color. Important soil physical properties include soil texture, soil structure, bulk density, porosity, and pore size distribution. These directly affect hydrologic conductivity and water storage and availability.

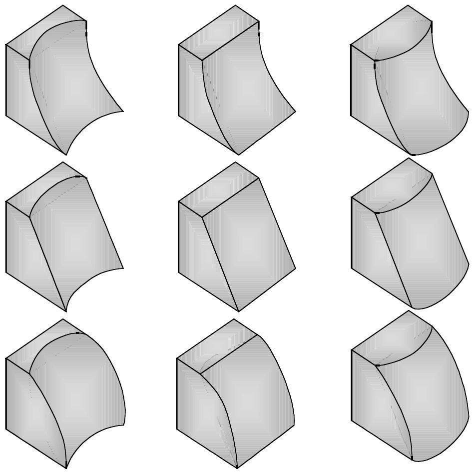

FIGURE 2.2
Diagrams illustrating concave, convex, linear, and combination contour curvatures typical of hillslopes.

Color is the most apparent soil morphological property, and it often indicates much about the composition and the hydrologic conditions of a soil. Soil scientists quantify soil color using the Munsell color system, which uses three quantities—hue, value, and chroma—to define a color. *Hue* refers to the spectral color: red (R), yellow (Y), green (G), blue (B), and purple (P) or neutral (N), which has no hue. These five principal hues (not including neutral), plus the intermediate hues, such as yellow-red (YR) or blue-green (BG), are used in the Munsell notation, with numbers placed before the hue letter(s) to designate four subdivisions within each of the ten major hues. A progression of Munsell hues from reds to yellows is: 5R-7.5R-10R-2.5YR-5YR-7.5YR-10YR-2.5Y-5Y. *Value* is a number between zero and ten that indicates the lightness or darkness of color relative to a neutral gray scale. A value of zero is pure black, and a value of ten is pure white. *Chroma* is a number that designates the purity or saturation of the color. A high chroma indicates a pure color, meaning that there is one clearly dominant hue. A low chroma indicates that the color is a mixture of more than one hue. This is often illustrated when a small child uses a set of watercolor paints and, invariably, does not rinse the brush when changing colors. The resulting dull, drab, and muted colors have low chroma. For soils, chroma can range from zero to about eight. The format for writing a Munsell color is "hue value/chroma"—such as 10YR 3/5.

Iron oxides and organic matter are the two primary coloring agents within most soils. Iron oxides give the soil a red, orange, or yellow color. Consequently, most soils are yellow-red in hue. Organic matter makes the soil brown or black, with a low value and low chroma. The majority of the soil, though, is made up of aluminosilicate minerals, which are white to gray in color. In the absence of iron oxides or organic matter, soil color is dull and grayish and has a low chroma. Such gray colors may be observed because iron oxides were never present in the soil, but more commonly, gray colors arise because iron oxides have been reduced, become soluble, and translocated within the soil, usually because of saturated and anaerobic conditions. Uniform low-chroma gray, or gley, colors are typical of prolonged saturated and anaerobic conditions in the soil. A mottled color pattern is often seen in soils that are wet for part of the year. The alternating patterns of red (high chroma) and gray (low chroma) colors indicate that some of the iron has been reduced or depleted (exposing the gray colors) and has been concentrated in the red patches.

The mineral fraction of a soil contains particles of various sizes. Clay particles are, by definition, those that are smaller than 0.002 mm in diameter. Silt particles are greater than 0.002 mm but less than 0.05 mm. The largest soil particles are sand particles, which are greater than 0.05 mm but less than 2.0 mm. Any particles greater than 2.0 mm are collectively termed *coarse fragments*. The most important aspect of soil particle size is the influence it has on surface area and pore size distribution. Clay particles have a high specific surface area, or surface area per gram of soil (up to 8,000,000 $cm^2\ g^{-1}$), whereas the larger sand particles have a low specific surface area ($<1000\ cm^2\ g^{-1}$). Most of the soil biogeochemical reactions occur at these particle surfaces, so soils with greater clay content tend to be much more reactive.

The relative proportions of these three soil particle size separates determine the texture of a soil. For convenience, soil scientists have defined 12 different soil textural classes that cover various ranges in sand, silt, and clay content (Fig. 2.3). Soil texture influences almost every other property of a soil. Additionally, soil texture is a relatively stable soil property that does not readily change over time or in response to soil management. Soils within each textural class possess many similar characteristics and can be treated and managed in the same way.

In most soils, the individual sand, silt, and clay particles are aggregated together to form secondary soil particles, or peds. The peds give the soil stability, and the spaces between the peds form the large pores that promote faster water movement, greater gas exchange, and easier root penetration. The combination of texture and structure control the bulk density, porosity, and pore size distribution of a soil. The bulk density is the mass of soil per total volume of soil, and it is inversely related to the total porosity, which is the volume of pores per total volume of soil. In general, a sandy soil has a higher bulk density and a lower porosity than a clayey soil. However, the pores within a sandy soil tend to be larger, while the pores in a clayey soil are smaller. A soil with more well-developed structure has greater total porosity, lower bulk density, and more large pores.

This internal architecture of the soil influences the water relations of the soil. For example, soils with relatively high sand content (sands, loamy sands, sandy loams) tend to have rapid infiltration and percolation rates, good aeration, and low water storage capacity. This is primarily due to the high proportion of large pores and low surface area associated with the sandy soil (Fig. 2.4a). Conversely, finer-textured soils tend to have slow rates of infiltration and percolation and poor aeration, mainly because of the lack of large pores that readily transmit water (Fig. 2.4b). However, finer-textured soils that have well-developed structure, and therefore have more large pores as created by the voids between individual peds, may also have rapid infiltration and percolation rates and good aeration (Fig. 2.4c). Clayey soils have a high water storage capacity, but many of the small pores hold water too tightly to be readily available to plants.

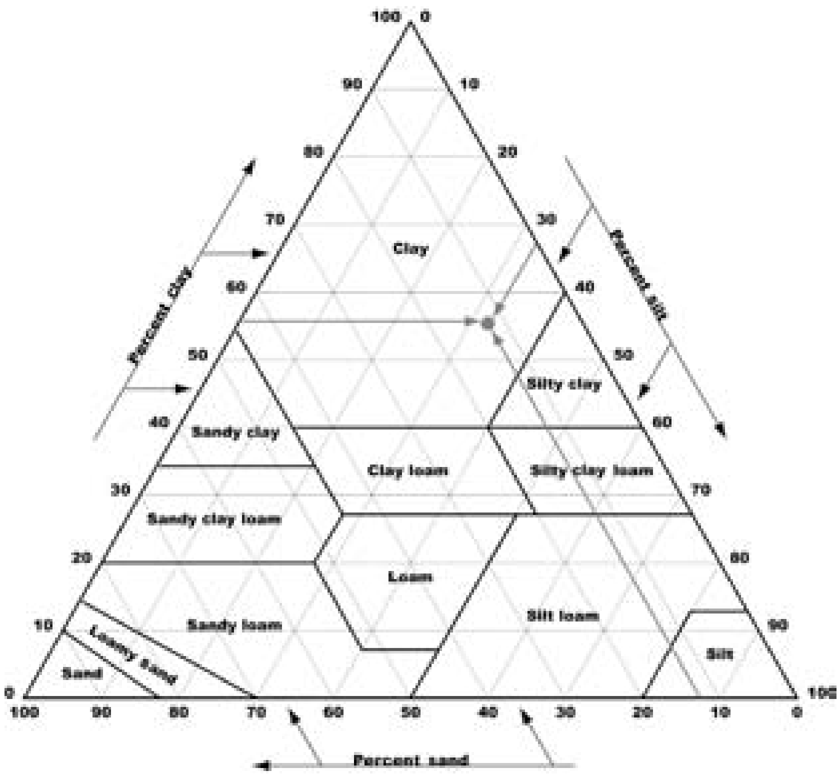

FIGURE 2.3
The soil textural triangle, illustrating the twelve soil textural classes.

The minerals that make up the clay particles in the soil—mostly secondary aluminosilicates, are also more chemically active than the predominant minerals of the silt and sand particles, which are mostly silica. Clay particles have a much higher cation exchange capacity, which gives clayey soils a greater ability to retain plant nutrients. The high surface area and cation exchange capacity of clay particles also promotes interactions between clay and organic matter particles, which fosters greater organic matter retention in finer-textured soils.

Along with soil texture, the other prominent property that greatly influences soil properties and processes is soil acidity, as quantified by pH. Soil acidity mainly influences the solubility of various elements in the soil, particularly plant nutrients. At low pH values (<5.8), the availability of certain plant nutrients, such as phosphorus, nitrogen, calcium, and magnesium may be limited. Microbial activity is also diminished when soil acidity is high. Conversely, aluminum and manganese availability is increased and may reach levels toxic to some plants. At high pH values (>7.5), the availability of phosphorus, iron, manganese, copper, and zinc is limited. The pH of a soil is controlled by the relative amounts of acidic (H^+ and Al^{3+}) versus nonacidic (Ca^{2+}, Mg^{2+}, K^+, Na^+) elements retained within the cation exchange capacity of a soil. If the soil parent materials are low in nonacidic cations,

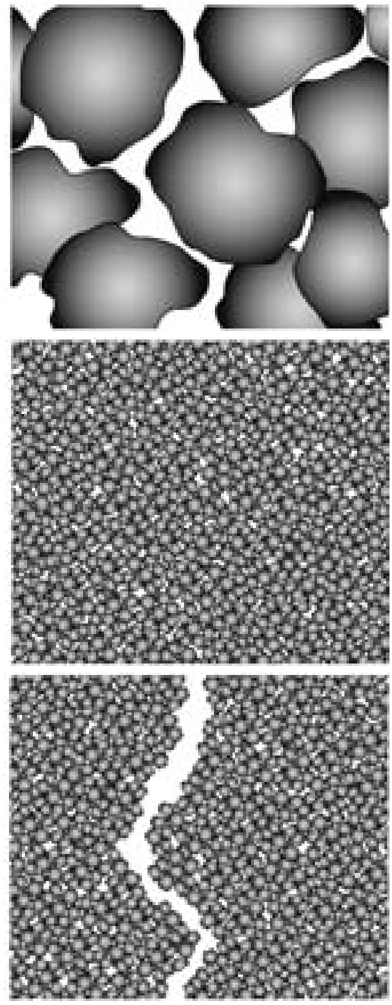

FIGURE 2.4
(A) Interparticle voids are relatively large between sand particles, creating numerous macropores. **(B)** These interparticle voids are much smaller between finer soil particles. **(C)** Structural development creates macropores between peds, which allows for greater water and air movement even in clayey soils.

the resulting soil will also be low in nonacidic cations. Rainfall and organic matter decomposition deposit acidic cations to the soil, while groundwater influx tends to be a source of nonacidic cations. Areas receiving groundwater discharge are often less acidic than areas that receive most of their water through precipitation. Leaching and plant uptake remove nonacidic cations and concentrate acidic cations within the cation exchange complex.

The soil property most commonly associated with wetland soils is increased organic matter content. The prolonged saturated and anaerobic conditions in wetland soils slow organic matter decomposition and lead to organic matter accumulation. Organic matter, specifically humus, in a mineral soil promotes aggregation and structural stability, lowers bulk density, increases porosity, and leads to higher infiltration and percolation rates. Organic matter also contains significant amounts of plant nutrients (in unavailable forms), which can be converted to available forms during organic matter decomposition. The complex humus molecules also add to the cation exchange capacity of the soil.

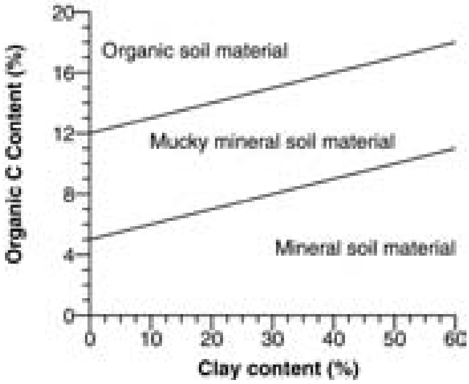

FIGURE 2.5
Organic soil materials are defined by the relationship between clay content and organic C content.

If the organic C content is greater than 12% to 18%, depending on the clay content (Fig. 2.5), the soil material is considered organic. Soils dominated by organic soil materials have a low bulk density, high porosity, and a high water holding capacity; however, water movement through organic soil materials is generally slow. While the nutrient content of the organic soil materials is high, much is not in available forms. The cation exchange capacity of organic soil materials is high, but the exchange complex is dominated by acidic cations, such that the pH of organic soil materials is generally low.

SOIL PROFILES

Soils properties differ with depth. Water movement over and through the soil (a) adds and removes materials, such as through erosion and deposition; (b) alters materials, such as through organic matter decomposition; and (c) redistributes materials within the profile, such as clay accumulation in the subsoil. These processes naturally lead to the development of layers within the soil. These layers are not depositional—they form in place as the soil develops from the parent material. The various soil horizons found with depth within a soil are approximately parallel to the soil surface. Each horizon will differ in its color, texture, structure, or other soil properties from the layers immediately below or above. These layers strongly affect the flow and distribution of soil water (Chapter 3) and the distribution of biological activity such as root growth; bacterial, fungal, and mycorrhizal growth (Chapter 5); and animal burrowing and feeding (Chapter 7). [SMF1]

Soil horizons are named in reference to their most important distinguishing characteristics. The master horizons, of which there are six, are designated by capital letters (Table 2.1). Lowercase letters sometimes follow the master horizon designations; these subordinate distinctions (Table 2.2) specify other important characteristics of the horizon. At the soil surface, many wetland soils have an O horizon composed of vegetative detritus (leaves, needles, twigs, etc.) in various states of decay along with living vegetative matter. Wetland soils in warm, humid climates with high biological activity will typically have thinner O horizons, while in cool and cold humid climates, the O horizons tend to be

TABLE 2.1 The Six Master Horizons and the Distinguishing Characteristics of Each

O	Layer dominated by *organic material*
A	*Mineral* layer formed at the surface (or below an O or another A horizon) characterized by *accumulation of humified organic matter;* or having properties resulting from cultivation or other agricultural activities
E	*Mineral* layer characterized by an *eluvial loss* of silicate clay, iron, and/or aluminum, leaving a concentration of sand- and silt-sized particles of quartz and/or other resistant minerals
B	*Mineral* layer dominated by one or more of the following: (a) *illuvial accumulation* of silicate clay, iron, aluminum, humus, carbonates, gypsum, and/or silica; (b) carbonate removal; (c) nonilluvial coatings or residual concentration of iron and/or aluminum sesquioxides; (d) structure development; (e) brittleness
C	*Mineral* layer that has been mostly *unaffected by pedogenic processes*
R	Hard *bedrock* layer

TABLE 2.2 Subordinate Soil Horizon Distinctions

a	Highly decomposed organic material (sapric)	n	Accumulation of sodium
b	Buried genetic horizons in a mineral soil	o	Residual accumulation of sesquioxides
c	Concretions or nodules	p	Plowing or similar disturbance
d	Physical root restriction (e.g., dense basal till, plow pans, and mechanically compacted zones)	q	Accumulation of secondary silica
e	Organic material of intermediate decomposition (hemic)	r	Weathered or soft bedrock
f	Frozen soil (permanent ice)	s	Illuvial accumulation of sesquioxides and organic matter
g	Strong gleying	ss	Presence of slickensides
h	Illuvial accumulation of organic matter	t	Accumulation of silicate clay
i	Slightly decomposed organic material (fibric)	v	Plinthite
j	Jarosite	w	Development of color or structure but with no illuvial accumulation
jj	Cryoterbation	x	Fragic or fragipan characteristics
k	Accumulation of pedogenic carbonates	y	Accumulation of gypsum
m	Continuous or nearly continuous cementation	z	Accumulation of salts more soluble than gypsum

thicker. The first mineral soil layer is the A horizon, which is often synonymous with the topsoil. A horizons can be of any texture but are usually loamy or sandy relative to subsoil materials. A horizons are characterized by darker colors (low value, low chroma) due to high organic matter content.

Depending on the characteristics of the parent material from which a soil profile was formed as well as other soil-forming factors, there may be one or more B horizons below the A horizon. The B horizons are the subsoil and are normally characterized by the accumulation of materials translocated from upper portions of the soil profile. Common B horizon types are those that feature high contents of clay (Bt), organic material (Bh), or iron (Bs) that have been removed from the A horizon through eluviation by infiltrating water and concentrated by illuviation in the B horizon. Weakly developed B horizons (Bw) and gleyed B horizons (Bg) are also common. Below the solum, or combined A and B horizons, is often found the C horizon(s), which are composed of less-weathered parent material. The physical, chemical, and mineralogical characteristics of the parent materials can have a profound effect on the properties of overlying soil horizons (Table 2.3). If consolidated bedrock is found within the soil profile, it is considered an R horizon. Between the A and B horizons, some soils feature a light-colored E horizon from which clay particles and organic matter have been eluviated.

Not every soil has all six master horizons. O horizons are not common, especially in disturbed or managed soils, such as agricultural land, where any horizons within the plow layer are mixed to form an Ap horizon. E horizons are found mainly in more highly weathered soils in warmer and moister climates. Young soils, typified by alluvial floodplain soils, or soils formed from parent materials highly resistant to weathering often lack a B horizon and feature an O or A horizon directly overlying C horizons.

Profile data from several seasonally saturated soils (Table 2.4) illustrate just a few of the variable horizon sequences that are commonly observed in and near wetland environments. Soils that experience prolonged saturation at or near the soil surface may develop thick O horizons, as is seen in the pocosin soil (Table 2.4). Below the highly decomposed (sapric) plant material (Oa horizons), there is little soil development in the mineral parent materials. These horizons are gleyed (Cg horizons) because of the near-continuous saturated and anaerobic conditions. Wet mineral soils in some environments, such as in poorly drained soils in drainageways (Table 2.4), show an accumulation in organic matter to greater depths, forming several black (low value, low chroma) A horizons, with gleyed (Bg) horizons below. Distinct redox concentrations throughout these horizons are further evidence of prolonged saturated and anaerobic conditions. Upland soils can also have water tables at or near the surface, especially if they occur in depressional landscape positions (Table 2.4). Impermeable subsoil horizons, such as the fragipan (Btx horizons), further contribute to the development of saturated and reducing conditions in such soils by promoting perched water tables. The Btg horizon immediately above the fragipan is evidence of the seasonally saturated conditions at a depth of 20 cm in this soil.

TABLE 2.3 Types of Soil Parent Materials, Their Characteristics, and Their Relationship to Soil Profile Properties

Soil Parent Material Type	General Description of Origin	Typical Geomorphic Position	Typical Soil Properties
Residuum	Weathered in place from underlying rock	Uplands—ridgetops and hillslopes	Highly variable; profiles typically include A, E, B, and C horizons
Colluvium	Weathered from chunks of upslope soil and bedrock carried by gravity; transport usually triggered by slope disturbance processes	Toes of hillslopes	Highly variable; profiles typically include A, E, B, and C horizons
Alluvium	Waterborne materials such as river sediment deposits	Floodplains	Sandy or silty; no B horizon
Lacustrine	Material formed by sediment deposition on lake bottoms	Current and former lake beds	Silty or clayey
Aeolian	Wind-deposited material	Downwind of current and former desert environments	Sandy or silty
Glacial till	Material overrun by a glacier	Anywhere affected by glaciation	Mixed sands, silts, and gravels; may be very dense with poor drainage
Glacial outwash	Material deposited by glacial meltwater	Broad glacial plains	Mixed sands and gravels; typically very porous; high conductivity
Marine	Material deposited by marine processes	Coastal plains	Mixed layers of sands and clays

The Btx horizons are not gleyed, but the macropores are lined with depleted (high value, low chroma) soil material.

SOIL PROCESSES

The shallow water tables and saturated soil conditions that are required for technical standards of wetland hydrology and hydric soil conditions initiate a series of biogeochemical

TABLE 2.4 Selected Morphological Properties by Horizon of Five Seasonally Saturated Soils

Horizon	Depth (cm)	Matrix Color	Redox Concentrations[a]	Redox Depletions[a]
Pocosin				
Oa1	0–5	7.5YR 3/2		
Oa2	5–60	7.5YR 3/1		
Oe	60–85	2.5YR 3/2		
Oa3	85–202	5YR 3/2		
A	202–228	5Y 3/1		
Cg1	228–237	5Y 3/1		
Cg2	237–240	5Y 4/1		
Drainageway				
Ap	0–20	10YR 2/1	c f 7.5YR 4/6	
A2	20–53	N 2/0	f f 7.5YR 4/6	
A3	53–64	10YR 2/1	f f 7.5YR 4/6	
Bg1	64–88	2.5Y 4/2	m f 7.5YR 4/6	
Bg2	88–102	2.5Y 6/2	m f 7.5YR 4/7	
Bg3	102–155	2.5Y 6/2	m c 7.5YR 4/6	c m 5BG 5/1
Upland depression				
A	0–8	10YR 3/1		
E	8–20	10YR 6/2		
Btg	20–46	10YR 6/2	c m 7.5YR 5/8	c m 10YR 4/1
Btx1	46–71	10YR 4/3	m m 7.5YR 5/6	m m 10YR 6/2
Btx2	71–117	7.5YR 4/4	m m 7.5YR 5/6	m m 10YR 6/1
R	117+			
Terrace				
A	0–9	10YR 3/1		
Bw	9–22	10YR 5/3	c m 5YR 4/6	
C1	22–59	2.5Y 6/4	c m 5YR 4/6	c m 2.5Y 7/2
C2	59–85	2.5Y 6/4	c m 5YR 4/6	c m 5Y 7/2
Cg1	85–179	2.5Y 7/2	c m 7.5YR 6/4	
Cg2	179–210	2.5Y 7/1	f f 7.5YR 6/4	

[a]First letter indicates abundance (f = few, c = common, m = many); second letter indicates size (f = fine, m = medium, c = coarse).

processes that create the special ecological environment of wetland systems and control the functions and values of wetlands. The biology of biogeochemical processes is primarily mediated by the microbial community, and that perspective is covered in detail in Chapter 5. Here, we focus on the geology and chemistry of biogeochemical reactions in wetland soils.

There is a general progression that occurs as a soil becomes saturated. As the water tables rise, air that is held in the soil pores is displaced by water (although a small fraction of pores retain entrapped air such that the degree of saturation never reaches 100%). The rate of oxygen diffusion into the soil is greatly diminished in a saturated soil. If temperature and bioavailable carbon are not limiting, microbes quickly deplete the oxygen that is trapped in the pores or dissolved in the soil solution of a saturated soil. Subsequently, the activity of facultative and obligate anaerobic microbes increases. These microbes function either as autotrophs, which may reduce Fe and Mn and employ the electron in ATP production; or as heterotrophs, which oxidize organic material and use Fe and Mn as electron acceptors during respiration.

Oxidation-Reduction Reactions

In theory, the utilization of available oxidants dictates preferential use of the species that provides the greatest amount of energy to the microbes. In the soil system, the order of electron acceptor preference is:

$$O_2 > NO_3^- > \mathrm{Mn(III\ or\ IV)} > \mathrm{Fe(III)} > SO_4^{2-} > H^+$$

The half-reactions that represent the reduction of each of these species are used to calculate the electrode potential associated with each reaction (Table 2.5). For a hypothetical reduction half-reaction:

[SMF2] $$\mathrm{Ox} + ne^- + mH^+ \leftrightarrow \mathrm{Red} + {}^{m}/_{2}\, H_2O$$

The electrode potential, *Eh,* is calculated as:

$$Eh = Eh^{\circ}\mathrm{D}\frac{RT}{nF}\,\xi\,\ln\frac{(\mathrm{Red})}{(Ox)\,\xi\,(H^+)^m}$$

where Ox and Red are the oxidized and reduced species, respectively, Eh° is the standard electrode potential, R is the gas constant, T is the absolute temperature, F is the Faraday constant, and values in parentheses are activities.

Redox potentials at which reduction of O_2, NO_3^-, Mn(III or IV), Fe(III), SO_4^{2-}, and H^+ occur in the soil are not as discrete as the calculated electrode potentials (Table 2.5), with significant overlap among the observed ranges. This occurs because of the nature of redox potential and its measurement: (a) the calculated electrode potential is an equilibrium potential, but the soil system does not reach oxidation-reduction equilibrium because of the constant additions and losses of oxidants and reductants within the system (Bohn et al. 1985); (b) the potential that is measured by the platinum electrode represents multiple oxidation-reduction reactions occurring in the soil at the electrode surface; and (c) each reaction is a function of concentration of reactants and activity of selective microbes that facilitate oxidation and reduction reactions around the electrode. Therefore, electrode potentials and redox potentials are not equivalent.

TABLE 2.5 Order of Utilization of Electron Acceptors in Soils and Measured Potential of These Reactions in Soils

Reaction	Electrode Potential, pH7	Measured Redox Potential in Soils
	V	V
$\frac{1}{2}O_2 + 2e^- + 2H^+ \leftrightarrow H_2O$	0.82	0.6 to 0.4
$NO_3^- + 2e^- + 2H^+ \leftrightarrow NO_2^- + H_2O$	0.54	0.5 to 0.2
$MnO_2 + 2e^- + 4H^+ \leftrightarrow Mn^{2+} + 2H_2O$	0.4	0.4 to 0.2
$FeOOH + e^- + 3H^+ \leftrightarrow Fe^{2+} + 2H_2O$	0.17	0.3 to 0.1
$SO_4^{2-} + 6e^- + 9H^+ \leftrightarrow HS^- + 4H_2O$	−0.16	0 to −0.15
$H^+ + e^- \leftrightarrow \frac{1}{2}H_2$	−0.41	−0.15 to −0.22
$(CH_2O)_n \leftrightarrow \frac{n}{2}CO_2 + \frac{n}{2}CH_4$	—	−0.15 to −0.22

NOTE: After Bohn et al. (1985).

Certain microbes catalyze the reduction of Fe(III) and Mn(III or IV) oxides, hydroxides, and oxyhydroxides (collectively "oxides"). When these microbes, such as *Micrococcus lactilyticus* and *Thiobacillus thiooxidans* (Zajic 1969), contact Fe and Mn "oxides" on soil particle surfaces, they reduce the Fe(III) or Mn(III or IV) to Fe(II) and Mn(II). The more soluble Fe(II) and Mn(II) ions readily dissolve into the soil solution (Fischer 1988). Depending on hydraulic and chemical gradients in the soil solution, the Fe^{2+} or Mn^{2+} may: (a) remain in the vicinity of the original soil particle surface until oxidizing conditions return; (b) become adsorbed to the cation exchange sites in the soil; (c) be translocated locally until an oxidizing environment is encountered and is reprecipitated as an Fe or Mn "oxide" mineral; or (d) be leached from the soil system. Depending on the fate of the reduced Fe or Mn, various morphological features may develop, such as low-chroma mottles in a high-chroma matrix, high-chroma mottles in a low-chroma matrix, or a gleyed soil.

According to Ponnamperuma (1972), soil saturation and development of anoxic conditions causes (a) a decrease in redox potential; (b) neutralization of pH; (c) changes in specific conductance and ion strength; (d) changes in certain mineral equilibria; (e) ion exchange reactions; and (f) sorption and desorption of ions. In a mixed system, such as the soil, the dominant redox couple determines the redox potential (Ponnamperuma 1972). The order of oxidant utilization and associated potential of these reactions in soils (Table 2.5) indicates the redox potential that may be expected when that reaction is controlling the redox chemistry of a soil.

Redoximorphic Feature Formation

There are several theories explaining the formation of redoximorphic features under different hydrologic regimes (Veneman et al. 1976, Fanning and Fanning 1989, Vepraskas 1992). The location of saturated and aerated soil zones, and therefore the source of Fe(III)

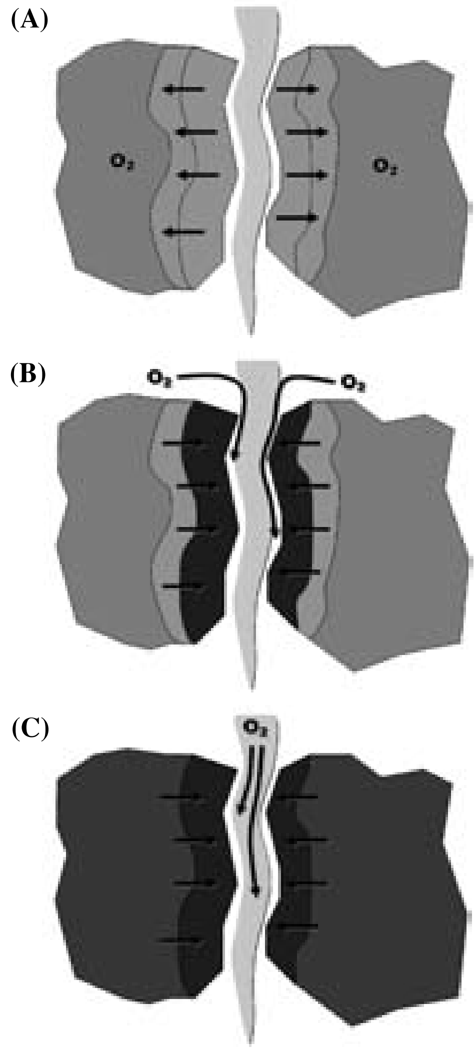

FIGURE 2.6
Models of redoximorphic feature formation. **(A)** Within a saturated and reduced pore, an adjacent soil is the site of Fe(III) reduction, and an aerated and oxidized matrix is the site of Fe(II) oxidation. **(B)** Saturated and reduced matrix is the site of Fe(III) reduction, and an aerated and oxidized pore is the site of Fe(II) oxidation. **(C)** Saturated and reduced matrix is the site of Fe(III) reduction, and an oxidize rhizosphere is the site of Fe(II) oxidation.

reduction within the soil, relative to pores or the soil matrix distinguishes between the hypothesized mechanisms of redoximorphic feature formation. Models of redoximorphic feature formation can be divided into two basic categories (Fig. 2.6): (a) within a saturated and reduced pore, an adjacent soil is the site of Fe(III) reduction, and an aerated and oxidized matrix is the site of Fe(II) oxidation (Fig. 2.6a); or (b) a saturated and reduced matrix is the site of Fe(III) reduction, and an aerated and oxidized pore is the site of Fe(II) oxidation (Fig. 2.6b). Both of these types of redoximorphic features are readily observed in seasonally saturated soils (Table 2.4). The redox depletions in the third Bg horizon of the drainageway soil and the Btx horizons of the upland depression soil (Table 2.4) formed when the macropores between the peds were strongly reducing and Fe was translocated away from the pore (Fig. 2.6a). Most of the redox concentrations in the subsoil horizons of the drainageway, upland depression, and terrace soils (Table 2.4) were formed when oxygen was reintroduced via macropores and reduced Fe reoxidized along the pore (Fig. 2.6b). A special case of this second mechanism of redoximorphic feature formation is seen prominently in dark A horizon materials, such as the upper horizons of the drainageway soil (Table 2.4). Roots of some wetland plants transport O_2 down to the roots. This can create an oxidized rhizosphere in which reduced Fe from the surrounding saturated soil will oxidize and precipitate around the root (Fig. 2.6c). This is often the only type of redoximorphic feature seen in surface horizons of wetland soils with thick, dark A horizons.

Organic Matter Decomposition and Accumulation

Organic matter is an important component to all wetland systems because it is the energy source for the microbial activity that drives the development of anaerobic and reducing conditions. The subsequent soil biogeochemical processes often lead to the accumulation of greater amounts of soil organic matter that, along with the presence of Fe-based redoximorphic features, is the property most commonly associated with wetland soils.

Soil microorganisms (bacteria and fungi) play the most significant role in organic matter decomposition in soils. In well-drained, aerobic soils, the rate of organic matter decomposition is often much greater than the rate of organic matter deposition from above- and below-ground biomass (leaves, stems, roots, macroorganisms, microorganisms). As a result, the equilibrium level of soil organic matter can be quite low (e.g., $<2\%$). However, under anaerobic conditions that develop in saturated wetland soils, the aerobic decomposers no longer function, and the facultative and obligate anaerobic microorganisms are left to decompose organic matter. These organisms do not derive as much energy when electron acceptors other then O_2 are used (Table 2.5), and organic matter decomposition can occur at a much slower rate in saturated and anaerobic soils (but see Chapter 5). Consequently, organic matter inputs can be much greater than outputs, and the equilibrium level of soil organic matter is higher in wetland soils (see pocosin and drainageway soils in Table 2.4).

DIFFERENTIATION OF WETLAND SOILS

While organic matter accumulation is typical of wetland soils, not all wetland soils have accumulated enough organic matter to have organic soil horizon at the soil surface. The presence of an O horizon or black A horizon at the soil surface is commonly associated with wetland soils. Other morphological properties that develop in seasonally saturated soils include Mn concentrations, Fe concentrations, and Fe depletions.

Hydric soils, which along with hydrophytic vegetation and wetland hydrology are identifying characteristics of wetlands, are specifically defined as soils that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part (Federal Register 1994). From this definition, the United States Department of Agriculture (USDA) Natural Resources Conservation Service

BOX 2.1 THE MANDATORY TECHNICAL CRITERIA FOR HYDRIC SOILS

NOTE: From http://soils.usda.gov/use/hydric/criteria.html.

---

1. All Histels except Folistels, and Histosols except Folists, or
2. Soils in Aquic suborders, great groups, or subgroups, Albolls suborder; Historthels great group; Historturbels great group; Pachic subgroups; or Cumulic subgroups that are:

    a. Somewhat poorly drained with a water table[a] equal to 0.0 foot (ft) from the surface during the growing season, or

    b. Poorly drained or very poorly drained and have either a:

        i. Water table equal to 0.0 ft during the growing season[b] if textures are coarse sand, sand, or fine sand in all layers within 20 inches (in), or for other soils

        ii. Water table at less than or equal to 0.5 ft from the surface during the growing season if permeability is equal to or greater than 6.0 in/hour (h) in all layers within 20 in, or

        iii. Water table at less than or equal to 1.0 ft from the surface during the growing season if permeability is less than 6.0 in/hour (h) in all layers within 20 in, or.

3. Soils that are frequently[c] ponded for long duration[d] or very long duration[e] duirng the growing season, or
4. Soils that are frequently flooded for long duration or very long duration during the growing season.

---

[a]Water table = the upper surface of ground water where the water is at atmospheric pressure. In the Map Unit Interpretation Record (MUIR) database, entries are made for the zone of saturation at the highest average depth during the wettest season. It is at least six inches thick and persists in the soil for more than a few weeks. In other databases, saturation, as defined in *Soil*
[SMF10] *Taxonomy* (Soil Survey Staff. 1999), is used to identify conditions that refer to a water table in
[SMF11] criteria 2.

[b]Growing season = the portion of the year when soil temperatures are above biological zero at 50 cm; defined by the soil temperature regime.

[c]Frequently = flooding, ponding, or saturation is likely to occur often under usual weather conditions (more than 50 percent chance in any year, or more than 50 times in 100 years).

[d]Long duration = a single event lasting 7 to 30 days.

[e]Very long duration 5 a single event lasting longer than 30 days.

BOX 2.2 FIELD INDICATORS OF HYDRIC SOILS [SMF14]

Note: From *Federal Manual for Delineating Wetlands* (1987). [SMF15]

1. Organic soils[a]
2. Histic epipedons[a]
3. Sulfidic material[b]
4. Aquic or peraquic moisture regime[a]
5. Direct observation of reducing soil conditions with α-α dipyridyl indicator solution
6. Gleyed, low-chroma, and low-chroma/mottled soils
   a. Gleyed soils
   b. Low-chroma soils and mottled soils
7. Iron and manganese concretions

[a]As defined in *Keys to Soil Taxonomy* (NRCS 2003). [SMF12]
[b]As evidenced by hydrogen sulfide, or rotten egg odor. [SMF13]

(NRCS) developed a set of mandatory technical criteria for hydric soils (http://soils.usda.gov/use/hydric/criteria.html). These criteria (Box 2.1) serve mainly as a means to retrieve a list of likely hydric soils from a database of soil information; however, the criteria can also be used as indicators for identification of hydric soils in the field. Hydric soil lists are developed and updated using these criteria and can be used in conjunction with published soil survey reports to generate preliminary inventories of hydric soils in an area (http://soils.usda.gov/use/hydric/). It is important to note that on-site field verification of the presence of hydric soils is required because soil survey maps cannot represent all soils within an area, only soil bodies that are large enough to be delineated at the scale of the map (usually larger than 1.2 ha). Also, being placed on a hydric soil list does not guarantee that a soil is indeed hydric. It only indicates that the range in properties associated with a given soil in a map unit overlap with those of the technical criteria.

Most hydric soil determinations are based on field indicators. The 1987 Federal Manual for Delineating Wetlands lists a series of field indicators intended to be used as general guidelines for field identification of hydric soil (Box 2.2). More detailed and specific field indicators (NRCS 2002) have been developed for on-site identification and delineation of hydric soils. These indicators (Box 2.3) are observable soil morphological properties that form when the soil is saturated, flooded, or ponded long enough during the growing season to develop

BOX 2.3 FIELD INDICATORS OF HYDRIC SOILS IN THE UNITED STATES

NOTE: NRCS 2002

ALL SOILS

A1 *Histosol or Histel*[a]—Soil classifies as a Histosol (except Folist) or as a Histel (except Folistel).

A2 *Histic Epipedon*[a]—Soil has a histic epipedon.

A3 *Black Histic*—Soil has a layer of peat, mucky peat, or muck 20 cm (8 in) or more thick starting within the upper 15 cm (6 in) of the soil surface having hue 10YR or yellower, value 3 or less, and chroma 1 or less.

A4 *Hydrogen Sulfide*—Soil has hydrogen sulfide odor within 30 cm (12 in) of the soil surface.

A5 *Stratified Layers*—Soil has several stratified layers starting within the upper 15 cm (6 in) of the soil surface. One or more of the layers has value 3 or less with chroma 1 or less, and/or it is muck, mucky peat, peat, or mucky modified mineral texture. The remaining layers have value 4 or more and chroma 2 or less.

A6 *Organic Bodies*—Soil has 2% or more organic bodies of muck or a mucky modified mineral texture, approximately 1 to 3 cm (0.5 to 1 in) in diameter, starting within 15 cm (6 in) of the soil surface.

A7 *5-cm Mucky Mineral*—Soil has a mucky modified mineral surface layer 5 cm (2 in) or more thick starting within 15 cm (6 in) of the soil surface.

A8 *Muck Presence*—Soil has a layer of muck that has a value 3 or less and chroma 1 or less within 15 cm (6 in) of the soil surface.

A9 *1-cm Muck*—Soil has a layer of muck 1 cm (0.5 in) or more thick with value 3 or less and chroma 1 or less starting within 15 cm (6 in) of the soil surface.

A10 *2-cm Muck*—Soil has a layer of muck 2 cm (0.75 in) or more thick with value 3 or less and chroma 1 or less starting within 15 cm (6 in) of the soil surface.

SANDY SOILS

S1 *Sandy Mucky Mineral*—Soil has a mucky modified sandy mineral layer 5 cm (2 in) or more thick starting within 15 cm (6 in) of the soil surface.

S2 *2.5-cm Mucky Peat or Peat*—Soil has a layer of mucky peat or peat 2.5 cm (1 in) or more thick with value 4 or less and chroma 3 or less starting within 15 cm (6 in) of the soil surface underlain by sandy soil material.

S3 *5-cm Mucky Peat or Peat*—Soil has a layer of mucky peat or peat 5 cm (2 in) or more thick with value 3 or less and chroma 2 or less starting within 15 cm (6 in) of the soil surface underlain by sandy soil material.

(continued)

S4 *Sandy Gleyed Matrix*[b]—Soil has a gleyed matrix that occupies 60% or more of a layer starting within 15 cm (6 in) of the soil surface.

S5 *Sandy Redox*—Soil has a layer starting within 15 cm (6 in) of the soil surface that is at least 10-cm (4 in) thick and has a matrix with 60% or more chroma 2 or less with 2% or more distinct or prominent redox concentrations as soft masses and/or pore linings.

S6 *Stripped Matrix*—Soil has a layer starting within 15 cm (6 in) of the soil surface in which iron/manganese oxides and/or organic matter have been stripped from the matrix, exposing the primary base color of soil materials. The stripped areas and translocated oxides and/or organic matter form a diffuse splotchy pattern of two or more colors. The stripped zones are 10% or more of the volume; they are rounded and approximately 1 to 3 cm (0.5 to 1 in) in diameter.

S7 *Dark Surface*—Soil has a layer 10 cm (4 in) or more thick starting within the upper 15 cm (6 in) of the soil surface with a matrix value 3 or less and chroma 1 or less. At least 70% of the visible soil particles must be covered, coated, or similarly masked with organic material. The matrix color of the layer immediately below the dark layer must have chroma 2 or less.

S8 *Polyvalue Below Surface*—Soil has a layer with value 3 or less and chroma 1 or less starting within 15 cm (6 in) of the soil surface underlain by a layer(s) where translocated organic matter unevenly covers the soil material, forming a diffuse splotchy pattern. At least 70% of the visible soil particles in the upper layer must be covered, coated, or masked with organic material. Immediately below this layer, the organic coating occupies 5% or more of the soil volume and has value 3 or less and chroma 1 or less. The remainder of the soil volume has value 4 or more and chroma 1 or less.

S9 *Thin Dark Surface*—Soil has a layer 5 cm (2 in) or more thick entirely within the upper 15 cm (6 in) of the surface, with value 3 or less and chroma 1 or less. At least 70% of the visible soil particles in this layer must be covered, coated, or masked with organic material. This layer is underlain by a layer(s) with value 4 or less and chroma 1 or less to a depth of 30 cm (12 in) or to the spodic horizon, whichever is less.

S10 *Alaska Gleyed*—Soil has a dominant hue N, 10Y, 5GY, 10GY, 5G, 10G, 5BG, 10BG, 5B, 10B, or 5PB, with value 4 or more in the matrix, within 30 cm (12 in) of the mineral surface, and underlain by hue 5Y or redder in the same type of parent material.

LOAMY AND CLAYEY SOILS

F1 *Loamy Mucky Mineral*—Soil has a mucky modified loamy or clayey mineral layer 10 cm (4 in) or more thick starting within 15 cm (6 in) of the soil surface.

(continued)

F2 *Loamy Gleyed Matrix*[b]—Soil has a gleyed matrix that occupies 60% or more of a layer starting within 30 cm (12 in) of the soil surface.

F3 *Depleted Matrix*[c]—Soil has a layer with a depleted matrix that has 60% or more chroma 2 or less that has a minimum thickness of either (a) 5 cm (2 in), if 5 cm (2 in) is entirely within the upper 15 cm (6 in) of the soil, or (b) 15 cm (6 in) and starts within 25 cm (10 in) of the soil surface.

F4 *Depleted Below Dark Surface*—Soil has a layer with a depleted matrix that has 60% or more chroma 2 or less starting within 30 cm (12 in) of the soil surface that has a minimum thickness of either (a) 15 cm (6 in) or (b) 5 cm (2 in), if the 5 cm (2 in) [SMF16] consists of fragmental soil material (see glossary). The layer(s) above the depleted matrix has value 3 or less and chroma 2 or less.

F5 *Thick Dark Surface*—Soil has a layer at least 15-cm (6 in) thick with a depleted matrix that has 60% or more chroma 2 or less (or a gleyed matrix) starting below 30 cm (12 in) of the surface. The layer(s) above the depleted or gleyed matrix has hue N and value 3 or less to a depth of 30 cm (12 in) and value 3 or less and chroma 1 or less in the remainder of the epipedon.

F6 *Redox Dark Surface*—Soil has a layer at least 10-cm (4 in) thick entirely within the upper 30 cm (12 in) of the mineral soil that has (a) a matrix value 3 or less and chroma 1 or less and 2% or more distinct or prominent redox concentrations as soft masses or pore linings, or (b) a matrix value 3 or less and chroma 2 or less and 5% or more distinct or prominent redox concentrations as soft masses or pore linings.

F7 *Depleted Dark Surface*—Soil has redox depletions, with value 5 or more and chroma 2 or less, in a layer at least 10-cm (4 in) thick entirely within the upper 30 cm (12 in) of the mineral soil that has (a) a matrix value 3 or less and chroma 1 or less and 10% or more redox depletions, or (b) a matrix value 3 or less and chroma 2 or less and 20% or more redox depletions.

F8 *Redox Depressions*—Soil is in closed depression subject to ponding, 5% or more distinct or prominent redox concentrations as soft masses or pore linings in a layer 5 cm (2 in) or more thick entirely within the upper 15 cm (6 in) of the soil surface.

F9 *Vernal Pools*—Soil is in closed depressions subject to ponding, presence of a depleted matrix in a layer 5-cm (2 in) thick entirely within the upper 15 cm (6 in) of the soil surface.

F10 *Marl*—Soil has a layer of marl that has a value 5 or more starting within 10 cm (4 in) of the soil surface.

F11 *Depleted Ochric*—Soil has a layer 10 cm (4 in) or more thick that has 60% or more of the matrix with value 4 or more and chroma 1 or less. The layer is entirely within the upper 25 cm (10 in) of the soil surface.

F12 *Iron/Manganese Masses*—Soil is on floodplains, with a layer 10 cm (4 in) or more thick with 40% or more chroma 2 or less, and 2% or more distinct or prominent

(continued)

BOX 2.3 CONTINUED

redox concentrations as soft iron/manganese masses and diffuse boundaries. The layer occurs entirely within 30 cm (12 in) of the soil surface. Iron/manganese masses have value 3 or less and chroma 3 or less; most commonly, they are black. The thickness requirement is waived if the layer is the mineral surface layer.

F13 *Umbric Surface*—Soil is in depressions and other concave landforms with a layer 25 cm (10 in) or more thick starting within 15 cm (6 in) of the soil surface in which the upper 15 cm (6 in) must have value 3 or less and chroma 1 or less, and the lower 10 cm (4 in) of the layer must have the same colors as above or any other color that has a chroma 2 or less.

F14 *Alaska Redox Gleyed*—Soil has a layer that has dominant matrix hue 5Y with chroma 3 or less, or hue N, 10Y, 5GY, 10GY, 5G, 10G, 5BG, 10BG, 5B, 10B, or 5PB, with 10% or more redox concentrations as pore linings with value and chroma 4 or more. The layer occurs within 30 cm (12 in) of the soil surface.

F15 *Alaska Gleyed Pores*—Soil has a presence of 10% hue N, 10Y, 5GY, 10GY, 5G, 10G, 5BG, 10BG, 5B, 10B, or 5PB with value 4 or more in the matrix or along channels containing dead roots or no roots within 30 cm (12 in) of the soil surface. The matrix has dominant chroma 2 or less.

F16 High Plains Depressions—Soil is in closed depressions subject to ponding, with a mineral soil that has chroma 1 or less to a depth of at least 35 cm (13.5 in) and a layer at least 10-cm (4 in) thick within the upper 35 cm (13.5 in) of the mineral soil that has either (a) 1% or more redox concentrations as nodules or concretions, or (b) redox concentrations as nodules or concretions with distinct or prominent corona.

---

[a]As defined in *Keys to Soil Taxonomy* (NRCS 2003). [SMF17]

[b]Soils that have a gleyed matrix have the following combinations of hue, value, and chroma, and the soils are not glauconitic: (a) 10Y, 5GY, 10GY, 10G, 5BG, 10BG, 5B, 10B, or 5PB with value 4 or more and chroma 1; or (b) 5G with value 4 or more and chroma 1 or 2; or (c) N with value 4 or more; or (d) (for testing only) 5Y, value 4 or more, and chroma 1. [SMF18]

[c]The following combinations of value and chroma identify a depleted matrix: (a) a matrix value 5 or more and chroma 1 with or without redox concentrations as soft masses and/or pore linings; or (b) a matrix value 6 or more and chroma 2 or 1 with or without redox concentrations as soft masses and/or pore linings; or (c) a matrix value 4 or 5 and chroma 2 and has 2% or more distinct or prominent redox concentrations as soft masses and/or pore linings; or (d) a matrix value 4 and chroma 1 and has 2% or more distinct or prominent redox concentrations as soft masses and/or pore linings.

anaerobic conditions in the upper part. Some indicators can be applied to all soil types, while others can only be applied to sandy soils or only to loamy and clayey soils. The variety of soil morphologies by which hydric soil conditions can be expressed is evidenced by the length of this list of indicators. However, the indicators are regionally specific, so not all of these indicators are applicable in all places. Normally, within a region, there are a small number of indicators that can reasonably be expected to be used in most circumstances.

Use of the indicators is comparative. After exposing and describing a soil profile to a depth of at least 50 cm, the descriptions of the field indicators are then compared with the field description. For example, the thick organic layers of the pocosin soil (Table 2.4) more than adequately meets the requirements of indicator A1, which requires a minimum of 40 cm of organic soil material in the upper 80 cm of soil. A thinner (20–40 cm) accumulation of organic soil materials at the surface might meet the requirements of indicator A2 or A3. Even less organic soil material at the surface may express indicator A7, A8, A9, or A10. The drainageway soil (Table 2.4) also has an accumulation of organic matter but not organic soil materials. Below the thick, dark A horizons is a layer with a depleted matrix. For this loamy soil, indicator F6 applies. If the surface horizon were thinner, indicators F3 or F4 may have applied. If the surface horizon had hue N like the second A horizon, the requirements of indicator F5 would have been met.

For soils without organic soil materials or thick, dark surfaces, it is the subsoil color that most often is the reliable indicator of seasonally saturated and reducing conditions. Specifically, the presence of gleyed matrix colors or the presence of a depleted (high value, low chroma) matrix is often used to identify hydric soils. Depending on the exact Munsell value and chroma, the presence of redoximorphic features may be required along with a depleted matrix. For the upland depression soil (Table 2.4), the Btg horizon, which starts at a depth of 20 cm, has a depleted matrix and meets indicator F3. This horizon has redox concentrations, but the relatively high value means that they are not required to meet this indicator. Conversely, when examining the terrace soil (Table 2.4), the presence of redox concentrations starting at a depth of 9 cm is not enough to meet any hydric soil indicator. This soil does experience high water table conditions during the year, as evidenced by the high value and low-chroma colors deeper in the profile, but prolonged saturated and reducing conditions do not occur close enough to the surface to meet the definition of a hydric soil.

SPECIFIC WETLAND TYPES: FORMATIVE PROCESSES, GEOMORPHOLOGY, AND SOILS

Wetland types vary in their geomorphology, soils, and the processes that lead to their presence in the landscape. In the previous section, we discussed the fundamental properties and processes that lead to wetland soil development. In this section, we introduce the three basic geomorphical settings and the types of wetlands that exist in those settings, specifically in North America. Those three basic geomorphical settings are depressional wetlands, nondepressional wetlands, and estuarine systems (Fig. 2.7).

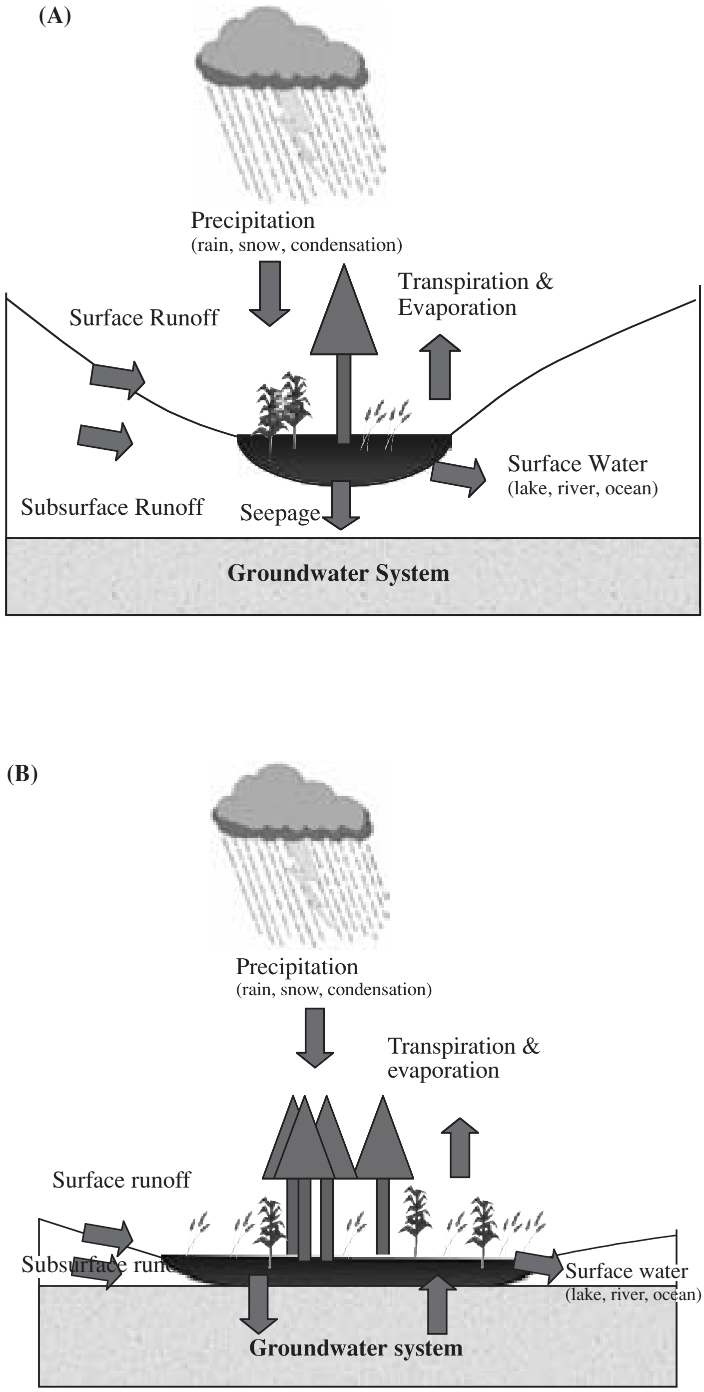

FIGURE 2.7
Typical wetland geomorphic positions including **(A)** depressional, **(B)** nondepressional, and **(C)** tidal or estuarine.

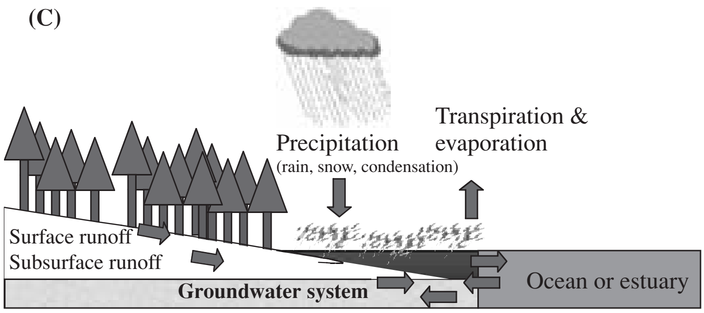

FIGURE 2.7
(Continued)

DEPRESSIONAL WETLANDS

Wetlands resulting from depressions are the most common types of wetlands found in North America, from bogs in Alaska to cypress domes in Florida. Although depressional wetlands are found in the highest number, they do not represent the greatest area of wetlands (see the next section on nondepressional wetlands). Most depressional wetlands are relatively small, ranging in size from less than a hectare to perhaps as large as several hundred hectares but most being at the low end of this range. Depressional wetlands result from "filling in" or the process known as *terrestrialization,* whereby depressions that were once water bodies or low areas in the landscape have accumulated organic matter and filled the depression. Depressional wetlands may or may not have groundwater influences depending on their relationship with the regional groundwater table. Many types of depressional wetlands are associated with "perched" water table conditions whereby the water table is local in origin and is mainly fed by only precipitation and runoff (both surface and subsurface runoff). Perched water tables result from a hydrologically limiting layer present in the soil such as a highly decomposed organic horizon or a clay-enriched mineral soil horizon. Vegetation can vary from forested to marsh and soils can either be organic or inorganic depending on the climate and geomorphic setting in the landscape (Table 2.6).

[SMF3] *Bogs*

DISTRIBUTION AND ORIGIN. *Bogs* are isolated depressional wetlands generally found in northern glaciated climates such as the Great Lakes area, Canada, and Alaska. The origin of bogs is related to glacial processes that have left depressions in the landscape. Many of the depressions left behind following glaciation are those from ice that broke off the receding glacier; the ice block was then covered with sediment; and ultimately it melted, creating the depression. These geomorphic features are known as *ice block depressions* and represent numerous wetlands in glaciated landscapes, although they do not represent the most wetland area (see fens in the nondepressional wetlands section). Other depressions

TABLE 2.6 Example Morphology, Color, pH, and Texture for Depressional Soils

Horizon	Depth (cm)	Matrix Color	pH	Texture
Northern bog				
Oi	0–15	5YR 4/4	Ext. Acid	O
Oa1	15–30	10YR 2/1	Ext. Acid	O
Oa2	30–115	5YR 2/2	Ext. Acid	O
Oa3	115–135	10YR 2/1	Ext. Acid	O
Oa4	135–150	5YR 2/2	Ext. Acid	O
Oe	150–200	5YR 3/3	Ext. Acid	O
Prairie pothole				
Ap	0–25	N 2/0	Neu.	SiCL
A1	25–55	N 2/0	Neu.	SiCL
A2	55–90	5Y 3/1	S. Alk.	SiCL
Cg	90–200	5Y 5/1	Mod. Alk.	SiCL
Carolina bay				
A	0–15	10YR 3/1	V.S. Acid	L
Btg	15–85	10YR 6/1	Str. Acid	C
BCg1	85–135	N 7/0	V.S. Acid	SCL
BCg2	135–180	N 7/0	V.S. Acid	SCL
C	180–200	N 7/0	V.S. Acid	SCL
Cypress dome				
Oa	0–30	N 2/0	Str. Acid	O
A	30–60	10YR 4/1	Neu.	S
Eg	60–110	10YR 4/2	Neu.	S
Btg/Eg	110–140	2.5Y 5/2	Mod. Alk.	SL
Btg	140–185	2.5Y 5/2	Mod. Alk.	SL
2C	185–200	10YR 7/2	Mod. Alk.	S
Seasonal wetland				
A	0–25	10YR 3/1	V.S. Acid	LS
Bg1	25–50	10YR 5/1	V.S. Acid	LS
Bg2	30–40	2.5Y 5/2	V.S. Acid	LS
2Bg3	40–65	2.5Y 5/2	V.S. Acid	SL
2C	65–200	7.5YR 4/4	Str. Acid	SL

NOTE: Soil pH categories include Ultra Acid (<3.5), Extremely (Ext.) Acid (3.5–4.4), Very Strongly (V.S.) Acid (4.5–5.0), Strongly (Str.) Acid (5.1–5.5), Moderately (Mod.) Acid (5.6–6.0), Slightly (S.) Acid (6.1–6.5), Neutral (Neu.) (6.6–7.3), Slightly Alkaline (S. Alk.) (7.4–7.8), Moderately Alkaline (Mod. Alk.) (7.9–8.4), Strongly Alkaline (Str. Alk) (8.5–9.0), and Very Strongly Alkaline (V.S. Alk.) (>9.0). Texture includes organic (O), sand or sandy (S), silt or silty (Si), clay or clayey (C), and loam or loamy (L).

include those created from the irregular deposition of glacial till and outwash creating both high and low spots in the landscape. Following glaciation, most of these systems were small open water bodies that began to fill in with vegetation. Because of the cool climate and low redox conditions that resulted from the ponded water, biomass production was greater than decomposition, and organic soils began to develop. Shallow areas filled in first, followed by the deeper areas. In some bog systems today, open water still is present, and the process of terrestrialization is continuing.

HYDROLOGY, SOILS, AND VEGETATION. Bogs are the result of perched water table conditions and have no current connection with regional groundwater systems. Evidence suggests that initially some bog systems were connected to regional groundwater systems but through time and the accumulation of organic matter ultimately separated from the regional groundwater (Mitsch and Gosselink 2000). Because bogs are perched, precipitation and upland runoff are the main sources of water to these systems. Bogs are convex or slightly domed in the middle, leading to runoff from the center of the bog to the edge. Upland runoff also flows to the bog edge, creating a hydrologically active zone around the bog called the *lagg*. In the typical bog condition, the lagg surrounding a bog eventually coalesces at the downstream end of the wetland and is the headwater of a stream that exits the bog. Because of the influence of relatively low pH precipitation and the organic acids that result from decomposition in bogs, soil water and stream waters exiting bogs are low in pH (3.5–4.5), cations, and other nutrients while being high in dissolved organic carbon.

Bogs generally have deep organic soils with deposition as great as 10+ m and accumulation rates as high as 100+ cm per 1000 years (Glaser et al. 1997). In general, bog soil horizons tend to be more compacted and hydrologically limiting with depth because of the weight of overlying soil. Bog soils provide a history of the vegetation present over time. Because climates and water tables have been changing since the last glacial period, vegetation communities have also changed. Through the use of pollen analysis, partial decomposition of plant material, and carbon dating, past vegetation communities can be reconstructed (Klimanov and Sirin 1997). Bog vegetation can vary in stature with conditions from relatively open to forested. *Sphagnum* moss species dominate the ground vegetation in bogs with a few grasses, forbs, and woody shrubs also common. Forested bogs are also common with similar understory vegetation as that found in open bogs with black spruce *(Picea mariana)* and tamarack *(Larix laricina)* being common tree species. Because of the low pH and nutrient poor conditions present in bogs, only a small suite of plants can exist, and species richness tends to be low. Although species richness within a bog is low, they support many unique species, and thus bogs can significantly add to the overall richness across bog-dominated landscapes.

Prairie Potholes

DISTRIBUTION AND ORIGIN. *Prairie potholes* are isolated wetlands and lakes found in the northern Great Plains from southern Alberta and Saskatchewan across the eastern Dakotas and western Minnesota and Iowa. The origin of prairie potholes is similar to that of bogs where low spots and ice block depressions were left behind following glaciation. Also, like bogs, most of these systems were open water bodies that began to fill in with vegetation, but many still have open water. Because the climate in the northern Great Plains is dryer and more susceptible to extended periods of drought than regions where bogs are found further east, prairie potholes tend to be mineral soil wetlands. Organic matter accumulation in prairie potholes is not as great as in bogs, and soils tend to be enriched in organic matter but not meeting the definition of an organic soil.

HYDROLOGY, SOILS, AND VEGETATION. Unlike bogs, prairie potholes tend to be associated with groundwater and typically have no outlet or stream exiting the wetland. Prairie potholes are concave with most of the hydrologic output through evapotranspiration and/or recharge of the regional groundwater. In general, most wetlands, including prairie potholes, are water discharge areas instead of groundwater recharge areas. Groundwater recharge generally occurs in upland environments in most landscapes as well as in depressional wetlands such as prairie potholes when water tables are below the soil surface and upland runoff and direct precipitation are greater than what is being discharged from evapotranspiration demands. Prairie potholes have shown to be both groundwater recharge and discharge areas and in some cases can be both depending on the climate of a particular year or season (Winter and Rosenberry 1995).

The connection to groundwater and mineral soils that are commonly carbonate rich generally leads to the nutrient-rich, circum-neutral, and higher pH surface and soil waters in prairie potholes. Mineral soils present in prairie potholes have accumulated significant organic matter since glaciation and have deep dark horizons near the surface. Soil scientists in the United States call these soils *Mollisols*, or mineral soils that have accumulated significant organic matter in the upper horizons but do not meet the criteria for a Histosol. [SMF4]

As described by the name, prairie potholes have prairie vegetation, which commonly is suites of grasses and forbs that tend to get shorter in stature from east to west (i.e., tall grass prairie in the east and short grass prairie in the west) following the precipitation gradient that decreases from east to west.

Carolina Bays

DISTRIBUTION AND ORIGIN. *Carolina bays* are isolated, closed depressional wetlands found along the eastern U.S. Coastal Plain and Piedmont from Florida to Maryland but are concentrated in the Carolinas. The origin of Carolina bays is speculation because of the mature (old) landscapes (nonglaciated) where they are found. Theories range about the origin of the depressions, from meteor showers to sink holes. However the depressions formed, they are typically elliptical in shape with their long-axis oriented in a northwest to southeast direction. Some research suggests that their oval nature and orientation are the result of wind and wave action that has occurred during past wetter climates when they held open water (Sharitz and Gibbons 1982). Supporting evidence for the theory includes sandy ridges around the southeastern rims of Carolina bays that may be a result of previous beaches that formed during these wetter times. Associated with their uncertainty in origin is an uncertainty in age. Through various dating methods, Carolina bay age has been found to range from 250,000 ybp (year before present) to 10,000 ybp (Sharitz and Gibbons 1982).

HYDROLOGY, SOILS, AND VEGETATION. Carolina bays are concave, closed systems that may or may not be connected to regional groundwater. Carolina bays that are connected to regional groundwater tend to have different hydrology, vegetation, and soil properties than those that are connected to perched water tables resulting from clay-enriched horizons present at depth in the soil profile (Sharitz 2003). Bays that are not connected to regional groundwater tables tend to have more variable hydrology with distinct drying and wetting cycles and less soil carbon accumulation, and are more likely to support forested communities. Carolina bays that are connected to groundwater tend to have more consistent water tables and more carbon accumulation, and support shorter stature vegetation communities. Soils can either be organic or mineral, with those bays connected to groundwater having a more likely chance of being organic. Mineral soils tend to be sandy in nature and are likely the result of surficial fluvial and marine deposits on stream terraces that occurred when ocean water levels were much lower than they are today.

Cypress Domes

DISTRIBUTION AND ORIGIN. *Cypress domes* are found embedded in low spots of the pine flatwoods region of Florida and southern Georgia. The term *dome* in the context of cypress domes refers to the appearance of a dome when observed from afar because trees in the center of wetland are typically taller than those on the edge. The soil surface is not domed as in bogs. Although there has been some conjecture on the reason why productivity is greater in the center than at the edge, no conclusive research has explained the phenomena (Mitsch and Gosselink 2000).

HYDROLOGY, SOILS, AND VEGETATION. Cypress domes are generally disconnected from regional groundwater with inputs mainly from precipitation and upland runoff. Typically, cypress domes are wettest during the summer growing season and driest during fall and spring, reflecting the precipitation patterns of the region. Although soils in cypress domes can range from sandy to clayey, typically a hydrologically limiting layer exists in the soil profile. Organic soils do accumulate in cypress domes and in some cases have the depth necessary to be considered a Histosol. As indicated by the wetland type, cypress domes are forested, typically with pondcypress *(Taxodium distichum* var. *nutans)*, black gum *(Nyssa sylvatica)*, slash pine *(Pinus elliottii)*, hardwood shrubs, and forbs.

Seasonal Wetlands

DISTRIBUTION AND ORIGIN. Seasonal wetlands include depressions that meet jurisdictional wetland requirements but do not easily fit within the description of those discussed above. [SMF5] As suggested by the term, *seasonal wetlands* are depressions that are only wet during various times in the average climate year. Mitsch and Gosselink (2000) describe several types of depressional wetlands that are seasonal in nature, including vernal pools found in the western United States and Mexico and playas found in the south central United States. Other seasonal depressional wetlands exist from the Great Lakes to the northeastern United States (Palik et al. 2003). The origin of seasonal wetlands in glaciated areas is mainly the result of landscape variability associated with glacial deposition. The deposition of till and outwash following glaciation left a heterogeneous landscape with numerous low spots even in higher portions of the landscape. In nonglaciated regions, geology and depositional/erosional environments control where in the landscape seasonal wetlands occur.

HYDROLOGY, SOILS, AND VEGETATION. Generally, seasonal wetlands are small, concave, and found in various landscape positions and are likely to have perched water tables if high in the landscape and possibly groundwater connections, at least at times, if low in the landscape. Hydrologic outputs are through evapotranspiration and groundwater recharge during high runoff periods such as in the spring. Mineral soils are typically found in seasonal wetlands because water is not ponded long enough to lead to the redox conditions that are more typical in more saturated types of wetlands. Vegetation varies from forested to marsh depending on the periodicity of saturation, length of saturation, and climate of the area. Seasonal wetlands in the west tend to be dominated by marshes, while seasonal wetlands in the Great Lakes and eastern United States are more likely to have forested vegetation.

NONDEPRESSIONAL WETLANDS

Like depressional wetlands, nondepressional wetlands are common across North America. Nondepressional wetlands include those wetlands that occur on upland slopes, near to streams or lakes, or otherwise have connections to groundwater (Fig. 2.7). Nondepressional wetlands develop due to a number of factors including a close connection to the regional groundwater table, being near an open water body, or a hydrologically limiting layer present in the soil. Nondepressional wetlands can cover huge expanses of land, as found in northern Minnesota, Canada, and parts of Russia. Although depressional wetlands are the most numerous, nondepressional wetlands cover the most area. As in most wetland types, soils can vary from mineral to organic (Table 2.7).

Northern Fens

DISTRIBUTION AND ORIGIN. Northern fens occur across the glaciated region of the northern Great Lakes states, Canada, and Alaska. Commonly, fens occur where glaciation left behind large areas of flat land such as till plains that are connected to the regional

TABLE 2.7 Example Morphology, Color, pH, and Texture for Nondepressional Soils

Horizon	Depth (cm)	Matrix Color	pH	Texture
Northern fen				
Oa	0–15	5YR 2/1	Str. Acid	O
Oe1	15–180	5YR 2/2	Med. Acid	O
Oe2	180–200	5YR 3/3	Med. Acid	O
Southern marsh				
Oa	0–20	7.5YR 3/2	S. Acid	O
Oe1	20–70	5YR 3/2	S. Acid	O
Oe2	70–200	7.5YR 3/2	S. Acid	O
Pocosin				
Oi	0–10	N 2/0	Ext. Acid	O
Oa1	10–30	N 2/0	Ext. Acid	O
Oa2	30–140	5YR 2/2	Ext. Acid	O
Oa3	140–165	5YR 2/2	Ext. Acid	O
2Cg1	165–180	10YR 3/2	Ext. Acid	S
2Cg2	180–200	10YR 4/1	Ext. Acid	S
Riverine				
A	0–10	10YR 4/2	Str. Acid	SL
Bg1	10–25	10YR 6/2	V.S. Acid	S
2Cg1	25–75	10YR 5/1	V.S. Acid	L
2Cg2	75–105	10YR 5/1	V.S. Acid	SiL
3Cg	105–200	10YR 6/1	V.S. Acid	S
Freshwater shoreline wetlands				
Oa	0–10	N 2/0	Neu.	O
A	10–35	10YR 2/2	S. Alk.	LS
Cg1	35–95	10YR 6/1	S. Alk.	S
2Cg2	95–200	10YR 5/1	S. Alk.	SiL

NOTE: Soil pH categories include Ultra Acid (<3.5), Extremely (Ext.) Acid (3.5–4.4), Very Strongly (V.S.) Acid (4.5–5.0), Strongly (Str.) Acid (5.1–5.5), Moderately (Mod.) Acid (5.6–6.0), Slightly (S.) Acid (6.1–6.5), Neutral (Neu.) (6.6–7.3), Slightly Alkaline (S. Alk.) (7.4–7.8), Moderately Alkaline (Mod. Alk.) (7.9–8.4), Strongly Alkaline (Str. Alk) (8.5–9.0), and Very Strongly Alkaline (V.S. Alk.) (>9.0). Texture includes organic (O), sand or sandy (S), silt or silty (Si), clay or clayey (C), and loam or loamy (L).

groundwater system. In heterogeneous glaciated landscapes, both bogs and fens can be present and in many cases can both be part of the same wetland complex. As compared with bogs that generally develop through the terrestrialization process, fens develop through the process of "paludification," which occurs when microtopographic low areas of mineral soil or sediment become inundated, decomposition slows because of anaerobic conditions, and organic material begins to build. Over time, the low areas fill and connect with other low areas, and ultimately a blanket of peat forms over the entire area.

HYDROLOGY, SOILS, AND VEGETATION. Northern fen hydrology is controlled by the flow of groundwater. Although precipitation and upland runoff contribute to fen inputs, groundwater is the dominant source of water to the system. Generally, groundwater in glaciated landscapes is relatively high in pH and nutrient rich because of its association with calcium carbonate–rich (calcareous) glacial deposits. Ecologists term these nutrient rich systems either as *rich* fens, or *minerotrophic* fens. However, some groundwater is associated with glacial deposits that are low in nutrients such as sandy outwash deposits and, hence, lead to lower pH, less-nutrient-rich fens with water chemistry and vegetation that can resemble bogs. Depending on the level of nutrients ecologist term these systems *intermediate, transitional, acidic,* or *poor* fens (Mitsch and Gosselink 2000). Organic soils in fens are typically shallower than those found in bogs but can be >5 m in depth. More typically, organic soil depths range from 50 cm to several meters. Vegetation communities will vary across the gradient of both nutrient and inundation conditions and can be open, low in stature to forested. Like bogs, many fens are dominated with *Sphagnum* species on the soil surface. In rich fens, open conditions will typically include various species of sedges, grasses, and forbs, while forested systems will typically include those species and tree species such as northern white cedar *(Thuja occidentalis)*, tamarack, birch species (*Betula* spp.), and willow species (*Salix* spp.).

Southern Swamps and Marshes

DISTRIBUTION AND ORIGIN. Across the southeastern United States are both large and small expanses of wetlands that are connected to regional groundwater systems and not necessarily riverine in nature. Both swamps (forested) and marshes (nonforested) exist across the region (Mitsch and Gosselink 2000). Probably the best known of these wetlands is the Florida Everglades. The swamps and marshes in the southeastern United States are found in low spots in the landscape or where water becomes ponded because of relatively impermeable soil or geologic layers.

HYDROLOGY, SOILS, AND VEGETATION. Typically, more inundated conditions for longer periods lead to marsh vegetation, whereas water tables that dry down periodically lead to forested systems. Soils can range from organic to mineral. Wetlands with a greater degree and longer soil saturation tend to form organic soil layers, so peat soils will be found more commonly in marshes than in swamps. Vegetation in marshes is comprised of grasses, grass-like plants (e.g., sedges and rushes), and numerous forbs. Vegetation in swamps is similar to riverine wetlands found in the Southeast and include bald cypress *(Taxodium distichum)*, black gum, green ash *(Fraxinus pennsylvanica)*, and red maple *(Acer rubrum)*.

Pocosins

DISTRIBUTION AND ORIGIN. *Pocosins* are freshwater wetlands found on the Atlantic Coastal Plain from Virginia to Florida, with the largest concentration occurring in North Carolina (Sharitz and Gibbons 1982). They have no characteristic shape and can range in size from less than a hectare to thousands of hectares. Pocosin origin is thought to have occurred following the last glaciation period 10,000 to 15,000 ybp. The ice sheet from the Wisconsinan glacial period led to falling ocean levels that subsequently led to increased downcutting of Coastal Plain streams. When the glacier receded, ocean water levels rose again, and streams were essentially blocked from flowing into the ocean. Stream flows were slowed, allowing for deposition of organic materials in the interstream areas. The blocking of the streams also led to shallow water tables across the Coastal Plain. The combination of shallow water tables, organic deposition, and the process of paludification (see [SMF6] discussion above on fens) led to the development of pocosins in the interstream areas of the Coastal Plain.

HYDROLOGY, SOILS, AND VEGETATION. Much like northern bogs, pocosins are typically raised in the middle and are perched from the regional groundwater. Initial development was a direct result of groundwater interaction, but since the last glacial period, peat has accumulated to the point where the peatland has separated from the regional groundwater. Perched water moves slowly out of the raised peatlands to surrounding areas, including, in some cases, being the headwaters of streams. Soils tend to be organic, and peat can be up to several meters deep. Mineral subsoils tend to be layered marine sediment ranging from clays to sands. Vegetation communities typically include broadleaf evergreen shrubs and pond pine *(Pinus serotina)*.

Atlantic White Cedar Swamps

DISTRIBUTION AND ORIGIN. Atlantic white cedar swamps exist near the Atlantic Coast from southern Maine to the Gulf Coast, with the greatest concentration existing in New Jersey, North Carolina, and Florida. Their origin is related to the hydrology associated with the growth of Atlantic white cedar. In the typical glaciated case, Atlantic white cedar swamps are really fens with Atlantic white cedar present *(Chamaecyparis thyoides)*. Outside the glaciated region, Atlantic white cedar can be found from peatland to mineral soil environments including stream floodplains.

HYDROLOGY, SOILS, AND VEGETATION. Atlantic white cedar swamps have moderate hydrology. They are not as saturated as marsh systems but are somewhat wetter than swamps (such as red maple swamps in the Northeast) (Mitsch and Gosselink 2000). Atlantic white cedar swamps are seasonably flooded, with some of that flooding occurring during the growing season. Atlantic white cedar swamps generally occur on peat soils but also exist where groundwater intersects mineral soils. As suggested by its name, Atlantic white cedar is a dominant tree species, but commonly, others such as red maple, gray birch *(Betula* *populifolia)*, black spruce, and eastern hemlock *(Tsuga canadensis)* in the North and bald cypress and redbay *(Persea borbonia)* in the South also occur.

Riverine Wetlands

DISTRIBUTION AND ORIGIN. Riverine wetlands occur across North America wherever there are wetlands associated with streams. Others term these types of wetlands as *riparian wetlands* or *floodplain wetlands,* but not all riparian areas or floodplains are wetlands, and not all riparian areas are associated with streams and rivers; lakes, for example, also have riparian areas. Riverine wetlands can be tens of kilometers wide on major river systems but more typically are found in a narrow zone next to the stream. As stream size increases and stream slope decreases, the potential for wetland occurrence increases because water movement is slowed, both in the stream and from the surrounding landscape. Generally, the wetland position in the landscape is controlled by the surficial geology that affects the channel, forming fluvial processes that govern where wet soil conditions can persist.

HYDROLOGY, SOILS, AND VEGETATION. Typically, streams are connected to the regional groundwater system, and wetlands next to the stream have water inputs from groundwater, precipitation, and upland runoff. In addition, wetlands near streams may also receive water inputs from overbank flows when stream flooding occurs. Soils range from organic to mineral, but usually, because of only periodic inundation, soils are mineral with relatively high concentrations of organic matter. Soils are also typically coarse textured because of the influence of fluvial processes that leads to the removal of fine-textured particle sizes as streams shift in their floodplains. Vegetation varies tremendously depending on the climate, the connectivity to groundwater, the chemistry of the receiving groundwater, and disturbance history of the watershed. Some of the more commonly known riverine wetland ecosystems are the cypress-tupelo swamps and bottomland hardwood systems in the southeastern United States, red maple swamps in the northeastern United States, northern white cedar and green ash swamps in the Great Lakes states, cottonwood *(Populus deltoides)* dominated wetlands near streams in the midwestern United States, and salt cedar *(Tamarix gallica)* wetland areas in the Southwest.

Freshwater Shoreline Wetlands

DISTRIBUTION AND ORIGIN. Typically, we think of shoreline wetlands associated with lakes in the glaciated region of North America; however, shoreline wetlands also exist around impoundments and reservoirs across the continent. In glaciated regions, lake distribution is related to glacial features such as heterogeneous deposition, ice block depressions, and moraine features that impounded water following glacial recession. Lakes can be either isolated, closed depressions like some wetland types, or a source of water for streams like other wetland types. Lakes in closed systems are referred to as *seepage lakes,* while those that are sources of surface water are termed *drainage lakes*.

HYDROLOGY, SOILS, AND VEGETATION. Wetlands associated with seepage and drainage lakes can be either sources or sinks for lake water, but typically, wetlands associated with seepage lakes are sinks for lake water, whereas wetlands associated with drainage lakes are sources of water to the lake. Wetlands associated with seepage lakes are typically driven by lake water "seeping" into the surrounding terrestrial landscape. Upland runoff and precipitation also contribute to seepage lake wetlands, but generally, wetland water levels are controlled by lake water levels. Drainage lake wetlands typically are areas where significant upland runoff and/or groundwater contributes to the lake and hydrologic gradients exist from the wetland to the lake. Freshwater shoreline wetland soils can be either mineral or organic depending on the period of inundation, [SMF7] with longer inundation periods leading to the more likely occurrence of organic soils. Vegetation also is variable depending on the hydrology, with less inundated conditions generally leading to forested wetlands and more inundated conditions leading to marsh systems.

ESTUARINE SYSTEMS

[SMF8] *Distribution and Origin*

Estuarine wetlands are distinguished from other types of wetlands because of the influence of oceanic tides on the hydrology of the wetlands. In North America, estuarine wetlands are found at the terrestrial edge of coasts of the Atlantic and Pacific oceans, and the Gulf of Mexico. Estuarine wetlands result from the periodic inundation of salt water as the tides rise and fall.

Hydrology, Soils, and Vegetation

Estuarine wetlands have hydrologic inputs from direct precipitation, subsurface runoff from associated uplands, and groundwater, and some marshes have surface runoff inputs from freshwater streams draining to the ocean (Fig. 2.7); however, the largest influence on hydrology is the daily tidal input. Three geomorphic settings describe the typical estuarine wetland (Rabenhorst 2001). *Estuarine marshes* are formed in mineral alluvial sediment deposited by freshwater streams entering estuaries, a typical delta situation. Soils are typically silty to clayey in nature but may contain lenses of organic soils if there are prolonged periods where mineral deposition does not occur (Table 2.8). *Submerging coastal marshes* are found behind barrier islands in a lagoon setting and form in both organic and mineral sediment. Soils can be either organic or mineral, and both can be present in close proximity. Also, soils will typically be layered because of sediment deposition during significant weather events such as hurricanes (Table 2.8). *Submerged upland marshes* are found along all coasts and are the result of rising water levels over the

TABLE 2.8 Example Morphology, Color, pH, and Texture for Estuarine Soils

Horizon	Depth (cm)	Matrix Color	pH	Texture
Estuarine marsh				
Ag	0–35	5Y 3/2	Neu.	SiL
Cg1	25–75	5Y 4/1	Neu.	SiL
Cg2	75–200	5Y 4/2	Neu.	SiCL
Submerging coastal marsh				
Oe	0–30	10YR 3/1	S. Acid	O
Cg1	30–55	10YR 5/1	Neu.	S
Cg2	55–200	2.5Y 5/1	Neu.	S
Submerged upland marsh				
Oi	0–15	10YR 4/2	Neu.	O
Oe	15–30	10YR 3/3	Neu.	O
Oa	30–55	10YR 2/1	Neu.	O
Ag	55–60	5Y 2/1	Neu.	SiL
Eg	60–90	10YR 5/1	Neu.	SiL
Btg1	60–120	5Y 4/1	Neu.	SiCL
Btg2	120–200	10YR 5/1	Neu.	SiCL

NOTE: Soil pH categories include Ultra Acid (<3.5), Extremely (Ext.) Acid (3.5–4.4), Very Strongly (V.S.) Acid (4.5–5.0), Strongly (Str.) Acid (5.1–5.5), Moderately (Mod.) Acid (5.6–6.0), Slightly (S.) Acid (6.1–6.5), Neutral (Neu.) (6.6–7.3), Slightly Alkaline (S. Alk.) (7.4–7.8), Moderately Alkaline (Mod. Alk.) (7.9–8.4), Strongly Alkaline (Str. Alk) (8.5–9.0), and Very Strongly Alkaline (V.S. Alk.) (>9.0). Texture includes organic (O), sand or sandy (S), silt or silty (Si), clay or clayey (C), and loam or loamy (L).

past several thousand years. Marsh soils have formed over underlying terrestrial soils (Table 2.8). As a result of greater inundation from rising sea levels, organic soils have typically developed with organic soil depth greatest at the seawater interface with a narrowing toward the upland interface (Rabenhorst 2001). All three wetland types are marshes consisting of salt tolerant grass or grass-like vegetation (e.g., sedges and rushes). Along the Gulf Coast, mangroves are also an important vegetation component of some marshes. Marsh vegetation is an important contributor of organic matter to the soils and slows the velocity of receding tides, allowing for mineral and organic deposition originating from outside the marsh. [SMF9]

CONCLUSIONS

In the first part of the chapter, we introduced the geomorphic conditions and soil processes that lead to the development of wetland soils. *Wetlands,* as suggested by the term, are wet. Soils that are permanently or periodically saturated with water develop differently than upland soils because of the biogeochemical reactions and microbial interactions in low oxygen conditions.

Although there are numerous exceptions, wetlands are commonly found in lower parts of the landscape where water is focused as a result of geomorphic processes. Alternatively, water can be perched higher up in the landscape as a result of impermeable soil layers being present. Typically, groundwater is very different chemically than water derived from surface or subsurface runoff. A connection to regional groundwater can influence both the vegetation communities and the biogeochemical processes occurring in wetlands. Groundwater-influenced wetlands also tend to have more consistent hydrology than those fed by only precipitation and runoff.

In the second part of the chapter, we introduced three groups of wetlands based on their geomorphology. Depressional wetlands develop in dips or holes in landscape where water is either focused or groundwater connections exists. Terrestrialization, or filling in of water bodies with organic material is an important process in depressional wetland development. Examples of depressional wetlands include bogs, prairie potholes, Carolina bays, cypress domes, and seasonal wetlands. Nondepressional wetlands occur as a result of numerous geomorphic and hydrologic conditions ranging from river flooding to groundwater influences. In some cases such as northern fens and pocosins, paludification––or blanketing an entire area with organic material––is an important wetland process. Other nondepressional wetlands include southern swamps and marshes, Atlantic white cedar swamps, riverine wetlands, and freshwater shoreline wetlands. Finally, we discussed three geomorphic types of estuarine wetlands or wetlands that are influenced by ocean tides. Estuarine marshes develop on alluvial sediment deposits of streams entering the ocean. Submerging coastal marshes are found in lagoon settings behind barrier islands. Submerged upland marshes occur where coastal marshes are creeping farther inland as a result of rising ocean levels.

It is important to realize that these broad groups of wetlands we have presented do not encompass all wetlands on the planet or even in North America. However, understanding the soil, geomorphic and hydrologic processes that lead to the development of the wetlands presented in this chapter should lead to an understanding of wetland development anywhere.