A Guide to Hydric Soils in the Mid-Atlantic Region

Version 1.0

Mid-Atlantic
Hydric Soils Committee

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Editors

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Cover: A profile of Othello silt loam (fine-silty, mixed, active, mesic Typic Endoaquults) from a mineral flat in Queen Anne's County, Maryland. This hydric soil meets Field Indicator F3 (Depleted Matrix). (Photo by M.C. Rabenhorst)

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Chapter 1
Hydric Soils and Wetland Functions

Bruce L. Vasilas

Introduction

Wetland functions are the biological, chemical, and physical processes that occur in wetlands. Wetland values are the benefits of these functions to society. Wetland functions are frequently classified as hydrologic, biogeochemical, or those functions that pertain to food webs and wildlife habitat. This chapter concentrates on wetland functions that are directly attributable to the soil component of wetlands, especially the role of hydric soils in affecting water quality. Hydric soils play a direct role in the wetland functions of water retention, sedimentation, and biogeochemical cycling of nutrients. In turn, these functions contribute to the development of hydric soils. Water retention leads to anaerobiosis, and sedimentation and carbon (C) sequestration provide inputs for soil formation. Redox reactions are critical to the development of hydric soil indicators and to the cycling of nitrogen (N), C, sulfur (S), iron (Fe), and manganese (Mn). Hydric soils provide the chemical environment and habitat for biogeochemical cycling. The efficiency of wetlands in biogeochemical cycling is directly linked to the close proximity of aerobic and anaerobic zones and to the cycles of wet and dry periods in hydric soils.

Hydrology

Wetlands are diverse ecosystems. Inherent to all wetlands, however, is the function of storage of excess water during some period. The volume of water stored depends on landscape position, microtopography, and the depth and porosity of the soil. By intercepting and storing storm water, hydric soils and the wetlands they occupy change sharp runoff peaks to slower discharges over longer periods of time. Wetlands also moderate ground water flow and discharge, and they effect dissipation of energy as water moves across the soil surface. These functions contribute significantly to the following values: flooding mitigation, soil conservation, aquifer recharge, water purification, and fish and wildlife habitat. Ground water recharge of as much as 20 percent of wetland volume annually is possible in some systems (Weller, 1981). It is believed that wetlands do not contribute significantly to aquifer recharge in the Mid-Atlantic Region because of the presence of impermeable or slowly permeable horizons in most of the hydric soils. Aquifer recharge occurs primarily on the edges of wetlands, and the rate of recharge is proportional to the edge-to-surface area ratio; therefore, aquifer recharge is most dynamic on an area basis in small wetlands.

Water Quality

Sedimentation is the removal of particulate matter from a water column. Wetlands typically trap 80 to 90 percent of sediment from runoff water (Johnston, 1991; Gilliam, 1994). Sedimentation is a relatively irreversible process that improves water quality by removing pollutants and pathogens adsorbed to the suspended solids, by removing a source of turbidity, and by decreasing biochemical oxygen demand (BOD)—the quantity of oxygen (O_2) required to decompose organic matter and oxidize inorganic compounds such as sulfides (S^{2-}). High BOD levels associated with loading a water source with organic matter such as sewage effluent leads to low levels of dissolved O_2, which can be detrimental to aquatic life. Wetlands can remove close to 100 percent of the BOD in the water column (Hemond and Benoit, 1988).

Mechanisms for nutrient/pollutant removal from water in wetlands include assimilation by higher plants, algae, and bacteria; chemical precipitation; sorption to soil colloids; and denitrification.

Nutrient cycling involves the processes of mineralization, immobilization, and transformation. Mineralization is the conversion of a nutrient from an organic form to an inorganic (mineral) form through the decomposition of organic matter. This process is critical to plant nutrition. For example, during the decomposition of proteins, amino acids are converted to carbon dioxide (CO_2) and ammonium (NH_4^+), which are easily assimilated by plants. Immobilization is the conversion of nutrients from inorganic forms to organic forms through assimilation by microbes and plants. Transformation refers to the conversion of a nutrient from one mineral form to another. Mineralization and immobilization are biologically mediated. Transformations are biologically and chemically mediated. Once a nutrient enters a wetland it may be altered, stored, or discharged via water and atmospheric fluxes.

Redox Reactions

Oxidation-reduction (redox) reactions are characterized by the transfer of electrons from one compound to another. In every redox reaction one compound is reduced (accepts electrons) and one compound is oxidized (donates electrons). Oxidation of organic compounds is the driving force in most redox reactions and results in the decomposition of soil organic matter. Under aerobic conditions O_2 is the terminal electron acceptor. In the absence of O_2, first nitrate (NO_3^-), then the manganic (oxidized) form of manganese (Mn^{4+}), then ferric iron (Fe^{3+}), then sulfate (SO_4^{2-}), and finally carbonate (CO_3^{2-}) serve as electron acceptors. Redox potential (Eh) is a measure of the tendency of a system to donate electrons (reduce). Since Eh represents an electrical potential, it is measured in millivolts. A soil is considered to have reducing conditions when iron is present in its reduced form (ferrous, Fe^{2+}).

Carbon Cycle

A biogeochemical function can be characterized in terms of inputs and outputs. For the C cycle the major inputs and outputs will depend on whether

the system is aerobic or anaerobic. In aerobic zones the major input is the assimilation of CO_2 into plant tissue via photosynthesis. Some C may enter the system as carbonates. The major output is CO_2 generated via aerobic respiration. In anaerobic zones, the major processes of C transformations are anaerobic respiration, fermentation, and methanogenesis. Anaerobic respiration and fermentation convert organic compounds into organic acids and alcohols. Under aerobic conditions, organic acids and alcohols are readily degraded by microbes into CO_2 and water. Methanogenesis is the microbial reduction of CO_2 to methane (CH_4), which is also known as swamp gas. Aerobic respiration is much more efficient than anaerobic respiration or fermentation, and the end product (CO_2) quickly leaves the system. Soil organic matter accumulates when biomass additions to the soil exceed microbial degradation; therefore, all other things being equal, a hydric soil will contain more organic matter than an upland soil. The organic matter content of a hydric soil will depend on the rate of primary biomass production and the duration of anaerobic conditions each year; however, in general, wetlands can be considered to be C sinks (i.e., a net accumulation of C in most years). Draining a wetland will lead to significant C losses through increased aerobic respiration and subsequent emissions to the atmosphere.

Nitrogen Cycle

Nitrogen enters wetlands via surface and ground waters, precipitation, and dinitrogen fixation. Dinitrogen fixation is the conversion of dinitrogen gas (N_2) to ammonia (NH_3), which is quickly converted to ammonium (NH_4^+). It is mediated by certain species of bacteria and algae, both as free living organisms and in symbiosis with higher plants such as alders and legumes. Precipitation supplies 15 to 20 lb N/acre/yr (17 to 22 kg/ha/yr). High fluxes of N to wetlands are generally the result of pollution, such as that from agricultural production systems.

Nitrogen is found in both organic and inorganic forms in soils. Inorganic forms and low molecular weight organic forms, such as amino acids, move readily between the soil and the water column. Most N transformations are mediated by bacteria, and the rate and direction of the transformation are influenced by soil pH and Eh. Nitrogen mineralization is the conversion of organic forms to inorganic forms during the decomposition of organic matter. Unless influenced by pollution, inorganic N levels in natural wetlands will be low. Mineralization rates will be low under anaerobic conditions, and mineralized N is readily assimilated by plants and microbes. Also, inorganic forms of N are unstable and readily transformed to water soluble or gaseous forms. One component of mineralization is ammonification, a process in which organic N is converted to NH_4^+. Nitrification is the conversion of NH_4^+ to NO_3^-. Ammonium can be held on soil exchange sites or fixed in clay lattices. Nitrate moves freely in the water column and readily leaves discharge systems. Denitrification is the reduction of NO_3^- under anaerobic conditions to gaseous forms (N_2, N_2O, NO) that quickly leave the system. It is the main reason why constructed wetlands are so effective at removing N from wastewater

(Johnston, 1991). When a surplus of available organic C is available, bacteria also convert NO_3^- to NH_4^+, a process referred to as "dissimilatory nitrate reduction." Under high pH conditions, a common occurrence in marshes with excessive algal blooms, NH_4^+ will be chemically converted to NH_3, which leaves the system as a gas. The efficiency of N removal from water moving through wetlands is generally in the range of 70 to 90 percent (Reilly, 1991).

Phosphorous

Natural wetlands are not as effective as upland ecosystems in serving as phosphorous (P) sinks. Phosphorus enters a wetland in both organic and inorganic forms and in both dissolved and particulate states. Unlike N, there is no mechanism for P losses to the atmosphere. Principal P removal mechanisms are precipitation as calcium (Ca) phosphates under high pH, precipitation as Fe and aluminum (Al) phosphates under acidic conditions, sorption to soil colloids, and assimilation by microbes and macrophytes. Biological assimilation represents short-term storage. Sediment/peat accumulation is the major long-term sink when the organisms die and their tissue becomes part of the litter zone. The interchange of P between soil and water phases depends on concentration gradients; pH; dissolved O_2 levels; concentrations of soluble Fe, Al, and Ca; intrinsic P levels; and hydrologic gradients and cycles. Soil can be a significant sink as dissolved, inorganic P is removed by adsorption to clays and precipitation as insoluble complexes of Fe, Al, and Ca. The efficiency of P removal from water entering wetlands is generally in the range of 40 to 50 percent (Gilliam, 1994; Johnston, 1991). However, some riverine wetlands can remove considerably higher quantities of P because of the high levels of Al and Fe associated with clays deposited in flood plains (Gambrell, 1994).

Wetland soils, especially those that are low in Fe and Al, can become saturated with P and serve as a source of P to surface and ground water systems. This export of P from wetlands is seasonal; as organic matter decomposes in the late summer, fall, and winter, P is released into the water column (Richardson, 1985). Drainage of wetlands can lead to significant loading of P into ditches, tile drains, streams, etc.

Sulfur Cycle

Sulfur enters wetlands primarily in the form of sulfate (SO_4^{2-}). Both oxidation and reduction of S compounds occur in hydric soils. Under aerobic conditions, Thiobacillus bacteria obtain energy through the oxidation of S. Other bacteria oxidize sulfides (S^{2-}) to elemental S (S^o), which, in turn, is oxidized to SO_4^{2-}. Under anaerobic conditions, once NO_3^-, Mn^{4+}, and Fe^{3+} are no longer available, obligate anaerobic bacteria use SO_4^{2-} as a terminal electron acceptor producing hydrogen sulfide (H_2S), which is the source of the rotten egg smell associated with some hydric soils. Purple sulfur bacteria use H_2S instead of water as an electron donor in photosynthesis and release S^o in the process. Sulfur cycling is extensive in tidal marsh soils. There is a constant supply of S in the water, and S reduction is most prevalent when pH is near neutral, as is common in tidal

marsh soils. Consequently, S^{2-} build up in the sediments. Oxidation of S compounds is an acidifying process. Draining these soils leads to the production of sulfuric acid, which may drop the pH to a level of 1.5.

Heavy Metals

Because of the health and ecological risks associated with heavy metal contamination of water, removal of metals from the water column is a critical function of wetlands. Depending on the metal and wetland characteristics, wetlands remove 20 to 100 percent of the metals in water passing through the area (Taylor et al., 1990). Tidal marshes are especially critical to this function because many are located near major cities and industries in the Mid-Atlantic Region. Vegetation appears to play a minor role in metal sequestration. Metal removal is primarily due to physical and chemical processes, such as the binding of metals to the ionized surface of clay particles or humic materials (peat), or precipitation as inorganic compounds, such as metal oxides, hydroxides, phosphates, and carbonates. Therefore, most of the metals accumulate in the upper part of the soil profile or in the sediments.

Chapter 2
The Factors of Soil Formation

Martin C. Rabenhorst

What is the Soil?

Soil can be defined in a variety of ways depending on one's outlook and purpose for considering or looking at soil, and these multiple views are not incompatible with each other. One person might think of soil as a medium from which plants extract water and nutrients in order to grow, while another might consider soil as a waste disposal medium that functions as a chemical and biological reactor to ameliorate elements harmful to the environment. Still another person might alternatively consider soil to be simply material with certain physical properties, within or upon which buildings or roads will be built. Most pedologists (soil scientists) consider soil to be a natural, three-dimensional entity occurring at the Earth's surface with identifiable horizons (layers), which have formed as a result of five soil-forming factors. These five factors are climate, organisms, parent material (geology), relief (topography), and time (Jenny, 1941). While each soil-forming factor can be considered individually, one should keep in mind that, in reality, the factors are often interrelated and interdependent.

$$\mathbf{S} = f\,(\mathbf{C, O, P, R, T})$$

Climate

The two major components of climate that affect soils are precipitation (mainly rainfall) and temperature. In some regions climatic variations are gradual over large distances. In some situations, however, climactic changes may be much more abrupt. Rainfall contributes moisture to the soil, after which important chemical reactions and biological activity can occur. In the eastern U.S.A. and other areas where rainfall is abundant and precipitation exceeds evapotranspiration, an excess of moisture may accumulate in the soil, causing percolation and leaching of soluble chemical constituents. Depending on the degree of leaching, soils may become acid to varying degrees. In parts of the western U.S.A. where rainfall is more limited and evapotranspiration exceeds precipitation, soluble chemical components may actually accumulate in the soil. Certain soil horizons may be especially enriched in calcium carbonate or gypsum (fig. 2-1).

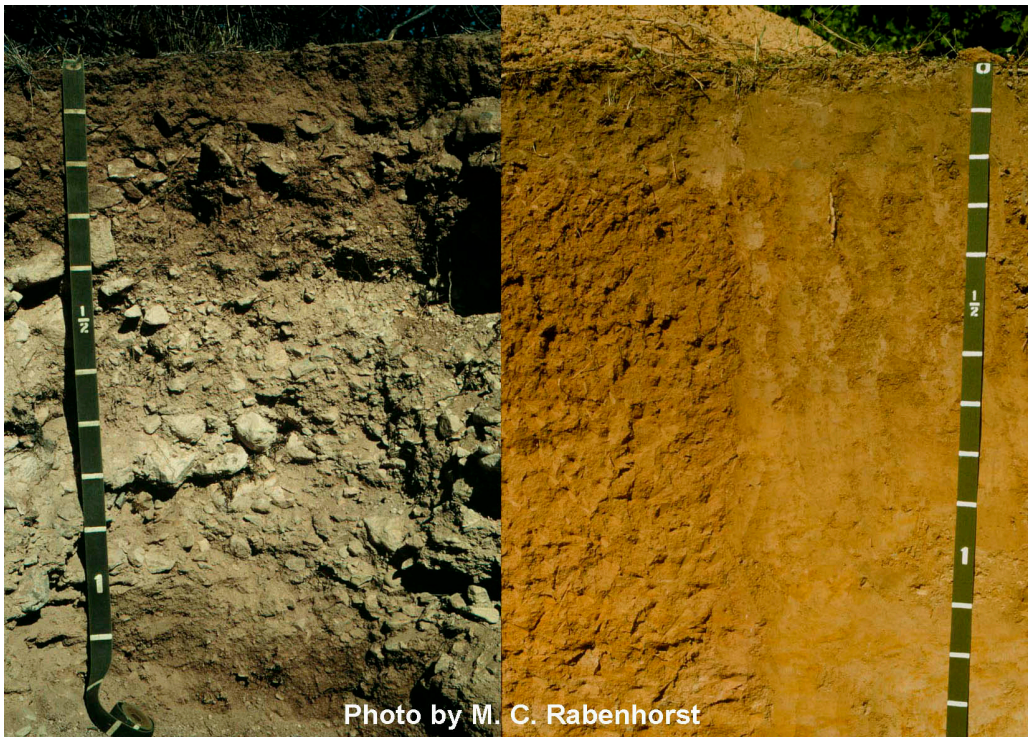

Figure 2-1.—These two soil profiles formed under dramatically different climates. The soil on the left formed under an arid climate (annual rainfall 12 in, or 300 mm) and has a zone of calcium carbonate accumulation in the Bk horizon that extends from 16 to 40 in (40 to 100 cm). The pH in the Bk horizon is approximately 8.1. The soil shown on the right formed in a humid environment (annual rainfall 44 in, or 1,100 mm) where soluble weathering products are quickly leached from the soil. This soil profile has no carbonates present at all. The pH of the Bt horizon, which extends from 8 to 28 in (20 to 70 cm), is approximately 5.5. Scale is in 4-in increments (10 cm).

Temperature also affects the moisture state of the soil because higher temperatures generally lead to greater evapotranspiration. Thus, the degree of leaching in a soil is related to temperature, as well as to rainfall. The balance between rainfall and precipitation will also affect the likelihood that a soil may have a seasonal high water table (where the soil porosity becomes filled with water and saturated close to the soil surface). Temperature also affects chemical reactions in the soil. The rates of most chemical reactions increase as temperatures rise. This is as true in the field as it is in the laboratory. The degradation and weathering of rocks and minerals in the soil is driven by various chemical reactions. Therefore, the weathering of soil minerals and rocks may be much more dramatic in warmer regions (such as the southeastern U.S.A.) than in the cooler ones (such as the Mid-Atlantic Region). Similarly, the decomposition of soil organic matter is generally faster under warmer soil conditions.

Organisms

Organisms that affect soil formation are both large and small and include plants, animals, and humans. The effects of large animals, such as burrowing rodents, often are more dramatic when observed but are probably less important than those of smaller invertebrates, such as earthworms and insects, that often ingest soil and help form small aggregates of finer mineral particles and, in special instances, cause significant mixing of the upper soil horizons (fig. 2-2).

Figure 2-2.—Soil organisms such as ants or termites can cause significant mixing of the upper horizons of the soil. Termites have mixed the soil during the formation of mounds in this Australian landscape.

All organisms living on or in the soil contribute organic matter to the soil, but the contributions by plants are generally held to be much greater than those of animals. Plants contribute organic matter to the soil directly as their roots grow and then die within the soil, and they also add organic matter to the surface through the senescence of above ground parts (such as stem or leaf fall). Soil animals may then help to incorporate leaves and stem parts into the soil. Different types of plants contribute different amounts of organic matter to the soil through leaves v. below ground parts. In the Great Plains, for example, grasses add a great deal of organic matter to the soil through their roots. This organic matter may extend to a depth of as much as 3 ft (1 m). Trees, on the other hand, contribute a greater proportion of organic matter onto the soil surface. Thus, the organic rich A horizons of prairie soils tend to be thicker and darker than those of soils formed under forest vegetation (fig. 2-3).

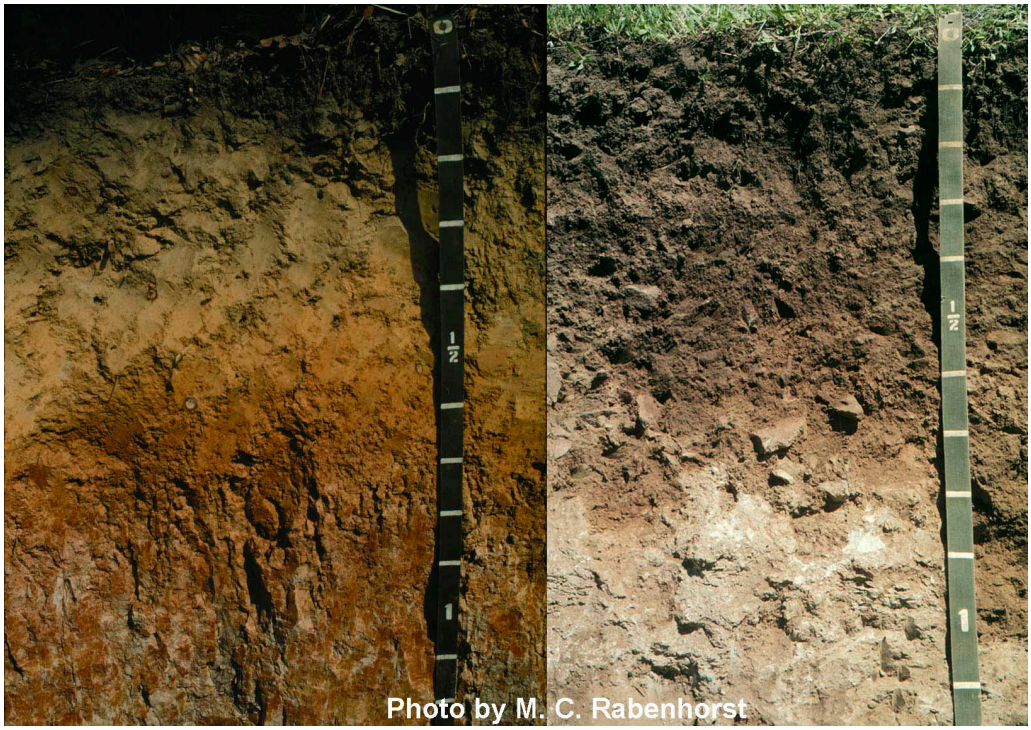

Figure 2-3.—The soil on the left, which has a fairly thin A horizon, formed under forest vegetation where much of the organic matter is added to the soil surface during leaf fall. The soil on the right, which has a much thicker A horizon, formed under prairie vegetation where much of the organic matter is added within the soil by grass roots. Scale is in 4-in increments (10 cm).

The nature of the organic debris from plants may also differ chemically. Certain plants, such as conifers and heather, tend to be very acidic, and their contribution of acidic organic matter may accentuate acid weathering reactions in some soils.

Humans often have profound effects on soil formation through alteration of soils and all five of the soil-forming factors. Humans alter soil climate (hydrology) by irrigating, flooding, ponding, and draining soils. Native vegetation is altered by agriculture and forestry, which further impact organic and nutrient cycling and hydrology. Heavy equipment is used to construct new landforms and alter relief on existing landforms. This often results in destruction of existing soil properties and the renewal of soil-forming processes as old soils are transformed into new soils.

Parent Material

Parent material is the geological material from which the soil originated. Parent materials may be residual, meaning that they are derived from the underlying, hard, consolidated bedrock (such as granite or limestone). They may also be transported, meaning that they have been moved by some agent, such as water, ice, wind, or gravity, and then subsequently deposited.

These parent materials include alluvium deposited by streams, till and outwash deposited by glaciers, loess and dune sand deposited by wind, and colluvium deposited downslope by gravity (fig. 2-4). Because the parent materials represent the starting point of soils, they often contribute many significant properties to the soils (as do parents contribute genetically to the characteristics of their offspring). The particle size, mineralogy, chemistry, and color of soils may all be initially related to (inherited from) the properties of the parent material. In locations where the diversity of parent materials is great over relatively small distances, there may be a disproportionately large number of different soils that form.

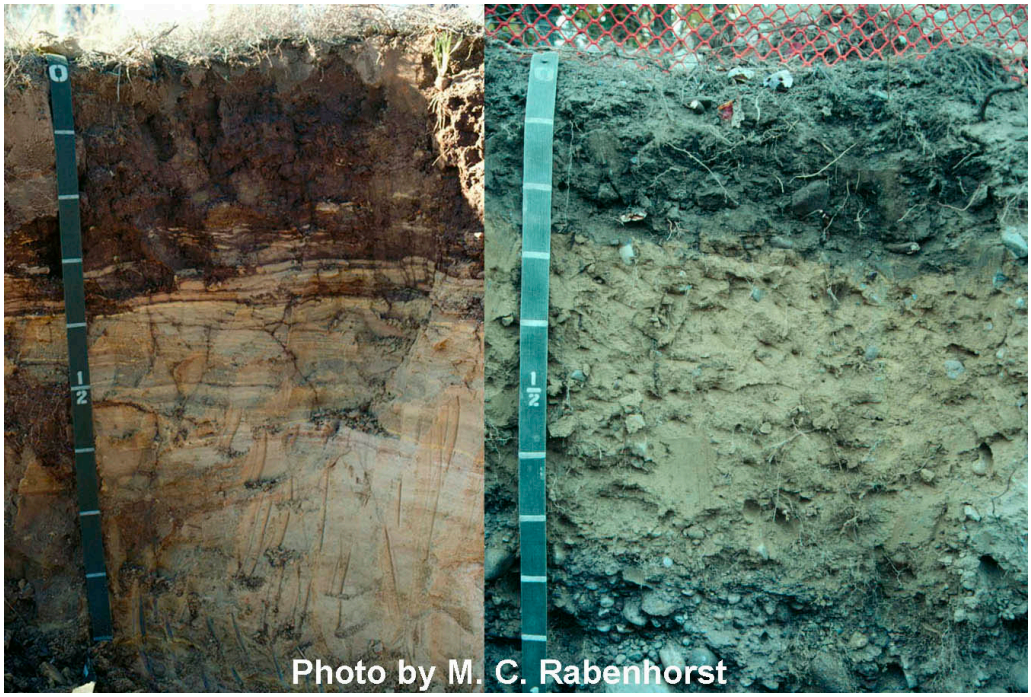

Figure 2-4.—The soil on the left formed in gray shale residuum. The shale bedrock is evident at a depth of about 16 in (40 cm). The soil on the right formed in sandy and gravelly sediments deposited by melting glaciers. Scale is in 4-in increments (10 cm).

Relief/Topography

Relief and topography refer to differences in the magnitude of slope, differences in location on the landscape (e.g., summit, shoulder, backslope, footslope), and differences in slope aspect (i.e., N, S, E, W). Both the position of a soil on the landscape as well as the magnitude of the slope (2 percent vs. 10 percent vs. 30 percent) have major effects on the degree to which a given soil is likely to be eroded (convex shoulders or steep backslopes) or is likely to receive additions of newly deposited materials (concave footslopes) or where it is likely to remain stable and experience little erosion or deposition (nearly level summits) (fig. 2-5).

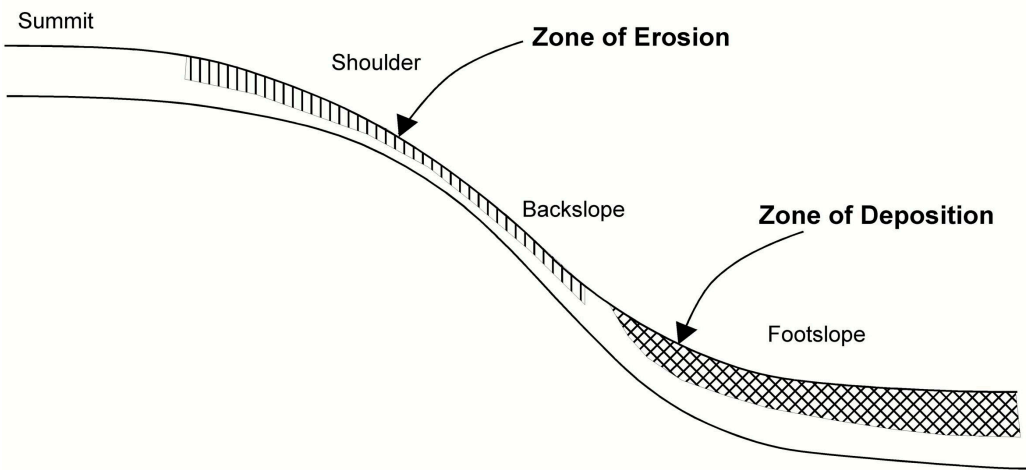

Figure 2-5.—A schematic diagram of a hillslope illustrating the various components. Erosional processes are generally most dramatic along the shoulder and backslope portions of the hillslope, and depositional processes are most pronounced in the footslope portion.

There may also be hydrological effects caused by the location of a soil along a particular landscape. The depth to the water table is generally not uniform across dissected landscapes. Soils occurring at particular positions on the landscape may be poorly drained; while well drained soils may be in close proximity but in other landscape settings. In highly dissected areas with steep slopes, the aspect of the slope may cause the soil temperatures to be different on north-facing slopes than those on south-facing slopes. As one might expect, soils on steep north-facing slopes tend to have cooler soil temperatures than those on the corresponding south-facing slopes. In general, the relief/topography factor of soil formation affects the erosion/sedimentation processes and also mediates climatic conditions (meaning that it can cause a soil to be wetter, drier, warmer, or cooler than it would otherwise be).

Time

The time factor is related to the age of the soil and must not be confused with the age of the parent material. The age of a soil is the amount of time that has passed since other soil-forming factors (climate, organisms, and relief) first began to impact the parent material and to form soil horizons. The age of soils may range from a few years (such as in soils formed in recent landslide deposits) all the way to millions of years (in the case of soils formed on very stable landscapes). The parent materials may be much older than the soil. For example, relatively recent tectonic uplift and erosion may have exposed granitic bedrock of Precambrian age (approximately 1 billion years old), but the landscape itself may have only been exposed to soil-forming processes a much shorter time—perhaps a few hundred thousand years ago.

Alternatively, the age of a soil may be approximately equal to the age of a glacial till deposit in which it has formed. Determining the age of a soil is often a difficult task, and in some cases there may be no clear way to accurately assess soil age.

In general, younger soils tend to strongly reflect the properties of their parent material. A soil that is 1 day old would look much like the parent material. As time goes on, soil-forming processes driven by soil-forming factors gradually cause changes in the parent material leading to the formation of soil horizons with distinct morphological, physical, chemical, mineralogical, and biological properties (fig. 2-6). Time then becomes the matrix within which the other soil-forming factors operate.

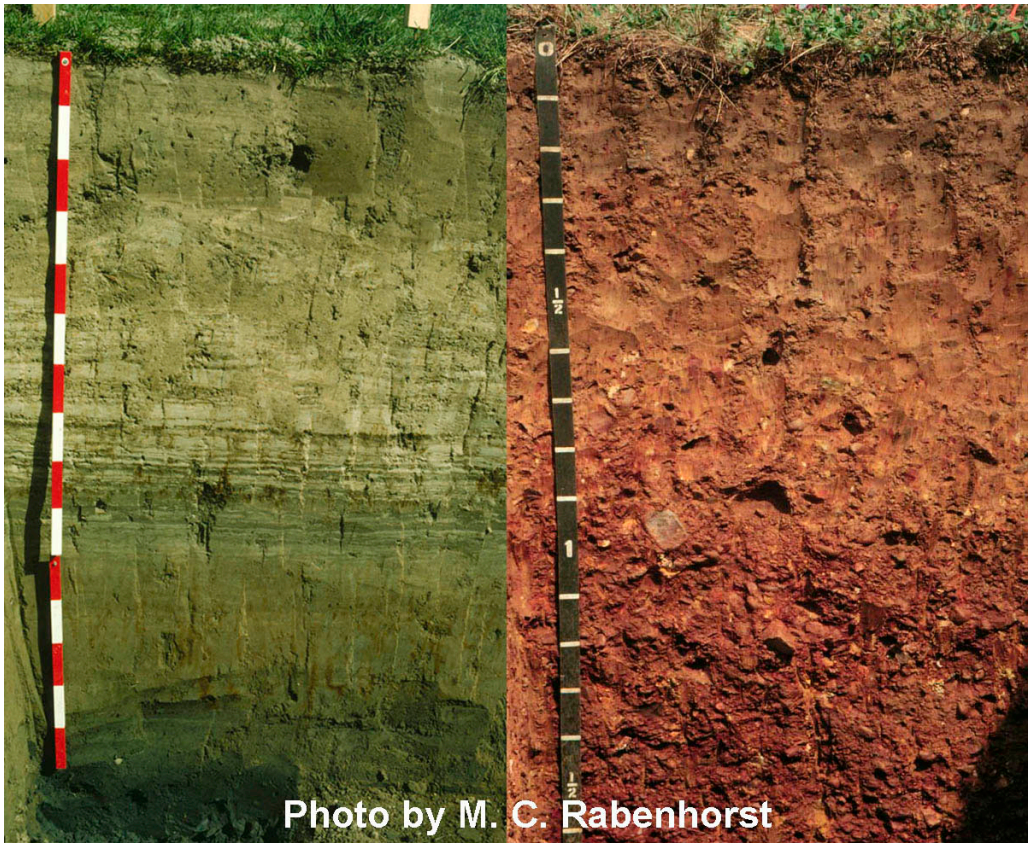

Figure 2-6.—The soil on the left is young (i.e., less than 100 years old), having formed in sediments deposited in the early 19th century. Note the absence of well developed horizons and the preservation of original sedimentary stratification at a depth of more than 20 in (50 cm). The very old soil on the right formed in terrace deposits, which are perhaps as much as 1 million years old. It has a strong argillic (Bt) horizon that begins at a depth of about 24 in (60 cm) and extends to a depth of almost 10 ft (3 m). Scale is in 4-in increments (10 cm).

Summary

There have been many published efforts to consider individual soil-forming factors and to try to analyze them in a quantitative fashion. These efforts have given rise to various mathematical functions, such as climofunctions, lithofunctions, and chronofunctions (or where the effects of climate, parent material, and time were evaluated, respectively). Although the five factors are often considered and evaluated as independent factors, often they function and interact in a way that reflects some degree of interdependency. As the climate changes across a region, for example, it is quite common for the vegetation to also demonstrate some systematic change that corresponds to the change in climate. Nevertheless, by considering the contributions that each of the five factors make toward the genesis of a soil, a person gains an important and invaluable understanding of the pedogenetic processes involved.

Chapter 3

Pedogenesis of Hydric Soils—Hydropedology

Martin C. Rabenhorst

Introduction

According to a model describing the fundamental processes of soil genesis, all of the processes related to the formation of soils can be summarized under one of four generalized processes (Simonson, 1959). These four processes are (1) additions of materials to the soil, such as physical deposition, the primary productivity of plants, or soluble components being contributed in surface water or ground water; (2) losses of components from the soil system, such as through erosion or leaching; (3) translocations or transfers of components from one place within the soil to another; and (4) transformations of organic or mineral components into another form—either mineral or chemical species—through biological or geochemical processes.

In many cases soil formation may involve a combination of two or more of these generalized processes. For example, the development of an A horizon in a soil involves (1) the addition of plant materials at and below the soil surface; (2) some transfers of organic materials from the surface to within the upper portion of the soil, often via the vector of invertebrate organisms; and (3) the biochemical transformation of fresh plant material into more humified forms, which are commonly observed in the A horizon of soils. Simonson's generalized model provides an excellent context within which to understand the pedogenesis of hydric soils. After a brief consideration of the conditions unique to hydric soils, various processes falling within the four generalized processes of Simonson's model in the formation of hydric soils will be examined.

Fundamentals of Soil Color

Many of the morphological features used in recognizing hydric soils are related to soil color and color patterns. Three fundamental components give soil its colors. First, there are the silicate mineral grains—sand, silt, and clay—themselves. When uncoated, these silicate grains are generally gray or white. Occasionally, uncoated soil minerals may appear to contribute other colors due to the presence of less common minerals such as microcline, which may be pink, or glauconite, which is green (fig. 3-1).

Figure 3-1.—Note the variety in color of uncoated mineral grains, which contribute to the color of soils. Iron oxides were removed from these soil materials, which are from six different soil series that formed in a variety of parent material.

The white sands on many beaches are common examples of uncoated silicate grains. The gray colors often associated with poorly drained soils also represent the colors of uncoated silicates. Most of the time, however, soils are not white or gray but various shades of brown to black and yellow, orange, or red due to the presence of the other two fundamental soil-coloring agents—organic matter (OM) and iron (Fe) oxides. The OM and Fe oxides have been dubbed "soil paints" (fig. 3-2). The darker colors commonly associated with A, O, and, less commonly, Bh horizons are caused by the presence of OM that covers, masks, or, in some cases, coats the silicate mineral grains. The source of OM in soils is primarily plants. As microbes decompose fresh plant material added to the soil, more humified components accumulate. Generally, the greater the quantity of soil OM, the darker the soil will appear; however, the color is also affected by the type or source of the OM (Schulze et al., 1993).

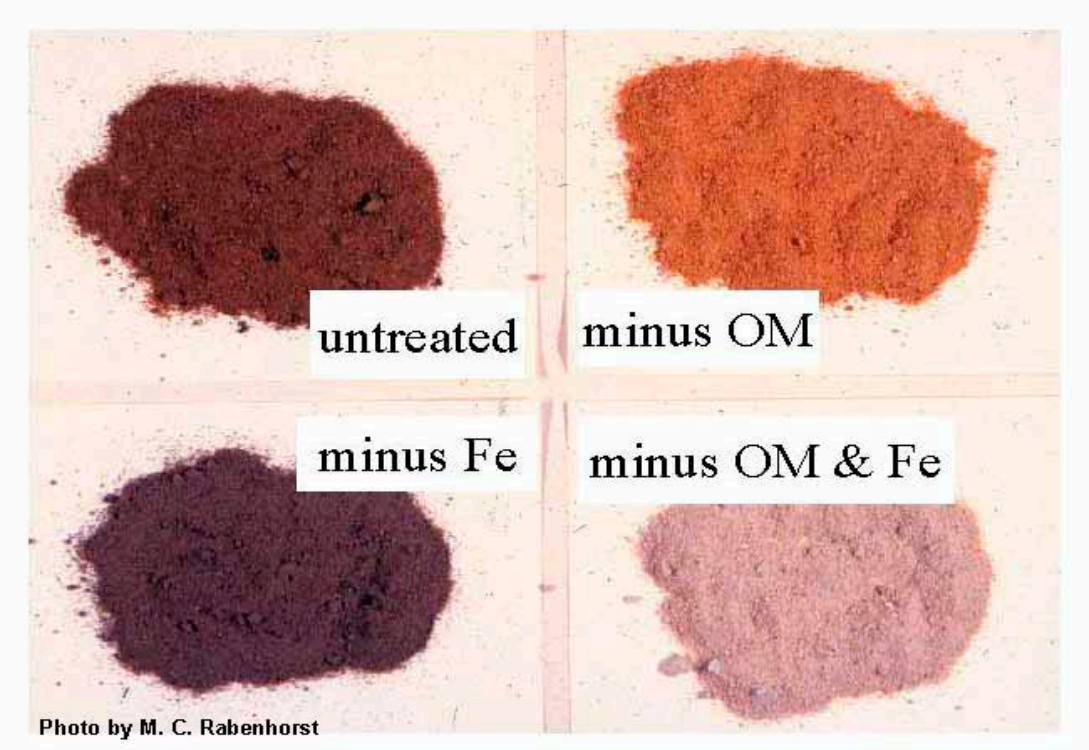

Figure 3-2.—The contributions of organic matter and iron oxides to soil color are evident in this soil sample of an Ap horizon from which organic matter and iron oxides have been removed.

From the surface horizon down to the subsoil, the quantity of organic compounds decreases markedly and those compounds have much less effect on soil color than the other major soil paint—Fe oxides (fig. 3-3). The phrase Fe oxides will be used to refer to both true oxides, such as hematite (Fe_2O_3), and oxyhydroxides, such as goethite (FeOOH). The covering or coating of silicate minerals with thin veneers of Fe oxides gives soils their yellow, red, or brown appearance. The origin of most Fe oxides is from the weathering of Fe-bearing silicates, such as biotite, amphiboles, pyroxenes, olivine, and, to a lesser extent, sulfides, such as pyrite. These minerals contain Fe in the ferrous (II) form. As the Fe(II) is released during mineral weathering, the Fe is generally oxidized to Fe(III) and then precipitated as a mineral. The actual color—hue, value, and chroma—of soils coated with Fe oxides is related to the type of Fe oxide mineral present, of which goethite, hematite, ferrihydrite, and lepidocrocite are the most common in soils; the quantity of the oxide present, which often affects the intensity of the color due to the thickness of the coatings on the silicates; and the crystal size of the Fe oxide minerals themselves (Schwertmann, 1993). In many cases, finer and larger crystals of the same Fe oxide contribute very different colors to the soil. In summary, the combined effects of the silicate mineral grains, the soil OM, and the Fe oxides determine what colors appear in the soil.

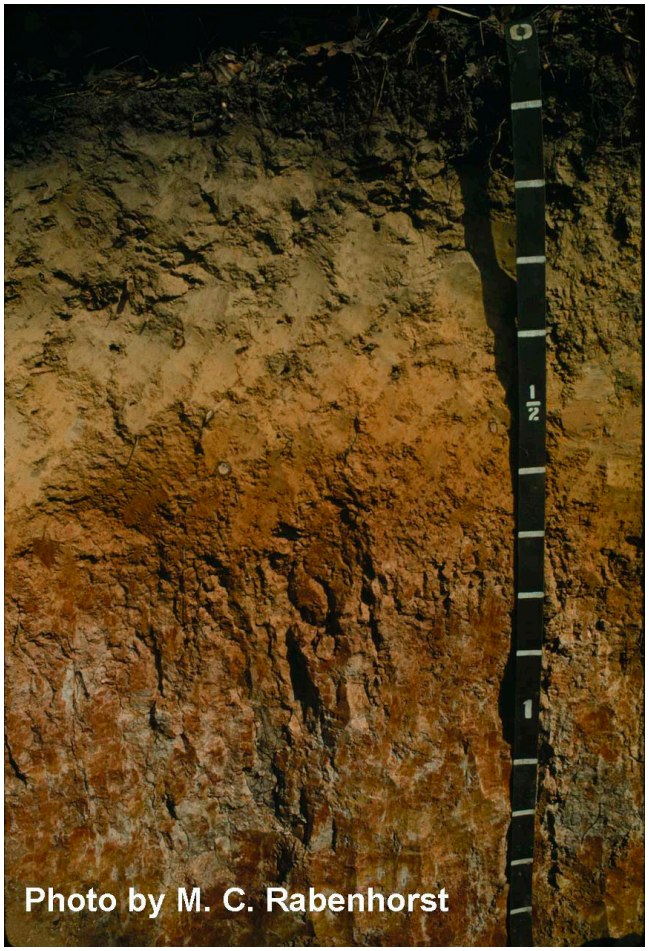

Figure 3-3.—The dark colors of the A horizon in this soil are due to enrichment with organic matter, while the reddish colors of the subsoil are primarily due to the coatings of iron oxides. Gray colors represent uncoated mineral grains where the iron oxides have been depleted.

The Uniqueness of Hydric Soils

According to scientific consensus and underscored by Federal regulations, a hydric soil is defined as "a soil 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, July 13, 1994). There are four important parts to this definition. The phrase "formed under conditions of" underlines the overall importance of pedogenesis, or soil formation, and implies that the present condition of the soil is less important than those conditions during the formation of the soil. It also implies that once a soil is hydric, it always is hydric; even if later, for example, hydrological properties become altered through a natural or constructed drainage system. The phrase "saturation, flooding, or ponding" refers to the driving force behind the formation of hydric soils, which is the hydrology—the water. The phrase "long

enough during the growing season" refers to auxiliary conditions and has recently been the focus of considerable debate. As will be discussed later, the relative significance of this phrase depends on whether one is concerned primarily with impacts on higher plants or, as the phrase that follows it implies, one is more concerned with temperature effects on the soil microbial activity. The final phrase "to develop anaerobic conditions in the upper part" refers to the effects that the previous conditions produce. This is the final result and ultimately the basis for concluding whether or not a soil is hydric. In short, what is unique to hydric soils is they formed under saturated conditions that led to anaerobiosis in the upper part of the soil.

From a pedogenic perspective, there are several conditions that must occur for anaerobic conditions to develop in hydric soils (table 3-1). First, the soil must experience saturation. Saturated conditions can be induced either by water covering the soil surface (flooding or ponding) or by a seasonal high ground water table. The significance of saturation is that essentially all of the soil pores become occupied by water rather than by air. This dramatically decreases the rate of diffusion of oxygen (O_2) into the soil. The rate of O_2 diffusion through water is approximately four orders of magnitude slower (10^{-4}) than that through air. For a saturated soil to become anaerobic, however, the O_2 dissolved in the soil water must be removed or consumed. Without this, a saturated soil may remain aerobic indefinitely. It is heterotrophic soil microbes that are responsible for the removal/consumption of dissolved O_2 in saturated soils. Microbes are nearly ubiquitous in soils, and estimates of microbial counts in soils often range up to 10^9 to 10^{10} per ounce (10^8 to 10^9 per gram) (Brady and Weil, 2002). To remove dissolved O_2 from the saturated soil, however, heterotrophic microbes must actively oxidize a source of energy that yields electrons for the reduction of O_2. In most soils, OM from plants provides the energy source used by heterotrophic microbes in affecting biochemical changes to the soil. As microbes oxidize the carbon (C) in plant OM to obtain energy [transforming the carbohydrates to carbon dioxide (CO_2)], electrons are released that reduce molecular O_2 to water.

Table 3-1.—Factors Necessary for the Formation of Anaerobic Conditions in Soils

1. Saturation of soil pores with water
2. The presence of heterotrophic microorganisms
3. The presence of a source of oxidizable organic matter (OM)
4. Temperatures sufficiently warm for microbial activity

The rates of biochemical reactions increase with warmer soil temperatures and decrease with cooler temperatures. Therefore, in order for the heterotrophic aerobes to be sufficiently active so that O_2 is reduced faster than it is replenished by diffusion through the saturated soil (leading to depletion of O_2 and the development of anaerobic conditions), all of the requisite conditions must occur at a time when the soil is experiencing sufficiently warm temperatures. During the winter when soil temperatures are much cooler, it takes much longer for a saturated soil to become anaerobic than when the soil temperatures are warmer. Some have suggested that if soil temperatures fall below 41 °F (5 °C), soil microbes become essentially inactive. This temperature threshold has been termed biological zero, and the concept has sometimes been associated with growing season in the hydric soil definition. The validity of biological zero has been debated on two fronts. In the first place, microbes are generally adapted to their environment, and there is evidence that in Alaska, for example, soil microbes will continue to metabolize, even in soils that are frozen (Chien Lu Ping, personal communication). Therefore, although the rates of microbial reactions do slow down as temperatures approach freezing, they probably do not cease. Secondly, there is growing evidence that many soils do not experience temperatures below biological zero. Data recently collected in forested soils of Maryland, Delaware, and New Jersey indicate that even at depths as shallow as 4 in (10 cm) from the surface, temperatures rarely were as low as 43 °F (6 °C) (fig. 3-4). Apparently, the O and A horizons that form in forested soils provide thermal insulation that prevents equilibration with subfreezing air temperatures. Further north in New England, snow cover may provide similar insulation keeping soil temperatures above biological zero.

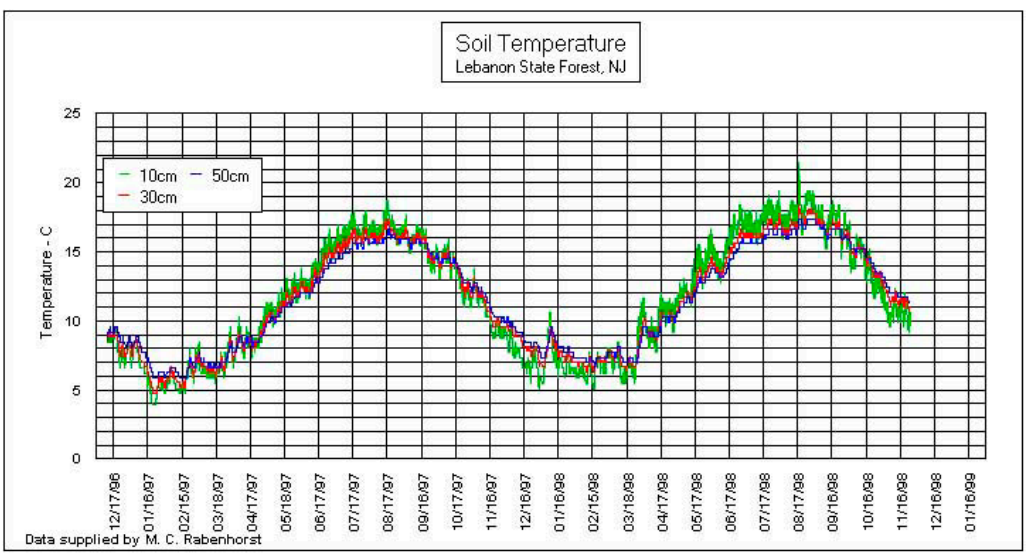

Figure 3-4.—A forested soil in New Jersey, where temperatures at depths of 10 to 50 cm did not reach "biological zero," or 41 °F (5 °C), during a 2-year period.

There are two fundamental sets of processes involved in hydropedogenesis (the genesis of hydric soils). One is related to the transformations, transfers, and losses of Fe oxides within the soil, and the other is related to additions and transformations of OM within the soil. Each of these processes will be addressed in turn.

Pedogenic Processes Related to Iron Oxides

A discussion of those soil processes related to Fe oxides necessitates a description of redox processes in soil. The microbial oxidation of OM in soils requires the presence of compounds to serve as electron acceptors (to be reduced). In equation 3-1, C in the carbohydrate (valence 0) is oxidized to CO_2 (with C valence +4) during which time four electrons are generated. In order to balance this reaction, O_2 (valence 0) is reduced to CO_2 and water (O valence -2).

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad \textbf{(Equation 3-1)}$$

As long as O_2 is present, it is the preferred electron acceptor. Under the saturated conditions of hydric soils, however, O_2 may become depleted more rapidly than it can be replenished through diffusion, in which case, alternate electron acceptors must be utilized. These alternate electron acceptors are normally utilized in a particular order related to the redox potential of that specific redox couple. Following the depletion of O_2, they are generally utilized in the following order: nitrate (NO_3^-), manganese (Mn^{2+}), Fe^{3+}, and sulfate (SO_4^{2-}). Nitrate and Mn^{2+} are generally present in only small quantities in soils. Iron, on the other hand, is more abundant; therefore, it becomes a significant component in soil redox chemistry. Figure 3-5 illustrates the relationship of redox potential and pH on the solubility of Fe oxides.

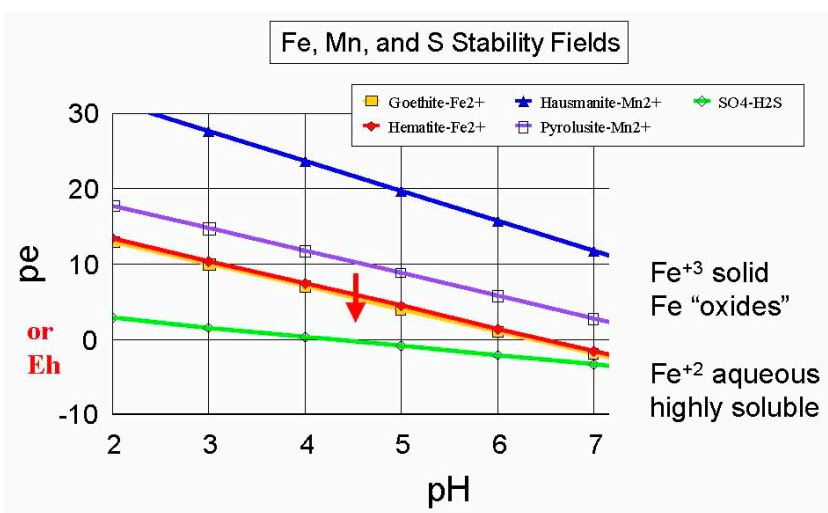

Figure 3-5.—The stability fields of various elements under particular pe (Eh) and pH conditions. In the zone above the orange and yellow lines, the oxidized form of iron is stable (solid phase iron oxides). In the zone below the lines, the reduced form of iron is stable (highly soluble ferrous iron). Note: Eh = 59•pe.

The two lines for hematite and goethite are very near to one another indicating the similarities in the thermodynamic properties of these minerals. When the pe (Note: pe=Eh/59) and the pH of a soil plot above the line, then the solid oxide phase (Fe^{3+}) is favored, and when they plot below the line, Fe^{2+} is favored and the oxides are predicted to be unstable. The Fe^{2+} phase has a much higher solubility than the Fe^{3+} (mineral) phases; therefore, as Fe is reduced from valence of +3 to +2, it becomes soluble and thus mobile.

Because soils are heterogeneous with regard to various properties, such as structure, texture, and bulk density, they can also be heterogeneous with regard to the distribution of organic carbon (OC) and to the degree of saturation of various zones. These properties, in turn, affect reduction, dissolution, and segregation of Fe oxides. For example, coarser textures lend themselves to more general dispersal of soluble OC through the soil, while fine textured (clayey) horizons or those with high bulk density facilitate the concentration of OC and water in macropores or along ped faces. Figure 3-6 shows a closeup view of a well defined prism face where plant roots have been concentrated and Fe oxides have been reduced and removed.

Figure 3-6.—Plant roots concentrated along the face of a well defined soil prism (soil structural unit) from a B horizon. The iron oxides have been reduced and removed from this soil.

In the soluble reduced form, Fe can be easily translocated within the soil profile. The soluble Fe moves either by diffusion, which is probably not very important, or it moves with the soil water according to moisture gradients or potentials, which may be related to pore size distribution or to the presence of roots. In extreme cases the soluble Fe can be completely lost from the soil. There are several schemes that can be used to describe the soil features that form as a result of the movement and segregation of Fe oxides during redox-induced processes. One useful approach defines the features with regard to their association with naturally occurring surfaces within the soil (Fanning and Fanning, 1989). "Type I mottles" are defined as zones where Fe oxides are concentrated along natural soil surfaces, while "Type II mottles" are defined as zones where Fe oxides are depleted from along natural soil surfaces. More recently, the term "redoximorphic feature" has been proposed to replace the older term "mottle" (Soil Survey Division Staff, 1993.)

Redoximorphic Features Related to Soil Structure

In imperfectly drained soils that are moderately or strongly structured, the nature and distribution of the redoximorphic features formed are related to a combination of factors that affect how quickly the soil peds become saturated relative to when the soil Fe oxides begin to be reduced. Figure 3-7a is a schematic illustration of the formation of Type I mottles as Fe oxides become concentrated along ped faces in a soil that becomes saturated quickly, relative to the onset of reducing conditions in the ped interior. The four steps depicted reflect: (1) the initial condition of the soil prior to saturation and reduction; (2) saturation of the ped (presumably due to a rising water table) and the development of reducing conditions throughout the interior of the ped; (3) drying at the ped face, which induces higher moisture potentials causing the soil water to move from the ped interior toward the ped face, carrying with it the soluble Fe(II), which oxidizes to Fe(III) in the vicinity of the ped face; and (4) the final dry condition with Type I mottles formed as concentrations of Fe at the ped face.

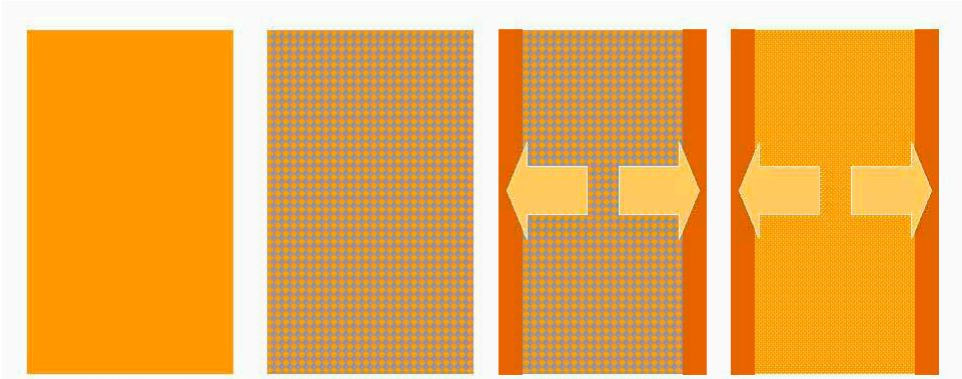

Figure 3-7a.—Four steps in the formation of Type I mottles where Fe oxides become concentrated along a ped surface: (1) the initial condition; (2) saturation of the ped and the development of reducing conditions throughout the interior of the ped; (3) drying that causes soil water to move toward the ped face, carrying soluble Fe(II) that then oxidizes to Fe(III); and (4) the final condition with Type I mottles formed at the ped face. (Diagram by M.C. Rabenhorst)

Figure 3-7b provides another schematic diagram illustrating peds before and after the same process.

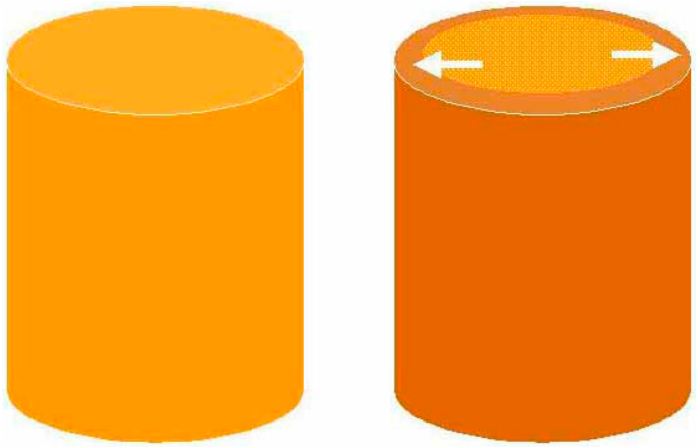

Figure 3-7b.—An illustration showing peds before and after processes that form Type I mottles. (Diagram by M.C. Rabenhorst)

An alternate set of soil conditions, however, can cause the formation of Type II mottles or depletions of Fe from the faces of soil peds (fig. 3-8). In this case, the soil becomes saturated very slowly (presumably because of the very fine textures or high bulk density), relative to the onset of reducing conditions in the pores between the peds. The three steps shown illustrate: (1) the initial condition of the soil; (2) following saturation of the pores between the peds but leaving the ped interiors dry, reducing conditions develop at the ped faces where the soil is saturated and where roots occur and contribute OC for the microbial reduction of Fe; and (3) moisture gradients carry soluble Fe(II) from the ped face toward the ped interior where it concentrates and reoxidizes to Fe(III).

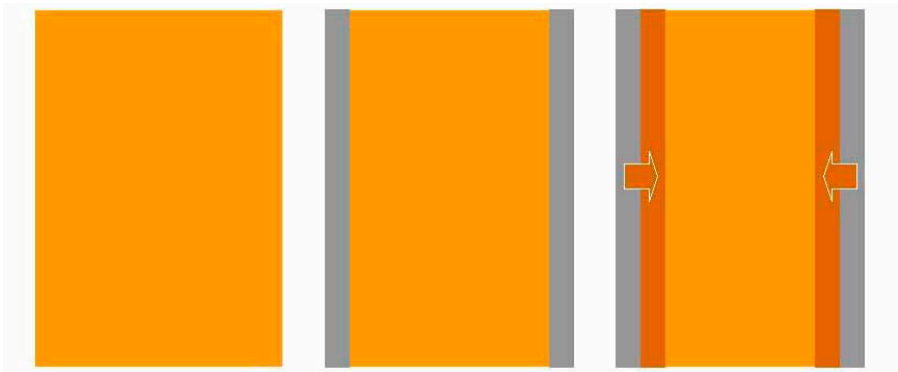

Figure 3-8.—Three steps in the formation of Type II mottles (where Fe oxides become depleted) from along a ped surface. Slow saturation of the peds relative to reduction conditions in the pores between the peds. The three steps shown illustrate: (1) the initial condition of the soil; (2) saturated and reducing conditions develop at the ped faces; and (3) moisture gradients move Fe(II) toward the ped interior where it reoxidizes to Fe(III).

One common example of this phenomenon is the depleted prism and polygon faces frequently observed in fragipans (Bx horizons) that sometimes have zones of Fe enrichment immediately subjacent to the depleted polygon face.

Redoximorphic Features Related to Plant Roots

Plant roots contribute to the formation of redoximorphic features in two primary ways. First, Fe oxides form around plant roots. Because plants extract soil moisture through the roots, lower moisture potentials form around roots. If a soil has become saturated and reduced, then soluble Fe(II) can be moved along moisture gradients toward the roots and become concentrated around the roots. When the soil later dries and reoxidizes, the concentration of Fe oxides around the root channel becomes evident (fig. 3-9).

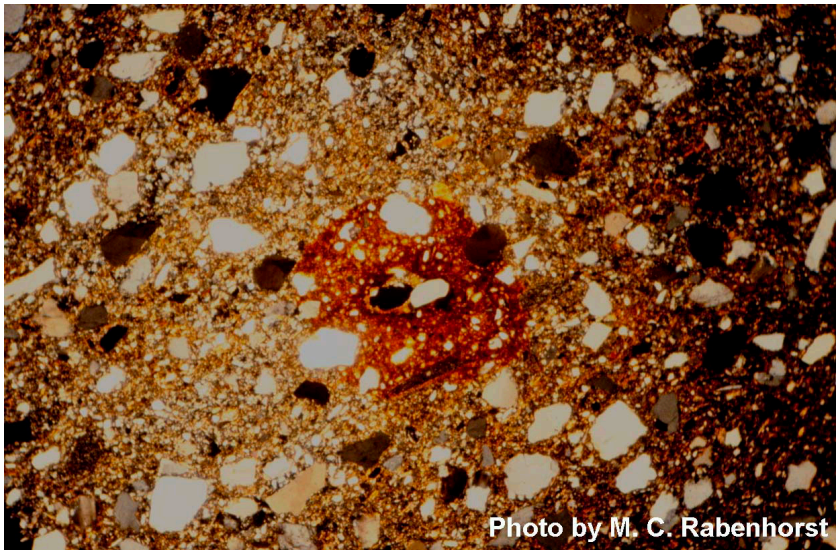

Figure 3-9.—Above is a photograph of a thin section showing a concentration of iron oxides surrounding a root channel. Note that the frame length is 0.2 in (5 mm) and that pores are black and quartz grains are light under cross polarized light.

To the right is a photograph showing the accumulation of iron oxides within the soil in proximity to a live root.

In some cases certain plants have the ability to induce oxidizing conditions immediately around the roots that can also cause precipitation of Fe oxides, creating a feature referred to as "oxidized rhizospheres."

The second significant way in which plant roots contribute to the formation of redoximorphic features is through the addition of OM at particular locations in the soil. Because a C source is necessary for microbes to cause reduction in saturated soils, reduction is sometimes restricted to zones where OM is concentrated. The senescence and death of plant roots in channels or between peds in strongly structured soils may result in the reduction, and possibly depletion, of Fe in those particular locations.

Depleted or Gray Soil Matrices

In cases where soils are saturated at or near the surface for long periods of time (i.e., poorly drained or very poorly drained soils), the extent of zones that are depleted of Fe may become so great that it becomes the dominant condition (fig. 3-10).

Figure 3-10.—Soil profile from which iron has been largely removed, resulting in a gray Btg horizon.

The soils that are dominantly gray in color (due to the abundance of uncoated silicate mineral grains) used to be referred to as "gleyed" and commonly were designated using the suffix "g" in the soil horizon nomenclature (e.g., Bg, Cg). Although the "g" is still used in the same manner, the term "gleyed" has recently been restricted to soils whose matrix color occurs on the "gley" page of the "Munsell® Soil Color Charts" [meaning that it has no hue (N) or hue greener than 10Y and chroma of 2 or less]. The dominantly gray colors indicate that there has been a substantial loss of Fe from the soil. The loss of Fe is particularly evident in soils that are highly permeable due to coarse (sandy) textures. The soils depicted in figure 3-11 formed in the same parent material and are in close proximity.

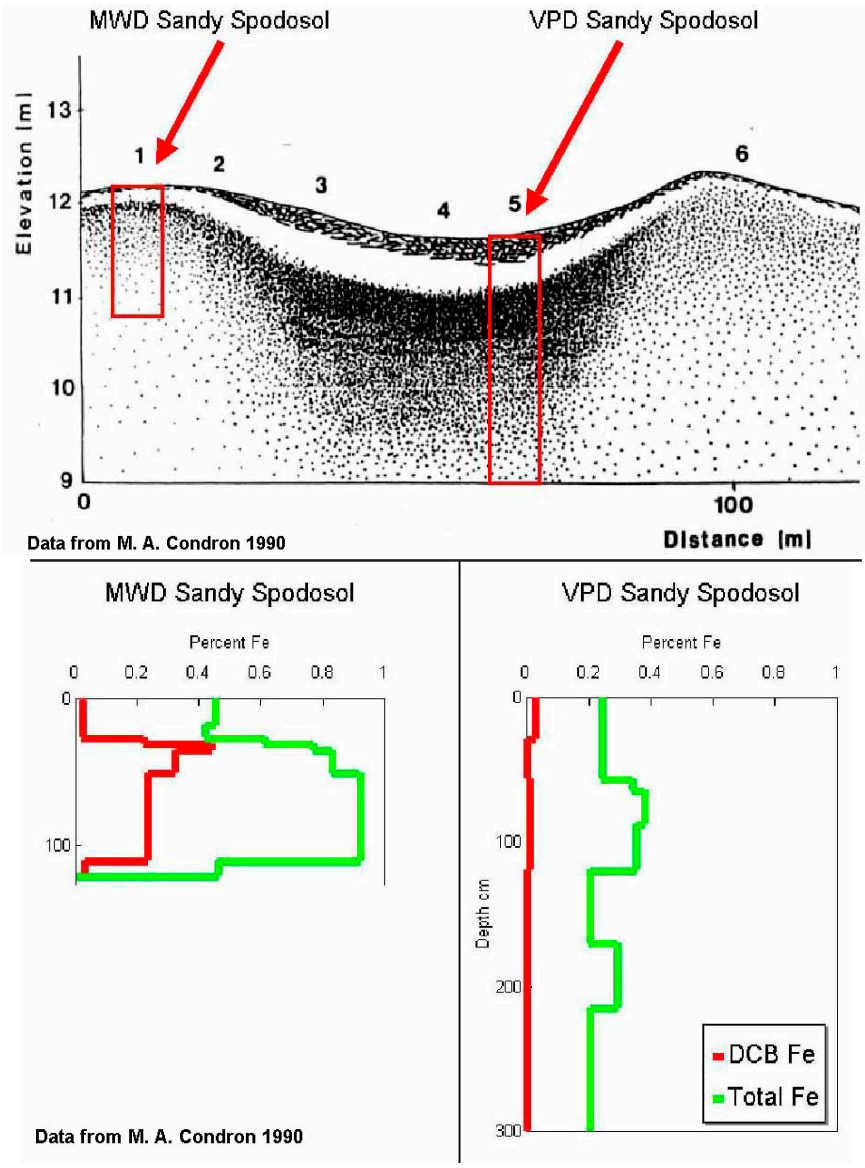

Figure 3-11.—Locations of moderately well drained and very poorly drained soils sampled from along a sandy dunal landscape. Data for total iron and DCB iron (extractable iron oxides) illustrate relative depletion of iron from the very poorly drained soil.

The illustrations show that the very poorly drained sandy soil has been nearly completely depleted of extractable (DCB) Fe compared to the moderately well drained soil. Loss of Fe from the wetter soil is further demonstrated by the levels of residual Fe (primarily silicate bound or ilmenite, ranging from 0.2 to 0.4 percent), which are considerably lower than the levels in the moderately well drained soil (0.4 to 0.7 percent).

The preceding cases are only intended to illustrate a few of the many possible scenarios that may occur in soils leading to the formation of redox concentrations or depletions of Fe. Care in studying the relationship of redoximorphic features with naturally occurring surfaces in soils can lead to a better understanding of the soil hydromorphology and of the specific processes that have contributed to the formation of a hydric soil.

Pedogenic Processes Related to Organic Matter

The anaerobic environment of wet soils also affects the dynamics of soil OM. In general, the anaerobic decomposition of OM is less efficient than under aerobic processes; therefore, there is a shift in the balance between inputs and losses of OM. In comparison with better drained soils, wet soils generally have similar or slightly elevated inputs of OM (plant primary production). The inefficiencies of anaerobic decomposition, however, result in slower rates of decomposition, which is illustrated in a box model in figure 3-12. The result is that there is a greater accumulation of soil OM under very poorly drained conditions, leading to the formation of a thicker, darker A or O horizon. This effect is most pronounced in cases where the anaerobic conditions exist within the uppermost horizons for extended periods (i.e., very poorly drained soils).

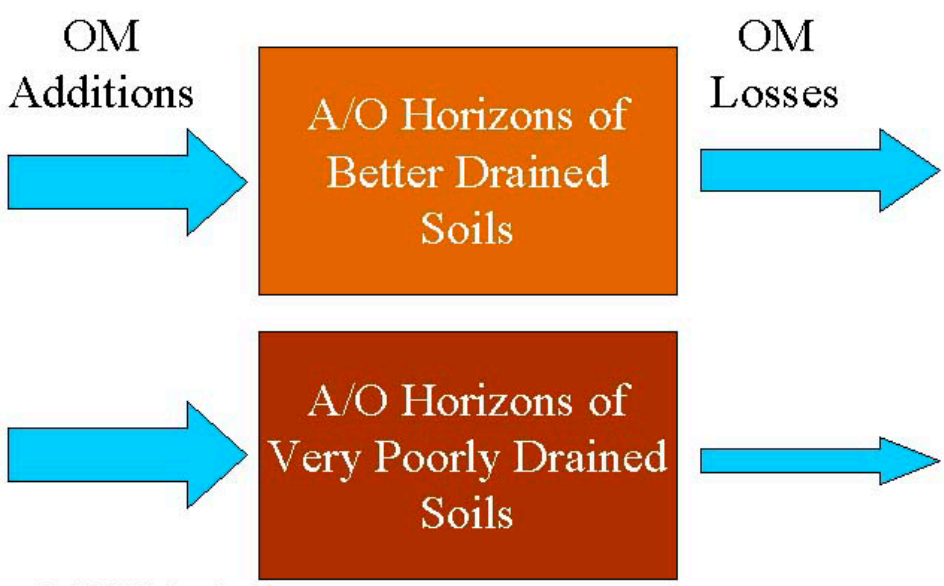

Figure 3-12.—Box model illustrating that the accumulation of organic matter (A or O horizon) in hydric soils is darker or thicker due to slower losses from anaerobic decomposition. (Diagram by M.C. Rabenhorst)

Soils that are poorly drained or better may not show significant differences in C accumulation (table 3-2).

Table 3-2.—Quantity of Organic Carbon Stored in Soils of a Silty Catena (after Rabenhorst, 1995)

			Organic carbon	
Series	Drainage class	Classification	kg/m^2 C in the upper m	lbs/ft^2 C in the upper 3 ft
Matapeake	Well	Typic Hapludults	5.6	1.00
Mattapex	Moderately well	Aquic Hapludults	4.6	0.82
Othello	Poorly	Typic Endoaquults	6.3	1.12
Sunken	Very poorly	Typic Endoaqualfs	18.1	3.32
Honga	Very poorly	Terric Sulifhemists	45.6	9.03

The nature of the A and O horizons that form in very wet soils can also be affected by the particle size (or texture) of the soil. The greater porosity and permeability of more sandy soils permit OM to move more easily into the soil to greater depths, causing the formation of thicker A horizons, than in comparable soils of finer textures; this is illustrated in figure 3-13 where a thicker A horizon (umbric epipedon) has formed in the coarse-loamy Pone series (left side of figure). The total quantity of OM accumulated in the A horizon of a corresponding silty soil (right side of figure) may be similar but is more concentrated near the surface, yielding a thinner A horizon.

Figure 3-13.—The thickness of the A horizon in two very poorly drained soils is affected by soil texture. The soil on the left has an umbric epipedon and is sandy, while the soil on the right has an ochric epipedon and is silty. The total organic matter that has accumulated in both soils is comparable. (Photos by M.C. Rabenhorst)

Soil hydrology (wetness or drainage class) not only affects the quantity of OM that accumulates in soil horizons, but it may also affect the nature of the OM. Figure 3-14 shows cores and thin sections from two sandy soils (somewhat poorly drained and very poorly drained) along a transect. In the thin section, the OM from the soil that is better drained (left) can be seen to be lighter and browner in color and that from the very poorly drained soil (right) can be seen to be darker and blacker. It is postulated that these differences in color reflect differences in the nature of the OM that accumulates under aerobic v. anaerobic conditions.

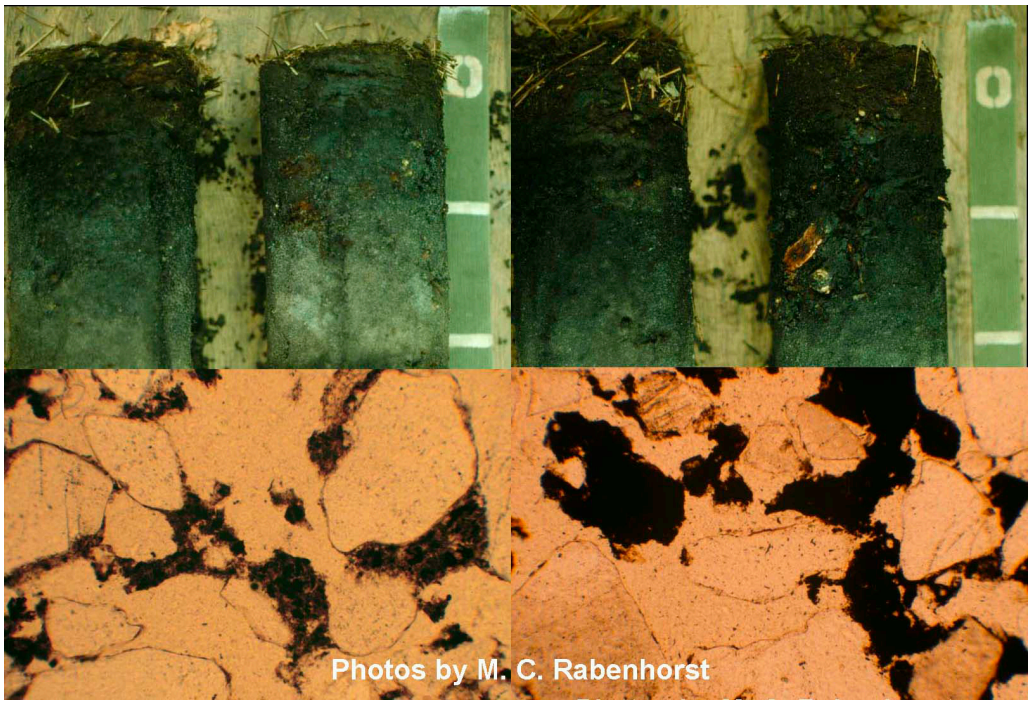

Figure 3-14.—The photographs in the upper part show cores taken from somewhat poorly drained and very poorly drained sandy soils. Note that the tape is in 4-in increments (10 cm). The thin section in the lower left corner of the illustration shows that the color of the organic matter is lighter and browner in the better drained soil, whereas that in the lower right corner is darker and blacker in the very poorly drained soil. Note frame length 0.2 in (5 mm); plane polarized light.

Chapter 4
Microbiology of Hydric Soils

Bruce L. Vasilas

Soil microbes are a diverse group of species that are critical to many of the functions associated with wetlands and to the decomposition of organic matter. They contribute to the development of the morphological features that are used as hydric soil indicators. These contributions are indirect through the development of anaerobic conditions and direct through the reduction of iron (Fe) and manganese (Mn).

Characterization of Soil Microorganisms

Microorganisms can be classified metabolically on the basis of their sources for carbon (C) and energy. Chemoheterotrophs derive C and energy from organic sources. The majority of soil microbes are saprophytes, or chemoheterotrophs that subsist on dead plant and animal remains and humic substances, which are critical to the C cycle. Photoautotrophs are photosynthetic, assimilating C as carbon dioxide (CO_2) and deriving energy from sunlight. They also are critical to the C cycle. Chemoautotrophs assimilate C as CO_2 and derive energy from inorganic compounds. They are important to nutrient cycles and the formation of redoximorphic features.

Microorganisms can also be categorized on their gaseous oxygen (O_2) requirement for respiration. Obligate aerobes derive energy only through aerobic respiration, which is characterized by its use of O_2 as a terminal electron acceptor. They cannot function under anaerobic conditions. Obligate anaerobes cannot function under aerobic conditions. They derive energy via anaerobic respiration in which inorganic ions other than O_2 are used as terminal electron acceptors or through fermentation in which internally generated compounds are used as terminal electron acceptors. Facultative anaerobes are capable of both aerobic and anaerobic respiration. In the presence of O_2, they rely on aerobic respiration, which is much more efficient (produces more energy) than anaerobic respiration or fermentation. Since aerobic respiration is more efficient than anaerobic respiration, it results in faster rates of organic matter decomposition.

Fungi are the principal agents for the decomposition of organic matter, especially complex molecules such as cellulose, hemicellulose, and lignin. Soil fungi are obligate aerobes (primarily) and facultative anaerobes. They usually represent the greatest percentage of microbial biomass in a soil at 450 to 4,500 lb/acre (500 to 5,000 kg/ha) (Metting, 1993). Most fungi produce filamentous growth (hyphae). The total filamentous body is referred to as a “mycelium.” An individual mycelium may extend several yards (meters) in the soil. Mushrooms

and toadstools are reproductive structures for many of the fungal species. Hyphae promote aggregation by binding soil particles together. Some of the fungi infect the roots of higher plants to form a mutually beneficial relationship or "symbiosis" referred to as "mycorrhyizae." The mycorrhizae improve the plant uptake of nutrients, especially phosphate, ammonium, and zinc, and are considered to be essential to the survival of gymnosperms.

Bacteria are the most prevalent soil microorganisms, numbering in the millions per ounce of topsoil (10^8 to 10^9 per gram) (Metting, 1993). Soil bacteria include obligate aerobes, facultative anaerobes, and obligate anaerobes. They are critical to nutrient cycling and the formation of redoximorphic features. Actinomycetes are filamentous bacteria that are much smaller than fungi. The musty smell of freshly plowed soil is due to compounds produced by actinomycetes. Most antinomycetes are saprophytic and are important to the decomposition of soil organic matter; however, most are aerobic and acid intolerant and do not grow well in saturated soils. Therefore, their contribution to microbial processes in hydric soils of the Mid-Atlantic Region is less than that of other bacteria and fungi.

Both terrestrial and aquatic algae occur in wetlands. Terrestrial species tend to be single celled and smaller than the aquatic species. All algae are photosynthetic and, therefore, a source of C inputs. Many algae (and some bacteria) "fix nitrogen" (N), converting dinitrogen gas (N_2) to ammonia (NH_3). Algal blooms, a rapid proliferation of algae in water, is a sign of eutrophication, or nutrient loading of surface waters. Since many of the algae fix N, algal blooms are usually in response to phosphorous (P) pollution. Algae may also bloom at the surface of soils and may impart a greenish coloration to the soil a day after a rainstorm.

Anaerobiosis

Microbes are inherent to the development of hydric soils. They contribute to the development of anaerobic conditions and are critical to the formation of redoximorphic features. Soils become anaerobic when O_2 use by plant roots and microbes exceeds O_2 diffusion into the soil from the atmosphere. Saturation decreases diffusion rates by four orders of magnitudes (Gambrell and Patrick, 1978). The length of time after saturation required for a soil to become anaerobic depends on soil temperature, available organic C levels, and the O_2 content of the water. High temperatures and a ready supply of available C lead to higher respiration rates by microbes. Under optimum conditions (high temperature, high levels of available C, and low O_2 concentrations in the water), soil can become anaerobic 1 day after saturation. Research (unpublished) conducted by the author in seasonally saturated wetlands on the Delmarva Coastal Plain revealed, in general, a 2-week delay between the onset of saturation in late winter or early spring and the development of reducing conditions.

Only the wettest soils are continuously saturated (peraquic moisture regime). The majority of hydric soils have a wet period and a dry period in most years but are wet enough close to the surface to have an aquic moisture regime (Soil

Survey Staff, 1999). Spatial variability is also common because O_2 levels are usually higher near the surface and alternating oxidized and reduced zones may be associated with structural units (ped interiors versus ped faces). Even saturated zones have aerobic microsites. Consequently, both aerobic and anaerobic respiration can occur concurrently in hydric soils.

Carbon Cycle

One characteristic associated with hydric soils that developed under extensive periods of anaerobiosis is a high organic matter content. A number of the hydric soil indicators are a function of organic matter accumulation. Histosols form in wetlands with frequent and extensive periods of saturation to the soil surface. Soil organic matter is basically plant and animal remains in various stages of decomposition. Accumulation of soil organic matter occurs when additions exceed decomposition; therefore, accumulation is favored by systems with high rates of biomass production and conditions unfavorable to decomposition. Both of these characteristics are common to wetlands. The level of organic matter in a hydric soil is a function of the hydroperiod, the seasonal pattern of water table fluctuations in a wetland. The longer the water table is close to the soil surface, the longer the period of anaerobiosis. Since most organic materials are deposited either at or near to the soil surface as roots or leaves, hydric soils that develop anaerobiosis close to the surface will accumulate more organic matter.

The rate of organic matter accumulation is also influenced by the type of vegetation. Grassland soils tend to have higher levels of organic matter than forest soils, yet forests produce more organic matter than grasslands. The primary source of organic matter in forests is the leaf litter, which is readily decomposed, both because of the composition of leaves and because the litter decomposes aerobically on the soil surface. The primary source of organic material in grasslands is root material, which is more resistant to decomposition than leaves. In addition, the roots decompose below ground where anaerobic conditions are more prevalent.

Organic matter decomposition in hydric soils during a wet cycle is limited by O_2 because anaerobic respiration is less efficient than aerobic respiration and some of the products of fermentation (e.g., ethanol) are inhibitory to many microbes. Decomposition rates for organic residues in wet soils could be as low as 13 percent of the decomposition rates of the same residues in aerated soils (Gambrell and Patrick, 1978). For hydric soils that are not continuously saturated, organic matter levels are inversely proportional to the number of wet/dry cycles per growing season. Under aerobic conditions, decomposition rates are limited by the availability of a nutrient, generally N.

One benefit of decomposition is that nutrients required for plant growth are converted from organic forms, which are unavailable to plants, to inorganic or mineral forms, which are available to plants. This process is referred to as mineralization. The reverse process, immobilization, ties up nutrients. Both processes occur simultaneously. Whether net mineralization (mineralization minus immobilization) occurs, depends on the nutrient composition of the

organic material that is decomposing. For example, decomposition of organic tissues with a C:N ratio of more than 15 or 20 to 1 will result in net immobilization of N because most of the N will become incorporated in the biomass of the microbial decomposers; however, microbial death and decay will mineralize some of this N. Decomposition of residues with low C:N ratios results in net mineralization of N because N levels are in excess of the microbial demand.

Redox Reactions

Oxidation-reduction (redox) reactions are characterized by the transfer of electrons from one compound to another. In each redox reaction, one compound is reduced (receives electrons) and one compound is oxidized (donates electrons). Microbially mediated redox reactions produce many of the morphological features associated with hydric soils and are the driving force behind biogeochemical cycling. During respiration microbes oxidize organic compounds and transfer the donated electrons through a series of biochemical steps. Under aerobic conditions the last compound to be reduced during respiration (terminal electron acceptor) is O_2. Once the soil is depleted of O_2, microbes will use the following compounds (listed in order of preference) as terminal electron acceptors: nitrate (NO_3^-), manganic manganese (Mn^{4+}), ferric iron (Fe^{3+}), sulfate (SO_4^{2-}), and CO_2. Redox potential, or Eh, is a measure of the tendency of a system to donate electrons. The switch from one terminal electron acceptor to another occurs in an orderly sequence within predictable Eh ranges. This reduction sequence is presented in table 4-1 (Mitsch and Gosselink, 2000).

Table 4-1.—Oxidized and Reduced Forms of Several Elements and Approximate Redox Potentials for Transformation

Element	Oxidized form	Reduced form	Approx. redox potential for transformation (mV)
Nitrogen	NO_3^- (nitrate)	N_2O, N_2, NH_4^+	250
Manganese	Mn^{4+} (manganic)	Mn^{2+} (manganous)	225
Iron	Fe^{3+} (ferric)	Fe^{2+} (ferrous)	+100 to -100
Sulfur	SO_4^{2-} (sulfate)	S^{2-} (sulfide)	-100 to -200
Carbon	CO_2 (carbon dioxide)	CH_4 (methane)	Below -200

The values in the table are approximate because they are pH and temperature dependent and influenced by other soil water constituents. For more on Eh and its measurement, see chapter 11, “Monitoring Hydric Soils.” The availability of other terminal electron acceptors can inhibit the reduction of specific compounds; for example, the presence of SO_4^{2-} inhibits CO_2 reduction (Widdell, 1988); and the presence of NO_3^- inhibits Fe^{3+} reduction (Lovely, 1991) but not Mn^{4+} reduction (Burdige and Nealson, 1985).

Denitrification is the reduction of NO_3^- (as a terminal electron acceptor) to gaseous N compounds (NO, N_2O, N_2). Biological denitrification is limited to facultative anaerobic bacteria. It is the process that is primarily responsible for the removal of dissolved N in created wetlands. A related process is dissimilatory nitrate reduction in which bacteria convert NO_3^- to ammonium (NH_4^+), which is then released from the cell. This process is favored by continuous anaerobiosis and a high ratio of available C to NO_3^-. If pH is high, this process can lead to loss of N as NH_3. A select few species of chemoautotrophic bacteria obtain energy by oxidizing NH_3 to nitrite (NO_2^-) and NO_2^- to NO_3^-.

Iron and Mn are oxidized and reduced both chemically and by microbes. Reduced forms are soluble and, therefore, mobile in the soil solution. Oxidized forms are insoluble and readily precipitate out of solution. Alternate cycles of aerobic and anaerobic conditions result in segregation of oxidized Fe that produces redox concentrations and depletions. Long wet cycles produce the gleyed matrix associated with reduced Fe. The dominant forms of Fe and Mn in the soil depend on Eh and pH. Low Eh and low pH favor Fe and Mn reduction. Ferrous (Fe^{2+}) and manganous (Mn^{2+}) forms are oxidized to Fe^{3+} and Mn^{4+} by chemoautotrophic bacteria under aerobic conditions. Many bacteria and some fungi reduce Fe^{3+} and Mn^{4+} during anaerobic respiration.

Common to wetlands rich in sulfur (S), such as tidal marshes, is S reduction in which bacteria use SO_4^{2-} as a terminal electron acceptor producing elemental sulfur (S^o) or hydrogen sulfide (H_2S), which has the characteristic odor of rotten eggs. Sulfur-oxidizing bacteria generate energy through the oxidation of sulfides and S^o. Although most are obligate anaerobes, at least one species can also use NO_3^- as a terminal electron acceptor.

Under the most reduced conditions, methanogenic bacteria use CO_2 as a terminal electron acceptor producing methane (CH_4) or swamp gas. Another group of bacteria, the methanotrophs, use CH_4 as their energy source and oxidize it to CO_2. Methanotrophs are obligate aerobes. In hydric soils they will be active just above the aerobic/anaerobic interface. A given soil can serve as both a CH_4 sink and a CH_4 source depending on redox potential. Direct CH_4 emissions from wetland soils account for one-third of the global CH_4 emissions to the atmosphere. In certain situations, however, methanotrophs can consume up to 90 percent of the CH_4 generated in a hydric soil before it can reach the atmosphere. Many herbaceous wetland plants contain arenchyma, a spongy tissue found in the pith, that readily transports O_2 to the roots. In wetlands dominated by vegetation with arenchyma, up to 90 percent of the CH_4 generated may reach the atmosphere via the arenchyma and, therefore, bypass the zone of methanotrophs (Schimel, 1995).

Microbial Activity

The formation of redoximorphic features is mediated by microbial processes; therefore, the rate at which redox features develop is a function of the intensity of microbial activity, which, in turn, is influenced by the soil O_2 level, soil pH, temperature, toxic compounds, and the availability of organic C. Under

anaerobic conditions, bacteria are more active than fungi and contribute more to anaerobic decomposition of organic matter and to the formation of redoximorphic features. The majority of bacteria display the greatest growth rates in soils that have a pH value of 6 to 8, while fungi are more competitive in soils that have a lower pH value (4 to 6) (Brady and Weil, 2002). Redoximorphic features are less likely to form in soils that have either a very high or a very low pH value. A temperature of 41 °F (5 °C) is considered to be "biological zero" because it had been assumed that microbial activity slows considerably or stops at lower temperatures. The 41 °F threshold is used in growing season calculations for wetland jurisdictional determinations. It should be noted that the concept of biological zero, especially the 41 °F threshold, is flawed, because it has been well documented that microbial activity occurs at much lower temperatures (Rivkina et al., 2000). Microbial activity increases with increasing temperatures up to 95 to 105 °F (35 to 40 °C) (Paul and Clark, 1996). It should be emphasized that the formation of redoximorphic features requires Mn and Fe in forms that can be reduced and an active microbial population. Problematic hydric soils occur when one of these two requirements is missing.

Both the quantity and quality of organic C affect microbial activity. Low organic C is generally the ultimate limiting factor for microbial activity in the soil. Organic compounds, such as simple carbohydrates (sugars) and amino acids, are more readily degraded (a more readily available energy source) than complex carbohydrates, such as cellulose, hemicellulose, and lignin, which are cell wall components of higher plants. Redoximorphic features may fail to form on flood plains because moving water readily removes amino acids and simple carbohydrates, which are water soluble.

Microbial populations vary with respect to total numbers and species composition according to soil depth and distance from plant roots. These differences are primarily in response to a gradient of available C. They have major ramifications with respect to the formation of redoximorphic features. The "rhizosphere" refers to the zone of soil close to and impacted by plant roots. The "rhizoplane" is the surface of plant roots. Microbial numbers are substantially higher (10-fold to 100-fold) (Paul and Clark, 1996) in the rhizosphere than in bulk soil and are inversely proportional to distance from the roots. The highest microbial numbers, by far, are on the rhizoplane. Plant roots supply most of the C that drives microbial activity in soils. Up to 90 percent of fine roots may die and decompose annually in forest soils. In addition, dead root cap cells slough off and supply organic C, and exudates from live roots include readily available C sources (sugars, organic acids), a readily available source of N (amino acids), and growth promoting (and sometimes inhibiting) compounds. The organic acids can increase the solubility of Fe and Mn by lowering the pH and by acting as chelating agents. Therefore, the formation of redoximorphic features may only be associated with root channels. For plants with arenchyma, the O_2 flux is frequently so strong that the roots pump O_2 into the soil, producing an oxidized rhizosphere. In such a situation there will be

aerobic microbial activity in the rhizosphere and anaerobic microbial activity outside of the rhizosphere.

Microbial activity in soils varies spatially and temporally. Microbial activity drops in response to temperature extremes and soil moisture extremes or when nutrients are deficient. Under unfavorable conditions for microbial growth, microbes become dormant. Although entering and exiting dormancy results in high mortality rates, enough individuals survive to recolonize the soil. For example, soil bacteria can increase in numbers by 100-fold when a dry soil is wetted if there are no other limiting factors. Therefore, microbial activity in soil is not limited by microbial numbers but by unfavorable environmental conditions.

Chapter 5
Hydrology of Hydric Soils

Bruce L. Vasilas

Wetlands are defined in Section 404 of the Clean Water Act as "those areas that are inundated or saturated by surface or ground water (hydrology) at a frequency and duration sufficient to support, and under normal circumstances do support, a prevalence of vegetation (hydrophytes) typically adapted to life in saturated soil conditions (hydric soils)." Therefore, inherent to wetlands and hydric soils is wetness for at least part of the year. It is this condition of excess water that results in the formation of hydric soils and drives the functions associated with wetlands. Critical to understanding the nature of wetlands and hydric soils is knowledge of hydrology—the science of water and its properties, distribution, and movement, both above and below ground.

The criterion for wetland hydrology is inundation or saturation to the soil surface for at least 5 percent of the growing season in most years. Inundation is a condition in which water covers the land surface. Saturation is the condition in which all easily drained pores are filled with water. The growing season, by definition, is the portion of the year when soil temperature at the 20 in (50 cm) depth is above 41 °F (5 °C). In the absence of soil data, growing seasons can be estimated from air temperature data presented in NRCS soil survey reports (published for an individual county, parish, or other area for which the survey was developed) or in NRCS National Weather and Climate Center WETS tables. The WETS tables present long-term air temperature and precipitation data. They can be accessed at <www.wcc.nrcs.usda.gov>. When using air temperature, the growing season is defined as the part of the year when air temperature exceeds 28 °F (-2 °C), with 70 percent probability. "In most years" means at least 51 years out of 100.

Hydric Soils

Hydric soils are 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, July 13, 1994). Flooding is temporary inundation by flowing water. Ponding is inundation in a closed depression. It is important to note that a soil meets the definition of a hydric soil if it developed under the stated hydrologic conditions. If those hydrologic conditions are altered through drainage or protection (levees), the soil is still considered to be hydric if "the soil in its undisturbed state meets the definition of a hydric soil."

The National Technical Committee for Hydric Soils (NTCHS) has developed the following standard for hydric soil hydrology: "For at least 14 consecutive

days, anaerobic conditions (confirmed by voltage readings below the Eh/pH line or by positive dipyridyl reaction, or both) and saturation conditions must exist for a soil to be considered hydric" (NTCHS, 2003a). The depth requirements for these conditions are 6 in (12.5 cm) for coarse textured soils (loamy fine sand or coarser) and 10 in (25 cm) for fine textured soils. This standard is further addressed in Chapter 11, "Monitoring Hydric Soils."

Soil Pores

Pores are spaces between aggregates (interaggregate pores) and within aggregates (intraaggregate pores). Pores are the pathways for water, and the rate of water movement will depend, in part, on the size, orientation, and tortuosity of the pores. Interaggregate pores tend to be larger and straighter than intraaggregate pores and, therefore, transmit water faster. Vesicular pores are closed at both ends and do not transmit water. Pores vary in size from animal burrows to root channels to microscopic spaces between soil particles. Pores with a cross-sectional diameter of more than 30 microns (1 inch=25,000 microns) are macropores and those less than 30 microns are micropores. Water is held in micropores by tension. Micropores are mostly responsible for water available for plant growth. Water flows freely in response to gravity in macropores; therefore, the flow of water through a soil is a function of the volume of macropores. A soil is considered to be at field capacity when the macropores are empty and the micropores are filled with water.

Porosity is the percentage of soil volume occupied by pores. It is generally in the range of 30 to 60 percent. For mineral soils, porosity will be greatest in well aggregated clay and lowest in sand. As bulk density increases (i.e., because of compaction), porosity decreases. With respect to organic soil materials, peat (least decomposed) has the largest pore spaces and muck (most decomposed) has the smallest pore spaces. Mucky peat is intermediate in the level of decomposition and in average pore size.

Soil Water

Water molecules are polar; they have a positively charged end and a negatively charged end. Because of this polarity, water molecules are attracted to each other, in that the positive end of one molecule will bond with the negative end of another. The attraction of water molecules to each other is referred to as "cohesion." Water molecules are also attracted to charged solid surfaces (adhesion). Compatible surfaces are found on soil organic matter and mineral particles; therefore, water will be attracted to the soil matrix and water molecules closest to a pore surface will be held in the pore by tension. Similarly, other water molecules will be held in the pore by cohesion. This has two effects—first, a film of water will cover the soil matrix even under dry conditions; and second, water will move from a saturated zone into micropores because of the phenomenon of capillarity as the combined forces of adhesion and cohesion are stronger than the pull of gravity in small pores.

A soil profile can be separated into zones on the basis of the physical characteristics of water in relation to the soil matrix. In the ground water zone,

water is at atmospheric pressure (zero pressure) or higher (positive pressure). Water in this zone is considered "free" in that it is not held by forces of tension. The water table is the upper limit of the ground water. It is defined as the equilibrium level of water in an unlined borehole. Just above the water table will be a zone in which the micropores are filled with water due to capillary rise. This zone is referred to as the "capillary fringe," or "tension-saturated zone," because the pressure head is negative. Although some large pores in the capillary fringe may not be completely filled with water, most of the soil matrix is saturated, and the zone is considered to be saturated for hydric soil purposes.

The height of the capillary fringe (i.e., capillary rise) is usually in the range of 1 to 16 in (2.5 to 40 cm). Capillary rise is affected by soil texture, soil structure, root density, organic matter content of the soil, and transpiration demand. It is promoted by a prominence of micropores and is inversely related to the diameter of the micropores. In homogeneous soil material, such as may be found in a C horizon, capillary rise is closely related to texture, which impacts pore size. In such a situation, capillary rise will be greater in a silt loam than in a sand. Well developed structure results in a high volume of macropores and, as a result, a decrease in capillary rise. Root growth and organic matter decrease capillary rise in direct and indirect manners. Both promote soil structure. The decaying roots leave behind macropores and add organic matter, which is hydrophobic, to the soil material. Therefore, for equivalent textures, capillary rise will be greater in a C horizon than in an A or Bt horizon. It also is seasonal since it decreases in response to increased evapotranspiration.

Above the capillary fringe is the unsaturated zone, which is referred to as the "vadose zone." In seasonally saturated wetlands the capillary fringe or the vadose zone, or both, will be absent during part of the year.

There are two types of saturation used to describe soil profiles—endosaturation and episaturation. Endosaturation is the condition where the entire soil profile below the vadose zone is saturated. Episaturation is a type of saturation indicating where, within the upper 6 ft (1.8 m) of the soil profile, an unsaturated zone separates an overlying, saturated zone (perched water table) from the apparent water table below. In many seasonally saturated wetlands, wetland hydrology is due to episaturation. In some cases episaturation is transient because the upper saturated zone will go dry during the summer or the two saturated zones merge during the winter.

Drainage class reflects the frequency and duration of wet periods under conditions similar to those during soil formation and the depth to the seasonal high water table in most years. Anthropogenic alterations of the water regime (e.g., ditches, levees, irrigation) are not considered unless they significantly impact soil morphology. Seven drainage classes are used in soil surveys—excessively drained, somewhat excessively drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained. Very poorly drained and poorly drained soils are most likely hydric, and somewhat poorly drained soils may be hydric. Drainage class is determined by soil morphology using the depth of the shallowest redox depletions to estimate depth to the seasonal high water table.

Landscape position influences the volume of water in a wetland and the sources of water just prior to entering a wetland. Wetlands close to a local topographic height would not be expected to be dominated by surface water hydrology. Side slope and toeslope wetlands are ground water driven because ground water actively discharges via seeps (low energy) or springs (high energy). Flood plains, by definition, are surface water driven. For wetlands at low points in the landscape, such as tidal marshes, surface water will be the dominant source of water. Mineral soil flats are precipitation driven. For depressional wetlands, the dominant water source may be precipitation or ground water. In general, depressional wetlands that are continuously wet are considered to be ground water driven, and those that are intermittent or seasonally saturated are precipitation driven. There is also a loose relationship between the plant community composition of depressional wetlands and the dominant source of hydrology. Depressions with woody strata tend to be precipitation driven, whereas emergent depressional wetlands tend to be ground water driven. Delmarva or Carolina Bays are primarily precipitation driven, although both surface and ground water flow can be significant contributors to hydrology.

Water Flow

Water flow in soils is a function of hydraulic head and hydraulic conductivity. Water flows in response to hydraulic head, the total mechanical energy per unit weight of water. Hydraulic head is the sum of three mechanical energies—kinetic energy, gravitational potential energy, and the energy of fluid pressures. Kinetic energy is the energy caused by motion; a moving fluid tends to remain in motion. Kinetic energy increases as speed and volume of the water increase. Gravitational potential energy causes water to flow from a high elevation to a lower elevation. Water tends to flow downhill. Initially, this is in response to gravitational pull. However, as the water moves downslope, it will pick up speed as kinetic energy increases. The energy of fluid pressures in a fluid mass results from the pressure of the surrounding fluid acting upon it. Pressure builds up because flowing water comes into contact with a confining layer in the soil. The pressure can result from the downward flow of water (percolation) or from a rising water table.

Hydraulic head is proportional to the height of the water column. Hydraulic conductivity is the ease that water can move through the soil. Confining layers are rarely impermeable. A soil horizon is confining when it has a significantly lower hydraulic conductivity than an adjacent horizon. As soil becomes wetter, hydraulic conductivity increases and water flows more readily. This occurs for several reasons. First, the drier the soil, the more tightly water is held by adhesion and cohesion. Second, unsaturated pores contain air, which builds up pressure in response to water flow. Hydraulic conductivity will be a function of the volume of soil occupied by macropores. It is favored by long, straight, continuous pores.

Both saturated and unsaturated flow occurs in soils. Saturated flow is approximated by percolation after a heavy rain event. It occurs when the

macropores are filled with water so hydraulic conductivity is high. Therefore, when responding to a significant hydraulic head, saturated flow can be quite rapid. Unsaturated flow occurs more often than saturated flow, except in soils that are continuously wet. After the macropores empty and the soil becomes progressively drier, the water is held tighter in the micropores. Water then flows in response to a water gradient, from wetter areas to dryer areas.

Permeability is the ease with which water passes through a bulk mass of soil or a soil layer. It is expressed as inches per hour for saturated flow. The permeability classes and rates are listed in table 5-1.

Table 5-1.—Permeability Classes for Soil

	Rates		
Classes	cm/hr	in/hr	Texture
Very slow	<0.15	<0.06	Clayey
Slow	0.15-0.5	0.06-0.2	
Moderately slow	0.5-1.5	0.2-0.6	Silty and loamy
Moderate	1.5-5	0.6-2	
Moderately rapid	5-15	2-6	
Rapid	15-51	6-20	Sandy
Very rapid	>51	>20	

Water flow is more rapid through a uniform medium than through stratified sediments that vary in hydraulic conductivity. Therefore, the textural differences in successive horizons that are common to coastal plain soils will impede vertical flow. Saturated flow from a coarse textured horizon will be impeded by an underlying fine textured horizon because the small pores in the underlying horizon will not transmit water as rapidly as the larger pores in the coarse textured horizon. Likewise, water flow from a fine textured horizon will be impeded by an underlying coarse textured horizon. In this case, the forces of adhesion and cohesion will keep the water in the fine pores of the upper horizon until the pressure head becomes too great; therefore, some perching will occur until the upper horizon approaches saturation. When the zone directly above or directly below a confining layer becomes saturated, water will flow laterally in response to fluid pressure.

The flow patterns of water in a wetland are shown in fig. 5-1. Infiltration is the entry of liquid water into the soil. Percolation is the downward movement of water through unsaturated zones. Infiltration and percolation are driven primarily by the attraction of water to dry soil surfaces and gravity. The boundary between the wet soil and dry soil is referred to as the “wetting front.” Behind the wetting front the soil is close to saturated.

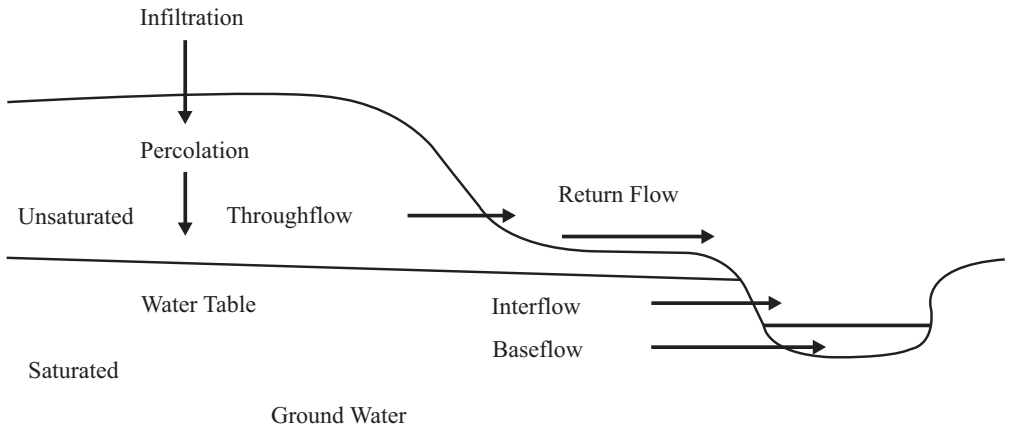

Figure 5-1.—Water flow patterns through soil.

When infiltration stops following a rain event, the wetting front advances at the expense of water behind it so that soil moisture content drops. Advancement of the wetting front stops when the soil behind it reaches the water-holding capacity. Throughflow and interflow are the lateral flow of water through unsaturated zones during and immediately after a rain event. Throughflow water leaves the soil via seeps and flows across the soil surface as return flow, ultimately contributing to surface waters. Interflow discharges directly into streams or lakes by subsurface flow. Baseflow is the direct discharge of ground water into streams.

The term "hydrodynamics" refers to the direction and speed (energy) of water flowing across or close to the soil surface. Water flow in mineral soil flats and depressions is predominately vertical and slow. The hydrodynamics of riverine and slope wetlands are lateral, unidirectional, and high energy, and those of tidal flats are lateral, bidirectional, and high energy.

Wetlands form in landscapes where water accumulates on or close to the soil surface for extensive periods of time. Water accumulates when inflows exceed outflows according to the law of mass balance: inflow=outflow+storage. When inflows equal outflows, a system is considered to be "hydrologically balanced." Wetlands generally are not hydrologically static. Geomorphology and microtopography affect inflow, outflow, and storage. Flat topography lowers surface flows (both in and out) relative to slopes. Depressions store surface waters. Microtopography, like pit-and-mound topography or tree throw depressions, helps to store water on flats and slopes. Surface roughness features such as microtopography, woody debris, and plants decrease the rate of surface flow and increase the rate of infiltration. As a result, storage increases and outflow from the wetland decreases. Water storage in the soil will be a function of soil depth and porosity, and it will be favored by those factors that promote saturated flow.

Wetlands can be classified as recharge systems or discharge systems, or a combination of both. Recharge refers to the addition of water to a ground water system. Depressional wetlands are commonly recharge systems because they can trap significant volumes of water per unit surface area. Many wetlands are wet because of the presence of a confining soil horizon that perches water. In those wetlands, most recharge occurs along the edges of the wetland. Discharge is the loss of water from a ground water system via seeps or springs where the ground water meets the soil surface. Flow-through wetlands combine recharge and discharge. This characteristic may be seasonal or geomorphic. For example, a seasonally saturated wetland may discharge water in late winter and early spring when the water table reaches the soil surface. The soil is saturated, and water received via precipitation will leave the wetland as runoff. During the drier months, the same wetland will trap and store water. Many slope wetlands have recharge and discharge characteristics as a result of landscape position. Water enters the wetland at its highest elevation via a seep. It then is trapped at the base of the wetland and, eventually, contributes to the ground water.

Water Budgets

A water budget can be used to calculate the change in volume of water stored in a wetland as follows: $V=Pn+Si+Gi-ET-So-Go\pm T$, where V=volume of water, Pn=net precipitation, Si=surface inflows, Gi=ground water inflows, ET=evapotranspiration, So=surface outflows, Go=ground water outflows, and T=tidal inflow (+) or outflow (-). Net precipitation is the sum of stem flow and throughfall. Stem flow is rainwater that was intercepted by plant canopies and follows branches and stems to the soil or water surface. Throughfall is precipitation that was not intercepted by plant canopies. Evapotranspiration is the sum of evaporation (gaseous losses of water to the atmosphere from soil or surface waters) and transpiration (gaseous losses of water to the atmosphere from plant leaves). Of all the water absorbed by plant roots during a season, at least 99 percent will be lost via transpiration, and wetlands can lose up to two-thirds of their annual water inputs via evapotranspiration (Richardson and McCarthy, 1994). Losses to evapotranspiration are maximized by high air temperatures, low humidity, air movement, and actively growing plants with large canopies. Surface inflows and outflows can be characterized as overland flow or streamflow. Overland flow is nonchannelized sheet flow from precipitation or snowmelt. Streamflow is channelized flow instream or flood episodes. Ground water inflow occurs when the water table of the wetland is at a lower elevation than the water table of surrounding land. Ground water outflow occurs when the water table of the wetland is at a higher elevation than the water table of the surrounding land.

Hydroperiods

The seasonal pattern of depth to the water table in a wetland is referred to as the "hydroperiod." It can be considered to be the hydrologic signature for each wetland type. The hydroperiod for a given wetland results from the balance between inflows and outflows, landscape surface contours, and subsurface features relating to soil, geology, and ground water features. In estuarine marshes depth to the water table fluctuates daily in response to tides. In freshwater wetlands it commonly varies seasonally and from year to year. The level of variability is influenced by the dominant water source. Precipitation driven systems will show the most year-to-year variability. Ground water driven systems will be more stable. Seasonal fluctuations in depth to the water table are in response to differences in precipitation and evapotranspiration. Many of the wooded wetlands in the Mid-Atlantic Coastal Plain are seasonally saturated. The entire surface layer of the soil will be saturated in late winter or early spring. When leafout occurs the water table will drop rapidly in response to the increased evapotranspiration demand. By early summer the water table will have dropped below auger depth. Water table fluctuations of lacustrine wetlands and riverine wetlands will be tied to the hydrology of adjacent lakes or rivers, respectively. Two representative hydroperiods are presented in figures 5-2 and 5-3.

The Possum Hill site (fig. 5-2) is a ground water driven, side slope wetland in the northern Delaware Piedmont. It is permanently saturated. There are deciduous trees on the periphery, but the dominant vegetation within the wetland consists of herbs and shrubs.

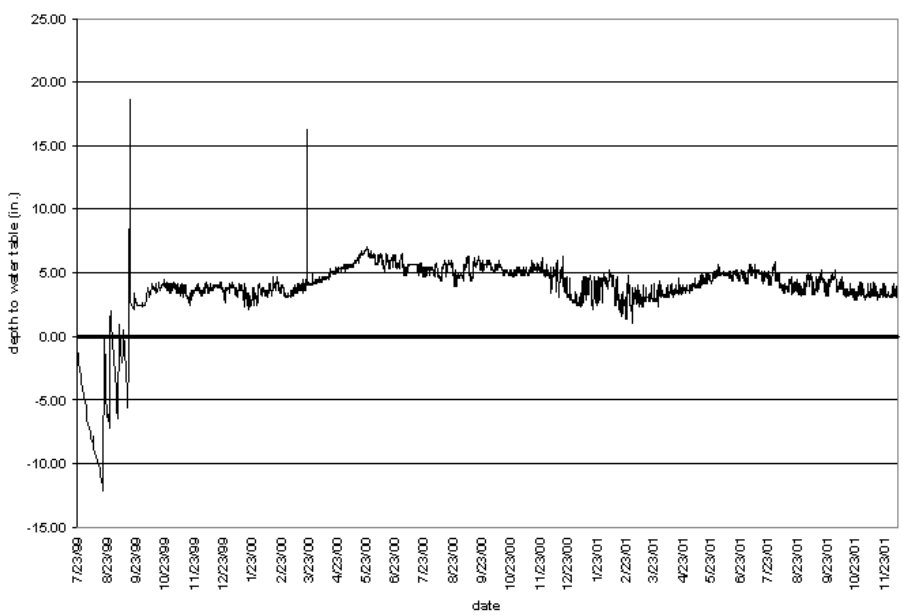

Figure 5-2.—Hydroperiod of permanently saturated wetland.

The Redden site (fig. 5-3) is a precipitation driven, mineral soil flat wetland in the Coastal Plain of southern Delaware. It is seasonally saturated. Loblolly pines and shrubs dominate the vegetative cover.

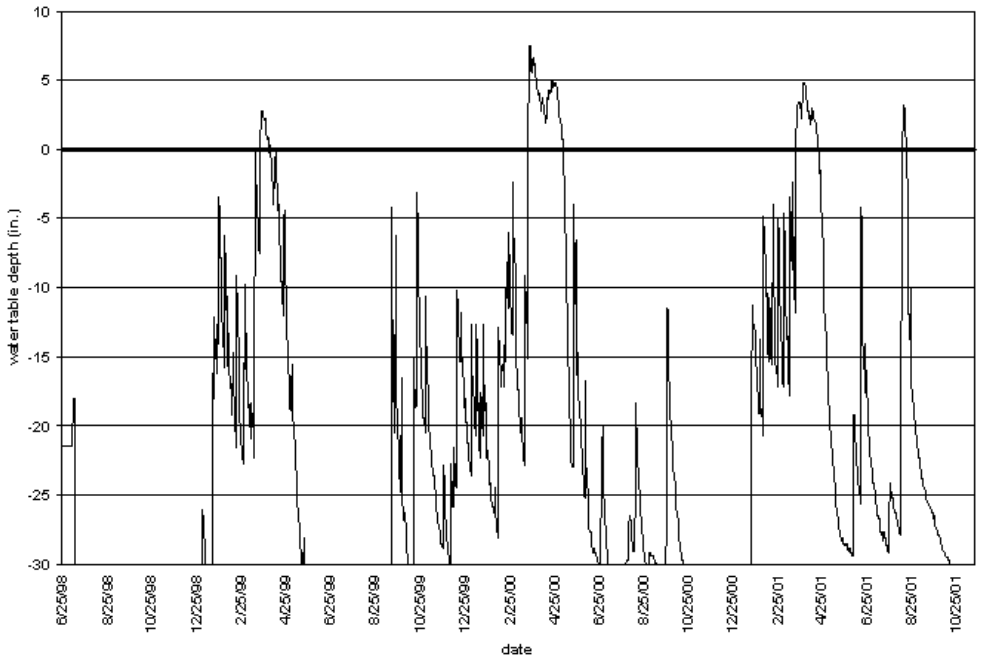

Figure 5-3.—Hydroperiod of seasonally saturated wetland.

Chapter 6
Describing Hydric Soils

John M. Galbraith and Lenore M. Vasilas

This chapter is based on the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS), standards for soil survey. It was written specifically for use when describing hydric soils and can be used in conjunction with the "Field Indicators of Hydric Soils in the United States" (USDA, NRCS, 2002) and the "Corps of Engineers Wetlands Delineation Manual" (Environmental Laboratory, 1987). Definitions of unfamiliar terms can be found in the "Internet Glossary of Soil Science Terms" on the Soil Science Society of America Web site <http://www.soils.org/sssagloss/>.

Guidelines for Describing Horizon Properties and Features

The "big picture" should be considered before selecting the soil site to be sampled and described. Information to consider includes landscape position, vegetation, and indicators of hydrology. The selected site should be uniform and relatively undisturbed (unless it is a mitigation site) and should represent the area around it. The larger the area described, the better the representation. Once a representative site is chosen for the soil description, the next step is to excavate the soil. The best dimensions for a pit are 6 ft (2 m) x 6 ft x 6 ft; however, digging a pit is not the most practical way of excavation. If a pit is not dug, a small hole is excavated to a depth of at least 18 in (45 cm) using a shovel or spade and the remainder of the profile can be sampled using an auger. As soil is removed from the hole, it is important to record depths where changes occur in the soil profile. The changes occur in layers called "horizons." As depths are recorded, a large representative sample of each layer is obtained to use to describe the soil profile. When collecting samples from the auger, it is best to discard the top 2 in (5 cm) because of contamination from material that fell into the hole. It is not always necessary to describe a soil to 6 ft (2 m) in order to identify a soil as hydric; however, in order to identify the soil series to use in the hydric soils list and local soil survey data, a 6-ft (2-m) profile must be described.

The soil description should fit the area described. Soil can have considerable spatial variability; so if what is expected is not seen, more holes should be dug nearby to see if what is described represents the whole area. Samples can also be taken to examine or test later or to compare to reference samples and guides.

All descriptions should start directly below last year's leaf fall (duff). Any organic material beneath last year's leaf fall is considered to be part of the soil. Components of a soil description that are helpful in identifying hydric soils and factors that might affect hydrology in the soil are texture, color, organic

features, redoximorphic features, structure, and consistence. Horizon designators are assigned after all other characteristics of the horizons are identified. The characteristics of the horizons are helpful when the horizon designators are selected.

Texture

Soil texture is the numerical proportion (percent by weight) of the separates for the particles less than 0.01 in (2 mm) in size (sand, silt, and clay). There are classes for both organic and mineral soil materials. Important textural breaks used in "Field Indicators of Hydric Soils in the United States" (USDA, NRCS, 2002) are organic soil materials from mineral soil materials, mucky modified mineral textures from plain mineral textures, and sandy textures from other mineral textures.

Organic Soil Material

Organic layers form near the surface when the accumulation of organic matter exceeds decomposition. They are often thin. Organic soil material has layers, or horizons, that have been saturated for long periods of time or have been artificially drained and, depending on the clay content, have an organic carbon (OC) content ranging from 12 to 18 percent (fig. 6-1).

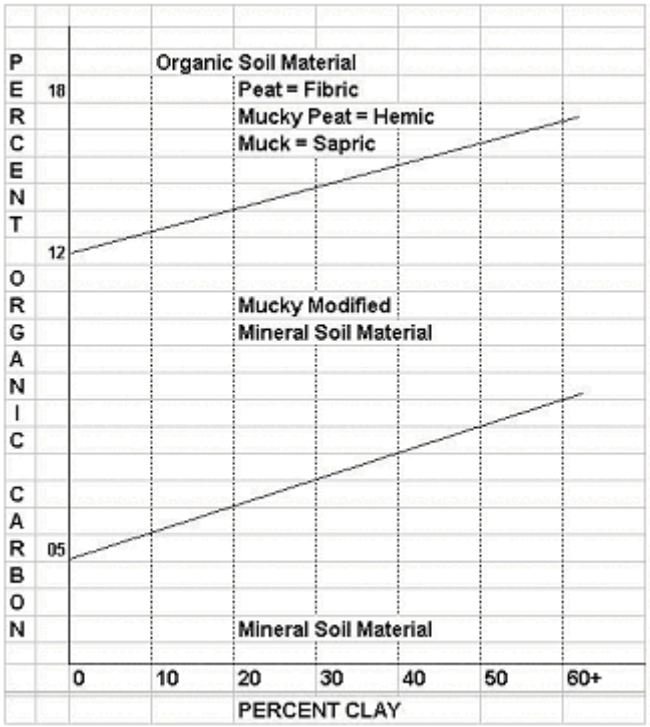

Figure 6-1.—Definition of organic and mineral soil materials based on percent organic carbon and clay. Mucky modifiers are used with some mineral material.

Layers with <60 percent clay that are saturated for longer periods or were saturated before being drained are organic if they either have ≥18 percent OC or the percent of OC≥12+(clay/10). Organic soil material is much lighter per unit volume than mineral soil material (one-tenth to one-half as heavy), has a greasy feeling, may have many visible fibers before rubbed, and generally is black.

Properties of organic soil material are affected by the kind and amount of mineral fraction, kind of organisms from which the organic material was derived, and the state of decomposition of the material. The accumulation of organic soil material is due to the anaerobic decomposition of saturated organic matter (OM). To identify organic soil material in the field, an equal amount of organic soil material and mineral soil material should be compared to one another. The organic soil material will be much lighter in weight than the mineral soil material. When the organic soil material is rubbed, it will feel greasy and mineral grains cannot be felt. When saturated organic soil material is squeezed, a darkened, sediment-free liquid will flow out. There are three types of organic soil material—muck, mucky peat, and peat. In order to identify the type of organic soil material, use firm pressure to rub a sample of the material between the thumb and fingers 10 times before rolling it into a ball. Split the ball in half, and visually estimate the amount of fibers. Peat is raw, largely undecomposed organic soil material that consists of more than three-quarters fibers. Muck is well decomposed, black organic soil material that consists of less than one-sixth fibers. Mucky peat is intermediate in texture between muck and peat. It consists of between one-sixth and three-quarters fibers.

Mineral Soil Material

Mineral soil material has layers, or horizons, that do not have enough OC to qualify as organic soils. A sample of soil material that feels light in density or is greasy, but not greasy enough to be considered organic material as described previously, is probably from a mucky mineral soil. If soil flows out of a saturated sample instead of the black liquid described previously, the texture is probably mucky mineral and the mineral texture must be determined. In order to make this determination, disregard the OC and categorize the texture as described in the following paragraph. Keep in mind, however, that OC often feels like silts and, therefore, a texture may feel higher in silt than it actually is if it is mucky mineral. The texture designation for mucky mineral soils would be mucky plus the mineral texture (e.g., mucky loamy sand, mucky clay loam).

Key to Textural Classes

Texture is defined as the relative proportion of sand, silt, and clay. A handful of soil from the middle of one horizon, or layer, is taken and kneaded, tossing out the rocks that are >0.01 in (>2 mm) and the live roots, to estimate soil texture. All other mineral material textures can be grouped into two major categories in the “COE Indicators”—sandy or finer than sandy.

Sandy texture classes include all of the sands plus all of the loamy sands except loamy very fine sand. Sand grains can be seen in the unrubbed sample of a soil that is sandy in texture. A sandy textured soil is squeezed between the thumb and first two fingers to form a ribbon 0.125 to 0.25 in (3 to 5 mm) thick and 0.5 to 1 in (1.25 to 2.5 cm) wide. The ribbon is pushed horizontally out of the hand over the forefinger until it breaks or doubles over from its own weight. If the ribbon is less than 0.5 in (1.25 cm) long, the soil is sandy in texture. If the ribbon is more than 0.5 in (1 cm) long, all of the textures in the soils are considered to be finer in texture.

USDA Textures

The ball drop or ribbon test, or both, can be used to determine the texture of soil material that is not organic. First, a ball is made (ball test) from the soil material and dropped from hand to hand at a vertical distance of about 18 in (45 cm). Then, the ball is squeezed between the thumb and first two fingers to form a ribbon 0.125 to 0.25 in (3 to 5 mm) thick and 0.5 to 1.0 in (1.25 to 2.5 cm) wide (ribbon test). The ribbon is pushed horizontally out of the hand across the forefinger until it breaks or doubles over from its own weight.

Sand shatters completely after dropping the ball and will not form a ribbon. Loamy sand holds together after dropping the ball and forms a very short ribbon or no ribbon. Sand and loamy sand textures must be modified to identify the dominant sand grain size. The choices are coarse sand, sand, fine sand, very fine sand, loamy coarse sand, loamy sand, and loamy fine sand. Loamy very fine sand acts like the finer texture; therefore, it falls into the finer textured class for use with Field Indicators (Soil Survey Division Staff, 1993).

For finer textures, clay percentages are estimated by doing the ribbon test previously described. Generally, every inch of ribbon is approximately 10 percent clay. The ribbon technique should be calibrated by testing known textural samples. Thickness and width of the ribbon, as well as moisture content, can affect the length of ribbon to clay ratio. Percentage sand is estimated by the sand wash test. Soil is rubbed in the palm of a cupped hand and then flooded with water. The soil is mixed in the water using a finger from the other hand until the finer particles are suspended in the water. Then, the water is poured off slowly. Only sand particles remain in the hand because they are too heavy to be suspended in the water. The percentage of the original sample left in the palm of the hand approximates the sand percentage.

The next step is to either use the textural triangle (fig. 6-2) or the key described in the following paragraph. To use the triangle, follow the line for clay percentage horizontally and the line for sand percentage diagonally from the lower right to the upper left of the triangle until the lines intersect. The polygon that encloses the intersection is the texture. For example, if a soil has 10 percent clay and 60 percent sand, the texture is a sandy loam.

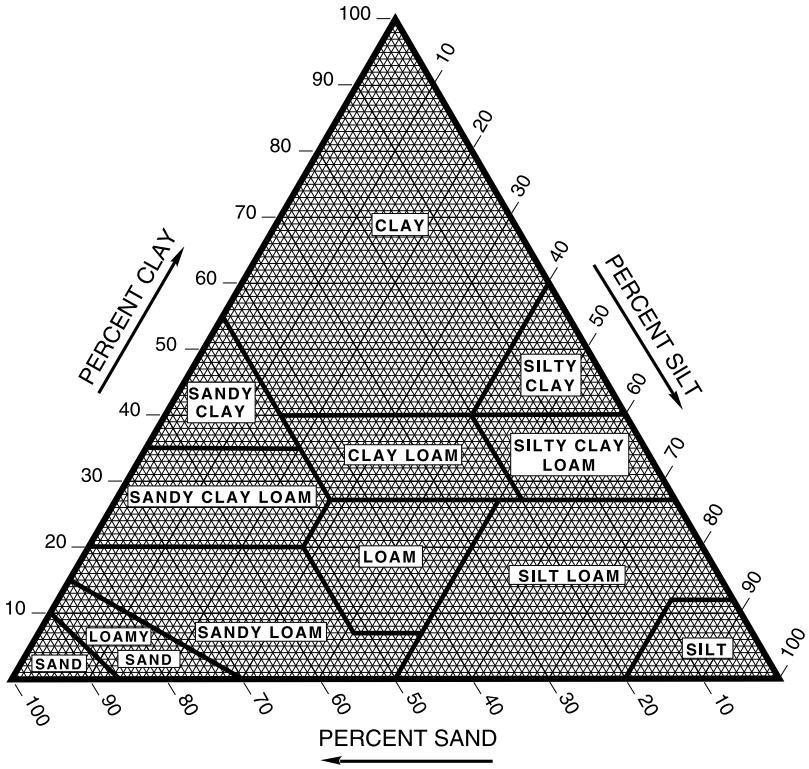

Figure 6-2.—Percentages of clay, silt, and sand in the basic USDA soil textural classes.

The following key can also be used to estimate texture. Sandy loam has 50 percent or more sand and forms a ribbon that is less than 2 in (5 cm) long. The soil is gritty, like sugar cookie dough. Sandy loam textures must also be split into sand grain sizes. Choices are coarse sandy loam, sandy loam, fine sandy loam, or very fine sandy loam (Soil Survey Division Staff, 1993). Silt loam forms ribbons that are clearly less than 2 in (5 cm) long. The soil is very smooth, like floury cookie dough. Loam also forms ribbons that are clearly less than 2 in (5 cm) long; however, the soil is not as smooth as silt loam or as sandy as sandy loam. Sandy clay loam is about 50 percent or more sand and forms a ribbon 2.0 to 3.5 in (5 to 9 cm) long. Silty clay loam forms a ribbon 2.0 to 3.5 in (5 to 9 cm) long. It is smooth, like putty. Sand grains cannot be felt in a silty clay loam. Clay loam forms ribbons 2.0 to 3.5 in (5 to 9 cm) long and the soil is not as smooth as silty clay loam or as gritty as sandy clay loam. Sandy clay is about 50 percent or more sand and has shiny ribbons that are 3.5 to 5.5 in (9 to 14 cm) long. Silty clay forms shiny ribbons 3.5 to 6.0 in (9 to 15 cm) long, and the soil is very smooth, like soft plastic or modeling clay. Clay forms shiny ribbons that are ≥4 in (10 cm) in length. It has a sand content between sandy clay and silty clay or forms shiny ribbons that are too long for either of those textures.

Organic Matter Features

Soil particles in the surface horizon of sandy hydric soils are normally covered, coated, or masked by OC; however, these coatings may not cover all individual particles. The percent of visible, uncoated particles should be estimated. See figure 6-3 for representative samples of soils with different percentages of uncoated sand grains.

Figure 6-3.—On the left, 70 percent of sand grains coated or masked by organic compounds; on the right, 50 percent of sand grains coated or masked by organic compounds.

Stripped areas may occur where OM has been removed, especially in sandy soils. These areas create a pattern of lighter zones in a dark matrix. The color, size, and abundance of these stripped areas should be recorded.

If there are small bodies of mucky organic material in the mineral matrix, the size and percentage of these bodies should be documented. These organic bodies are attached to roots of woody plants, much like bulbs on a string of lights. See figures 6-4 and 6-5 for proportion estimation guides.

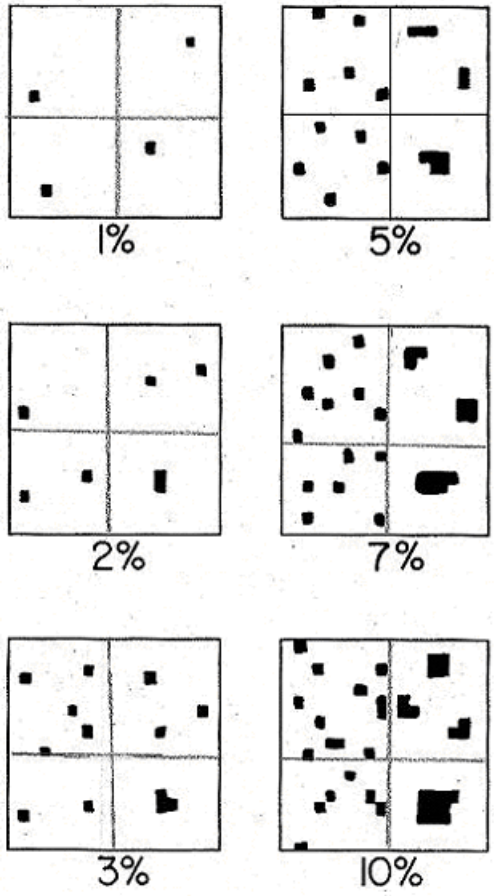

Figure 6-4.—Guide for estimating proportions from 1 to 10 percent.

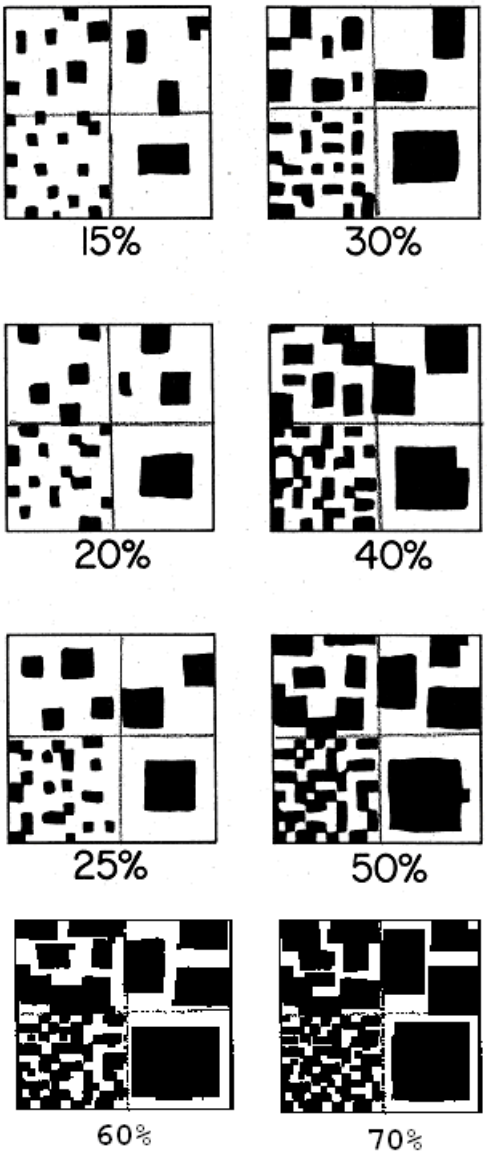

Figure 6-5.—Guide for estimating proportions from 15 to 70 percent.

Soil Color

The following sections provide information about the components of soil color, conditions for measuring the color, and important color determinations. They also provide information on how to describe soil color.

Components of Soil Color

The three components that have the most effect on soil color are organic compounds (usually black), manganese (Mn) oxides (usually black), iron (Fe) oxides (usually red, orange, or yellow), and the color of the mineral grains (usually clear or neutral gray). Soil color is determined by matching moist soil to a chip included in the "Munsell® Soil Color Charts." Each chip has a specific hue, value, and chroma, which are identified on the printed page facing each page of chips.

Hue is the chromatic composition (color) of light that reaches the eye. Each Munsell® page has the name of a different hue printed on the upper, right corner. The colors of most soils in the Mid-Atlantic Region are on the 10YR (yellow red) page, with redder colors on pages preceding (to the left) the 10YR pages and more yellow and grayer colors on pages following (to the right) the 10YR pages. Additional hues are also on pages used to describe gleyed soils. These hues include greens, blues, and neutral colors (pure white, gray, and black).

Value is the degree of lightness or darkness of soil color. The value notations are along the left margin of each page beside each row. The darker colors have lower values, while the lighter colors have higher values. Whenever soil colors do not match a value chip exactly, round to the nearest chip.

Chroma is the strength or purity of color. The chroma notations are in the bottom margin of each page under each column. The lower chromas have more neutral (often grayer) colors, while the highest chromas have the strongest expression of that particular hue. Soil colors that do not match a chroma chip exactly should be rounded to the next highest chip.

Conditions for Measuring Soil Color

Ideally, soil color should always be read on a ped (clump of soil) interior, immediately after excavation, in a moist state, and under direct, natural light. Hydric soils, especially when they are saturated, may change color quickly upon exposure to oxygen; therefore, it is important to describe the color soon after excavation. If the soil does change color with time, also record the color of the soil once it has changed and the amount of time passed since excavation. Peds should always be broken, and colors are read on ped interiors. Soil is not smeared prior to reading soil color.

Although it is best to describe color when the soil is moist, often a hydric soil is saturated and thus it is impossible to acquire a moist sample while in the field. In this case, documentation that the soil color was read under saturated

conditions is made and a sample may be collected and allowed to dry to a moist state before soil color is read again. A saturated soil may change color as it dries, indicating a reduced matrix (Fe is reduced in situ). Moisture content of the soil may affect its value, while a change due to reducing conditions will most likely change its chroma.

Soil color should be read under natural light, at a 90-degree angle from the sun. It is best to do this during midday when the sun is high. If soil color is read in the woods, the color should be read in a spot where the sun is shining through the canopy. Morning and evening sunlight makes it much more difficult to distinguish between different colors, especially in the winter. The date, time, and weather conditions (e.g., sunny, overcast) should always be recorded so that differences in conditions might be explained when soil colors are not the same during different site visits.

Important Color Determinations

The color of the matrix is the most common color in the horizon. A matrix with ≥60 percent volume is an important soil color criteria for a gleyed matrix and a depleted matrix as defined in "Field Indicators of Hydric Soils in the United States" (USDA, NRCS, 2002). Mottles are splotches of other less dominant colors. The mottles that are due to saturation and reduction of Fe and Mn are called redoximorphic features. It is important to describe all the colors that are evident in the soil sample, as well as their proportions and locations. Also, a matrix color may change if the soil is reduced prior to excavation. Redoximorphic features may be more evident or prominent upon exposure to air after excavation.

Describing Soil Color

A matrix color is always described. It is the predominant color. If there are two or more colors that appear to be equally dominant, then the soil is described as having a mixed matrix. If the soil has a mixed matrix, list the dominant colors and the percentage of each of the colors.

Each mottle color is also described. Record if the mottles were caused by wetness or by weathering of the parent material or some other source of contrasting color. It is important to describe the kind, location, color, abundance, and contrast of all redoximorphic features. A more complete explanation is found in "Redoximorphic Features for Identifying Aquic Conditions" (Vepraskas, 1996). Color is described in terms of hue, value, and chroma in the "Munsell® Soil Color Charts." Abundance is the estimated volume percent of the horizon, based on visual comparison with the charts in figures 6-4 and 6-5. Each quarter of the square shows abundance based on size of the features. Contrast refers to the degree of visual distinction that is evident between associated colors (table 6-1).

Table 6-1.—Contrast Chart for Redox Features

(Record the color difference between the redox feature and the dominant matrix color [Schoeneberger et al., 2002])

Contrast class	Code	Difference in color between matrix and features (Δ means "difference between")				
		Hue (h)		Value (v)		Chroma (c)
Faint*	F	Δh=0;		Δv≤2	and	Δc≤1
		Δh=1;		Δv≤1	and	Δc≤1
		Δh=2;		Δv=0	and	Δc=0
Distinct*	D	Δh=0;		Δv≤2	and	Δc>1 to <4
			or	Δv>2 to <4	and	Δc<4
		Δh=1;		Δv≤1	and	Δc>1 to <3
			or	Δv>1 to <3	and	Δc<3
		Δh=2;		Δv=0	and	Δc>0 to <2
			or	Δv>0 to <2	and	Δc<2
Prominent*	P	Δh=0;		Δv≥4	or	Δc≥4
		Δh=1;		Δv≥3	or	Δc≥3
		Δh=2;		Δv≥2	or	Δc≥2
		Δh≥3;		any		any

* If compared colors have both value ≤3 and chroma of ≤2, the contrast is faint, regardless of the difference in hue.

There are three types of redoximorphic features. They are redox concentrations, redox depletions, and reduced matrices. Redox concentrations are zones where reduced, soluble Fe and Mn have been exposed to free oxygen and precipitated as oxidized insoluble oxides. Types of redox concentrations include concretions, nodules, soft masses, and pore linings. Concretions and nodules are cemented and hardened masses of Mn and Fe oxides. Soft masses are diffuse zones of oxide concentration in the soil aggregates. Pore linings are zones of oxide concentration along pores, root channels, animal burrows, or aggregate surfaces.

Redox depletions typically are zones of color that have value ≥4 and chroma ≤2 as a result of saturation, reduction, and translocation of Fe and Mn. In some problem situations, redox depletions may have chroma >2 but lower than that of the matrix color. Clay depletions are zones where both oxides and clay have been removed. Fe and Mn depletions are zones where there are no oxidized forms of Fe or Mn. A depleted matrix is the volume of a soil horizon or

subhorizon from which Fe has been removed or transformed by processes of reduction and translocation to create colors that have low chroma and high value defined as follows. A and E horizons can have low chroma and high value and, therefore, may be mistaken for a depleted matrix; however, they are excluded from the concept of depleted matrix unless common or many, distinct or prominent redox concentrations as soft masses or pore linings occur or if there is a reduced matrix (color change upon exposure to air). The following colors identify a depleted matrix in other horizons: matrix value of 5 or more and chroma of 1 or less with or without redox concentrations as soft masses or pore linings, or both; matrix value of 6 or more and chroma of 2 or less with or without redox concentrations as soft masses or pore linings, or both; matrix value of 4 or 5 and chroma of 2 with 2 percent or more distinct or prominent redox concentrations as soft masses or pore linings, or both; or matrix value of 4 and chroma of 1 with 2 percent or more distinct or prominent redox concentrations as soft masses or pore linings, or both.

Reduced matrices have reduced Fe in solution that changes color upon exposure to air. Reduced matrices often have gleyed matrices. Gleyed matrices have the following combinations of hue, value, and chroma (in nonglauconitic soils): 10Y, 5GY, 10GY, 10G, 5BG, 10BG, 5B, 10B, or 5PB with value of 4 or more and chroma of 1; 5G with value of 4 or more and chroma of 1 or 2; N with value of 4 or more; or (for testing only) 5Y with value of 4 and chroma of 1.

Soil Structure

Soil structure is the naturally occurring aggregation of soil particles into units called clods or peds, as opposed to clod formation from digging by humans or animals. Clay and organic compounds are the binding materials. Soil structure is very important because it affects water movement in the soil. When describing soil structure, list the size, grade, and shape.

Grade can be structureless, weak, moderate, or strong. Structureless soil material has no discrete clods (peds) observable in place or in hand sample. Soils with weak structure have units that are barely observable in place or in hand sample. Soils with moderate structure have units that are well formed and evident in place or in hand sample. Soils with strong structure have units that are distinct in place and separate cleanly when disturbed.

The basic shape of structural units can be platy, granular, columnar, prismatic, angular blocky, subangular blocky, single grain, or massive (fig. 6-6). Platy units are flattened along the vertical axis like potato chips or poker chips. Granular units are small and rounded or irregular in shape. They are generally in the surface horizon. Columnar units are vertically elongated with flat tops. Columnar structure occurs in sodium-affected soils, which do not occur in the Mid-Atlantic Region. Prismatic units are vertically elongated with flat tops. Angular blocky units are blocklike with surfaces that intersect at sharp angles, forming sharp edges. They are in subsurface horizons only. Subangular blocky units are blocklike with surfaces that intersect at obtuse angles, forming

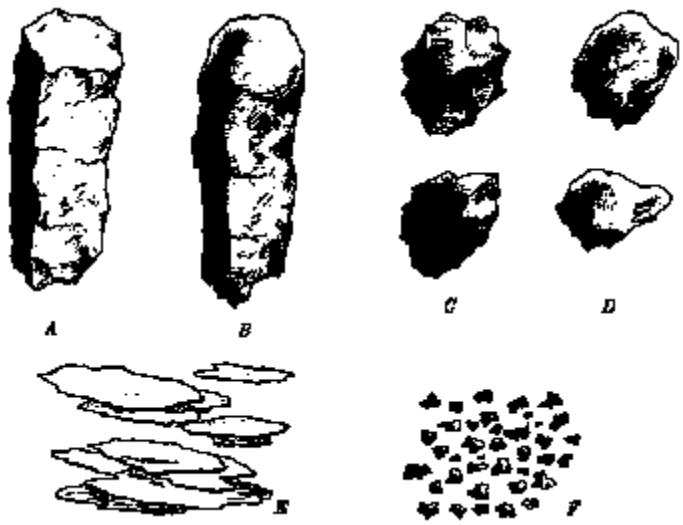

Figure 6-6.—Structure shapes: A, prismatic; B, columnar; C, angular blocky; D, subangular blocky; E, platy; and F, granular.

subrounded edges. Single grain units are entirely noncoherent (loose) sand. Massive structure units are coherent material. Single grain and massive units are in structureless horizons.

The size classes are as follows:

Platy.—Very thin <0.04 in (<1 mm), thin 0.04 to <0.08 in (1 to <2 mm), medium 0.08 to <0.2 in (2 to <5 mm), thick 0.2 to <0.4 in (5 to <10 mm), and very thick ≥0.4 in (≥10 mm).

Granular.—Very fine <0.04 in (<1 mm), fine 0.04 to <0.08 in (1 to <2 mm), medium 0.08 to <0.2 in (2 to <5 mm), coarse 0.2 to <0.4 in (5 to <10 mm), and very coarse ≥0.4 in (≥10 mm).

Columnar and prismatic.—Very fine <0.4 in (<10 mm), fine 0.4 to <0.8 in (10 to <20 mm), medium 0.8 to <2 in (20 to <50 mm), coarse 2 to <4 in (50 to <100 mm), very coarse 4 to <20 in (100 to <500 mm), and extremely coarse ≥20 in (≥500 mm).

Angular and subangular blocky.—Very fine <0.2 in (<5 mm), fine 0.2 to <0.4 in (5 to <10 mm), medium 0.4 to <0.8 in (10 to <20 mm), coarse 0.8 to <2 in (20 to <50 mm), and very coarse ≥2 in (≥50 mm).

Designation for Horizons and Other Layers

The following paragraphs describe the different designators used to describe the master horizons and layers. They also describe the suffix symbols that are used.

Master Horizons and Layers

The capital letters O, A, E, B, C, and R represent the master horizons or layers of soils. These capital letters are the base symbols to which other

characters are added to complete the designations. Most horizons are given a single capital-letter symbol, but some require two letters (fig. 6-7). O horizons contain organic material. A horizons are mineral soil layers that formed at the surface or below an O horizon. They are high in OM and are usually black or brown in color. E horizons are mineral soil layers in which the main feature is loss of silicate clay, Fe, or aluminum (Al), leaving a concentration of sand and silt particles. They are usually paler in color than A horizons or B horizons and lighter in texture (due to the loss of clay) than the underlying B horizon. B horizons are mineral layers that have formed below an A, E, or O horizon. They are the zone of accumulation of clay, Fe, and Al from overlying A and E horizons. They are generally heavier in texture, brighter in color, and stronger in structure than the overlying E horizon. C horizons are mineral horizons or layers that have been little affected by soil-forming processes. They do not have the properties found in the O, A, E, or B horizons. They may have rock structure but are not hard bedrock. R layers are hard bedrock. Granite, basalt, quartzite, and hard limestone or sandstone are examples of bedrock designated R. These layers are cemented, and excavation is difficult. The R layer is sufficiently coherent when moist to make handdigging with a spade impractical, although the bedrock may be chipped or scraped.

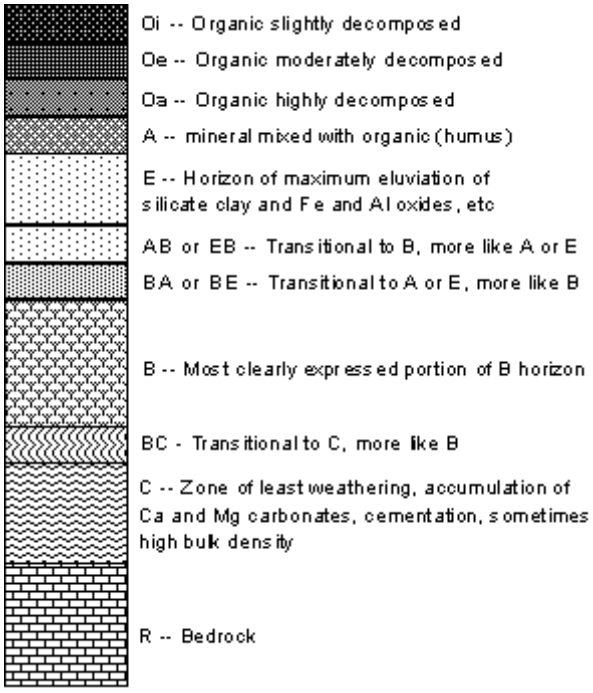

Figure 6-7.—Graphic representation of an idealized soil profile.

Generally, soil horizons occur in the order presented in the preceding text. Not all soils have all master horizons. For example, plowing mixes the O, A, and E horizons, leaving only an A horizon. Also, although soils form in the sequence the horizons are described, soils may be buried (e.g., alluvial

sediments deposited on flood plains), leaving soils with horizons out of sequence. An O or A horizon always forms at soil surfaces. On flood plains, however, they are commonly buried by alluvial sediment. When a horizon is out of sequence, the landscape position and surrounding land use can be used to interpret the cause.

Horizons may contain characteristics of more than one master horizon. They are called transition horizons. For example, a horizon below an A horizon that is still high in OM but not as high as the A horizon, is paler in color than the horizon above or below, and is lighter in texture than the horizon below has characteristics of an A horizon (high OM), but the loss of clay, Fe, and Al also give it characteristics of an E horizon. This would be a transitional horizon. The horizon designation would be an AE horizon or an EA horizon, depending on which characteristics were more predominant—the characteristics of the A horizon or those of the E horizon.

Suffix Symbols

Lowercase letters are used as suffixes to designate specific kinds of master horizons and layers and may be important in designating Field Indicators for hydric soils. The O horizon must use a suffix of an "a," "e," or "i." The "a" designates highly decomposed sapric organic material (muck) with less than 17 percent, by volume, fibers visible after rubbing. The "e" designates hemic organic material (mucky peat) of intermediate decomposition. The "i" designates slightly decomposed fibric organic material (peat) with more than 40 percent, by volume, fibers visible after rubbing. The A horizon may have a "p" designation, indicating mixing through plowing, pasturing, timbering, or other manipulation of the soil surface. The B horizon, like the O horizon, must also have a suffix. Common suffixes used in hydric soils in the Mid-Atlantic Region include the "g," which designates horizons with matrix values of chroma of 2 or less due to saturation and reduction of Fe (can also be used with the A, E, and C horizons); the "h," which designates an accumulation of black OM ± oxides and hydroxides of Fe and Al in sandy soils (commonly found in Spodosols); the "s," which indicates the accumulation of reddish OM/Al ± Fe (also found in Spodosols and may be used together with the "h" as a Bhs); the "t," which indicates an accumulation of illuviated clay; and the "x," which indicates the presence of a fragipan.

Chapter 7
Hydric Soils and Wetland Regulation

Lenore M. Vasilas

According to the "Corps of Engineers Wetland Delineation Manual" (hereafter referred to as the "COE 87 Manual") (Environmental Laboratory, 1987), the presence of a hydric soil is one of three parameters that must be met in order for an area to meet the definition of a jurisdictional wetland. The other two are the presence of hydrophytic vegetation and wetland hydrology. The use of the COE 87 Manual is required for all Federal agencies involved in identification of wetlands, as well as most states that have environmental programs to protect wetlands. The COE 87 Manual generally is used on all lands not classified as agricultural lands. The only exception in the Mid-Atlantic Region is New Jersey, which has assumed the wetland regulatory program and uses the "Federal Manual for Identifying and Delineating Jurisdictional Wetlands" (hereafter referred to as the "COE 89 Manual") on all lands (Federal Interagency Committee for Wetland Delineation, 1989). The requirements for hydric soils in the COE 89 Manual, however, are similar to the requirements in the COE 87 Manual. The National Technical Committee for Hydric Soils (NTCHS) has the responsibility of providing technical leadership in the formulation, evaluation, and application of hydric soil identification.

Hydric soils are defined by the NTCHS as soils that formed under conditions of saturation, ponding, or flooding long enough during the growing season to develop anaerobic conditions in the upper part of the soil (Federal Register, July 13, 1994). For a soil to qualify as a hydric soil for regulatory purposes, it must meet the definition of a hydric soil.

Criteria for Hydric Soils

Hydric soil criteria (NTCHS, 2003b) were set up to be used as a query for the Natural Resources Conservation Service (NRCS) database to produce a list of soil series that are hydric soils. The hydric soil criteria are given in table 7-1.

Table 7-1.—Current Criteria for Hydric Soils

1. All Histels except Folistels and Histosols except Folists, or
2. Soils in Aquic suborders, great groups, or subgroups, Albolls suborder, Historthels great group, Histoturbels great group, Pachic subgroups, or Cumulic subgroups that are:
    a. Somewhat poorly drained with a water table* equal to 0.0 foot (ft) from the surface during the growing season, or

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

   i. water table* equal to 0.0 ft during the growing season 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/h in any layer within 20 in, or

3. Soils that are frequently ponded for long duration or very long duration during the growing season, or

4. Soils that are frequently flooded for long duration or very long duration during the growing season.

---

* Water table refers to 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 6 in. thick and persists in the soil for more than a few weeks. In other databases, saturation, as defined in soil taxonomy, is used to identify conditions that refer to water table in criterion 2 (Soil Survey Staff, 1999).

Criteria 1, 3, and 4 can be used to identify hydric soils in the field. If a soil is identified as a histosol that is not a Folist, it is a hydric soil. If it is proven that a soil in question is ponded or flooded frequently (at least 50 percent of the time; e.g., 5 out of 10 years) for a long or very long duration (at least 7 consecutive days), the soil is a hydric soil. Criterion 2 is not meant to be used in the field; it is only meant to be used as a query to pull soil series that are hydric from the NRCS database. Criteria occasionally change, reflecting changes in soil taxonomy and the format of the NRCS database. For example, Histels and Folistels are part of the Gellisol soil order, which was developed for permafrost soils. The Gellisol soil order did not exist when prior versions of the hydric soil criteria were developed and soils that now classify out as Histels and Folistels would have classified out as Histosols and Folists, respectively. Changes to the hydric soil criteria have not changed which soil series appear on the hydric soil lists.

Hydric soil lists are created by comparing estimated soil properties with the hydric soil criteria. The interpretive rating of whether a soil has a probability of being a hydric soil is obtained by comparing the estimated soil properties stored in the NRCS database with the hydric soil criteria. If any portion of the range of

estimated properties for a soil is within the criteria, that soil appears on the hydric soil list; therefore, it is important to do a field investigation when determining if the soil is in fact hydric.

Hydric Soil Indicators

Hydric soil indicators are physical characteristics in the soil that indicate the soil meets the definition of a hydric soil. Not all hydric soils will produce easily identifiable characteristics that indicate they are hydric soils. It is important to remember that a soil that does not contain a hydric soil indicator may in fact be hydric if it meets the definition of a hydric soil; this soil is an example of what is referred to as a "problem soil."

There are two sets of hydric soil indicators—the COE 87 Manual Indicators and the Field Indicators described in "Field Indicators of Hydric Soils in the United States" (USDA, NRCS, 2002). Hydric soil determinations, which are done on agricultural land and require use of the Food Security Act Manual methodology for wetland determinations, also require use of the Field Indicators. Hydric soil determinations requiring use of the COE 87 Manual must use those COE Indicators listed in the manual; however, the Field Indicators can be used to assist in a determination per a March 21, 1997, regulatory guidance letter from the U.S. Army COE headquarters. The Field Indicators can also be used as stand alone indicators if the soil is a problem soil. To assist in cross referencing the two sets of indicators, there is a table in appendix B of "Field Indicators of Hydric Soils in the United States" that correlates the two sets of indicators.

Many years have passed since the development of the COE 87 Manual Indicators and a great deal of research has been done since their development. The COE 87 Manual Indicators are valid indicators; however, there are times when a soil that is not hydric meets one of the indicators in the COE 87 Manual. The Field Indicators are proof positive, meaning if a soil meets an indicator, it is hydric. They have been developed and refined through continuing research and data collected on hydric soils.

The National Technical Committee for Hydric Soils is responsible for keeping the Field Indicators up to date. These indicators are usually updated yearly, as new information is gathered. The Field Indicators are regional, making it easier to refine the COE Indicators to be proof positive (meaning if the soil meets a Field Indicator, it is a hydric soil). They are much more specific than the COE 87 Manual Indicators, leaving less room for argument. The Field Indicators also include COE Indicators for specific problem soils, such as those associated with flood plains, depressions, and problem parent materials.

This technical standard for hydric soils was developed by the NTCHS to be used for long-term monitoring of soils. It is used to evaluate the functional status of wetland restoration, mitigation, creation, and construction; to evaluate the current functional hydric status of a soil onsite; and with appropriate regional data, to modify, eliminate, or adopt hydric soil Field Indicators for a region. It includes requirements to determine that the soils are saturated,

ponded, or flooded through water table monitoring and proof that the soils are anaerobic and reducing through measurements of redox potential or alpha,alpha-dipyridyl dye, or both. (See Chapter 11, "Monitoring Hydric Soils," for more details on the technical standard.)

Any updated information on hydric soils is provided through the NTCHS. Information and periodic updates can be obtained at <http://soils.usda.gov>.

Chapter 8

Mid-Atlantic Wetland Landscapes and Hydric Soil Indicators

Mary Anne Thiesing, Lenore M. Vasilas,
and Erin Patrick

Background

With the advent of increasingly sophisticated technology, the way to evaluate and study large-scale land surface systems, or landscapes, has changed dramatically. The term "landscape" is variously defined depending on the scope of a study. It can mean a land surface that is visible to the eye in a single view (Watts and Carlisle, 2000), which is the common meaning of the term among soil scientists. Landscape at this scale becomes an influencing parameter. Among landscape ecologists, the term may refer to a land surface that is much larger in size and is viewed via remote sensing technologies ranging from simple aerial photographs to digital satellite images at high resolution. For the purposes of this document, "landscape" is considered to be the land surface that the eye can comprehend in a single view.

Any understanding of wetlands within a region must include consideration of the relationship between wetlands and the landscape. Wetlands develop and are maintained through time because of the interaction of the hydrologic cycle with the landscape. They occur in particular hydrogeological settings where characteristics of the landscape and climate favor the accumulation or retention of surface water or soil water, or both. "Hydrogeologic setting" is the position of the wetland on the landscape with respect to the flow of surface water and ground water and the geological characteristics that control the flow of the water. Controlling geological characteristics include surface relief and slope of the land surface; thickness and permeability of the soils; and the composition, stratigraphy, and hydraulic properties of the underlying geological materials (Bedford, 1996).

This functional interaction of hydrology, geology, and topography within the landscape can be used to classify wetland types within landscapes. The interaction of these three factors is the basis of a classification system for wetland types called the "hydrogeomorphic classification" system (HGM) (Brinson, 1993). Because both the source and flow of water on the landscape are the primary controlling factors in the development and maintenance of wetlands, HGM classifies wetlands into major classes based on water source, hydrodynamics, and geomorphic setting.

The ecosystem identity is highly predictable using only geomorphic and soil variables because these variables control the development of vegetation (Palik et al., 2000). Consequently, knowledge of the HGM class and the soils of a given wetland are likely to be predictive of the plant community in the wetland, as well as the processes occurring within that wetland.

In the Mid-Atlantic Region, the U.S. Geological Survey has identified nine different major physiographic regions; eight of these major regions are in New York State alone. The nine major regions are New England; St. Lawrence Valley; Adirondack; Central Lowland; Coastal Plain; Piedmont; Blue Ridge; Ridge and Valley; and Appalachian Plateau (fig. 8-1).

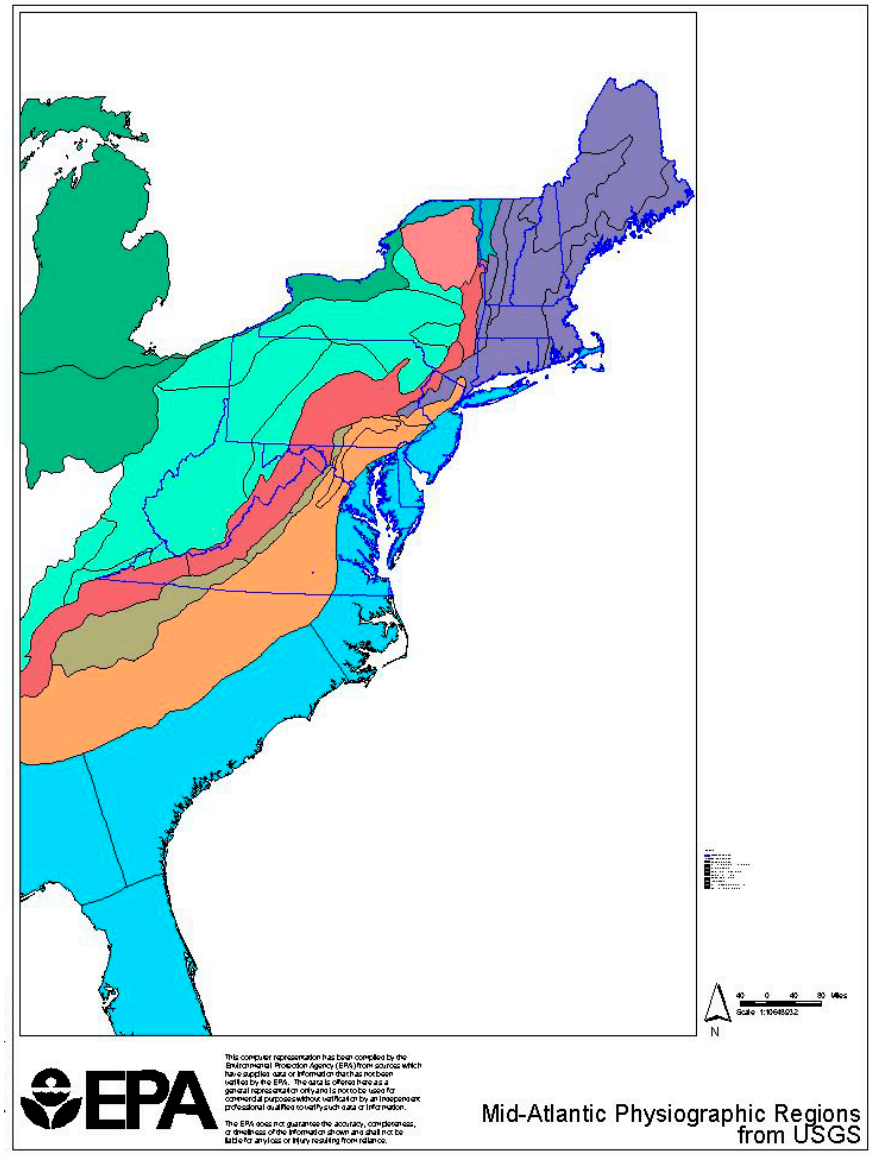

Figure 8-1.—Map of the mid-Atlantic physiographic regions.

This diversity of physiography provides great variability in landscapes, which in turn gives rise to a large variety of wetland types. In the Mid-Atlantic Region, there are five major HGM classes of wetlands. They are depressions, fringe wetlands, riverine wetlands, slope wetlands, and flats. Within each of these classes, soils are variable; however, there is consistency in the distribution of hydric soil indicators among the different classes.

Depressional Wetlands

Depressional wetlands occur in topographic depressions having no outlet or defined drainage network. They occur in many types of terrains, including Wisconsin-age glaciated areas in the Mid-Atlantic Region. Small depressional wetlands are extensive in these areas of glacial deposits because integrated drainage networks have not had sufficient time to develop (Bedford, 1996). They may be driven by surface water, ground water, or a combination of both, and the presence of standing water in a depression may be either permanent or seasonal. Because these areas do not have natural outlets and drainage networks, water may leave depressional wetlands as it permeates the soils, but most of the water is lost through evapotranspiration.

In the Mid-Atlantic Region, depressional wetlands take on a variety of forms. Examples include vernal pools, which may occur in forested wetlands or meadows, as well as shallow ponds and lakes. Other examples include larger depressional areas, such as the Delmarva and Carolina Bays. The vegetation in forested areas of these wetlands includes water-tolerant hardwoods or shrubs, or both. Grasses, sedges, rushes, and other herbaceous plants grow in nonforested depressions. In many instances depressional wetlands are surrounded by wetlands that fall into other HGM classes.

The Field Indicators in "Field Indicators of Hydric Soils in the United States" (USDA, NRCS, 2002) are regionalized to specific Land Resource Regions (LRRs) (fig. 8-2). The common Field Indicators in depressions in the Mid-Atlantic Region are A9 (1 cm [0.4 in] Muck) in LRRs P and T; A10 (2 cm [0.8 in] Muck) in LRRs M and N; S7 (Redox Dark Surface) in LRRs N, P, R, S, and T; and S5 (Sandy Redox), F3 (Depleted Matrix), F6 (Redox Dark Surface), and F8 (Redox Depressions) in all LRRs that occur in the Mid-Atlantic Region.

Other Field Indicators in depressions in the area are A7 (5 cm [1 in] Mucky Mineral) and F13 (Umbric Surface) in LRRs P and T; S9 (Thin Dark Surface) in LRRs R, S, and T; and A3 (Black Histic), A4 (Hydrogen Sulfide), S1 (Sandy Mucky Mineral), S4 (Sandy Gleyed Matrix), S6 (Stripped Matrix), F2 (Loamy Gleyed Matrix), F4 (Depleted Below Dark Surface), and F7 (Depleted Dark Surface) in all LRRs that occur in the Mid-Atlantic Region. For depressional areas that do not exhibit classic hydric soil morphology, consider Field Indicators F3, F6, F8, or F13.

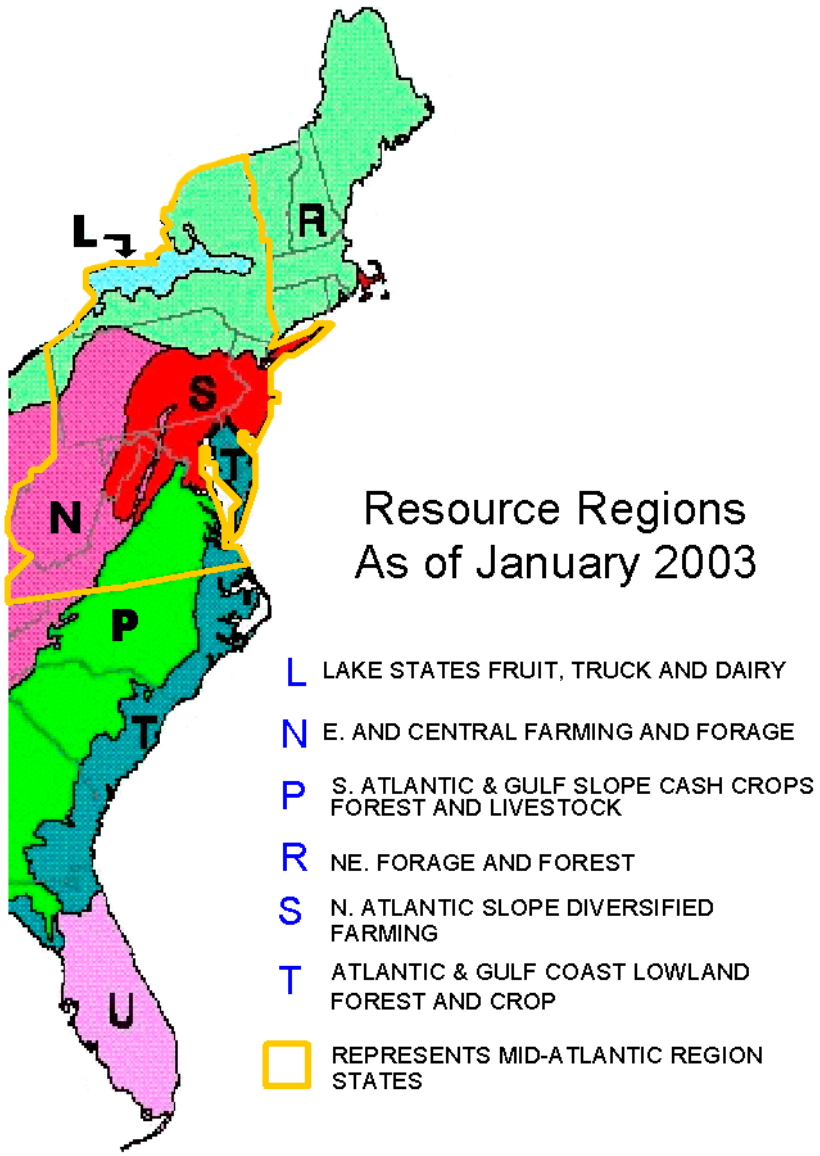

Figure 8-2.—Land resource region (LRR) map of the mid-Atlantic region.

Fringe Wetlands

Fringe wetlands are adjacent to large bodies of water. There are two types of fringe wetlands—lacustrine (adjacent to large lakes) and estuarine (tidal). In tidal fringe wetlands, water enters the fringe wetlands through the periodic flooding from tidal action and, to a lesser extent, may enter through ground water discharge at the upslope edge of the wetlands. In a similar manner, water may enter fringe wetlands along large lakes as a result of ground water discharge or through periodic rise and fall in lake levels. Lacustrine wetlands can be permanently or seasonally saturated or inundated, while estuarine fringe wetlands generally are permanently saturated and are flooded twice daily during

high tide. Water leaves fringe wetlands through evapotranspiration, as well as through flow back into the water body after a flood.

Vegetation in fringe wetlands tends to be dominated by herbaceous plants that are tolerant of saturation and flooding. Water-tolerant trees and shrubs may grow in lacustrine fringe wetlands. Estuarine fringe vegetation may include shrubs such as *Iva* spp. and *Baccharis* spp. in high marsh areas, but it is dominated by herbaceous species. The estuarine vegetation must be salt tolerant.

The common Field Indicators in Mid-Atlantic fringe wetlands are S5 in LRRs N, P, R, S, and T and A3, A4, S4, F2, F3, and F6 in all LRRs that occur in the Mid-Atlantic Region. Other indicators that occur less frequently in Mid-Atlantic fringe wetlands are A7 and A9 in LRRs P and T; A10 in LRRs M and N; S9 in LRRs R, S, and T; and A5 (Stratified Layers), S1, S7, F4, and F7 in all LRRs that occur in the Mid-Atlantic Region.

The identification of Field Indicators in fringe wetlands benefits from the determination of soil colors at two different times—shortly after excavation and after a 20-minute wait. Commonly, fringe wetlands contain soils that have a reduced matrix; therefore, the soil will change color upon exposure to air. Also, exposure to air sometimes results in the formation of redox concentrations in soils that have a matrix with value and chroma of 4/1, 4/2, or 5/2 or have a dark surface layer with value of 3 or less and chroma of 2 or less.

Riverine Wetlands

Riverine wetlands are on the flood plains of rivers and streams or on linear landscapes below headwater seeps. Water sources include both overbank flooding and ground water discharge. Water leaves these wetlands through overbank or ground water flow to streams, evapotranspiration, or recharge to ground water. Riverine wetlands are often seasonally saturated or inundated but may be semipermanently or permanently saturated, depending on stream order. The seasonality, as well as the range of the wetland hydrology, often results in a plant community that is dominated by facultative species.

The common Field Indicators in Mid-Atlantic riverine wetlands are S7 in LRRs N, P, R, S, and T; S9 in LRRs R, S, and T; F12 (Iron/Manganese Masses) in LRRs N, P, and T; and S5 (Sandy Redox) and F3 in all LRRs that occur in the Mid-Atlantic Region. Other indicators in Mid-Atlantic riverine wetlands are S8 (Polyvalue Below Dark Surface) in LRRs R, S, and T and A5, S6, F4, F6, and F7 in all LRRs that occur in the Mid-Atlantic Region. Common Field Indicators in areas that do not have typical hydric soil morphology are F12 in LRRs N, P, and T and F5 (Stratified Layers Thick Dark Surface) and F3 in all LRRs that occur in the Mid-Atlantic Region. Field Indicator F12 is a test indicator in LRR S.

Slope Wetlands

Slope wetlands are on hillsides where discontinuities in the water table or in the slope of the land surface result in ground water discharge to the surface. Ground water exits the soil profile and flows downslope and may exit the slope

wetland into a riverine or depressional wetland. Slope wetlands may be permanently or seasonally saturated. The common vegetation in Mid-Atlantic slope wetlands is herbaceous. It includes forbs, such as skunk cabbage, ferns, grasses, sedges, and rushes. Water-tolerant shrubs occasionally grow in these areas.

The common Field Indicators in Mid-Atlantic slope wetlands are S7 in LRRs N, P, R, S, and T; S9 in LRRs S and T; and S1, S5, F3, F4, and F6 in all LRRs that occur in the Mid-Atlantic Region. Other indicators in Mid-Atlantic slope wetlands are A7 and A9 in LRRs P and T; A10 in LRRs M and N; S8 in LRRs R, S, and T; and A3, S4, S6, F2, and F7 in all LRRs that occur in the Mid-Atlantic Region. In some cases slope wetlands may not have a hydric soil indicator because of the flow of oxygenated water through the upper part of the soil.

Flats

Wetlands can develop on flats in areas of minimal land slope, where the slow surface drainage, often combined with slow permeability, causes water to remain either at or near the surface for significant periods of time. The flats are classified as either mineral or organic, according to the soil type. Water generally enters the wetland through precipitation and exits through evapotranspiration. Mineral flats generally are seasonally saturated, while organic flats are more likely to be permanently saturated.

Organic soils on flats are commonly underlain by silts and clays, which restrict the vertical movement of water to and from peatland. The formation of organic soils over such deposits tends to result in longer retention of the surface water because of the water's inability to move downward. The accumulation of organic sediments can also (given the appropriate climate) obstruct and reroute ground water flows to adjacent areas that may in turn accumulate peat, thus causing the wetland to enlarge (Bedford, 1996).

Common vegetation in mineral flats includes water-tolerant pines, hardwoods, and shrubs; however, in areas where the wetlands were cultivated, herbaceous vegetation may dominate meadows. Common vegetation in organic flats includes cedar and other water-tolerant pines, hardwoods, and shrubs. Flats are most commonly on the Coastal Plain of the Mid-Atlantic Region.

The common Field Indicator in areas of organic flats is A3. The common Field Indicators in areas of mineral flats are A9 in LRRs P and T; A10 in LRRs M and N; S7 in LRRs N, P, R, S, and T; S9 in LRRs R, S, and T; and A3, S5, F3, F4, and F6 in all LRRs that occur in the Mid-Atlantic Region. Other Field Indicators in areas of mineral flats are A6 (Organic Bodies) and A7 in LRRs P and T and S1, S4, S6, S8, F2, F5, and F7 in all LRRs that occur in the Mid-Atlantic Region. Generally, in the absence of problem parent material, the soils in areas on wetland flats exhibit typical hydric soil morphology. However, visible indicators of wetland hydrology are often missing; therefore, the accurate identification and delineation of hydric soils is critical to jurisdictional determinations of mineral flat wetlands.

Chapter 9

Using Soil Survey Information to Identify Hydric Soils

John M. Galbraith and Pam J. Thomas

Background

A soil survey is carried out by systematically examining, describing, classifying, and mapping soils in a survey area. The soil survey report includes maps, descriptions, and interpretations of the soils in a survey area. It is a publication of the National Cooperative Soil Survey (NCSS), a joint effort of the United States Department of Agriculture and other Federal agencies, State agencies including the Agricultural Experiment Stations, land-grant universities, and local agencies. The NCSS was established to produce soil surveys for private landowners. The Natural Resources Conservation Service (formerly the Soil Conservation Service) has leadership for the Federal part of the National Cooperative Soil Survey. As of 1990, a modern soil survey report has been completed for all private agricultural land in the United States that has a history of being used as cropland or the potential for growing crops. No similar program has been established for Federal land, except for in a few areas where the agency that owns the land has signed a contract with the U.S. Department of Agriculture, Natural Resources Conservation Service, to survey the soils and ensure quality control of the data and the maps.

The standard, multiple-purpose soil surveys for farm- or ranch-scale planning have maps with a scale of 1:12,000, 1:15,840, 1:20,000, or 1:24,000. The scale of the map determines the smallest delineation that can be identified, generally 4 acres (1.6 ha) or more for a scale of 1:20,000 and 1.5 acres (0.6 ha) or more for a scale of 1:12,000. Landscape units, such as summits, shoulders, backslopes, footslopes, terraces, or flood plains, are identified and delineated using topographic maps or aerial photo references. The soil scientists subdivide the landscape units into soil map units with a composition as pure and as predictable as possible for the scale of the field maps used.

Where possible, soils are identified at the soil series level, the lowest category of the U.S. system of soil taxonomy (Soil Survey Staff, 1999). A soil series is a conceptualized class of soils with the same classification and similar major characteristics that influence their behavior or potential uses (Soil Survey Division Staff, 1993). Extremely variable soils, such as those on flood plains subject to frequent flooding, are often classified at the suborder level (e.g., Aquepts) or at the great group level (e.g., Fluvaqents) in soil taxonomy (Soil Survey Staff, 1999). These soils are called higher taxa in soil surveys.

Map units are named for the dominant soils or miscellaneous areas in the map unit delineation. Other soils or miscellaneous areas that are of lesser extent in the map unit are called inclusions. They are either similar or dissimilar to the dominant soils or miscellaneous areas. Consociations are made up of one dominant soil and similar soils, which generally make up 15 percent or less of the map unit. They may include areas of dissimilar soils, which generally make up 25 percent or less of the map unit. These dissimilar soils can limit land use more than the dominant soil. Complexes are made up of two or more soils or miscellaneous areas in such an intricate pattern or in such small areas that they cannot be shown separately on the maps. The pattern and proportion of the soils or miscellaneous areas are somewhat similar on the maps. An undifferentiated group is used to identify map units where the dominant soils do not occur predictably in all delineations. The named soil or soils in consociations and complexes are in all delineations, but those in undifferentiated groups are not necessarily present in all delineations and the composition of the named soil varies widely. Other small but important features, such as rock outcrop or small wet areas that do not occur in a regular predictable pattern, are indicated on maps by special spot symbols (Soil Survey Division Staff, 1993).

Hydric Soils

Hydric soils satisfy all requirements of the hydric soil definition: "A hydric soil is a soil 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, July 13, 1994). The soils on a hydric soil list meet some part of the hydric soil criteria. The hydric soil criteria presented in table 9-1 are used to generate hydric soil lists. Hydric soil lists are created by comparing the range of soil series properties in the official soil series description (Soil Survey Division, 2003a) with hydric soil criteria developed by the National Technical Committee for Hydric Soils (NTCHS, 2003b). Soil series that overlap the criteria are interpreted to meet the hydric soil criteria. Thus, the presence of a soil on a hydric soil list is only an interpretive rating and does not necessarily mean that the soil in question is, in fact, hydric.

Table 9-1.—Current Criteria for Hydric Soils

1. All Histels except Folistels and Histosols except Folists, or
2. Soils in Aquic suborders, great groups, or subgroups, Albolls suborder, Historthels great group, Histoturbels great group, Pachic subgroups, or Cumulic subgroups that are:
    a. Somewhat poorly drained with a water table* equal to 0.0 foot (ft) from the surface during the growing season, or
    b. poorly drained or very poorly drained and have either:

i. water table* equal to 0.0 ft during the growing season 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/h in any layer within 20 in, or

3. Soils that are frequently ponded for long duration or very long duration during the growing season, or
4. Soils that are frequently flooded for long duration or very long duration during the growing season.

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* Water table refers to 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 6 in. thick and persists in the soil for more than a few weeks. In other databases, saturation, as defined in soil taxonomy, is used to identify conditions that refer to water table in criterion 2 (Soil Survey Staff, 1999).

Hydric soil criteria and hydric soil lists, along with standard soil surveys, are used as offsite assessment tools for planning and management. Onsite evaluations are conducted to confirm that the soil meets the hydric soil definition through the positive morphological evidence outlined in the COE 87 Manual and updates (Environmental Laboratory, 1987) and in the latest version of "Field Indicators of Hydric Soils of the United States" published by the U.S. Department of Agriculture, Natural Resources Conservation Service. According to the National Technical Committee for Hydric Soils, criteria 1, 3, and 4 can be used to document the presence of a hydric soil (NTCHS, 2003c); however, proof of anaerobiosis must also be obtained. Criterion 2 cannot be used to document the presence of a hydric soil; Field Indicators are used to document the presence of hydric soil morphology in saturated soils. For further explanation, see "Delineating Hydric Soils" in "Wetland Soils: Genesis, Hydrology, Landscapes, and Classification" (Hurt and Carlisle, 2001).

Hydric Soils and Soil Survey

Detailed soil surveys (scales of 1:100 to 1:400) or onsite investigations must be conducted for the single purpose of delineating hydric soils. The standard soil surveys were drawn with a minimum delineation size, which is not detailed enough to identify wetlands as small as 5,000 ft^2 (0.05 ha) as required by some

regulations; therefore, they are best used with hydric soil lists for offsite planning and resource evaluation. The most important information in a printed or digital soil survey is the recorded knowledge of the relationships between soils, landscape positions, hydrology, and vegetation in the survey area. The location of a suspected wetland on a detailed soil map provides the names of soils to check against the hydric soil list and to record as part of the COE 87 Manual delineation process. The information in standard soil surveys is also useful for prediction of hydric soils and for reconnaissance of soil resources prior to onsite investigation. Several spot symbols, such as those for springs, seeps, wet spots, and marshes, that are used on detailed soil maps can also be reliable indicators of the presence of hydric soils. For further explanation, see "Delineating Hydric Soils" in "Wetland Soils: Genesis, Hydrology, Landscapes, and Classification" (Hurt and Carlisle, 2001).

Precautions must be taken in using standard soil surveys for gathering hydric soil information because map units commonly contain both hydric and nonhydric soils. The location of hydric soils within any map unit delineation is generally unknown (1) unless detailed landscape position descriptions were given for major and minor components and (2) because the range of a soil series may include hydric and nonhydric soils. Knowledge of the limitations of soil surveys is important in order to appreciate the possible and appropriate uses of soil surveys for hydric soil identification. Both printed and digital standard soil surveys have information concerning hydric soils, although each is slightly different.

Wetland Hydrology and Soil Surveys

The COE 87 Manual and subsequent guidance allow the use of local soil survey data as a secondary indicator of wetland hydrology. Indicators of wetland hydrology include primary and secondary indicators. Primary indicators are stand alone indicators, while two secondary indicators must be present to identify a site as having wetland hydrology. To use local soil survey data as a secondary indicator of hydrology, the soil found onsite must be identified to the soil series level by matching the characteristics of the soil onsite to the range of characteristics in the official series description. If the soil series onsite has a seasonal high water table in the upper 12 in (30 cm) of the profile, the local soil survey indicator is met. The water features table in the soil survey can be used to identify seasonal high water table depths for the map units in that soil survey area. Onsite field soil data must be used to identify the soil series onsite. Soil survey maps are helpful when trying to identify map units likely to meet the local soil survey data, but soil series found onsite must be verified with field data to ensure that the site is not located in an inclusion of dissimilar soils that do not have the same seasonal high water table as the soil series listed in the map unit name. When hydrology alteration is evident onsite, caution should be used when applying this indicator. Soil survey data refers to the natural state of that soil series.

Printed Soil Surveys

The following list of sections and tables that are included in soil survey reports is useful in identifying hydric soil resources. The text and tables may be printed, online, on a CD, or a combination of these (Soil Survey Division, 2003b). Not all soil surveys have the same tables, but most soil surveys published after the mid-1970s should contain similar information. The text and tables that may be helpful when identifying hydric soils are listed in order of decreasing reliability. They are as follows:

1. Information in the climate tables ("Temperature and Precipitation," "Freeze Dates in Spring and Fall," and "Growing Season") can be used to identify the growing season as part of the hydric soil definition.
2. Some newer soil surveys include hydric soil lists. In others the national, state, or county hydric soil list (Soil Survey Division, 2003c) can be compared with higher taxa, series, and phase names in the "Soil Legend" or the "Index to Map Units."
3. The "Classification of the Soils" table can provide information by comparison against the hydric soils criteria 1, 3, and 4 in table 9-1, which is near the beginning of this chapter.
4. The "Soil and Water Features" table includes information about the frequency of flooding and ponding to be matched against hydric soils criteria 3 and 4 in table 9-1. Also, the columns "Depth" and "Months" under "High water table" may be matched against hydric soil criteria 2a and 2b in table 9-1 to provide, but not to confirm, general information about meeting the hydric soil definition. Table 9-1 is also used to confirm that a soil series found onsite meets the secondary indicator (local soil survey data) of hydrology in the COE 87 Manual.
5. The "Soil Series and Their Morphology" section gives a detailed description of representative soil morphology. These descriptions may be detailed enough to match against current Field Indicators.
6. The section "Detailed Soil Map Units" gives hydrology indicators, such as drainage class and depth to the water table, and a relative description of landscape position. Soils that are poorly drained or very poorly drained and that are in flooded, ponded, low lying, or nearly level landscape positions are likely to be hydric soils.
7. Other supportive interpretative information can be gathered from the "Woodland Management and Productivity" table, which lists trees that may be wetland indicators.
8. The "Wildlife Habitat" table gives information about potential habitat for wetland plants and shallow water areas.

Digital Soil Surveys—Tabular Data

Many standard soil surveys have been converted to a digital version called the Soil Survey Geographic Database (SSURGO) (Soil Survey Division, 2003d). The following information exists in the database tables downloaded with the spatial files.

As shown by example in table 9-2, the tables are related by fields (columns) that provide soil survey information, such as map unit symbol in the *musym* field, sequence of the named soil map unit components in the *seqnum* field, the name of the map unit component in the *compname* field, the soil series identification number in the *s5id* field, and the map unit composition percentage in the *comppct* field.

Table 9-2.—Example of data from Montgomery County, Virginia
SSURGO ***comp*** **(map unit composition)** table

Stssaid	*Muid*	*Seqnum*	*Musym*	*Compname*	*S5id*	*Comppct*
VA121	12110	1	10	CRAIGSVILLE	VA0072	100
VA121	12111B	1	11B	DUFFIELD	PA0013	45
VA121	12111B	2	11B	ERNEST	WV0018	35

Fields are filled with code values that are identified in the *codes* table. The following list of tables and fields, which are listed in order of decreasing reliability, may be helpful when identifying hydric soils.

1. The *comp* (map unit component) table identifies the named map unit components that are hydric soils in the *hydric* field; annual flooding in the *anflood, anflodur, anflobeg,* and *anfloend* fields; flooding and ponding during the growing season in the *pnddepl, pnddeph, pnddur, pndbeg, pndend, gsflobeg, gsflodur, gsfloend,* and *gsflood* fields; soil classification in the *clascode* field; drainage class in the *drainage* field; and water table information in the *wtdepl, wtdeph, wtkind, wtbeg,* and *wtend* fields as shown by example in table 9-3.

Table 9-3.—Example of data from Montgomery County, Virginia
SSURGO ***comp*** **(map unit composition)** table

Muid	*Seqnum*	*Musym*	*Compname*	*S5id*	*Comppct*	*Hydric*	*Anflood*	*Anflodur*	*Anflobeg*	*Anfloend*
12124D	1	24D	JEFFERSON	KY0113	100	N				
12125	1	25	MCGARY	IN0112	40	N	OCCAS	BRIEF	JAN	MAY
12125	2	25	PURDY	WV0034	35	Y				

Muid	*Seqnum*	*Musym*	*Gsflood*	*Gsflodur*	*Gsflobeg*	*Gsfloend*	*Pnddepl*	*Pnddeph*	*Pnddur*	*Pndbeg*	*Pndend*
12124D	1	24D					0	0			
12125	1	25					0	0			
12125	2	25					0	0			

Muid	*Seqnum*	*Musym*	*Clascode*	*Drainage*	*Wtdepl*	*Wtdeph*	*Wtkind*	*Wtbeg*	*Wtend*
12124D	1	24D	UUDHAAA 09602460202021602	W	0	0			
12125	1	25	AAQEPAE 12602340202021602	SP	1	3	APPAR	JAN	APR
12125	2	25	UAQENAA 11402340202021602	P	0	0	APPAR	NOV	JUN

2. The *inclusn* (hydric soil inclusions) table identifies the named map unit components that are hydric soils in the *hydric* field, the soil that is considered hydric in the *inclsoil* field, the map unit percent composition of the included hydric soil in the *inclpct* field, the landform location in the *landfmlo* field, the criteria under which the soil met the hydric soil criteria in the *hydcrit* field as shown by example in table 9-4, and the hydric soil criteria that must be identified onsite in the *onsite* field.

Table 9-4.—Example of data from Montgomery County, Virginia
SSURGO ***inclusn*** **(hydric soil inclusions)** table

Muid	*Seqnum*	*Inclsoil*	*Inclpct*	*Hydric*	*Landfmlo*	*Condition*	*Hydcrit*	*Onsite*
12121C	1	PURDY		Y	FP		2B3	3
12125	1	PONDED SOILS			DP		2B3	3
12125	2	FLOODED SOILS			FP		2B3	4

3. The *hydcond* (hydric condition) field is available in the *comp* (map unit component) and *inclusn* (hydric soil inclusions) tables downloaded with the spatial files. The hydric condition field identifies each map unit component and all map unit inclusions that meet current hydric soil criteria and Field Indicators.

4. The *mapunit* (map unit) table identifies the name of the map unit components and any special varieties (phases) in the *muname* field for comparison with national, state, or county hydric soil lists as shown by example in table 9-5.

Table 9-5.—Example of data from Montgomery County, Virginia
SSURGO ***mapunit*** **(map unit)** table

state	*ssaid*	*musym*	*Muname*
VA	121	10	Craigsville soils
VA	121	11B	Duffield-Ernest complex, 2 to 7 percent slopes
VA	121	11C	Duffield-Ernest complex, 7 to 15 percent slopes

5. The *taxclass* (classification) table identifies the classification in the *clascode* field for comparison with hydric soil criteria 1, 3, and 4 as shown by example in table 9-6.

Table 9-6.—Example of data from Montgomery County, Virginia
SSURGO ***taxclass*** **(classification)** table

clascode:c	*class:c*
AAQEPAE 12602340202021602	Fine, mixed, mesic Aeric Epiaqualfs
AUDHAAA 12602340202021602	Fine, mixed, mesic Typic Hapludalfs
AUDHAAQ0612602340202021602	Fine, mixed, mesic Aquic Hapludalfs

6. The *wlhabit* (wildlife habitat) table identifies suitability of the soil to produce the habitat (wetland) requirements for wetland wildlife in the *wlwet* field, the wildlife (wetland plants) habitat element in the *wlwetplt* field, and the habitat (shallow water) element in the *wlshlwat* field as shown by example in table 9-7.

Table 9-7.—Example of data from Montgomery County, Virginia
SSURGO ***wlhabit* (wildlife habitat)** table

Stssaid	*Muid*	*Seqnum*	*Wlwetplt*	*Wlshlwat*	*Wlwet*
VA121	12124D	1	VERY POOR	VERY POOR	VERY POOR
VA121	12125	1	FAIR	FAIR	FAIR
VA121	12125	2	GOOD	GOOD	GOOD

Digital Soil Surveys—Spatial Data

Soil Data Viewer (Soil Survey Division, 2002e) is available as an extension tool to ArcView™, a software product of Environmental Systems Research Institute in Redlands, California. It allows users to easily create hydric soil maps. This tool is designed to make maps from SSURGO spatial data and data tables.

Outside of using Soil Data Viewer, advanced users of geographic information systems software may generate hydric soil maps using the hydric soil *hydric* field in the *comp* (component) and *inclusn* (hydric soil inclusion) tables, as shown in tables 9-3 and 9-4. Maps that show delineations with hydric soils reveal spatial relationships that may indicate the likely occurrence of hydric soils. For example, the map units with the following characteristics are likely to have hydric soils within most delineations. They include map units (1) on flood plains, especially between and adjacent to hydric units; (2) in level and nearly level areas with shallow, perching layers, such as fragipans, or somewhat poorly drained soils; (3) that include spot symbols, such as springs, seeps, wet spots, and marshes; and (4) with soils that have a shallow water table during the growing season.

Chapter 10

Identifying Problem Hydric Soils in the Mid-Atlantic Region

Carl E. Robinette, Martin C. Rabenhorst, and Lenore M. Vasilas

Background

Most hydric soils are readily identified by observing either a predominance of gray color with redoximorphic concentrations (formerly called "red mottles") near the surface of the soil or a thick accumulation of organic matter on the surface. These readily observable soil morphologies are indicators that the soil has been chemically reduced and fits the standard "saturated soil/wet soil morphology" paradigm. They are the result of the oxidation-reduction of mostly iron near the surface and the accumulation of organic matter, and they comprise the primary hydric soil indicators in the COE 87 Manual (Environmental Laboratory, 1987). In the quest to accurately identify all hydric soils and develop corresponding field morphological indicators, however, soil scientists and other wetland practitioners are met with the realization that it is an imperfect world. For a myriad of reasons, some of which are still poorly understood, there are some relatively small but significant areas that are, or appear to be, anomalies to the standard "saturated soil/wet soil morphology" paradigm. That is, not all hydric soils develop diagnostic redoximorphic features, and some soils have colors that suggest they formed under saturated conditions when, in fact, they did not. It is these anomalous soil morphologies that are so difficult to interpret and are easily misinterpreted by the layperson that have become known collectively as "problem soils."

More specifically, these problem soils can be divided into two kinds. The first is the true "problem hydric soil," which includes saturated soils that do not have the common redoximorphic features characteristic of standard wet soil morphology. For more information, see "Aquic Conditions and Hydric Soils: The Problem Soils," which is a technical summary detailing studies of many of these kinds of soils (Vepraskas and Sprecher, 1997). The second includes those cases where soil morphology may suggest saturation, but where, in fact, the soils are dry or represent situations that are easily misinterpreted. These problematic soil situations will be referred to as "dry hydric morphologies."

Since the outset of hydric soil identification, soil scientists have been well aware of many of the "problem hydric soils." Reference to problem soils, such as those that formed in red parent material and wet Entisols, wet Mollisols, wet Spodosols, and wet sandy soils, was made in the COE 87 Manual. Problem soils have been the subject of extensive research over the past decade and have contributed greatly to our knowledge of soil wetness/soil morphology

relationships (Vepraskas and Sprecher, 1997). Problem soil issues have been the catalyst for many studies in the Mid-Atlantic Region (Elless et al., 1996; Rabenhorst and Parikh, 2000; Shaw and Rabenhorst, 1999) and continue to be the focus of research by members of the Mid-Atlantic Hydric Soil Committee to identify and fine-tune problem hydric soil indicators. While the primary objective for the development of "Field Indicators of Hydric Soils of the United States" was to provide test positive morphological hydric soil indicators for the standard saturated soil/wet soil morphology paradigm, it also provided indicators for many of the so-called early problem soils that involved wet sandy soils and Mollisols (USDA, NRCS, 1996). The subsequent versions (USDA, NRCS, 1998, 2002) are testaments to the continuing efforts by soil scientists to refine indicators and develop new indicators for problem hydric soil situations. All hydric soil indicators presented in this chapter are Field Indicators.

Field identification of a problem hydric soil situation or dry hydric morphology is dictated by either the practitioner's level of soil science knowledge and field experience or by technical soil morphology factors, or both. For example, many experienced soil scientists know that certain soils exist in landscape positions that they believe are sufficiently wet to warrant hydric soil status, yet their morphologies suggest a nonhydric condition. These are problem hydric soils and are represented by wet soils with inherent colors (red, green, yellow) that interfere with standard hydric soil indicators or soils that are subject to flooding or ponding or have a seasonal high water table for (or close to) the minimum duration of time or within (or near) the minimum depth required to meet hydric soil criteria. The problem with dry hydric morphology arises largely from lack of knowledge and experience with local soils, parent materials, and geology. These soils are commonly, but not always, on higher and drier landscape positions, which are not wet, yet they have morphologies that, without very close and detailed examination, can easily be misinterpreted as wet. To facilitate the accurate identification of all hydric soils, it is incumbent upon practitioners to have an awareness of both problem hydric soils and dry hydric morphologies in a region.

Problem Hydric Soils

The following paragraphs provide information about true problem hydric soils mentioned earlier in this chapter.

Soils with Red Parent Material

These are red soils (fig. 10-1) derived from parent material with a natural, inherent reddish color attributable to the presence of highly oxidized forms of iron (hematite) as coatings on, and occluded within, mineral grains. Consequently, the capacity of such soils to evolve predominantly gray matrix colors in response to seasonal saturation is vastly diminished compared to other soils. Red soils in depressional or concave landscape positions that are inundated for very long periods or are saturated for 6 months or more commonly have a gray matrix (fig. 10-2). The problem occurs in areas where the duration of seasonal saturation is shorter, and it is most pronounced in the transition zone to nonhydric soils where minimum hydrology criteria are met.

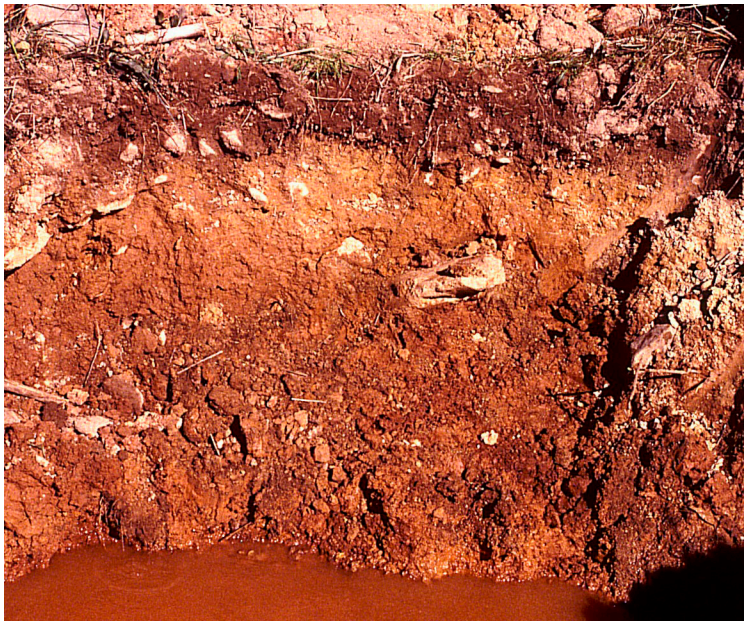

Figure 10-1.—A hydric soil formed in red parent material that meets Field Indicator TF2 (Red Parent Material) but does not have the typical gray matrix that would meet Field Indicator F3 (Depleted Matrix).

Figure 10-2.—A hydric soil formed in alluvium derived from red parent material. This soil is in a drainage swale at a Mid-Atlantic Hydric Soils Committee study site. The red parent material was confirmed by CCPI testing. The profile is sufficiently wet for a very long period of time and meets Field Indicator F3 (Depleted Matrix).

Soil scientists' observations and studies confirm soils that formed in red parent material and are seasonally saturated for 1 to 3 months commonly retain matrix hues of 7.5YR or redder and value and chroma of 3 or 4, although they may develop a few redox concentrations or depletions (Elless et al., 1996).

The objective of current studies by members of the Mid-Atlantic Hydric Soil Committee is to identify which hydromorphological expressions correspond to the minimum periods of saturation necessary for classification as a wetland. In particular, committee members are testing and gathering data to refine Test Indicator TF2 (Red Parent Material) so that it might be adopted as a test-positive indicator on soils formed in red parent material. Key points of contention at this time revolve around the percentage of redox concentrations and depletions that are necessary in an otherwise reddish matrix to confirm minimum saturation.

Another common issue is to determine in what specific locations can, or should, red parent material indicators be applied. Field Indicators tie Test Indicator TF2 to specific locations and geologic formations. In the Mid-Atlantic Region, the soils formed in red parent material are associated with Triassic-age sediments in the Piedmont of Virginia, Maryland, Pennsylvania, and New Jersey; with Devonian- and Mississippian-age sediments of the Hampshire and Mauch Chunk Formations in the Ridge and Valley and Appalachian Plateau Regions of Maryland, West Virginia, and Pennsylvania; and with Permian-age sediments of the Dunkard Group in West Virginia. They also occur in colluvial deposits and on alluvial flood plains that emanate from the previously referenced sediments. In particular, the question of Test Indicator TF2 applicability has arisen on colluvial deposits and flood plains and in other areas of distinctly red soils. Recent work has yielded an approach known as CCPI (Color Change Propensity Index), which appears to answer this question (Rabenhorst and Parikh, 2000). Application of CCPI involves laboratory tests and colorimeter measurements. The results of these tests are combined into the Index, which shows the inherent resistance of a soil to the development of redoximorphic color changes.

Anomalous, Bright Loamy Soils

These bright loamy soils, which are on coastal plains, formed in silty to loamy materials with brownish to yellowish matrix colors in the subsoil, which contains redoximorphic features typically indicative of moderately well drained soils (fig. 10-3); yet casual observations suggest the presence of saturation or inundation sufficient to meet the hydrology of a hydric soil. These soils are located in relative close proximity to coastal waters or marshes and most commonly occur at elevations near sea level. They have been identified on the Eastern Shore of Maryland and in Delaware. A research project is currently underway at several locations to confirm hydromorphology and to determine the cause of the anomalous soil morphology.

Figure 10-3.—An anomalous, bright, loamy hydric soil from a University of Maryland study site. The typical matrix is 10YR 5/3 or 4/4 at a depth of 8 to 20 in (20 to 50 cm) and 10YR 4/6 at a depth of 20 to 32 in (50 to 80 cm). It has common medium distinct 10YR 5/2 redox depletions and common medium distinct 7.5YR 4/6 redox concentrations, which occur as soft masses.

Anomalous, Bright Sandy Soils

These bright sandy soils are on coastal plains. They have color morphology and hydromorphology and are in locations similar to those of the previously mentioned loamy soils (fig. 10-4); however, they have been identified and described in New Jersey at a National Hydric Soil Workshop field site. They are presumed also to occur along the coastline of Delaware, Maryland, and Virginia.

Figure 10-4.—An anomalous, bright, sandy hydric soil within 200 ft (8 m) of a tidal marsh. The surface layer is thick because it has been plowed. From 0 to 13 in (0 to 32 cm), it is 10YR 3/2 with few fine distinct 7.5YR 3/4 redox concentrations occurring as soft masses. The soil has a 10YR 4/6 matrix at a depth of 13 to 24 in (32 to 70 cm).

Piedmont Flood Plain Soils

These relatively young soils developed in alluvium that is believed to be of post-colonial settlement age. They generally are 20 to 30 in (50 to 75 cm) or more thick and, in many cases, have buried hydric soils with strong indicators. The layers in the upper part of the subsoil typically have matrix hues of 10YR or 2.5Y, value of 4 or 5, and chroma of 3 or 4 with common to many redox concentrations and few to many redox depletions of chroma of 2 or less (fig. 10-5). Soil morphology is indicative of somewhat poorly drained or moderately well drained soils, yet anecdotal observations suggest hydrological conditions due to a seasonal high water table may be sufficient to qualify as hydric. Some studies have been initiated to quantify hydromorphology. Commonly, the Piedmont flood plain soils occur in proximity to hydric soils with indicators in the wettest part of the landscape. Such areas have been observed and characterized in the Piedmont of Maryland and Pennsylvania but are believed to occur throughout the Mid-Atlantic Region.

Marl Soils

Marl soils have been identified on flood plains in the Great Limestone Valley (Hagerstown Valley) in the Ridge and Valley physiographic province of Maryland, West Virginia, Pennsylvania, and, perhaps, in Virginia and

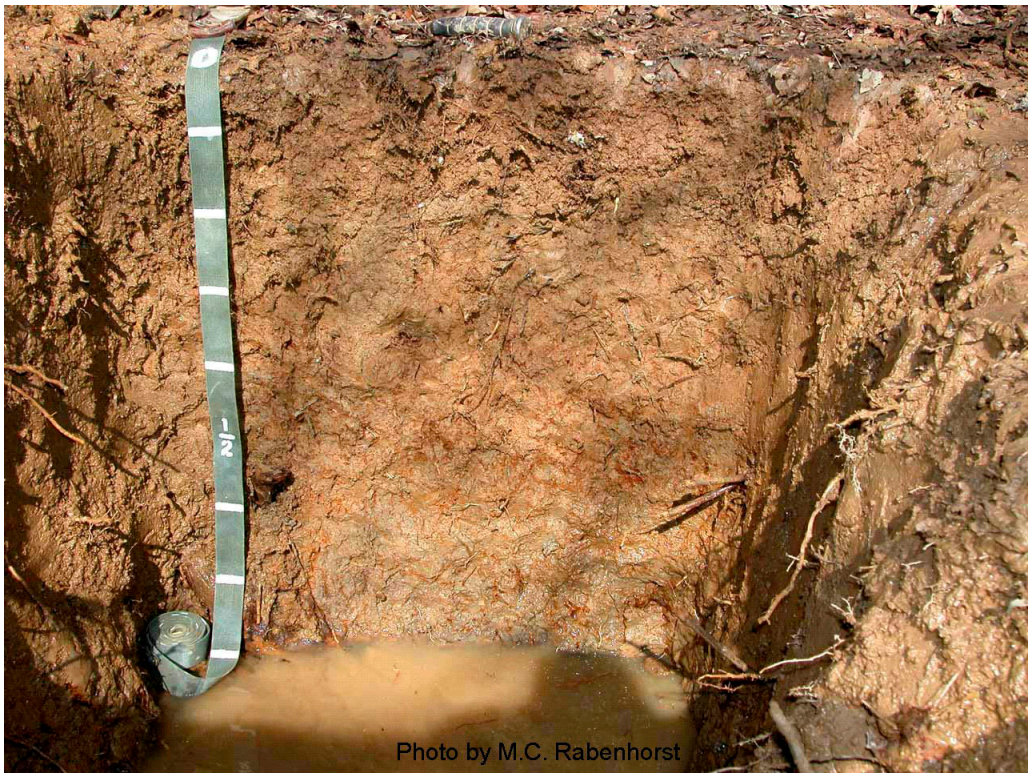

Figure 10-5.—A hydric soil from a University of Maryland study site on a Piedmont flood plain. It has a bright matrix near the surface.

New York. They have also been identified in minor limestone valleys in West Virginia. These soils developed in marl sediments deposited in water by precipitation of calcium carbonate by algae and have been recently studied and characterized (Shaw and Rabenhorst, 1999). In this document, the word "marl" is restricted in meaning to the definition in "Field Indicators of Hydric Soils of the United States": "An earthy, unconsolidated deposit consisting chiefly of calcium carbonate mixed with clay in approximately equal proportions, formed primarily under freshwater lacustrine conditions." Marl soils are particularly problematic since the inherent color of precipitated calcium carbonate is gray to white with matrix chroma of 1 or 2, and they commonly contain few to common, distinct or prominent iron oxide concentrations. Consequently, drier areas of these soils could easily be misinterpreted as meeting Field Indicator F3 (Depleted Matrix).

Typical profiles also contain alternating buried surface layers with a varying content of organic carbon (fig. 10-6). While all profiles appear to be very similar, hydrology varies from well drained to poorly drained. The true hydric soils commonly occur in concave backwater sloughs and drainage areas immediately adjoining major limestone springs. Some areas of these soils could be falsely interpreted as hydric by Field Indicator F10 (Marl) if the indicator were not restricted to use in South Florida.

Figure 10-6.—A hydric soil derived from marl, located in a concave, backwater slough. The profile consists of 98 percent calcium carbonate throughout. Some pedons meet Field Indicator F3 (Depleted Matrix), F4 (Depleted Below Dark Surface), or F10 (Marl) if used for testing in the Mid-Atlantic Region.

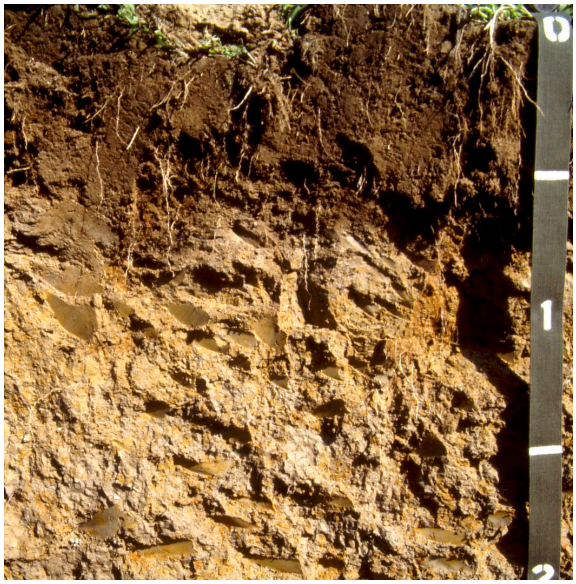

Figure 10-7.—A coastal plain hydric soil containing glauconite. Below the A horizon the soil meets Field Indicator F3 (Depleted Matrix), but it is difficult to differentiate the ≤2 chroma colors of the glauconite from the redox depletions.

Glauconitic Soils

Glauconitic soils have been mapped in a band predominantly in the upper Coastal Plain, running from Maryland through Delaware and New Jersey. These soils contain relatively high amounts of glauconite, a clay that has an inherent dark green color (fig. 10-7). Where sufficient glauconite is present, the matrix can easily have chroma of 2 or less and the matrix color can fall on the gley page of the "Munsell® Soil Color Charts" as well. For this reason, glauconitic soils are excluded from the definition of "gleyed matrix" in "Field Indicators of Hydric Soils of the United States." Similarly, these low-chroma and gley-inherited matrix colors can mask true low-chroma depletions attributable to

anaerobiosis and reduction. The resulting color patterns and associated concentrations can be categorized by some as meeting the depleted matrix indicators, even though hydromorphology is not met, and, at the same time, they can be overlooked by other practitioners with the justification that gray colors are attributable to glauconite, although the soil is, in fact, wet. Also, because the glauconitic parent material inevitably contains sulfides in the unoxidized zone, geologic weathering and oxidation of sulfides may produce iron concentrations that are not associated with a seasonal high water table or wet conditions and may even be evident in well drained soils. In 2002, upland glauconitic soils in New Jersey were observed to meet Field Indicator F6 (Redox Dark Surface) during a field trip by members of the Mid-Atlantic Hydric Soil Committee. At this time, the best indication of qualifying as a hydric soil in these materials is a concave position on the landscape, predominance of facultative wet and obligate hydrophytic vegetation, and observation of hydromorphology. One pedon in Anne Arundel County, Maryland, has been described as having color changes on exposure to air commensurate with a "reduced matrix."

Dry Hydric Morphologies

The following paragraphs provide information about instances where the soil morphology may suggest saturation but where the soils are dry or the situation is misinterpreted.

Well Drained Spodosols and Sandy Soils with a Thick E Horizon

Some of these soils can have a thick albic E horizon with matrix chroma of 2 or less, which can easily be interpreted as a depleted matrix (figs. 10-8 and 10-9). Careful examination of the E horizon will show an absence of redox concentrations and anaerobically decomposing organic matter, and deeper observation of underlying subsoil layers will show matrices with chromas of 4 to 6.

Hydric Spodosols and sandy soils (fig. 10-10) can be identified by the presence of redox concentrations in the E horizon, splotchy colors due to translocated organic matter in the E horizon, or a combination of these.

Figure 10-8.—A dry Spodosol with a thick E horizon that could be mistaken for a hydric soil by meeting Field Indicator F3 (Depleted Matrix).

Figure 10-9.—A dry, coastal plain, sandy soil with a thick, gray E horizon. This soil may be mistaken for a hydric soil because it has a thick, gray E horizon.

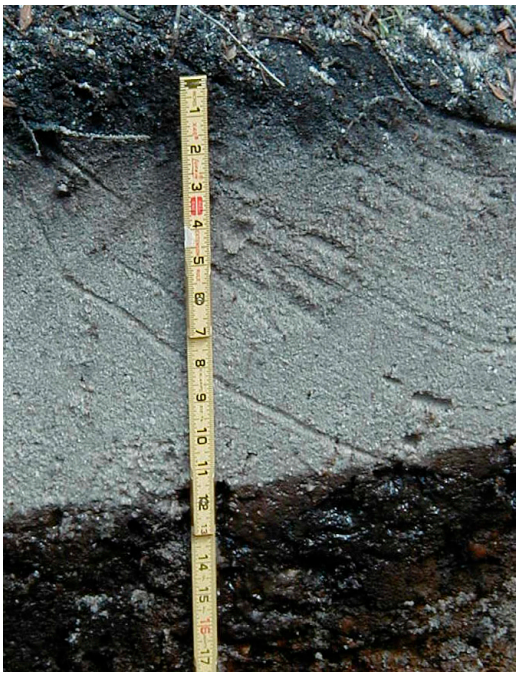

Figure 10-10.—A hydric, coastal plain Spodosol having a gray E horizon with translocated organic matter creating a splotchy pattern throughout the horizon.

Marl Soils

About one-half to two-thirds of the marl soils mapped in the Great Limestone Valley, as described previously, are, in fact, moderately well drained or even well drained but have soil morphology that qualifies as Field Indicator F3 (fig. 10-11). Commonly, the subsoil matrix has chroma of 2 and few to common redox concentrations occur. The concentrations are primarily nodules or concretions. Their location in smooth or convex areas apart from sloughs and drainageways emanating from major spring seeps helps to separate upland marl soils from hydric marl soils.

Figure 10-11.—A moderately well drained soil formed in material derived from marl that, within the morphological range, may meet Field Indicator F3 (Depleted Matrix), F4 (Depleted Below Dark Surface), or F10 (Marl) if it is used for testing in the mid-Atlantic region.

Iron- and Manganese-Rich Soils

In some small areas in the Piedmont of Maryland, soils that are extremely rich in iron and manganese oxide formed in material derived from calciferous schist and marble. These soils may be easily misinterpreted as containing high amounts of organic carbon and may be classified as hydric because of the dark colors (values of 3 or less and chroma of 2 or less) and the seemingly low densities (fig. 10-12). The dark color is, in reality, due to manganese oxide that, in combination with iron oxide, has been measured as high as 25 to 30 percent, by weight. These dark soils are common in convex positions on the landscape. They can be confirmed as "nonorganic" with the application of cold, 3 percent hydrogen peroxide, which will evolve a whitish cloud of gas (fig. 10-13) in the presence of manganese oxide.

Figure 10-12.—An upland soil containing high amounts of manganese. The black color and low density of the soil could be mistaken for organic matter.

Figure 10-13.—Soils high in manganese can be confirmed as nonorganic with the application of cold, 3 percent hydrogen peroxide, which will evolve a whitish cloud of gas in the presence of manganese oxide.

Burnt Shale Soils

These soils mostly formed in material derived from shale or fine grained sandstone. They have inherited gray colors in the matrix. The colors are attributable to extreme metamorphism during the period of geologic formation. These soils, which are common in the Piedmont of Maryland, occur in long, very narrow bands paralleling intrusions of igneous basalt dikes within and adjoining Triassic red shales. They are easily misinterpreted because the subsoil has a predominantly gray matrix and commonly contains few to many, very fine, reddish shale parachanners (figs. 14 and 15). They mostly are in smooth or convex positions on the landscape. If these soils are in concave positions in drainageways, a darker, thicker surface layer, along with the presence of redox concentrations as soft masses, should be relied upon as perhaps indicating hydric conditions.

Figure 10-14.—An upland soil formed in material derived from burnt shale on a convex ridgetop. The dark surface layer and the 1-chroma matrix in the B horizon are inherited from the parent material. They could easily be misinterpreted as redox features.

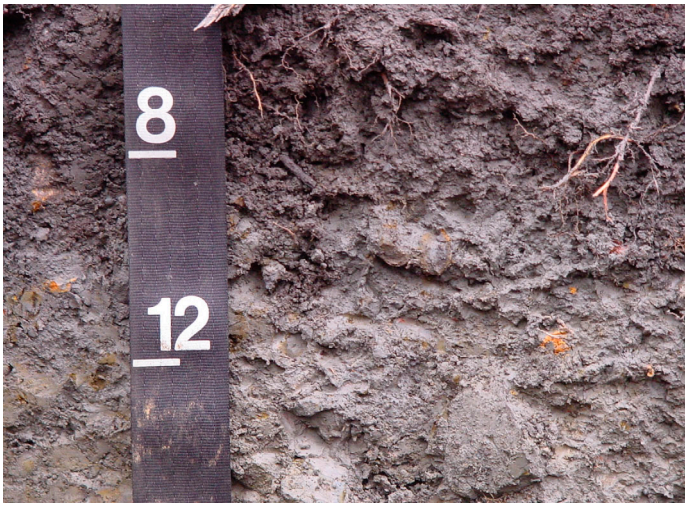

Figure 10-15.—A closeup of burnt shale showing the reddish parachanners and pseudomorphs that can be misinterpreted as redox concentrations.

Black or Dark Parent Materials

Soils formed in glacial till derived from local, dark or black shale bedrock are in the extreme northeastern part of the Allegheny Plateau and along the southern edge of the Mohawk Valley. The shale often is high in organic carbon, and matrix colors often have value of 2 or 3 and chroma of 1 or 2. Common redox concentrations may be high enough in the profile to meet Field Indicator F6 (Redox Dark Surface) in soils that are not hydric. This same problem also occurs in soils that formed in deposits of black coal fines on flood plains in areas of the Ridge and Valley physiographic province.

Soils With a High Content of Organic Matter

These soils have accumulated sufficient organic carbon in the surface layer to qualify as having mucky modified textures (5 to 18 percent depending upon clay content). In addition, in a few areas the soils have been identified as having an organically enriched surface layer that is of sufficient thickness to meet the 2 in (5 cm) criterion for Field Indicator A7 (Mucky Mineral) or the 4 in (10 cm) criterion for Field Indicator F1 (Loamy Mucky Mineral). The soils have been identified at the western edge of the Piedmont in Maryland on treads of mountain backslopes and in coves of Catoctin Mountain. It is interesting to note that charcoal production was a major enterprise in this area in the early 1900s. Charcoal production involved stacking logs, covering the logs with soil to allow for slow controlled burning for a set period of time, and subsequently collecting the charcoal. It is reasonable to assume that charcoal was scattered considerably around the piles during the collection process and when the wind blew. Laboratory analysis for organic carbon in these soils shows increased levels compared to soils in the surrounding area. Also, the surface layer of these soils is darker than that of other soils in the surrounding area.

Soils with a high content of organic matter also have been identified in areas of the Appalachian Plateau Region and in areas of frigid soil temperature regime in West Virginia, Maryland, Pennsylvania, and New York, where organic carbon accumulation can be attributed to cooler temperatures, which depress decomposition. As a consequence, Field Indicators A7 and F1 are not used in LRRs N, R, and S. In these areas a common clue to nonhydric status is matrix chromas of more than 2 directly below the surface.

Glauconitic Soils

As previously enumerated under the “Problem Hydric Soils” section, these are coastal plain soils containing high amounts of glauconite, which has an inherent dark green color. Where sufficient glauconite is present, matrix colors can easily be chroma of 2 or less and can fall on the gley page of the “Munsell® Soil Color Chart.” For this reason, glauconitic soils are specifically excluded from the definition “gleyed matrix” in COE Indicators. In addition, these soils commonly have medium to coarse, irregular, iron-rich bodies in color hues of

7.5YR to 10R that can easily be misinterpreted as current-day redox concentrations. Perhaps these "red mottles" are relict redox concentrations from a previously wet hydromorphic environment or are simply attributable to the production of iron concentrations from the geologic weathering and oxidation of sulfides in these glauconitic parent materials. Such characteristics, which were observed in New Jersey by the NTCHS in 2002, resulted in some pedons in upland positions erroneously meeting Field Indicator F6 (Redox Dark Surface) (fig. 10-16). Factors helpful in discerning these soils as having dry hydric morphology include site locations on convex or smooth landscapes, the absence of hydrophytic vegetation, and very abrupt boundaries between iron-rich bodies (mottles) and the surrounding 2-chroma or gleyed matrix.

Figure 10-16.—A soil sample taken from the surface horizon of a glauconitic soil. The soil meets the color criteria of NRCS Field Indicator F6 (Redox Dark Surface) because of the dark greenish black color of the glauconite combined with the redox concentrations.

Soils Formed in Phyllite Parent Material

These soils formed in material derived from metamorphic phyllite rock, which commonly has inherited colors ranging from bluish green to steel gray to purple to black (fig. 10-17). Matrix colors can range from those falling on the gley page of the "Munsell® Soil Color Chart" to chroma of 2 or less or to very dark or black colors with value of 3 or less and chroma of 2 or less in the case of graphitic phyllite. Further confounding interpretation, particularly for the layperson, is the common presence of very fine, iron-rich parachanners that, when scraped with a shovel or knife, can resemble a redox concentration. These soils are in the Piedmont physiographic province. Aside from profiles formed in graphitic phyllite, the greatest chance for occurrence is on highly eroded, convex summits, shoulders, and the upper part of backslopes where hydromorphology is highly unlikely. Soils formed in material derived from graphitic phyllite are more of a problem since the B horizon, even in uneroded areas, is very black; however, their geographic distribution is very limited.

Figure 10-17.—A soil formed in material derived from phyllite. The absence of redox features in the dark matrix helps to distinguish this soil from a hydric soil, but parachanners and pseudomorphs of reddish phyllite may be mistaken for redox concentrations.

Soils Formed in Diatomaceous Earth

These soils formed in highly siliceous, fine-earth deposits composed chiefly of the cell walls of diatoms (microscopic, unicellular, marine or freshwater algae having siliceous cell walls). These deposits, as well as previously described marls, are limnic materials that change irreversibly on drying from a matrix color value of 3, 4, or 5 to a common value of 7 or 8. Chroma is commonly 2 or 3 in the matrix. When chroma of 2 or 3 is coupled with prominent clay films having hue of 10YR, 7.5YR, or 5YR from overlying or previously overlying mineral sediments, these soils can be easily misinterpreted as hydric (fig. 10-18).

Figure 10-18.—An upland soil formed in material derived from diatomaceous earth. It has a matrix with chroma of 2 below a depth of 18 in (45 cm) and 5YR 4/6 clay films in pores and along ped faces. The colors of the matrix could be misinterpreted as evidence of an aquic moisture regime.

Small areas of these soils have been identified in conjunction with the very old, Miocene-age, coastal plain sediments in southern Maryland. The problem morphology is most prevalent in areas on narrow, convex, eroded summits and shoulders where mineral sediments overlying the diatomaceous earth have eroded away or never existed. Key properties to differentiate this dry hydric morphology are position of the soils on the landscape; identification of reddish materials as clay films, which are primarily on faces of peds and in pores; and value of 7 or 8 in the matrix. Typically, the depletion of iron due to the gleization process in wet soils of this region seldom, if ever, results in value of more than 6 in the matrix.

Historic and Relict Hydric Soils

These soils formed under hydrologic conditions of saturation and anaerobiosis but are no longer wet. Dry hydric soils resulting from geologic or geomorphological landscape changes in hydrology are referred to as "relict" hydric soils. Those resulting from anthropogenic features (e.g., ditches, levees, fill) are referred to as "historic" hydric soils. Both types are problems hydrologically because they commonly have a gray matrix with redox concentrations. Morphological differentiation of a relict hydric soil (dry hydric morphology) from current-day, wet hydric morphology is extremely difficult, if not impossible, except for perhaps those hydrology regime changes associated with the geologic past (many thousands of years ago). Such is the case for soils in the upper Coastal Plain in southern Maryland and in areas of soils that formed in Cretaceous-age, coastal plain sediments that are now in convex, highly dissected landscapes. In these soils, ped interiors have chroma of 2 or 1, but macroprism faces, as well as most faces of smaller subangular or angular blocky peds, are coated with highly oxidized, reddish clay films (values of 4, 5, or 6 and chroma of 6 or 8). In addition, a sharp (color changes in less than $^{1}/_{20}$ in [$^{1}/_{10}$ mm]) boundary between redox concentrations and a gray matrix is a common indicator of a relict soil condition (Vepraskas, 1996). Commonly, these boundaries will be diffuse with the color change being gradational over a distance of $^{1}/_{10}$ in (2 mm) or more when reduction and anaerobiosis processes are active.

Morphological changes resulting from contemporary drainage or even due to hydrologic changes caused by accelerated erosion in postcolonial times is extremely difficult, if not impossible, to detect since, in many cases, it is doubtful that any observable changes have occurred. It is hypothesized that, in the Piedmont where weatherable minerals are relatively high, it would take many decades, if not centuries, to release sufficient free iron oxide to materially change color morphology. To be more certain regarding color change estimates, additional study is necessary. Comparatively speaking, the odds of observable morphological soil change on the lower Coastal Plain, where most of the drained hydric soils are located, are probably much less likely than in the Piedmont. Most of these coastal plain soils are very low in weatherable

minerals and very high in quartz, affording little opportunity, even over many millennia, to release sufficient iron oxide to materially change matrix colors. The only conceivable guide is to discern the length of time needed to change diffuse boundaries between redox concentrations and the matrix to sharp boundaries.

Conclusions

A working knowledge of the saturated soil/wet soil morphology paradigm and of the Field Indicators will lead to the identification of most hydric soils. However, the accurate identification of all hydric soils in a region also requires an awareness of both problem hydric soils and dry hydric morphologies as described in this chapter. While the apparent situations were enumerated in the chapter, it is likely that other situations exist.

In addressing problem hydric soils or dry hydric morphologies, there is no substitute for accurately assessing landscape position and the presence or lack of hydrophytic vegetation, along with other positive indications of hydrology, and correlating these observations with soil morphology. With an awareness of what the possible anomalies are, the importance of using a local soil survey report cannot be overstated. Studying typical profile descriptions, in particular the color morphology of horizons, and comparing these to drainage class and to soil wetness data in the water features table will provide insight into possible anomalous relationships. In addition, the introductory paragraphs to these descriptions will provide direct information about the parent material, landscape position, and relationship to adjoining soils. If interpretive issues still exist, a qualified soil scientist who is knowledgeable of local soil morphology and hydrology relationships should be consulted.

Chapter 11
Monitoring Hydric Soils

Bruce L. Vasilas and Lenore M. Vasilas

Hydrology

Monitoring wells and piezometers are used to evaluate hydrology. The difference between the two is in the length of the pipe that is slotted. Monitoring wells are slotted for most of the length of pipe below ground. The water level in the well reflects the average water pressure across the entire length of the perforated pipe. Monitoring wells are also referred to as "perforated pipes," "open-sided wells," or "observation wells." Piezometers either are not slotted with open bottoms or have slots for a short length of the pipe near the bottom. The water level reflects the water pressure at the base of the pipe. Piezometers are sometimes referred to as "cased wells." Monitoring wells and piezometers may be simple and require manual readings, or they can be automated and programmed to monitor and record water level depth at any desired interval.

The choice of a monitoring well versus a piezometer depends on the intended information. A well measures the water table depth. It should be used to verify if a site has wetland hydrology. Piezometers measure hydraulic head, which changes with elevation and pressure on the water. A nest of piezometers at several depths should be used to obtain information pertaining to ground water recharge and discharge, direction of water flow, saturation at specific depths in the soil, and episaturation (perched systems).

A full soil profile description should be completed prior to installing a well or piezometer. This description is critical for determining the length of pipe that is appropriate and in the interpretation of well data. The desired pipe length will depend on soil characteristics and the intended data. In many wetlands on the Mid-Atlantic Coastal Plain, wetland hydrology is due to episaturation. If only one well is used in such a situation, it must be installed above the confining layer; otherwise, the well data will be misleading and give a false (low) reading. Conversely, in artesian systems, a well that starts below a confining layer will give a false (high) reading. To be effective, piezometers must be installed both above and below confining layers.

The spatial arrangement of wells and piezometers should reflect the dominant hydrology of the wetland. This is especially important in situations when there is pit-and-mound topography. When several wells are nested, they should be installed at the same soil surface elevation and adjacent wells should be no more than 6 ft (2 m) apart.

To install a monitoring well (or piezometer), a borehole is first augered to the desired well depth. It should be slightly larger in diameter to the well. The diameter of the hole should be large enough to allow for pouring and tamping backfill material. Prior to installing the well, the sides of the borehole should be brushed to counter any possible smearing caused by augering. Smearing, especially in fine textured soils, can interfere with the lateral movement of water. A graduated cylinder brush works well in this regard. During well installation it is critical that the distance from the mineral soil surface to the calibration point (for automated wells) or the top of the well (for simple wells) be determined and recorded. These values are used to adjust well readings, which are essentially the distance from the water table to the calibration point or well top, and do not necessarily reflect the depth of the water table below the mineral soil surface. This distance should be checked each spring because freezing and thawing cycles can cause a vertical displacement of as much as 3 in (7.5 cm). Wells should have a small diameter hole above the soil surface to allow for air to exit the well as the water table rises; otherwise, the increase in air pressure in the well will result in a false (low) reading. Wells usually have solid bases. A hole should be drilled into the base to allow water to drain out; otherwise, false (high) readings will be obtained during dry periods. Efforts should be made to ensure that the well slots do not become clogged by soil, either by covering the well with landscaping fabric (a weed guard) or filter socks or by backfilling with pea gravel or sand. In some situations, a combination of fabric and gravel will be necessary. The opening between the well and the soil should be backfilled to within 1 to 2 in (2.5 to 5 cm) of the soil mineral surface. The remaining space should be filled with bentonite to prevent side-flow, which will cause a false (high) reading, down the outside of the pipe. A 50:50 mixture of soil and bentonite should then be mounded up around the well to a height of 4 in (10 cm). Inundation can wash the soil and bentonite away from the well, so this process may have to be repeated. In early spring each well should be evaluated by comparing its reading with the water depth in an adjacent unlined borehole. If there is a large discrepancy, the well should be reinstalled.

Simple wells and piezometers can be read with a measuring tape or with an automated well reader that produces an audio signal when the sensor hits water. Dowel rods should not be used to take readings because, depending on the pipe and dowel diameters, the rod can displace enough water to effect an erroneous reading. For example, with a dowel rod of ½ in (1.3 cm) diameter and a pipe with an inside diameter of 1 in (2.5 cm), each foot (30 cm) of rod in the water will raise the water level 3 in (7.5 cm). Errors also will be introduced if the readings are not corrected for the distance between the mineral soil surface and the top of the well or piezometer. For additional information, see “Installing Monitoring Wells/Piezometers in Wetlands” (U.S. Army, COE, 1993).

The frequency of well and piezometer sampling (i.e., the interval between readings) is a critical decision that should be based primarily on the objective for collecting the data and secondarily on the project budget. Ideally, the longest

sampling interval that provides the data set necessary to meet the project objectives should be employed. Extended sampling intervals result in decreased accuracy and precision and in lost information and can lead to inaccurate interpretations, while unjustified short sampling intervals provide redundant data and can inflate project costs. For automated systems this decision is less important because the instruments can be programmed to take multiple readings per day at no additional cost and the primary expenditure is in the cost of the instrument itself. For simple wells and piezometers, the initial expenditure is minimal and the primary costs are proportional to the frequency of manual readings, especially when significant travel time is involved.

The authors of "Effect of Measurement Frequency on Water-Level Summary Statistics" took a water level data set collected daily from seven wetlands and, for comparison, created additional data sets representing sampling intervals of 2, 4, 7, 14, and 28 days (Shaffer et al., 2000). From these data the authors made the following conclusions with respect to sampling intervals:

1. For comparing wetlands in different hydrogeomorphic (HGM) classes, 1-month sampling intervals can effectively characterize water levels if supplemented by crest gauge data.
2. For characterizing the monthly variability in water levels, 7-day sampling intervals provide the margin of error acceptable for most projects.
3. For determining whether hydrology exceeded specific thresholds for water table depth and duration (e.g., for jurisdictional determinations), the maximum frequency of sampling is daily. For documentation of inundation for more than 14 days, sampling at 7-day intervals often resulted in missed events or false (positive) readings corresponding with short-term spikes in water table depths.

These conclusions provide a starting point for determining sampling frequency. They should be refined to accommodate local soil, hydrologic, and geomorphic conditions. For example, water levels in ground water driven systems generally are more stable than those in precipitation driven systems; therefore, they would require less frequent readings. Likewise, episaturated (perched) systems are more dependent on precipitation than endosaturated systems; therefore, they require more frequent readings.

Even when wells and piezometers are installed correctly and the data is read correctly, the data collected can be misleading if it is not accurately interpreted. Common hydrologic scenarios are shown in figures 11-1 to 11-4. It is important to remember that well data represents the depth to free water (water table). Water levels in a piezometer represent conditions at the base of the piezometer, which change with changes in water pressure and depth, the combination of which is called "hydraulic head." Piezometers measure the hydraulic head and also show whether the soil is saturated at the base. They can also be used to determine the direction of water flow in a landscape because water moves from points of high hydraulic head to points of lower hydraulic head in the soil and across the landscape.

In figure 11-1, two piezometers at different depths give the same readings; therefore, the hydraulic head is the same at the bottoms of both piezometers and water is neither moving up nor down. This indicates that the system is static; the water table is neither rising nor falling. In such a situation, a well and a piezometer will give identical readings. This is most likely to occur in unstratified materials on flat landscapes.

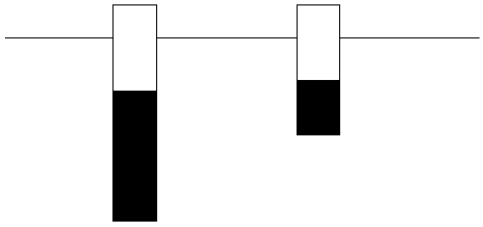

Figure 11-1.—Piezometers in a static water table.

In figure 11-2, the water level is highest in the shallowest piezometer. This means that the hydraulic head decreases with depth and is indicative of a recharge system; the water is moving downward.

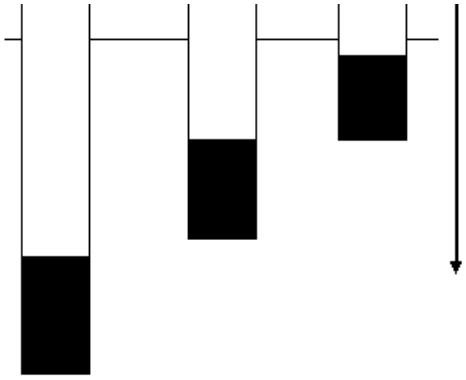

Figure 11-2.—Piezometers in a recharge wetland.

In figure 11-3, the water level is highest in the deepest piezometer. This means that the hydraulic head increases with depth and is indicative of a discharge system; the water is flowing upward.

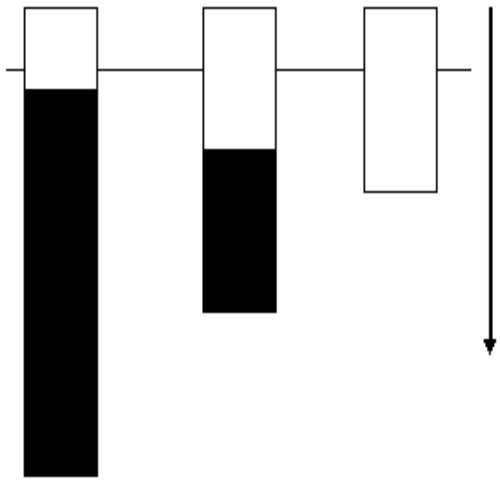

Figure 11-3.—Piezometers in a discharge wetland.

In figure 11-4, the water table is perched (episaturation); the shallow piezometer contains water, and the deeper piezometer is dry. This demonstrates the importance of placing wells above confining layers because, in this situation, the deeper well produces a false (low) reading.

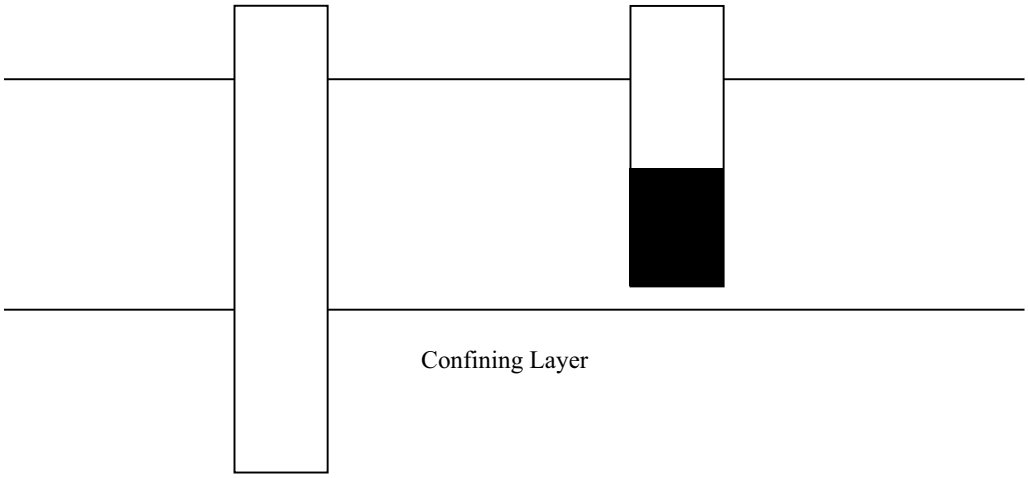

Figure 11-4.—Piezometers in a perched system.

Soil Moisture

A wide variety of instruments can be used to measure soil moisture. They range from fairly simple devices, such as tensiometers and electrical resistance blocks, to more technical devices, such as neutron probes, capacitance instruments, and time domain reflectometry (TDR) instruments. There currently are no set standards for using soil moisture measurements to evaluate wetland hydrology, and the National Technical Committee for Hydric Soils (NTCHS) does not recommend such measurements; however, the measurements are sometimes used to evaluate soils in wetlands and mitigation sites.

A few things need to be taken into account when evaluating the use of soil moisture measurements. Many of the devices loose their accuracy at very high and very low moisture levels, so the measurements may not be accurate enough to evaluate if the soils are truly saturated. There currently is no set standard as to what level of moisture is needed to be considered saturated. One could assume that soil moisture measurements should be read at 6 in (12.5 cm) in a sandy soil and at 12 in (25 cm) in a fine textured soil; however, no set standard is currently available. Soil moisture measurements are much more temporal than water table measurements or redox measurements, so measurements may be required much more often. A soil may be saturated after a rainfall event, but that saturation could disappear within a few hours. Rainfall data, in conjunction with soil moisture data, is critical to evaluating the data.

Technical Standard for Redox Potential

Redox potential (Eh) is a measure of the tendency of a system to donate electrons. It is expressed in millivolts. As free oxygen is depleted from a soil, the Eh drops and conditions favor reduction (a gain of electrons). For wetland determinations, a soil is considered to be anaerobic when the Eh is low enough that virtually all free oxygen has been removed from the soil water. A threshold for anaerobic conditions is given in the NTCHS technical standard for hydric soils. This threshold Eh is pH dependent and is as follows: Eh=595-(60xpH) (fig. 11-5).

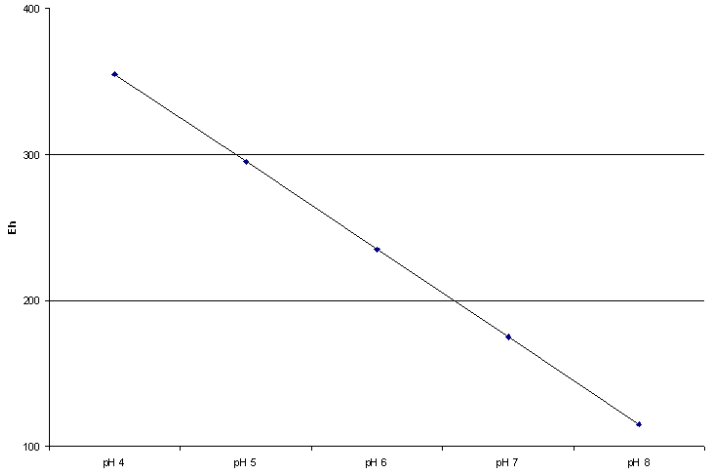

Figure 11-5.—Eh/pH threshold for anaerobic conditions.

A soil is considered to meet the threshold for Eh, according to the technical standard, if anaerobic conditions exist at a specific depth for at least 14 consecutive days. Eh is measured using a voltmeter, a platinum electrode, and a reference electrode. At least five platinum electrodes should be used to account for soil variability. Each set of readings should not be averaged to produce one mean value; instead, a positive reading for anaerobic conditions results when more than 50 percent of the electrodes give a reading below the threshold.

The depth that the platinum electrode tips should be placed is dependent on soil texture. For coarse textured soils (loamy fine sand or coarser), the electrodes should be installed to a depth of 6 in (12.5 cm). For fine textured soils, the electrode depth should be 10 in (25 cm). Depth of the reference electrode is not important; however, it is critical that there is a solid contact between the reference electrode and the soil water. To ensure this, the electrode should be installed into a mud slurry. All readings for a given location should be taken at least weekly at approximately the same time of day. The Eh reading will be adjusted based on the type of reference electrode used and the soil temperature (table 11-1). The appropriate correction value is added to the field reading. Therefore, soil temperature must be taken at the same depth as the platinum electrodes. Soil pH must be determined on three random samples taken from the same depth as the platinum electrodes so that the appropriate threshold Eh value can be determined. These samples should also be tested for the presence of reduced iron. Soil pH can be expected to move closer to neutrality as the soil goes from the aerobic state to the anaerobic state.

Table 11-1.—Soil Temperature and Reference Electrode Type Dependent Conversion Factors for Eh

°C	°F	*Ag/AgCl	Calomel
25	77	197	244
20	68	200	248
15	59	204	251
10	50	207	254
5	41	210	257
0	32	214	260

* The Ag/AgCl conversion factors are based on the assumption that the electrode contains saturated KCl solution.

In any given set of redox measurements, large discrepancies may exist in the readings from electrode to electrode. It is critical to determine the reason for the discrepancies—true soil variability or equipment malfunction. Some variability in soil redox potential is common across small horizontal distances. Aerobic microsites may be found in zones of extended periods of saturation; conversely, anaerobic microsites are common in unsaturated zones, generally in close proximity to decomposing organic materials.

Large discrepancies, however, may also be due to equipment malfunction. The accuracy of platinum electrodes may be compromised by a crack in the junction of the platinum wire and copper wire, a crack in the epoxy that seals the junction, or by a film on the exposed platinum surface. The electrodes should be numbered to facilitate the identification of faulty electrodes. An electrode that consistently produces values that are outside the range of the other electrodes in the set should be tested against a standard solution. All electrodes should be tested for accuracy prior to and subsequent to their use. One standard solution is comprised of 39.21 g ferrous ammonium sulfate/L, 48.22 g ferric ammonium sulfate/ L, 56.2 ml sulfuric acid/L, and deionized water. It has a target Eh of 476±10 mV. The standard solutions have a short shelf life; therefore, a new batch should be produced each time electrodes are to be tested. For additional information, see "Redox Chemistry of Hydric Soils" (Vepraskas and Faulkner, 2001).

It is not uncommon for the platinum tips to pick up contaminants from the soil solution, which can compromise their accuracy. The tips can be cleaned with fine steel wool, toothpaste, or dilute hydrochloric acid. They should be rinsed with deionized water after they are cleaned.

Alpha,alpha-dipyridyl dye is used to confirm the presence of ferrous iron; therefore, it can be of assistance in identifying reducing conditions. The soil tested should be at the same depth as for the platinum electrodes. In the presence of ferrous iron, the dye quickly turns bright pink or red. If a soil tests positive for 14 consecutive days, it is hydric. The absence of this response does not necessarily mean that reducing conditions are not present. Other factors that can lead to a negative response are as follows:

1. The dye is bad. Dye has a short shelf life. Its degradation is accelerated by sunlight and high temperatures; therefore, the dye should be stored in an amber bottle in a refrigerator. The dye can be tested by placing a few drops on a spade.

2. The soil is so low in iron that ferrous iron is not present in adequate concentrations to produce a reaction. This is most likely to occur with sands and organic soil material. The accuracy of the test with organic soil material may be improved by combining the soil with the dye and table salt in a vial and then shaking the vial. The sodium in the salt displaces ferrous iron on the exchange sites, putting it in solution.

3. The iron is in crystalline form and cannot be reduced. See chapter 10, "Identifying Problem Hydric Soils in the Mid-Atlantic Region," for more information.

4. Microbial activity is limited by low soil temperatures or by low levels of organic carbon. See chapter 4, "Microbiology of Hydric Soils," for more information.

Normal Rainfall

Any data collected to evaluate hydric soils should be correlated to rainfall. Normal rainfall data, for wetland purposes, are available in NRCS National Weather and Climate Center WETS (wetlands determination) tables. WETS tables are produced for local weather stations throughout the United States. They can be accessed at <http://www.wcc.nrcs.usda.gov/climate/wetlands.html>. To evaluate if a given year has had normal precipitation, local rainfall data (either from a local weather station or from an onsite rain gauge) are compared to data in the geographically appropriate WETS table. Table 11-2 is an example of the WETS table for the Annapolis Police Barracks. Rainfall is normal for any given month if the amount of rain falls between the values for that month in the columns "30 percent chance will have less than" and "30 percent chance will have more than." For example, if Annapolis had 2.3 inches of rainfall in January, that month's rainfall would be normal. Water table depths for a given time period are impacted not only by precipitation during that timeframe but also by precipitation in the preceding months; therefore, any evaluation of rainfall data for a given time period should also include consideration of the precipitation patterns prior to the time period of interest. Although, a given month may have normal rainfall, if the last 6-month period was above normal or below normal, that fact needs to be taken into consideration.

Table 11-2.—WETS Table for Annapolis Police Barracks Used to Determine Normal Rainfall

WETS Station : Annapolis Police Brks, MD0193 Creation Date: 08/27/1999
Latitude: 3859 Longitude: 07630 Elevation: 00030
State FIPS/County(FIPS): 24003 County Name: Anne Arundel
Start yr. - 1961 End yr. - 1990

Month	Temperature (Degrees F)			Precipitation (Inches)				
	avg daily max	avg daily min	avg	avg	30% chance will have less than	30% chance will have more than	avg # of days w/.1 or more	avg total snow fall
January	42.0	24.0	33.0	2.99	1.80	3.62	5	4.7
February	44.3	26.5	35.4	3.17	1.94	3.84	6	4.2
March	55.4	34.5	45.0	3.65	2.47	4.37	6	1.4
April	65.5	43.8	54.6	3.41	2.27	4.09	7	0.0
May	76.0	53.6	64.8	4.17	2.94	4.95	7	0.0
June	84.3	62.4	73.3	3.19	2.21	3.79	5	0.0
July	87.8	67.5	77.6	3.62	2.12	4.40	6	0.0
August	86.2	66.1	76.1	3.68	2.04	4.49	5	0.0
September	80.2	59.7	70.0	3.32	1.84	4.04	4	0.0
October	68.1	47.3	57.7	3.36	2.33	4.00	5	0.0
November	57.4	38.0	47.7	3.26	1.96	3.95	5	0.6
December	46.6	28.6	37.6	3.38	1.95	4.12	6	2.4
Annual Average	-----	-----	-----	------	28.54	42.64	--	----
	66.2	46.0	56.1	------	------	------	--	----
Total	-----	-----	-----	41.21	------	------	67	13.3

Chapter 12

Assessing Soil and Hydrologic Properties for the Successful Creation of Nontidal Wetlands

W. Lee Daniels and G. Richard Whittecar

Federal and state wetland regulations require the mitigation of impact to jurisdictional wetlands via avoidance and minimization of damage whenever possible. Many activities that disturb the land, such as constructing highways and developing urban areas, however, result in unavoidable impacts that usually are mitigated through the construction of offsite compensatory created wetlands. These constructed wetlands will supposedly replace the form, function, and ecosystem services associated with the original impacted systems. Natural "reference wetlands" are frequently employed for comparative functional assessment (Brinson and Rheinhardt, 1996) of created wetlands. However, the ability of created wetlands to fully replace the functions of natural wetlands is under current scientific debate. Because of the uncertainty associated with the success of historical offsite wetland impact compensation sites, most wetland disturbance permits require the return of a 2:1 to 5:1 ratio of "created:original" wetland areas. This mitigation ratio is utilized to ensure that the national policy of "no net loss" of wetlands is maintained even if a significant portion of created mitigation wetlands fails to meet the permit-based success criteria.

Physical, chemical, biogeochemical, and hydrologic properties of soils play a major role in the relative success of nontidal wetland mitigation efforts in the Mid-Atlantic Region. Since the total for acquiring, constructing, planting, and monitoring these sites frequently exceeds $40,000 per acre ($100,000 per hectare), it has become increasingly obvious to mitigation site designers and their regulators that the re-creation of appropriate soil conditions is important to ensure success. Therefore, this chapter focuses upon (1) soil and site assessment strategies for the location of appropriate nontidal wetland mitigation sites, (2) soil reconstruction protocols, and (3) methods of assessing soil properties in constructed, nontidal wetlands to determine if they warrant jurisdictional designation.

Locating and Assessing Potential Mitigation Sites

Offsite created or restored mitigation wetlands are usually required by permit conditions to be (1) located within or near the originally disturbed watershed and (2) returned to the same dominant vegetative community

(e.g., type-for-type replacement) as the originally impacted site. Thus, the local extent of soil landscapes available to potentially serve as mitigation sites for a given project's impact is usually limited. Two general types of suitable landscapes are available for mitigation: (1) areas where hydric soils have been converted previously (drained) and where restoration efforts often are the focus and (2) areas in the uplands where soils must be excavated in order to achieve wetland hydrology appropriate for wetland creation. This chapter focuses on the latter type of mitigation sites (excavated uplands) since they are generally much more difficult to locate, confirm, and design. However, much of the site location and hydrologic assessment protocols described in this chapter are also applicable to assessment of previously converted (drained) farmland.

The expenses for excavation, fill disposal, and site grading are usually the single major cost component of mitigation site development, although land acquisition costs can also be significant if the site is in a watershed that is being developed for urban uses. Proximity to road corridors or other active earth moving contracting areas, or both, is also highly desirable for both excavation cost efficiency and ease of monitoring. Thus, in its simplest form, looking for a potential wetland mitigation site usually entails surveying the soil landscape resources within some prescribed vicinity looking primarily for areas of soil that (1) are large enough to meet permit-mandated area requirements, (2) allow appropriate access for construction equipment and monitoring, (3) are "dry enough" to be nonjurisdictional, (4) but are also "wet enough" to minimize excavation volumes and grading costs, and (5) are similar in geomorphic setting and water balance characteristics (Brinson, 1993, 1996) to the impacted wetland to ensure that a similar vegetative community and the associated hydrology will become established and will persist on the chosen site. This last criterion is often the most difficult one to successfully satisfy.

The first step in locating a suitable site is to utilize U.S. Department of Agriculture, NRCS, National Cooperative Soil Survey maps, local jurisdictional wetland determinations (if available), and hydric soil lists to identify areas where significant acreages of poorly drained, somewhat poorly drained, and moderately well drained soils have been mapped. If possible, these areas should be adjacent to downgradient hydric soils to avoid the construction of isolated wetlands. Secondly, a detailed (scale ≤1:5,000) soil investigation must be performed to confirm soil delineations and classification and to confirm depths to redoximorphic features associated with wetness (Hurt et al., 2000; Vepraskas, 1996). Quite frequently, wetland site designers use the shallowest depth of significant redox depletions or concentrations to estimate the top of the high saturated zone/capillary fringe in winter along with depth to the complete absence of redox concentrations (or a completely gleyed matrix) to indicate the maximum depth of water table drawdown in summer. However, great caution must be taken in the interpretation of the type and abundance of redoximorphic features with respect to the length of duration of seasonal saturation at a given depth (Genthner et al., 1998). Wherever possible, an appropriate array of water table monitoring wells and nested piezometers

should be installed at any proposed mitigation site and monitored for at least one full fall/winter/spring season to establish the local seasonal hydroperiod (high/low cycle), ground water gradients, and episaturation v. endosaturation. In episaturated soils, aquic soil conditions are induced near the surface by restricted downward water infiltration, or "perching," usually over a drainage restricting layer. In endosaturated soils, the seasonal rise of the water table saturates horizons near the surface during winter and spring. The level and duration of winter/spring saturation are particularly important to mitigation site design, and fortunately for endosaturated soils, high levels in winter are much more consistent from year to year than the dynamics of the water table in summer and fall (Genthner et al., 1998). While much less information on seasonal dynamics of episaturated soils is currently available in the literature, it is assumed that their water level fluctuations during the growing season are much more variable from year to year because of their direct dependence on the seasonal rainfall pattern.

As mentioned previously, a detailed hydrologic assessment of potential mitigation sites is essential to their successful design and implementation. Assuming that type-for-type replacement is mandated, this also implies that a similar assessment should be made of the impacted site or a designated reference area in order to develop an appropriate design. For example, if the disturbed wetland was a part of a broad, flat, pocosin-type landscape that served as an aquifer recharge area, then it is likely that its annual hydroperiod fluctuations would be much greater than would be observed for a riparian wetland receiving considerable net ground water discharge. Many riparian wetlands receive considerable ground water inputs that tend to reduce hydroperiod fluctuations. As a part of the site hydrologic evaluation process, some estimation should be made of the potential effects of excavation and grading practices upon the postconstruction hydrologic regime (Whittecar and Daniels, 1999) (fig. 12-1).

Anecdotally, the authors have observed several wetland development sites that were excavated into broad interfluves (which served as regional recharge areas) where the magnitude of the annual hydroperiod fluctuation increased markedly following deep (≥6 ft; ≥2 m) excavation. At these sites, the floor of the wetland design was based upon a combination of well and soil morphologic data that presumably predicted the top of the depth of winter/spring saturation. This was more than likely due to enhanced evapotranspiration losses since the former water table was essentially "moved up" into the active plant root zone and was then subjected to much greater evapotranspiration water losses during the growing season.

Conversely, the authors have also observed numerous sites where placement of created wetlands into riparian ground water discharge zones has resulted in sites that are much wetter than intended, resulting in a dominance of emergent and shrub-scrub vegetation rather than forest vegetation. It is also important to note that many current wetland designs rely primarily upon surface water additions, coupled with highly compacted and sealed subsoil layers, to "perch" a wetland system and essentially isolate it from ground water inputs and losses.

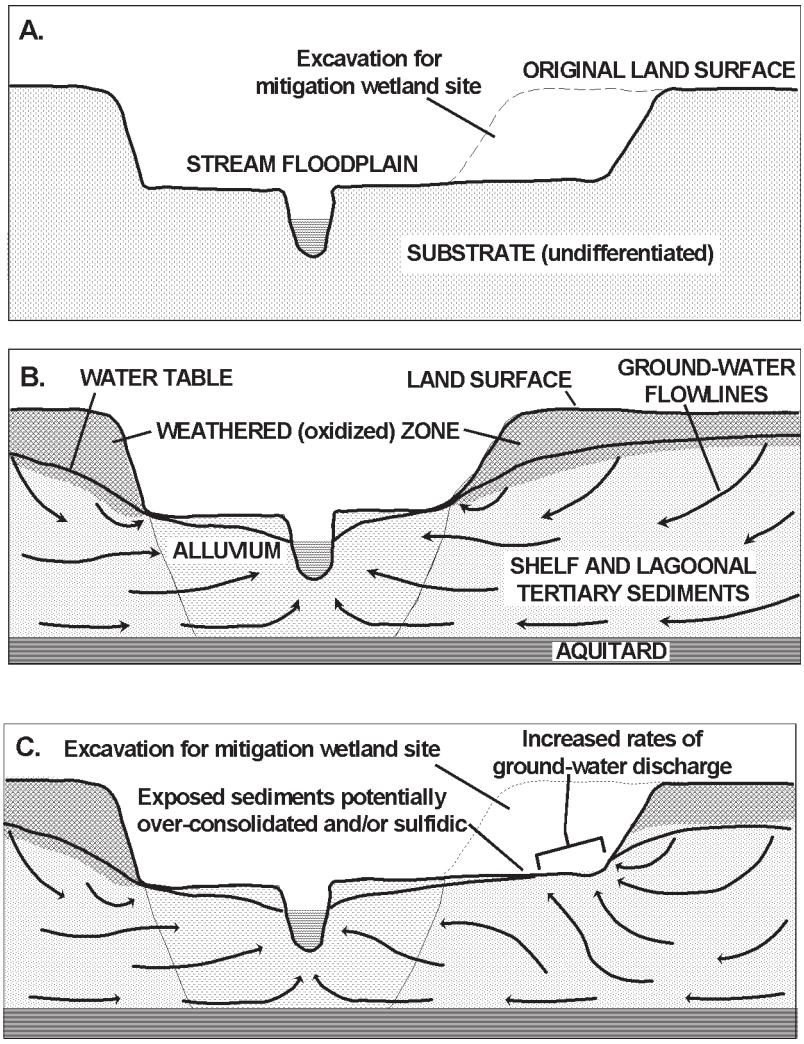

Figure 12-1. In drawing A, a schematic cross section illustrating a procedure commonly used in the Mid-Atlantic Region to create nontidal wetland mitigation sites. In drawings B and C, geomorphic processes and conditions that can result from application of this procedure to a landscape in the Mid-Atlantic Coastal Plain. Stratigraphic units and ground-water flowlines are generalized to represent a range of potential conditions and results. Significant problems can arise if wetland designers and managers do not anticipate (1) the increased upwelling of ground water often produced by excavation in these landscape positions and (2) the high sulfur content and high bulk density common to many unweathered marine strata in the Coastal Plain.

Studies cited earlier in this chapter and others that were not cited (such as a 1999 study by Hunt and others) indicate that ground water inputs are a major component of many natural and created forested wetland sites, so many of these perched wetland designs are essentially substituting episaturated systems for endosaturated systems. For further details on the application of hydrogeomorphic (HGM) concepts to mitigation site design, see “Use of Hydrogeomorphic Concepts to Design Created Wetlands in

Southeastern Virginia" (Whittecar and Daniels, 1999). For further information on the problems inherent in mitigation site water budgeting, see "Wetland Water Balance Studies: 1994-1998" (Daniels et al., 2000).

Finally, and perhaps most importantly, all potential mitigation sites must be carefully screened for the occurrence of sulfidic materials in permanently reduced zones (e.g., below the seasonal high water table). Sulfidic materials have been routinely encountered in potential mitigation sites and highway corridors throughout Virginia (Orndorff, 2001) and are particularly abundant in lower Tertiary deposits of the Coastal Plain. When exposed and oxidized in dewatered cut and fill areas, these materials quickly oxidize, generating extremely acidic (pH <3.0) and phytotoxic conditions (Fanning and Fanning, 1989). Once these materials are exposed, heavy liming (5 to 50 tons/acre [10 to >100 Mg/ha]) or resaturation of the materials is required to neutralize the potential acidity present, and serious local soil and water quality degradation is inevitable (Orndorff, 2001).

Constructing Appropriate Soil Conditions in Mitigation Sites

As mentioned earlier in this chapter, the vast majority of created wetland sites in the Mid-Atlantic Region involve extensive excavation and grading (fig. 12-2), and generally, the reconstructed soil profile generated is considerably different in fundamental physical and chemical properties than that of the original soils at the impacted site.

Figure 12-2.—A riparian created wetland made by excavating upland soils down to the presumed winter high water table. This site receives considerable surface and ground water inputs. Excavation of more than 30 in (0.75 m) of soil was required with considerable soil disturbance and compaction. (Photo courtesy of Steve Long, Virginia Department of Transportation.)

More often than not, the resulting soil profile consists of less than 10 in (25 cm) of O and A horizon material spread over a cut and compacted B or C horizon. Even when the original O and A horizons from the wetland are salvaged and reutilized (referred to as "mucking"), the mitigation ratio dictates that there will never be enough material to return the mitigation site's surface horizon to the original natural depth. Upland topsoil materials from the surface of the construction site are frequently salvaged and respread, and in recent years organic amendments have been increasingly employed. Unfortunately, many mitigation sites in the Mid-Atlantic Region have been prepared without returning any topsoil or organic soil material, leaving cut and smeared, strongly acidic B horizon (argillic/kandic) materials to develop into the postconstruction A horizon. Occasionally, grading plans require complete removal of the solum, leaving C horizon materials as the revegetation substrate. These C horizon materials can range from loamy saprolites in Piedmont settings to coarse textured, nonacidic coastal plain sediments to highly acidic, sulfidic marine sediments, all of which will need significant modification and amendment.

Recently, five wetlands that were constructed 4 to 7 years ago in Virginia were studied and paired with adjacent palustrine forested and scrub-shrub reference wetlands (Cummings 1999; Stolt et al., 2000, 2001). The studies revealed major differences in topography, hydrology, soil properties, and other environmental conditions such as soil temperature and redox potential. Microrelief was much greater in reference wetlands than in the associated constructed wetlands. Seasonal fluctuations in water table levels were similar in both wetland types. Soils in the mitigation wetlands, however, had much lower levels of soil carbon (C) and nitrogen (N) and had higher bulk densities in both the A horizon and in the subsoil layer than their paired reference wetlands. Similar results were reported for mitigation wetlands in Pennsylvania (Bishel-Machung et al., 1996).

The lack of short-range microtopographic variability in constructed wetlands has also been pointed out and the importance of its re-creation identified as an important element to successful mitigation designs (Barry et al., 1996; Rossiter and Crawford, 1982). Even minor variations in surface topography across a wetland can cause short-range differentials in soil wetness/redox regimes, leading to a wider range of edaphic niches for wetland plants, animals, and microbial populations. In natural wetlands, wetland traits, such as the overall wetness of the root zone and the associated redox potential, and floristic properties are usually strongly tied to soil properties within the upper 12 in (30 cm) of the profile (Faulkner and Patrick, 1992; Hook et al., 1994).

Re-creating the appropriate soil wetness regime in mitigation sites is an essential prerequisite for mitigation success, regardless of soil properties. The majority of nontidal wetland mitigation in the Mid-Atlantic Region is designed to replace palustrine forested wetland. However, the re-creation of the deep, annual hydroperiod that is typical of the soil-hydrologic conditions at many forested wetland sites is very difficult to plan for and to execute through typical

a priori water-budgeting procedures (Daniels et al., 2000), especially when deep excavations are involved. The re-creation of an appropriate soil wetness regime is further complicated by the widespread use of surface water driven, episaturated "perching designs" as described earlier. Thus, the difficulties involved in accurately predicting the postconstruction water budget and associated hydroperiod for a given mitigation site design are considerable. Despite these difficulties, the studies previously cited have indicated that many mitigation sites do develop a seasonal hydroperiod that is very similar to nearby reference wetlands. However, many of these same sites subsequently suffer from very dry, hot midsummer conditions because of (1) the adverse effects of a high content of clay and high bulk density in the surface soil, (2) a low content of organic matter and the associated low water-holding capacity, and (3) the lack of an insulating canopy and a well developed layer of forest litter. Cummings (1999) observed several areas in created wetlands that were clearly "wet enough" to meet jurisdictional criteria in the spring but still supported a dominance of facultative upland and upland vegetation. Therefore, it is likely that a lack of organic matter, coupled with a very slow infiltration rate and low water-holding capacity caused by compaction, effectively prevented these soils from maintaining low redox soil conditions from late spring through fall, directly limiting the competitiveness of wetland vegetation. It is also evident that the widespread application of "perching designs" without a sufficient thickness of cover soils having low bulk density has led to restricted rooting depth and lowered potential productivity.

In general, the body of scientific work cited previously strongly points toward "soil differences" as being important in explaining differences between plant growth in natural and constructed wetlands, and it reinforces the need for a thorough understanding of how a given mitigation site fits within its regional hydrogeologic setting. In particular, a lack of soil organic matter and litter layers, coupled with soil compaction at shallow depths, have been indicated by a wide range of studies as being directly related to the lack of "mitigation success." Therefore, offsite created wetland designs should incorporate measures to fully re-create appropriate surface soil conditions (e.g., bulk density ≤85 lb/ft^3 or 1.35 g/cc; organic matter ≥5 percent). Furthermore, creation of appropriate microtopographic variability is also recommended, along with a vegetation planting scheme that rapidly establishes summer canopy shade while not being overly competitive with establishment and maintenance of wetland tree species. Finally, the surface application of a wood chip or leaf mulch layer to rebuild the litter layer and buffer midsummer soil temperature and moisture extremes is also beneficial. However, because of the high C:N ratio of many mulches, appropriate N fertilization of planted stock should be employed, particularly when the organic amendments are incorporated to any extent.

Therefore, the following guidelines are recommended for re-creating appropriate wetland soil conditions in typical excavated and regraded mitigation sites:

1. Before any available topsoil materials are applied, the subsoil grade should be ripped or chisel-plowed to reduce bulk density to 85 lb/ft^3 (1.35 g/cm^3) or less. The surface of the subsoil should also be limed or otherwise amended as necessary to avoid excessively low or excessively high pH levels for the target vegetative community. Obviously, this step cannot be implemented when a shallow (<20 in; <50 cm), compacted subsoil is required by site designers to "perch" an episaturated wetland.
2. All potential donor organic soil materials or other topsoil materials should be applied to the mitigation site. A minimum depth of 10 in (25 cm) of material is recommended, provided the donor soil's seed bank is low in undesirable invasive species.
3. Some degree of kettle-and-mound microtopography should be re-created with a backhoe to mimic that present in local reference areas. The exact density and depth variation of these features should be determined by reference site studies. Based upon the authors' observations in eastern Virginia, these features should be placed approximately 30 to 60 ft (10 to 20 m) apart and should consist of shallow (approximately 15 inches deep by 50 inches in diameter [35 cm by 1.25 m]) pits and adjacent, low mounds.
4. The wetland creation area should be amended with yard-waste compost or other suitable organic amendments at approximately 50 tons/acre (110 Mg/ha) to offset removal or damage of the A horizon and forest litter layer. This step may be modified based upon the organic matter content of the topsoiling materials used and will not be necessary if the topsoil material applied is at least 5 percent organic matter.
5. The final surface of the restoration area will need to be carefully tilled with a combination of a chisel-plow and a heavy disk to loosen final grading-related soil compaction and mix the organic amendments into the reconstructed A horizon. The bulk density following all grading and tillage procedures should be ≤85 lb/ft^3 (1.35 g/cm^3). Obviously, some accommodation for hummocks and pits will need to be made in tillage.
6. Finally, the application of 1 to 3 in (3 to 7 cm) of wood chips or leaf mulch to reconstruct a litter layer would be highly beneficial but would need to be managed so as to be compatible with initial vegetation establishment.

Offsite mitigation designs are obviously highly site specific, so any guidance beyond these general recommendations is not possible. It also is important to point out that implementation of the procedures outlined here would add considerable expense to many current designs and simply may not be feasible at certain locations.

Evaluation of Soil Development in Mitigation Sites

Once a mitigation site has been developed and planted, permit requirements usually mandate 5 to 10 years of vegetative cover plus water level monitoring, along with an assessment of whether or not hydric soils (1) are present or (2) appear to be developing "in the right direction" at the site. Most frequently, the soil profile is assessed for the presence of Field Indicators described in "Field Indicators of Hydric Soils in the United States" (USDA, NRCS, 2002), and the decision of whether or not the site's soils have "become hydric" is based upon the presence or absence of indicators such as Field Indicator F3 (Depleted Matrix). To the trained pedologist, however, this approach poses a number of profound complications of interpretation.

First of all, the vast majority of these sites are heavily disturbed, and it can be very difficult to determine whether or not redoximorphic features observed in the re-created soil are due to contemporary or relict processes. For example, the authors have observed many supposedly hydric soils in created wetlands where Field Indicator F3 was met simply because the site had been graded down into Btg, Bwg, or Cg materials or cut materials sufficient to meet the requirements of Field Indicator F3 had been filled into place, or both. Similarly, the replacement of a thick layer of O and A horizon materials from a hydric soil into a nonwetland site could meet other hydric soil indicator requirements (e.g., Field Indicator F5, Thick Dark Surface) for several years before sufficient organic matter would oxidize away.

Secondly, since the vast majority of natural wetland soils that are typically used as comparative references are at least several thousand years old, taking this assessment approach may really be "comparing apples to oranges." Is it reasonable to expect that a morphologically similar hydric soil could develop via natural processes of organic matter accumulation and associated development of appropriate biogeochemical conditions in 5 to 10 years?

Several studies have been conducted in mitigation soil environments, and they can offer some guidance as to rates and extent of formation of contemporary redoximorphic features in mitigation sites. For example, differential development of redoximorphic features within 5 years has been reported to occur across a relatively short distance in a deep-water marsh/upland edge transition (Vepraskas et al., 1999), and distinct differences in the development of oxidized rhizospheres have been reported to occur across an emergent to upland forested transect in a Virginia mitigation site at Fort Lee (fig. 12-3) in 5 years (Cummings, 1999). A very strong and consistent relationship has been observed between local soil drainage conditions and the abundance of oxidized rhizospheres and Fe masses at Fort Lee (Cummings, 1999), but such relationships are more than likely site-specific and would probably need to be reconfirmed for each site evaluated.

Therefore, it is the authors' opinion that the best way to assess hydric soil development processes in created wetlands is to (1) acquire detailed soil descriptions at the site before disturbance and immediately after final grading and (2) continue monitoring changes in soil morphology over time.

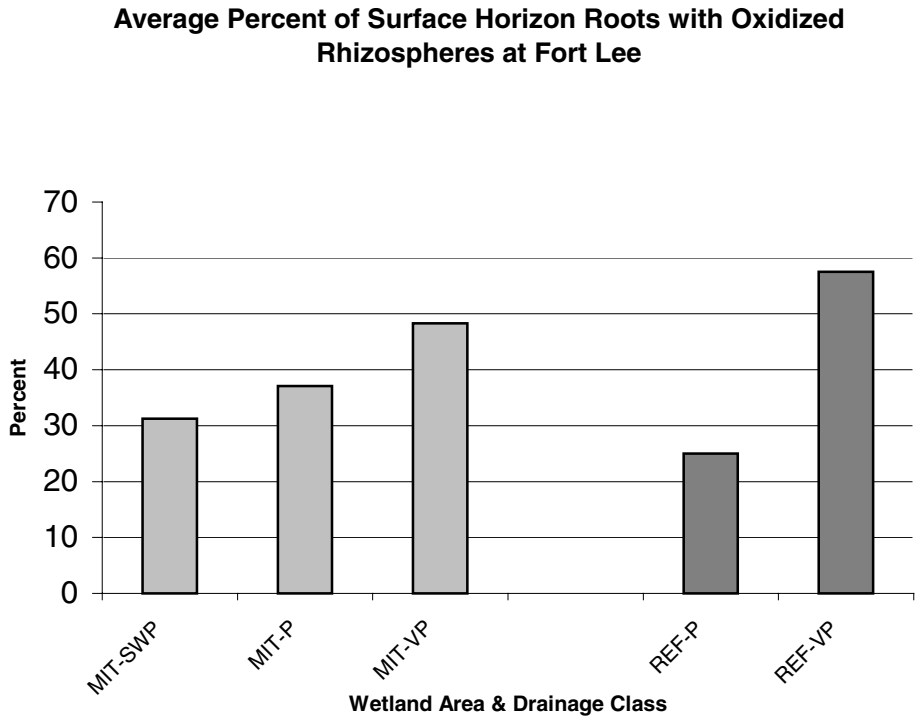

Figure 12-3.—An abundance of oxidized rhizospheres (iron concentrations) at the Fort Lee mitigation wetland (MIT) and an adjacent reference area (REF) as described by Cummings (1999). Soil drainage class was assigned based on wells directly adjacent to pedons on three study transects. Abundance of oxidized rhizospheres increased regularly as soils moved from somewhat poorly drained (SWP) to poorly drained (P) to very poorly drained (VP) conditions. The reference area soils were very high in organic matter, which may have limited or masked development of similar features in comparison.

For example, at one site in Maryland, it has been documented that the overall chroma of the majority of topsoiling materials salvaged and returned to a large, 20-acre (10 ha), lower Coastal Plain mitigation site was 4 to 5, and that over a 5-year period, the overall chroma at the vast majority of more than 200 gridded soil sampling locations decreased to 3 (Daniels et al., 2000; unpublished data). Additionally, it was noted that many locations exhibited faint to distinct, medium Fe depletions and associated prominent Fe masses and oxidized rhizospheres. The abundance and contrast of these redoximorphic features were well correlated with vegetation indicators at this site, and the original, undisturbed soil descriptions allowed the authors to clearly allocate subsoil redox features to either the original underlying soil material or the imported fill. It is important to point out, however, that very few of the re-created soils at this particular site rigorously met Field Indicator requirements, but it was clear that the soils were developing in the appropriate direction. Obviously, this approach requires detailed pit descriptions before disturbance and multiple soil observations over time to confirm the direction and extent of change in soil properties.

The determination of whether or not a given mitigation site meets jurisdictional wetland hydrology and vegetation criteria for release is relatively straightforward. However, as previously described, the determination of whether or not the soil criterion is met is much more difficult to assess. Clearly, the key to soil assessment at these sites is being able to estimate whether or not a given hydric soil indicator or redoximorphic feature is contemporary or relict and the direction of change in morphological development over time. This requires repetitive and accurate soil morphological descriptions and pedogenic interpretations by a person adequately trained in soil morphology and genesis. It is also likely that the rate of development of various redoximorphic features and their response to local differences in drainage will vary from site to site.

Summary and Conclusions

The successful location, design, and functional assessment of created wetland mitigation sites are highly dependent upon the appropriate application of basic principles of soil science, particularly an understanding of soil morphology and genesis. Redoximorphic features are routinely utilized in locating potential mitigation sites and estimating required final grading depths, but care must be taken to correlate these features with the actual seasonal response of the saturated zone. All potential wetland creation sites must be evaluated for the presence of sulfidic materials. Once a site has been constructed, mitigation site soils are usually profoundly different from their natural counterparts, and successful soil reconstruction strategies must rely on tillage to loosen compacted zones and organic amendments or wetland soil replacement to return appropriate biogeochemical conditions. The overall regional hydrologic setting of a mitigation site must be understood, and whenever possible these sites should be constructed in landscape positions where their overall postgrading hydrology will be similar to that of the wetland impact area. Field Indicators of hydric soils can be used judiciously to assess whether or not a given created wetland is developing in an appropriate direction. However, it is important to document changes in overall soil morphology, particularly the development of redoximorphic features over time, to ensure that soils at the site are progressing toward hydric soil conditions.

References

Barry, W.J., A.S. Garlo, and C.A. Wood. 1996. Duplicating the mound-and-pool microtopography of forested wetlands. Restor. and Mgmt. Notes 14:15-21.

Bedford, B.L. 1996. The need to define hydrologic equivalence at the landscape scale for freshwater wetland mitigation. Ecol. Applic. 6:57-98.

Bishel-Machung, L., R.P. Brooks, S.S. Yates, and K.L. Hoover. 1996. Soil properties of reference wetlands and wetland creation projects in Pennsylvania. Wetlands 16:532-541.

Brady, N.C., and R.R. Weil. 2002. The nature and properties of soils. 13th ed. Prentice Hall, Upper Saddle River, NJ.

Brinson, M.M. 1993. A hydrogeomorphic classification for wetlands. Tech. Rep. WRP-DE-4. U.S. Army Engineer Waterways Exp. Stn., Vicksburg, MS.

Brinson, M.M. 1996. Assessing wetland functions using HGM. Natl. Wetlands News. Jan.-Feb., p. 10-16.

Brinson, M.M., and R.D. Rheinhardt. 1996. The role of reference wetlands in functional assessment and mitigation. Ecol. Applic. 6:69-76.

Burdige, D.J., and K.H. Nealson. 1985. Microbial manganese reduction by enrichment cultures from coastal marine sediments. Appl. Environ. Microbiol. 50:491-497.

Cummings, A.R. 1999. An analysis of palustrine mitigation wetlands in the Virginia Coastal Plain. M.S. thesis. Virginia Polytechnic Inst. & State Univ., Blacksburg.

Daniels, W.L., A. Cummings, M. Schmidt, N. Fomchenko, G. Speiran, M. Focazio, and M. Fitch. 2000. Wetland water balance studies: 1994-1998. Final Rep. Virginia Transportation Research Council, Charlottesville.

Elless, M.P., M.C. Rabenhorst, and B.R. James. 1996. Redoximorphic features in soils of the Triassic Culpepper Basin. Soil Sci. 161:58-59.

Environmental Laboratory. 1987. Corps of Engineers wetlands delineation manual. Tech. Rep. Y-87-1. U.S. Army Engineer Waterways Exp. Stn., Vicksburg, MS. Online with updates at <http://www.wes.army.mil/el/wetlands/> (Verified Apr. 2, 2003).

Fanning, D.S., and M.C.B. Fanning. 1989. Soil morphology, genesis, and classification. John Wiley & Sons, New York, NY.

Faulkner, S.P., and W.H. Patrick, Jr. 1992. Redox processes and diagnostic wetland soil indicators in bottomland hardwood forests. Soil Sci. Soc. Am. J. 56:856-865.

Federal Interagency Committee for Wetland Delineation. 1989. Federal manual for identifying and delineating jurisdictional wetlands. Coop. Tech. Publ. U.S. Army, COE; USEPA; USF&WS; USDA, SCS. Washington, DC.

Federal Register. July 13, 1994. Changes in hydric soils of the United States. Washington, DC.

Gambrell, R.P. 1994. Trace and toxic metals in wetlands—a review. J. Environ. Qual. 23:883-892.

Gambrell, R.P., and W.H. Patrick, Jr. 1978. Chemical and microbiological properties of anaerobic soils and sediments. p.375-423. *In* D.D. Hook and R.M. Crawford (ed.). Plant life in anaerobic environments. Ann Arbor Science Publishers., Inc., Ann Arbor, MI.

Genthner, M.H., W.L. Daniels, R.L. Hodges, and P.J. Thomas. 1998. Redoximorphic features of the seasonal high water table, Upper Coastal Plain, Virginia. p. 43-60. *In* M.L. Rabenhorst, J.C. Bell, and P.A. McDaniels (ed.). Quantifying soil hydromorphology. SSSA Spec. Publ. 54, SSSA, Madison, WI.

Gilliam, J.W. 1994. Riparian wetlands and water quality. J. Environ. Qual. 23:896-900.

Hemond, H.F., and J. Benoit. 1988. Cumulative impacts on water quality functions of wetlands. Environ. Mgmt. 12:639-653.

Hook, D.D., W.H. McKee, Jr., T.M. Williams, S. Jones, D. Van Blaricom, and J. Parsons. 1994. Hydrologic and wetland characteristics of a Piedmont bottom in South Carolina. Water, Air, Soil Pollut. 77:293-320.

Hunt, R.J., J.F. Walker, and D.P. Krabbenhoft. 1999. Characterizing hydrology and the importance of ground-water discharge in natural and constructed wetlands. Wetlands 19:458-472.

Hurt, G.W., and V.W. Carlisle. 2001. Delineating hydric soils. p. 183-206. *In* J.L. Richardson and M.J. Vepraskas (eds.). Wetland soils: Genesis, hydrology, landscapes, and classification. Lewis Publ., Boca Raton, FL.

Hurt, G.W., F.C. Watts, and V.W. Carlisle. 2000. Using soil morphology for the identification of seasonal high saturation. p. 51-54. *In* V.W. Carlisle and G.W. Hurt (ed.). Hydric soils of Florida handbook. 3rd ed. Florida Assoc. Environ. Soil Scientists, Gainesville, FL.

Jenny, H. 1941. Factors of soil formation: A system of quantitative pedology. McGraw-Hill Book Co., Inc., New York, NY.

Johnston, C.A. 1991. Sediment and nutrient retention by freshwater wetlands: Effects on surface water quality. Crit. Rev. Environ. Control 21:491-565.

Lovely, D.R. 1991. Dissimilatory iron (III) and manganese (IV) reduction. Microbiol. Rev. 55:259-287.

Metting, F.B. 1993. Structure and physiological ecology of soil microbial communities. p. 3-25. *In* F.B. Metting (ed.). Soil microbial ecology: Applications in agricultural and environmental management. Marcel Decker, Inc., New York, NY.

Mitsch, W.J., and J.G. Gosselink. 2000. Wetlands, 3rd ed. John Wiley & Sons, Inc., New York, NY.

National Technical Committee for Hydric Soils. 2003a. The hydric soil technical standard. Hydric Soils Tech. Note 11, <http://soils.usda.gov/use/hydric/ntchs/tech_notes/index.html> (Verified Dec. 8, 2003).

National Technical Committee for Hydric Soils. 2003b. Hydric soils—criteria. <http://soils.usda.gov/use/hydric/index.html> (Verified Dec. 8, 2003).

National Technical Committee for Hydric Soils. 2003c. Proper use of hydric soil terminology. Hydric Soils Tech. Note 1, <http://soils.usda.gov/use/hydric/ntchs/tech_notes/index.html> (Verified Dec. 8, 2003).

Orndorff, Z.W. 2001. Evaluation of sulfidic materials in Virginia highway corridors. Ph.D. diss. Virginia Polytechnic Inst. & State Univ., Blacksburg.

Palik, B.J., P.C. Goebel, L.K. Kirkman, and L. West. 2000. Using landscape hierarchies to guide restoration of disturbed ecosystems. Ecol. Applic. 10:189-202.

Paul, E.A., and F.C. Clark. 1996. Soil biology and biochemistry. Academic Press, New York, NY.

Rabenhorst, M.C. 1995. Carbon storage in tidal marsh soils. p. 93-103. *In* R. Lal, J. Kimble, E. Levine, and B.A. Stewart (ed.). Soils and global change. Proc. Int. Soil Symp. on Greenhouse Gases and Carbon Sequestration. Columbus, Ohio, Apr. 5-9, 1993, Lewis Publishers, CRC, Boca Raton, FL.

Rabenhorst, M.C., and S. Parikh. 2000. Propensity of soils to develop redoximorphic color changes. Soil Sci. Soc. Am. J. 64:1904-1910.

Reilly, W. 1991. Testimony for July 10, 1991, hearing before the Senate Subcommittee on Environmental Protection regarding Section 404 of the Clean Water Act. USEPA.

Richardson, C.J. 1985. Mechanisms controlling phosphorous retention capacity in freshwater wetlands. Science 228:1424-1427.

Richardson, C.J., and E.J. McCarthy. 1994. Effect of land development and forest management on hydrologic response in southeastern coastal wetlands: A review. Wetlands 14:56-71.

Rivkina, E.M., E.I. Friedmann, C.P. McKay, and D.A. Gilchinsky. 2000. Metabolic activity of permafrost bacteria below the freezing point. Appl. Environ. Microbiol. 66:3230-3233.

Rossiter, J.A., and R.D. Crawford. 1982. Evaluation of artificial wetlands in North Dakota: Recommendations for future design and construction. Transp. Res. Rec. 948:21-25.

Schimel, J.P. 1995. Plant transport and methane production as controls on methane flux from artic wet meadow tundra. Biogeochemistry 28:183-200.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson (ed.). 2002. Field book for describing and sampling soils. Natural Resources Conservation Service, National Soil Survey Center. Lincoln, NE.

Schulze, D.G., J.L. Nagel, G.E. Van Scoyoc, T.L. Henderson, M.F. Baumgardner, and D.E. Stott. 1993. Significance of organic matter in determining soil colors. p. 71-90. *In* J.M. Bigham and E.J. Ciolkosz (ed.). Soil color. SSSA Spec. Publ. 31, SSSA, Madison, WI.

Schwertmann, U. 1993. Relations between iron oxides, soil color, and soil formation. p. 51-69. *In* J.M. Bigham and E.J. Ciolkosz (ed.). Soil color. SSSA Spec. Publ. 31. SSSA, Madison, WI.

Shaffer, P.W., C.A. Cole, M.E. Cole, and R.P. Brooks. 2000. Effect of measurement frequency on water-level summary statistics. Wetlands. 20:148-161.

Shaw, J.N., and M.C. Rabenhorst. 1999. Pedogenic and morphological characteristics of marl-derived soils in the Ridge and Valley Province, Eastern United States. Soil Sci. 164:936-945.

Simonson. R.W. 1959. Outline of a generalized theory of soil genesis. SSSA Proc. 23:152-156.

Soil Survey Division. 2003a. Official soil series descriptions. USDA, NRCS, <http://soils.usda.gov/technical/classification/osd/index.html> (Verified Febr. 19, 2004).

Soil Survey Division. 2003b. Online soil surveys. USDA, NRCS, <http://soils.usda.gov/survey/> (Verified Dec. 8, 2003).

Soil Survey Division. 2003c. Hydric soils of the United States. USDA, NRCS, <http://soils.usda.gov/use/hydric/> (Verified Dec. 8, 2003).

Soil Survey Division. 2003d. Soil survey geographic database. USDA, NRCS, <http://www.ftw.nrcs.usda.gov/ssur_data.html> (Verified Apr. 2, 2003).

Soil Survey Division. 2003e. Soil data viewer. USDA, NRCS, <http://www.itc.nrcs.usda.gov/soildataviewer/> (Verified Apr. 2, 2003).

Soil Survey Division Staff. 1993. Soil survey manual. U.S. Department of Agriculture Handbook 18. Soil Conservation Service, <http://soils.usda.gov/technical/manual> (Verified Dec. 8, 2003).

Soil Survey Staff. 1999. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd ed. USDA, NRCS, U.S. Gov. Print. Office, Washington, D.C. Online with updates at <http://soils.usda.gov/technical/classification/taxonomy> (Verified Dec. 8, 2003).

Stolt, M.H., M.H. Genthner, W.L. Daniels, and V.A. Groover. 2001. Spatial variability in wetlands. Soil Sci. Soc. Am. J. 65:527-535.

Stolt, M.H., M.H. Genthner, W.L. Daniels, V.A. Groover, S.M. Nagle, and K.C. Haering. 2000. Comparison of soil and other environmental conditions in constructed and adjacent palustrine reference wetlands. Wetlands 20:671-683.

Taylor, J.R., M.A. Chadamone, and W.J. Mitsch. 1990. Bottomland hardwood forests: Their functions and values. p. 13-86. *In* G. Gosselink (ed.). Ecological processes and cumulative impacts. JLewis Publishers, Chelsea, MI.

U.S. Army, Corps of Engineers. 1993. Installing monitoring wells/piezometers in wetlands. WRP Tech. Note HY-IA-3.1.

U.S. Department of Agriculture, Natural Resources Conservation Service. 1996. Field indicators of hydric soils in the United States, ver. 3.2. G.W. Hurt, P.M. Whited, and R.F. Pringle (ed.) USDA, NRCS, in cooperation with the National Technical Committee for Hydric Soils, Fort Worth, TX.

U.S. Department of Agriculture, Natural Resources Conservation Service. 1998. Field indicators of hydric soils in the United States, ver. 4.0. G.W. Hurt, P.M. Whited, and R.F. Pringle (ed.). USDA, NRCS, in cooperation with the National Technical Committee for Hydric Soils, Fort Worth, TX.

U.S. Department of Agriculture, Natural Resources Conservation Service. 2002. Field indicators of hydric soils in the United States, ver. 5.0. G.W. Hurt, P.M.Whited, and R.F. Pringle (ed.) USDA, NRCS, in cooperation with the National Technical Committee for Hydric Soils, Fort Worth, TX. Online with edits at <ftp://ftp-fc.sc.egov.usda.gov/NSSC/Hydric_Soils/FieldIndicators_v5_01.pdf> (Verified Dec. 31, 2003).

Vepraskas, M.J. 1996. Redoximorphic features for identifying aquic conditions. N. Car. Agric. Res. Serv. Tech. Bull. 301. NC St. Univ., Raleigh, NC.

Vepraskas, M.J., and S.P. Faulkner. 2001. Redox chemistry of hydric soils. p. 85-106. *In* J.L. Richardson and M.J. Vepraskas (ed.). Wetland soils: Genesis, hydrology, landscapes, and classification. Lewis Publishers, New York, NY.

Vepraskas, M.J., and S.W. Sprecher (ed.). 1997. Aquic conditions and hydric soils: The problem soils. SSSA Spec. Publ. 50. SSSA, Madison, WI.

Vepraskas, M.J., J.L. Richardson, J.P. Tandrich, and S.J. Teets. 1999. Dynamics of hydric soil formation across the edge of a created deep marsh. Wetlands 19:78-89.

Watts, F.C., and V.W. Carlisle. 2000. Landscapes and major landforms of Florida. p. 55-60. *In* V.W. Carlisle and G.W. Hurt (ed.). Hydric soils of Florida handbook. 3rd ed. Florida Assoc. Environ. Soil Scientists, Gainesville, FL.

Weller, M.W. 1981. Freshwater marshes. Univ. Minnesota Press, Minneapolis, MN.

Whittecar, G.R., and W.L. Daniels. 1999. Use of hydrogeomorphic concepts to design created wetlands in southeastern Virginia. Geomorphology 31:355-371.

Widdell, F. 1988. Microbiology and ecology of sulfate- and sulfur-reducing bacteria. p. 469-585. *In* A.J.B. Zehnder (ed.). Biology of anaerobic microorganisms. John Wiley & Sons, New York, NY.