Riparian Area Management

Riparian-Wetland Soils

Technical Reference 1737-19

2003

U.S. Department of the Interior • Bureau of Land Management

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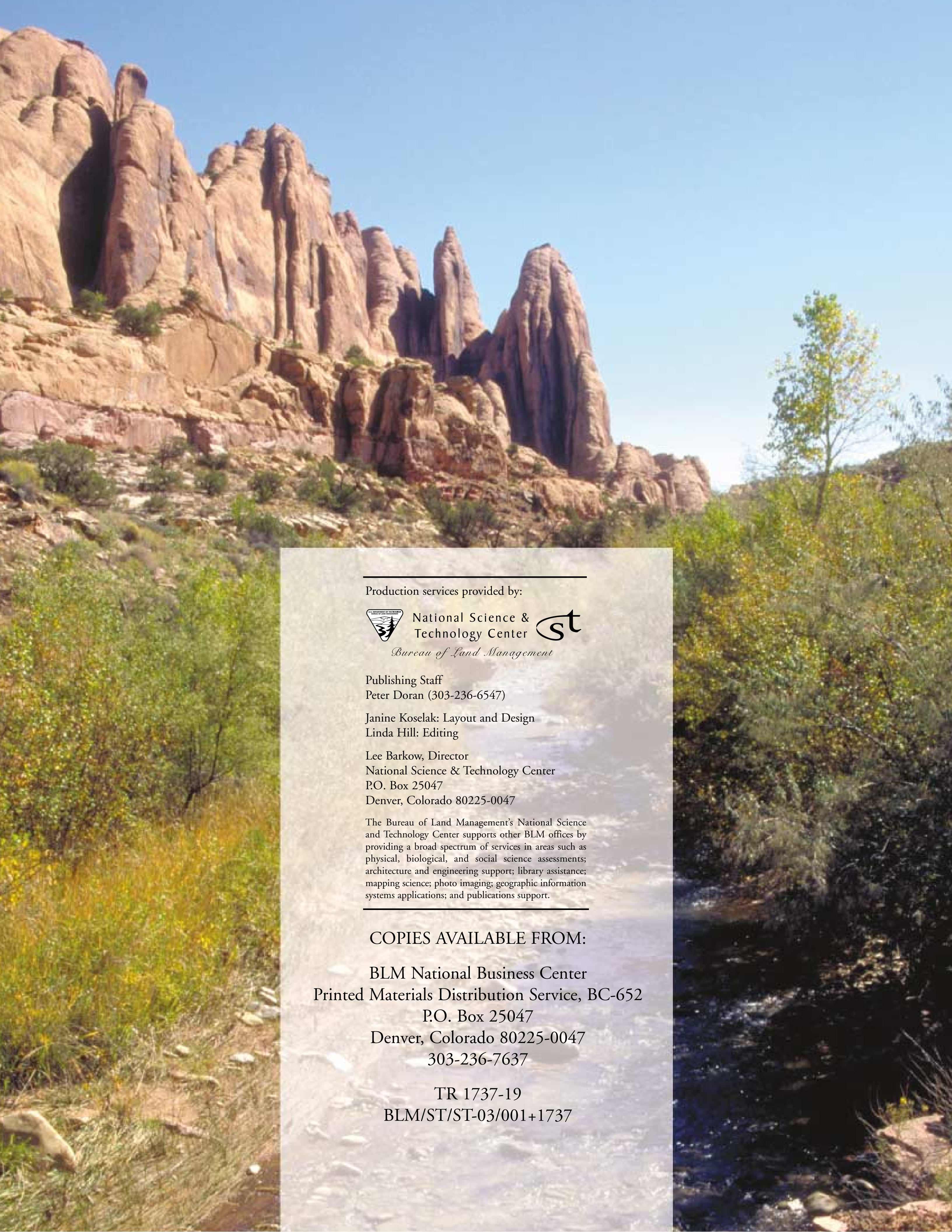

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Foreword

IT HAS OFTEN BEEN SAID, “Under all is the land,” but few people ever completely grasp this important concept. As we calmly stroll along the margins of a wetland or the banks of a stream, our minds are often caught up in a world of mesmerizing beauty and splendor. The flora and fauna produced in these biologically rich areas are known to absorb stress, inspire poetry, provide the colors for brush and canvas, and become the notes for musical scores. The ability of these rich ecosystems to renew and produce tremendous amounts of biomass is often taken for granted. However, the soils under these natural treasures have been forming for thousands of years. Every inch of riparian-wetland soil under our feet started out as parent rock that was slowly weathered, combined with other elements, and finally deposited. Soil formation has gone on for millions of years, and if the soils created by these processes are lost, they cannot be replaced in any single lifetime.

In *Soils and Men, The Yearbook of Agriculture, 1938*, there is a story about a man and his fine horse: “This horse was his pride and wealth. One morning he got up early to go out to the stable, and found it empty. The horse had been stolen. He stayed awake many nights after that, thinking what a fool he had been not to put a good stout lock on the stable door. It would have cost only a couple of dollars and saved his most prized possession. He resolved he would give better protection to the next horse, but knew he would never get one as good as the one lost.” Soil, and the processes that create and recreate it, inspires respect and awe among those who recognize its complexity. Those who use or impact soil, without regard to its value, risk “losing their horse.”

WAYNE ELMORE
Team Leader
National Riparian Service Team

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Contents

Introduction

> "Writing this technical reference about riparian-wetland soil has been a journey of discovering the secrets of her beauty and the mysteries of her soul."
>
> Lisa Lewis
> 2003

Riparian-wetland soils constitute one of the largest freshwater reservoirs on Earth. They are an important component of both standing water (lentic) systems, such as swamps, marshes, and bogs, and running water (lotic) systems, such as rivers, streams, and springs. Riparian-wetland areas are the "green zones," or the links, between aquatic environments and upland, terrestrial ecosystems. Healthy riparian-wetland areas provide several important ecological functions. These functions include water storage and aquifer recharge, filtering of chemical and organic wastes, sediment trapping, streambank building and maintenance, flow energy dissipation, and primary biotic (vegetative and animal) production.

Riparian-wetland areas are intimately related to adjacent waterways since the presence of water for all or part of the growing season is their distinguishing characteristic. In fact, the nature and condition of a riparian-wetland area fundamentally affects the aquatic ecosystem. In addition to water, there are three other essential components of riparian-wetland areas: soil, vegetation, and landform. In a healthy riparian-wetland ecosystem, the four are in balance and mutually support one another.

Because of the presence of water, riparian-wetlands have soil properties that differ from upland areas. For example, most upland soils are derived from in-place weathering processes and relatively little soil material is derived from offsite sources. In contrast, riparian-wetland soils are constantly changing because of the influx of new material being deposited by different storm events and overland flow. As a result, great variability in soil types can occur in short distances.

This great variation in soils has an effect on hydrology and vegetation, as well as on erosion and deposition. The soil in streambanks and floodplains, and the substrate under the channel, act as a sponge to retain water. This stored water is released as subsurface water or ground water over time, extending the availability of water in the watershed for a longer period in the summer or recharging the underground aquifer. Water-restricting soil types

such as clay or hardpans often have impermeable layers that support the water table of standing water riparian-wetland ecosystems. Water movement over, into, and through the soil is what drives hydrology.

Vegetative composition of riparian-wetland areas is also strongly influenced by the amount of moisture and oxygen levels in the soil. For example, the type of riparian-wetland soil, the amount of soil organic matter, the depth to which the water table will rise, the climate, and the season and duration of high water will determine the kinds of plants that will grow in riparian-wetland areas.

Sediment, though necessary in some amounts, must be in balance with the amount of water and vegetation to prevent excessive erosion or deposition. Soils, interacting with geology, water, and vegetation, play a critical role in determining the health and, thus, the rate of erosion and deposition in riparian-wetland areas.

The purpose of this publication is to further the understanding and appreciation of riparian-wetland soils. Specifically, it explores the relationship of these soils to hydrology, vegetation, and erosion or deposition, which is important information for assessing the condition of both lotic and lentic riparian-wetland areas. The information presented was developed cooperatively by the Bureau of Land Management and the Forest Service working with the Natural Resources Conservation Service.

The first section of this publication examines basic soil concepts and land-forming processes. While these concepts and processes may be commonly understood by those who have studied soils, they may be helpful to others who are less familiar with this subject and fundamental for understanding the riparian-wetland soil chapters. The last section presents examples of how soils information can be interpreted and applied in understanding, managing, and protecting riparian-wetland soils.

Soil as a Basic Resource

A. Soil and its components

What is soil? The answer to this question is as varied as the number of people asked. To a farmer, soil provides the medium for successful agriculture. In contrast, a mining engineer might consider soil overlying a mineral deposit to be material that should be removed.

Today's most widely used definition is provided by the Natural Resources Conservation Service (NRCS), which states that soil is "the collection of natural bodies in the Earth's surface, in places modified or even made by man of earthy materials; containing living matter and supporting or capable of supporting plants out-of-doors" (USDA 1993).

Soil characteristics vary widely from place to place. For example, soils on steep mountain slopes are generally not as deep and productive as soils within the more gentle terrain of riparian-wetland areas. While the soil mantle of the Earth is far from uniform, all soils have some things in common. Every soil consists of mineral and organic matter, water, and air. The proportions vary, but the major components remain the same.

1. Minerals

The more solid part of the soil, and naturally the most noticeable, is composed of mineral fragments in various stages of decomposition and disintegration. The mineral portion of the soil has its origin in geologic material and can be described in terms of soil texture and soil structure.

a. Soil texture

Soil "**texture**" is the coarseness or fineness of the soil and refers to the percentage of sand-, silt-, and clay-sized particles the soil contains (Table 1).

"Soil, like faith, is the substance of things hoped for, the evidence of things not seen. It is the foundation for all living things that inhabit the Earth. The flowers, fruits, and vegetables that grow in the garden, the trees that tower in the woods and forests, and the grains and grasses that flourish in the fields, as well as the animals that consume them—all owe part of their existence to the soil. And humans, by way of the food they eat, are a product of the soil, and to the soil their bodies will be returned" (Bear et al. 1986).

"Soil is the uppermost part of the mantle rock, which serves as a source of food for plants. It varies in thickness from two or three inches to as many feet, and locally, much more. Soil consists of small particles of mineral, usually mixed with partly decayed vegetable matter or humus" (Salisbury et al. 1913).

"In agriculture this word is used to describe the thin layer of surface Earth that, like some great blanket, is tucked around the wrinkled and age-beaten form of our globe" (Burkett et al. 1914).

"That part of the Earth's crust permeated by the roots of plants" (Ferguson and Lewis 1920).

Table 1: The U.S. Department of Agriculture's classification of soil particles according to size (particle diameter, mm) (USDA 1993).

		Sand					
Clay	Silt	Very fine	Fine	Medium	Coarse	Very Coarse	Gravel
0.002	0.05	0.10	0.25	0.5	1.0	2.0	

- Sand is the 0.05- to 2.0-mm-sized fraction and is subdivided into very fine, fine, medium, coarse, and very coarse sand separates. Since sand particles are relatively large, spaces between particles are also relatively large. These larger pores result in the least amount of surface area, so sandy soils have the lowest capacity to hold water and allow water to drain rapidly (Figure 1).

Figure 1. A Florida beach with 0.05-mm granitic sand and 2.0-mm shell sand. Notice the sand has both white- and tan-colored particles. The white sand consists of tiny particles of quartz, originally from the granite of the Appalachian Mountains, brought to this Florida beach by erosion, wind, and water. The tan-colored sand grains are bits of seashells (calcium carbonate).

- Silt-sized particles, 0.05 to 0.002 mm in diameter, are smaller than sand particles and larger than clay. Soils high in silt content have the greatest capacity for retaining available water for plant growth due to a unique combination of surface area and pore sizes. Soil containing clay and silt sustains plant growth because it remains wetter longer than sands, releasing water more slowly over a longer period of time.

- Clay-sized particles are less than 0.002 mm in diameter, and while they have the smallest particle size, they have the largest volume of pore spaces and the highest total water- and nutrient-holding capacity. Water moves slowly through clays and is not released easily to plants. When dry, the small clay particles are compact and hard and may impede plant growth.

In the field, the textural class of a soil is generally determined by *feel*. It is ascertained by rubbing a sample of the soil, usually in a moist to wet condition, between the thumb and fingers. The way a wet soil develops a continuous ribbon when pressed between the thumb and fingers indicates the amount of clay present. In general, the higher the clay content, the longer and more flexible the ribbon. Sands are loose and incoherent and do not form ribbons. In general, silts feel creamy when wet, unlike clays that feel sticky or sands that feel gritty. The *"feel"* method is used in soil survey and land classification (Brady 1990). Table 2 gives some general criteria for determining soil texture in the field.

Table 2. Criteria used for field determination of soil texture.

Criterion	Sand	Sandy loam*	Loam	Silt loam	Clay loam	Clay
1. Individual grains visible to eye	Yes	Yes	Some	Few	No	No
2. Stability of dry clods	Clods do not form	Clods do not form	Easily broken	Moderately easily broken	Hard and stable	Very hard and stable
3. Stability of wet clods	Unstable	Slightly stable	Moderately stable	Stable	Very stable	Very stable
4. Stability of "ribbon" when wet soil rubbed between thumb and fingers	Ribbon does not form	Ribbon does not form	Ribbon does not form	Broken appearance	Thin, will break	Very long, flexible

*A loam is defined as a mixture of sand, silt, and clay particles that exhibits the properties of those separates in about equal proportions. Usually, however, the varying quantities of sand, silt, and clay in the soil require a modified textural class name. Thus, a loam in which sand is dominant is classified as a sandy loam; in the same way, there may be silt loams, silty clay loams, sandy clay loams, and clay loams.

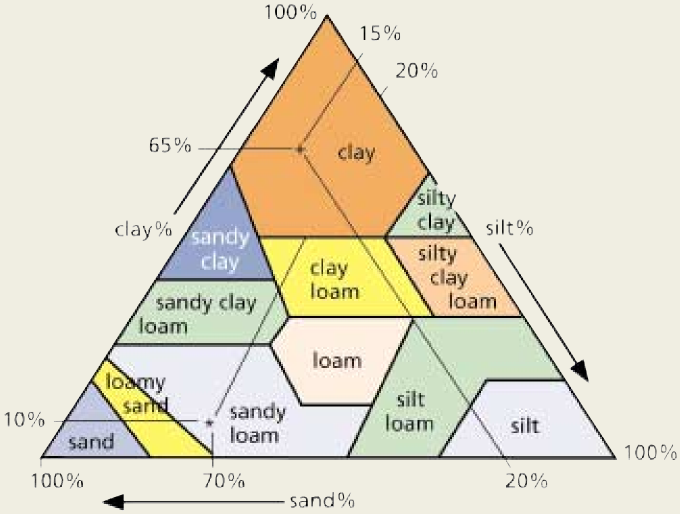
Figure 2 illustrates that a soil is a mixture of particles of different sizes (e.g., sandy loam). It shows how particle-size analyses of field soils can be used to check the accuracy of the soil surveyor's classifications by feel (Brady 1990).

"In its broad meaning, soil is that friable, upper stratum of the Earth composed for the most part of mineral matter resulting from the breaking up and decay of rocks. It may extend to solid rock, varying in depth from an inch to many hundreds of feet" (Weir 1923).

"The surface of most land is covered with vegetation. Beneath this vegetation there is loose material consisting of clay, sand and gravel, and broken rock known collectively as mantle rock. This layer varies from a few inches to hundreds of feet in thickness. The upper part of the mantle rock is commonly called the soil" (Chamberlin 1928).

"Rocks and soils are aggregates of minerals" (Gilluly 1959).

Figure 2. The USDA Soil Textural Triangle for determining the percentages of sand, silt, and clay (USDA 1993). The point at which the two projections cross will identify the class name. For example, locate the (+) and (*). A clay-textured soil (+), contains 20 percent sand, 15 percent silt, and 65 percent clay, whereas a sandy loam (*) contains 70 percent sand, 20 percent silt, and 10 percent clay.



b. Soil structure

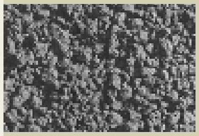
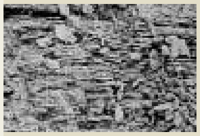
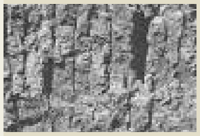
Soil "**structure**" is the arrangement of the sand, silt, and clay particles within the soil, and it is as important as the relative amounts of these particles present (soil texture). The particles may remain relatively independent of each other, but more commonly they are found associated together in "**aggregates.**" These aggregates vary from granules to plates, blocks, prisms, and columns (Table 3). Such structural forms are very important in influencing water and air movement in the soil and are therefore used as criteria in classifying soils.

Several factors are known to influence the formation of soil aggregates. These include: (1) wetting and drying; (2) freezing and thawing; (3) the physical effects of root extension and soil animal activity; (4) the influence of decaying organic matter and of the slimes from microorganisms and other life forms; (5) the modifying effects of adsorbed cations (positively charged ions held on soil particle surfaces); and (6) soil disturbance.

The stability of aggregates is of great importance. Some aggregates readily succumb to disturbance while others resist disintegration. Three major factors appear to influence aggregate stability:

1. The temporary mechanical binding action of microorganisms, especially the threadlike filaments of fungi.
2. The cementing action of the intermediate products of microbial synthesis and decay, such as microbial-produced gums and certain polysaccharides.
3. The cementing action of the more resistant, stable humus. "**Humus**," the soil organic materials remaining after the major portions of added

Table 3. Soil aggregate descriptions (adapted from Brady and Buchman 1969; Brady 1990).

	**Granular**	All rounded aggregates not over 1/2 inch in diameter. They usually lie loosely and are readily shaken apart. Relatively nonporous.
	Crumb	Similar to granular, but relatively porous.
	**Platy**	Aggregates are arranged in thin horizontal plates, leaflets, or lenses. These plates often overlap and can impair water and air conveyance.
	**Blocky and subangular blocky**	Original aggregates reduced to blocks, irregularly six-faced, and with three dimensions more or less equal. Size ranges from a fraction of an inch to 3 to 4 inches in thickness. If blocks have rounded edges they are considered to be subangular blocky.
	**Prismatic**	Vertically oriented aggregates or pillars that may reach a diameter of 6 inches or more.
	**Columnar**	Similar to prismatic, but with rounded tops.

plant and animal residues have decomposed, provides most of the long-term aggregate stability.

The ability of sand, silt, and clay particles to aggregate and form larger particles influences a soil's stability and the ability of water to infiltrate the soil's surface and percolate through the soil layers. Coarse fragments, such as gravel, stones, cobbles, and boulders, also modify soil behavior. A high volume of these materials reduces the soil's water-holding capacity but helps make it resistant to erosion.

2. Organic matter

The second soil component, organic matter, is the soil mass that contains living organisms or nonliving material derived from organisms. Normally, the largest amount of organic matter is in the surface layer of a soil. The organic content of soil ranges from less than 0.05 percent to greater than 80 percent (in highly organic soil such as peat), but is most often found between 2 and 5 percent (Winegardner 1996). Figure 3 shows the different components of soil organic matter (USDA NRCS 1999). In general, soil organic matter is made up of roughly equal parts of humus and active organic matter. Active organic matter is the portion available to soil organisms.

Aggregate stability involves a continual interaction between organic and inorganic components. Polyvalent inorganic cations that cause flocculation (e.g., Calcium, magnesium, iron, and aluminum are also thought to provide mutual attraction between the organic matter and soil clays, encouraging the development of clay-organic matter complexes. In addition, films of clay called "clay skins" often surround the soil aggregates and help provide stability. The noted stability of aggregates in red and yellow soils of tropical and semitropical areas is due to the hydrated oxides of iron they contain.

Organic matter represents the accumulation of plant and animal residues that are generally in an active state of decay (Figure 4). When organic matter decomposes by action of microorganisms and other forces, it produces substances and nutrients that help support plant life. Soil organic matter is thus considered the storehouse for energy and nutrients used by plants and soil organisms. For example, as organic matter mixes into soils and oxidizes, organic acids are produced. Organic acids, in turn, increase nutrient solubility. This makes nutrients more available to plants, but also more susceptible to leaching.

Figure 3. Components of soil organic matter (USDA NRCS 1999).

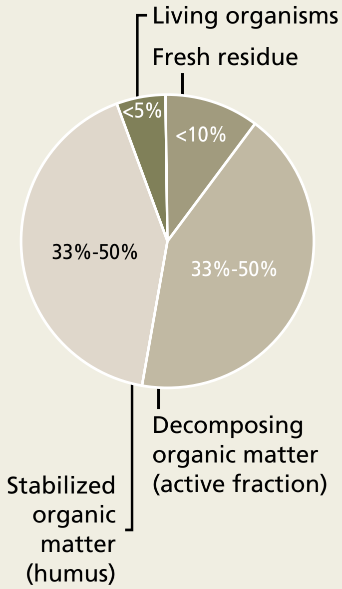
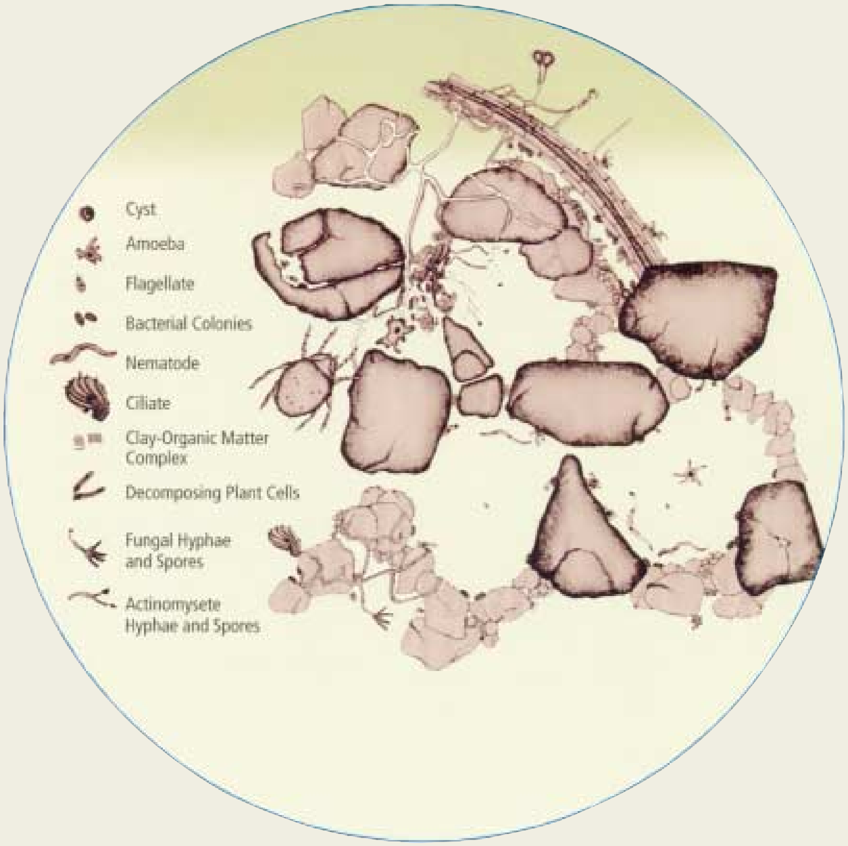


Figure 4. Soil microorganisms within and between soil particles (illustration by S. Rose and E.T. Elliott, used with permission).



a. Organic matter and its effect on physical soil properties

Organic matter and soil mineralogy (texture and structure) also have an effect on a soil's bulk density. "**Bulk density**" is defined as the weight of a unit volume of dry soil (both solids and pores). As soil organic matter increases, bulk density decreases. With an increase in organic matter, soil particles stick together and form aggregates. These aggregates have higher infiltration rates than a soil low in organic matter or without aggregates. Because there is greater pore space with aggregates, the soil is able to hold more water and more air. Thus, water "**infiltration**" (downward entry of water into the soil) and "**percolation**" (downward movement of water through soil) improves. With more pore space, it is also easier for plant roots to grow through the soil.

Soil with low bulk density (good structure and coarse texture) provides an environment for "**aerobic**" (oxygenated) microorganisms, which increases the decomposition of organic matter. On the other hand, soils with high bulk density are poorly drained due to their position in the landscape, soil structure, thick organic matter, or fine soil texture, and provide an environment where oxygen is missing and "**anaerobic**" (lacking oxygen) organisms dominate. Under these circumstances, organic matter does not readily decompose, but instead accumulates. Also, some nutrients, such as phosphorus, nitrogen, and calcium, are usually limited under anaerobic conditions.

b. Organic matter and its effect on chemical soil properties

In upland soils, the decomposition of organic matter involves a large diversity of organisms, each playing an indispensable and specific role. Generally, the whole process is strictly aerobic, and includes organisms ranging from rather large, like earthworms and arthropods, down to miniscule, single-celled protozoa and bacteria. Every stage of decomposition is associated with a specific size of organism, each shredding the organic materials to a finer size, thereby preparing the soil for the next smaller organism (Hunt 1972). In riparian-wetland soils, most of these higher organisms are restricted due to the lack of aeration. Anaerobic bacteria accomplish what little decomposition takes place in these wetter areas.

Soil organic matter, whatever its origin, is the day-to-day food of soil microorganisms. This organic matter, being largely the refuse of plants, is composed mostly of sugars, starches, cellulose, lignin, oils, and proteins. Any animal bodies that may be present in the soil will be made up mostly of proteins and fats. The fats of animals are closely related to the oils of plants. When the microbes have digested this organic matter it will be changed to carbon dioxide, nitrate, and water (Bear et al. 1986).

Except for its protein and mineral matter, most of the soil organic matter is made up of carbon, hydrogen, and oxygen—all derived from the carbon dioxide gas that was breathed in through the leaves of plants and from the water that was absorbed by their roots. Proteins, however, contain carbon, hydrogen, and oxygen, as well as nitrogen. Most of Earth's nitrogen exists as

By controlling soil water-holding characteristics, the soil texture, structure, and organic matter content determine which nutrients are available and which microbial populations survive.

a gas in the atmosphere. But only legumes, such as many varieties of clovers, peas, and beans, can make use of this atmospheric nitrogen. They do this by way of the soil bacteria living in the small nodules that are attached to their roots.

Nonlegume plants obtain their nitrogen from the soil in the form of nitrate that a specific group of microbes produces out of proteins. This nitrate might well be calcium nitrate or nitrate of lime, but in the soil, it exists only in its dissolved form. This nitrate is produced in three steps and by three groups of microorganisms: the first releases ammonia from the protein, the second changes the ammonia to a nitrite, and the third completes the process by producing a nitrate (Bear et al. 1986).

Soil organic matter represents some of the most complex arrays of chemicals known to occur in nature because it contains a collection of breakdown products in various stages of partial decay from every conceivable source.

3. Water

The pore space of a soil is that portion of the soil volume occupied by water and air. Considerable differences occur in the total pore space of various soils, depending upon their texture, structure, organic matter content, and various other characteristics.

There are two types of individual pore spaces, -macro and micro-, that occur in soils. Macropores (greater than 0.06 mm in diameter) are important in conveying nontensioned or gravitational water (Brady 1990). They provide infiltration capacity into the soil and percolation capacity through the soil as they connect surface soil with subsoil via larger channels that have greater hydraulic conductivity.

In contrast, micropores (less than 0.06 mm in diameter) are mostly filled with water in a moist soil and do not permit much air movement into or out of the soil. The water movement also is slow. Micropores have a function in a soil's "**capillary action**," which is traditionally illustrated as upward water adjustment. The movement, however, can be in any direction: downward in response to gravity, upward as water moves to the soil surface to replace that lost by evaporation, and in any direction toward plant roots as they absorb this important liquid.

When the soil moisture content is the most favorable for plant growth, the water can move in the soil and can be used by plants. Although the growing plants remove some of the soil moisture, some remains in the micropores and in thin films around soil particles. The soil solids strongly attract this soil water and consequently compete with plant roots for it.

Plants must be able to overcome the surface tension to use water and nutrients held by soil particles. "**Surface tension**" is an important property of water

In the book "The Good Earth," Pearl Buck wrote: "And he stooped sometimes and gathered some of the Earth up in his hand and he sat and held it thus, and it seemed full of life between his fingers."

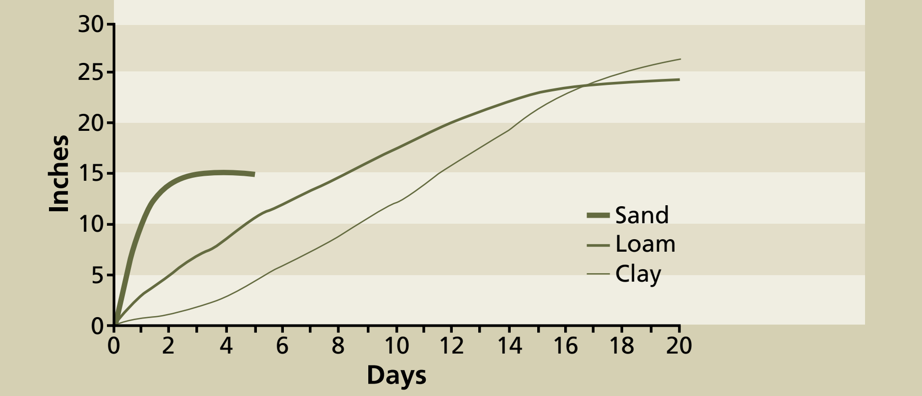
The seemingly lifeless soil is alive with an intricately organized society of countless billions of living things, and each group has a specific piece of work to do. In fact, more life lives underground than above and soil is by far the most biologically diverse part of the Earth (USDA NRCS 1999).

Total pore space in sandy surface soils ranges from 35 to 50 percent, whereas medium- to fine-textured soils vary from 40 to 60 percent. Total pore space also varies with depth; some compact subsoils drop as low as 25 to 30 percent because of the inadequate aeration of soil layers.

that markedly influences its behavior in soils, especially as a factor in capillary action, which determines how water moves and is retained in soil. This phenomenon is commonly evidenced at liquid-air interfaces and results from the greater attraction of water molecules to each other (cohesion) than to the air above.

Capillary forces are at work in all moist soils. However, the rate of movement and the rise in height are less than one would expect. One reason is that soil pores are not straight, uniform openings. Furthermore, some soil pores are filled with air, which may be entrapped, slowing down or preventing the movement of water by capillary action. Usually the height of capillary rise is greater with fine-textured soils if sufficient time is allowed and the pores are not too small. With sandy soils the adjustment rate is rapid, but so many of the pores are noncapillary that the height of rise cannot be great (Figure 5). Table 4 compares soil water properties between sand, silt, and clay particles.

Figure 5. Upward movement of water in soil.



The more surface area a soil particle has, the greater its ability to act as a reservoir for water, air, and nutrients. An ounce of soil consisting of very coarse sand-sized particles may have a surface area equal to 50 square inches, whereas an ounce of silt or clay may have a surface area thousands or millions times greater than sand. Silts and clays, therefore, have a much greater ability to hold water and nutrients. Fine-textured soils (clays) have the maximum *total* water-holding capacity, but medium-textured soils (silts) have the maximum *available* water-holding capacity.

4. Air

Pore space is not only critical to soil water-holding capacity, but it is also tied to soil aeration. "**Soil aeration**" is a vital process because it largely controls the soil levels of two life-sustaining gases, oxygen and carbon dioxide. These gases have a role in the respiration of plant roots and soil microorganisms. For respiration to continue in the soil, oxygen must be supplied and carbon dioxide removed. Through aeration, there is an exchange of these two gases between the soil and the atmosphere (Brady 1990).

Macropores are sensitive to compaction, as the spaces are usually larger than soil particles and can become plugged and filled with soil. Once macropores are damaged or eliminated, it takes a long time to rebuild them, since they are completely organic in origin. Soil fauna (small mammals, earthworms, larvae, beetles, and decaying plant roots) produce macropores over time. Micropores are relatively insensitive to compactive forces and are primarily a function of soil texture (Trimble and Mendel 1995).

Table 4. Water and air properties associated with soil type and texture.

Soil Type	Soil Texture	Soil Properties
Sand	**Coarse**	Less total pore space Greater proportion of macropores Easy water movement through soil (low resistance) Inability to hold plant water Low capillary action
Silt	**Moderate**	Moderate amount of total pore space Range of micro- to macropores Moderate ability to hold plant-available water Moderate resistance in moving water Moderate capillary action
Clay	**Fine**	More total pore space Greater proportion of micropores Ability to hold large amounts of plant-available water Moderate to high resistance in moving water High capillary action

Although the soil surface appears solid, air moves freely in and out. Air in the upper 8 inches of a well-drained soil, for example, is completely renewed about every hour.

The content and composition of soil air are largely determined by the water content of the soil, since the air occupies those soil pores not filled with water. After a heavy rain or irrigation, large pores are the first to drain and fill with air, followed by the medium pores, and finally by the small pores as water is removed by evaporation and plant use.

This drainage sequence explains the tendency for soils with a high proportion of tiny pores to be poorly aerated. In such soils, water dominates. The soil air content is low and the rate of diffusion of the air into and out of the soil to equilibrate with the atmosphere is slow.

Several terms are used interchangeably to describe the state of aeration in soils. The terms aerobic and anaerobic are used to describe the presence or lack of free oxygen. These terms are also used to describe bacterial metabolism as requiring or not requiring oxygen. The terms oxic and anoxic describe whether or not soil material is in a fully oxidized condition. Well-drained "**oxic**" soils are air rich and chemically oxidized in an aerated condition. To the contrary, soils that are not well-aerated are "**anoxic**," or "**gleyed**." Gleyed soils are in a chemically reduced condition, dark gray in color, and saturated with water. The various shades of gray (also gray-blue or gray-green) in soils are referred to as gleyed colors.

In riparian-wetland soils, the demand for soil oxygen far outweighs supply. The microbes in riparian-wetland soil prefer oxygen for respiration and the quantity of oxygen required is known as "**biochemical oxygen demand**" (BOD). BOD represents a major portion of oxygen demand within the soil, but it is by no means the only demand. Accumulating organic detritus uses oxygen in decomposition either through microbial processes or through simple oxidation in contact with air. Plant roots need oxygen to respire and they account for as much as one-third of the total soil respiration.

Depending on the state of aeration of a soil, the relative mix of various gases may or may not be significantly different from gases in the atmosphere. Typically, atmospheric air consists of 79 percent nitrogen, 20.97 percent oxygen, and 0.03 percent carbon dioxide. A well-aerated soil (at the 6-inch depth) shows slight changes: 79.2 percent nitrogen, 20.6 percent oxygen, and 0.2 percent carbon dioxide. This mixture of gases can change dramatically depending on biological activity, soil texture, and soil temperature (Alexander 1977). Oxygen content in fine-textured soils normally falls below 1 percent during fall, winter, and early spring. In contrast, the carbon dioxide content may reach 12 percent during warm summer months when biological activity peaks. Upon waterlogging, soils containing organic matter have been shown to completely change the composition of gases to contain 70.7 percent methane, 27.3 percent carbon dioxide, and only 2 percent nitrogen due to microbial activity (Carson 1974).

B. Soil development

1. Landforms and soil-forming factors

Soil is the part of the Earth composed of mineral and organic matter resulting from the breakup and decay of rocks. After the hot crust of the Earth began to cool billions of years ago, water and the action of dissolved gases began to weather and decompose surface rocks. About 4.5 billion years ago, when the surface was cool enough to allow water to lie on it, the weathering of rocks and formation of soil began.

However, those ancient soils are not the same soils that now cover the Earth because they are constantly changing and are being modified by the five soil-forming factors of climate, parent (geologic) material, biology, topography, and time (Jenny 1941). Table 5 shows the influence these soil-forming factors have on soil properties.

The soil-forming factors affect the development of landforms on all landscapes. Landforms may include hills, sideslopes, terraces, toeslopes, shoulders, and floodplains. The soils that make up these landforms can be categorized

Landforms make up a landscape and landscape is what is seen from a distance.

Table 5. Varying soil-forming factors causes variations in soil properties.

Factor	Soil property
Climate	Soils in drier climates often have lower organic matter content and salts closer to the surface; they are a lighter color and drier than soils in moist climates.
Parent material	Soils derived from coarse materials (sands or coarse-grained rocks) tend to have less water-holding capacity, faster infiltration and percolation rates, lower erosion rates, and lower nutrient-holding capacity than soils formed from finer textured materials.
Biological factors	Soils that supports lush vegetation have higher organic matter content, greater moisture-holding capacity, increased structural stability, and increased nutrient availability. Also includes other components such as microbes, lichens, mosses, fungi, and algae.
Topography	Soil properties, such as temperature, water-holding capacity, erodibility, and depth are influenced by elevation, aspect, and shape of slope.
Time	Soil formation processes are continuous and variable across the Earth's surface. Soils develop and erode over time and exhibit features that reflect the other four soil-forming factors.

ecologically and by landscape position such as mesas, south-facing slopes, valley bottoms, north-facing slopes, and mountaintops. Figure 6 and Table 6 show differences in soil properties along a cross-valley transect.

> "Land must be expertly cared for if it is to be maintained in a productive state."
>
> H.H. Bennett
> 1959

a. The role of time

Time is a vital element in soil development. Some soil characteristics form in decades, such as organic matter. Others take a few thousand years to develop. For example, most weathering processes that break rocks down into their respective mineral components, as well as those that alter minerals into weathering products such as clays, happen on geologic time scales.

Various terminology is used to describe geologic time, but as applied to soil formation in North America, terms associated with deposits by major glacial events are most often used (Table 7). These terms refer to time periods going back more than 250,000 years before present (YBP).

Time, in close correlation with climatic factors, converts geologic materials into weathering products in various stages of advancement. Over time, soil development leads to sorting and redistributing of certain particle sizes or soluble compounds into areas of concentration, or by the accumulation of clay and organic matter compounds that allow aggregates to form. These processes are often dominated by chemical alterations initiated by water infiltration. Consequently, drier climates take longer to leach out minerals and accumulate organic matter than areas with wetter climates.

Table 6. Typical changes in soils and site characteristics along a valley cross section.

Landforms	Soils and site characteristics
Mesa (1)	Stable, low water erosion, susceptible to wind erosion, well-developed soils.
South-facing slope (2)	Direct sun exposure, drier, warmer, soil loss by gravity and erosion, more shallow than soils in valley bottoms, often has less vegetation but more diverse species.
Valley bottom (3)	Deep depositional soils, darker, higher moisture content, stream influenced, productive with abundant vegetation.
North-facing slope (4)	Shaded; formed under cooler, moister conditions; soil loss by gravity and mass wasting; more organic matter than soils on south-facing slopes, often has less diverse species present.
Mountaintop (5)	More shallow, drier, higher erosion rates than soils on the mesa.

Figure 6. A valley cross section.

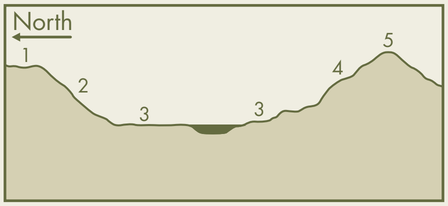


Table 7. Ages associated with time periods used in describing soil development features (Birkeland 1974).

Time period	Approximate age in years before present
Holocene	0 – 10,000
Pleistocene	The epoch of geologic time, 1 or 2 million years in duration, that ended 10,000 years ago:
Late Wisconsin	10,000 – 30,000
Middle Wisconsin	30,000 – 40,000
Early Wisconsin	40,000 – 130,000
Sangamon	130,000 – 250,000+
Illinoian	250,000+

b. Parent material and mineralization

Many soil properties are inherited directly from the mineral composition of the parent material, such as the physical characteristics of color, texture, and nutrient status.

The following examples illustrate the influence parent material has over soil characteristics:

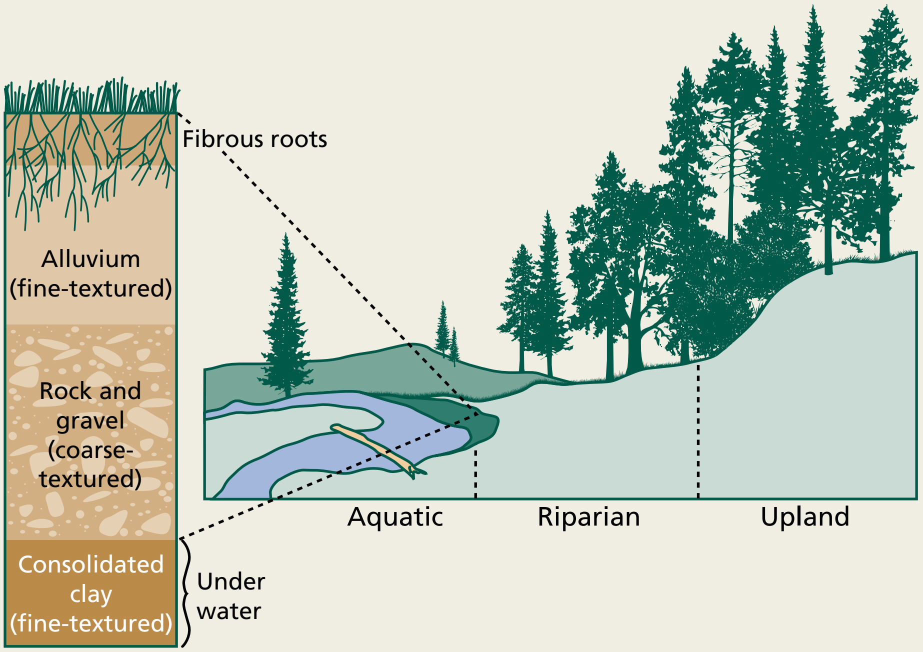
- Quartz, the more resistant mineral, weathers to sand or silt particles.
- Feldspars and micas, the easily disintegrated rock minerals, form clays.
- Volcanic cinders or lava of basalt generally are low in quartz, contain high levels of calcium, and magnesium, and have a very fine-grained mineral composition due to rapid cooling. Upon weathering, these fine-grained minerals readily form fine-grained soil textures that are high in clays.
- If soils are derived from a variety of parent material rocks, as in a glacial till deposit, soil textures will represent a mix of mineral and rock types from which the till was derived.
- Natural processes, such as erosion and deposition on hillsides and streambanks, as well as prevailing winds and surface runoff, add or subtract soil materials to a given site and influence soil characteristics.

There are two groups of inorganic parent materials. "**Sedentary materials**" are residual, or formed in place. "**Transported materials**" are subdivided according to the agencies of transportation and deposition. These agencies include gravity, water, ice, and wind.

2. Soil development processes

Examination of a vertical soil section, as seen in a roadside cut, a streambank, or in the walls of a pit dug in the field, reveals the presence of more or less distinct horizontal layers called "**horizons**" (Figure 7). This soil section is

Figure 7. A view of a streambank that reveals soil layering and the distinctive character of a soil profile (adapted from Brady 1990).



called a “**profile**.” Every well-developed, undisturbed soil has its own distinctive profile characteristics. A soil profile carries its history and development within itself, which is useful for classifying it, surveying it, and determining how it can best be managed.

Soil development is brought about by a series of processes, the most significant of which are:

- *weathering and organic matter breakdown*, by which some soil components are modified or destroyed and others are synthesized;
- *translocation* of inorganic and organic materials up and down the soil profile, with the materials being moved mostly by water but also by soil organisms; and
- *accumulation* of soil materials in horizons in the soil profile, either as they are formed in place or translocated from above or below the zone of accumulation.

In general, the role of these three major processes can be seen by following the changes that take place as a soil forms from relatively uniform parent material. When plants begin to grow and their residues are deposited on the surface of the parent materials, soil formation has truly begun. The plant residues are disintegrated and partly decomposed by soil organisms that also synthesize new organic compounds that make up humus. Earthworms, which burrow into and live in the soil, along with other small animals such as ants and termites, mix these organic materials with the underlying mineral matter near the surface of the parent material. This mixture, which comes into being rather quickly, is commonly the first soil horizon developed; it is different in color and composition from the original parent material.

As plant residues decay, organic acids are formed. These acids are carried by percolating waters into the soil where they stimulate the weathering processes. For example, percolating water makes some chemicals soluble. The chemicals are then translocated (leached) from upper to lower horizons or completely removed from the emerging soil.

As weathering proceeds, some primary minerals are disintegrated and altered to form different kinds of silicate clays. Others are decomposed and the decomposition products are recombined into new minerals such as other silicate clays and hydrous oxides or iron and aluminum.

The newly formed minerals may accumulate in place or may move downward and accumulate in lower soil layers. As materials are translocated from one soil layer to another, soil horizons are formed. Upper horizons may be characterized by the removal of specific components, while the accumulation of these or other components may characterize the lower horizons. In either case, soil horizons are created that are different in character from the original parent material.

> “Nature paints the best part of the picture, carves the best part of the statue, builds the best part of the house, and speaks the best part of the oration.”
>
> Ralph Waldo Emerson

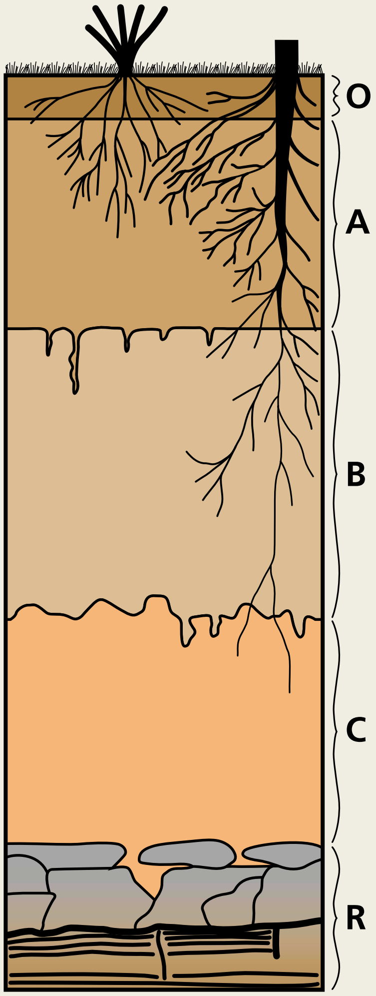
For convenience in description, five primary soil horizons are recognized in Figure 8. These are designated using the capital letters O, A, E, B, and C. Subordinate layers within the primary horizons are designated by lowercase letters. Figure 8 shows a common sequence of horizons within a soil profile.

O Horizons (Organic). The O group is comprised of organic horizons that form above the mineral soil. They result from litter derived from dead plants and animals. O horizons usually occur in forested and riparian-wetland areas and are generally absent in grassland regions. The specific horizons are:

- Oi: Organic horizon of the original plant and animal residues only slightly decomposed.
- Oe: Organic horizon, residues intermediately decomposed.
- Oa: Organic horizon, residues highly decomposed.

A Horizons. A horizons are the topmost mineral horizons. They contain a strong mixture of partially decomposed (humified) organic matter, which tends to impart a darker color than that of the lower horizons.

Figure 8. A hypothetical mineral soil profile showing the primary horizons that may be present in a well-drained soil in the temperate humid region (adapted from Brady 1990). The presence and depth of these horizons varies in each soil profile.



E Horizons. E horizons are those of maximum leaching or “**eluviation**” of clay, iron, or aluminum oxides, which leaves a concentration of resistant minerals, such as quartz, in the sand and silt sizes. An E horizon is generally lighter in color than an A horizon and is found under the A horizon.

B Horizons. The subsurface B horizons include layers in which illuviation of materials has taken place from above and even from below. “**Illuviation**” is the process of deposition of soil material removed from one horizon to another in the soil and usually from the upper to a lower horizon in the soil profile. In humid regions, the B horizons are the layers of maximum accumulation of materials such as iron and aluminum oxides and silicate clays. In arid and semiarid regions, calcium carbonate, calcium sulfate, and other salts may accumulate in the B horizon.

C Horizons. The C horizon is the unconsolidated material underlying the solum (A and B). It may or may not be the same as the parent material from which the solum formed. The C horizon is outside the zones of major biological activities and is generally not affected by the processes that formed the horizons above it. Its upper layers may in time become a part of the solum as weathering and erosion continue.

R Layers. The R layers are the underlying consolidated rock that show little evidence of weathering.

Transition Horizons. These horizons are transitional between the primary horizons (O, A, E, B, and C). They may be dominated by properties of one horizon but have prominent characteristics of another. Both capital letters are used to designate the transition horizons (e.g., AE, EB, BE, BC), with the dominant horizon being listed before the subordinate one. Letter combinations such as E/B are used to designate transition horizons where distinct parts of the horizon have properties of E and other parts have properties of B.

C. Soil classification system—soil taxonomy

Because the Earth's surface has a huge diversity of geology, vegetation, and climatic patterns, there is a corresponding variability of soils. Soil classification seeks to organize these characteristics so properties and relationships among them may be easily remembered, understood, and shared. The classification system provides a common language.

Throughout history, humans used some kind of system to name and classify soils. From the time crops were first cultivated, humans noticed differences in soils and classified them, if only in terms of "good" and "bad." Soils also have been classified in terms of the geological parent materials from which they were formed. Terms such as "*sandy*" or "*clayey*" soils, as well as "*limestone*" soils and "*lake-laid*" soils, have a geological connotation and are used today.

The concept of soils as natural bodies was first developed by the Russian soil scientist V. Dokuchaev and his associates. They noted the relationship among climate, vegetation, and soil characteristics, a concept that Dokuchaev published in 1883. His concept was not promoted in the United States until the early part of the 20th century. C.F. Marbut of the U.S. Department of Agriculture grasped the concept of soils as natural bodies, and in 1927 he

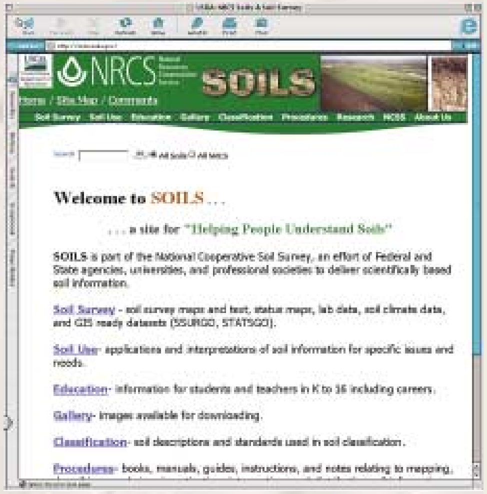
Over very long periods of time, the development of different soil textures result from clay accumulations in soil. Clay formation and "translocation" (the transference of soil materials from one part of the soil to another) are very slow processes, and are often tied to alternating periods of moisture and drought. If parent material already contains clay, translocation into zones of accumulation can take 40,000 years. In parent materials that must be weathered to form clays, argillic horizons can exceed 300,000 years of age (Birkeland 1974).

developed a soil classification scheme based on this principle. The scheme was improved in 1935 and more comprehensive schemes followed in 1938 and 1949, the 1949 system serving well for about 25 years.

The U.S. Department of Agriculture, in cooperation with soil scientists in other countries, developed a new comprehensive system of soil classification based on soil properties. This system has been in use in the United States since 1965 and is used, at least to some degree, by scientists in 45 other countries.

"**Soil taxonomy**" is based on the properties of soils as they are found today. Through such classification systems, the soil is perceived as being composed of a large number of individual units or natural bodies called "**soils**." Each individual soil has a given range of soil properties that distinguish it from other soil. Physical, chemical, and biological properties presented in this text are used as criteria for soil taxonomy. The presence or absence of certain diagnostic soil horizons also determines the place of a soil in the classification system.

Soils are classified into twelve *"soil orders."* They include Entisols, Vertisols, Inceptisols, Aridisols, Mollisols, Spodisols, Alfisols, Ultisols, Oxisols, Histosols, Andisols, and Gelisols. These twelve soil orders have been developed mainly on the basis of the kinds of horizons found in soils and the properties of these horizons. Sixty-four *"suborders"* are recognized at the next level of classification and there are about 300 *"great groups"* and more than 2,400 *"subgroups."* Soils within a subgroup that have similar physical and chemical properties that affect their responses to management and manipulation are *"families."* The *"soil series"* is the lowest category in the soil classification system.



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. . . a site for "Helping People Understand Soils"

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For detailed information about soil taxonomy or your local soils, contact the USDA NRCS National Soil Survey Center or visit their Web site at http://soils.usda.gov. The Center has produced a CD containing all the major manuals, handbooks, and guides used for conducting soil surveys, including the Soil Survey Manual, Soil Taxonomy Keys, National Soil Survey Handbook, Soil Survey Laboratory Methods Manual and Information Manual, and others. Copies can be ordered from USDA NRCS NSSC; Attn: Margaret Hitz; Federal Building, Room 152-Mail Stop 35; 100 Centennial Mall North; Lincoln NE 68508-3866; 402-437-4002; or by e-mail to margaret.hitz@nssc.usda.gov.

Riparian-Wetlands

Riparian-wetland areas are much more dynamic than uplands. They can change dramatically and often in relatively short time periods. They can be influenced by flooding (either temporary or more long-term, as when caused by beavers); deposition of sediment on streambanks and floodplains; accumulation of organic materials in areas such as wet meadows, swamps, and bogs; dewatering by a variety of means (for example, irrigation diversions); and changes in actual channel location.

The overall distribution and makeup of plant and animal communities is a reflection of these dynamic processes. Floods, in particular, result not only in the erosion of established biota (vegetation and animals), but also in the deposition of substrates where colonization and succession of plant species begin again. Over time, these events create complex patterns of soil and ground-water dynamics that direct the development of specialized riparian vegetation and animal communities. The support and benefit of wildlife to riparian-wetland soils is not always passive. Many animals, such as "**annelid worms**" (elongated, segmented worms) and "**oligochaete worms**" (class of hermaphroditic worms without specialized heads), crayfish, small mammals, and mollusks also augment the function of riparian-wetland soils by creating burrows and tunnels that provide conduits for oxygen and water movement (Figure 9). These conduits assist in oxygenating the soil and contributing to the development of hydric soil features.

As a result of these dynamic properties, each riparian-wetland has its own unique characteristics and level of ability to withstand natural and human-induced stress (Buckhouse and Elmore 1993). The natural variation of riparian-wetland areas is an important consideration in understanding and subsequently managing these areas. Knowledge of the four physical riparian-wetland components—landform processes, soil, water, and vegetation—is also essential to perceiving and comprehending the significant variations among riparian-wetland areas.

Figure 9. A worm burrow.

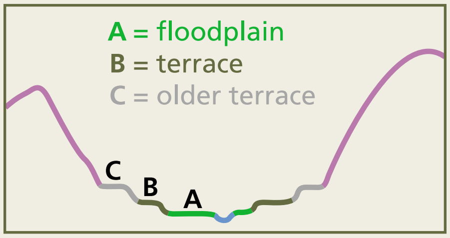
A. Land-forming processes of lotic (riverine) systems

Flowing water is the paramount force shaping most of the landscape. A stream is a complicated, dynamic system that freely adjusts to inputs and other factors. The input to a given stream section consists of the discharge and sediment load from farther upstream. The stream responds to its inputs by adjusting its channel shape and size, its slope, the sinuosity of its course, the speed of its flow, and the roughness of its bed.

Riparian-wetland soil properties change with landscape position. For example, elevation differences generally mark the boundaries of soils and different landforms generally have different types of sediment beneath them. Three major landforms associated with lotic systems include floodplains, terraces, and alluvial fans (Ruhe 1975).

1. Floodplains

Figure 10. A floodplain and terrace.



"**Floodplains**" are relatively flat areas bordering streams and that were constructed by the stream in the present climate and inundated during periods of high flow (Leopold 1994) (Figure 10). Floodplains are an important and inseparable part of the perennial channel. Under normal conditions, and when streams are in a balanced configuration known as proper functioning condition (Prichard et al. 1993), the channel is completely filled during "**bankfull**" flow.

Evaluation of bankfull stage is key to determining whether or not the topographic floodplain feature is connected to the stream. Water enters the floodplain when flows exceed bankfull discharge. Bankfull discharge is significant for riparian-wetland resource management because it represents a measure of interaction between the stream and its adjacent valley bottom and strongly influences the geomorphic and biological characteristics of the riparian-wetland environment. Bankfull discharge, on the majority of streams, has a recurrence interval between 1 and 3 years; 1.5 years is considered a reasonable average (Leopold 1994). This means that bankfull flows are equaled or exceeded 2 out of every 3 years. When bankfull flow is exceeded, water spreads out onto flat adjacent lands during events known as "**floods**." At this time, floodplains are constructed as the channel migrates across the valley.

Channels that adjusts their boundaries under different flow and sediment conditions are called "**alluvial channels**." Flows exceeding bankfull are thought to be largely responsible for forming alluvial channels because these channels occur wherever local sediment supply equals or exceeds transport capacity. As water exceeds bankfull stage, velocity decreases over the floodplain. This flowing water cannot hold the suspended sediment that it could in the main channel and this material is deposited onto the floodplain. During peak flows, larger particles such as gravels, cobbles, and boulders are more easily transported and deposited, while during lower flows (e.g., receding flood flows) only finer materials may be deposited. These finer materials are also collectively called "**valley fill alluvium**." Over time this process can fill whole valleys. Floodplain inundation frequently results in visible grain size sorting with increased distance from the active channel; however, the great variation in flow velocities results in many irregular pockets of uniform particle size normally encountered in soil of fluvial (water-derived) origin. Consequently, soils may vary greatly based on the flood history a particular stream has experienced.

2. Terraces

Abandoned floodplains are called a "**terraces**." They generally have the same origin as floodplains; however, they are rarely, if ever, inundated by flooding (Figure 10). As a valley is gradually deepened through erosive forces over geologic time, the highest floodplains receive floodwaters less often, finally remaining totally dry even during high-magnitude floods. These land areas usually retain their physical shapes and are easily recognized as associated with the given drainage system (Ruhe 1975). Terraces often retain relict fluvial features, such as old abandoned channels, and irregular pockets of sand, gravel, and cobble, which are often visible in exposed cut banks. Because the relative age of alluvium on terraces varies as a function of its time of deposition,

"Out of the long list of nature's gifts to man, none is perhaps so utterly essential to human life as soil."
H.H. Bennett
1939

the level of soil development found on a particular terrace corresponds to elapsed time since the last flood disturbance. Sometimes valleys cut down through bedrock, such as in the Grand Canyon of Arizona. The resulting flat rock surfaces are referred to as benches, rather than terraces.

3. Alluvial fans

"**Alluvial fans**" are also geomorphic features shaped and deposited by moving water (Figure 11). Alluvial fans are composed of "**alluvium**" (sediment deposited by streams and varying widely in particle size) and are normally found where narrow valleys or canyons empty out onto broad valley floors. Alluvial fans form when rapidly flowing water of relatively high velocity is allowed to spread out over a wider area, resulting in less velocity and sediment being deposited. The sediment is deposited in a fan-shaped feature at the mouth of a valley or canyon (Ruhe 1975). Alluvial fans generally demonstrate grain size sorting that decreases in size with distance from the mouth of the valley. Alluvial fans generally produce typical fluvial soil consisting of irregular pockets of similar grain size. Soil development, again, is dependent on the relative age of sediments since deposition or the last major disturbance.

Figure 11. An alluvial fan. Photo by Martin Miller.

In glaciated regions, another type of alluvial fan is a proglacial landform. "**Proglacial landforms**" are those alluvial fans built by streams extending beyond a glacial ice front (Figure 12). They include outwash fans, deltas and aprons, valley trains, and pitted and nonpitted outwash plains (Thornburg 1951). Many small meltwater streams build local outwash fans, or aprons beyond an ice front, or moraines. Down major drainage lines, or sluiceways, more extensive and continuous outwash valley trains extend many miles into unglaciated areas. As ice recedes, valley trains extend headward as long as

Figure 12. Proglacial landform.

sluiceways continue to receive glacial meltwaters. As a result, some valley trains are several hundred miles long. In areas of mountain glaciation, most valley trains are preserved today as terrace remnants along former sluiceways. Such terraces are common features in Alaska, the Pacific Northwest, and along the Mississippi, Missouri, Illinois, Wabash, Ohio valleys, and many lesser valleys in North America. The headwater portions of valley trains consist largely of sand and gravel, but outwash becomes progressively finer down the valley and grades into silt and clay in the lower valley courses. However, along major sluiceways, silt and clay may have been largely carried out to sea.

4. Mobilization of soil and rock fragments in lotic systems

Particle size sorting is largely a function of water velocity. However, particle sizes can also affect particle size sorting.

Clay has considerable cohesion between its individual particles. This strong cohesive force can resist the erosive forces of flowing water, which means clay generally has relatively low mobility. However, certain types of clay will readily disperse in water, depending on their mineralogy and internal chemical bonding. These clay particles can be so small and lightweight that they will not settle out in response to gravity and are held in suspension. These clay particles are kept in suspension by vibrating water molecules bumping them around and keeping them from settling out.

Silt and very fine sand constitute the greatest volume of sediment transported by water. Because silt and sand are not cohesive to each other, they are therefore easily detached and transported.

The relative mobility of given soil particle sizes is similar whether transported by wind or water. For example, silt-sized particles are much larger and heavier than clay, yet they have the greatest mobility of all. In thick, wind-blown deposits, silt is known as "loess" soil (Bloom 1978). In contrast, sand is slightly larger and heavier; it does not travel as far but stays local to form sand dunes.

Soils of active channels form the lowest and usually the youngest surfaces in the stream corridor. There is generally no soil development on these surfaces since the unconsolidated materials forming the stream bottom and banks are constantly being eroded, transported, and redeposited.

Particles greater than 2.00 mm, such as gravel, cobble, or boulder, are parent materials of future riparian-wetland soils. The energy or stream velocity required to move these larger particles is primarily a function of mass, with larger particles needing greater water velocity to move or be held in suspension. The process of moving particles by partial suspension and partial bouncing along the streambed is known as "**saltation**" (Bates and Jackson 1984).

B. Land-forming processes of lentic (standing water) systems

Essentially, lentic systems are the transition between uplands and lotic systems. These areas not only include jurisdictional wetlands as defined by the U.S. Army Corps of Engineers (1987), but also nonjurisdictional (e.g., deep water, freshwater, saline, marine, and estuarine) areas that provide enough available water to the root zone to establish and maintain riparian-wetland soils and vegetation.

1. Wetlands

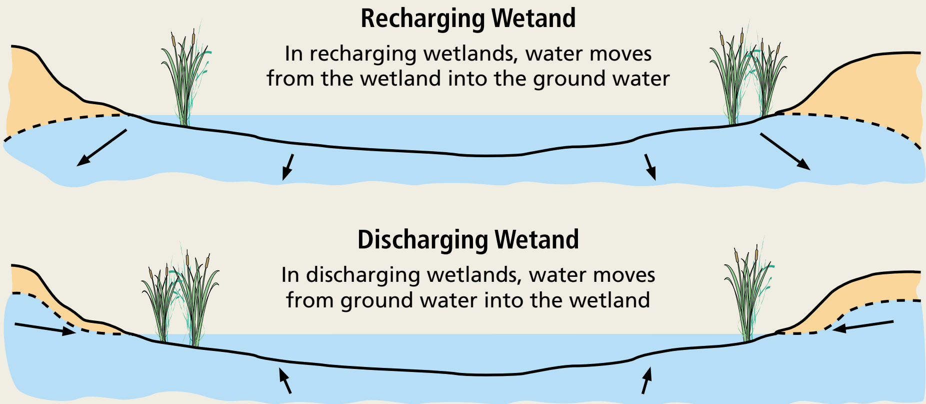
Natural depressions in the landscape where runoff and sediments collect form lakes or ponds when they are deep enough or wetlands when the sediment inflow provides a medium for the growth of aquatic and wetland plants. Since wetlands occur in a transition area, a small difference in the amount, timing, and duration of the water supply can result in a profound change in the nature of the wetland and its unique plants, animals, and processes (Figure 13).

Figure 13. Wetlands provide a medium for the growth of aquatic vegetation like this pitcher plant.

The "**hydroperiod**" is the seasonal pattern of the water level that results from the combination of the water budget and the storage capacity of the wetland. The "**water budget**" is the net of all the water flowing into and all the water flowing out of a wetland. The "**storage capacity**" is determined by the geology, subsurface soil, ground-water levels, surface contours, and vegetation of the wetland. The seasonal events that affect the water level are spring thaw, fall rains, and intermittent storm events (Welsch et al. 1995).

“**Residence time**” is a measure of the time it takes a given amount of water to move into, through, and out of the wetland. Wetlands receiving inflow from ground water are known as “**discharging wetlands**” because water flows or discharges from the ground water to the wetland. A “**recharge wetland**” refers to the reverse case, where water flows from the wetland to the ground water. Recharge and discharge are determined by the elevation of the water level in the wetland and the water table in the surrounding area. Some wetlands have both functions; they may be a discharging wetland in a season of high flow and a recharging wetland during a dry season (Figure 14).

Figure 14. The effect of fluctuating water tables on wetlands.



Inflow water reaches the wetland from precipitation, surface flow, subsurface flow, and ground-water flow. Surface flow includes surface runoff, streamflow, and floodwaters. Outflow leaves the wetland by evaporation, transpiration, surface flow, subsurface flow, or ground-water flow. Wetlands are often connected, to a degree, with surface- and ground-water outflows of one wetland supplying the inflows to other wetlands that are supplying the inflows to other wetlands lower in the watershed. The water supply to the lower wetland can be delayed until the upper wetland fills to a point where additional water runs off. As a result, some wetlands will not be as well-supplied as others in dry periods.

As stated earlier, the soil, ground-water level, and the surface contour affect the water storage capacity of a wetland. Wetlands generally occur in natural depressions in the landscape where geologic or soil layers restrict drainage. The surface contours collect precipitation and runoff water and feed it to the depressed area. Ground-water recharge can take place if the soil is not already saturated and the surface contours of the basin hold the water in place long enough for it to percolate into the soil. The shape of the wetland often is such that precipitation or floodwaters can rapidly collect and then slowly be released by a restricted surface outlet, by slowly permeable soil, or by geologic conditions. Wetlands tend to have longer response times and lower peak stormflows over longer time periods. In contrast, urban and developed lands tend to have short response times and high-volume, short-duration

Delineating the aerial extent of wetlands is not overly complex, but due to the number of decisions required in borderline cases, strict definitions come into play that must be adhered to and thoroughly understood. The U.S. Army Corps of Engineers (COE) is the sole agency for legally defining what are known as jurisdictional wetlands. Currently, the accepted manual describing this procedure is the Corps of Engineers Wetlands Delineation Manual of 1987. From this process, the term “jurisdictional wetland” was coined, to refer to those lands that have all three environmental parameters of legally recognized wetlands: hydric soils, hydrophytic vegetation, and wetland hydrology. The combined use of indicators for all three parameters increases the technical credibility of wetland determinations (COE 1987). Through this process, the area in question is designated either as “wetland” or “nonwetland;” no other terminology is applied. What constitutes a wetland, under the Corps of Engineers definition, includes lentic as well as lotic areas. These terms, definitions, and determinations are important to Clean Water Act permitting processes (Sections 401 and 404) aimed at protecting wetlands.

stormflow discharges. The overall effect is that watersheds with wetlands tend to store and distribute stormflows over longer time periods, resulting in lower levels of streamflow and reduced probability of flooding. Appendix C, Wetland Bioremediation, provides information about restoring wetlands.

One of the identifying characteristics of wetland soils, both from ecological and statutory points of view, is the presence of hydric, or wet, soils. Hydric soils are defined by the NRCS (USDA 1998) 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."

The three critical factors that must exist for the soil to be classified as hydric soil are saturation, reduction, and redoximorphic features.

- "**Saturation**," the first factor, occurs when enough water is present to limit the diffusion of air into the soil. When the soil is saturated for extended periods of time, a layer of decomposing organic matter accumulates at the soil surface.
- "**Reduction**," the second factor, occurs when the soil is virtually free of elemental oxygen. Under these conditions, soil microbes must substitute oxygen-containing iron compounds in their respiratory process or cease their decomposition of organic matter.
- "**Redoximorphic features**," the third factor, include gray layers and gray mottles, both of which occur when iron compounds are reduced by soil microbes in anaerobic soils. Iron, in its reduced form, is mobile and can be carried in the ground-water solution. When the iron and its brown color are thus removed, the soils show the gray color of their sand particles. The anaerobic, reduced zones can be recognized by their gray, blue, or blue-gray color. The mobilized iron tends to collect in aerobic zones within the soil where it oxidizes, or combines with additional oxygen, to form splotches of bright red-orange color called mottles (Figure 15). The mottles are most prevalent in the zones of fluctuating water and help mark the seasonal high water table.

When a dominant portion of the soil exhibits these three elements, the soil is classified as a hydric soil.

The blue-gray layer with mottling is generally present in wetland mineral soils. However, where saturation is prolonged, the slowed decomposition rate results in the formation of a dark organic layer over the top of the blue-gray mineral layer. Although the classification criteria are somewhat complex, soils with less than 20 percent organic matter are

Figure 15. Redoximorphic features.

The Natural Valley Storage Project, a 1976 study by the U.S. Army Corps of Engineers (COE), concluded that retaining 8,500 acres of wetlands in the Charles River Basin near Boston, Massachusetts, could prevent flood damages estimated at $6 million for a single hurricane event. Projecting into perpetuity, the value of such protection is enormous. Based on this study, the COE opted to purchase the wetlands for $7.3 million in lieu of building a $30 million flood control structure (Thibodeau and Ostro 1981).

The U.S. Fish and Wildlife Service (FWS) adopted a separate set of standards and definitions for the purpose of mapping wetlands. Cowardin et al. (1979) published the Classification of Wetlands and Deepwater Habitats of the United States, which later became the guiding document for the National Wetland Inventory (NWI). At the time of publication, the work of Cowardin and others formed an outline of

—continued on 29—

generally classified as mineral soils, and soils with more than 20 percent organic matter are classified as organic soils.

The organic soils are separated in the soil survey into Fibrists, Saprists, and Hemists. The Fibrists, or peat soils, consist of colors in which the layer is brown to black, with most of the decomposing plant material still recognizable. In Saprists, or muck soils, the layer is black-colored and the plant materials are decomposed beyond recognition. The mucks are greasy when moist and almost liquid when wet. Mucks have few discernible fibers when rubbed between the fingers and will stain the hands. The Hemists, or mucky peats, lie in between the Fibrists and Saprists in both color and degree of decomposition. The County Soil Survey Report, available from the county offices of the NRCS, provides an indication of whether an area contains any hydric or wetland soils.

2. Shoreline deposits

The shorelines along oceans, lakes, and ponds consist of deposits that vary greatly in soil particle composition and grain size, depending upon the depth and size of the body of water, the parent materials, and the wave energies that are dissipated on the shoreline (Figure 16). For example, some large lakes, such as Lake Superior, only form a narrow bank of coarse cobbles along the beach. Fine materials are carried away by powerful wind and wave action and dropped into the depths of the lake. Oceans, lakes, and ponds with shallow shorelines allow wave energies to dissipate and accumulate fine materials such as sand and silt.

Figure 16. Beach deposits along the western coast of Vieques Island, Puerto Rico. Photo by Lisa Clark.

—continued from 28—

habitat classification; however, mapping standards for the NWI did not appear until 1994 and 1995. In 1997, the FWS recognized a "riparian" category, separate from their concept of "wetlands," which slightly changed previous definitions and concepts. The term riparian was used to designate areas wetter than adjacent uplands, but lacking the amount or duration of water usually present in what are classified as wetlands (USFWS 1997). The riparian habitat classification system was designed for use in conjunction with the wetland habitats of Cowardin et al. Presently, NWI is a standardized and progressive inventory of all wetlands and riparian areas in the United States. NWI does a good job of classifying habitats but does not include an inventory of soil types or soil classifications, as would a soil survey or ecosystem inventory. In addition, NWI does not make reference to any type of stream or riparian "condition." "Nonjurisdictional wetland" was coined through the NWI inventory and refers to land missing one of the three elements required to be a true jurisdictional wetland, such as wet barren lands that are next to a river but have no vegetation. Nonjurisdictional wetlands are used in a descriptive sense rather than in the sense of a legal definition. All of these determinations and mapping delineations are normally made through aerial photo interpretation.

C. Organic matter in riparian-wetland environments

In most upland soils, organic matter is derived from decaying plants. Since the source material comes from the surface, a gradual decline of organic content with depth is the normal distribution pattern in an upland soil profile. The amount of organic material found in a soil profile is simply a function of the productivity of that soil and climate. Areas receiving more rainfall tend to accumulate more organic matter, but many other factors are part of the equation. Average temperatures and evaporation rates affect plant-available soil moisture, resulting in changes in biomass production and rates of decay.

In the riverine environments of most lotic riparian areas, organic materials originate from onsite production or accumulate in deposits from offsite sources. The amounts of organic materials that accumulate in a given system depend on many factors, such as climate, amount and type of vegetation produced in the watershed, and condition of the watershed. In addition, stream gradient plays a role in sediment being deposited on the floodplains versus being transported downstream. The magnitude of flood events determines the type of materials being deposited, which can vary in organic matter content and the grain size of mineral deposits. In lotic soils, organic matter content does not uniformly decrease with depth as in uplands and can bounce from high to low at any depth. This is not to say that lotic environments always produce variable soils. In instances of long-term watershed stability, substantial depths of relatively uniform materials can accumulate, while not immediately appearing to be of fluvial origin. However, on close examination, the subtle signs of normal hydrological variability become apparent.

In contrast, organic matter accumulates in the standing water environments of lentic areas. These areas are habitats for water-loving plants such as sedges, rushes, pondweeds, cattails, mosses, shrubs, and even some trees. For generations, the residues of these plants have sunk into the water, reducing oxygen availability and inhibiting their oxidation and decay and, consequently, have acted as a partial preservative. As one generation of plants follows another, layer upon layer of organic residue is deposited in the swamp or marsh. The structure of these successive layers changes as time goes on because a sequence of different plant life occurs. The succession is by no means regular or definite, as a slight change in climate or water level may alter the sequence entirely. The profile of an organic deposit is, therefore, characterized by layers that differ in their degree of decomposition and in the nature of the original plant tissue. Good examples of organic accumulations in lentic areas of past geologic times are the world's coal and peat deposits.

In cold boreal environments, such as in marshes and bogs in northern Canada and all across the northern latitudes of Europe and Siberia, peat bogs accumulate organic material because their soils are saturated and anaerobic. Another important factor in these environments is that they are very cold for a good part of the year. Temperatures below 40 °F prevent microbial decay and support very little biological activity. In spite of having a relatively short growing season and limited biomass production, these areas capture and accumulate most of what they produce. A soil profile of a submersed wetland soil is generally uniform, as the events leading to its formation are uniform.

Wetlands are being evaluated as effective "carbon sinks" in which the majority of biomass production is captured in saturated anaerobic soils where the plant material—carbon—accumulates. These sinks offset massive carbon dioxide emissions from combustion of fossil fuels. Carbon sequestration in cold and wet environments is faster than that in forests.

D. Wetland soil biology and biogeochemistry

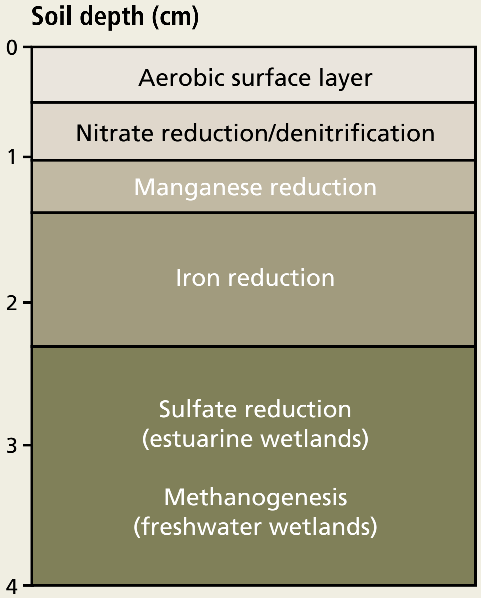
The basic elements that occur in living organisms move through the environment in a series of naturally occurring physical, chemical, and biological processes known as the "**biogeochemical cycle**." The cycle generally describes the physical state, chemical form, and biogeochemical processes affecting the substance at each point in the cycle of an undisturbed ecosystem. Microbial populations that are naturally adapted to life in aerobic (oxygenated) or anaerobic (oxygen-free) conditions influence many of these processes. Because both of these conditions are readily created by varied and fluctuating water levels, wetlands support a greater variety of these processes than other ecosystems.

The actual process of breaking chemical bonds and simplifying the complex organic molecules through enzyme activity is accomplished through bacterial action (Paul and Ladd 1981). The only serious competition in this process comes from the fungi, which are sometimes able to grow rapidly to colonize and take advantage of organic food sources before bacteria can take over (Marschner 1986; Killham 1994). However, since fungi are tied to aerobic environments, they offer no competition in wetlands. In wetland soils, invertebrates and fungi are entirely removed from the picture and specialized bacteria take over. Figure 17 is a generalized diagram of different microbial-reducing reactions found within a wetland soil profile.

Aerobic respiration processes are tied to shallow layers of surface soils where atmospheric oxygen can dissipate into soil water through gas diffusion. As this is a slow process, only small amounts of oxygen can dissolve into moist soil and microbial respiration can quickly deplete all available free oxygen in oxidizing organic residue and turn it into carbon dioxide. Below the shallow layer of aerated wet soils, anaerobic metabolism takes over and other species of bacteria use other compounds instead of oxygen. Although this type of environment would be debilitating to most aerobic organisms, microbial life goes on without the slightest hesitation. There is almost no limit to the types of environments that are colonized by bacteria.

> "The whole of life is, in its simplest terms, a struggle for free energy, whether it be between shrub and tree for a place in the sun, between locust and rabbit for the energy-building compounds of leaves, or between lion and tiger for the flesh of the antelope. Free energy all living things must have, for without it change is petrified—and change is life."
>
> Ralph W. Gerard

Figure 17. Generalized diagram of the relative importance of different microbial-reducing reactions (adapted from Richardson and Vepraskas 2001).



As anaerobic bacteria are common in wetland soils, they strongly influence wetland soil characteristics. For example, bacterial metabolism and respiration can become visible as soil wetness indicators, while other reactions become total barriers to vascular plants. Chemical reactions run in two different directions and depend on gain or loss of electrons. One direction is "**oxidizing**" (losing electrons) and the other direction is "**reducing**" (gaining electrons). The presence of these reduced forms is an indication of restricted drainage and poor aeration. These are also known as "**redox**" reactions.

Bacteria, having evolved some 3.8 billion years ago before free oxygen was present in the atmosphere, have specialized ability to respire or gain energy using reactions that do not involve free oxygen as the oxidizing agent or electron acceptor. These anaerobic reactions yield very small amounts of energy and are suited to sustain very small organisms, such as bacteria. Contrarily, the very high energy requirement of mammals can only be sustained by a much higher energy flux resulting from free-oxygen-based respiration.

In wet soils, bacteria respire anaerobically and use many different chemical compounds and elemental ions dissolved in the soil solution. These compounds are unique in that they possess a distinct energy potential, which is a function of how easily they can be reduced. This is called "**redox potential**" (a measure of the oxidation-reduction potential status of a soil) and results in a distinct sequence in which these compounds are used by various microbes. The existence or disappearance of certain compounds from the soil thereby characterizes its state of reduction, as measured by redox potential. The unit of measure used to describe redox potential is millivolts (mV). If the mV measurement is positive and high, strong oxidizing conditions exist. If it is low or even negative, elements are in reduced forms.

The process of aerobic respiration, using free oxygen, has a redox potential of +820 mV and is characteristically used by plant roots and aerobic microbes. When free oxygen is used up, anaerobic reactions begin.

“**Denitrification**” is the biological reduction of nitrogen to ammonia, molecular nitrogen, or oxides of nitrogen, resulting in loss of nitrogen into the atmosphere. Denitrification of nitrates to nitrogen gas (Paul and Ladd 1981) occurs at a potential of about +420 mV (at pH 7) and is driven by microbes of the *Pseudomonas, Bacillus,* and *Escherichia* genera (Fenchel et al. 1988). This process may not always go to completion and may cease in intermediate stages with the release of nitrous oxide. The immediate denitrification of wet soils is the underlying reason for severe nitrogen deficiency of most waterlogged areas. Some marsh plants (e.g., grasses, sedges, and rushes) have evolved adaptations to this hardship.

Manganese reduction occurs next at about +410 mV and is driven by various microbes in the genus *Bacillus*. Examples of biological manganese depositions are common in certain areas of the ocean floor and are found in the form of large nodules. In most wet soils, not enough manganese is present to become visible in these reactions. Organic matter reduction to organic acids is also used as an electron acceptor, as in fermentation processes involving *Clostridium*. The redox potential of organic matter reduction lies near +400 mV, and does not differ greatly from that of either manganese or nitrate reduction. Often, these three processes happen more or less simultaneously, but go to completion before the next phase involving iron.

Reduction of iron takes place at a redox potential of -180 mV and is a large step beyond previous reactions. The iron pool is normally very large in soils and reduction often does not exceed this stage in lotic systems, as moving water maintains a limited level of oxygenation. In contrast, lentic soils, under stagnant waters (low oxygen) usually exceed this stage and result in gleyed soils. Reduction of ferric to ferrous iron may happen spontaneously in anaerobic soils, but may also be catalyzed by the nitrate reducers *Pseudomonas*. Several species of *Aquaspirillum, Geobacter,* and *Shewanella* may also be involved in iron reduction reactions and have demonstrated the ability to reduce oxides of uranium and selenium (Fenchel et al. 1988).

The reduction of iron is significant because it represents the first readily observable stage of reduction in wetland soils. Iron, in its oxidized form, is yellow to orange (rust) in color, depending on concentration, while reduced iron causes the dark gray to green and blue colors of gleyed soils. This striking color difference is the cause of mottled colors in seasonal wetland soils and is a key indicator of hydric soil.

Unlike oxidized iron, reduced iron ions are highly water-soluble. When changing from an oxidized form to a reduced form, iron changes its solubility in water. In a reduced state, water-soluble iron ions can relocate within the soil profile. This can produce areas of depletion as well as areas of concentration, which become distinctly visible pockets as soon as the soil drains and oxidizes.

At times, reduced iron can be oxidized in direct contact with plant roots through oxygen dissipating out of root tissues. This process creates the characteristic “oxidized rhizospheres” that are often used to help identify wetlands (Tiner 1998). It may be a defensive reaction by waterlogged plants to limit absorption of reduced iron that is toxic to roots.

Bog iron ore is a poor grade of iron ore, but it eventually led to the discovery of iron and the Iron Age in medieval Europe.

Iron bacteria are anaerobes. They proliferate on iron or steel surfaces and may become problematic in plugging well screens and iron pipes.

In medieval northern Europe, the commonly observed phenomenon of phosphorescence, or spontaneous combustion, gave rise to extensive folklore and sagas of supernatural beings, such as elves, living in bogs and marshes and luring people off course to their death. In England especially, these faint lights are known by many different names, such as will-of-the-wisp, night fire, elf fire, moss light, Jack-o-lantern, fen fire, or ignis fatuus, which is medieval Latin for "foolish fire."

Iron is involved in both reducing and oxidizing reactions that are catalyzed by bacteria. The bacterium *Gallionella* exists in both marine and fresh water and has the capability to oxidize reduced iron into an oxide that is deposited as "**ochre**" (an earthy mineral oxide of iron mingled with varying amounts of sand and clay, occurring in brown, yellow, or red) (Figure 18). Such biogenic deposits, known as bog iron ore (Marschner 1986), can reach substantial thickness around iron-rich springs. In fresh water, *Sphaerotilus* and *Leptothrix* contribute to ferrous iron oxidation and excrete ferric iron. Evidence even suggests that iron is cycled between different species of bacteria in a closed loop of oxidation and reduction reactions when in close contact with each other (Fenchel et al. 1988).

Figure 18. Brown, yellow, or red colors showing oxidation of reduced iron. Photo by Jim Turenne.

At a redox potential of around -220 mV, *Desulfovibrio* microbes start to reduce sulfates into sulfides (hydrogen sulfide). This process can start to take place before all of the iron pool is exhausted, giving organic-rich hydric soils a rotten egg odor. These anaerobic organisms developed a metabolic process that evolved early on, long before free oxygen became available in the atmosphere. Since these organisms are made of carbohydrates, they obtained oxygen by reducing sulfate. Their environments continue to be limited to sulfate-rich hot springs (Fenchel et al. 1988).

At even lower redox potentials (-240 mV) and beyond the reduction of sulfate, *Methanobacterium* reduce dissolved carbon dioxide (carbonic acid) to gaseous methane. These organisms use methanogenesis in their strictly anaerobic respiration, yet the exact mechanism of energy conservation and accumulation is not quite understood. "**Methanogenesis**" refers to a very specific type of anaerobic microbial respiration, which results in production of methane ($CH4$). These microbes are also important in anaerobic sewage digestion. Liberation of methane from saturated soil in bogs and marshes, also known as swamp gas, can take place in the form of "**ebullition**" (boiling up of large bubbles) that eventually rises through the wet sediments and surface (Marschner 1986). Methane is normally released in conjunction with various other gases such as hydrogen sulfides and hydrogen. Upon contact with oxygen in air, these gases can, under certain conditions, phosphoresce or spontaneously combust, giving off a faint blue flicker visible in the dark of the night.

Riparian-Wetland Soil Relationships

A. Riparian-wetland soil functions

Riparian-wetland soils perform a variety of functions that are of vital importance, not only in a watershed, but also to the society whose existence depends on the quality of these environments. Riparian-wetland soils serve as a medium for a complex set of physical, chemical, and biological processes and interactions that enable a riparian-wetland area to:

- Capture and store water from adjacent land, high flows, and precipitation (considered a "catchment" area or "sponge")
- Infiltrate water from these different sources for gradual release into streams and ground water
- Store water between rains, which initiates the "**carbon sequestration**" (photosynthetic respiration in plants, resulting in carbohydrate synthesis through the use of chlorophyll) in wetlands and helps offset carbon dioxide emissions from fossil fuel consumption
- Recharge aquifers
- Act as a medium for plants and microorganisms to cycle nutrients
- Store nutrients that would otherwise be discharged from the watershed
- Filter pollutants
- Dissipate energy

Riparian-wetland soil information is important for doing proper functioning condition (PFC) assessments. PFC is a qualitative method for assessing the condition of riparian-wetland areas. The term PFC is used to describe both the assessment process and a defined, on-the-ground condition of a riparian-wetland area. It refers to how well the physical processes are functioning. PFC is a state of resiliency that will allow a riparian-wetland area to remain intact during high-flow events with a high degree of reliability.

The PFC assessment also refers to a consistent approach for considering hydrology, vegetation, and erosion and deposition attributes and processes to determine the condition of riparian-wetland areas associated with lotic and lentic systems. The following information is provided to assist in answering items on the PFC standard checklist for lotic systems (Appendix A) and the PFC standard checklist for lentic systems (Appendix B).

"Take care of the land and the land will take care of you...."

H.H. Bennett
1947

B. Relationship of riparian-wetland soils to hydrology

The original source of all water in riparian-wetland areas is precipitation. The pathways precipitation takes after it falls to Earth affect many aspects of water quantity, quality, and timing (FISRWG 1998). Water movement over, into, and through soil is what drives hydrology. Upon reaching a riparian-wetland area landform, moving water is slowed by vegetation (or large woody debris), which provides stability and habitat for aquatic species.

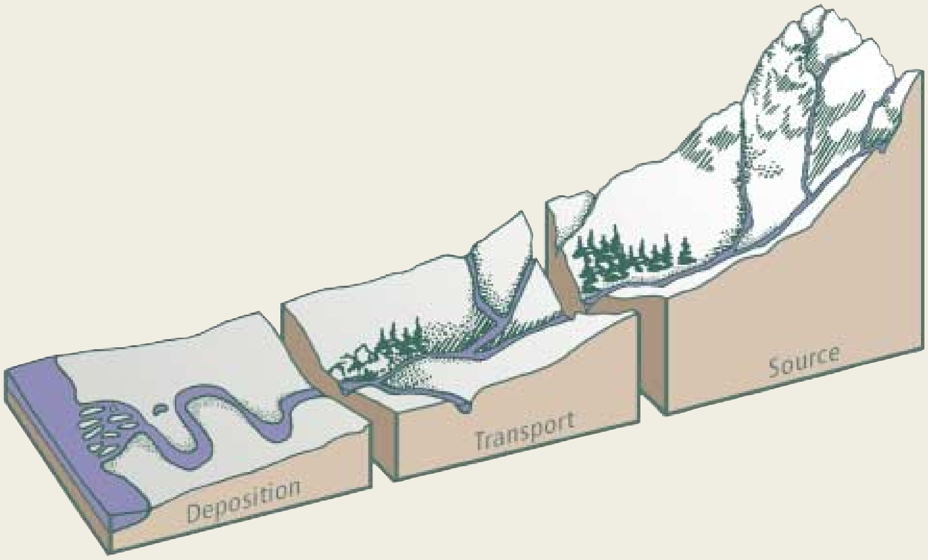
1. Lotic riparian-wetland soils

Geology and soils influence the size, character, and quantity of debris that is contributed to streams and rivers. The ability of flowing water to move this debris and carve a channel depends on the force of gravity and the resistances offered to it. In stream channels, typical resistance factors include roughness contributed from soil particle sizes, changing forms on the streambed generated by movement of bedload (stones, sand, silt, and clay on the bottom of the channel) in waves or other configurations, riparian-wetland vegetation, meanders, and obstructions (Leopold et al. 1964). Riparian-wetland soils in lotic flow areas are made of material that has moved from hill slopes to stream channels, then moved through the channel network downstream by floods, and deposited to form streambanks and floodplains.

A key point is that sediment production, transport, deposition, and storage is a complex balanced system in which modification of one part will affect other parts (Dissmeyer 2000). Particle sizes and the texture of sediment deposits depend on geology and stream energy to move material during high flows. The amount of energy depends on stream size (larger streams have more water during floods to carry and push sediment along) and stream slope (steeper streams have more potential energy than low-gradient streams). Small (silt-size) sediment tends to move rapidly in suspension through a channel system, while larger sediment tends to move slower as bedload.

Most streams can be roughly divided into three zones with different channel-forming processes (Schumm 1977; FISRWG 1998). Some of the changes in the zones are characterized in Figure 19. It is important to note that source, transport, and deposition occur at small scales in all zones (FISRWG 1998). The width and gradient of a valley bottom dictates the extent of storage area

Figure 19. Drawing of three longitudinal profile zones (adapted from Miller 1990). Channel and floodplain characteristics change as rivers travel from the headwaters to the mouth.



available for riparian-wetland soils to develop and helps determine soil characteristics and floodplain function. This concept is explained as follows:

Figure 20. A very narrow valley bottom, steep gradient—King Hill Creek, Idaho.

- Very Narrow Valley Bottom, Steep Gradient—Mountain headwater streams flow swiftly down steep slopes and cut deep V-shaped valleys. Rapids and step pools are common (FISRWG 1998). The steep slopes are known as a "**source**" area because they deliver sediment directly to the stream. These steep streams have tremendous energy that gives them a large sediment transport potential during high flows. There is very little sediment storage area in the narrow valley bottom, so most of the material is moved downstream. The small area that is available for storage of materials can vary from bedrock to soils occurring as colluvium (material moved by gravity that tends to be angular in particle shape because it has not been transported far), landslide debris, glacial tills, and other similar depositional materials (Rosgen 1996). These high-energy steep streams tend to move fine materials easily during floods, depending on geology, and they leave behind larger particles (Figure 20).

"...Nothing that is can pause or stay
The moon will wax and
the moon will wane
The mist and cloud will turn to rain
The rain to mist and cloud again,
Tomorrow be today..."
Keramos

- Narrow to Moderate Valley Bottom, Moderate Gradient—Mid-elevation streams merge and flow down moderately steep slopes. The valley broadens and the river meanders slightly. Stream energy is sufficient to transport suspended load and some bedload. This is known as a "**transport**" area because the narrow to moderately wide valley bottom has moderate space for storage, so much of the material delivered from the source area above is transported through the system. There is limited space for the development of a wide floodplain. Stored materials are colluvium (angular material moved by gravity) and alluvium (material moved by water that tends to be rounded because of abrasion) (Figure 21).

Figure 21. Moderate valley bottom width and moderate gradient—Whitehorse Creek, Trout Creek Mountains, Oregon.

Figure 22. Wide valley bottom width and gentle gradient—Mississippi River near Cassville, Wisconsin, in 1966.

- Wide Valley Bottom, Gentle Gradient—At lower elevations a river meanders slowly across a broad, nearly flat valley. This is known as a "**depositional**" area because the stream has less energy to move what has been delivered from the source and transport reaches above. The valley bottom is much wider so there is more storage area. The stream, or river, with alluvial deposition constructs well-developed floodplains (Figure 22).

Floodplains are formed by two types of deposition. One type is point bar formation, where one side of a meander bend erodes and the material is deposited on the point bar downstream (Figure 23). The second type of deposition occurs when discharge exceeds the ability of a channel to carry it, water spreads over much of the valley floor, and sediment carried by the water is deposited in a thin layer over the surface. Though both of these processes occur, the extension of point bars accounts for most of the material making up the floodplain (Leopold 1997). These two depositional processes often produce floodplain soils composed of stratified layers that are not continuous across valley bottoms. The smallest size classes will tend to be deposited in the areas of less energy, like backwaters and eddies, while larger

Figure 23. Point bar formation where one side of a meander bend erodes and the material is deposited on the point bar downstream.

size particles are deposited nearer the stream channel once the high flows recede and there is no longer enough energy to push them along.

2. Lentic riparian-wetland soils

Lentic riparian-wetland soils must be inundated or saturated at or near the surface, often enough and long enough to develop anaerobic conditions on a reoccurring basis. The rate at which water can move over and through these soils and the amount of water the riparian-wetland soil can store have a great effect on the process of saturation and inundation.

The hydrologic processes of lentic soils are influenced by the physical arrangement of uplands and riparian-wetland areas within a watershed (catchment), the geology of the watershed, and the lentic area's topographic position in the landscape (top, middle, or bottom). Even modest changes in hydrologic conditions (amount and timing of water flows) may result in significant changes in the physical and biological function (USDA NRCS 1992). Therefore, the watershed surrounding a lentic area must be understood. For example, a wetland is a sink for sediments from the surrounding watershed and is filling in over time. If erosion is increased in the upper watershed, this sediment filling process and the progression of states can be accelerated.

Lentic riparian-wetland areas exhibit wide variations in terms of the amount and timing of water input and output, motion of water and the capacity to do work (energy), soils, dominant vegetation, and relative sensitivity to

> "With less than half of the country's original wetlands remaining and many of those left degraded, it is important to take action to protect, restore, and enhance America's wetlands. In doing this, wetland functions such as water-quality renovation, shoreline stabilization, and floodwater storage, which benefit all citizens, will be maintained and hopefully improved. At the same time, habitats for many unique and interesting forms of wildlife and plantlife, vital components of the earth's biodiversity, will be conserved and restored, thereby allowing the more-visible species to continue to provide pleasure for Americans of all ages. Wetland protection could be a lasting gift from all of us to future generations of Americans."
>
> Ralph Tiner

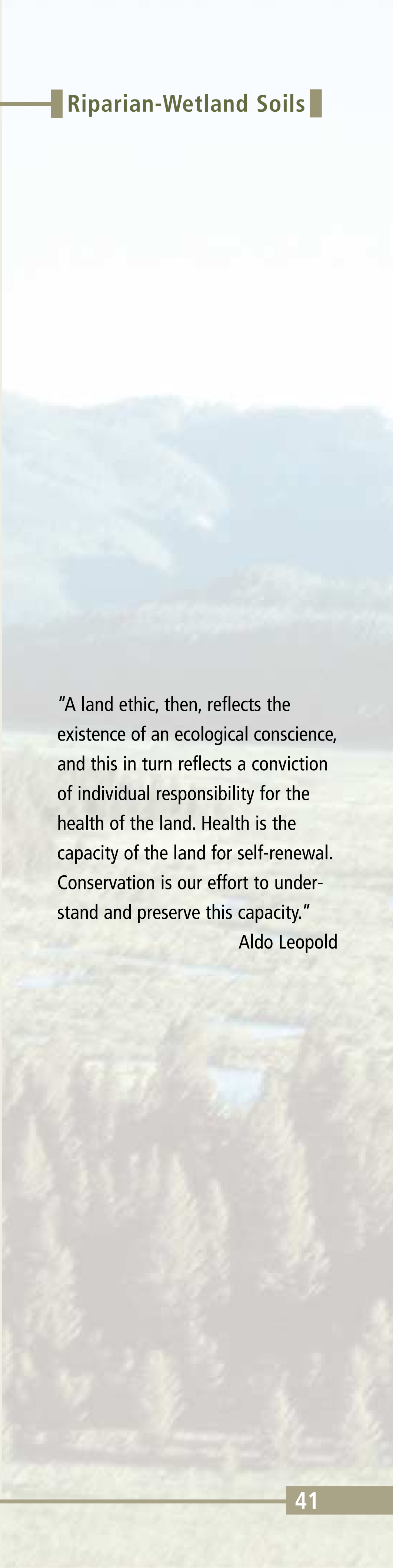
change. Lentic types include slope wetlands to depressional wetlands like prairie potholes and playas with no outlets (Figure 24).

Some riparian-wetlands are wet year-round, and others are wet only seasonally. Water sources may be precipitation, ground water, or surface and near-surface flows. Ground water moving into lentic areas flows into and through riparian-wetland soils. Ground water may be derived from perched water tables or regional ground-water systems. Perched water tables have a restricting layer that keeps water in the soil from percolating farther down into the regional aquifer. Regional ground water may have recharge areas that are far away from the lentic area receiving the water.

Energy from water movement in lentic systems varies from high-energy systems where winds produce waves (e.g., Great Lakes) to sites with low energy from overland flow. Vegetation, landform, or debris needs to be present to dissipate energy in order to maintain physical processes. Vegetation may not always be necessary, since large material such as boulders, cobbles, or bedrock can buffer the forces of water.

Lentic riparian-wetland areas that form in slack water generally have fine-textured soils that settle out in even layers. They are composed of deposits of sediment and organic matter that were carried to the site by water, or grown onsite (e.g., dead plant roots and leaves). Seepage slope wetlands that exist because groundwater comes at or near the surface on a steep slope may have relatively shallow and coarse soils. Most of the organic matter comes from onsite sources.

Figure 24. A playa.



Alteration of surface or subsurface flow patterns may affect the functionality of a lentic riparian-wetland area by lowering the water table and changing the energies involved. If surface or subsurface flows are diverted from a lentic riparian-wetland area, its water table is lowered and wetland size changes. For areas where riparian-wetland vegetation is important, a change in flow patterns may mean a change in vegetation type (wetland species to upland species), creating a site unable to retain water and dissipate energies to function properly (Prichard et al. 1999). For example, a hiking or livestock trail cut deep into a wet meadow may drain or lower the water table and ultimately convert the lentic area into a lotic system. Dams, dikes, levees, roads, rills, and gullies can also alter surface and subsurface flow patterns.

Pollutants in water can affect the health and vigor of plant life. Plants with low vigor will not produce as many aboveground leaves and stems or roots. If these problems exist in a lentic area, the amount of organic matter being added to riparian-wetland soils is affected. Excessive fluctuation of water levels can also affect plant health and vigor if they are outside the range of a plant's tolerance to such change. Any condition that causes a loss of riparian-wetland vegetation can affect energy dissipation and lead to increased erosion.

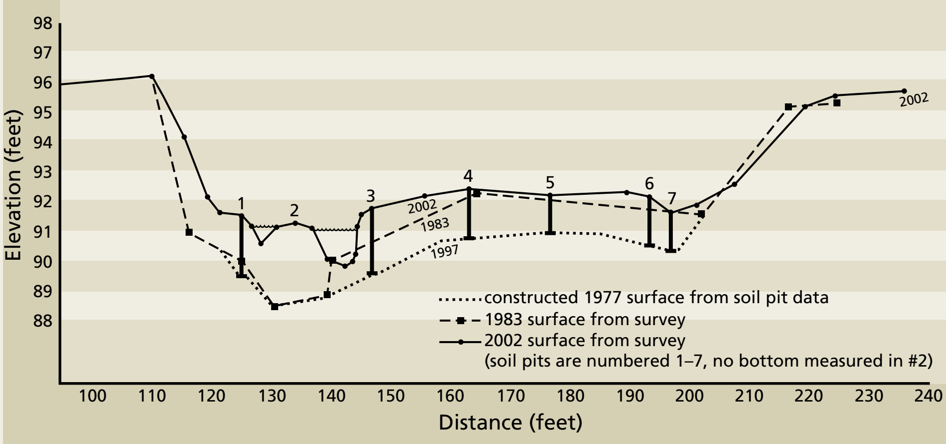
3. Ties to proper functioning condition assessments

Floodplains are very important for energy dissipation in moderate to wide valley bottom streams. Overflow onto the floodplain accommodates the water of floods that cannot be carried within the channel. Floods can happen in various magnitudes and are commonly referred to in terms of their statistical recurrence intervals. The 100-year flood has a 1 percent chance of being equaled or exceeded during any given year. The 100-year flood is an uncommon event of great magnitude, though it can occur in consecutive years or only a few years apart. The 100-year flood is a statistical product that relies on existing data and is only as good as the number of years in the record. The 10-year event has a 10 percent chance of being equaled or exceeded during any given year, occurs much more often than the 100-year flood, but the flood magnitude is less. As stated earlier, the floodplain is constructed by the stream in the present climate and inundated during periods of high flow. A terrace is usually no longer constructed by the stream in the present climate, so is not part of the floodplain, even though it can be inundated during rare, large events.

> "A land ethic, then, reflects the existence of an ecological conscience, and this in turn reflects a conviction of individual responsibility for the health of the land. Health is the capacity of the land for self-renewal. Conservation is our effort to understand and preserve this capacity."
>
> Aldo Leopold

Riparian-wetland vegetation and material such as large woody debris provide surface roughness to slow water velocities on a floodplain. Their added frictional resistance allows sediments to drop out and water to infiltrate into the soil. When riparian-wetland vegetation becomes established on new deposits, it binds this material with root mass and increases floodwater retention and ground-water recharge. Typically, stored water in the floodplain slowly moves toward the channel, sustaining streamflow during periods of little or no precipitation. Figure 25 shows the cross-section data on Bear Creek near Prineville Reservoir in central Oregon. Note how the amount of area available for water storage increased as sediments were deposited and stabilized by riparian-wetland vegetation. If deposits are not stabilized, they wash away during the next high flow event and are deposited downstream.

Figure 25. Cross section of Bear Creek at river mile 4.75 near Prineville Reservoir, Oregon, from 1983 and 2002 with a 1:5 vertical-to-horizontal plotting ratio. The channel and floodplain have raised approximately 2 feet, resulting in increased area for water storage in the floodplain.



Riparian-wetland soils influence stream features, such as "**sinuosity**" (meander) and "**width to depth ratio**" (ratio of the bankfull surface width to the mean depth of the bankfull channel), that play important roles in how well a stream dissipates energy. As channel gradient and dominant particle size decrease, there is generally a corresponding increase in sinuosity. Stream width is a function of stream discharge (magnitude, duration, and frequency), sediment discharge (size and type), and the relative resistance of the channel bed and banks, including the rooting characteristics of the streamside vegetation. Channels that laterally migrate through natural meandering processes, while maintaining their width to depth ratio, are generally considered dynamically stable and in balance with the landscape setting. Channels with erodible banks, that have lost the protection of riparian-wetland vegetation, tend to erode laterally resulting in a wide and shallow channel. This sets in motion many changes, including a change in water velocity distribution that induces accelerated sediment deposition. All else being equal, a narrow deep stream is more efficient at moving bedload than a wide shallow stream.

Beaver dams can serve as hydrologic modifiers, which change site progression and create wetlands. A dam may cause a pond and fringe wetland to develop with associated deposition of sediment in the slower moving water. This could change a seasonally flooded soil into a permanently flooded soil. Sediment trapped in beaver ponds can augment floodplain development. If a beaver dam is not active and stable, degradation may result if the beaver dam

washes out during high flows. The increased energy can cause erosion either laterally or vertically depending on the channel bed and bank materials (Gebhardt et al. 1989; Smith and Prichard 1992). Beavers have learned to pack mud into their dams, which are made of pieces of woody material (Smith and Prichard 1992). This gives the “cuttings” a better chance to sprout and stabilize the dam with their extensive root systems (Gebhardt et al. 1989).

“Productive soil is life, and productive soil is vanishing with each passing year.”

H.H. Bennett
1943

C. Relationship of riparian-wetland soils to vegetation

Different vegetation types provide evidence of the associated climate and soils.

- Riparian-wetland plants are divided into categories relative to the likelihood of their occurrence in wetlands or nonwetlands (e.g., Reed 1988). These categories are obligate wetland or OBL (>99 percent occurrence), facultative wetland or FACW (67-98 percent occurrence), facultative or FAC (34-66 percent occurrence), facultative upland or FACU (found in wetlands 1-33 percent of the time), and obligate upland or UPL (<1 percent occurrence in wetlands). Plants that occur in wetlands are hydrophytes, and they have to be in contact with the water table, which is why they can be used as indicators of soil moisture conditions.
- In dry climates, streams often lose discharge volume to ground-water recharge in their lower elevations and are known as “**losing streams**.” Riparian-wetland vegetation along losing streams typically show signs of having less water available. Obligate wetland and facultative wetland species disappear, leaving the facultative and facultative upland species as the last indicator of riparian influence as the stream turns into a dry wash. However, even dry washes that cannot sustain riparian-wetland vegetation of any kind may retain soil characteristics that reveal their fluvial origin.
- In wetter climates, streams normally increase in flow volume with length as the surrounding watershed discharges ground water into the stream. Such drainages are known as “**gaining streams**.” At the top of these watersheds, where flows are largely ephemeral, only facultative and facultative upland plants are expected, and soil may or may not show signs of soil saturation. Further down the watershed, facultative wetland and obligate upland vegetation exists where streamflows are perennial and soils show signs of saturation. These plants can be found on regularly inundated floodplains and shallow water tables.

Since vegetation responds to plant-available water, very wet vegetation communities can be found in arid climates as long as soil water is present for a sufficient length of time. In deserts, for example, alkaline or saline marshes and playas may be prevalent. For the most part, local climate and the soils that form as a result of present parent material, moisture, and temperature are reflected in the existing vegetation.

Soil provides important clues to the past. If an area no longer has the moisture to support riparian-wetland vegetation, one might assume that the site was never a riparian-wetland system. However, soil features are persistent and reflect the past hydrology. Redoximorphic features, such as mottles and gleyed horizons, typically indicate that a shallow and fluctuating water table was present for long enough to create these properties (see the “Wetlands” section in Chapter III). Relict peat layers may also be present long after the plant community has shifted to non-riparian-wetland vegetation.

These soil features persist onsite, even after vegetation has changed in response to the drier soil conditions. Organic matter, for example, would oxidize or decompose. Subsidence, or settling, would occur to a level where soil was wet enough to support organic matter or until all organic matter was gone. Investigating soils will provide valuable information on the past vegetation and hydrology of an area, which helps in determining site history and potential. Reference, or relict, potential vegetation depends on the channel condition and past and current hydrologic regime.

In the northern boreal forest, peatlands, such as fens and bogs, are common due to the accumulation of peat, or dead plant material, resulting from the wet, cold climate. In the Southeast, swamps, or tree-dominated wetlands, are common. The Southeast also houses the Everglades, which is a large “river of grass.”

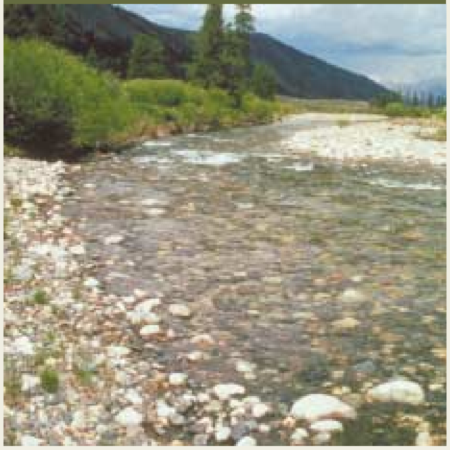
1. Influences of soil properties on riparian-wetland vegetation

Vegetation associated with riparian-wetland areas can typically tolerate growing conditions restrictive to other species (e.g., anaerobic conditions and limited nutrients or dramatic physical disturbance, such as landslides, in lotic areas). Vegetative composition of riparian-wetland areas is strongly influenced by the amount of ground water and oxygen in the soil. These two variables are in turn influenced by soil texture.

Figure 26. Cattails and other aquatic vegetation are adapted to saturated soil conditions.

- Fine-textured (e.g., clayey, silty) mineral soils have small pore spaces and are more likely to be anaerobic and organic, particularly in lentic systems. Redoximorphic features are typically prevalent. Species that tolerate these conditions include some willows (particularly low-growing willows); bald cypress; bog birch; bog blueberry; submergents (or floating-leaved plants) such as pondweed and water lily; emergents such as bulrush, cattail, and burreed; and sedges, rushes, and many grasses and forbs (Figure 26).

Figure 27. An example of coarse-textured mineral soil.



- Coarse-textured mineral soils are most commonly associated with lotic systems (Figure 27). Lotic riparian-wetland areas with a channel gradient greater than 2 percent have a sandy soil or cobble substrate. Soil development is typically minimal due to frequent sediment deposition and erosion. Many soils belong to the Entisol soil order. This means they are developmentally "young" and fluvial in origin. Most shrubs and trees prefer these well-aerated, coarse-textured substrates. Tree and shrub species that thrive tend to be adapted to disturbance due to flooding. Examples include tall willows, birch, dogwood, alder, cottonwood, and more upland species that are able to tolerate periodic soil wetness.
- Organic soils form on landscapes that accumulate water faster than it can drain away. Flat topography, like that of coastal plains, lowers flow gradients. In depressional basins, water retention can actually alter the land-forming processes. As water retention increases, the water table can rise above the levels of the original landform. The higher water table allows for organic matter to form above the surface of the original landform. So, over time, surface- or groundwater-flow wetlands become primarily precipitation driven (Tiner 1998). The organic matter content closely follows the distribution of grass roots because much of the organic matter is the result of the annual death and regrowth of the grass roots. Freshwater wetlands are occupied primarily by either herbaceous emergent vegetation (marshes), woody vegetation (swamp forests), or peat mosses (*Sphagnum* spp.) and other acid-tolerant plants (bogs). The estuarine wetlands, except for mangroves, are dominated by herbaceous vegetation. Mangrove forests are found along tropical and subtropical shorelines (Figure 28). These estuarine wetlands occupy areas of the landscape that are dominated by salt and freshwater tidal marshes in temperate regions (Tiner 1998).

Figure 28. Mangrove forest near Guanica, Puerto Rico. Photo by Lisa Clark.

In any soil textural category there are two variables: (1) oxygen content, or the amount of water the soil will hold, and (2) transmission rate, or the rate at which water will move through the soil. These concepts are represented in Table 8.

Table 8. Ground-water transmission rates and soil oxygen content in lotic systems.

Soil Textural Category	Transmission Rates	Oxygen Content
large stone, cobble, gravel	rapid	high
gravel and sand	moderate	moderate
fine sand and silt	slow	low
clay	very slow	very low

The following examples demonstrate how soils affect plant community response to disturbance:

- In the first example, two valley bottoms are wide and flat and occur in midmontane forests. Both valley bottoms are in glaciated mountains and have a willow and sedge community type mosaic. However, one valley bottom has fine-textured, clayey soils derived from sedimentary alluvium (parent material) (Figure 29), and the other has coarse-textured, sandy soils derived from granitic alluvium (Figure 30). Assuming there is no disturbance that dramatically altered the hydrology (e.g., lowered the water table), these two systems would appear the same, with everything being equal except the soils. Once disturbed, however, these two systems would respond differently.

Figure 29. Fine-textured valley bottom (sedges/rushes).

Figure 30. Coarse-textured valley bottom (willows).

The importance of soils in this example relates to how cohesive the soil particles are and how soil texture influences plant-available water. If the water table drops, plant available water will be influenced by the thickness of the capillary fringe. Fine-textured soils wick water into the upper horizon (the rooting zone), whereas coarse-textured sandy soils do not have a thick capillary fringe. This means that water will not wick up into the rooting zone and the shallower rooted herbaceous species in the undergrowth will likely be replaced by drier site species. Eventually, the large mature woody species (willows in this example) will die off and will not be replaced by young woody species in this drier site. In the fine-textured soil site, the same changes still occur, but at a slower rate, due to the availability of water at the rooting zones. Table 9 lists the significant differences between soil textures.

Table 9. Significant differences between different soil textures.

Sand	Silt and Clay
Streams widen when disturbed	Streams incise when disturbed
Droughty soils, low water-holding capacity	Moist soils, high water-holding capacity
Narrow capillary fringe	Thick capillary fringe
Species composition shifts to dry site species more quickly	Slower shift to dry site species

- Another example is the clay and silt soil horizons that prevent the downward movement of floodwater. This essentially traps water on the surface. Where sufficient roughness and perpendicular control exists (e.g., beaver dams), spring floodwater can remain on the surface or near the surface for many months.

2. Vegetation influences on riparian-wetland soil development

In lotic systems, depending on valley or stream gradients and the amount of stream meander, vegetation has varying degrees of influence on soil development. In a wide valley bottom with a highly sinuous stream and a fine-textured substrate, soil development is more advanced. In contrast, in a steep outwash plain with a braided stream and coarse-textured substrate, vegetation is less likely to have an influence on soil development.

Vegetation influences soil development to a much greater degree in lentic systems. For example, in peat land systems, particularly in cold wet soils, vegetation influences soil formation and associated characteristics through deposition and organic matter accumulation. Typically, due to frequent dieback and regrowth of fine roots, there are several significant changes, all directly related to higher organic matter. These changes include, but are not limited to enhanced soil structure (aggregate formation) due to increased organic matter content and the high density of very fine roots, and increased water-holding capacity due to increased organic matter content (Lyon et al. 1952). Vegetation types affect the rate of dieback, regrowth, and soil development. For example, remains of acidic (evergreen) plants are not broken down as quickly by microbes as those of nonacidic (deciduous) plants (Tiner 1998).

Many species of shrubs and trees have evolved to live in riparian-wetland soils. For example, cottonwood trees and willows often establish on point bars of coarse-textured, well-aerated soils, and within the 2- to10-year high-water levels on floodplains or where that water table decline does not exceed the physical capacity of root growth. Seed dispersal for these species also coincides with late spring flows when water tables are high, fresh alluvium has been deposited, and competition has been minimized. This vegetation, in turn, provides coarse wood for beaver, cavities and nesting material and space for neotropical migrant birds, shade to maintain water temperatures for fish habitat, cover for small mammals and amphibians, foliage for herbivores, habitat for aquatic invertebrates, and resistance to erosion.

In both lentic and lotic systems:

- Herbaceous species, particularly rhizomatous sedges, have an extremely high density of fine roots that are constantly dying and regrowing, providing a continuous and sustained amount of organic matter and "**root exudates**" (substances that bind soils and enhance structure) (Lyon et al. 1952).
- Deciduous shrubs (e.g., willows, birch, and alder) have coarser, mostly woody roots, which are a good long-term source of nutrients to soils (i.e., a slower decomposition rate and a higher carbon/nitrogen ratio). Deciduous trees (e.g., cottonwoods, hawthorn, and aspen) and coniferous trees (e.g., spruce and fir) also are important sources of soil wood, with possibly slower decomposition rates.

3. Environmental challenges for plants because of wet soils

Limiting characteristics of plants revolve around restricted soil aeration (e.g., more buildup of organic matter means less oxidation), but many other characteristics can also become limiting. For example, wet soils can be very limited in certain essential nutrients, such as nitrogen, or can become toxic by an overabundance of certain soluble metal ions such as iron. In addition, decomposing organic matter can cause soils to become very acidic, leaching base ions out of the soil and also causing extreme nutrient deficiency.

Plants living in totally submersed environments, such as in muck soils found in shallow lakes or swamps, have an additional set of conditions to adapt to regarding pollination, structural support, and very limited lighting. Many plants living in shallow water have a different growth form or differently shaped leaves when growing below water versus above water. Usually, greater leaf area is located above water, making the plant far more efficient in gathering light and energy. Most aquatic and wetland species send their flowers to the surface so wind and insects accomplish pollination. A few plant species, however, have evolved underwater pollination.

In general, plants adapted to wet environments are grouped into three broad categories called xeroriparian, mesoriparian, and hydroriparian. These categories describe plant communities and the soil conditions with which they are associated.

- "**Xeroriparian**" (Johnson et al. 1984) plants are those found in the upland to wetland intergrades where soils are never saturated but the benefits of limited moisture are present. These may include upland plants that take advantage of greater moisture availability and grow to larger stature, as well as species found in drier riparian environments that cannot tolerate saturated conditions. Examples abound and may include maples, walnuts, ashes, some alders, hackberries, and a variety of moisture-loving shrubs. The USDI Fish and Wildlife Service refers to these as obligate upland plants.

"...All seasons and their changes,
all please alike;
Sweet is the breath of morn,
her rising sweet
With charm of earliest birds;
pleasant the sun
When first on this delightful
land he spreads
His orient beams on herb,
tree, fruit, and flower
Glist'ning with dew;
fragrant the fertile earth
After soft showers;
and sweet the coming on
Of grateful en'ning mild,
then silent night..."
John Milton

- "**Mesoriparian**" plants are cottonwoods and willows found along streams and on regularly inundated floodplains and shallow water tables. These areas are seasonally saturated to the surface. The USDI Fish and Wildlife Service refers to these as facultative and facultative upland plants.
- "**Hydroriparian**" plants, or hydrophytes, are true aquatic plants that need total inundation or continual surface wetness. They include rushes or cattails. These plants have to be in contact with the water table, which is why they can be used as indicators of soil moisture conditions. The USDI Fish and Wildlife Service refers to these as obligate wetland and facultative wetland plants.

4. Plant adaptations to soil saturation

a. Seed germination

Water and oxygen trigger seed germination in wetland plants. Temperature plays a role in activating seed germination of upland plants; however, it is less of a factor in wet environments. The seeds of wetland plants that grow in stagnant swamp water, such as swamp tupelo and bald cypress, have adapted to unfavorable conditions during germination by staying dormant while the area is flooded. Seed viability is maintained for long durations (e.g., hundreds of years), corresponding to the long periods of time that the environment stays flooded. When conditions become more advantageous and soil aeration increases, seeds quickly germinate.

Plants adapted to fluvial environments have developed an entirely different strategy for seedling establishment. Their habitat is normally associated with relatively short-duration floods generated by heavy rains or snowmelt periods. Floodwaters that spread across wide floodplains are then utilized as a seed dispersal mechanism. The seeds of many common species associated with rivers, such as cottonwoods, willows, and sycamores, are able to initiate seed germination while still immersed in flowing water. They become established as water drains away from barren sandbars and flood deposits. These areas also offer another advantage in that they are often devoid of established plants, which reduces competition, especially after severe flood events. Seed susceptibility to inundation or submergence varies between species and even among subspecies.

b. Vegetative reproduction

Vegetative reproduction includes all reproduction that originates from detached or broken pieces of live plants that grow new roots and eventually become new plants. No seed stage is needed. Plant fragments include live branches, roots, or whole trees that become buried in sediments. Although vegetative reproduction is not limited to aquatic or riparian-wetland plants, it is much more common among plants adapted to these wet environments.

True aquatic plants often establish new plants from broken fragments that drift away and sprout roots while still free-floating. While usually rooted in

bottom sediments, fully submerged aquatic plants obtain their nutrients through stem and leaf tissues directly from the water solution they grow in. Therefore, many aquatic species do not have well-developed conductive tissue, as nutrients and water do not need to be transported throughout these plants as much as in upland plants. Broken off pieces can therefore remain alive for long periods of time and, after growing new roots, are ready to colonize new sites. Many other riparian species, such as willows and cottonwoods, also have the ability to quickly root from detached pieces of branches or "cuttings." Such reproductive strategies can be significant to species subjected to powerful floodwaters that break apart and scatter established mature plants.

Some forms of vegetative reproduction allow the plant to spread out and occupy more area without going through a seed stage. For example, some willows and sedges that grow along low-gradient streams often are rooted in fine-textured sediments, which are poorly aerated and relatively shallow (Lamb 1915). Silts and fine sands typical of low-gradient systems are also often rich in organic residue, which has high-microbial respiration adding to biologic oxygen demand. It is difficult for seeds to become established in these environments due to poor soil conditions and vegetation is usually dense, making competition severe for light and mineral soils at ground level. In such situations, reproduction by root suckering, cloning, or rhizomes is advantageous, as young plants are nourished by existing stands of mature plants rather than depending upon new root development. This type of reproduction is evident in coyote willow (*Salix exigua*) and sedges (*Carex* spp.).

The mechanism of injury to plants subjected to flooding is complex and affects functions within the plant. Photosynthesis is quickly reduced through a reaction that causes stomatal closure within hours of flooding. Closed stomas then reduce gas exchange in the leaf, which results in lowered carbon dioxide (CO_2) uptake and, necessarily, a lower rate of metabolism. Roots lower their ability to absorb nutrients.

c. Shoot growth and leaf area

The root growth of flood-intolerant species can be severely affected if they are flooded for extended periods of time. Common symptoms of flooding and anaerobic conditions are premature leaf senescence (deterioration of cell function) and abscission (shedding), chlorosis (reduced chlorophyll synthesis resulting in pale color) of the leaves, a reduction of leaf expansion below full potential, and reduced height growth (Marschner 1986). Some species commonly found in riparian-wetland areas, such as sycamore (*Platanus* spp.), red alder (*Alnus rubra*), and river birch (*Betula nigra*), can also show signs of reduced height and diameter growth if inundated for longer periods during the growing season. Due to different conditions of soil aeration, flowing water usually has less adverse impact than stagnant water. Flood-tolerant species are generally unaffected by flooding.

d. Root growth

Root growth is severely affected in flood-intolerant species. Extension of the existing roots, as well as the formation of new roots, is essentially stopped in anaerobic wet soils. Significant root dieback is common in many intolerant species during extended periods of inundation. The death of root tissue in flooded soils is often linked to an increase in activity of *Phytophthora* fungi, which are stimulated by the lower vigor of host plants. This fungus causes

“damping off,” which results in the death of nursery seedlings growing in soil conditions that are too wet (Boyce 1961). *Phytophthora* fungi roots are able to tolerate degrees of anaerobic soil conditions and are attracted to highly soluble solutions of plant metabolites, such as ethanol, sugars, and amino acids, that exude out of roots. Contrarily, most mycorrhizal fungi, which significantly assist upland plants in nutrient absorption, are mostly aerobic and therefore are greatly diminished in anaerobic wet soils (Killham 1994). Root tissues of flood-intolerant plants also decrease their macronutrient uptake while inundated. This is due to the fact that nitrogen is less available in wet soils as nitrates (NO_3) are rapidly converted to nitrogen dioxide (NO_2) or nitrogen gas (N_2) through microbial denitrification. In wet anaerobic soils, the process of denitrification takes the place of oxygen in microbial respiration. Root metabolism is slowed by the lack of soil oxygen, resulting in reduced absorptive capacity and increased root cell membrane permeability. As a result, nutrients are lost through leaching.

Saturated and anaerobic soils will eventually kill most trees and shrubs, whether they are flood-tolerant or not. The mangrove thickets growing in southeastern tidewaters may be an exception, but even bald cypress needs a period of drier soil while water levels are low. The reasons for this sensitivity to flooding are likely multifaceted, but are dominated by the fact that strong, deep roots are required to structurally support large plants such as trees and shrubs. When roots cannot survive, the plant cannot maintain its erect form, and either it topples over or dies. Some plants, such as the black spruce (*Picea mariana*) that grows along riparian-wetlands in Alaska (Walker et al. 1989) or ponderosa pine (*Pinus ponderosa*) that grows in Arizona, take advantage of elevated microsites to stay out of saturated soils. The black spruce is normally a shallow-rooted species adapted to wet soils, whereas pine is a deep tap-rooted species, which makes it even more susceptible to damage through high water tables. If the period of soil saturation occurs during the dormant season and the periods of soil saturation do not come too often or last too long, the ponderosa pine can survive such conditions as long as it occupies a small hummock.

5. Morphological adaptations to limited soil aeration

Maintaining aeration within root tissue is absolutely vital to plants. While upland plants are especially sensitive to anaerobic soils and lethal conditions are reached in relatively short periods, riparian-wetland plants have developed various methods to compensate for these restrictive conditions. These methods include aerenchyma tissue, lenticels, and specialized root structures.

a. Aerenchyma tissue

Many plants exposed to anaerobic and saturated soil conditions develop aerenchyma tissue within their roots and stems (Marschner 1986). Aerenchyma tissue consists of an open and spongy cell arrangement with many interconnected air spaces, allowing an easier exchange of gases. The

Water lilies have adapted a unique method of "pumping" air through the aerenchyma tissue in their stems into their root crown and root system, which is fully embedded in anaerobic sediments. In full sunshine and during the heat of the day, water lilies can close their stoma, which pressurizes the gases inside the leaf, forcing them down through aerenchyma tissue into the roots. During cooler temperatures, stoma reopen, allowing the plant to "exhale" and thereby enhancing the rate of gas diffusion.

separation of cells, or dissolution of cell walls, is a result of a cellulase enzyme that dissolves cellulose and produces aerenchymous tissues (Figure 31). Many wetland species rely on aerenchyma tissue to diffuse oxygen absorbed from aerial tissues down into their root systems. This process works well over relatively short distances, but becomes inefficient and insufficient when oxygen is needed in root tips that are a longer distance from leaves.

Figure 31. Alligator weed with progressively larger aerenchyma formations.

b. Lenticels

Lenticels are another specialized feature that plants have to overcome oxygen deficiency during saturation. Lenticels are pores on the surface of the normally thick and impermeable bark that allow the passage of gas to and from the interior tissue. They become expanded in woody species that are inundated with water. Upon flooding, they expand and become hypertrophied (enlarged) features that usually bulge out beyond the surface of the bark (Kozlowski et al. 1991; Tiner 1998). Lenticels are intimately connected to aerenchyma tissue and conductive tissues within the stems. These specialized cells facilitate gas exchange and assist in discharging potentially toxic compounds, keeping them from building up within the plant. Compounds such as ethanol and ethylene are normally metabolized but tend to accumulate to toxic levels during oxygen deficiency.

c. Specialized roots

Various specialized root structures have evolved in plants growing in shallow water or in areas inundated by tides. Mangroves, for example, have developed stilt roots that assist the gas exchange of the submerged portion of the root system. Other plant species have designed specialized roots that protrude straight up and out of the anaerobic soils they grow in, rising above the tidewater surface to allow gas exchange through lenticels. The buttresses or "knees" of bald cypress may also be tied to aeration but are likely more related to extra physical support for the large trees growing in soft soils.

Adventitious roots, another type of specialized root structure, form below water and protrude out of the submerged part of a main stem, out of lenticels, or out of aboveground roots. Their internal structure is porous with aerenchyma tissue, and the cells are larger and thicker like those of lenticels (Marschner 1986). The development of adventitious roots is dependent on the relative aeration of the water the plant is growing in. In stagnant waters low in dissolved oxygen, very few if any adventitious roots develop; however, in aerated flowing water, they seem to grow profusely. For example, alder and sycamore will produce abundant adventitious roots in adjacent streams. It appears the primary function of such roots is to maintain oxygenation within the plant, as flowing water contains far more dissolved oxygen than saturated soils.

Moisture and nutrients are not the primary targets of adventitious roots, as they are both abundant in wet soils. Due to their improved internal aeration, flood-induced adventitious roots play a significant role in oxidizing soils in immediate contact with roots. This process is slow, but helps minimize absorption of potentially toxic levels of water-soluble ions, such as iron and other metals. When reduced iron is oxidized, it becomes water insoluble and is thereby immobilized. Also, maintaining aeration of the rhizosphere directly around the root helps maintain aerobic microbes involved in plant nutrition. In saturated soils, normally gleyed throughout, these small oxidized zones surrounding roots are visible to the naked eye as rust-colored, orange-yellow soils, brightly contrasting the gray matrix colors. These oxidized rhizospheres are commonly observed within saturated surface soils but do not extend deeply into permanently saturated soils. Most species commonly occurring in soils saturated to the surface are shallowly rooted because aerenchyma tissue cannot supply deep roots with oxygen, and gas diffusion in wet soils is slow and also cannot supply oxygen to any significant depth (Marschner 1986).

6. Metabolic adaptations to anaerobic soils

Some plants have developed biochemical adaptations that allow them to tolerate anaerobic soil conditions. By adjusting carbon sequestration and metabolic rates, some plants can balance or reduce toxic products. A buildup of the various intermediate products of metabolism will lead to toxicity and tissue damage. Ethylene gas, for example, can lead to dying root tips faster than oxygen deficiency. To survive, some species will accumulate glucose as an energy reserve (Marschner 1986).

Along with metabolic adaptation, riparian-wetland plants use special means to acquire nitrogen. Saturated soils are deficient in available nitrogen due to rapid denitrification processes from anaerobic microbial respiration. Rotting plant material (such as logs) cannot be used as a nitrogen source as it is in aerated environments. In this situation, anaerobic soil microbes deplete this nitrogen supply very rapidly.

Mycorrhizal root associations significantly contribute nitrogen to upland plants. Some riparian-wetland plants, such as alder, use nitrogen-fixing bacteria in root nodules, similar to legumes in upland situations. Many species of the legume family thrive in the nitrogen-poor soils of disturbed sites. They can colonize these sites as early seral or pioneer species due to their independence of external nitrogen sources due to microbial symbiosis.

Alder, an early seral species, is found in riparian-wetland areas after flood events have removed or reduced previous plant communities, competition, and soil surface horizons. Raw fluvial sediments left by large flood events are poor in nitrogen, giving alder an advantage in establishment.

In wet meadows, limited nitrogen is a problem that some plants solve through parasitism. Some species of paintbrushes (*Castilleja* sp.) can become semiparasitic when given an opportunity to tie into an adjacent plant's root system. Nitrogen is likely the first target of such relationships.

One of the most interesting solutions to nitrogen deficiency in wet anaerobic soils is the evolution of carnivorous plants. Plants that capture small fauna, mostly insects, can be found in all sorts of wet soil environments, including bogs dominated by plants with aerial foliage, as well as shallow waters in streams and swamps supporting only submerged aquatic plants. All of these habitats have severe nitrogen deficiency in common. Through capturing small insects, plants can extract sufficient quantities of nitrogen from animal proteins, which are high in nitrogen. The pitcher plant (*Sarraceniaceae* sp.) and the Venus flytrap (*Droseraceae* sp.) are examples of carnivorous swamp plants, while bladderworts (*Utricularia* sp.) are a common example of carnivorous aquatic plants.

7. Plant succession in lotic soils

The forces of flowing water influence lotic systems. These forces create and alter sites where riparian-wetland species germinate, grow, and establish dominance. The energy of runoff can deposit significant amounts of sediments, creating fluvial surfaces that are elevated just enough to allow germination, but remain wet enough for the right length of time to allow cottonwood and willow species to sink roots and tap into deep soil moisture (Merigliano 1994; Boggs and Weaver in Clary et al. 1992; Chapin et al. in Wigington and Beschta 2000) (Figure 32). Since willow and cottonwood seeds are only viable for 2 weeks, millions of seeds are dispersed, usually in conjunction

Figure 32. Cottonwood establishment in freshly deposited sediments.

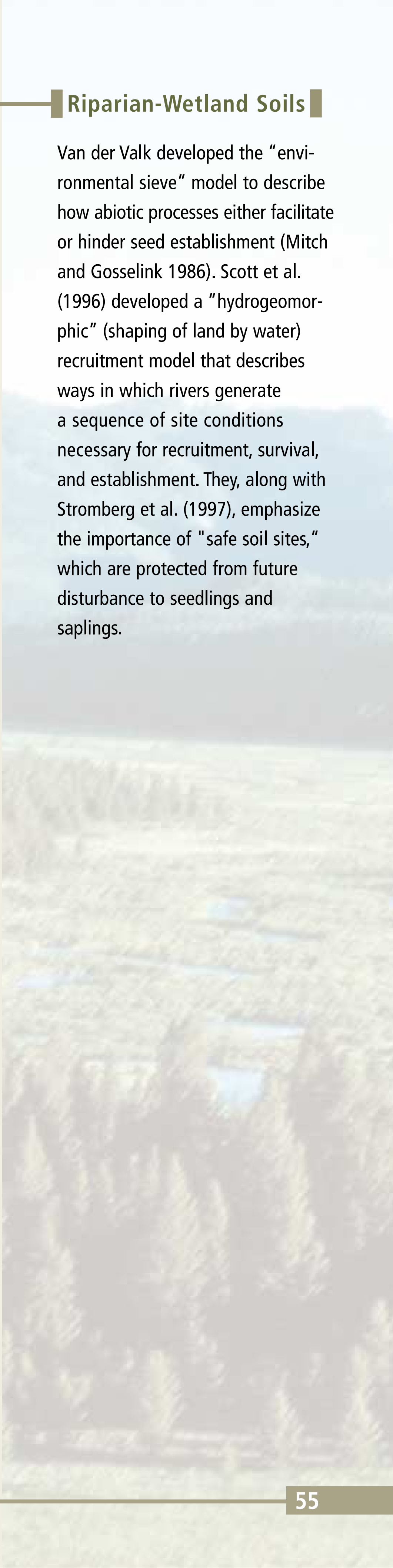
with receding flows, which expose bare, wet, mineral soils (stream bars). This "shotgun" approach to establishment and colonization has been described by van der Valk (1981) as a "temporary window" created by a disturbance (flooding), which establishes a plant-free area with the right conditions for germination.

Riparian species sort themselves along a soil moisture gradient and can be grouped into xero-, meso- and hydroriparian types (see "Environmental challenges for plants because of wet soils" section). Johnson et al. (1984), Gregory et al. (1989), and Gebhardt et al. (1989) stress that valley bottom vegetation types, associated landforms (e.g., floodplains, terraces, toe slopes), soil texture and structure, stream types, substrate, and flow regime dictate when, where, and how succession will proceed. Leonard et al. (1992) also describe "process pathways" and "triggering mechanisms" driven by the presence and abundance of soil water. These external biophysical factors seem to dominate. However, once a willow or cottonwood community gets established and is occupying a stable soil surface, (e.g., low floodplain), "**autogenic**" (the vegetation itself strongly influences successional dynamics) factors, such as competition for soil water, nutrients, and light, alter the structural and floristic composition. If, however, a large flood was to either scour or deposit large amounts of sediment on this fluvial surface, the successional clock would be once again set back. This "cyclical succession" has been demonstrated in a number of riparian-wetland systems (Barbour et al. 1987).

Streams and rivers can either aggrade (build up sediment) or degrade (incise, cut down through the sediments, or entrench). These two processes can affect the direction of plant succession, and the latter is often considered retrogressive (as opposed to progressive) succession (Barbour et al. 1987). Since these "**allogenic**" (external factors influence succession) processes are completely independent of the plant community that they influence, it is harder to predict what a given plant community will specifically look like in the future as long as flowing water, debris torrents, woody debris jams, beavers, and other external factors are at work. However, one could also conclude that as long as these forces are not removing water from the system, certain types of vegetation are expected to colonize these new fluvial surfaces or "safe soil sites."

This could be argued for uplands, but riparian-wetland species are at a competitive advantage because they are so highly adapted to wet soils. Once a soil dries, which is usually due to some external factor (e.g., rapid vertical stream adjustment), the soil is no longer conducive to riparian-wetland species establishment and survival. Typically upland species move in and occupy these drier soils (Figure 33). These soils no longer have the potential to support riparian-wetland species, and until soil moisture conditions are once again reestablished (e.g., stream aggradation after incision), the mechanism for riparian-wetland establishment and function is no longer present.

Van der Valk developed the "environmental sieve" model to describe how abiotic processes either facilitate or hinder seed establishment (Mitch and Gosselink 1986). Scott et al. (1996) developed a "hydrogeomorphic" (shaping of land by water) recruitment model that describes ways in which rivers generate a sequence of site conditions necessary for recruitment, survival, and establishment. They, along with Stromberg et al. (1997), emphasize the importance of "safe soil sites," which are protected from future disturbance to seedlings and saplings.



"All ethics so far evolved rest upon a single premise: that the individual is a member of a community of interdependent parts....The land ethic simply enlarges the boundaries of the community to include soils, waters, plants, and animals, or collectively: the land."

Aldo Leopold
1949

8. Plant succession in lentic soils

Figure 33. Downcut stream, drop in water table, and shift from riparian-wetland species to upland plants. Photo by M. Manning.

Wet meadows, willow carrs (shrub-dominated peatlands), fens, bogs, swamps, marshes, sideslope seeps, and even playas are primarily influenced by the amount, duration, and timing of soil water. Soil water characteristics largely determine the persistence of species (Walker and Wehrhahn 1971; Mitch and Gosselink 1986).

Some lentic systems, such as wet meadows and fens, were once thought to be temporary features of the landscape. However, research using pollen analysis and stratigraphy has clearly demonstrated that these systems are permanent and self-perpetuating (Wood 1975; Benedict and Major 1982; Benedict 1982; Bartolome et al. 1990), as long as soil water is present. The presence and persistence of a shallow water table is the single most important factor influencing distribution of meadows (Wood 1975). Both Wood (1975) and Benedict (1982) found that, as long as the supporting wet meadows (and fens) were geologically stable, the wetland vegetation would persist over time. Bartolome et al. (1990) verified this in their research on lodgepole pine encroachment into wet meadows. They also concluded that meadows are stable and long-lived, and that conversion to a lodgepole pine forest will not occur as long as the underlying substrate continues to support the soil water regime necessary for wet meadow vegetation.

Succession in lentic systems is typically self-forming, or autogenic, as long as the soil water source is constant. Much research has documented the formation of raised bogs and blanket bogs in the northern landscapes of Alaska and Canada (Mitch and Gosselink 1986). The expansion of peatlands is called "**paludification**." Peat formation and an associated increase in the water table (Crum 1988) drive this self-perpetuating process. Wetland vegetation in cold, wet climates decomposes so slowly that it accumulates faster than it decays. As a result, organic soils form and peatland hydrology dominates. Peatland soils are composed almost entirely of plant material in various stages of decomposition (Chadde et al. 1998). As a result, the vegetation itself has altered the abiotic characteristics of the site and influenced which species will grow and survive. For example, strongly rhizomatous sedges will aggressively occupy a site to the exclusion of many other species (Del Moral 1985, Kuramoto and Bliss 1970). Sedges adapt to anaerobic conditions by developing aerenchyma cells in their roots. This adaptation, along with the aggressive rhizomatous growth habit, creates a competitive edge over other species.

Homogeneous patches form in large wet meadow complexes, usually comprised of one parent with numerous offspring (van der Valk in Glenn-Lewin et al. 1992). These patches move in time and space, but require the presence of soil water for a certain length of time, and at a certain depth, for their survival and competitive advantage. Although one could view succession in these systems as autogenic, relay floristics are less likely to occur. Niche occupation and competition at the species level (rather than the plant community level) are primary factors of community development. Wood (1975), Benedict (1982), and Allen-Diaz (1991) found that individual species response to soil water, in particular the depth and duration of the water table, along with nutrients and pH, is the dominant factor influencing species distribution and abundance. An allogenic (external) lowering of the water table will significantly alter the species composition of the site, making it unfavorable for the current species.

9. Ties to proper functioning condition assessments

When using the PFC process, it is important to consider how vegetation modifies the physical environment so that it stays functional over time.

Riparian-wetland vegetation dissipates energy associated with high waterflows, thereby reducing erosion and improving water quality. Vegetation from multistemmed species is very effective at slowing streamflow and creating channel and floodplain “roughness” (Figure 34). The size, density, and extent of this “comb” influence how sediment is trapped and stored. The effectiveness of different vegetation is also a function of stream power. For example, a fine-toothed comb comprised of rhizomatous sedges, grasses, and rushes is very effective in trapping fine-textured silt and clay of smaller channels or those with less flow. Large, multistemmed woody species, such as willows,

Figure 34. Willows slowing streamflow and creating channel and floodplain roughness.

alder, and birch, create an effective coarse-toothed comb for sands and cobbles in larger streams with higher discharge.

Riparian-wetland vegetation improves soil water retention and ground-water recharge. Dense riparian-wetland vegetation, and the resulting increased organic matter, creates a "sponge and filter" that increases the water-holding capacity of soils. These systems store water longer and release it slowly. If this layer is thick enough or compressed, it can become impermeable and perch the local water table (Mitch and Gosselink 1986).

Riparian-wetland vegetation develops root masses that stabilize streambanks and shorelines. Certain plant species, such as rhizomatous sedges, have an extensive fibrous root system consisting of fine roots plus very strong underground stems, or rhizomes, that create a mat or sod that holds the soils in place. Weakly rooted species, such as bluegrass or redtop, are rhizomatous, but do not have the robust root system of most sedges. These upland plants cannot armor the streambank or shoreline against high flows or wave action. Typically, the densely rooted species occupy streambanks and wet meadows when they are properly managed and functioning. Shifts in composition to bluegrass and sagebrush are a result of various outside disturbances.

"**Erosion**" is the wearing away of the Earth's surface by water, wind, ice, gravity, and other forces. Natural erosion has sculptured landforms on the uplands and built landforms on the lowlands (USDA 1993). Erosion is a two-step process. The first step consists of "detachment," where individual soil particles (e.g., a sand grain) separate from the larger soil structural unit (e.g., a granular structure). Detachment can occur from raindrop impact or flowing water (USDA 1993). The weaker the soil structure, the more easily this detachment occurs. The second step consists of transporting the smaller particles to another location. Smaller particles require less energy to transport them. Thus, infiltration capacity, soil texture, coarse fragment content, organic matter content, clay amount and type, and structural stability have major impacts on erosion (Buckman and Brady 1966).

D. Relationship of riparian-wetland soils to erosion and deposition

Erosion and deposition occur both within and outside riparian-wetland areas. Upland erosion and runoff rates have a direct impact upon erosion and deposition in both lotic and lentic riparian-wetland sites.

Soil mineralogy can also impact erosion. Expansive clays may be more prone to erosion as they shrink and swell, resulting in soil aggregate breakdown (Baver et al. 1972). When dispersive clays have a preponderance of sodium in their pore water, they lack the cohesive nature of other clays, which makes them highly erodible. Some minerals (e.g., silica and calcium) can act as cementing agents in soil-forming hardpans that are very resistant to erosion.

1. Lotic ecosystems

Channel characteristics and soil material that form the streambed and banks of any segment of a lotic riparian system are a function of the landform setting for that stream or river. Steep-gradient, confined streams are going to have high stream energy associated with them (Figure 35). Often, the smaller soil particles have been washed downstream, leaving mainly bedrock, boulders, and cobbles in their streambed and banks, especially in the active channel. These larger size, coarse fragments are an important factor in dissipating the high energy in these streams. They are also very resistant to erosion due to the high energy required to transport them. Steep-gradient streams can be very efficient in removing fine sediments when massive amounts of sediment are deposited from landslides or debris torrents.

Low-gradient, meandering streams in broad, gentle-sloping valleys have much lower stream energy. These are depositional zones with smaller particles such as gravel, sand, silt, and clay forming the streambed and banks, especially in eddies and backwater areas (Figure 36).

Figure 35. Steep-gradient streams have high stream energy, which often washes smaller soil particles downstream, leaving larger materials behind.

Figure 36. Low-gradient streams are depositional zones for smaller soil particles.

The parent material also determines the actual size of particles in a high- or low-gradient stream segment. The dynamics of streambank erosion, deposition from flood events, and stream channel migration across the valley create a complex horizontal and vertical pattern of soil particle size in a riparian-wetland area.

Low-gradient, meandering streams and rivers often have a floodplain and overflow channels associated with them that serve a critical role in dissipating high-streamflow energies. Vegetation plays a very prominent role in maintaining the integrity of the floodplain and overflow channels during high-flow events. However, soil material also plays a role. Coarse fragments help reduce streambank erosion. Single-grain sand particles will erode more easily in a streambed or bank than the more cohesive clay particles that are bound together into relatively stable aggregates. Silts are intermediate in their erosivity and cohesion.

The landform type and size and quantity of soil particles transported by the stream regulate point bar formation, the vegetation type growing on them, and stream stability. If soil characteristics do not allow for colonization of point bars by deep-rooted riparian-wetland plants, the point bars will not be stable. The filtering of sediments by riparian-wetland plants on point bars helps maintain the buildup of these point bars as the stream meanders across the valley.

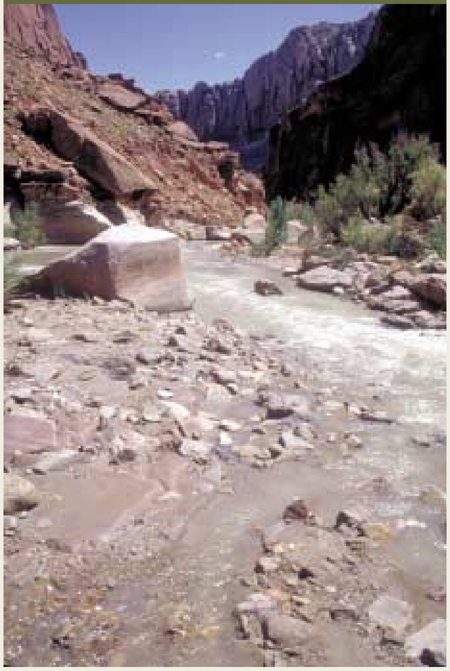
"**Deposition**" is the opposite of erosion. It consists of material being deposited at a site by water, wind, ice, gravity, and other forces. Deposition represents a loss of energy of the transporting medium. As the medium loses energy, it deposits materials that were in suspension or in motion.

Animal or human trails and vehicle traffic can contribute to bank sloughing. The physical damage of binding plant roots, compaction, and soil surface cracking that increases water lubrication of the slip plane and the increased load on the soil result in loss of shear strength and collapse of the banks. Noncohesive, sandy soils are more susceptible to sloughing than cohesive, finer textured soils. Overhanging banks found in some low-gradient, meandering streams are especially susceptible.

Lateral and vertical stability is essential in lotic systems. For example, streams naturally move laterally across broad, low-gradient valleys. However, this is a relatively slow process that maintains the width to depth ratio associated with that stream type. When the lateral movement becomes excessive, the stream becomes unstable with the potential for an increased width to depth ratio, reduced sinuosity, unstable streambanks, increased gradient, and formation of multiple channels (Prichard et al. 1998). The texture of soil material in the streambed and banks can influence the lateral stability of the stream. A meandering stream will often have higher bank erosion rates if the bank material is loose sandy material compared to cohesive silts and clays. Riparian-wetland vegetation and its root masses, which are capable of binding soil materials together, are necessary to stabilize these streambanks. The filtering of sediments by this vegetation helps maintain floodplain and streambank integrity. In addition, soil organic matter resulting from decaying plants helps bind soils together.

Indicators of lateral stability include maintenance of a single-thread channel; stable streambanks, especially on straight segments between meanders; and natural deposition with no change in sinuosity, gradient, or width to depth ratio. When lateral stream movement is excessive, it can have serious impacts on the overall function of a riparian-wetland area, limiting its ability to dissipate energies. Coarse-textured soil and channel bed materials are more susceptible to lateral migration (Figure 37).

Figure 37. Coarse-textured soil and channel bed material are more susceptible to lateral migration.



Vertical stability of the stream or river is essential to maintain access to the floodplain for high flows and to maintain water table levels in the soil. Degradation, or lowering of the channel level, is a natural process. When accelerated, however, it results in drastic changes to stream function. Fine-textured soils are more susceptible to stream downcutting than coarse-textured soils with rock fragments in them. If a headcut occurs in streams with soil characteristics susceptible to downcutting (i.e., fine-textured) (Figure 38), it will proceed upstream until it reaches a knickpoint such as large boulders, bedrock, logs, roots, or a manmade structure.

The texture of soil material in the streambed and banks can influence the vertical and lateral stability of the stream (Figure 39). Stream downcutting often results in oversteepened streambanks, bank failures, and mass wasting, and may be accompanied by stream channel widening and straightening. Eventually the stream may create a new floodplain in the deposited alluvium at a lower elevation. The previous floodplain then becomes a stream terrace and the water storage capacity of the old floodplain is lost (Figure 40).

Dark soil colors from organic matter accumulations, light gray colors from

Figure 38. A headcut occurring in fine-textured soils.

Figure 39. The texture of soil material in the streambed and banks can influence the vertical and lateral stability of the stream. (Insets used with permission from the Montana Department of Environmental Quality.)

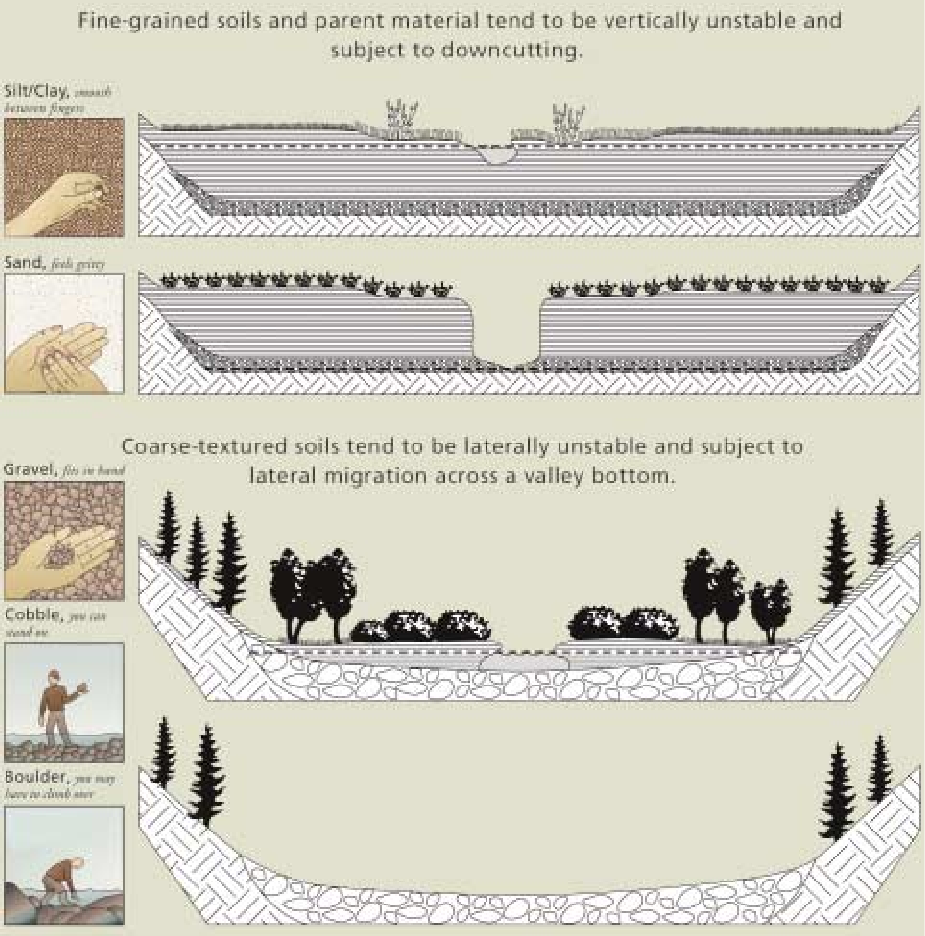
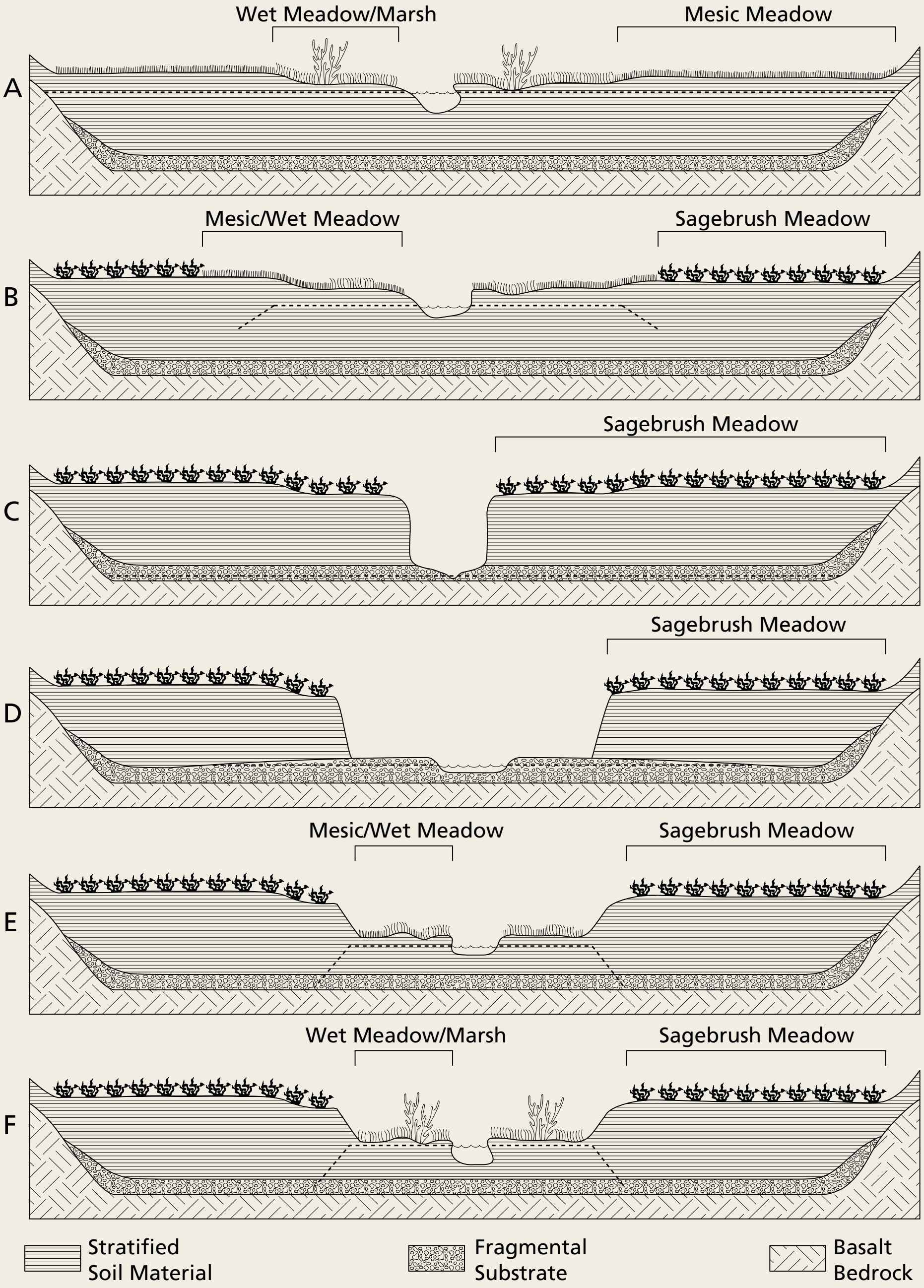


Figure 40. Channel stages for recovery.



iron depletion, and bright orange or yellow colors from iron concentrations can be used to indicate the presence of past riparian-wetland areas that have been drained by downcutting. However, care must be taken not to interpret these colors as the result of relict riparian-wetland features from a different climate regime.

The balance between water and sediment being supplied by the watershed may shift, resulting in excessive erosion or deposition. This can lead single-channel streams to become braided if excessive deposition occurs. Glacial outwash streams in the Northwest and alluvial fans in the Southwest are often multichanneled and frequently shift. Some very low-gradient streams in the Southeast with stable, well-vegetated, fine-textured banks are also multichanneled. However, most other stream channels are typically single-threaded unless excessive deposition occurs (Prichard et al. 1998). Excessive erosion and the associated lateral instability or downcutting could be the result of excessive water or sediment being supplied by the watershed as described previously.

2. Lentic ecosystems

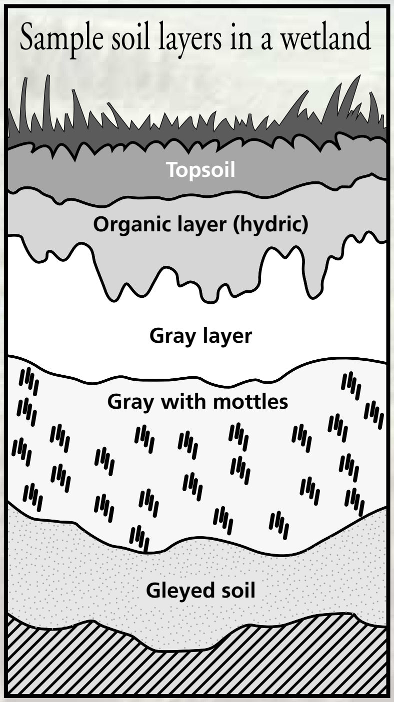
"He who knows what sweets and virtues are in the ground, the waters, the plants, the heavens, and how to come at these enchantments, is the rich and royal man."
Ralph Waldo Emerson
1844

Lentic systems typically form fine-textured soils due to their low energy and the associated deposition of fine-textured sediments. The erosive forces of lentic riparian-wetland ecosystems can be very different from those of lotic systems. The energy in lentic systems is primarily from overland flow, wave action, and wind action (Prichard et al. 1994). Large lakes typically have considerable wind and wave action. This results in the formation of sandy beaches along the shorelines, especially on the side receiving the full force of prevailing winds across open water. An excellent example is the huge sand dunes formed on the eastern shores of Lake Michigan as a result of the predominant westerly winds blowing across the lake.

Islands and the shorelines of lakes need to be able to dissipate wind and wave event energies to achieve proper functioning condition. Most require riparian-wetland vegetation to accomplish this, but rocks and woody material can also dissipate this energy (Figure 41).

Figure 41. Lake entrance to swamp in La Ceiba, Honduras. Photo by Lisa Clark.

Hydric soils in a lentic system need to be saturated, flooded, or ponded for long enough periods to develop anaerobic conditions in the upper part. Field indicators of hydric soils include reduction or depletion of the iron and manganese oxides (light gray colors) in the soil matrix and accumulation of iron and manganese oxides (reddish/orange colors) in localized concentrations. See section III, Riparian-Wetlands, for a detailed description. Hydric soils may be difficult to identify in the field if they are derived from grayish or reddish parent materials, have a high pH or low organic matter content, are dark colored Mollisols or Vertisols, have relict redox features, or have been highly disturbed (USDA 1998).


Sample soil layers in a wetland

Lentic systems naturally fill in with sediment supplied by the watershed over geologic time (Prichard et al. 1999). However, this is a very slow process and these systems often maintain themselves over a very long period of time. If the water and sediment being supplied by the watershed are out of balance, excessive erosion or deposition may occur. Natural surface and subsurface flow patterns can be altered by disturbances that can increase or decrease waterflow to the lentic riparian-wetland area. This could result in excess erosion or the loss of water needed to maintain the system, depending upon whether flow is increased or decreased. Conversely, an increase in sediment to the lentic system would result in an increase in deposition and potential loss of riparian-wetland function.

Lentic riparian-wetland areas can be sinks for chemicals from uplands or chemicals may be deposited directly into them. The accumulation of these chemicals may greatly affect plant productivity and composition. Some chemicals, such as phosphates and nitrates, may actually enhance soil fertility and plant production. However, they may also cause algae blooms, reduce dissolved oxygen in open water systems, and increase eutrophication (Prichard et al. 1999). Some toxic chemicals may seriously harm vegetation and result in a impoverished and stunted plant community. Salts that accumulate in lentic systems can also impact plant communities. Soil texture, mineralogy, and associated buffering capacity will help determine the degree of these impacts.

Alteration of the soil ponding, flooding, or saturation characteristics may result in the loss of ability to maintain hydric soils in a lentic system. This could result in a loss of water table and riparian-wetland plants.

Bedrock, permafrost, or water-restricting soil types such as clay or hardpans often have impermeable layers that support the water table for lentic riparian-wetland ecosystems. Clay minerals, especially expanding clay like montmorillonite or bentonite, are often very efficient at restricting water percolation. Hardpans that do not dissolve in water can also perform this function. Disturbance can alter a restrictive layer so that it no longer limits water movement with a resultant loss of water table and riparian-wetland function. Sometimes, this can be corrected by the application of bentonite, synthetic fabrics, or chemicals to reseal the restrictive layer or form a new restrictive layer.

3. Ties to proper functioning condition assessments

Soils, interacting with geology, water, and vegetation, play a major role in determining the functioning condition of riparian-wetland areas. Erosion and deposition need to be in balance to ensure the stability of soils in a riparian-wetland area. High stream, wind, and wave energy need to be dissipated by soils and associated factors to reduce erosion, improve water quality, and perform the other functions of a riparian-wetland area (Prichard et al. 1993). Sediment needs to be in balance with the water supply to prevent excessive deposition or erosion.

Gathering and Interpreting Soil Information for Riparian-Wetland Management

"The nation that destroys its soil, destroys itself."

Franklin D. Roosevelt

Soils, and their parent materials, are the literal foundation of the watershed and all ecosystems. Watershed and ecosystem processes, as well as cropland, forest, and rangeland products from water to timber to wildlife, depend fundamentally on soils and the many crucial functions they provide. Soil quality is the suitability of a specific kind of soil to function within its surroundings. Soil supports plant and animal productivity, maintains or enhances water and air quality, and supports human health and habitation. Healthy soils enable a forest, rangeland, or riparian-wetland area to maintain its resilience and inherent productivity through soil development and vegetative growth. Soil information plays an important role in assessing the overall health of riparian-wetland areas.

Human health is a composite picture of the condition of the body's various parts and functions. Human health is assessed by looking at many factors and forming an overall sense of how the body is working. In the same way, soil quality is a composite picture of the state of a soil's many physical, chemical, and biological properties and of the processes that interact to determine this quality (Figure 42). Furthermore, as human health varies from person to person, soil health varies among soil types.

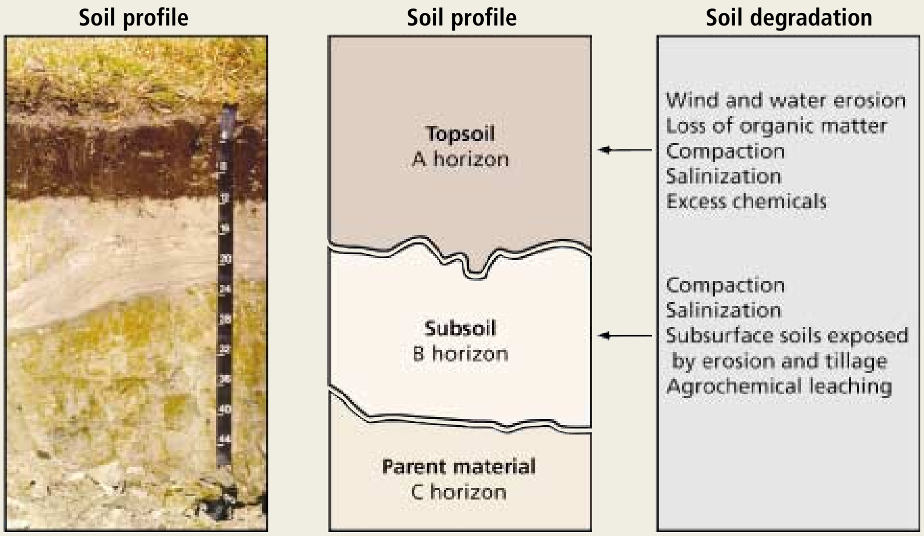
Following are some suggested guidelines for assessing soil quality. These guidelines are useful for people with extensive knowledge of soils, as well as for those who are new to soil science.

A. Soil information

To observe changes in soil quality over time and area, a set of baseline data should be established. This set of observations serves as information to determine what is happening today and is also the reference point against which to compare all future observations.

"Soon shall the winter's foil be here;
Soon shall these icy ligatures unbind
and melt - A little while,
And air, soil, wave, suffused shall be
in softness, bloom and growth -
a thousand forms shall rise
From these dead clods and chills as
from low burial graves.
Thine eyes, ears—all thy best
attributes—all that takes
cognizance of natural beauty,
Shall wake and fill. Thou shalt
perceive the simple shows, the
delicate miracles of earth,
Dandelions, clover, the emerald
grass, the early scents and flowers,
The arbutus under foot, the willow's
yellow-green, the blossoming
plum and cherry;
With these the robin, lark and
thrush, singing their songs -
the flitting bluebird;
For such the scenes the annual play
brings on."
Walt Whitman

Figure 42. A composite of a soil's physical, chemical, and biological properties. Photo by Jim Turenne.



1. Natural history

Recording the natural history (e.g., how the area formed, the area's geology, soil formation processes, climatic patterns, major storm events, etc.) is important information for understanding the inherent or natural quality of a soil (Figure 43).

Figure 43. Hood Canal in northwest Washington State.

2. Land use history

The characteristics of a natural soil can be changed by human activities (Figure 44). A decline in inherent soil quality can occur because of erosion,

Figure 44. Forest road construction in the 1970s in Olympic National Forest.

loss of organic matter, compaction, desertification, and other degradative processes. Information collected should include:

- site identification (including legal and ecological descriptions),
- site history (including land acquisition, land management in the early years, and major changes in management practices)
- current land management practices.

3. Soil survey information and relief maps

Soil survey reports include the soil survey maps and the names and descriptions of the soils in a particular area. These soil survey reports are published by the National Cooperative Soil Survey and are available to everyone from their local county extension office. These reports generally provide information on geomorphic processes, soil parent material, soil substrata, landforms, soil temperature and moisture regimes, and other soil-related factors of a particular landscape.

Relief maps display landforms, such as ridges and gullies, and drainage direction, and they provide the background for overlaying other soil and landform features. This broad visual assessment is helpful in locating and mapping wet soils and riparian-wetland vegetation boundaries. Particular attention should be given to changes in microtopography over short distances, as small changes in elevation may result in changes to soil-water relationships. Relief maps also allow strategic location of soil sampling points.

4. Soil sampling

Soil sampling information is valuable in determining the potential extent of a riparian-wetland area. Riparian-wetland soil features can be used to deduce or infer information about the past and present hydrology of a site (Figure 45). For example, if vegetation currently occupying a site does not reflect wet soil conditions or redoximorphic features, one could incorrectly assume the site does not have the potential to be a riparian-wetland site. However, riparian-wetland soil features must be understood in terms of historical changes in climate and flooding.

Figure 45. Riparian-wetland soil features can provide clues about the past and present hydrology of a site.

Pits should be located across the delineated area to determine if the soil has evidence of redoximorphic features or gleying. A few well-placed soil pits can provide the depth and extent of redoximorphic features (mottling). Riparian-wetland soils may develop these distinct features in as few as 3 to 5 years of persistent water table elevation. Once soils develop redoximorphic features or a gleyed matrix from high water tables, these qualities persist for many decades, even if a lowering of the water table has occurred that dries the site (USDA Forest Service 1992).

Wet soil determinations are normally accomplished using the location's vegetation composition, hydrology, underlying geology, and soils (COE 1987). Determination of the exact extent of riparian-wetland areas can be challenging enough when all three elements of the ecosystem are present and in relatively undisturbed condition. However, when an area has been altered and elements normally used to recognize wetland limits are missing (e.g., vegetation) different techniques need to be used to make the same determination. Soils of a wetland area are most often the last remnant of its original character, as they do not readily change or lose their wetland characteristics. Indicators

Figure 46. Wetland soil indicator of iron concentration.

of saturated soils consist of durable concentrations of elements such as iron, which are easily visible (Figure 46). These characteristics then become the key indicators of historical and current ecological conditions, fixed in time. The durability of these indicators, in conjunction with their stratigraphy, is evident in remnant soils dating to preglacial times of thousands of years before the present (Leopold et al. 1964). Many different soil characteristics can be used to determine such things as the outlines of waterlogged or saturated areas, or even to reconstruct past climates. Soils tend to preserve the physical and chemical integrity of most things that become incorporated or buried in the profile.

5. Soil physical properties

a. Soil erosion

Erosion of riparian-wetland soils is most commonly accomplished through channel bank erosion. Severely degraded riparian-wetland areas may have little or no vegetation to buffer the highly erosive soils from channel or overland flows and high erosion rates may result.

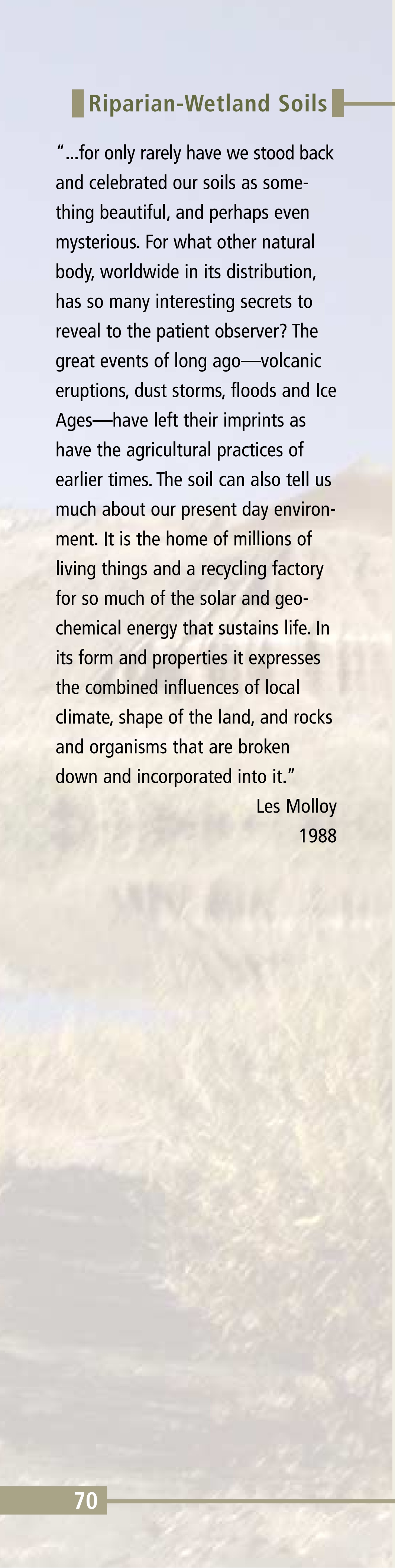
For each soil type, a general qualitative soil erosion statement can be made. For example, compacted soils that have a weakly fractured surface, are low in coarse fragment content, are high in fine-textured subsoils, and are comprised of silt or sand texture will have increased erosion rates. In contrast, compacted soils that have very friable and strongly structured surfaces are high in coarse fragment content, are high in coarse-textured subsoils, and are comprised of fine textures such as clay or clay loam will have low erosion rates.

b. Soil compaction

Soils differ in their inherent ability to resist compaction. Important factors to evaluate include soil texture, soil structure, organic matter content, and rock fragment content. The susceptibility to compaction is most common in medium-textured soils with moisture contents between 12 and 28 percent (by weight) and compacted forces estimated to be greater than 7 pounds per square inch (Harris 1971). Prolonged trampling by humans or animals can compress the soil surface to the same degree as mechanical equipment.

Compaction of soil structure reduces water infiltration into soil and percolation through the soil. If the granular structure in the soil's surface changes to a dispersed crust or platy structure, this modification is called puddling. Puddling inhibits water from entering the soil and reduces seedling emergence.

In addition to soil sampling, aerial photos and intensive transects are tools used for properly delineating riparian-wetland areas when gathering soil information. A landscape view, in conjunction with vegetation, hydrology, and soil information, is necessary to determine if a riparian-wetland area is shrinking, widening, or has achieved its potential extent.



> "...for only rarely have we stood back and celebrated our soils as something beautiful, and perhaps even mysterious. For what other natural body, worldwide in its distribution, has so many interesting secrets to reveal to the patient observer? The great events of long ago—volcanic eruptions, dust storms, floods and Ice Ages—have left their imprints as have the agricultural practices of earlier times. The soil can also tell us much about our present day environment. It is the home of millions of living things and a recycling factory for so much of the solar and geochemical energy that sustains life. In its form and properties it expresses the combined influences of local climate, shape of the land, and rocks and organisms that are broken down and incorporated into it."
>
> Les Molloy
> 1988

If water is unable to enter the soil, it will be lost to runoff and evaporation. Compacted layers restrict water movement and keep water near the surface and away from plant roots. The presence of compacted layers near the surface, plus capillary action and evaporation, increases the chance of salt accumulation near the surface where it is a concern. Infiltration is best measured with a double ring infiltrometer.

Measuring soil strength by using a penetrometer gives only a relative indication of soil compaction. In order to gather meaningful data with the penetrometer, it is necessary to have a control area for a reference, or undisturbed, site. Penetrometer readings will vary depending on soil moisture content, so care must be taken when interpreting data. To compare two areas, the moisture content must be the same. Readings from the penetrometer are expressed in tons per square foot. Classes used are slight, moderate, and severe, with 0 to 1.5 being slight; 1.6 to 3.0 being moderate; and 3.1 to 5.0 being severe.

Using the penetrometer data and comparing existing and predisturbed or expected natural bulk density will indicate the extent to which the soil property has been affected. Generally, an increase in soil bulk density of 15 percent or more is considered detrimental. Technically, penetrometers measure soil strength not bulk density. Bulk density can be calculated from known volumes of soil and their dry weight in grams/cc.

Other physical indicators of soil quality include:

- Soil structure - retention and transportation of water and nutrients and habitat quality for microorganisms
- Infiltration and bulk density - water movement, porosity, and workability
- Water-holding capacity - water storage and availability

Recognizing the interactions among key ecosystem features—soils, hydrology, and vegetation and wildlife—is essential to the management and restoration of riparian-wetland soils. While hydrologic, climatic, and geomorphic forces strongly determine the function of riparian-wetland zones, humans also have an important influence on the structure and function of riparian vegetation and wildlife. By taking an adaptive management approach to implementing riparian-wetland soil restoration and conservation, managers can prevent further failure of these systems and the loss of additional terrestrial and aquatic species.

B. Case studies

The soil information that is gathered and assessed becomes an important component of decisions regarding management of riparian-wetland areas. The following case studies demonstrate how the soils information can be used to develop management recommendations.

1. Case study #1

In October 2001, a PFC assessment of this area was done to provide technical management information to land managers on vegetation, grazing, and the transportation system relative to watersheds and riparian values.

a. PFC assessment

The site had a history of use, which is reflected in the assessment findings. Old wagon routes, for example, followed stream corridors since they offered water and forage for horses and other livestock, housed fish and game for food supplies, and provided wood for fire and building materials.

Figure 47. Road following old, established wagon route.

Early roads followed old established routes along stream bottoms, where construction was easier and less expensive (Figure 47). Drainage structures and maintenance practices were designed to move water away from the road to keep the travelway's surface and subsurface dry. Infrequent drainage structures, augmented with extensive ditch networks, were preferred over numerous small structures to save effort and expense. Maintenance practices commonly routed water and sediments from the road surface and ditches directly into stream courses for rapid removal. This benefited the transportation system, but commonly caused unintentional harm to other resources by fostering extensive road surface erosion, sediment transport and deposition, and erosion of riparian areas.

Figure 48. Inadequate surface drainage is a common problem across the area.

Over time, riparian areas in poor condition became a common sight and people grew to accept these conditions as normal. Land managers, whose livelihoods were most directly affected by riparian losses, recognized problems, spurring on-the-ground improvements. Many well-designed roads are evidence of this. Unfortunately, there are also problems associated with the roads that can be observed today (Figure 48).

As noted in the PFC assessment, most streams within the management area have downcut, widened, and are in some level of improved health. Some

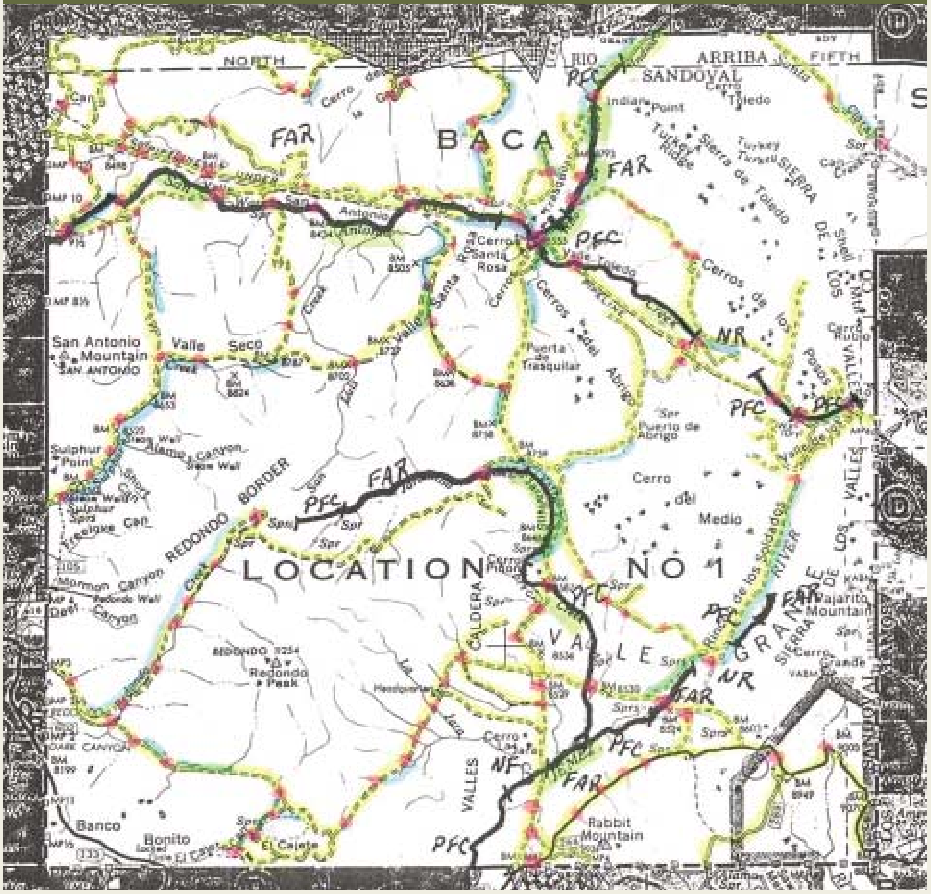
riparian segments have even completely recovered. However, the watershed condition assessment report from the summer of 2000 and the watershed concerns report from the summer of 2001 identified several basic categories of road problems that were slowing or reversing recovery of these riparian systems. Field reconnaissance revealed several specific road problems and management opportunities (Table 10).

Table 10. Road management opportunities.

Road Problems	Resulting Damage
Inadequate surface drainage	• inadequate filtering of surface drainage between roads and riparian areas • breached, damaged, and bypassed drainage structures • roads worn away to below grade, concentration of surface flow, direct water and sediment connection to riparian areas • loss of road surface material • standing water saturation of surface and subsurface, reduction of bearing strength, and deterioration of road surface • formation of berms
Ditch or lead-out ditch problems	• erosion, sedimentation, and deposition • undermining of fill and back slopes • drop inlets covered with sediments
Channel impacts and increased drainage density	• erosion, sedimentation, and deposition • increased drainage density and extension of the stream network • multiple crossings of the same stream
Road and stream crossing problems	• wood bridges rotting and falling apart • rusting and decomposing culverts • enlarged inlet basin • increased hydraulic energy • inadequate capacity • culvert inlets plugging
Channel encroachment from road alignment in channel and floodplain	• stream straightening and confinement • loss of road prism • channel erosion • isolation of floodplain

The effects of increased sediment delivery from these roads depend on numerous factors. Most sediment is from surface erosion (sheets, rills, and gullies) delivered during normal annual rainfall events and is relatively chronic. Also noted, but to a lesser degree, were road-related landslides and stream-crossing structure failures. These types of sediment sources are episodic and often result from significant rainfall events. High risk factors for the roads include surface erosion, road fill failure, and the proximity of road segments to streams (Figure 49).

Figure 49. Yellow highlights major roads within the area, red indicates road stream crossings, and blue identifies areas of channel encroachment from road alignment.



b. Recommendations

Within the 89,000-acre area, there are approximately 1,000 miles of roads, of which 100 miles have been surveyed. The watershed condition assessment validated the need for a full road assessment within the management site. A comprehensive road plan would establish what roads are needed. The road management plan on the adjoining national forest is a good example to follow and would provide long-term management guidelines for open roads and recommendations for temporary and permanent road closures. Defining a base road network should be the first step in managing roads within the area (Figure 50).

Definitions:

- "**Surface erosion**" is the removal of soil surface layers by wind, water, and ice.
- "**Sheet erosion**" is the removal by wind, water, and ice from sloping land in thin soil layers.
- "**Rilling**" is soil removal by water from very small (inches) but well -defined visible channels.
- "**Gullying**," is an intermittent channel, larger than rills and too deep to be crossed in a wheeled vehicle.

"We know more about the movement of celestial bodies than about the soil underfoot."
Leonardo da Vinci

Road improvement recommendations for open roads are listed in Table 11.

A road management plan would identify other travelway improvements, as well as presenting standards for permanent and temporary closures. The plan and subsequent projects would increase short-term road management operating costs.

Figure 50. Without maintenance and proper management, roads will continue to degrade and supply sediment to adjacent riparian areas.

Table 11. Road management recommendations for open roads.

Road Problems	Improvement Recommendations
Inadequate surface drainage	• Remove water from the travelway surface. Surface sloping (raising roads above grade, turnpiking, outsloping, and crowning travelways) and cross-drainage installation are recommended. • Surface roads with crushed rock mulch. • Limit use during wet or thawing periods. • Maintain and repair culverts and cross-drainage structures. • Grade the road surface when it no longer drains properly. • Remove berms that channel water. • Use minimum road width.
Ditch or lead-out ditch problems	• Upgrade culverts and install cross drains and lead-out ditches. • Replace failing drainage structures.
Channel impacts and increased drainage density	• Avoid and remove multiple crossings of the same stream.
Road and stream crossing problems	• Design culverts, bridges, and low-water crossings to withstand high flows. • Armor fills below high water levels. • Design culverts to limit water velocity.
Channel encroachment from road alignment in channel and floodplain	• Avoid new roads parallel to streams. • Relocate or realign roads away from streams. • Minimize road length in these locations and limit size of fills.

The benefits of a road management plan and subsequent projects would include:

- A reduction in sediment entering waters where current road conditions pose a high risk of sediment delivery.
- The potential to reduce sediment entering streams, allow for a higher level of road maintenance, and reduce long-term road management costs through the more efficient allocation of limited resources for road repairs and maintenance.
- The opportunity to develop a road management model for public land with local, regional, and national implications and to provide continuing education for landowners and operators specific to road construction and maintenance practices.
- A systematic means for remedying road problems (Figure 51).

Additional road information can be found in Appendix D.

Figure 51. A hypothetical example from a road management plan.

INADEQUATE SURFACE DRAINAGE

EXAMPLE

Problem

Road X, milepost XX - located in the XXX section of the project area. Water has been running directly down the 10-percent-grade road. Previous maintenance efforts to smooth out ruts have left the road slightly below grade, encouraging surface water runoff to concentrate into erosion channels and deliver sediments to the adjacent riparian area. The road, as originally located, will continue to suffer needless erosion and rutting. Any future maintenance efforts to smooth the rutted road surface will only tend to lower the road further below grade, causing increased erosion problems, new ruts, and increased sediment input to the adjacent riparian area.

Solution

The solution proposed for this situation is to relocate the existing downslope road so that it contours around the hillside at a gentle 2 to 3 percent grade.

Results

The relocated road has adequate grade changes to divert water off of the surface. The 4 to 6 percent outslope of the new road prevents water from accumulating. There should no longer be a need for annual maintenance to smooth out the irregular ruts that develop during rain events. The original road would heal more quickly if rehabilitated and converted back to productive pasture. The relocated road was constructed with a medium-sized loader scraper in about 3 hours at a cost of $200.

> "As soils are depleted, human health, vitality, and intelligence go with them."
>
> Louis Bromfield

> "Like winds and sunsets, wild things were taken for granted until progress began to do away with them. Now we face the question whether a still higher "standard of living" is worth its cost in things natural, wild, and free."
>
> Aldo Leopold

2. Case study #2

This area was being assessed for proposed restoration work within the local creek. The purpose of the assessment was to determine the historic, current, and potential health of this stream; develop natural alternative solutions to accelerate recovery of this valuable urban creek to a near historic condition; develop a draft project design; and refine the final restoration design.

Restoration of the creek was being guided by collaborative efforts among local action groups. Due to the size of the task, they were initially focusing on specific segments of the creek. The experience and knowledge gained would then be applied to the remaining segments of the creek.

a. PFC assessment

Many materials were reviewed prior to beginning fieldwork, including maps, aerial photographs, and other background information such as:

- documentation of land uses
- erosion and sediment source inventory
- preliminary hydrologic analysis
- analysis of riparian conditions and stream habitat
- watershed analysis and action plan
- project restoration philosophy and mechanisms

As described in the watershed analysis and action plan, human influences from mining activities, railroad and road construction, urbanization, stream realignment, and other activities have all played a role in defining this stream's current health status.

Exposed soils in eroded streambanks provided evidence that the creek was once a perennial system. Today, this intermittent stream flows only at certain times of the year. Landform and channel features also provided clues that the creek had channel and floodplain characteristics (rocks, overflow channels, and large woody material) adequate to dissipate stream energy associated with high waterflows. Remnants of riparian-wetland vegetation still exist and suggest large, diverse communities of plant species with the capability of withstanding high streamflow events.

Land use activities in the watershed changed these conditions and altered the amount of water and sediment being supplied to the system. As a result, riparian-wetland vegetation disappeared. Exposed banks eroded and channel beds aggraded. Today, the sinuosity, width to depth ratio, and gradient are out of balance with the landscape setting and out of balance with water and sediment being supplied by the watershed. The creek is now functioning at-risk and with a downward health trend.

b. Recommendations

- Direct flow around the local motel and away from the steep eroding hillside, thereby reducing erosion and improving water quality. The recommended strategy would include installation of three rock vanes.
- Monitor bedload transport and, if needed, construct and maintain the proposed debris basin. The proposed idea of keeping the large bedload (results of historic dredging) out of the new channel is warranted.
- Abandon the currently incised channel and allow it to function as a seasonal floodwater retention area. This area would filter sediment, capture bedload, and increase water storage in the floodplain. The recommended strategy would include installation of a high-flow bifurcation so high floodflows can access the abandoned channel, thereby reducing flood effects to the nearby school.
- Provide access to a floodplain and overflow channels to dissipate stream energy associated with high waterflow, thereby reducing erosion, improving water quality, and increasing water storage in the floodplain. These conditions would provide an environment for maintenance and recruitment of riparian vegetation. This recommended strategy would include excavating a new 300-foot-long section of streambed and realigning the creek to a healthy, well-established 600-foot-long riparian corridor.
- The old-growth oak riparian segment and undisturbed beaver pond reach should be used as functioning templates for stream restoration and recovery.

Putting the stream back into its old channel, with access to a broader floodplain and overflow channels, will accelerate stream recovery. Minimizing disturbance, encouraging continued recovery of the functioning portions of the creek, and accelerating restoration by mimicking natural recovery of existing healthy physical processes should all be considered.

3. Case study #3

Local land managers were seeking a description of conditions, including natural and management-related erosion, as well as potential grazing management alternatives for this area to resolve disagreements over land conditions and proposed management actions, especially for the land contained in the wilderness area.

a. PFC assessment

The wilderness area contains steep, rocky mountains flanked with alpine meadows that provide views of rolling mountainsides and vast lakebed valleys sprinkled with farms and cattle ranches. Every landform within this area tells a story about the processes that formed it and continue to shape it today.

The mountain area, for example, was created by a double fault where basically the mountains rose, the valley dropped, and erosion helped shape present landscape features. In addition, hillsides with exposed soils revealed thick layers of loose volcanic ash deposits. Careful and repeated measurements indicated the rate of uplift in active regions, such as in the wilderness area where natural processes of building, eroding, and reshaping continue to mold this area's surface into its multitudinous forms, is about 15 to 30 feet per 1,000 years.

Other landscape changes, which are on a much shorter time scale, are easier to detect, such as floodwaters altering the river's channel or a landslide tearing away a hillside. Intense rainfall, rapid snowmelt, water level changes, and earthquakes have induced major landslides that have significantly modified the form of slopes and stream channels within this area. Such events are relatively infrequent.

Other gradual changes occur over a period of a few years, such as streams and rivers continually altering their course across the land. The work being done by flowing water mainly occurs during frequent events that recur on an average of every 1.5 years.

Figure 52. Surface erosion on upper reaches of the watershed.

Surface erosion, in the form of sheets, rills, and gullies, occurs naturally in the wilderness area and was likely triggered by the loss of protective vegetative cover from wildland fires (Figure 52). Grazing practices, at the turn of the 20th century, also contributed to the loss of stabilizing plants, which resulted in an increase in size and frequency of these surface erosion areas. However, nothing indicated that current grazing management activities were accelerating surface erosion on this particular hillside.

Surface erosion is still active, especially in the headwaters and steeper portions of the eroding gully channels. Side gully channels, with less severe slope angles, have upland pioneer species stabilizing the area. Aerial photographs also showed large areas of vegetation growing at the base of these slope features. Basically, these sites are healing from the top down and from the bottom up, with a lot of bare ground in between.

In the gullied stream system above the falls, exposed streambanks revealed evidence of a natural mass-wasting event in the form of a debris flow that extends throughout the channel. This landslide was likely a result of unusually heavy precipitation, thawing of snow or frozen soil, or earthquakes. As soon as the debris flow occurred, channel downcutting from the falls up began. The process of filling and downcutting was probably repeated many times and led to the formation of the current terraces. Paired terraces of equal height on both sides of the stream channel indicate an episode of downcutting that began on a level floodplain.

The meadow adjacent to the stream segments is composed of fine sediments washed down into the basin floor from neighboring hillsides (alluvium). Since no remnants of landslide rock were found in the meadow, it is thought that the sediment formed in separate events.

Evidence indicates that the debris flow was a natural event and not initiated by human activity. A primary clue was that many old trees were buried in the landslide debris and large-diameter pines were growing on top of the landslide deposits. This situation indicates that the landslide is several hundred years old.

In contrast, meadow headcuts are more recent (last few decades) and are linked to poor grazing management practices and the loss of deep-rooting, riparian-wetland plants critical to holding these fine-textured meadow soils together.

Source areas for the debris flow are still active, but aerial photograph interpretation showed riparian vegetation growing at the base of the landslides. Basically, the landslide feature is healing from the bottom up. The gullied stream system is still adjusting (cutting and filling), but at a very slow rate. For example, there was no evidence of recent scouring and deposition, but the stream is slow in developing a new floodplain. It is, however, dissipating energy through its stepped-down shape and boulders and wood imbedded in the channel.

The meadow headcuts are no longer active, but are susceptible to continued downcutting because of the inadequate amount of riparian-wetland vegetation necessary to hold the system together in a high-flow event.

Definitions:

- A "**landslide**" or "**mass wasting**" is the falling or spreading of fairly large masses and is usually a rapid event.
- "**Debris flows**" are a highly mobile slurry of soil, rock, vegetation, and water that can travel miles from their point of initiation.

"Soil erosion, if not controlled, has demonstrated its ability to undermine nations and civilizations regardless of what may have been the social or economic conditions that set it going or stimulated its destructiveness."

Walter Clay Lowdermilk
1943

b. Recommendations

Areas with surface erosion are very slow to recover. However, these areas can be managed to encourage a positive health trend through continued vegetative establishment and growth.

Implementation of a grazing management strategy will be key for encouraging continued growth of riparian vegetation. Timing, frequency, and duration of grazing are critical for increasing diversity and abundance of stabilizing vegetation.

Summary

Riparian-wetland areas represent the transitions of land to water. These areas are generally wetter than surrounding uplands and have characteristics reflecting permanent surface or subsurface water influence. Riparian-wetland areas are grouped into two major categories: 1) lentic areas, which include standing water habitats such as lakes, ponds, seeps, bogs, and meadows, and 2) lotic areas, which include running water habitats such as rivers, streams, and springs. The presence of water produces persistent features that help characterize riparian-wetland soils.

In contrast to upland soils, riparian-wetland soils have been repeatedly eroded and reworked with new parent material by glaciers, flowing water, wind, or volcanic activity. Once deposited, soils form in place and develop stratified layers. Soil depth represents many different ages of deposits.

Landforming processes and parent material directly influence the properties and types of riparian-wetland soil complexes that occur in the landscape. The inherent properties of bedrock and geologic parent material relate directly to soils and landforms in the riparian-wetland complexes. Soil particle size distribution and other soil properties result directly from the weathering and transport of the parent materials. The older the soil, the greater its tendency to reflect the nature of the climate and natural vegetation rather than that of the original rock from which it was formed.

Riparian-wetland soils are an important component of the hydrologic cycle because they intercept and retain water on the land and are considered the largest freshwater reservoirs on Earth. Riparian-wetland area soils in functioning floodplains, for example, retard discharge of water from the watershed by acting as a sponge. These soils capture precipitation, floodflows, and surface and subsurface runoff from adjacent lands and slowly release these stored waters over a longer time period.

Different vegetation types provide a clue to the associated climate and soil. Since vegetation responds to plant-available water, there can be very wet vegetation communities in arid climates, as long as soil water is present for a sufficient length of time. For the most part, however, local climate and the soils that form as a result of parent material, moisture, and temperature can be reflected in the vegetation present.

Soil mineralogy can impact erosion. Expansive clays, for example, may be more prone to erosion as they shrink and swell, resulting in soil aggregate breakdown. Dispersive clays have a preponderance of sodium in their pore water and lack the cohesive nature of other clays, making them highly erodible. Some minerals (e.g., silica and calcium) can act as cementing agents in soil-forming hardpans that are very resistant to erosion.

Deposition is the opposite of erosion. It consists of material being deposited at a site by water, wind, ice, gravity, and other forces. Deposition represents a loss of energy of the transporting medium. As the medium loses energy, it deposits materials that were in suspension or motion.

Soils interacting with geology, water, and vegetation play a major role in determining the functioning condition of riparian-wetland areas. Erosion and deposition need to be in balance to ensure the stability of soils in a riparian-wetland area. High stream, wind, and wave energy need to be dissipated by the soil and associated factors to reduce erosion, improve water quality, and perform the other functions of a riparian-wetland area. Sediment needs to be in balance with the water supply to prevent excessive deposition.

A land manager's challenge is to understand riparian-wetland soil qualities and anticipate how they will react to natural and management-induced stresses. These stresses often result in predictable changes, but the complexity of interactions among geology, soil, hydrology, and vegetation are best foreseen by an experienced interdisciplinary team.

Soils in riparian-wetlands are unique and valuable. In the 1500s, Leonardo Da Vinci remarked, "We know more about the movement of celestial bodies than about the soils underfoot." Hopefully, this reference has provided valuable riparian-wetland soil information to increase an interdisciplinary team's field observational skills, enhance appreciation, and stimulate interest in learning more about this valuable resource.

Appendix A

Proper Functioning Condition Assessments: Lotic Standard Checklist

Lotic Standard Checklist

Name of Riparian-Wetland Area: ______________________________
Date: ______________ Segment/Reach ID: ______________________
Miles: ______________ Acres: ______________________________
ID Team Observers: ______________________________

Yes	**No**	**N/A**	**HYDROLOGY**
			1) Floodplain above bankfull is inundated in "relatively frequent" events
			2) Where beaver dams are present they are active and stable
		▨	3) Sinuosity, width/depth ratio, and gradient are in balance with the landscape setting (i.e., landform, geology, and bioclimatic region)
			4) Riparian–wetland area is widening or has achieved potential extent
		▨	5) Upland watershed is not contributing to riparian-wetland degradation
Yes	**No**	**N/A**	**VEGETATION**
			6) There is diverse age-class distribution of riparian-wetland vegetation (recruitment for maintenance/recovery)
			7) There is diverse composition of riparian-wetland vegetation (for maintenance/recovery)
			8) Species present indicate maintenance of riparian-wetland soil moisture characteristics
			9) Streambank vegetation is comprised of those plants or plant communities that have root masses capable of withstanding high-streamflow events
			10) Riparian–wetland plants exhibit high vigor
			11) Adequate riparian-wetland vegetative cover is present to protect banks and dissipate energy during high flows
			12) Plant communities are an adequate source of coarse and/or large woody material (for maintenance/recovery)
Yes	**No**	**N/A**	**EROSION/DEPOSITION**
		▨	13) Floodplain and channel characteristics (i.e., rocks, overflow channels, coarse and/or large woody material) adequate to dissipate energy
			14) Point bars are revegetating with riparian-wetland vegetation
		▨	15) Lateral stream movement is associated with natural sinuosity
		▨	16) System is vertically stable
		▨	17) Stream is in balance with the water and sediment being supplied by the watershed (i.e., no excessive erosion or deposition)

Remarks

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Summary Determination

Functional Rating:

Proper Functioning Condition ____
Functional—At Risk ____
Nonfunctional ____
Unknown ____

Trend for Functional—At Risk:

Upward ____
Downward ____
Not Apparent ____

Are factors contributing to unacceptable conditions outside the control of the manager?

Yes ____
No ____

If yes, what are those factors?

____ Flow regulations
____ Channelization
____ Augmented flows
____ Mining activities
____ Road encroachment
____ Other (specify) ______________________________
____ Upstream channel condition
____ Oil field water discharge

Appendix B

Proper Functioning Condition Assessments: Lentic Standard Checklist

Lentic Standard Checklist

Name of Riparian-Wetland Area: ____________________

Date: __________ Area/Segment: ____________________ Acres: __________

ID Team Observers: ____________________

Yes	No	N/A	HYDROLOGY
		■	1) Riparian-wetland area is saturated at or near the surface or inundated in "relatively frequent" events
			2) Fluctuation of water levels is not excessive
			3) Riparian-wetland area is enlarging or has achieved potential extent
		■	4) Upland watershed is not contributing to riparian-wetland degradation
			5) Water quality is sufficient to support riparian-wetland plants
		■	6) Natural surface or subsurface flow patterns are not altered by disturbance (i.e., hoof action, dams, dikes, trails, roads, rills, gullies, drilling activities)
			7) Structure accommodates safe passage of flows (e.g., no headcut affecting dam or spillway)
Yes	**No**	**N/A**	**VEGETATION**
			8) There is diverse age-class distribution of riparian-wetland vegetation (recruitment for maintenance/recovery)
			9) There is diverse composition of riparian-wetland vegetation (for maintenance/recovery)
			10) Species present indicate maintenance of riparian-wetland soil moisture characteristics
			11) Vegetation is comprised of those plants or plant communities that have root masses capable of withstanding wind events, wave flow events, or overland flows (e.g., storm events, snowmelt)
			12) Riparian-wetland plants exhibit high vigor
			13) Adequate riparian-wetland vegetative cover is present to protect shorelines/soil surface and dissipate energy during high wind and wave events or overland flows
			14) Frost or abnormal hydrologic heaving is not present
			15) Favorable microsite condition (i.e., woody debris, water temperature, etc.) is maintained by adjacent site characteristics
Yes	**No**	**N/A**	**EROSION/DEPOSITION**
			16) Accumulation of chemicals affecting plant productivity/composition is not apparent
			17) Saturation of soils (i.e., ponding, flooding frequency, and duration) is sufficient to compose and maintain hydric soils
			18) Underlying geologic structure/soil material/permafrost is capable of restricting water percolation
		■	19) Riparian-wetland is in balance with the water and sediment being supplied by the watershed (i.e., no excessive erosion or deposition)
			20) Islands and shoreline characteristics (i.e., rocks, coarse and/or large woody material) are adequate to dissipate wind and wave event energies

Remarks

Summary Determination

Functional Rating:

Proper Functioning Condition _____
Functional—At Risk _____
Nonfunctional _____
Unknown _____

Trend for Functional—At Risk:

Upward _____
Downward _____
Not Apparent _____

Are factors contributing to unacceptable conditions outside the control of the manager?

Yes _____
No _____

If yes, what are those factors?

_____ Dewatering
_____ Dredging activities
_____ Other (specify) ____________________
_____ Mining activities
_____ Road encroachment
_____ Watershed condition
_____ Land ownership

Appendix C

Wetland Bioremediation

The quality of life on Earth is linked intimately to the overall quality of the environment. The multitude and enormous volume of liquid and solid pollutants that are generated by human activity result in a variety of environmental and health-related hazards. The United States generates over 270 million metric tons of hazardous waste per year, of which only 10 percent is disposed of properly (Fekete 1994). It has been estimated that cleanup of Federal and non-Federal lands could cost $1.7 trillion using conventional approaches (National Science and Technology Council 1995). These approaches, in turn, produce noxious waste byproducts and impose additional cleanup or environmental costs. Due to its comparatively low cost and generally benign environmental impact, bioremediation offers an attractive alternative or supplement to more conventional cleanup technologies.

The American Academy of Microbiology defines bioremediation as the use of living organisms to reduce or eliminate environmental hazards resulting from accumulations of toxic chemicals and other hazardous wastes. Wetland bioremediation is the use of wetlands to accomplish this process. The effectiveness of wetland bioremediation has been demonstrated in a multitude of studies in a variety of settings, including natural marshes, swamps, strands, bogs, peatlands, cypress domes, and constructed wetlands (Society of Mining, Metallurgy, and Exploration, Inc. 1998).

Microorganisms, primarily bacteria and fungi, have the capability to transform natural and synthetic chemicals into sources of energy and raw materials for their own growth. Harmful chemicals can be degraded into less toxic or nontoxic compounds such as carbon dioxide, water, and fatty acids. When microorganisms are exposed to contaminants, they tend to develop an increased ability to degrade those substances (EPA 1991). Only a very small fraction of the microbial diversity of the Earth has been identified and even a smaller fraction has been studied for its bioremediation potential. New bioremediation technologies will be possible once the biochemical and ecological nature of microbial biodegradations of pollutants are understood. This complex process is further compounded by the fact that microorganisms seldom exist or act as single species, but rather act collectively as groups of species.

Much of the information about bioremediation has come from studies of aerobic bacteria. However, success in dealing with polluted wetland sites or using wetlands to clean up pollutants requires information about anaerobic organisms. Their potential use in environmental biotechnology has only recently emerged due to the difficulty of isolating and culturing such organisms in the lab. Fortunately, recent developments in molecular biology now make it possible to isolate and study genes of almost any organism.

Wetlands are considered low-cost alternatives for treating municipal, industrial, mining, and agricultural contaminants. While many wetlands are sensitive to these contaminants, others are capable of degrading pollutants. This is due to differences in physical, chemical, and biological conditions that impact transformations, transport processes, and treatment efficiency. Soil type affects the rate of transport of nutrients, contaminants, water, air, and pH adjusters. This in turn affects the rate of the degradation process and potential for migration of the wastes and amendments. In addition, highly organic soils can be sorptive and act as a barrier to organic migration.

Some naturally occurring wetlands can accomplish bioremediation, but environmental regulations limit the release of polluted substances into these areas. Thus, constructed and restored wetlands are becoming increasingly used for this purpose. There are about 1,000 constructed wetland systems currently operating worldwide and about 500 in the United States (Society for Mining, Metallurgy, and Exploration, Inc. 1998). Constructed wetlands consist of a series of plots filled with crushed rock, sand or other soils, and gravel. The plots are lined with plastic to prevent waste from leaching into ground water, and they are populated with wetland plants and microbes to aid in wastewater treatment. These constructed wetlands mechanically filter, chemically transform, and biologically consume pollutants. Two types of constructed wetlands are subsurface flow systems, where water flows through gravel and stones, and surface flow systems, where water travels over the surface of soils. In subsurface flow systems, interaction of the contaminated effluent with plant roots and microbes is greatly enhanced since water moves throughout the gravel or rock medium as opposed to the surface flow system where waterflow is restricted in the soil (Sikora et al. 1997). For larger, municipal wastewater treatment facilities, multistage systems can be designed using sedimentation basins for primary treatment and a series of constructed wetlands for secondary treatment.

When doing riparian-wetland restoration, especially on areas where the vegetation has been altered by agricultural activities, the redoximorphic soil features are the primary way to monitor success of a restored wetland. Having a fully functioning hydric soil should be a requirement for restoring a lentic site.

The benefits of constructed wetlands for bioremediation include (Hammer and Bastian 1989):

- They are relatively inexpensive to construct and operate
- They are easy to maintain
- They provide effective and reliable treatment
- They can be constructed to handle large or small volumes of water and varying contaminant levels
- They are aesthetically pleasing and provide habitat for wildlife and human enjoyment

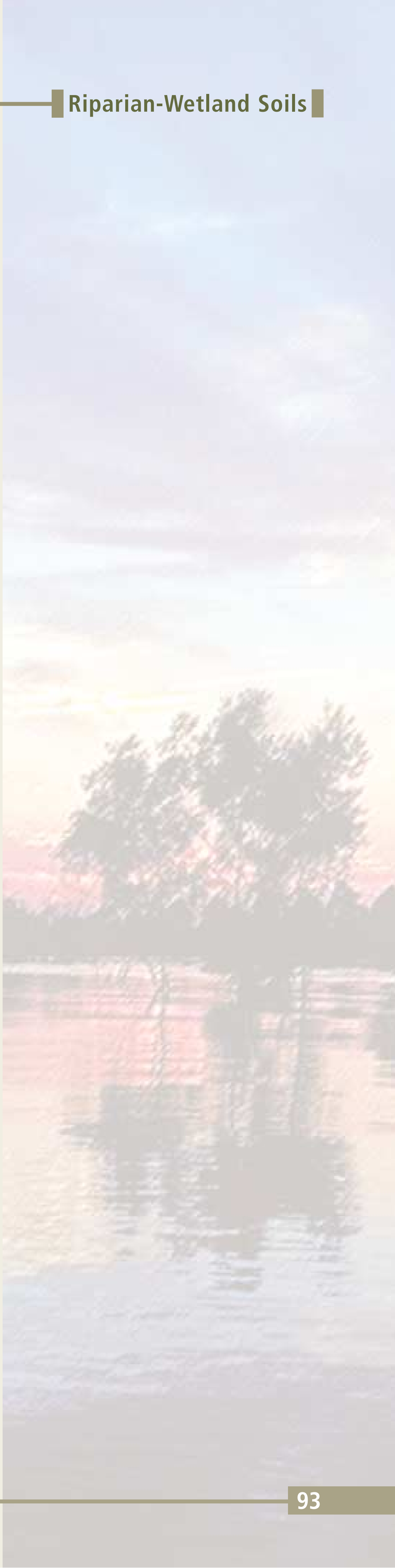
The disadvantages of constructed wetlands include (Hammer and Bastian 1989):

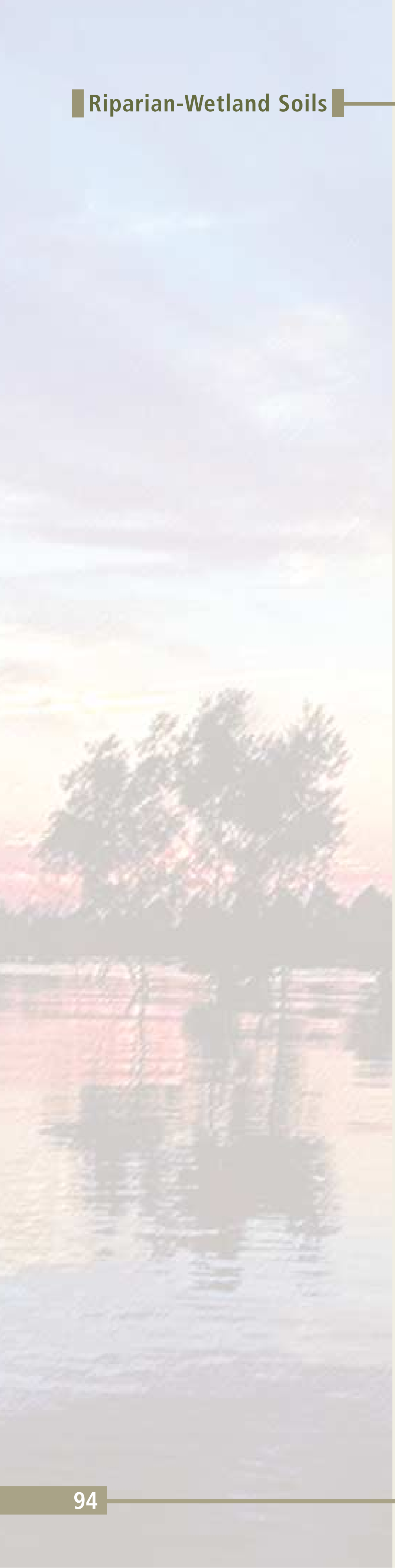
- They could require a large area of land
- The design and operating criteria is not precise
- The biological and hydrological processes are not fully understood
- There could be problems with human health hazards

Wetland bioremediation has been successfully used globally to treat a variety of sites and pollutants in diverse climates. Currently, there are thousands of wetland-based municipal and residential sewage, landfill effluent, industrial wastewater, and urban stormwater treatment systems around the world (Reddy and D'Angelo 1997). Wetlands are especially attractive to underdeveloped countries due to their low cost and ease of maintenance. Pollutants treated include carbon, nitrogen, phosphorus, metals, sediment, and toxic organic compounds via processes including mechanical filtering, mineralization, ammonia volatilization, denitrification, adsorption, and desorption. Biochemical oxygen demand (BOD) resulting from microbial decomposition can rob fish and aquatic wildlife of needed oxygen. A constructed wetland will mechanically filter out most solid nutrients while microbes use dissolved organics.

Agricultural activities are a major source of both point and nonpoint pollution worldwide. Agricultural pollution from swine, dairy, and cattle feedlot wastewater, meat processing wastewater, and discharges from agricultural watersheds has been successfully treated with wetland bioremediation. Pollutants treated include pesticides, sediment, metals, excess nutrients, and human health pathogens.

Petroleum spills, fuel tank leaks, petrochemical wastewater, and oil sludge waste from oil field operations are other important sources of pollutants. Both marine and freshwater natural and constructed wetlands have been used successfully to help clean up these pollutants from the environment. Military complexes polluted by fuel spills and munitions contamination are also promising candidates for wetland bioremediation.





The largest environmental issue facing the mining industry is acid mine drainage (Sobelewski 1997). It can be a problem for mines long after they cease to operate and environmental impacts can be severe. Numerous wetlands have been investigated that naturally remediated this effluent. One tiny wetland in the Keno Hill area, Yukon Territories, Canada, neutralized mine water from a pH of 1.1 to 6.6 within a distance of 10 feet (Sobelewski 1997). Constructed wetlands are being increasingly used to treat acid mine drainage and remove heavy metals from coal and precious/base metal mine drainage. Conditions are created that favor microbial and chemical-reducing processes, converting soluble metals to insoluble forms, which settle out in the wetlands.

The use of plants to concentrate pollutants is also an emerging bioremediation technique called phytoremediation. These plants filter out solid organic matter and sediment and take up pollutants such as excess nutrients and metals in their roots and, to a lesser extent, in their stems. Aquatic plant species vary greatly in their ability to accumulate metals. Research has shown that some floating and emergent plants have remarkable abilities to volatilize and accumulate specific metals. Duckweed can concentrate heavy metals such as cadmium up to 1,300 times their concentration in the effluent (Zayed et al. 1998). Other plants are unspecific collectors of various metals. Wetland plant species like coontail, giant duckweed, bacopa, and wild rice were able to accumulate appreciable amounts of various metals including copper, chromium, iron, manganese, cadmium, and lead. Continued research will help identify the most suitable plant species and develop genetic strains most efficient for phytoremediation of specific pollutants.

Accumulation of toxic substances in plants can pose a threat to wildlife. One management option is to periodically harvest these plant materials from the site and dispose of them in a suitable way. The other way to remove the toxic substances from the site is to use plants that volatilize the substances but accumulate low levels in their tissues.

Bacteria display a high degree of genetic plasticity or changeability. Genetic engineering can be used to modify organisms to provide the characteristics needed for bioremediation. Recombinant microorganisms with expanded degradation capabilities have been developed recently. Genes from different species have been combined into one strain of bacteria that can degrade multiple types of pollutants. Similar efforts should make it possible to tailor bacteria for bioremediation of sites contaminated with specific combinations of toxic compounds.

The survival of life as we know it on Earth requires a safe life support system, thus the urgency to use bioremediation to the fullest extent as an economically feasible and environmentally responsible form of environmental cleanup. Wetland bioremediation is a rapidly growing field that will continue to expand as a viable alternative for pollution abatement. The value of wetlands and the need to preserve them and create new wetlands will become increasingly critical to our society.

Appendix D

Managing Riparian-Wetland Roads

Management objectives change as soil properties, such as climate, elevation, steepness, and aspect, change. For example, north-facing slopes generally retain snowpack longer than south-facing slopes. The steeper the slope, the more it costs to build roads due to landslide and stability risks. The same principles apply to roadbuilding in riparian-wetland areas. Construction in or near riparian-wetland areas must account for saturated soils and possible flooding. Steepness of slope and elevation, accompanied by increased distance from the stream, will reflect in construction costs.

The role of soils in restoration and management of riparian-wetland roads is important relative to how roads change and modify soil attributes. For example, the presence of a road in a riparian-wetland area often modifies soil and soil water movement, which often reduces the amount, kind, and distribution of vegetation in a riparian-wetland area.

Vegetation plays an important role in raindrop interception. Once vegetation has been removed and road surfaces compacted, the impact of a raindrop is increased over preexisting conditions. Compacted surfaces have smaller pore size, which decreases infiltration and increases runoff and the potential for erosion. Roads located within riparian-wetland areas can transport sediments offsite into the fluvial system and adversely affect the aquatic habitat. Every road becomes an ephemeral stream channel that concentrates water energy. The addition of roads disrupts the original drainage pattern and has potential for serious alteration of the watershed.

A. Potential effects of roads to riparian-wetland areas

Transportation systems provide tremendous opportunities and, if properly located on the landscape with well-designed drainage features, can remain stable for years with negligible effects to riparian-wetland areas. Unfortunately, some roads adversely affect soil health and quality by accelerating erosion, modifying soil moisture regimes, and reducing the infiltration capability of soils due to compaction of the road travelway. Other impacts can include:

- Intercepting ground water or subsurface flows
- Acting as a dam, levee, or french drain
- Ditches draining water tables in wetlands and meadows
- Accelerating erosion in the form of surface (sheet, rill, and gully erosion) and mass wasting
- Changing soil moisture and vegetation
- Accelerating streambank erosion and deteriorating water quality and quantity
- Treating roads with oil can be toxic to riparian-wetland plants

B. Road restoration that addresses soil resources

Prior to employing any road riparian-wetland restoration technique, an interdisciplinary team should identify the cause and effect relations of the current road and or crossing. Once the team has identified cause and effect, it is possible to identify resource objectives and best management practices (BMP) for the roads and crossings.

The first question is to determine the need for the road.

- Are there alternative access routes that exist or could be developed?
- Is there another location for the road or crossing that would mitigate the cause and effect the team had previously identified?

Once the team determines that access is needed, then the type of access should be pursued.

- Is access needed year-round?
- What types of vehicles require access?

Based on this information, the team can identify other resource goals and objectives for the road and or crossing. From the soil resource perspective, the goal is to *restore and maintain soil health and quality*. This goal has the following objectives:

- Limit excavation and compaction while providing transportation.
- Reduce sheet, rill, and gully erosion.
- Reduce and minimize the adverse impacts of mass wasting and landslides.
- Maintain soil moisture and vegetative composition based on the inherent soil capabilities of the site.
- Reduce accelerated streambank erosion and altered water quality.

It is important to note the following techniques pertain primarily to the achievement of the soil resource objectives. These treatments may not meet other resource objectives and the interdisciplinary team needs to be able to clearly state which resource objectives a given treatment can meet.

C. Sheet, rill, and gully erosion

In situations where there is sheet, rill, or gully erosion, there is a high probability of a water control issue either from the hillslope, ditch, or road surface.

To reduce sheet erosion, opportunities to minimize bare soil should be identified.

- Consider paving or rocking steep road pitches.
- Limit roadway width.
- Roll the grade to limit excavation and disturbance and provide backup surface drainage (rolling dips are built in).
- Provide frequent cross-drainage to effectively accommodate muddy runoff from roads.
- Limit excavation, cut and fill heights, and width of clearing.
- Establish effective soil cover on cut and fill slopes.
- Reduce soil compaction along road cuts and seed progressively to reduce the amount of bare soil exposed.
- Use outslope drainage template (with backup rolling dips) whenever feasible to reduce excavation, drainage problems, road maintenance, and ditch-related erosion.
- Mulch and revegetate cut and fill slopes.

To reduce rill and gully erosion efforts, minimize concentrated waterflows by using the following options.

- Pave bridge approaches to reduce sediment.
- Disperse concentrated flows by incorporating rolling dips in conjunction with road outsloping.
- Modify road drainage from being insloped to being outsloped.
- Install a multiple array of culverts.
- Pave or rock steep slopes and use curbs to control water.

D. Mass wasting and landslides

In areas prone to mass wasting, there are several measures that can be taken to reduce the destabilizing effect of roads.

First, identify areas that are geologically unstable and avoid these in locating roads. Review the past management in the area and try to determine what type of response had occurred on similar soils. Many landslide areas are waiting for the right conditions to move and the lack of recent soil movement is not an indication of stability. It is necessary to look at previous records to identify when drainage structures or roads were put in place. Determine what type of management activity is associated with the road construction such as timber harvest, campground development, or alternate access.

The following options may help reduce and minimize the effect of a landslide.

- Design structures to accommodate potentially large amounts of material.
- Use bridges at sites prone to debris torrents.
- Use a hardened crossing that includes box culverts with concrete aprons and metal grates.
- Build new and upgrade existing crossings so that they do not have the potential to divert streamflows should they become plugged.
- Decommission unneccessary roads that are altering hillslope hydrology and concentrating waterflow onto the landslide.
- Armor crossing by incorporating large boulders and providing a dip to enable the material to pass over the road with minimal impact.

E. Change in soil moisture and effects to vegetation

Two common changes in soil moisture and vegetative composition include:

- Conversion of a wet meadow site to a drier meadow through headcuts within the channel.
- Change in soil moisture regime where wetlands had been created by road structure improvements.

Treatments to reduce adverse impacts to wet meadows

- Relocate the road to minimize the impact on the meadow or wetland.
- Disperse flows by using a multiple array of culverts across a meadow or wetland.
- Cross the meadow, wetland, and riparian area with a bridge.
- Use a low-water crossing.
- Restore cutoff meanders that may have existed previously.

- Use permeable fills, which allow for water movement across the meadow.
- Change the type of access to the area to reduce the amount of compacted surfaces in or adjacent to the meadow or wetland.

In areas where the intent is to improve or create a wetland with a road, the following techniques have been successfully applied.

- Multiple arrays of culverts set at a predetermined height.
- Drop inlet structure that impounds water on ephemeral systems.

An important caveat that needs to be considered with the above treatments is that the team needs to clearly identify the stream type associated with the meadow or wetland type and the attributes and processes necessary for that stream type to function properly. In addition, whether the channel is seasonally flowing or perennial will often dictate what type of structure would work best. There are numerous guides that provide information to interdisciplinary teams, including the Stream Corridor Restoration handbook (FISWRG 1998). The hydrologist and engineer on the team can help develop this type of information.

F. Accelerated streambank erosion

Streambank erosion often occurs from channel confinement due to the location of the road within the floodplain. Several treatments have been successfully employed to reduce accelerated streambank erosion on a variety of systems ranging from headwater treatments to major rivers.

- Identify opportunities to relocate roads out of the floodplain.
- Restore cutoff meanders that allow for the stream to dissipate its energy at higher flows.
- Redesign the stream and road to allow for an increased stream channel.
- Armor the road (fill slope and travelway) with larger boulders and smaller surface material to reduce the consequence of finer road material entering the stream channel.
- Use engineered logjams to redirect stream energy away from the road.
- Define access for vehicles and recreationists to reduce compaction along the streambank.

The treatments identified above are all tools that can and have been used successfully across the nation. The treatments can help to maintain soil health and productivity while minimizing the adverse effects of roads to soils in riparian areas.

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Soils, interacting with water, vegetation, and landform, play a critical role in determining the health of riparian-wetland areas. Soils in these areas differ from those in upland areas. Riparian-wetland soils are constantly changing as new materials are deposited by different storm events and overland flow. Consequently, great variability in soil types can occur in short distances. This variation affects the hydrology and vegetation, as well as erosion and deposition, in riparian-wetland areas. Understanding these relationships is essential when assessing the condition of both lotic (running water) and lentic (standing water) systems. Soils information gathered during an assessment can be interpreted and applied to help manage and protect riparian-wetland soils.

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Deposition	Riparian areas	

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