Journal of Contemporary
Water Research & Education

Issue 154
April 2015



A Primer on Watershed Management

A Publication of the
Universities Council on Water Resources

JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION

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ISSN 1936-7031

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Subscription Information: The *Journal of Contemporary Water Research & Education* is published by the Universities Council on Water Resources. The annual subscription rate is $35 (domestic) and $80 (international). Prices per copy for past issues are $15 (domestic) and $30 (international). Members of UCOWR receive the *Journal of Contemporary Water Research & Education* as a part of their membership.

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Printed by the authority of the State of Illinois. April 2015. 600 copies. Order Number XXXXXXX.

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A Primer on Watershed Management

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As the title indicates, the contents of this issue of the Journal of Contemporary Water Research & Education provide a "Primer on Watershed Management." Introductory material on any subject is rarely available in journals so we have deviated from typical journal approach and format in this issue. Our intent is to address individuals who are interested in water resources and watershed management, but who may not have the strong scientific background in these subjects held by professional practitioners and researchers in watershed sciences. Primer information typically is presented in short 'fact sheets' or web pages created by state or federal governments, such as the U.S. Environmental Protection Agency. These materials are useful, but the coverage is limited due to their brevity. Furthermore, the focus of most of these resources are hydrologic or aquatic responses or behaviors that result from human activities in the watershed, but there tends to be little information explaining the underlying processes that lead to those responses. Without that knowledge, it is difficult to take information from one situation and understand how it applies to others.

Several of the co-authors of papers in this issue have discussed the need for journal-quality papers focused on water resources that introduce concepts to teachers, students, and citizens in watershed coalitions who are hungry for such information, but are often frustrated by the technical aspects of typical journal papers. However, individuals, communities, and watershed coalition groups have tremendous influence on management and policy decisions that affect watershed conditions, so a well-informed citizenry is critical to the integrity of water resources and aquatic health. This issue is the culmination of efforts to achieve this outcome, so it is special to many of us.

The topics of the papers in this issue were selected to provide a breadth of information that could serve as a foundational understanding of watershed management and water resources. However, the papers should not be considered to be a comprehensive review nor do they cover all topics applicable to watershed management. Instead, we hope that the information presented here will pique readers' interests about watershed management, the specific concepts presented, or subjects alluded to but not covered in these papers, and challenge them to delve deeper into these topics.

The paper "Fundamentals of Watershed Hydrology" introduces the hydrologic cycle. The term 'watershed' is defined and discussed from the perspective of the inextricable connection between watershed boundaries and the hydrologic cycle. Components of streamflow are illustrated using hydrographs, and ephemeral, intermittent, and perennial streams are defined based upon their water sources. The water budget equation is introduced and its utility for predicting how different components of the hydrologic cycle, especially streamflow, will respond to different management actions in a watershed is demonstrated.

"An Introduction to Soil Concepts and the Role of Soils in Watershed Management" describes the importance of the watershed's surface from the perspective of its role in partitioning water into many components in the hydrologic cycle, its effects on water quality, and the importance of managing lands for ensuring soil sustainability. The various layers of soil and the processes involved in their development are described. Soil classification is summarized to provide an understanding of major groupings of soils. Additionally, descriptions of the physical, chemical, and biological characteristics of soils explain how and why water moves through

the soil, and the factors that influence its chemistry. Watershed management activities can influence many soil properties, so some agriculture, forestry, and urbanization effects are presented, including a discussion on erosion and soil conservation. Finally, readers are instructed on how to evaluate soil on their own land and provided with additional resources to obtain management assistance.

Because of its importance and ubiquity as a water pollutant from virtually all types of land uses, soil, as sediment, is revisited more extensively in "Soil Erosion in Humid Regions: A Review." The three processes of erosion, particle detachment, transport, and deposition are differentiated, and interrill and rill erosion are defined and described. Soil, precipitation, landscape, and biological characteristics that can contribute to erosion and sedimentation processes are detailed. Because unpaved roads can be a chronic source of sediment to water bodies, an introduction to forest roads also is provided.

Application of the technical concepts in these aforementioned papers is the subject of "Guiding Principles for Watershed Management Forested, Agricultural, and Urban Watersheds." Managed forests, agricultural lands, and urban landscapes are covered in this paper, as these are some of the most common land uses in U.S. watersheds. The influences of land management actions on hydrologic components, especially streamflow, stream morphology, and water quality are described. Special attention is given to best management practices (BMPs), which are tools and techniques that can help control nonpoint source pollutant levels in receiving waters. Nonpoint source pollutants include sediment, chemical, biological, and thermal pollutants whose sources cannot be specifically pinpointed (versus pollutant emissions from a pipe). As indicated by their mention in multiple papers in this issue, BMPs are an important topic. This is because BMPs can be implemented by individual citizens on their own lands and can contribute meaningfully to water resource protection.

We would be remiss not to include a discussion of the influences of human behavior and societal needs on watershed management. After all, human actions dictate the land management (or mismanagement) actions that occur within all watersheds on the Earth, and we have a profound effect on water use, water conservation, the hydrologic cycle, water quality, and aquatic health. The paper "The Role of Social Science in Successfully Implementing Watershed Management Strategies" describes how community and individual attitudes, norms, and behaviors influence our decisions and actions, how to more effectively target information to different stakeholders, and the role that group interactions play in implementing conservation actions and BMPs. The latter half of the paper provides information that can empower watershed stakeholders and watershed groups to move watersheds toward improved sustainability and resilience rather than focus on traditional short-term objectives.

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Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 154, Pages 3-20, April 2015

Fundamentals of Watershed Hydrology

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Abstract: This is a primer about hydrology, the science of water. Watersheds are the basic land unit for water resource management and their delineation, importance, and variation are explained and illustrated. The hydrologic cycle and its components (precipitation, evaporation, transpiration, soil water, groundwater, and streamflow) which collectively provide a foundation for how landscapes and water interact are discussed at length. Important hydrologic concepts and methods are described in detail but primarily within the context of forested watersheds since most of the nation's fresh water originates from forest lands. The contents of this paper are designed to provide fundamental hydrologic principles to both citizens and policy makers, with the intention of helping to guide informed watershed management activities.

Keywords: *forest hydrology, hydrologic cycle, watersheds, stream types, streamflow generation, groundwater aquifers, hydrograph components, water budget*

While life on Earth depends upon water, many people have little or no understanding of **hydrology** – the science of water. However, because everyone influences water quality and availability by their actions and use of water, the protection, conservation, and management of water supplies and water quality depend upon all of us understanding the basic concepts of hydrology. Consequently, the intent of this paper is to provide a primer about hydrology and the hydrologic cycle to allow citizens in watershed groups, students, educators, and policy makers to be more informed about water resources and their behavior and management.

Much of the focus of this paper is on forested ecosystems. The reason for this is that 80 percent of fresh water in the U.S. originates on forested lands (Sedell et al. 2000). However, many of the processes and management principles that are discussed for forests also have relevance to other types of ecosystems, although the degree or importance of specific hydrologic processes or components in these other ecosystems may differ from that in forested ecosystems.

Wetland ecosystems are excluded from discussion in this paper because their hydrologic responses depend upon how they receive or lose water, which varies by type of wetland system. However, wetlands are extremely important in regulating hydrologic responses, so readers who are interested in wetland hydrology should refer to Verry (1997, 1981), Sun et al. (2001) and Xu et al. (2002) as starting points for more information on this subject. These authors provide descriptions of different types of wetland systems and wetland watershed responses from a different management actions in different regions.

Hydrology and Watersheds

Different disciplines analyze and describe data based on different land-based units. For example, timber management employs the forest stand, agriculture uses pastures, fields, or grazing allotments, and urban land managers focus on the city or municipality. In hydrology, the land unit is the **watershed**, which also may be referred to as a **basin** or **catchment**.

A watershed is defined as an area of land in which all of the incoming precipitation drains (i.e., "sheds") to the same place -- toward the same body of water or the same topographic low area (e.g., a sinkhole) -- as a result of its topography. This

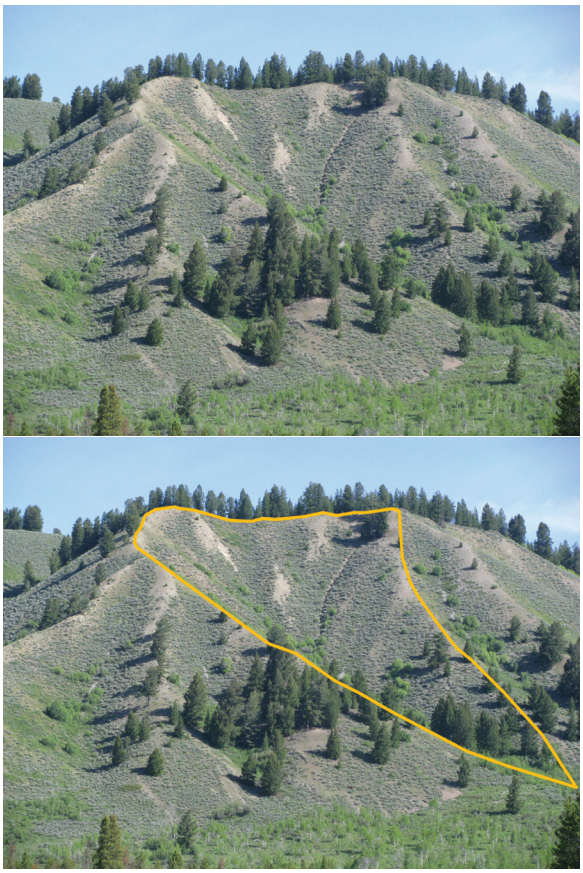

Figure 1. A small watershed in Wyoming. The watershed boundaries are the topographic high points (i.e., ridges) in the top photograph, which are outlined in yellow in the bottom photograph. Photograph courtesy of David Mince.



Figure 2. Smaller watersheds, outlined in white in this photograph are nested within the larger watershed outlined in yellow. Streams are shown in blue. The upper ridgelines compose the watershed boundaries of both the smaller and larger catchments. Other smaller watersheds also exist in this larger one but are not delineated because their boundaries are not clearly identifiable from this perspective.

means that a watershed's boundary is defined by its topographic high points. Watersheds are fairly simple to identify in mountainous or hilly terrain because their boundaries are defined by ridges (Figure 1). However, in flatland watersheds, such as in the Coastal Plain of the Southeast, identifying topographic high points can be very challenging because the highest and lowest elevations may differ only by a few centimeters.

No matter where you are on the earth's land surface, you are in a watershed – even if you are in a desert where there is no evidence that surface flow ever occurs. This is because differences in elevation still exist, and when precipitation does occur, no matter how infrequently, the topographical features in the watershed will determine where water will accumulate and flow. After all, streams and rivers are simply low points on the land where surface flow accumulates.

Smaller watersheds are nested within larger watersheds (Figure 2), so at most locations on Earth you are in multiple watersheds at the same time. A watershed reaches its maximum size when the stream or river involved flows directly into an ocean or sea. The largest watersheds (in area) that are fully within the continental U.S. are the Mississippi, Missouri, St. Lawrence, Rio Grande, Columbia, Colorado, and Ohio River watersheds (Kammerer 1990).

For water resource planning and data management, watersheds are identified numerically by **hydrologic unit codes**, or **HUC**s. There are six HUC levels, organized by size of watershed in descending order. The official names for these levels are Region, Subregion, Basin, Subbasin, Watershed, and Subwatershed although Basin and Subbasin HUCs, respectively, also are referred to as Accounting Units and Cataloging Units. Each of the six HUC levels is defined by a two-digit code. As additional two-digit identifiers are added onto a HUC, the location and size of the watershed becomes more specifically defined (Seaber et al. 1987; USGS and USDA-NRCS 2012); thus, the greater the number of digits, the smaller the watershed area (Table 1). While the HUC designations are defined by the Federal Interagency Geographic Agency Committee to identify watershed locations and to illustrate the hierarchical nature of nested watersheds, confusion

Table 1. The six levels of hydrologic unit codes (HUCs) for watersheds in the United States.

	Region	Subregion	Basin	Subbasin	Watershed	Subwatershed
Number of digits	2	4	6	8	10	12
HUC Level	1st	2nd	3rd	4th	5th	6th
HUC example	05	0502	050200	05020006	0502000603	050200060302
Additional information	Major land areas; 21 HUC Regions in U.S.	Each region has 3 to 30 Subregions; 222 HUC Subregions in U.S.	352 Basins in U.S.	2,149 Subbasins in U.S.; smallest is 181,300 hectares	Typically 16,200 to 101,200 hectares; previously referred to as HUC-11	Typically 4,050 to 16,200 hectares; previously referred to as HUC-14

with the nomenclature can occur because all of the official HUC level names also are used and applied less formally and consistently outside the context of HUCs. For example, HUC Subwatersheds describe areas of 4,050 to 16,200 hectares, but the term subwatershed often is used informally to describe much smaller watersheds, including those only a few hectares to a few hundred hectares in area.

Using watershed terminology, the term "**headwaters**" describes the uplands of a watershed or the upper reaches of a watershed's drainages where soil moisture and surface flow first accumulate. In small watersheds (e.g., Figure 1), the headwater area may be small, but in large watersheds, the headwater area typically includes several small- to moderate-sized watersheds nested within the larger watersheds. For example, the Mississippi River watershed which includes an area of approximately 3.1 million km^2, has headwaters that extend from Pennsylvania to Montana (Kammerer 1990). The **mouth** of a watershed is the area of outflow for the watershed, at the point where a stream or river meets or feeds another water body. This point of merger of two or more water bodies is termed the **confluence**.

The Hydrologic Cycle

Understanding how water is used and cycled through a watershed provides the foundation for understanding and describing how landscapes and water interact. The most basic and essential tool for understanding these interactions is the **hydrologic cycle**. As the term implies, the hydrologic cycle describes how water is stored and moves within and among watersheds (Figure 3). The major components of the hydrologic cycle are precipitation, evaporation, transpiration, soil water, groundwater, and streamflow.

Precipitation provides the input of water to watersheds, primarily as rain, snow, sleet, and hail. Fog and freezing fog also may provide a substantial amount of the annual precipitation input in some high-elevation ecosystems. Regions that receive the majority of their precipitation as rainfall are classified as rain-dominated systems, whereas those that receive primarily snowfall are classified as snow-dominated systems. In the United States, snow-dominated systems tend to be located in the West and at higher elevations. These climates may have rainfall, even commonly, during the growing season (e.g., short afternoon thunderstorms in some Rocky Mountain areas), but in terms of the total annual contributions to **streamflow**, rainfall inputs are small. As a result, streamflow throughout most of the year in these climates is dependent upon snowmelt from high-elevation snowpacks. By contrast, forests in the East and coastal forests of the Pacific Northwest are dominated by rainfall. If snow occurs at all,

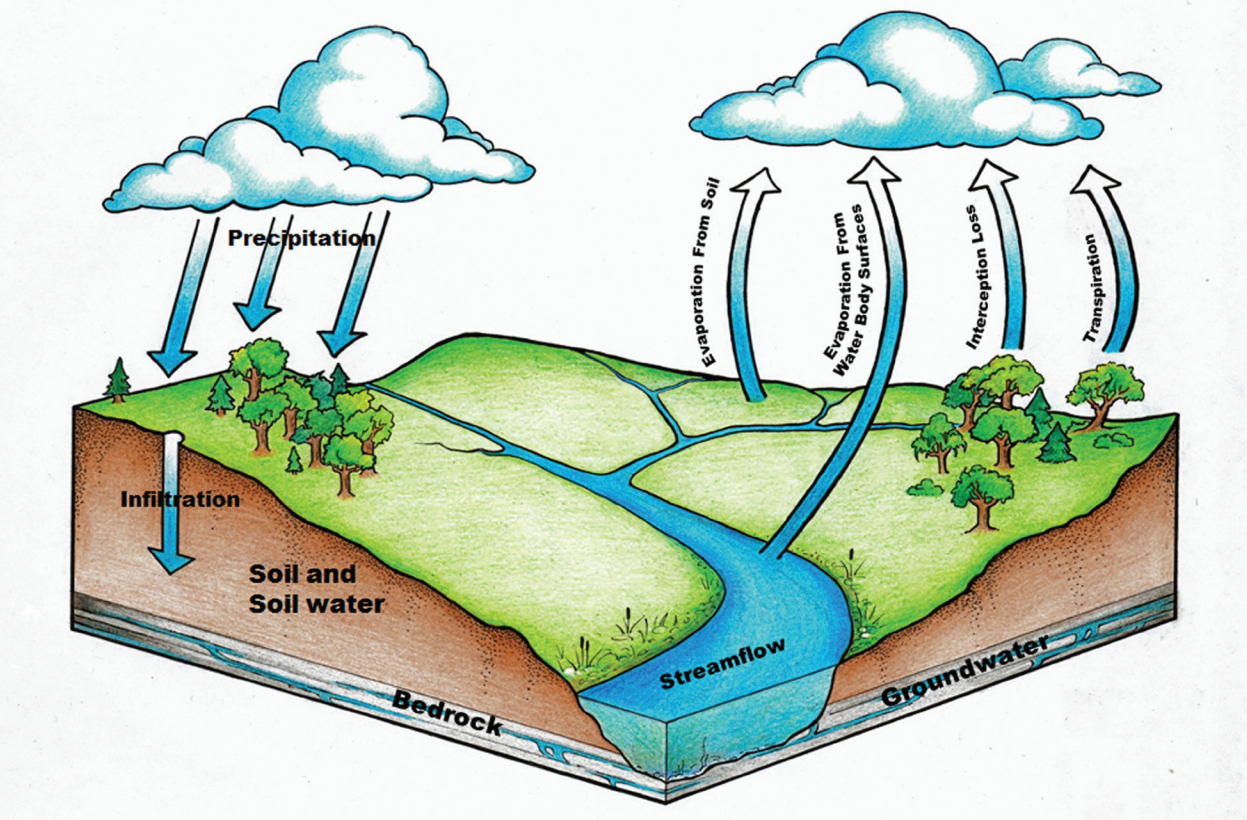

Figure 3. A simple schematic of the hydrologic cycle. Drawing by Robin L. Quinlivan.

season-long snowpack accumulation may be rare because intermittently occurring warm fronts result in rain-on-snow events that limit the life of the snowpack and release water to streamflow throughout the winter. Even where snowfall is an important contributor to annual precipitation inputs and snowpacks extend throughout much of the winter (e.g., New England or the Lake States), rainfall is the more important component because snowpacks are fully melted by late spring and growing season moisture depends upon rainfall.

Precipitation inputs vary greatly across the United States. For example, the desert Southwest receives only a few tens of millimeters of precipitation a year, while the Appalachian region receives from 890 mm in the valleys to up to 2,040 mm in the highest mountains. Average annual precipitation in the Pacific Northwest varies from 1,270 mm in the southern portion of the geographical area to 5,080 mm on the mountain slopes of Washington. Even greater annual totals are recorded in some areas of southeastern Alaska and portions of the Hawaiian Islands.

As these regional values suggest, precipitation is influenced by elevation. Mountainous areas tend to have greater amounts of precipitation than surrounding lowlands due to the **orographic effect**, in which rising air currents cool and release their moisture as precipitation (Figure 4). The orographic effect also causes the leeward sides of mountains or mountain ranges to receive less precipitation than the windward sides because most of the available moisture is lost to precipitation before the air mass reaches the leeward side. The area receiving less precipitation is known as a **rain shadow**. Because most wind currents in the U.S. generally move from west to east, the windward side is on the western side of mountains, and the leeward side is on the eastern side.

Differences in precipitation between the windward and leeward sides of mountains can be great and can result in substantially different ecosystems. Some high-elevation mountain ranges, such as in the Cascade or Sierra Nevada ranges, support forests on the windward side, but have arid lands on the leeward side. Even in

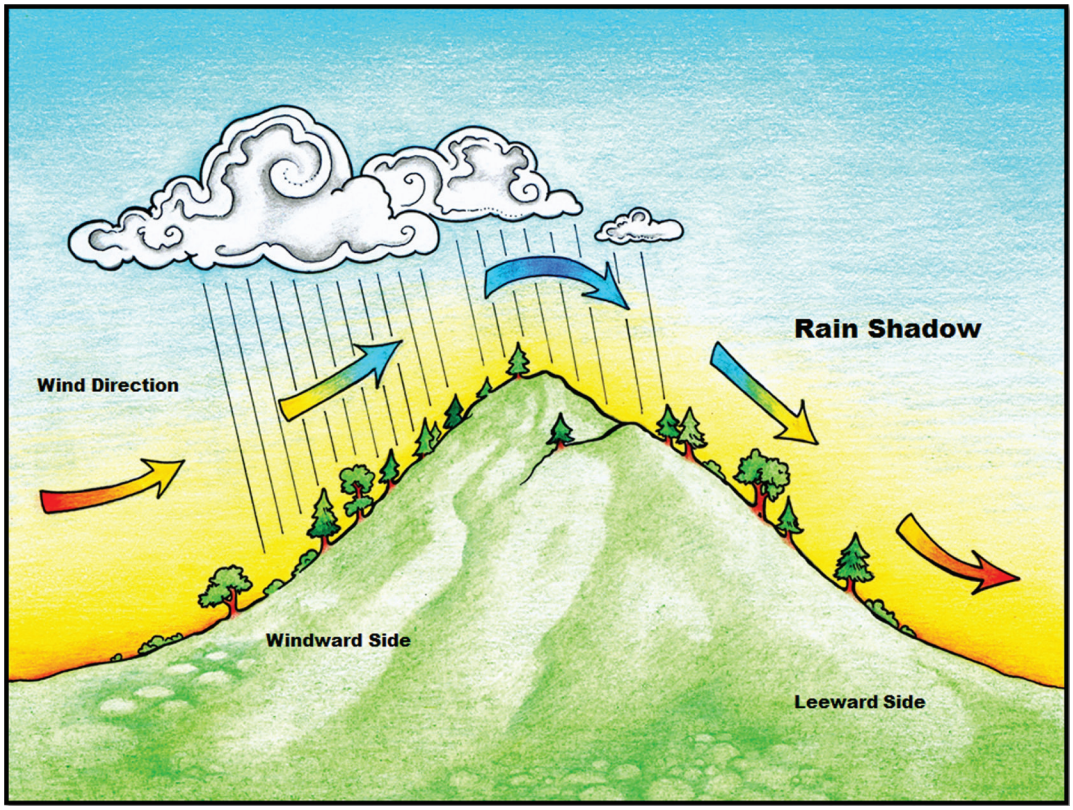

Figure 4. Effects of orographic lifting. Air currents rise when they encounter mountains, which results in the air mass cooling. Less moisture can be held by cooler air so clouds form and precipitation occurs during lifting. After the air mass crosses over the mountain, it begins to fall and warm, the clouds disappear, and more moisture can be stored in the air as water vapor (humidity). Thus, the windward side of the mountain is wetter, and a rain shadow develops on the leeward side of the mountain. Drawing by Robin L. Quinlivan.

the humid East, the reduction in precipitation in the rain shadow can be as much as 760 mm or more per year, so that while forests may exist on both the windward and leeward sides, those on the eastern side are dominated by vegetation that grows well in drier conditions.

In forests, most precipitation must pass through vegetation to reach the ground. When leaves are present only a small portion falls directly to the ground without touching the canopy. Precipitation caught by the forest canopy is termed **interception**. Some intercepted precipitation never reaches the ground because it is evaporated back to the atmosphere. This loss of precipitation is termed **interception loss**. In the winter, interception losses of snow also can occur by **sublimation**, which is the transformation of solid precipitation (snow or ice) directly to a gas. Interception losses also can occur when precipitation is captured by other surfaces, including other types of vegetation as well as man-made surfaces. However, forest vegetation typically results in greater interception losses than most other types of surfaces because forests are composed of multiple, thick layers of leaves that provide substantial opportunity to intercept and retain precipitation.

Within forests, the portion of intercepted precipitation that makes its way to the ground does so as either **throughfall** or **stemflow**. Throughfall is the portion of intercepted precipitation that drips or falls to the ground from the canopy. Stemflow is the portion that runs down the branches and trunk of the tree to reach the ground. When liquid precipitation is involved, individual throughfall droplets often coalesce into larger droplets on leaf, twig, or branch surfaces, and their larger masses help ensure their successful delivery through the layered leaf canopy. Similarly, stemflow drops

coalesce and become bigger as they move down a tree, which increases their potential to reach the ground before evaporation occurs.

The amount of precipitation lost to interception or that becomes throughfall or stemflow each year in forests depends upon many factors, including the type and intensity of precipitation, other weather conditions, and the species of trees present (Crockford and Richardson 2000; Muzylo et al. 2009; Garcia-Estringana et al. 2010). In general, intense rainfall events have smaller percentages of intercepted and evaporated precipitation because they tend to have larger rain drops that drive through the canopy more easily. Additionally, intense rainfall events often include periods of high winds that contribute to transporting throughfall droplets to the ground. Wind can hasten evaporation, but primarily after precipitation has ended and the atmosphere is no longer saturated with moisture. Wind also plays a large role in controlling interception losses and throughfall of snow. It can blow snow that has accumulated in the canopy to the ground, but it also can sublimate substantial amounts of snow stored in tree crowns, thereby reducing the amount of precipitation that reaches the ground.

The tree species present within a forested watershed have a large influence on precipitation interception and delivery of precipitation to the ground due to differences in canopy architecture, branch and tree trunk surface characteristics, and leaf characteristics, such as leaf area or leaf density. Trees with more upright branching can have greater interception losses than trees with more downward-facing branching because the latter tend to be more conducive to shedding precipitation, especially snow. Flexible branches that are easily moved by the wind can yield more moisture to the ground than stiff branches that resist the wind's energy. Consequently, throughfall contributions can be greater from sapling-sized trees than from mature trees of the same species because the former have more flexible branches and trunks. Stemflow, which usually constitutes only about 2 to 5 percent of precipitation that reaches the ground (Chang 2006), is more efficiently delivered on smooth-barked trees (e.g., maple and beech) than on rough-barked trees (e.g., oak and conifers).

Tree species with high leaf areas typically have larger interception losses because it is more difficult for throughfall droplets to successfully make their way to the ground before they are evaporated or sublimated. Interception losses from conifers tend to be much greater than from most hardwood species because conifers have very high leaf (i.e., needle) densities and they retain their needles throughout the winter. Hardwoods have much greater interception losses during the growing season when leaves are present than during the dormant season after they lose their leaves. After leaf fall, rain simply passes through hardwood canopies with little contact with the branches. Snowfall in hardwoods is held primarily in the forks of large branches, and much of that eventually reaches the ground due to wind, gravity, or snowmelt. The fact that snow loads can break the tops of hardwoods when leaves are present, but not after leaf fall is evidence of the differences in interception capacity between canopies with and without leaves.

Unlike precipitation, which is an input to the hydrologic cycle, **evaporation** is a loss of moisture from a watershed. While sublimation (a solid changing directly to gas) is technically different from evaporation (a liquid changing directly to gas), sublimation generally is considered part of evaporation in the hydrologic cycle. Water can be evaporated from any surface, including plants, water bodies, the soil surface, buildings, roads, and parking areas. In forests, the litter layer, or the accumulation of leaves, twigs, and other vegetative debris on the soil surface provides a very effective shade barrier and it reduces the rate of air exchange between the soil and the atmosphere, so forest litter is important for restricting evaporation from the soil.

Transpiration is another way moisture is lost from a watershed. Transpiration is evaporation of water from leaf stomata (i.e., tiny leaf openings where gases are exchanged) following movement of ground moisture from the roots upward through the tree (i.e., translocation). Consequently, for transpiration to occur, moisture must be present in the upper layers of the soil where feeder roots are predominantly present. In forests, transpiration accounts for much greater losses of moisture than any other mechanism in the hydrologic cycle. A single mature tree can transpire tens to hundreds

of liters of water per day, depending upon soil moisture availability. In a worldwide review of vegetative water use, trees with at least a 51-cm diameter transpired an average of 265 liters per day (Wullschleger et al. 1998). Because evaporation and transpiration depend on the same physical processes to transform water from a liquid to a gas and because they each result in losses of moisture from a watershed, the two are often considered together and termed **evapotranspiration** in the hydrologic cycle.

Evaporation and transpiration rates vary widely depending upon many factors, including precipitation, temperature, aspect, humidity, and wind (Gregersen et al. 2007). Higher temperatures usually result in elevated evaporation and transpiration unless soil moisture is limited. Under those circumstances, transpiration actually can decline because stomata close during soil-moisture stress. If soil-moisture deficits are prolonged, wilting and leaf fall can occur (Ward and Elliot 1995; Schoonover and Crim 2015, this issue). Different **aspects** (i.e., the position of an object relative to the sun) receive different amounts of solar radiation and heat with the result that both evaporation and transpiration increase from north- to east- to west- to south-facing aspects. Lower relative humidity also can contribute to increasing evaporation and transpiration because dry air has a greater capacity to accept moisture than more humid air of the same temperature. This explains why very little evaporation and transpiration occur during rain events when the air is saturated with water. Evaporation rates also can increase in response to wind because the wind energizes the change from liquid water to water vapor (gas) at the molecular level, and more importantly, because moist air is moved away from the water source and replaced by drier air. Similarly, when plants transpire, a thin layer of air around the leaves becomes saturated; if wind moves that air away and replaces it with drier air, evaporation from stomata increases.

Because transpiration requires solar energy and the presence of leaves, transpiration rates are much different during dormant and growing seasons. For hardwoods, transpiration declines during leaf senescence (i.e., the final stage of leaf development) and terminates once leaf fall occurs. Conversely, conifers retain their needles year-round so they continue to transpire during the winter. However, their rates of transpiration in the winter are much lower than during the growing season due to shorter day lengths, reduced solar energy inputs, and lower temperatures. Frozen surface soil also can inhibit moisture uptake by roots.

Infiltration of precipitation into the soil does not ensure that moisture will be available to plants. To be available to plants, soil moisture must be retained in small-sized soil pores, or voids between soil particles or soil aggregates (clumps of soil particles). These **micropores** (Table 2) are the primary sources of moisture for plants, and are essentially the only sources during periods between precipitation events. Moisture in micropores is held by adhesion between soil particles or soil aggregates so water does not move freely in response to gravity. Instead, water in micropores moves only by **matric potential** in response to spatial differences in soil moisture. That is, as soil dries (e.g., through moisture uptake by vegetation), soil moisture from wetter areas can migrate toward drier areas due to adhesive forces between soil water and soil particles. A common example of matric potential familiar to most people is the upward movement of water into potted plants watered from the bottom.

The majority of pores within most soils are micropores. Their dominance in controlling soil moisture retention is critical to retaining moisture within the soil mantle during storm-free or snowmelt-free periods. If these micropores did not dominate, most incoming precipitation would drain from the soil quickly, resulting in xeric (dry) soils and associated xeric plant communities, which would largely exclude forest trees.

However, larger-sized pores are not uncommon in soils. Medium and large-sized pores are called **mesopores** and **macropores** (Table 2), respectively, and unlike micropores they freely transmit moisture due to gravity (Wilson and Luxmoore 1988; Luxmoore 1981). Such rapid loss of water during and immediately following rainfall or snowmelt events means moisture in mesopores and macropores contributes little to transpiration since it moves below the rooting zone or exits the soil (to streams or groundwater)

Table 2. Soil pore designations and characteristics suggested by Luxmoore (1981). Specific pore or pressure ranges have not been formally adopted for differentiating among micropores, mesopores, or macropores; however, the ranges presented here provide examples of the comparative values for each designation. The pressure range is a measure of how tightly water is held by adhesive forces in soil voids; the more negative the pressure range, the more tightly the water is held.

Soil pore designation	**Pore diameter range** (μm)	**Pressure range** (kPa)
Micropore	< 10	< -30
Mesopore	10 to 1,000	-30 to -0.3
Macropore	> 1,000	> -0.3

before it can be used by plants. Mesopores and macropores are formed by shrinking and swelling of clays, freeze and thaw cycles in soils, chemical weathering of minerals, root decay, burrowing animals or insects, earthworms, and subsurface erosion processes (Beven and Germann 1982). The largest macropores may be several centimeters or wider in diameter and are easily visible if intersected during soil excavation.

The length and connectivity of mesopores and macropores determines the fate of gravity-drained soil water. When these pores are highly connected to each other, considerable volumes of soil moisture can be transported rapidly for relatively long distances. However, not all large pores form long continuous pathways; instead they start and stop erratically. When this occurs, water may back up within the pores and eventually disperse into smaller neighboring pores slowly through matric potential. This process helps supplement longer-term soil moisture reserves in micropores.

Precipitation moving in macropores and mesopores that are well connected vertically through the entire soil mantle is the primary mechanism for the resupply of **groundwater**, known as **groundwater recharge**. Groundwater occurs in all types of bedrock beneath the soil. Many people imagine groundwater existing as free-flowing underground streams or rivers of water in bedrock, but this situation rarely exists except occasionally in limestone geology where the rock itself is relatively easily dissolved by groundwater. Instead, in most geologies groundwater exists in and flows through small fractures and voids (mm- or cm-scale) in the rock (Figure 3). The term groundwater refers to underground areas where the bedrock or soil is saturated (i.e., all the fractures and voids are filled with water). The rock or soil material that holds groundwater is called an **aquifer**, and the **water table** is the top surface of the groundwater and the aquifer. Consequently, the water table separates the **saturated zone** from the overlying **unsaturated zone** where fractures and voids contain water along with air.

Groundwater aquifers that are located relatively near the ground surface tend to be small and are termed **seasonal aquifers**, or **local aquifers**. Their water sources usually originate from relatively recent precipitation events (e.g., within the past year). Groundwater aquifers that are located in deep bedrock typically are much larger, and are termed **regional aquifers** because they may extend under many small and/or large watersheds. They tend to be very thick and hold large quantities of old water (e.g., tens of years to thousands of years old). Concentrations of total dissolved solids in water in seasonal aquifers generally are lower than in regional groundwater aquifers because of differences in contact time with the surrounding bedrock (Hem 1970). Regional aquifers are important sources of water for drinking, irrigation, and industrial uses in many parts of the U.S. Some of the largest and most important aquifers in the U.S. are shown in Figure 5.

Groundwater also provides water for streamflow through contributions known as **baseflow**. Baseflow is the portion of streamflow that is not attributable to current precipitation or snowmelt inputs and is the only portion of streamflow that is present during precipitation-free and snowmelt-

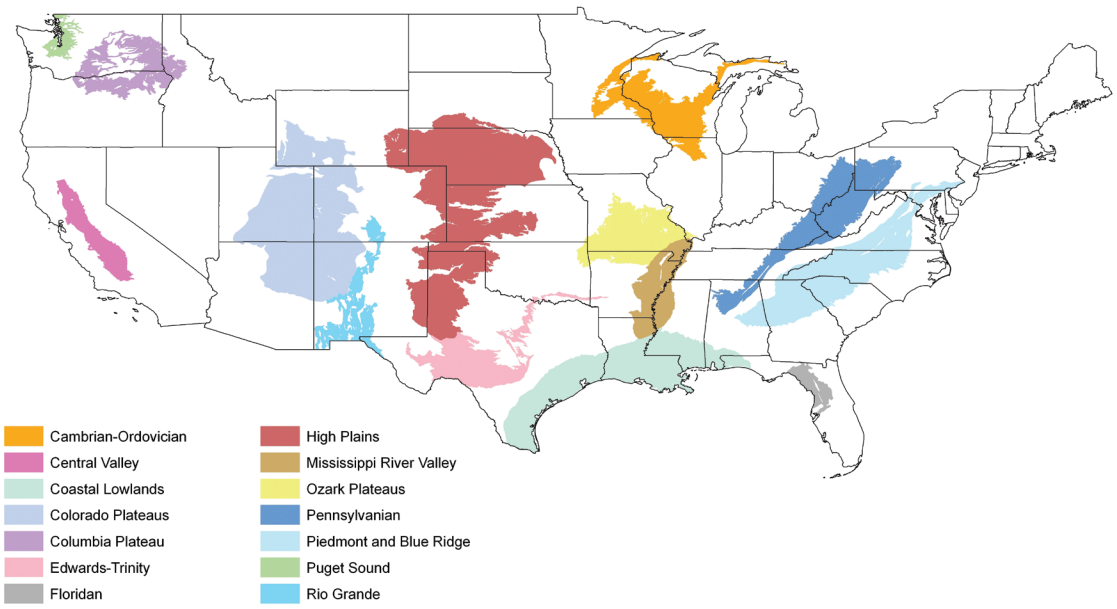

Figure. 5. Some of the major groundwater aquifers in the U.S. Most are named for their location (e.g., Floridan) while two are named after the geologic age of the rocks that host the aquifer (the Cambrian-Ordovician aquifer and the Pennsylvanian aquifer). Note the large area that each of these regional aquifers occupies.

free periods. Baseflow exists because the water table intersects the bed of local stream or river channels. Because storm-free and melt-free periods dominate most U.S. climates, baseflow is the main source of streamflow in U.S. streams and rivers.

Stormflow is the component of streamflow that results directly from current precipitation or snowmelt events. Stormflow is delivered to surface waters primarily by subsurface flow through macropores and mesopores that connect to stream or river channels. While these pathways can exist anywhere within the soil, in many (if not most) forested watersheds, the location of many of these pores is believed to be directly on top of bedrock or soil layers with low permeability. Thus, water is transmitted vertically downward to the impermeable layer and it then flows along the top of that layer until it is discharged into the water body. Some precipitation or throughfall may fall directly into a water body, and this is called **direct channel precipitation** or **channel interception**. Channel precipitation can contribute to stormflow, but the total input generally averages less than 10 percent of total stormflow (Buda and DeWalle 2009; Crayosky et al. 1999). Because micropores hold soil moisture under tensions that exceed gravitational forces, they do not contribute water to streamflow.

The actual process of stormflow delivery in forests is described by the **variable source area concept** (Hewlett and Hibbert 1967), whereby stormflow sources change during the course of a precipitation event. Initially only small portions of the watershed area actively contribute to stormflow, but contributing areas expand non-uniformly throughout the event (Figure 6). Most of the areas that contribute directly to stormflow tend to be either nearest to the channels, where soils already have higher pre-storm, or antecedent soil moisture levels, or in areas with shallow soils that become saturated rapidly, and therefore can release water for streamflow quickly.

In watersheds dominated by land uses other than forests, streamflow generation can occur quite differently. For example, in agricultural systems where soil tilling has occurred, a till layer (or plow pan) that is more compacted than the overlying soil often forms just below the depth of the tilling implement (i.e., ~ 15 to 20 cm below the surface). When water infiltrates the soil, its downward movement may be retarded by the till

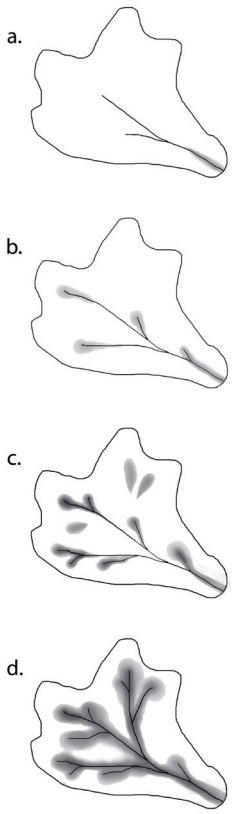

Figure 6. A schematic illustrating the progression of soil-moisture wetting and streamflow development in forested watersheds, following the variable source area concept. Shaded areas in each illustration indicate water-saturated soils. The duration of precipitation as well as the volume of streamflow are increasing from illustration "a." to "d.". The portion of the watershed contributing soil moisture to streamflow changes non-uniformly through time. As the soil becomes increasingly wet, channel length expands and streamflow may develop in ephemeral reaches. After precipitation ends and soil moisture decreases, the contributing areas and channel length shrink, moving in the direction from "d." to "a.", though reversal does not necessarily follow the exact inverse patterns of wetting. Drawing by Robin L. Quinlivan.

layer and diverted along it at this shallow depth. Consequently, water may be transferred laterally by subsurface flow at a relatively rapid rate, so precipitation becomes streamflow quickly. In the Midwest, agricultural soils are commonly drained by lines of perforated tile, which can have a similar effect. During the dormant season when crops are not transpiring, water in the upper soil layers is delivered rapidly via the tile drains to ditches and small streams. In watersheds dominated by urban development, there is much less opportunity for precipitation to infiltrate into soils because large areas are composed of impervious surfaces, such as streets, parking lots, and building roofs. Urban runoff typically is diverted through drains directly to streams and rivers, so streamflow can increase very rapidly. Localized flooding can result when a water body is no longer capable of containing the extreme amounts of runoff that it receives. In some areas, detention basins (or stormwater ponds) are constructed to temporarily store runoff and reduce the amount discharged to surface waters (see Edwards et al. 2015, Guiding Principles for Management of Forested, Agricultural, and Urban Watersheds, this issue).

In response to the occurrence or absence of precipitation, snowmelt, and evapotranspiration, streamflow (also called **discharge**) is constantly changing. Graphical displays of discharge volumes in streams and river systems plotted against time are known as **hydrographs**. Hydrographs can be depicted over any period of time, including but not restricted to, a single storm, a day, a week, a month, a season, or a year. Respectively, each of these is termed a **storm hydrograph** (Figure 7), **daily hydrograph**, **weekly hydrograph**, **monthly hydrograph, seasonal hydrograph**, and **annual hydrograph**.

Hydrographs often are compared among watersheds to understand hydrology in different catchments. Similarly, hydrographs can be compared before and after a disturbance or management activity (e.g., urbanization or harvesting) to determine how that activity affects total discharge or hydrograph responses for specific periods – often storms. Rather than comparing

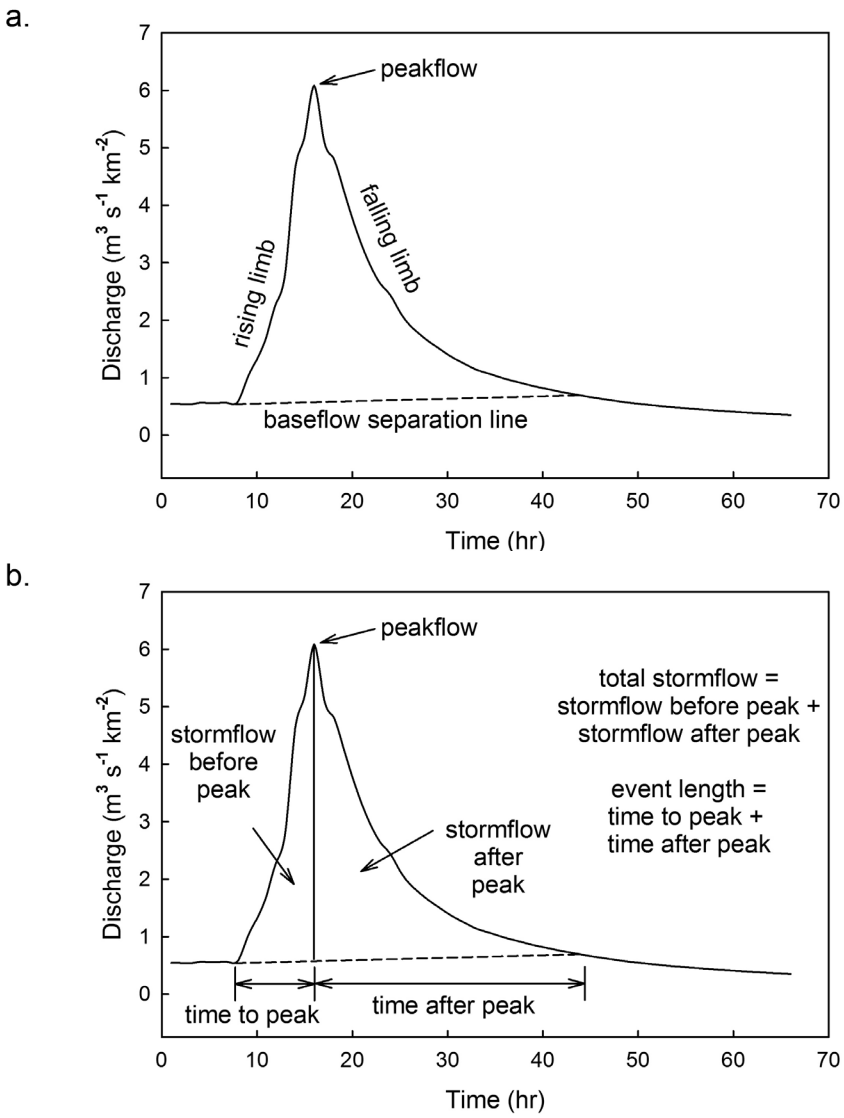

Figure 7. a.) The general components of a storm hydrograph. b.) The hydrograph variables stormflow volume before peak, stormflow volume after peak, total stormflow volume, peakflow, time to peak, time after peak, and total event length are defined from the general components and can be quantified for comparison between different time periods or to other watersheds.

entire storm hydrographs, individual parts of storm hydrographs are compared. The major components of a storm hydrograph are the **rising limb** (or **climbing limb**), the hydrograph **peak** (or **peakflow** or **instantaneous peakflow**), the **falling limb** (or **recession limb**), and the **baseflow separation line** (Figure 7b). From these, several time and volume variables of storm hydrographs can be quantified for comparison among watersheds or between time periods.

When actual baseflow contributions are unknown, the baseflow separation line is used to estimate baseflow contributions and separate them from stormflow or snowmelt contributions. The discharge represented by the area under the hydrograph and above the baseflow separation line is commonly referred to as **stormflow** or **quickflow**. The discharge represented below the baseflow separation line is considered baseflow. There are many ways to delineate the baseflow separation line for any storm hydrograph (Brodie and Hostetler 2005). The approach shown in Figure 7 depicts a simple graphical separation method known as the **constant slope method**. In this

example, the baseflow separation line has a fixed slope of 5 percent extending from the start of the rising limb to where it intersects the falling limb.

Baseflow is the critical component for distinguishing between the three different types of stream channels (Figure 8). **Perennial streams** have baseflow (i.e., flow) present year-round because they are fed by regional groundwater aquifers. **Intermittent streams** also receive groundwater inputs, but from less expansive seasonal aquifers; consequently, rather than having streamflow present year-round, intermittent channels have surface flow present only part of the year – typically 5 to 9 months – when the seasonal groundwater aquifer is in contact with the channel bed. This period with flow corresponds primarily to seasons when precipitation is high, or evapotranspiration is low, or both. Groundwater reserves in seasonal aquifers swell in areal extent in response to recent periods of plentiful precipitation, and shrink during periods of little precipitation or high evapotranspiration. Consequently, the length of an intermittent channel that has surface flow changes throughout the year (Figure 9). Eventually the seasonal water table will fall entirely below the intermittent channel and surface flow will disappear until substantial groundwater recharge occurs.

Ephemeral streams are the final type of stream. Streamflow is present in ephemeral channels only during or immediately after storm or snowmelt events, and the source of water is soil moisture contributions from macropore and mesopore flow, and **overland flow** if present. Groundwater never contributes to streamflow in an ephemeral channel because the water table is always below the streambed (Figure 8).

Even though stormflow provides the flow for ephemeral streams, surface flow will not necessarily be generated by every storm or snowmelt event in every ephemeral channel. Some ephemeral channels begin to flow quickly during most events, at least those with some minimum amount of precipitation or melt, while others flow only rarely, such as when soil moisture is saturated or nearly saturated – this is the essence of the non-uniformity of moisture delivery at the heart of the variable source area concept (Figure 6). The frequency of stormflow and extent of flow length in ephemeral channels is especially dependent upon soil thickness, the degree of connectivity and density of mesopores and macropores near the stream, and the presence of soil or geologic layers with low permeability.

In most forested watersheds, ephemeral channels are a very important part of the stream channel network. It is common for the length of ephemeral channels to exceed the combined total length of intermittent and perennial channels (Hansen 2001). Limestone geology provides the exception to this generalization. The high permeability of limestone and the commonness of subsurface caves within limestone terrains, circumvent the lateral movement of stormflow needed for development of ephemeral channels. Instead, water can move quickly downward into the bedrock to become groundwater that contributes to perennial or intermittent streams.

Although ephemeral, intermittent, and perennial channels are described as distinct from one another, in reality they are simply different segments, or reaches, of the same stream. Typically, ephemeral channels are present in the uppermost headwaters of a catchment. Locally, they may be small, well-defined channels, but elsewhere they may be identifiable only by small amounts of soil scour or litter displacement on the soil surface. Identification of ephemeral channels that flow rarely, especially those that flow once or less per year can be difficult because they may look more like swales than actual channels. Due to prolonged periods without streamflow, ephemeral reaches either do not support aquatic life, or they support only limited types of highly specialized aquatic fauna (McDonough et al. 2011).

Ephemeral stream reaches typically transition to intermittent channels further downstream. Intermittent channels generally are characterized by well-developed channels but they tend to be narrower than perennial channels in the same topography or geology. Even so, it can be difficult to visually distinguish between intermittent reaches and perennial reaches without previous knowledge of the stream in question. While intermittent reaches cannot support fish year-round, they sometimes provide refuge to fish during periods with very high flow or stressful water quality (e.g., high sediment levels during large runoff events).

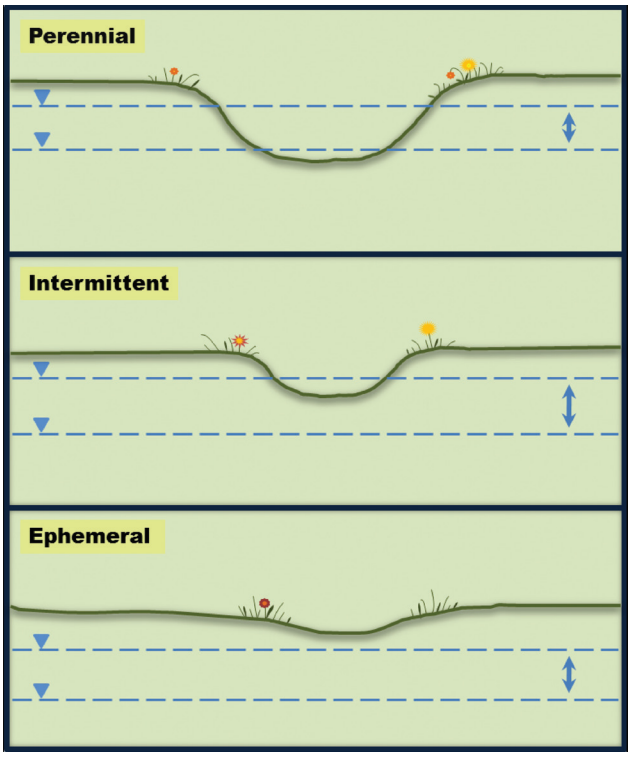

Figure 8. Channels are defined as perennial, intermittent, or ephemeral based on the duration that they receive groundwater inputs. The water table (top of groundwater) at various times throughout the year is shown by the dashed blue lines with the inverted triangles. The ground surface and stream channel bottom are shown by the shaded dark gray line. In perennial channels, the water table is always above or at least level with the bed of the channel so streamflow is present year-round (excluding years of extreme drought). In intermittent channels, the water table is above the channel bed during part of the year, usually 5 to 9 months. In drier months the water table drops below the channel bed and the intermittent channel reaches dry up. When soil moisture is replenished, the water table rises above the bottom of the channel and streamflow begins again. Ephemeral channels receive no groundwater inputs because the water table is always below the streambed. Consequently, streamflow in ephemeral channels is comprised only of stormflow and snowmelt. Drawing by Robin L. Quinlivan.

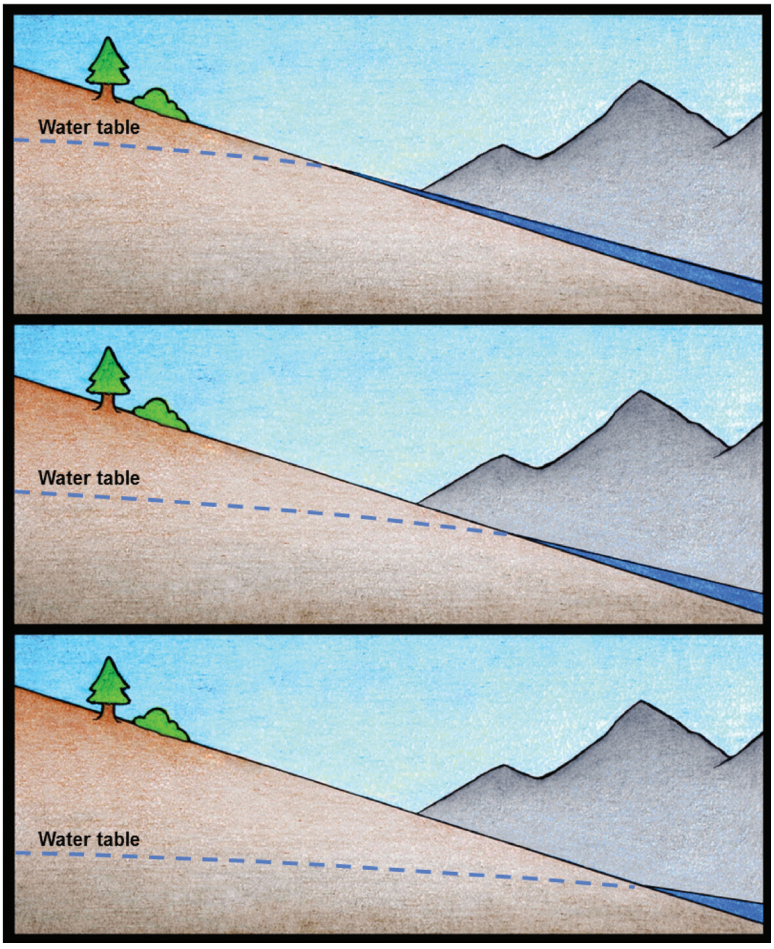

Figure 9. The position where surface flow is present in intermittent channels changes throughout the time that these streams hold surface water. When the water table (dashed blued line) is at its highest level, streamflow (solid blue area) in intermittent channels extends furthest upstream (top drawing). As the water table falls (moving from the upper to middle to lower drawing), groundwater intersects the channel bed progressively further downstream, shortening the length of surface flow. Drawing by Robin L. Quinlivan.

Fish move into the intermittent reaches for short periods, and as water levels drop they return to perennial reaches. Intermittent reaches do support other aquatic life forms (e.g., some snail species and many aquatic insect species) that are adapted to the cycles of flow/no flow conditions. Adaptations to survive these conditions include burrowing into the moist streambed after surface flow has ended, reaching adult phases and flying away prior to drying, floating into downstream perennial reaches prior to complete loss of seasonal groundwater, and developing drought resistant eggs (Gordon et al. 2004). Perennial reaches generally are found downstream of intermittent reaches, and they have well-defined channels. Fish and aquatic macroinvertebrates that require year-long water are present in perennial reaches, provided other requirements (habitat, temperature, water quality, etc.) are conducive to sustaining aquatic life.

The classical depiction of stream channel progression in headwater catchments is the transition described above: ephemeral reaches in the headwaters followed by intermittent reaches downstream that eventually become perennial. However, it is important to understand that other patterns of channel reaches are possible, particularly where bedrock is near the soil surface. For example, it is common to find instances where perennial reaches sporadically exist within a longer intermittent reach because bedrock exposed in the streambed transmits groundwater to the surface. In this situation, emergent groundwater enters the channel in the perennial reach and during dry periods typically infiltrates into the channel bed downstream in the next intermittent reach. In some ecosystems, reach transitions can be complex, making it difficult to identify the type of channel present based solely on visual characteristics (Hansen 2001).

The Water Budget Equation

The hydrologic cycle for a watershed is described mathematically by the **water budget equation**:

$$Q = P - ET \pm \Delta S \pm \Delta GW \qquad \text{Equation 1}$$

where Q is streamflow or discharge, P is precipitation, ET is evapotranspiration, ΔS is the change in soil moisture storage (i.e., water present in all types of soil pores), and ΔGW is the change in groundwater aquifer storage. As mentioned previously, precipitation is an input of water to a watershed, and evapotranspiration is a loss or output of water; by comparison, the soil moisture storage and groundwater terms are "change" terms, in that they may increase and decrease during the period of interest. Therefore, the influence of these two terms on streamflow depends upon how much they change and the net direction of that change during that time. The form of the equation shown in equation 1 is used to calculate streamflow, but conceptually it can be used to solve for any of the variables. As written, the water budget equation illustrates an important fact of the hydrologic cycle: streamflow will occur only if inputs of water to the watershed exceed all of the other outputs or uses of water in the watershed. If other demands or outputs exceed total inputs, streamflow will cease.

In practice, to complete the calculations in equation 1 all of the components of the water budget must be in the same units. Standard units for use in the water budget equation are typically volume or depth units. Volume units are fairly straight forward and easy to understand. By contrast, depth units – or at least the concept of depth units – are not so straight forward. The depth for each of the variables in the equation is equivalent to the depth of water that would result if the entire volume of water for each respective variable for the time period of interest was spread evenly over the entire watershed surface, assuming no runoff or infiltration. Consequently, for a watershed with a total of 750 mm of streamflow for a year, that water would be 750 mm deep if it was spread over the surface of the watershed. This value should not be confused with the depth of water in the channel, although this is a common misconception.

On an annual basis, the water budget equation can be shortened to:

$$Q = P - ET \qquad \text{Equation 2}$$

This is because annual periods can be defined for a given watershed that can result in the ΔS and ΔGW terms becoming approximately zero. This is done by using a 12-month "**water year**" that begins and ends in either the consistently wettest time or the consistently driest time of the year for

that watershed. In the wettest part of the year, soil moisture and groundwater are close to a normal maximum, so ΔS and ΔGW approximate zero. Analogously, by starting and ending the water year in the driest part of the year, the soil moisture and groundwater levels will be close to their normal minimums so the change in those variables over the water year is also approximately zero.

The exact water year used for a particular watershed should be determined using historical information for that area to identify months that consistently have the wettest or driest watershed conditions. These times typically correspond to periods with high and low precipitation, respectively, but not necessarily with the months that have absolutely the greatest or the least precipitation; other factors, such as levels of evapotranspiration during those times may negate some of the precipitation effects, or the driest periods may correspond to months that are influenced erratically by tropical storms.

There is no standard water year used nationally, or even regionally, but there are some water year designations that are fairly common in the U.S. These include October 1 to September 30, May 1 to April 30, and July 1 to June 30. The use of water years extending from January 1 to December 31 is rare, so the water year designation typically corresponds to the calendar year that has the most months of that water year. For example, water year May 1, 2010 through April 30, 2011 would be termed water year 2010 because 8 months of that water year occur within the 2010 calendar year.

The water budget equation provides a relatively simple mathematical tool for predicting how water availability will change with different watershed management scenarios – this application is described in more detail in Guiding Principles for Management of Forested, Agricultural, and Urban Watersheds (Edwards et al. 2015, this issue). It is important to understand that the water budget equation is used to describe and predict hydrologic responses for an entire watershed, not just for a part of a watershed. This is because the watershed is assumed to operate like a closed system such that outputs from a watershed are fully dependent only on the inputs within the watershed. The boundaries of most watersheds ensure that this relationship generally holds. However, there are some situations where transfers of water occur across watershed boundaries, and without accounting for the magnitude of those losses or gains, any calculations from the water budget equation will be in error.

The most significant examples of transfers across watershed boundaries are man-made. These are called **inter-basin transfers** or **trans-basin diversions**. Such transfers typically involve conveyance of streamflow via pipelines or aqueducts from one watershed to another where water is less available. Many metropolitan areas in the U.S., including Denver and Los Angeles, depend upon inter-basin transfers for human potable water supplies. Diverted water also has other uses including hydropower production and agricultural irrigation. There are many social and environmental considerations associated with inter-basin transfers of water that are beyond the scope of this paper, but a plethora of scholarly papers can be found on these topics (e.g., Snaddon and Davies 1998; Gibbins et al. 2000).

In addition to these human-engineered trans-basin diversions, there are also natural transfers of water between watersheds. These too must be accounted for in hydrologic budget calculations, but it is difficult to know of these transfers because they result from the orientation and composition of bedrock geology which are not evident from the watershed surface. Bedrock that dips toward an adjacent watershed and that is sufficiently non-porous and unfractured (i.e., impermeable) to prohibit vertical downward moisture movement can divert groundwater or soil water across watershed boundaries (Figure 10). In terms of water budgets, these dip transfers are much less significant than human-engineered transfers and can be considered negligible in most watersheds because bedrock most commonly dips where there has been uplift during mountain formation. Uplifting processes also increase the likelihood of bedrock fractures which promote vertical moisture movement rather than cross watershed-boundary moisture diversion.

Conclusion

Hydrologic processes govern how water moves through terrestrial environments and becomes

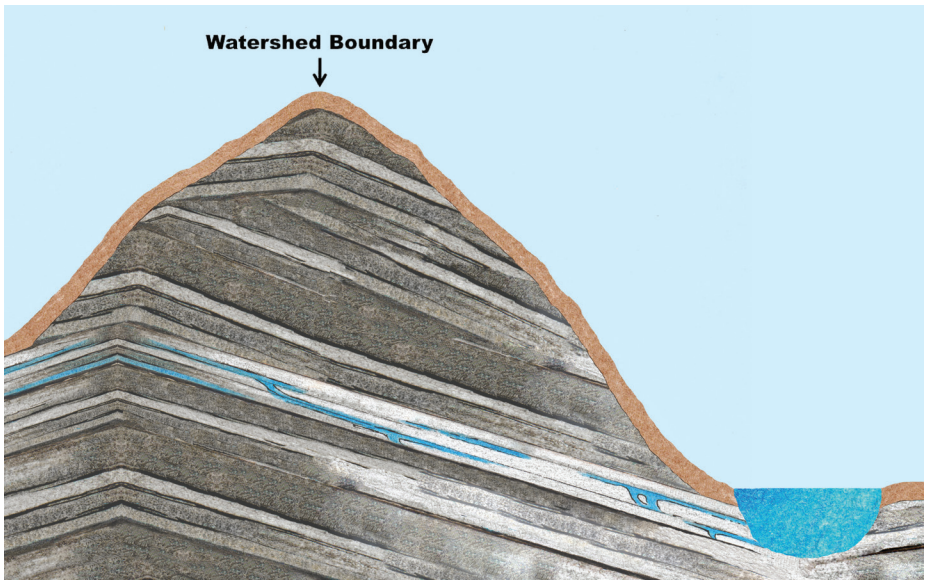

Figure 10. The dip of folded or tilted bedrock can transfer water across watershed boundaries where geologic layers are unfractured and relatively impermeable. Drawing by Robin L. Quinlivan.

groundwater and surface water. The water budget equation provides a relatively simple mathematical tool for explaining, in relative terms or as calculated values, how water availability will change with alterations to inputs or outputs of the hydrologic cycle. Similarly, knowledge of basic watershed characteristics, such as the percentages of different land uses, levels of soil compaction and infiltration capacities, and the sources of streamflow can provide valuable information for managing and protecting water resources.

Historically, watershed protection was considered the responsibility of state or federal governments. However, as high quality water has become less available and there are competing uses for every liter of water, the protection and conservation of water resources is becoming increasingly reliant on grass-roots, citizen-led efforts. Therefore, it is critical for all citizens, as well as current and future leaders, to have a solid foundation in the science of hydrology.

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Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 154, Pages 21-47, April 2015

An Introduction to Soil Concepts and the Role of Soils in Watershed Management

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Abstract: Soil is a non-renewable dynamic natural resource that is essential to life. Water movement, water quality, land use, and vegetation productivity all have relationships with soil. This article introduces many important soil concepts including development, classification, properties (physical, chemical, and biological), quality, and conservation. A general understanding of soil concepts and these interwoven relationships is essential to making sound land management decisions.

Keywords: *soil conservation, soil developoment, soil disturbance, soil management, soil properties, soil quality, soil taxonomy*

Soil plays a vital role in sustaining life on the planet. Nearly all of the food that humans consume, except for what is harvested from marine environments, is grown in the Earth's soils. Other obvious functions that soils provide humans include fiber for paper and clothing, fuelwood production, and foundations for roads and buildings. Less obvious functions that soils serve are providing a medium to attenuate pollutants and excess water, groundwater recharge, nutrient cycling, and habitat for microorganisms and biota. Soils also have many secondary uses such as ingredients in confectionaries, insecticides, inks, paints, makeup, and medicines; uses of clays range from drilling muds, pottery, and artwork, to providing glossy finishes on various paper products.

Soil is a critical component of nearly every ecosystem, but is often taken for granted. Soil can be thought of as the ecosystem foundation, as soil productivity determines what an ecosystem will look like in terms of the plant and animal life it can support. For example, in forest ecosystems, soils can determine species composition, timber productivity, and wildlife habitat, richness, and diversity. The role soil plays in forests is also critical to maintaining water quality and long-term site productivity. In cultivated fields, soil quality plays a significant role in crop productivity since soil nutrients and soil physical properties can directly impact yields. In urbanized areas, soil plays a vital role in reducing runoff through infiltration and nutrient attenuation. The value of soil is easily overlooked until soil quality becomes degraded and the critical services the soil once provided are diminished.

Soil Overview

Soil Defined

The definition of soil is relative to the function it provides to the person(s) defining it. From a morphological stance, the Natural Resource Conservation Service (NRCS) defines **soil** as: "a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment" (Soil Survey Staff 2014a). The Soil Science Society of America (SSSA) defines **soil** in terms of its genetic and environmental factors: Soil is "[T]he unconsolidated mineral or organic matter on the surface of the Earth that has been subjected to and shows effects of genetic

and environmental factors of: climate (including water and temperature effects), and macro- and microorganisms, conditioned by relief, acting on parent material over a period of time. A product-soil differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics" (SSSA 2008).

The Soil Profile

The vertical section of soil that shows the presence of distinct horizontal layers is known as the **soil profile** (SSSA 2008). The term **horizon** refers to the individual or distinct layers within the soil profile. Most soils are composed of several horizons (Figure 1). Typically, horizons of a soil profile will follow the topography of a landscape. Designation of horizon boundaries also comes from measurements of soil color, texture, structure, consistence, root distribution, effervescence, rock fragments, and reactivity.

The uppermost layer, the **O horizon**, consists primarily of organic material. Forested areas usually have a distinct O horizon. However, in some settings such as a grassland or cultivated field, there may be no O horizon present. Factors such as erosion or constant tillage contribute to the lack of organic matter. The O horizon has three major sub-classifications, or subordinate distinctions (designated by the lowercase letter): hemic (Oe), fibric (Oi), and sapric (Oa). The hemic layer consists of decaying material that is slightly decomposed, yet the origin is still identifiable. The fibric layer is composed of organic material that is slightly more decomposed and unidentifiable, but is not decayed entirely. The sapric layer consists of fully decomposed material whose origin is completely unidentifiable.

The **A horizon** is a mineral horizon that is formed at or just below the soil surface. It is commonly referred to as the "surface soil." Some characteristics of an A horizon may include the accumulation of organic matter and/or the presence of a plow pan. A plow plan (or plow layer) is a common characteristic of soils that have undergone conventional tillage at some point in recent time. The darkness of the A horizon can sometimes be attributed to the movement of organic matter from the overlying O horizon. Soils under intense cultivation will incorporate materials that would normally be considered part of the O horizon. These organic materials also contribute to the A horizon leading to a higher organic content than other horizons.

The **E horizon** (eluvial layer) is a common mineral horizon in forest soils that is distinguished by its lack of clay, iron (Fe), or aluminum (Al). The loss of the above materials is known as **eluviation**, which entails that these substances and dark minerals have been stripped from the soil particles. Clay, Fe, and/or Al are removed from the E horizon via leaching, which causes its light color compared to the adjacent horizons. **Leaching** is the loss of nutrients from the root zone due to the movement of water through the soil profile. The E horizon is comprised of concentrations of quartz, silica, or other minerals that are less susceptible to leaching.

The **B horizon**, known as the "zone of accumulation", occurs below the O, A, and/or E horizons, if present. The B horizon receives deposits of **illuviated** materials such as clay particles, Fe and Al oxides, humus (organic matter formed from the decay of plant and animal matter), carbonates, gypsum, and silicates leached from the overlying horizons. The common presence of Fe and Al oxide coatings often give the B horizon a redder or darker color than the adjacent horizons.

The **C horizon** is the soil layer that generally sees little influence from pedogenic weathering processes and is therefore comprised of partially weathered parent material. The C horizon represents a transition between soil and bedrock. As the upper portion of the C horizon undergoes weathering, it may eventually become part of the overlaying horizons. There is an obvious shift in soil structure between strongly developed B and C horizons that aids in identifying the horizon boundary in the field; however, the structure shift may be more subtle in weakly developed soils.

Under the C horizon comes the **R horizon**, or bedrock. Depending on the geographic location, environmental conditions, and landscape position, bedrock may be found in excess of 100 feet deep or merely centimeters from the soil surface. Bedrock is a consolidated layer of rock material that gave way to the soil properties found on the site. Bedrock is occasionally disrupted or broken

up by tree roots, but roots generally cannot cause enough stress on the rock to fracture it, so much of the deeper bedrock weathering is biochemical in nature. The layer of freshly weathered material, in contrast to the solid rock (i.e., bedrock), is generally termed saprolite/saprock.

The division of the soil profile termed the **regolith** is defined as "the unconsolidated mantle of weathered rock and soil material on the Earth's surface which extends from the soil surface to the bottom of the parent material" (SSSA 2008). So basically, the regolith is the heterogeneous material that lies on top of solid rock. The soil **solum** is the weathered soil material in the upper soil horizons (typically A, E, and B horizons) located above the parent material (C horizon). Not every soil profile is comprised of the same horizons. Some profiles will contain O, A, E, B, C, and R horizons while another soil profile may only be composed of a C and R horizon. These differences in horizonation are what make soils unique. The unique characteristics of soil allow soil scientists to classify soils into different categories via Soil Taxonomy (see Soil Classification section).

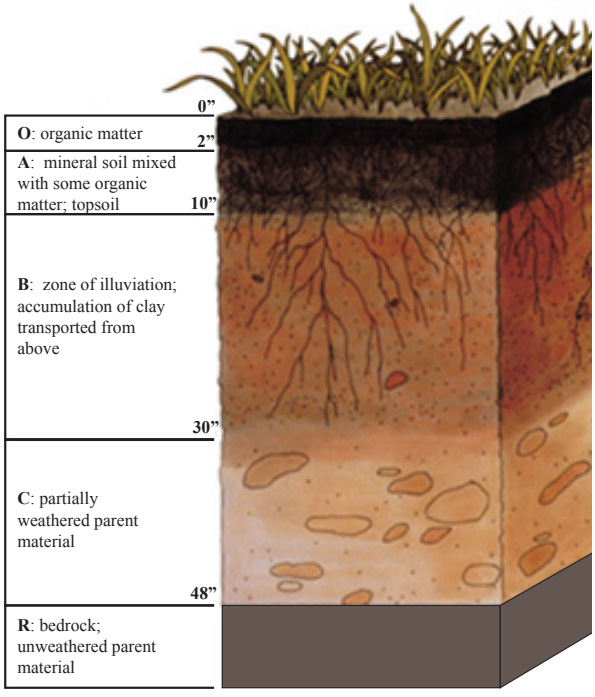

Figure 1. Master horizons identified in a typical soil profile. Source: USDA NRCS; adapted.

Soil Formation

The 5 soil-forming factors that influence the development of soil were first termed by Hans Jenny, an American soil pedologist in the early- to mid-1900s. The factors he determined as essential in the formation of soil include: parent material, climate, biota, topography, and time (Jenny 1994). Hans presented these factors as a formula: s = f (PM, Cl, O, R, T). The formula roughly translates to soil is a function of parent material, climate, organisms, relief, and time. This section will briefly discuss the role of each of the soil-forming factors and how each factor aids in soil development.

Parent material. Parent material is the unconsolidated and chemically-weathered mineral or organic matter from which the soil is developed. It consists of any number of combinations such as limestone, sandstone, or even volcanic rock. The area of the soil profile known as the "C Horizon" is comprised of parent material. Parent materials attribute to both the chemical and physical properties of a soil and can affect soil drainage, porosity, and plant available water, among other things. Parent material in any location can vary greatly even in areas adjacent to one another. For instance, Illinois contains eight different soil regions that are a result of glaciations, wind-blown materials, and continuous weathering of parent material.

Climate. In early soil profile development, parent material gives way to the major physical and chemical properties of a soil. As the soil becomes more developed (through horizon formation and increased soil structure over time), its characteristics depend more heavily on the climatic conditions to which it is exposed. Climate plays a significant role in the formation of soil and any number of climate-related occurrences (e.g., precipitation and temperature) may influence soil development.

Biota. Soil profile features related to biotic (plant and animal) activity such as burrows, mounds, root channels, and worm castings contribute to soil profile development because each of these processes change the porosity of the soil. The burrowing of animals, much like old root channels,

creates large pores for rapid movement of water, gases, and solutes through the soil. The structure of some surface horizons is formed entirely by animal activity (earthworms, ants, termites, and other organisms). Earthworms are capable of consuming their own body weight in food daily (Minnich 1977). They are also responsible for the 'sinking' of objects through the soil profile over time (Darwin 1897). Charles Darwin devoted his last book, "The Formation of Vegetable Mould Through the Action of Worms" to the process of **bioturbation**, the process in which plants and animals facilitate the mixing, or rearrangement, of the soil profile.

Much like animals, plants can have a strong influence on soil properties. For example, whether a soil is formed under forest cover or prairie vegetation can greatly influence the carbon inputs into the system and ultimately how the soil is classified (see Soil Classification section). Plant roots increase infiltration, break up dense soil layers, and can pull nutrients and moisture from deep within the soil profile. Further, windthrow (uprooting of trees by wind) can create a pit and mound topography that helps physically weather the soil by dislodging and breaking rock. Windthrow can also expose deeper soils to surface conditions that may lead to accelerated chemical weathering.

Topography. Topography (slope and aspect) also has a strong influence on soil characteristics. Slope can influence erosion and deposition along a hillslope (Figure 2). Steep soils are susceptible to accelerated erosion and generally have a shallower A horizon and overall less development. Conversely, soil development in flat areas is heavily influenced by soil drainage, where well-drained soils tend to have greater development compared to poorly drained soils. A flat, poorly-drained soil retains water, leaving the soil profile saturated, which slows soil profile development. In well-drained soils, E horizons can develop above a well-developed B horizon due to the eluviation (transport of materials via water) of clay from the upper soil horizons. Additionally, the aspect (or horizontal direction) on which a soil is formed affects profile development. South-facing slopes receive more intense solar radiation than north-facing slopes, which affects soil temperature and moisture conditions. In the Appalachians, south-facing slopes are dominated by coniferous species while north-facing slopes are dominated by hardwood species due to differences in microclimate. Furthermore, topographic position (i.e., summit, shoulder, backslope, and toeslope) influences the development of soils. Generally, summits are well-drained and have strong horizon development, whereas shoulder and backslopes

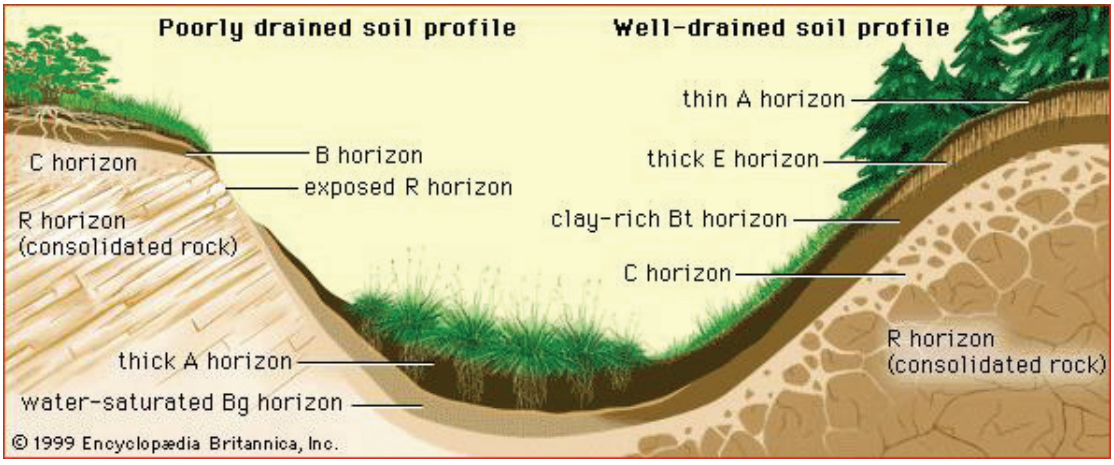

Figure 2. A comparison of hillslope soil profile development in poorly-drained and well-drained conditions. Surface erosion may occur in poorly-drained soils, exposing subsurface soils and transporting soil from upper horizons to the slope bottom. Source: http://www.britannica.com/EBchecked/media/19383/Soil-profiles-on-hillslopes-The-thickness-and-composition-of-soil (Encyclopedia Britannica, Inc. 1999) .

are influenced by erosion and have shallower topsoils and less infiltration. Toeslopes typically accumulate organic matter and topsoil from both alluvial (deposited by streams) and colluvial (primarily deposited by gravity) inputs, leading to thicker A-horizons overlaying relatively young soils.

Time. The duration of time a soil has undergone development is determined largely by the degree of weathering of the soil. Time has two separate meanings in terms of soil formation. Soil is influenced by both chronological and physiological time. The 'age' of a soil commonly refers to the degree or amount of weathering the soil has undergone. This age is not referring to chronological time, but the physiological characteristics attributed to the soil via the weathering process.

Soil Classification

Around the globe, many soil classifications systems have been developed to categorize soils into groups based on morphological and/or chemical properties. The most widely-used classification system is the Soil Taxonomy system that was made known by the United States Department of Agriculture (USDA) (Soil Survey Staff 1999). This system is a morphogenetic system that utilizes both quantitative factors and soil genesis themes and assumptions to guide soil groupings (Buol et al. 1997). "Keys to Soil Taxonomy", a free publication distributed by the USDA, is a great resource for in-depth classification of soils (Soil Survey Staff 2014a). The USDA has also published a free resource titled "Illustrated Guide to Soil Taxonomy" that is similar to "Keys of Soil Taxonomy", but written for a broader audience (Soil Survey Staff 2014b). Both resources can be found on the USDA website listed in the Soil Resources section of this article.

The Soil Taxonomy system is a hierarchical scheme consisting of 6 classification levels. In order from broadest to narrowest, the levels of classification are: 1) Order, 2) Suborder, 3) Great Group, 4) Subgroup, 5) Family, and 6) Series. Currently, there are 12 soil orders, 65 suborders, 344 great groups, ~ 18,000 subgroups, and over 23,000 soil series (Bockheim et al. 2014). The distribution of soil orders across the United States is shown in Figure 3. The defining characteristics of the broadest levels of classification are based on soil-forming processes and parent materials, whereas the narrower levels become much more specific and consider the arrangement of horizons, colors, textures, etc. The soil-forming factor "climate" has a predominate role in Soil Taxonomy classification, followed by parent material, and biota; topography and time are not utilized in defining taxa (Bockheim et al. 2014).

Soil Orders

Entisols are the 'youngest', or most recently formed soils of all the soil orders. Characteristics of Entisols include weak profile development where very little, if any, horizonation can be documented. Entisols sometimes contain a weakly formed A or Ap (plow layer) horizon. These soils can be found on steep slopes with severe erosion, on floodplains that receive alluvial deposits, and any number of scenarios in between.

Another soil order with notably weak profile characteristics is the **Inceptisol** order. When Soil Taxonomy was first established in 1975, Inceptisols were commonly referred to as the 'wastebasket soil order'. These soils generally did not fit into the other soil orders at the time. When additional soil orders were introduced, many Inceptisols were reclassified and the 'wastebasket' title no longer applies. Inceptisols are somewhere between the stages of no profile development and weak profile development. Inceptisols are commonly found along major rivers and streams due to the weak profile development. Over time, both Entisols and Inceptisols have the potential to develop more horizons, at which time they would likely be reclassified into a different soil order. The features of 'young' soils like Entisols and Inceptisols are more heavily influenced by their parent material, whereas 'old' soils are more influenced by climate and vegetation factors.

Gelisols are also 'young' soils in regard to geologic time and were developed under cold temperatures or frozen conditions. These soils are often associated with permafrost conditions and cryoturbation (frost churning) in places like Canada and Alaska. Permafrost is a perennially frozen soil horizon (SSSA 2008).

Mollisols are commonly referred to as the 'prairie soil'. These soils were formed primarily under grassy prairies and are characterized by their high organic matter content, dark color, and deep A horizon. The A horizon must be greater than 8 inches in depth and requires at least a 50 % base saturation (at least 50 % of the cation exchange sites are occupied; see Soil Chemistry section for more information). Mollisols are common in the midwestern United States where native prairies once dominated the landscape.

Alfisols, formed under deciduous forests, are also very common in the midwestern United States. Alfisols are generally found in humid regions of the world and often contain an E horizon in the soil profile. These soils must have a base saturation of at least 35 %.

Spodosols generally originate from coarse-textured (i.e., increased sand content), acidic parent materials. Spodosols are formed under forest vegetation, especially coniferous forests due to the buildup of pine needles that inherently have high acidic resins. When pine litter decomposes, strongly acidic compounds are leached through the coarse materials, transporting Fe, Al, and humus (Brady and Weil 2007). Thus, an illuvial layer of humus and Fe/Al oxides form. Like the Alfisols, an E horizon is commonly found in Spodosol soil profiles. In many cases, a Spodosol will have a white E horizon on top of a bright red B horizon. Spodosols are associated with loamy or sandy soil conditions and can be found in Wisconsin, Michigan, the northeastern United States, and on the coastal plains of the eastern and southeastern United States.

Aridisols are commonly associated with semi-arid and arid regions. These regions have a low mean annual rainfall. The lack of moisture in the soil affects the soil development and weathering process. Therefore, these soils are primarily affected by physical weathering, not chemical weathering (weathering processes discussed in the Soil Chemistry section). Aridisols are characterized by a high base saturation percentage of ~ 100 %. These soils can be found throughout the deserts or drier areas of the western United States.

Ultisols can be found in humid and warm regions such as the southeastern United States. Ultisols have a high amount of clay mineral

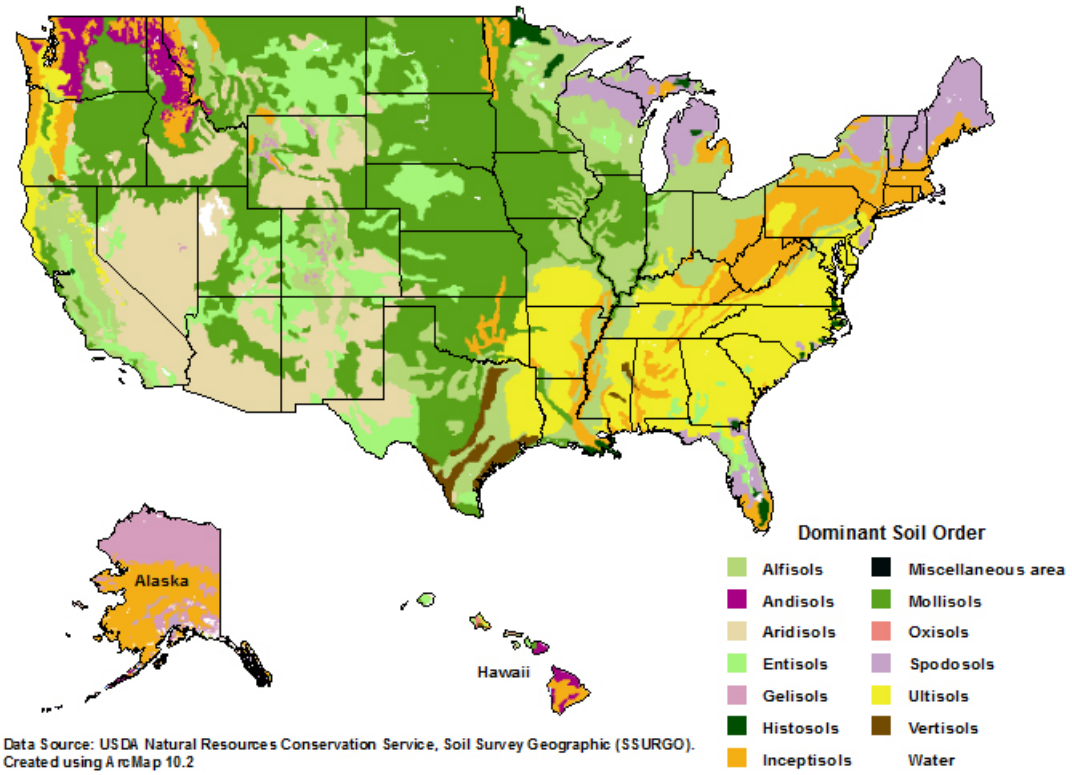

Figure 3. Distribution of soil orders across the United States.

weathering and translocation that leads to a subsurface accumulation of clays (Brady and Weil 2007). They have a base saturation of < 35 % and are naturally less fertile than Alfisols or Mollisols. However, Ultisols respond favorably to nutrient management and are cultivated in many regions of the world. These soils are characterized by a high degree of weathering and are typically more acidic than Alfisols, but less acidic than Spodosols.

Oxisols are the most highly weathered soil order in the U.S. classification system. Oxisols get their name from being oxidized. They are dominated by high clay content and Fe/Al hydrous oxides that typically give the soil a red hue. Oxisols can be found in tropical and sub-tropical regions of the world such as Hawaii, Puerto Rico, South America and Africa. Oxisols are generally formed in wetter environments, but can be found in areas that are presently drier than during the time the soils were formed (Brady and Weil 2007).

Vertisols are soils that lack profile development due to the expansion and contraction of clay-rich soil. These processes cause the soil to mix, which does not allow for clear soil profile development. During dry conditions, the soil shrinks and cracks form that can extend to ~ 80 cm deep and 2 to 3 cm wide. Vertisols are found in the southern United States in places like southeast Texas and eastern Mississippi where smectite, montmorillonite, and vermiculite clays are present.

The **Andisol** order was developed in 1990. Previously, these soils were grouped with the Inceptisol order. Andisols are soils of recent origin (young) that are developed from volcanic materials. They are found in Hawaii and the northwestern United States in places like Washington, Idaho, and Oregon.

Histosols are the only organic soil order in the classification system. Histosols are comprised of several different subhorizons within the O horizon and contain at least 20 % organic matter. Histosols occupy a small total area, but are found in various places in the United States and Canada such as Wisconsin, Minnesota, the Florida Everglades, and along the Gulf Coast.

Suborder, Great Group, Subgroup, Family, and Series

Suborders categorize properties associated with a climatic connotation of the soil. **Great groups** account for the most significant properties of the soil as a whole, including the type and arrangement of soil horizons, temperature regimes, and moisture regimes. Scientists use **subgroups** to further classify soils by assessing the degree of similarity between particular soils and grouping them accordingly. These are intergrades that reflect transitions to other orders, suborders, or great groups. The **family** grouping has similar physical, chemical, and mineralogical properties, which often relate to plant growth. A **soil series** is the lowest level of taxonomy, or the most specific to the soil in question. The soil series classification narrows characteristics of similar soils down to a local level where not only physical, chemical, and mineralogical properties matter, but also management, land-use history, vegetation, topography, and landscape position. Most soil series are named based on the location where the series was first discovered. An example of the taxonomic classification for the Illinois state soil is provided (Table 1).

Pedologists (scientists who study the origin and composition of soils as a component of natural systems) continue to learn more about soil morphology, chemistry, mineralogy, and biota, thus tighter limits on groupings of soils are being defined. Soil scientists are constantly reevaluating soil taxonomy as technology and

Table 1. Example of the taxonomic classification according to U.S. Taxonomy for the state soil of Illinois, USA.

Taxonomic Level	Example for IL State Soil
Order	Mollisol
Suborder	aquoll
Great Group	Endoaquoll
Subgroup	Typic Endoaquoll
Family	Fine-silty, mixed, superactive, mesic Typic Endoaquoll
Series	Drummer

science progress. It is important to remember that soils are dynamic, living environments. Soils are ever-changing through both chemical and physical weathering processes and can vary across the landscape, resulting in corresponding changes in soil classification over time.

Soil Physical Properties

In this section, soil physical properties will be introduced, examples for measurement will be provided, and the applicability in the field will be discussed. Soil physical properties have a profound effect on how soils influence soil quality and productivity. Oftentimes soil quality is driven by soil physical properties that determine nutrient and moisture levels in soils. The physical properties of soil include soil texture, bulk density, water holding capacity, organic matter content, soil structure, soil color, and soil consistence. A useful field guide for describing soil properties is "Field book for describing and sampling soils" (Schoeneberger et al. 2012).

Soil Texture

Soil texture is determined by the amount of sand, silt, and clay in a soil sample. Table 2 shows the size comparison of sand, silt, and clay particles based on the United States Department of Agriculture (USDA) System, one of the most commonly used among several particle size classification systems. Clays have a particle size diameter of < 0.002 mm, silts between 0.002 and 0.05 mm, and sands 0.05 to 2.0 mm. Percentages of sand, silt, and clay categorize soil into different textural classes. Particle size percentages can be compared to the USDA soil textural triangle (Figure 4) to determine soil texture. For instance, a soil with 18 % clay, 60 % sand, and 22 % silt would be considered a sandy loam. Soil texture can be determined in the lab via particle-size analysis using the hydrometer method; this method determines particle-size distribution by measuring the time it takes for soil particles in water to settle out of suspension. The hydrometer method can be time consuming, requires certain equipment, and is not optimal for most people. However, anyone can determine textural class using the "Feel" Method. This involves forming a moist soil sample into a ball and squeezing it between the thumb and index finger to make a ribbon. Texture is determined by ribbon length (if one can be formed at all) and grittiness or smoothness of the sample. A step-by-step guide to the "Feel" Method is available on the NRCS website (see Soil Resources section). With practice, the "Feel" Method provides an immediate and accurate way to determine textural class, and even percent sand, silt, or clay, while in the field. Laser Particle Size Analysis (LPSA) has become more commonly used in labs across the country. Although this method is accurate, it requires training/skill to use the analytical instrument and the initial cost is high.

Table 2. Particle diameter (mm) of sand, silt, and clay based on the United States Department of Agriculture System.

Texture Size Class	Particle Diameter (mm)
Very coarse sand (vcos)	1.0 - 2.0
Coarse sand (cos)	0.5 - 1.0
Medium sand (s)	0.25 - 0.5
Fine sand (fs)	0.1 - 0.25
Very fine sand (vfs)	0.05 - 0.1
Silt (si)	0.002 - 0.05
Clay (c)	< 0.002

Bulk Density

Bulk density is the mass of the soil in relation to a known volume of soil and is often used as an indicator of soil compaction. Soil compaction decreases the ability of a plant's roots to penetrate through the soil profile. Bulk density is related to soil textural class and soil porosity. Soils containing a high percentage of porosity will have a lower bulk density. Typically fine-textured soils have lower bulk densities than coarse-textured soils because of increased pore space both

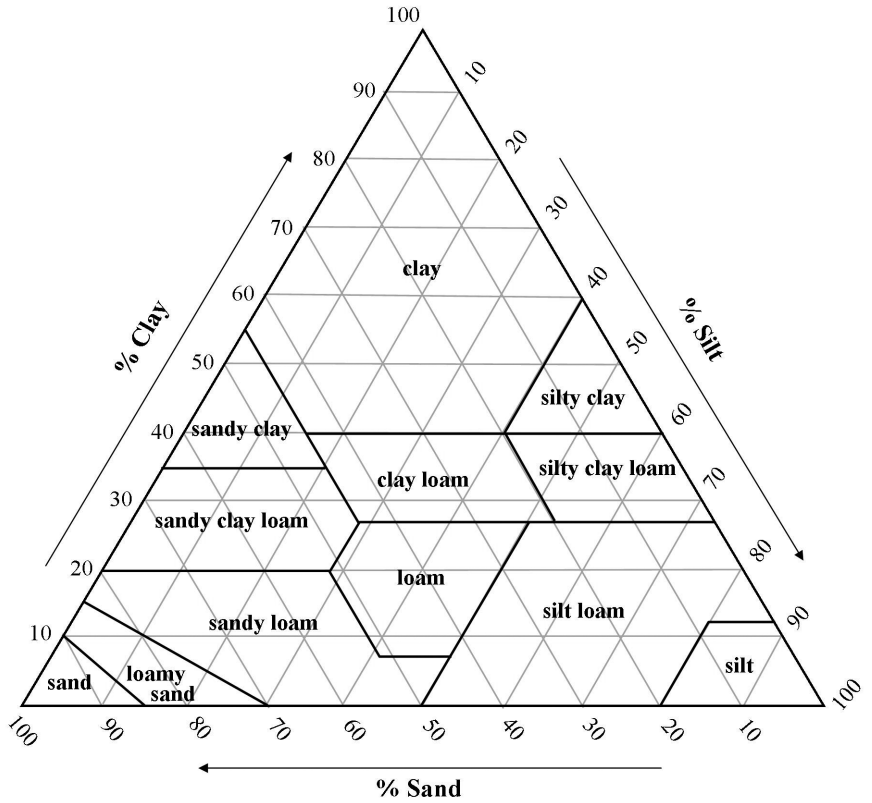

Figure 4. Soil textural triangle. Texture class is based on particle size percentages. Source: USDA NRCS soil textural triangle; adapted.

between (interstructural pores) and within (matrix pores) soil aggregates. Ideal bulk densities for plant growth range from < 1.10 g cm^{-3} for clays to < 1.6 g cm^{-3} for sands (Table 3). Bulk density is also affected by grain size and arrangement of coarse-textured soils. If sandy soils are loosely-packed and of uniform size, porosity is higher and therefore bulk density is lower than sandy soils with tightly-packed aggregates of different grain sizes. If a textural class has a bulk density reading that exceeds the growth-limiting factor for that class, then conditions for plant life are not optimal. Daddow and Warrington (1983) determined growth-limiting bulk densities according to particle size. Generally, the greater the clay percentage is within a soil, the lower the growth-limiting bulk density of the soil because of the increased pore space in clays. The growth-limiting bulk density is ~ 1.40 g cm^{-3} for soils with > 80 % clay and ~ 1.70 g cm^{-3} for soils with < 20 % clay (Daddow and Warrington 1983). The impact of bulk density on root growth according to textural class is shown in Table 3. In addition to texture, land cover and management also impact bulk density. Typically, bulk density readings in a forest are much lower than readings in an agricultural field or an urban area. Forest soils tend to have a higher amount of porosity because of tree rooting, increased biotic activity, increased organic matter on the soil surface, and less anthropogenic disturbances. Bulk density readings, soil texture data, infiltration capacity readings, and penetration resistance data can be compiled to explain soil porosity or degree of compaction. Compaction affects both root penetration and the soil's ability to allow precipitation to infiltrate into the soil profile. Bulk density is commonly measured using a core method where a known volume of soil is collected with a cylindrical soil core, then oven-dried, and weighed. Results are reported as a mass per unit volume (e.g., g cm^{-3}). Bulk density can also be determined via the clod method, where a clod (or ped) of soil is coated in paraffin wax and placed in water to determine the exact volume based on displacement. The clod is then oven-dried,

Table 3. Relationship between bulk density and root growth based on soil texture. Source: Arshad et al. 1996.

Textural class	Ideal bulk density (g cm^{-3})	Bulk density that may affect root growth (g cm^{-3})	Bulk density that restricts root growth (g cm^{-3})
Sands, loamy sands	< 1.60	1.69	> 1.80
Sandy loams, loams	< 1.40	1.63	> 1.80
Sandy clay loams, clay loams	< 1.40	1.60	> 1.75
Silts, silt loams	< 1.30	1.60	> 1.75
Silt loams, silty clay loams	< 1.40	1.55	> 1.65
Sandy clays, silty clays, some clay loams (35 - 45 % clay)	< 1.10	1.49	> 1.58
Clays (> 45 % clay)	< 1.10	1.39	> 1.47

weighed, and reported on a mass/volume basis like the core method. 3-D scanners are also used to determine accurate clod volumes.

Water Holding Capacity

Water holding capacity is the amount of water held by soil. The water holding capacity of a soil is reliant on soil texture, structure, organic matter content, and arrangement of soil pores. Organic matter has a high degree of microporosity, which allows it to retain more water. Therefore, soils with a higher amount of organic matter and/or a large percentage of micropores (e.g., fine-textured soils like clays) generally have a higher water holding capacity. Soil compaction also impacts water holding capacity since soil compaction weakens soil structure and collapses pores, thereby decreasing the soil's ability to hold water. There are several different terms used to discuss water capacity in soils. **Available water** is the amount of water that is readily available for plant uptake; conversely, unavailable water is water that plants cannot utilize. **Gravitational water** (water that drains freely until field capacity is reached) is a form of unavailable water. **Field capacity** refers to the water held by the soil following 24 to 48 hours of free drainage and is available for plant uptake. The **permanent wilting point** is the point at which plants wilt and are unable to recover due to a lack of plant available water. Lastly, **saturation** occurs when all pores are filled with water (Figure 5).

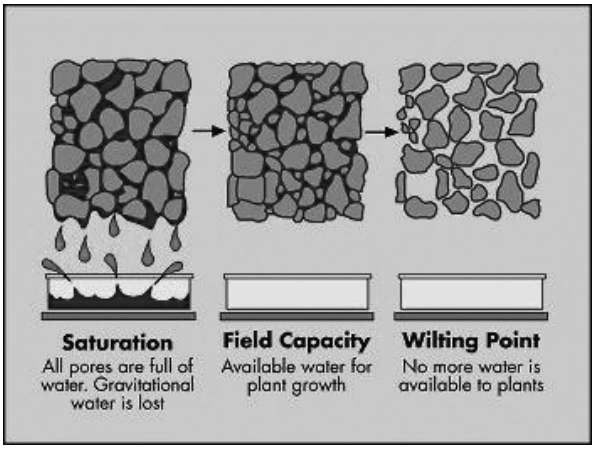

Figure 5. Water holding capacity stages within the soil. Source: Department of Agriculture Bulletin 462, 1960.

Soil Structure

Soil structure is the description of how individual soil particles (sand, silt, and clay) are arranged into soil **aggregates** (also called **peds**) and reflects both physical and chemical weathering. Several factors influence soil structure, including soil texture, soil moisture, organic matter content, compaction, the activity of soil organisms, and management practices. Soil structure is easiest to observe in dry soil. When characterizing soil structure, the shape, size, and grade of the structural units (peds) are defined. The primary soil structure shapes are granular, platy, blocky, prismatic, and columnar. **Granular** soil structure contains peds that are

generally small and round and are commonly found in horizons near the surface where high amounts of root activity are present and porosity is greater. **Platy** soil structure consists of peds that are plate-like (flat and thin) and usually oriented horizontally. Platy soil structure may occur throughout the soil profile, but is common in E horizons or compacted soil. **Blocky** soil structure consists of sharp-edged peds arranged in square or angular blocks and is typically found in the subsoil, especially in humid regions. **Prismatic** soil structure contains peds that are longer vertically than horizontally and have flat tops. **Columnar** soil structure is similar to prismatic, but peds have distinct rounded tops. Both prismatic and columnar soil structure are commonly found in the subsoil of arid and semi-arid regions. Soils can also be defined as "structureless" where soil structure is **single-grained** (typically sand particles that do not stick together) or **massive** (aggregation is not present). Aggregate **size** is typically described as very fine, fine, medium, coarse, or very coarse and the size limits of these classes depend on the aggregate shape. **Grade** describes the distinctness of the peds and is classified as weak, moderate, or strong. More information on size and grade can be found in the Soil Survey Manual (Soil Survey Division Staff 1993). A soil structure description is written as "grade, size, shape", such as "moderate medium subangular blocky structure." Soil structure greatly impacts soil porosity, thereby influencing soil water movement. General infiltration rates (rapid to slow) associated with soil structure shapes are shown in Figure 6.

Soil Consistence

Soil consistence is a measure of the response of soil to applied pressure at various moisture contents. In other words, how well does the soil hold together when under applied stress? Soil consistence is measured separately for dry, moist, and wet soil because moisture content impacts how a soil responds to pressure. In the field, soil consistence is measured by testing the ease with which the soil is crushed between the thumb and forefinger, or underfoot. Additionally, the terms stickiness and plasticity are often used to describe wet consistence. **Stickiness** refers to how well wet soil adheres to other objects (like your fingers) after pressure is released, while **plasticity** describes the malleability of wet soil. Further reading on the topic, including the scale used to describe consistence at different moisture contents, can be found in chapter 3 of the Soil Survey Manual (Soil Survey Division Staff 1993). Soil consistence is one of many soil physical properties used to determine site suitability for agriculture or engineering purposes.

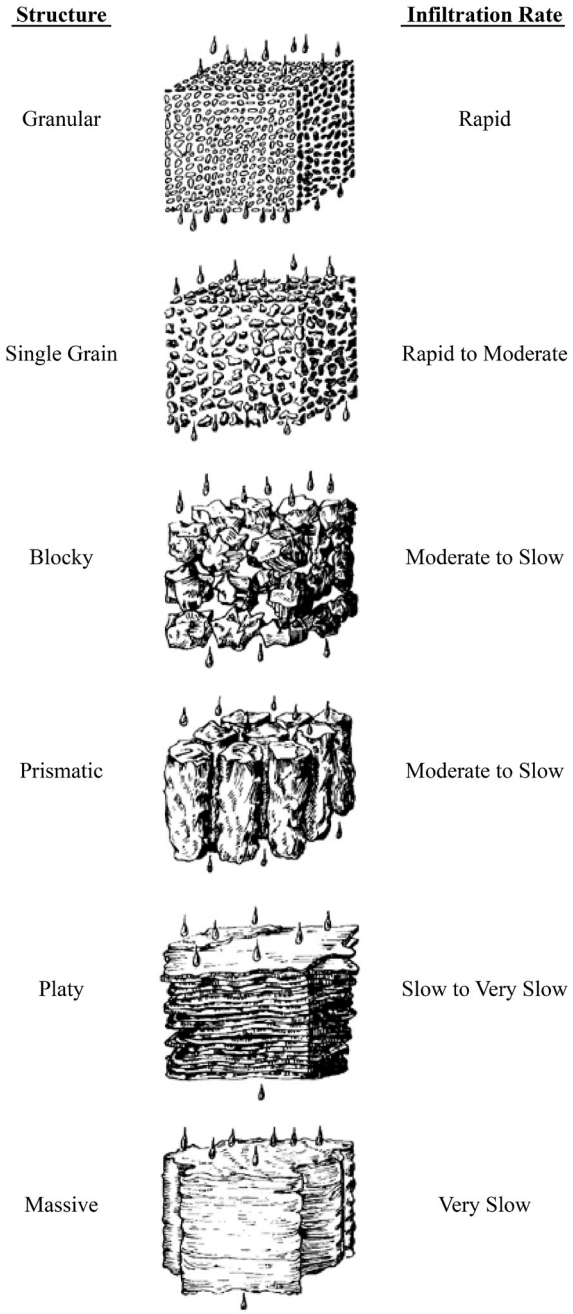

Figure 6. Water infiltration rates associated with typical soil structure shapes. Source: USDA; adapted.

Soil Color

Soil color is important in determining soil classification. The **Munsell color chart**, a book containing standard color chips similar to paint chips found at a hardware store, was developed as the standard system for determining soil color. Color is determined from three characteristics: hue, value, and chroma. **Hue** refers to the degree of redness or yellowness of soil. **Value** refers to the lightness or darkness of soil. **Chroma** refers to the brightness or dullness of soil. A freshly exposed face or ped is used to determine color. Using moist soil is most common and dry soil may be misted with water. In direct sunlight, the moist soil ped is compared to the Munsell color chart to determine the hue, value, and chroma. Soil color varies with topography, climatic factors, and soil depth, among other variables. Drainage characteristics of a soil can have a large impact on soil color; thus, soil color can reveal insights into the local hydrologic regime. Soils that are well-drained tend to be brighter than poorly-drained soils. Poorly-drained soils create anaerobic conditions in which the Fe in the soil is reduced, resulting in very dull colors. Soils with extremely reduced conditions and a chroma < 2 are referred to as "gleyed" soils.

Organic Matter

Organic matter content has a profound influence on both soil processes and soil quality. In the field, high organic content may be recognized by a dark soil color in the surface horizons. In the lab, organic matter content is quantified by Loss on Ignition, a process in which a soil sample is exposed to high temperatures (360° C) and the amount of weight lost after exposure is assumed to be organic carbon. Organic matter in soils promotes biotic growth since it serves as a food source for earthworms and other organisms. Organic matter has a high water infiltration capacity, a high moisture holding capacity (it can hold between 80 and 90 % of its weight in water), and contains many plant-essential nutrients. The increased water holding capacity allows more water to be available to plants over a longer timeframe. Along with aiding in the retention of soil moisture, organic matter protects the soil against the kinetic energy of raindrops and also acts as an insulation layer for the soil surface. Without organic matter, bare mineral soil is much more susceptible to accelerated erosion processes. Since billons of tons of soil in the world are displaced every year, it is important for soil organic matter to remain intact whenever possible. Additionally, organic matter acts as a binding agent for nutrients and potential contaminants, and therefore aids in reducing inputs of these contaminants to waterbodies. Depending on environmental conditions, organic matter can be stored in the soil for long periods of time. Warm, humid conditions promote breakdown of organic matter by microorganisms, whereas cooler, drier climates limit decomposition and soils act as a carbon reservoir. Tillage also impacts organic matter storage in agricultural soils. Tillage generally reduces organic matter content, as it improves conditions for decomposition by increasing pore space and moisture content and by exposing organic matter adsorbed to soil aggregates; converting to no-till agriculture has been shown to increase organic matter content in soils (Schlesinger and Andrews 2000).

Soil Water Movement

Soil water is the amount of water present in the **vadose zone**, or the zone of unsaturated flow, of the soil profile. The term **groundwater** refers to the area of saturated flow in the soil. Water enters the soil profile through the process of **infiltration**, and then moves through the soil profile via **percolation**. These processes depend on various soil properties that range from soil porosity to the shape and arrangement of soil peds (Figure 7). Water moves through the available pore space more readily and at a faster rate in soils with granular structure when compared to the longer flow path that platy soil structure provides (Figure 7). The percentages of micropores, mesopores, and macropores in the soil horizons also influence how quickly water enters into and moves through the soil profile. **Micropores**, or capillary pores, are the smallest soil pores and contain most of the plant-available water in soil. Water is held in these pores by the combined matric forces of adhesion and cohesion. **Adhesion** is the ability of a water molecule to adhere to a soil particle. **Cohesion** is the ability of a water molecule to stick to itself (or other water molecules). **Mesopores** are medium-sized pores formed by numerous processes like

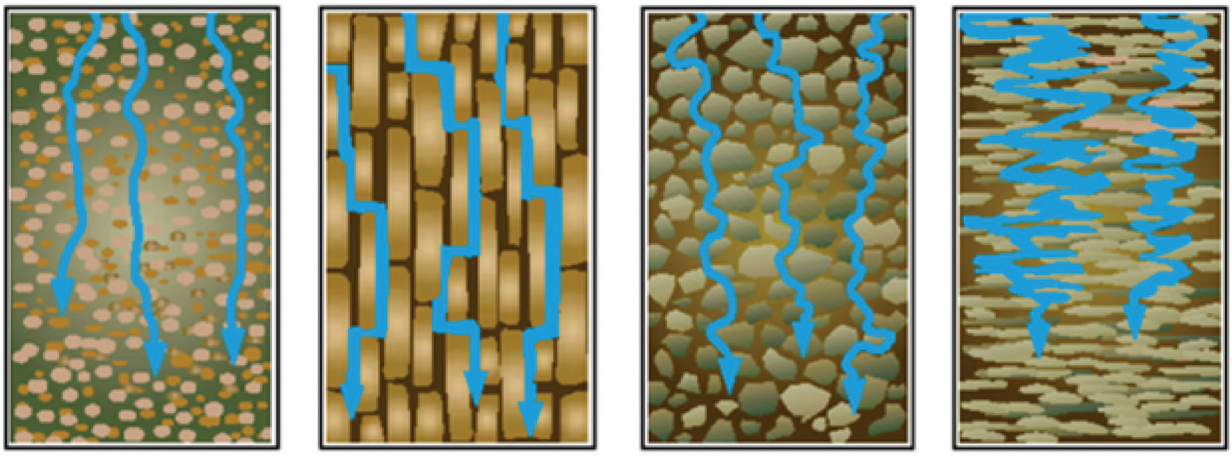

Figure 7. Water movement through soils with differing soil structure. Source: USDA NRCS, adapted.

the shrinking and swelling of clays, earthworm activity, and freeze-thaw cycles. These pores are primarily drained during the period of free drainage (gravity-driven drainage immediately following a rain event), although some water drained by mesopores is eventually plant available if the drainage network leads into micropore spaces. **Macropores** are the largest of the soil pore classification. Some macropores are formed by the burrowing of animals (**non-matrix pores**) while others exist because tree roots that once occupied the soil have rotted away. Drainage in macropores is gravity-driven and rapid. The water in these pores is quickly replaced by air; therefore, macropores cannot supply plants with needed water. Soils containing a range of pore sizes will have good drainage and air available to plants (from large pores), in addition to water plants can access (from small pores). Ideal pore distribution is generally found in a well-structured soil with the majority of small pores within soil aggregates (**matrix pores**) and large pores between soil aggregates (**interstructural pores**) (Kimmins 1997). Forest soils contain a larger percentage of organic matter that results in better soil aggregation and porosity; thus, moisture availability in forests is usually greater than in agricultural or urban environments.

Soil Water Potential

Soil water potential is the measure of the energy status of the soil water and reflects the amount of water available for plant uptake. Water moves from areas of high energy to areas of low energy within the soil.

Soil water has three types of energy: gravitational, matric, and osmotic. **Gravitational potential** refers to the energy related to the elevation of water within the soil; water at the soil surface has a high gravitational potential, but once it reaches the water table the gravitational potential is zero. **Matric potential** is the energy associated with adhesion and cohesion within the soil matrix (or profile) and is a negative potential since it opposes gravitational and osmotic potential. **Osmotic potential** measures dissolved chemicals within the soil; the higher the concentration of dissolved chemicals, the less room water has to move, though typically this has little contribution to overall soil water movement except in saline soils. Soil water potential is presented as the following simplified formula:

$$\Psi_T = \Psi_G + \Psi_M + \Psi_O$$

where Ψ_T is total soil water potential, Ψ_G is gravitational potential, Ψ_M is matric potential, and Ψ_O is osmotic potential. This energy status reflects the amount of energy required to extract water from the soil.

Soil water potential is typically measured in bars or kilopascals of pressure. It is important to note that soil water potentials in the vadose zone are recorded as negative pressures. Positive pressure values would indicate that the soil is saturated and when this occurs, it means that the water being

evaluated is not true vadose zone soil water since the vadose zone is unsaturated. The most common device used for measuring soil water potential in the field is a water-filled tube called a tensiometer. Water flows from a higher potential (inside the tube) to a lower potential (within the soil matrix) until an equilibrium is reached and the soil water potential is displayed as a negative value (range of 0 to -85 kPa) on the tensiometer vacuum gage. The closer the value is to 0, the closer the soil is to saturation. Smaller values (closer to -85 kPa on the negative scale) mean drier soil and that more energy is required to extract water.

Texture and structure may vary from one horizon to another, which can influence the movement of water through the soil profile. Soil texture affects how water moves through the soil and how much water can be stored in the soil. Soil structure affects the ability of roots to penetrate the soil, the amount of water a plant can uptake, and water movement through the soil. A poorly structured soil may have as little as 35 % total porosity, while a well-structured soil of the same texture may have 65 % total porosity (Kimmins 1997). A well-structured soil will be more efficient at soil water movement and plant uptake. Additionally, because small pores have more matric potential (adhesion and cohesion forces) than large pores, fine-textured soils that contain more micropores generally hold more water than coarse-textured soils containing a greater percentage of macropores. By the time **field capacity** (**FC**) (soil is not saturated, but wet) is reached, most of the gravitational water is lost, larger pores become filled with air, and water is held within smaller pores. At FC, most water is plant available and soil water potential values typically show ~ -10 to -30 kPa (Brady and Weil 2000). The **permanent wilting point** (**PWP**) is the potential at which soil water is unavailable for plant uptake (~ -1500 kPa). At PWP, plants cannot recover from water stress and will remain wilted. However, there is still a small amount of hygroscopic water in the smallest pores. The **available water content** (**AWC**) is considered to be the soil water retained between FC and PWP and is presented as the formula:

$$AWC = FC - PWP.$$

From this formula, the t**otal available water content** (**TAW**) can be obtained by multiplying the AWC by the depth of the plant root zone (Rd) or:

$$TAW = AWC * Rd.$$

Soil Chemistry and Plant Uptake

Soil chemistry plays a key role in vegetative productivity and species composition and is largely determined by weathering of rock, rock type, the cation exchange capacity of the soil, acid production resulting from microbial and root respiration, and management strategies of the soil. The soil provides nutrients necessary for plant growth. The sources of plant nutrients range from biogeochemical cycling inputs, decaying organic matter, amendments added by humans (e.g., fertilizers and pesticides), and nutrients naturally occurring within mineral soil.

Weathering

There are two processes associated with soil weathering: physical and chemical weathering. **Physical weathering** is the establishment of sufficient stress on a rock so that it *physically* breaks the rock. Mechanisms that fall within the category of physical weathering include erosion, freeze-thaw cycles, bioturbation (plants and animals physically disturb the soil and plant roots may physically crack rock apart), and formation of cracks or gaps in soils. Parent material weathers to release primary minerals to soils. **Chemical weathering** is defined as a change in the chemical nature of rock, resulting in a change in mineral structure, reactivity, surface area, and particle size; it is driven by the instability of primary minerals at the earth's surface. The minerals must be exposed to the environment for weathering to take place. Primary minerals include quartz, feldspars, muscovite, and biotite. These minerals have persisted through geologic time and their mineral composition shows only negligible differences from their original state. Chemical weathering is generally responsible for the formation of secondary minerals, which are derivatives of primary minerals. Secondary minerals are the fine materials that make up clay particles in the soil. The presence of clay in a soil signifies an active history of weathering. An example of a primary mineral weathering to form a secondary mineral

is the breakdown of feldspar (primary) into clay (secondary). Chemical weathering reactions increase in warm, humid climates and are also enhanced by the presence of water and oxygen, as well as biological agents including the acids produced by microbial and plant-root metabolism (Brady and Weil 2007).

The four primary chemical weathering processes are oxidation, reduction, hydration, and hydrolysis. **Oxidation** occurs when the oxygen supply is high and an element loses electrons; an example is when ferrous Fe combines with oxygen to form ferric Fe oxide (or rust). **Reduction** occurs when an element gains electrons and generally occurs in anoxic (oxygen-depleted) environments. **Hydration** is a result of the association of water molecules onto the mineral structure (e.g., anhydrite and water forms gypsum). Lastly, **hydrolysis** is essentially an attack on the silicate structure by hydrogen ions, meaning water breaks down the rock. Chemical weathering weakens the rock structure and makes it more susceptible to additional weathering.

Cation Exchange Capacity

Clay and organic matter have what is referred to as **cation exchange capacity** (**CEC**), which is the total sum of exchangeable cations that a soil can adsorb. Clay and organic matter are negatively charged, thereby possessing the ability to adsorb and hold cations (positively charged ions) onto what is known as the cation exchange complex. Cations, such as K^+, Na^+, and Ca^{2+}, can be adsorbed onto soil or organic **colloids** (very small chemically reactive particles with a large surface area per unit mass), making the cations available for plant uptake by preventing cation leaching from the system (Brady and Weil 2007). Soils high in organic matter and/or clay generally have a greater CEC than soils with little humus or clay (i.e., sandy soils), though CEC can vary greatly depending upon the type of clay and amount of organic matter present. CEC must be measured in a lab.

Soil pH

Soil pH is a measure of the hydronium ion in the soil solution, which determines the acidity or alkalinity of the soil. Soil pH varies by region and acidic soils are typically found in wet climates, whereas alkaline soils are generally found in areas with limited rainfall. Soils may become acidic through the weathering of rocks rich in silica, production of acids from organisms, and through the release of acids from decaying organic material. Alkaline soils are a result of the weathering of rocks such as limestone that contain large amounts of calcium carbonate (salts) and from the dust inputs of salts resulting from the evaporation of drainage basins, primarily in arid regions. Soil pH affects nutrient solubility and decomposition rates in soil and thereby has a profound effect on the availability of nutrients to plants. A slightly acidic pH of between 6 and 7 appears to provide optimal nutrient availability to plants, though there are exceptions (Kimmins 1997). Most macronutrients are available within this range. Knowledge of the soil pH profile is especially important in making crop management decisions as some plants may require a set pH range for optimal growth. Soil pH can be measured in the lab using a pH meter or in the field with quick test strips.

Nutrients

There are a number of essential elements required for plant growth that are categorized as macronutrients or micronutrients. The difference lies in the quantities needed for plant growth. **Macronutrients** are elements that are needed in greater quantities, whereas **micronutrients** are required in smaller portions. All are required in varying quantities for optimal growth. Macronutrients include nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and sulfur (S). Micronutrients include chlorine (Cl), iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), cobalt (Co) and nickel (Ni). Macronutrients can further be classified into primary and secondary nutrients. Generally N, P, and K are considered primary nutrients because they are most often the nutrients limiting plant growth. Ca, Mg, and S are rarely limiting nutrients and as such are considered secondary nutrients. Primary nutrients are discussed in greater detail below.

Nitrogen. Nitrogen is the nutrient needed in the greatest quantities by plants and is generally one of the most limiting to plant growth due to lack of environmental availability. The atmosphere contains a large reservoir of nitrogen gas (~79 %

of the atmosphere), most of which is unavailable to plants and animals. Both inorganic and organic forms of N are found in soils; however, only the inorganic form is available for plant uptake. Most of the soil N (> 95 %) exists in organic form and is therefore unavailable. Nitrate (NO_3^-) and ammonium (NH_4^+) ions are the two inorganic forms utilized by plants. Nitrate is held primarily in solution and is readily available for plant uptake. Ammonium ions are mostly held on the cation exchange complex. Fortunately, soil microbes can break down organic N (NH_2) and convert it to forms usable by plants (NH_4^+ and NO_3^-) in a process known as nitrogen mineralization. Immobilization of N can also occur when inorganic N is converted to unusable organic form.

Sources of N are primarily from the atmosphere, biological fixation, and fertilization. Biological fixation accounts for the majority of N inputs in most ecosystems (Kimmins 1997). In agricultural systems, annual biological N fixation is estimated at 50 - 70 million metric tons of N globally, primarily from the symbiotic relationship between leguminous crops (dominated by soybeans) and rhizobia (nitrogen-fixing bacteria) (Herridge et al. 2008). Nitrogen deficiencies in plants are typically noticed by the yellowing of foliage and stunted growth. Because N deficiencies are widespread and can lead to poor crop yields, N is often applied in excess. Nitrate is extremely mobile and readily leached from the soil if not used by plants. High NO_3^- concentrations (> 10 mg L^{-1}) in drinking water are a danger to public and ecosystem health, thus nitrate in drinking water is regulated by the Environmental Protection Agency. Additionally, excess N in the soil can lead to incomplete denitrification, which generates nitrous oxide into the atmosphere. Nitrogen is a nutrient requiring careful management, critical for both successful crop production and environmental quality.

Phosphorus. Phosphorus is second only to nitrogen in the amount needed for optimal plant growth. The majority of soil P is derived from mineral weathering and organic matter decomposition, but concentrations of plant-available P are generally very low in soils. Most soil P is in insoluble forms that are unavailable to plants and when soluble forms of P are added via fertilization, they can be converted to insoluble forms over time. Decomposition returns P to the soil, but if crops are removed, the P is also removed from the system. For these reasons, P is often a limiting nutrient in the soil. Phosphorus deficiency in plants is recognized by bluish-green foliage, sparse flowering, and stunted, thin stems. Because plants require large quantities of P and there is little natural available P from weathering, crop harvesting removes the majority of P from the field. Without P amendments, the subsequent crop will likely be P deficient, which has led to the over-fertilization of fields and an accumulation of P in the soil. Unlike nitrate, which is mobile downward through the soil profile, P binds readily to sediment and is easily transported in this bounded state to streams and rivers. Excessive P in runoff can promote the **eutrophication** (over-abundance of algae growth caused by excessive nutrient accumulation) of downstream water bodies. The resulting algal growth decreases the dissolved oxygen levels in the water, which may lead to substantial fish kills. With the Mississippi River Watershed draining much of the nation's cropland, the Gulf of Mexico consistently has one of the largest dead zones in the world due to eutrophication; the average size of the dead zone over the last 5 years is ~ 5,500 mi^2. For this reason, P management in watersheds is of primary concern.

Potassium. Potassium is available in greater quantities than any other soil macronutrient and is essential in providing protection against crop disease. However, most of the K within the soil exists as a mineral and is not readily available for plant uptake. The K-containing minerals, such as feldspars and micas, are resistant to weathering; this leads to minimal K inputs from weathering during a growing season. Only ~ 2 % of soil K is readily available for plant uptake and is either in solution form or exchangeable form (Brady and Weil 2007). Potassium in the soil solution is immediately available to plants. Exchangeable K is a part of the cation exchange capacity of soils and is adsorbed on the soil colloid. The dissolved and exchangeable K concentrations are in equilibrium. For instance, when plants remove K from the soil solution, K is released from the cation exchange complex into the soil solution until K equilibrium is reached. Potassium also occurs in nonexchangeable or fixed form. Fixed

K is trapped between clay particles and remains unavailable until it converts to exchangeable K. This conversion usually does not occur within the span of one growing season; therefore, fixed K is considered a slowly available form of K.

Plants uptake large amounts of K in their aboveground biomass, often more than needed for growth. Because of this excessive uptake, harvesting crops or forests can remove large amounts of K from the system each year. Potassium deficiency is normally seen first on the lower plant leaves because K is translocated from older to younger tissue. Deficiency symptoms include yellow scorching along the leaf edge, slow growth, and weak stalks. Like nitrate, K is extremely mobile and readily lost via leaching. Applying substantial amounts of K fertilizer can lead to excessive plant uptake and loss to leaching. In addition to the soil itself as a natural K source, leaving crop residue on the soil can return a significant portion of K to the soil.

Role of Soil Biology

One critical function of soil is to provide a home for organisms. Soil biota plays an integral role in soil ecosystems by decomposing leaves, downed logs, and animals, and also providing the primary nutrient source for vegetation. Soil biota includes both flora (plants) and fauna (animals). Soil fauna subsists on a wide variety of energy sources, including: living plant material (herbivores), animals (carnivores), dead material (detritivores), fungi (fungivores), and bacteria (bacterivores). The size of soil fauna also varies. Macrofauna (> 2 mm) includes animals such as groundhogs, moles, earthworms, centipedes, ants, and termites; mesofauna (0.1 - 2.0 mm) includes springtails and mites; microfauna (< 0.1 mm) includes species such as rotifers, nematodes, and other single-celled organisms. Soil flora includes organisms as small as diatoms and algae up to the size of tree roots. An important member of soil flora is mycorrhizae, fungi that form a symbiotic (mutually beneficial) relationship with plant roots. Most plants contain roots infected with mycorrhizal fungi. Mycorrhizae enhance water and nutrient absorption by increasing root surface area and accelerate mineral weathering which releases nutrients to the soil (Fisher and Binkley 2000). Collectively, soil biota carries out enzymatic and physical processes that decompose organic matter, build soil humus, and make nutrients available for plants. Table 4 provides a description of the microfauna numbers found in a teaspoon of soil.

Decomposition is one of the most critical roles that soil biota play in an ecosystem. Without efficient decomposition, organic material would accumulate on the soil surface and nutrients would be bound within the material. Decomposition is initiated immediately when a leaf, twig, or fruit hits the ground. Once on the ground surface, biota begins to physically break down the material, creating more surface area to which flora can adhere.

Soils and Roots

Roots are a critical component in the soil environment. Plants rely on roots for structure,

Table 4. Brief description of the organisms in a teaspoon of soil. (Source: Melendrez 1975).

Organism	Number of Individuals per Teaspoon of Soil	Primary Role
Bacteria	5 to 500 million in agricultural soils; 20 million to 2 billion in forest soils	Consume readily decomposable materials
Fungi	Up to 40 miles of fungal hyphae	Consume hard to decompose organic matter
Protozoa	100 to 100,000	Feed on bacteria and each other
Nematodes	5 to 500 with high variability among soils	Feed on bacteria, fungi, and plant roots
Microarthropods	Several species	Feed on fungi, plants, and organic matter

support, water, and nutrient uptake. The relationship between roots and mycorrhizal fungi increases nutrient availability and absorption. Roots also act as a reservoir for food storage (starches) and sometimes synthesize growth hormones for the plant. Root growth is controlled by soil moisture, compaction, structure, texture, temperature, and chemistry. Once roots decay, the channels left behind improve air and water movement within the soil.

Nutrients are taken up by roots by the processes of root interception, mass flow, and diffusion. **Root interception** occurs when roots grow towards nutrients in nutrient-rich soil so that they can be utilized by the plant. Since the roots must continually grow in undepleted soil for root interception to occur, this process is limited. **Mass flow** occurs when nutrients are transported with soil water to a root that is actively extracting water from the soil. This process is most effective in periods of rapid transpiration with high concentrations of nutrients in the soil water solution. **Diffusion** occurs when nutrients move from high concentration areas (nutrient saturated) to low concentration areas (nutrient depleted) near the root surface. Rates of uptake via diffusion depend on concentration gradients, soil water contents, ion size and charge, soil temperature, and root adsorption rates. Water enters the root through root hairs or the cortex. Osmotic pressure (movement of water from areas of high to low concentration) causes the water to enter into the plant cell. The expansion and contraction of the roots cause water to move up through the cortex, through the xylem vessels, the stem, and into the rest of the plant. A manometer, an instrument used for measuring the pressure of a fluid, is used to measure the pressure of a root system. Root pressure is the pressure exerted on the liquid contents of cortical cells in roots. Cortical cells, which aid in the transport and storage of water and nutrients, are either turgid (expanded) or flaccid (contracted). Turgor pressure is the actual hydrostatic pressure developed inside a cell. This pressure is due to endosmosis, or the inward flow of water from outside of the cell. Flaccidity is when the cell undergoes exosmosis, the opposite of endosmosis, where water is lost and the cell becomes limp. To understand how root pressure works, cut a well-watered plant close to the ground, quickly attach a manometer to the stem and observe how the pressure changes on the gauge. The cut stem will exude water, suggesting pressure from the roots to the stem is being released. Although most water is absorbed through roots, some plants have developed the ability to absorb water through their leaves. Along the California coast, ~ 80 % of the redwood species, *Sequoia sempervirens*, absorb water deposited by fog through their leaves (Limm et al. 2009). This adaptation is especially useful in areas prone to drought, like California.

Plants have both primary roots and secondary roots (Figure 8), which come in many different shapes and sizes. Plant root networks are heterogeneous and no two root systems will be identical. Roots adapt and grow in response to environmental conditions. There are three common root systems of North American tree species (Figure 9). **Tap root** systems have a prominent tap root and smaller (secondary) lateral roots that grow off the side of the dominant primary root. Tap root systems are effective in areas where access to water is located deep within the soil profile so water can be accessed in periods of drought. Thus, many tree species with tap roots are well-adapted for upland and dry site conditions. **Heart root** systems occur in both upland and bottomland tree species and are adapted for mesic (moderately moist) site conditions. **Flat roots** are shallow root systems that often occur in bottomland species. Tree species with flat root systems are commonly uprooted in high windstorms when the ground is near saturation. Contrary to popular belief, ~ 90 to 95 % of tree roots are found within 1 m of the soil surface and most tree root systems extend out ~ 2 times the width of the crown. Absorption of nutrients occurs mainly in fine roots (< 2 mm in diameter) which are concentrated in the surface horizons (Kimmins 1997). Trees rely on these roots for access to water and nutrients. Root systems of various tree species are shown in Table 5.

Soil Erosion and Conservation

Soil erosion is a major concern around the globe. In order to properly prevent and manage erosion, it is important to understand erosion concepts. Soil erosion is both naturally-occurring

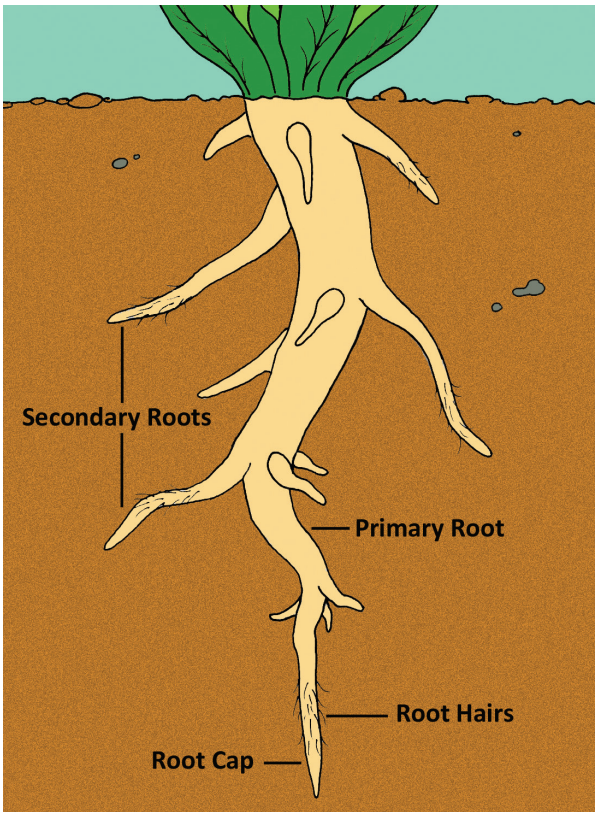

Figure 8. Common root system shapes for North American tree species. Drawing by Robin L Quinlivan.

Table 5. Common root systems for various tree species in the United States.

Tap root	Heart Root	Flat root
Hickory	Red Oak	Fir
White Oak	Honey Locust	Spruce
Butternut	Basswood	Sugar Maple
Walnut	Sycamore	Cottonwood
Hornbeam	Pine	Silver Maple

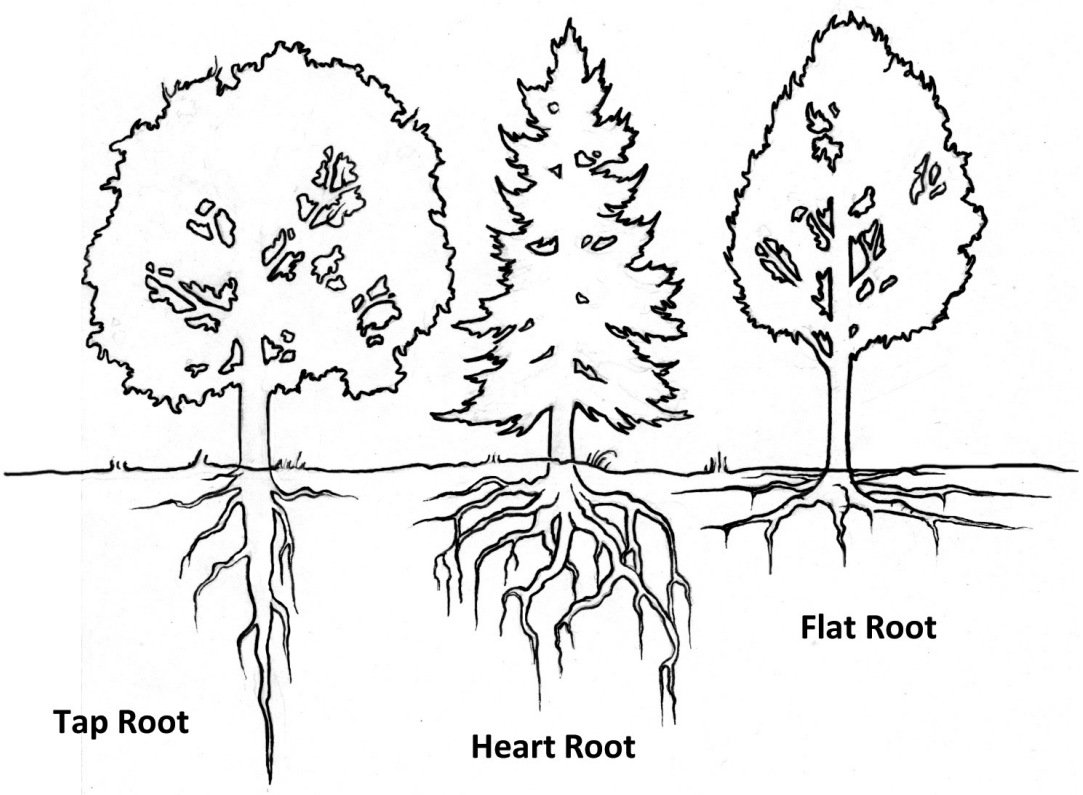

Figure 9. Major features of a root. Drawing by Robin L Quinlivan.

(**geologic erosion**) and influenced by humans (**accelerated erosion**). Accelerated erosion can be 10 to 1000 times more damaging than geologic erosion (Brady and Weil 2007). Examples include disturbance of soil or natural vegetation by grazing livestock, deforestation, tillage, and construction, each of which are exacerbated by high rainfall and/or steep slopes.

Globally, ~ 15 % of total land area is eroded, of which over half is severely eroded (Blanco-Canqui and Lal 2008). Soil erosion rates are greater than soil formation rates, posing a threat to sustainable agriculture (Pimentel 2006). Productive land is < 11 % of earth's total land area (Eswaran et al. 2001), yet it must supply food to the world's population (> 7 billion people). Pimentel (2006) suggested that soil is being lost at a rate that is 10 to 40 times faster than soil formation and ~ 10 million ha of cropland is lost yearly to erosion. Agriculture accounts for ~ 75 % of soil erosion worldwide (Pimentel 2006). Soil erosion is lowest in the U.S. and Europe (~ 10 metric tons ha^{-1} yr^{-1} soil lost) and much more severe in the rest of the world (~ 30 – 40 metric tons ha^{-1} yr^{-1} soil lost) where resources and incentives for implementing conservation measures are inadequate (Blanco-Canqui and Lal 2008).

Erosion is defined by the Soil Science Society of America (SSSA 2008, 19) as: "(i) The wearing away of the land surface by rain or irrigation water, wind, ice, or other natural or anthropogenic agents that abrade, detach, and remove geologic parent material or soil from one point on the earth's surface and deposit it elsewhere, including such processes as gravitational creep and so-called tillage erosion. (ii) The detachment and movement of soil or rock by water, wind, ice, or gravity."

Essentially, erosion occurs in a three-step process of detachment, transport, and deposition. The first step, detachment, is the removal of soil material from the soil mass by raindrops, running water, wind, or human/animal activities. The detached soil materials are then transported downhill by method of splashing, floating, dragging, or rolling. Sand particles are heavier than silt or clay, and therefore cannot be transported as far or at the same velocity. Silts and clays often become suspended in water and may be transported long distances. The third step, deposition, usually occurs in floodplains, fields, wetlands, lakes/reservoirs, rivers, and streams. In agricultural fields, sediment may also be deposited in front of control structures such as dry dams, terraces, or vegetative filters (e.g., riparian areas and grass waterways).

Soil erosion is divided up into different categories: rill erosion, interrill or sheet erosion, and gully erosion. **Rill** erosion is the formation of tiny channels across a soil surface that often occurs in sloping agricultural fields. **Interrill** erosion is the removal of a somewhat uniform layer of soil which is attributed to the splash effect of raindrop impact and also sheet flow. If rill erosion persists, it is likely that gully erosion will occur. **Gully** erosion is the erosion process that removes large amounts of soil and results in a narrow, deep channel.

Eventually, high amounts of erosion will destroy soil quality, which in turn, compromises long-term food and timber production. The Dust Bowl of the 1930s raised awareness to the need for soil conservation and prompted implementation of conservation practices. Several government programs geared towards soil conservation are in place to minimize and prevent unnaturally high occurrences of soil erosion by wind and water. The Food and Security Act of 1985 included conservation measures that helped reduce erosion from U.S. cropland by 1.3 billion metric tons between 1982 and 1997 (Montgomery 2007). For example, the Conservation Reserve Program (CRP) (included in the Food and Security Act of 1985) provides economic incentives to landowners who implement soil conservation measures on highly erodible cropland. In 2010, 10.7 metric tons ha^{-1} of cropland was lost in the U.S., whereas CRP land reported a total of 1.7 metric tons ha^{-1} lost to wind and water erosion (USDA 2013). Since the CRP was implemented in 1986, soil erosion has been reduced by > 7 billion metric tons (USDA 2010). Additionally, recent adoption of notill farming has contributed to a reduction in soil erosion. In a review of studies comparing conventional and notill methods, Montgomery (2007) found that notill practices reduced soil erosion by 2.5 to > 1,000 times compared to conventional methods.

Although adoption of conservation practices is increasing, there are several obstacles that land managers interested in soil conservation must

overcome. At times, the initial implementation of conservation practices can be more costly than the economic return. The fear of the unknown will sometimes steer people away from adopting new conservation technologies. It is also difficult to convey the importance of soil conservation to every individual, whether it is due to lack of interest or unavailable information.

The **Universal Soil Loss Equation** (**USLE**), a model based on extensive erosion data from small plot studies across the U.S., was created by countless federal and university scientists in the mid-1900s to predict soil loss. The USLE has been used worldwide to estimate soil erosion and guide soil conservation efforts. The USLE equation accounts for slope, rainfall, soil series, topography, crop system, and management practices on a landscape. The equation has been revised over time and is now referred to as Revised Universal Soil Loss Equation, Version 2 (RUSLE2), a computer-based equation. However, to understand the principles of estimating soil erosion rates, it is important to analyze the original formula:

$$\text{USLE: } A = R * K * LS * C * P$$

where A is annual soil loss (tons ac^{-1} yr^{-1}), R is erosivity factor, K is erodability factor, LS is slope length and slope steepness factor, C is cover and management factors, and P is conservation practices factor.

The e**rosivity factor** (**R**) assesses the total rainfall, intensity, and seasonal distribution of rainfall in a geographic location. The R factor accounts for the driving force of rill and interrill erosion. In other words, the R factor recognizes that high intensity rainfall will cause more catastrophic damage than a lower intensity rainfall event. The e**rodability factor** (**K**) assesses how susceptible the soil is to erosion, which includes a soil's infiltration capacity, texture, and its structural stability/integrity.

Only three of the factors in the equation can be manipulated. The **slope length** factor (**LS**) can be changed by reshaping the land into terraces, dry dams, or other erosion control structures. The **cover factor** (**C**) is probably the easiest factor to change. In forests, limiting harvesting and road structures can greatly improve this value. In agriculture fields, perennial crops (e.g., alfalfa, orchard grass) that retain groundcover in the winter versus annually harvested crops (e.g., soybeans, corn) will improve the C factor, as will planting cover crops during times the field would normally be fallow. The **conservation practices factor** (**P**) can be changed by installing various conservation structures and implementing contour cropping wherever necessary. An example of a conservation structure would be installing a water bar after a timber harvest. Water bars are used to divert water away from logging roads and into vegetated areas, decreasing erosion of these roads.

Soil Quality

The basic definition of **soil quality** is the capacity of a soil to function (Karlen et al. 1997). This functional definition balances the physical, biological, and chemical components of soil. The expanded version of this functional definition is "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al. 1997). What constitutes good soil quality may be different according to land use and/or geographic region. For this reason, Karlen et al. (1997) suggests a relational approach to evaluating soil quality, as opposed to an absolute approach. Similarly, Doran et al. (1996) suggest that soil quality should be evaluated based on how well a soil functions within its specific ecosystem (agriculture, urban, etc.). For example, in an agricultural field, the capacity of a soil to function at sustaining crop growth would depend on several soil characteristics including bulk density, soil moisture, infiltration, and biological activity, to name a few. Many of these properties can be changed by management (e.g., infiltration and organic matter content) and soil quality can be improved according to its function. As seen throughout this article, soil also affects water quality, air quality, and biotic quality. Protecting and/or improving soil quality can provide a stepping stone to improving environmental quality as a whole. For example, planting cover crops when a field would otherwise be bare, helps reduce soil erosion and aids in soil and nutrient retention on site, limiting its

transportation to waterways where water quality would be affected.

Land Use and Soils

Cultivated and Grazed Soils

In cultivated areas, soils are mechanically worked to break up compaction and amended with fertilizers, herbicides, and pesticides to enhance crop production and provide weed and pest control. These processes can expose bare mineral soil and increase the risk of water and wind erosion. Under improper management, agriculture can devastate the landscape. For example, intense cotton farming in the southeastern United States was blamed for the loss of 10 to 30 cm of topsoil (with an average of ~ 18 cm), which led to the accumulation of large volumes of legacy sediment in the floodplains (Trimble 1974). Similarly, poor farming practices coupled with a drought, caused millions of acres of farmland to become lost during the time known as the "dust bowl" or "dirty thirties" era. Fortunately, recent farming practices have adopted environmentally conscientious methods to reduce soil erosion and other impacts on the environment. Farmers now understand that crop selection and farm management decisions should be based on soil characteristics and land conditions. Farmers seek to maximize yields while simultaneously creating a sustainable farming system.

Land use change can have significant impacts on soil quality. If cultivated areas are abandoned, shrubs and trees quickly reoccupy the site; however, carbon pools and nutrient dynamics within the soil may be slow to recover. For example, following a 30-yr succession in North Carolina, most available carbon was allocated to aboveground standing biomass and not towards soil organic matter accumulation (Richter et al. 1995).

Impacts of grazing on soils fall into two categories: 1) physical impacts from animals and 2) chemical and biological impacts from animal waste. Livestock, such as cattle, compact the soil structure and typically consume vegetation in heavily used areas, such as feeding or watering sites. As a result, the compacted bare areas are more susceptible to erosion and surface runoff. Waste associated with livestock is also a problem. Urine and feces from livestock can create hotspots for nutrients and bacteria. In these areas the vegetative uptake often is much lower than the supply of nutrients. Nitrogen, for instance, either leaves the site through groundwater or surface runoff or is denitrified under optimal conditions. Oftentimes in heavily grazed land, the carbon supply for completed denitrification is lacking, thus incomplete conversion of NO_3 to N_2 gas occurs, resulting in nitrous oxide pollution into the atmosphere.

Forest Soils

Forest soils tend to be on land unsuitable for row-crop agriculture or grazing. Thus, forests are typically in areas of steep topography, poor drainage, or where soils are too rocky for farming. Contrary to agricultural soils, forest soils typically have an intact litter layer that can protect soils from temperature and moisture fluctuations and from wind and water erosion.

Forest Harvesting. Forest harvesting is a common occurrence in the United States and around the world. Harvesting provides the nation with wood products needed in our daily lives. Along with these benefits come potential damages to our environment. The majority of compaction in a forest is caused by forest harvesting procedures. Surprisingly, the primary source of erosion during a harvest results from the construction of roads into the forest and not from the actual logging practices, as one might expect. It is the job of foresters and ecologists to conduct sustainable forest harvesting using best management practices in an effort to reduce site impacts. Harvesting timber has a variety of different effects on the soil, depending on the kind of harvest and caution used while harvesting. The harvesting process opens up the canopy, which in turn allows for more light to hit the forest floor. This increase in light exposure changes the chemical processes occurring in the soil. These changes can then shift the plant and animal species composition found on the site. The exposure of mineral soil from harvesting can increase the potential for erosion and leaching of nutrients.

Loggers use a variety of methods for harvesting timber. Common equipment includes log skidders, feller-bunchers, and cable logging, each with their own pros and cons. Heavy machinery equipped

with wide tracks instead of pressured wheels reduces the degree to which the machine compacts the soil. Types of machinery used often depend upon the region. In places like the Midwest where there are large tracts of agricultural land and few tracts of forestland, access to state-of-the-art logging equipment is limited. Detailed guidelines on Best Management Practices (BMPs) associated with forest harvesting are described in "Guiding Principles for Management of Forested, Agricultural, and Urban Watersheds" (Edwards et al. 2015, this issue).

Long-term site productivity continues to be a concern to natural resource managers. An increase in the industries of biofuel production, whole-tree harvesting, woodchip utilization, and wood pellets have researchers and managers studying how long forests can sustain the continuous removal of biomass from forests. A potential short-term solution to this problem could be the introduction of fertilization into forest ecosystems to replenish nutrients exported from the site via whole-tree removal. Large-scale fertilization of forests has increased in the last decade. However, it is unclear how large-scale fertilization affects long-term site productivity because a longer monitoring period is needed to assess the changes in site quality.

Fire. Fire plays a key role in shaping the structure of a forest community; however, fire can also be both beneficial and detrimental to forest soils. Fire can alter the chemical and physical status of soils, impact hydrology, increase soil erosion, and influence the biotic structure of soils. The severity of fire impacts generally depends on burn intensity, climatic conditions following the burn, landscape, and soil characteristics. Following intense burns, nutrient cycling can be disrupted and lead to leaching, volatilization, and/or transformation. When vegetation is consumed by fire, some of the litter-incorporated N, P, K, Ca, Mg, Cu, Fe, Mn, and Zn are volatilized and lost from the system, while metallic nutrients such as K, Ca, and Mg are converted into oxides and accrued in ash (DeBano et al. 1998). The long-term effects of fire on the soil nutrient status can be significant (Williard et al. 2005). Repeated low intensity fires, such as prescribed fires or single large fires, can reduce soil nitrogen pools significantly (Gagnon 1965; Carreira et al 1994). In fact, Gagnon (1965) documented that a historical fire (20 years earlier) exhibited long-term effects on soil nitrogen and tree nutrition. Vegetation following a 500 km^2 burn showed deficiencies of both nitrogen and phosphorus in foliar analyses.

Using properly executed prescribed fire may actually increase nutrient uptake and provide greater surface roughness through the establishment of dense vegetation post-burn. The increased surface roughness from the newly established and vigorous vegetation growth can reduce surface runoff velocities, in turn reducing the risk of soil erosion. Additionally, the flush of vegetation can increase nutrient uptake, thereby retaining the nutrients on site. Conversely, uncontrolled fire can be detrimental to a forest ecosystem. Under conditions where all vegetation is consumed, the risk of soil erosion is increased, nutrient uptake by plants may be reduced, and high stream temperatures may result. As vegetation is removed, evapotranspiration in the watershed is reduced, thus providing a greater volume of water that can produce surface runoff. Increased overland flow combined with a consumed litter layer can lead to serious erosion problems and result in higher stream discharges. To compound the problem, intense burns can produce hydrophobic conditions in the soil that ultimately reduce infiltration and increase surface runoff. Hydrophobic conditions are generally produced during moderate to high severity burns (175° - 200° C), in coarse textured soils, and at lower soil water contents (DeBano et al. 1998). Both nutrient runoff and erosion can be exacerbated in areas of steep slopes and high rainfall.

Soil heating is the primary mechanism by which fires impact a soil's physical and biotic structure (Neary et al. 1999). The degree of soil heating during a fire is highly variable across a site, but depends on fuel characteristics (size, arrangement, and moisture status), soil properties (texture, structure, and both the moisture and organic content), and fire behavior (intensity and duration). Generally 8 - 10 % of the aboveground heat can be transferred to the soil, resulting in higher soil temperatures (DeBano et al. 1977). Fuels differ in terms of maximum temperatures produced and the duration that they can burn. For example, downed logs and stumps can burn

for days following the passage of the fire front, which will induce a more sustained soil heating. Further, finer textured soils (i.e., increased clay content) tend to transfer heat better than quartz-based soils.

Organic content of soils can also be impacted by fire. The consumption of soil organic matter, which is a cementing agent in soils, can result in a loss of soil structure. Reduced structure can reduce porosity, increase bulk density, and decrease infiltration and percolation. Structure takes time to rebuild, and under severe conditions where the soil biota was impacted, the recovery can be even greater since soil invertebrates play a key role in maintaining soil porosity. The degree to which soil invertebrates are impacted relates to soil temperature and moisture. Biota can tolerate higher temperatures in dry soils compared to moist soils.

Urban Soils

Soils are modified by anthropogenic activities in urban environments. The impacts of urban infrastructure on the environment create changes in the physical, chemical, and biological properties of urban soils. Notably, pore space is reduced due to soil compaction from building and road engineering, thereby increasing soil bulk densities. Additionally, the loss of pore space and soil structure combined with increased impervious surfaces leads to reduced infiltration and increased surface runoff. Compaction may also lead to poor establishment of plant communities in urban areas. Pouyat et al. (2007) found that K, P, bulk density, and pH were higher in urban residential soils compared to forest soils, likely a result of lawn fertilizers and intensity of use. However, other soil variables measured were related to parent material rather than land use, including soil texture, Al, Fe, and other micronutrients (Pouyat et al. 2007). While urbanization can impact some soil characteristics, especially bulk density and infiltration, other surface soil characteristics are still predetermined by parent material. Urban soils can recover over time. Scharenbroch et al. (2005) found that as time since the initial disturbance of urban soils increased and allowed for soil development, bulk densities decreased and organic matter and biological activity increased. Time is a soil-forming factor that plays an important role in reducing the impacts of urbanization on soil characteristics.

Knowledge of urban soil properties can lead to better management of water resources in terms of both quantity and quality. Duration of irrigation in urban areas should be based on the water holding capacity of the soil. Organic matter can be incorporated into the soil to increase pore space and soil aggregate stability, thereby increasing infiltration and nutrient retention and reducing runoff. Soil texture should be considered when determining fertilizer management. For instance, sandy soils exhibit poor nutrient retention and nutrients that leach below the rooting zone may eventually travel to ground and surface waterbodies, impacting water quality. Nitrate is especially mobile and nitrate that is not used by plants or microbes is easily transported from the soil water to groundwater.

Evaluating Your Soil

This article has provided an introduction to soils and stressed the importance of considering soil characteristics when making land management decisions. How does one learn about the soil specific to a given watershed in order to make sound management decisions? There are many helpful internet sites available to land and watershed managers; one place to start is a soil survey. The USDA NRCS operates the Web Soil Survey (Soil Survey Staff). Users obtain soils information by entering coordinates, interactively selecting a field area with a map interface, or by importing a shapefile. An example of soil series data produced from a user-defined area of interest in Jackson County, IL, is provided in Figure 10. Soil surveys contain information on the suitability and limitations of soils in the specified geographic area and are created from on-site surveys of the soil profile collected by soil scientists. These surveys can help determine if a site is suitable for a basement, prone to flooding, or a good site for a septic system, among many other applications. It should be noted that spatial variability is inherent in soils and a 100 hectare site may contain several different soil series with contrasting soil properties. If interested in the nutrient, organic

Map Unit Legend

Jackson County, Illinois (IL077)

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
122C2	Colp silt loam, 5 to 10 percent slopes, eroded	0.6	0.2%
214B	Hosmer silt loam, 2 to 5 percent slopes	74.5	27.1%
214C2	Hosmer silt loam, 5 to 10 percent slopes, eroded	7.1	2.6%
214C3	Hosmer silt loam, 5 to 10 percent slopes, severely eroded	54.0	19.6%
437B	Redbud silt loam, 2 to 5 percent slopes	3.8	1.4%
801B	Orthents, silty, undulating	10.0	3.6%
3108A	Bonnie silt loam, 0 to 2 percent slopes, frequently flooded	80.8	29.4%
3382A	Belknap silt loam, 0 to 2 percent slopes, frequently flooded	32.4	11.8%
8108A	Bonnie silt loam, 0 to 2 percent slopes, occasionally flooded	11.7	4.3%
Totals for Area of Interest		275.0	100.0%

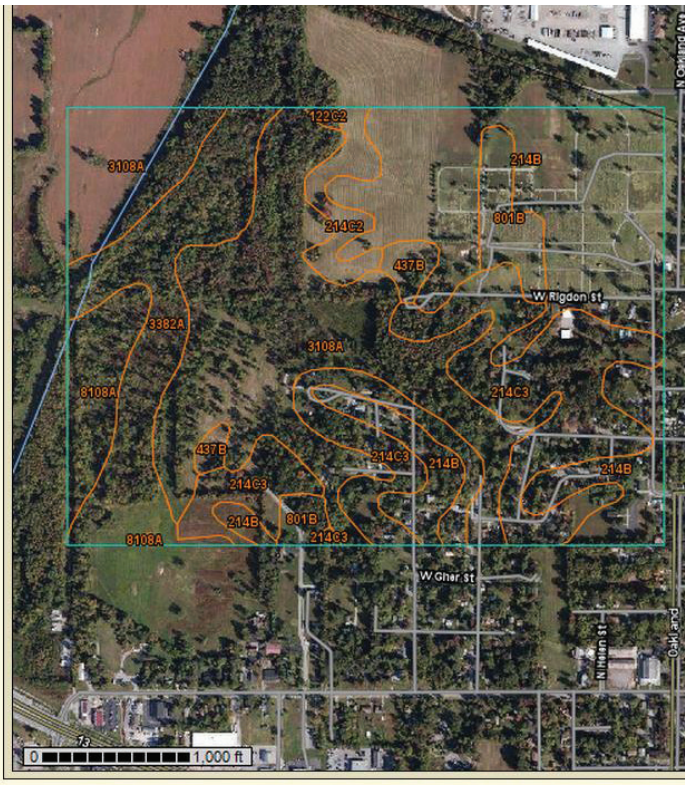

Figure 10. Soil survey data of an area in Jackson County, IL. Produced from Web Soil Survey (Soil Survey Staff).

matter content, or pH of your soil for gardening or farming, soil samples can be taken or shipped to various laboratories around the country that will provide basic to extensive soil information. These soil data can be useful to develop appropriate land management practices.

Conclusion

Watershed management, from urban to rural environments, must incorporate the functionality of the soils within the watershed. Understanding watershed soil characteristics allows for a greater understanding of the processes controlling erosion, water movement and storage, pollutant runoff, and site productivity, among others. Soil is a finite resource and as such it is important for watershed managers to consider both soil quality and conservation in watershed management plans. In terms of conservation, it is important to minimize erosion through structural and/or vegetative measures. Measures should not only be cost-effective, but also sustainable and practical based on the land conditions. In terms of soil quality, management decisions must consider the capacity of the soil to function within the framework of the ecosystem.

Soil Information Resources

Web Soil Survey:
http://websoilsurvey.nrcs.usda.gov/

"Feel" Method Guide to Soil Texture:
http://www.nrcs.usda.gov/Internet/FSE_MEDIA/nrcs142p2_050352.jpg

Soil Taxonomy:
http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/class/taxonomy/

Official Soil Series Descriptions:
http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053587

Acknowledgment

This work was supported by funds from the USDA McIntire Stennis Cooperative Forestry Research Program.

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Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 154, Pages 48-59, April 2015

Soil Erosion in Humid Regions: A Review

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Abstract: Soil erosion has significant implications for land productivity and surface water quality, as sediment is the leading water pollutant worldwide. Here, erosion processes are defined. The dominant factors influencing soil erosion in humid areas are reviewed, with an emphasis on the roles of precipitation, soil moisture, soil porosity, slope steepness and length, vegetation, and soil organisms. Erosion dynamics in forested watersheds are the focus with some examples from agricultural watersheds included as well. Lastly, best management practices for controlling surface erosion are discussed.

Keywords: *best management practices, erosion control, forest, precipitation, sediment, surface erosion, water quality, watershed management*

Erosion is a critical process for land and watershed managers to understand, as sediment is the world's leading surface water pollutant. Excessive erosion results in significant topsoil losses, leading to declines in agricultural productivity. Reservoir lifespans can be shortened due to excessive sedimentation behind dams. Sediment can carry bound nutrients such as phosphorus, which contribute to the eutrophication of freshwater resources and coastal estuaries (Rabalais et al. 2010). Stream and river habitat for fish and macroinvertebrates can become degraded when benthic habitats are covered with sediment, resulting in declines in freshwater biodiversity (Bilotta and Brazier 2008).

Process of Erosion

Erosion is a natural process, where energy provided by water, wind, and gravity drives the detachment, transport, and deposition of soil particles. **Detachment** occurs when the forces holding a soil particle in place are overcome by the forces of raindrop impact, moving water, or wind (Joy et al. 2002; Rose 1960). A portion of the energy from raindrop impact is first spent to deform **peds** (i.e., aggregrates of soil particles) and detach soil particles from the surface. Remaining energy activates the second step of the erosion process, particle **transport** (Rose 1960; Savat and Poesen 1981). **Deposition** is the third and final step in the erosion process and occurs simultaneously with the first two steps (Huang et al. 1999). When the sediment load of moving water is greater than its transport capacity, deposition occurs (Foster and Meyer 1972). Recently-deposited soil is more vulnerable for re-detachment and transport than residual soil because the original bonding forces have been broken (Hairsine et al. 1992; Woo et al. 1997). However, a layer of recently deposited loose soil can help prevent detachment of underlying soil (Kinnell 2005). Individual soil particles can be detached, transported, and deposited several times during a single storm event (Hairsine et al. 1992).

Physics of Erosion

This review focuses on erosion by water, as it is the dominant form of erosion in humid climates. Erosion by water is categorized by the type of runoff or overland flow across the earth's surface. During precipitation events, overland flow is generated when precipitation exceeds the infiltration capacity of the soil (Horton 1933) or when precipitation falls on saturated soils with a high water table (Dunne 1983). The resulting overland flow begins

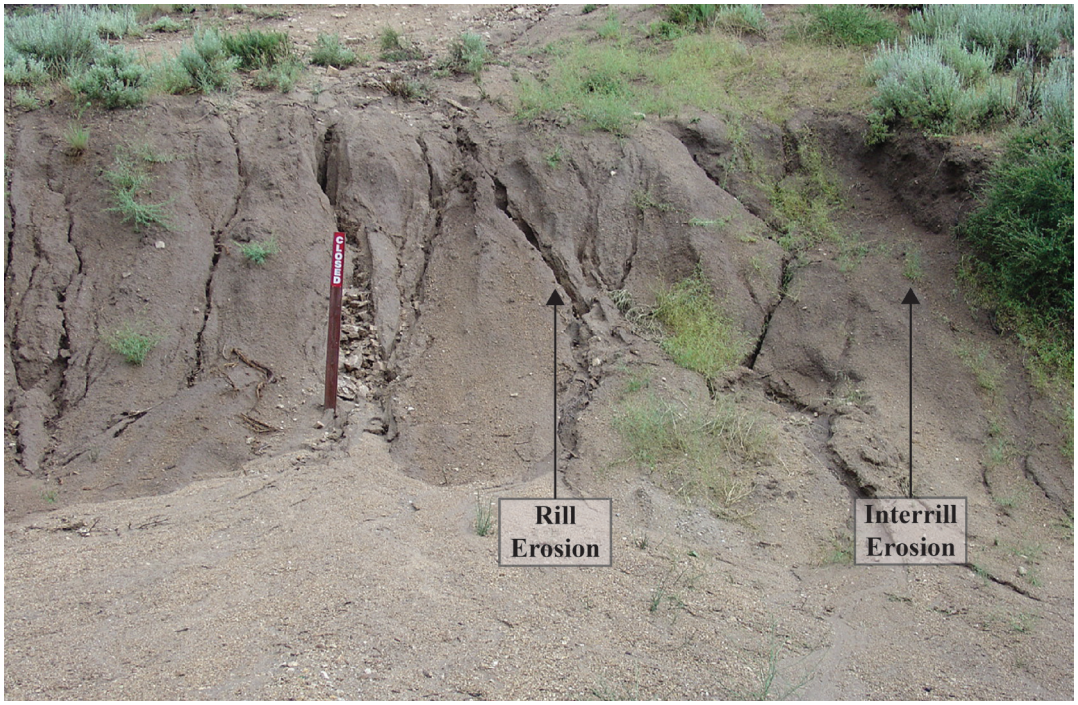

Figure 1. Rill and interrill erosion on a cutslope portion of a road prism in the western United States. Note the multiple rills or small eroded channels. The areas between the rills experience interrill erosion (Photo credit: USDA Forest Service).

as **sheetflow** (i.e. shallow, dispersed runoff). The energy associated with raindrop impact and sheetflow can detach and transport soil particles and is termed **interrill erosion** (Meyer 1981) (Figure 1). Of the two forces, raindrop impact supplies most of the kinetic energy needed for interrill erosion to occur (Rose 1960; Salles and Poesen 2000,; Kinnell 2005). The kinetic energy of the raindrop is proportional to its mass and its velocity squared; bigger drops have more mass and greater terminal velocity, and thus, more energy (Laws 1941). The effect of the energy depends on soil characteristics and conditions. Some energy is used to wet, deform, and detach soil particles, while the remaining energy is used to move the soil vertically and laterally (Rose 1960; Savat and Poesson 1981). At the start of a rainfall event on dry soil, raindrops can deform the soil surface. As the soil wets beyond its plastic limit (i.e., the moisture content of soil when it first becomes malleable), its shear strength decreases, rendering soil particles more vulnerable to detachment and transport (Bryan 2000).

Since the earth's surface is irregular and not perfectly smooth, **sheetflow** quickly concentrates into micro-channels, or **rills**, becoming **concentrated overland flow** (Rauws and Govers 1988; Torri et al. 1987) (Figure 1). **Rill erosion** occurs at the point at which flowing water has enough energy to dislodge soil particles from the surface and begin incision. When rill erosion first occurs, erosion rates can increase dramatically (Römkens et al. 1997; Bryan 1990). Rills are the primary conveyor of eroded soil from the landscape and are capable of long distance transport (Kinnell 2005). Interrill and rill erosion can occur simultaneously since raindrop impact continues to occur between established and developing rills (Bryan 2000). If rill erosion progresses, gullies can form and create larger and more permanent channels (Figure 2) (Sidorchuk 1999). As runoff volume increases, more energy is available for additional erosion (Huang et al. 1999).

Physical and Hydraulic Soil Properties Influencing Erosion

Physical and hydraulic soil properties are the most important factors that determine soil



Figure 2. An active gully below a road drain point in the western United States (Photo credit: USDA Forest Service).

erodibility (Pierzynski et al. 2005). These soil properties include **antecedent moisture** (i.e., moisture level prior to a rain or wind event), porosity, surface roughness, texture, and **aggregation** (i.e., binding together of individual soil particles). Individually, these properties have varying, dynamic, and interdependent effects on erosion rates (Römkens et al. 2001).

Antecedent soil moisture is the single most important property influencing erosion during storm events because it affects the structure and hydraulic response of the soil (Cresswell et al. 1992). In general, wetter soils will saturate quicker during a rain storm and thus produce overland flow sooner, resulting in more potential for erosion. However, wet conditions can result in more ponding on the surface, which can protect the soil from raindrop impact (Hairsine et al. 1992). In general, soils with < 30 percent moisture break down and form a **seal** (i.e., condition where surface porosity is reduced by plugging by soil particles or compaction) faster than soils with > 30 percent moisture, especially with rapid wetting (Le Bissonnais et. al. 1989; Luk 1985). Soil seals form by raindrop impact and by sediment deposition from the infiltration of sediment-laden overland flow (Moss 1991). Seal development impedes infiltration and increases overland flow, and therefore, erosion potential (Poesen 1993). However, under some conditions, a seal can decrease erosion rates because it increases soil shear strength (Römkens et al. 1997). Soil aggregates, or peds (Figure 3) (Pierzynski et al. 2005), generally experience an exponential increase in shear strength from almost zero at saturation to their highest potential strength at their plastic limit (Tengbeh 1993). Frequent wetting and drying cycles decrease aggregate stability and increase erodibility (Tisdall et al. 1978; Shiel et al. 1988; Römkens and Wang 1987). The breakdown of aggregates is fastest under rapidly wetting conditions (LeBissonnais et al. 1989; Lado et al. 2004). The increased aggregate breakdown is due to **slaking**, which is the process of air escaping from soil pores as water moves in (Rudolf et al. 1997).

Soil porosity is the single most important control on infiltration rates. Soils with high surface porosity have greater infiltration rates and less runoff, thereby limiting erosion (Pierzynski et al. 2005). **Porosity** is a function of the small-sized (micropores) and intermediate-sized spaces (mesopores) among individual soil particles and the larger spaces between peds (macropores) caused primarily by biological activity (Brooks et al. 2013). Macropores connected to the surface have the ability to transmit large quantities of water quickly away from the surface, thereby maintaining high infiltration rates.

In the absence of vegetation, **surface roughness** is the major factor affecting soil seal development, runoff, and erosion (Cogo et al. 1983). Rougher surfaces generally delay sealing because the increased relative surface area of the soil creates lower raindrop impact density (Roth and Helming 1992). Rough surfaces also have depressions where ponding occurs, increasing the surface storage of rain water and decreasing runoff velocity (Hairsine et al. 1992; Onstad 1984). On small test plots, ponding decreased the amount of surface smoothing (Rudolf et al. 1997), but on larger plots leveling was greater when ponding occurred (Bertuzzi et al. 1990). The larger plot allowed runoff to reach a higher velocity, and



Figure 3. A forest soil showing peds or aggregates of individual soil particles near Parsons, West Virginia (Photo credit: Adrienne Nottingham).

therefore, greater shear stress. Surface roughness has a large effect on rill development (Römkens et al. 2001). Greater surface roughness may increase rill development by concentrating flow (Abrahams and Parsons 1990; Helming et al. 1998; Römkens et al. 2001).

Soil **texture** affects infiltration and runoff rates, soil shear strength (Poesen 1993), and aggregate stability (Lado et al. 2004). Clay content plays a major role in aggregate stability and seal formation (Lado et al. 2004). Aggregates of 1:1 type clays are stronger than aggregates formed by 2:1 clays (Troeh et al. 1999). Ben-Hur et al. (1985) found soils with intermediate clay content (10 to 30 percent) resulted in weak aggregates that broke down under simulated rainfall, providing loose, easily erodible soil that formed an infiltration seal and reduced soil porosity. The combination of loose soil and reduced porosity increased erosion potential. However, soils with < 10 percent clay content did not have enough clay to form a seal or reduce porosity when exposed to raindrop impact; therefore, they maintained high infiltration rates and low erosion potential. Clay contents above 30 percent provided sufficient aggregate stability to resist slaking and seal formation under the simulated rainfall conditions, thus, reducing detachment and overland flow, and erosion potential. Poesen (1993) found a silt loam soil resisted aggregate breakdown and maintained high infiltration rates. However, soil seals formed faster as sand content increased to 90 percent, while 100 percent sand resulted in no surface sealing and high infiltration rates. Quansah (1981) observed that sand, with the lowest cohesion of all soil types, had the highest splash-detachment rates, followed by clay, then clay loam. Splash transport was highest for clay because less energy is required to move smaller clay particles than sand particles (Quansah 1981).

Large soil aggregates require more energy to transport than small aggregates; therefore, they strongly resist erosion unless they are broken into smaller pieces (Hairsine and Rose 1992). However, large aggregates resist breakdown more than smaller aggregates (Freebairn et al. 1991). In addition to size, antecedent moisture (Truman et al. 1990), organic matter content, soil cations (i.e., positively charged ions), clay content, and clay mineralogy influence aggregate stability (Haynes and Swift 1990; Perfect and Kay 1990). Slightly acidic soils (pH range of 4.5 to 6.0) tend to form more stable aggregates than those with high amounts of sodium, magnesium, and potassium (Troeh et al. 1999). Organic matter can act as a

binding agent and help to form stronger aggregates as well (Tengbeh 1993; Troeh et al. 1999; Traore et al. 2000).

Precipitation Characteristics and Erosion

As the primary means of water input to landscapes, precipitation can exert a significant influence on erosion. Precipitation is characterized by amount, duration, intensity (i.e., amount/duration) and sequence (i.e., the order and timing of rainfalls) (Meyer 1981). Rainfall intensity is usually the most important of the four factors affecting erosion (Nichols and Sexton 1932). As intensity increases so does the kinetic energy of the raindrops, increasing detachment and transport of soil (Ellison 1944; Quansah 1981). The intensity and size of raindrops are important because the force of raindrop impact can compress or collapse soil pores and detach soil particles, which can further plug soil pores and increase runoff (Moss 1991). Climate change models predict that the earth will experience more intense storm events, resulting in greater erosion rates (Intergovernmental Panel on Climate Change 2015).

Increases in rainfall duration increase the erodibility of soil (Tisdall et al. 1978). As rainfall volume increases with duration, soil becomes saturated. After saturation, surface runoff develops, which has the potential to transport sediment and increase erosion rates (Pierzynski et al. 2005). Soil shear strength decreases exponentially as the soil approaches saturation (Tengbeh 1993), resulting in increased potential for sediment entrainment in overland flow.

The sequence of rainfall events is important because it directly affects some soil properties, primarily soil moisture. As discussed previously, soil moisture affects soil shear strength. Greater periods of time between rainfall events generally result in drier soils, while frequent rain events lead to more consistently moist soils. Recently deposited soil from previous storms is more erodible due to poor aggregation (Hairsine et al. 1992), and frequent rainfall events can lead to decreasing sediment yield due to flushing (i.e., transport of stored sediment) (Croke et al. 2006). When frequent precipitation occurs, easily erodible soil is detached and transported during the first few storms, leaving less erodible soil for subsequent storms. This can result in decreasing erosion rates from rain event to rain event, assuming the storms have similar rainfall characteristics.

Topographic Influences on Erosion

Slope steepness and length are critical factors controlling overland flow and erosion (Bryan and Poesen 1989). As the slope increases, so does the probability that splashed soil will move downslope (Ellison 1944). In a laboratory experiment, Quansah (1981) found that detachment rates increased slightly, and sediment transport capacity increased greatly on steeper slopes. Steeper slopes also enhance erosion via rill development due to increased shear velocities (Chaplot and LeBissonnais 2000). On sloping land, there is usually net transport of soil downslope because displaced soil can travel further downhill than uphill due to gravity and slope angle. On a 10 percent slope, up to 75 percent of the splashed soil can move downhill (Ellison 1944). Huang et al. (1999) found that slopes < 5 percent resulted in net sediment deposition during simulated rain events in a laboratory experiment. On relatively flat surfaces, raindrop splash causes essentially no net soil loss because displaced particles are replaced by nearby soil particles that were displaced by raindrop impacts (Troeh et al. 1999).

Long slopes generally result in high amounts of soil loss (Troeh et al. 1999; Brooks et al. 2013). However, the effects of slope length are complicated by the processes of seal development, rill development, and deposition. All of these processes have varying effects on infiltration and runoff and can occur simultaneously (Bryan and Poesen 1989). Research suggests that slope length is not an important factor affecting runoff velocity on grades < 8 to 10 percent (Chaplot and LeBissonnais 2000; Kinnell 2000). At lower gradients, runoff reaches a relatively low maximum velocity in a short distance (e.g., 4 percent slope at 3 m). As slope increases, maximum potential runoff velocity increases along with the distance required to reach that velocity (Chaplot and LeBissonnais 2000). Greater runoff velocity results in greater transport capacity and erosion rates (Table 1) (Chaplot and LeBissonnais 2000).

Table 1. Erosion rates under different surface slopes and plot sizes following a 30 mm h^{-1} simulated rainfall (from Chaplot and LeBissonnais 2000).

Slope (%)	Surface Area (m^2)	Soil Loss ($g\ m^{-2}h^{-1}$)
4	1	60
4	10	70
8	1	90
8	10	190

Biological Influences on Erosion

Vegetation

It is well documented that soil covered with vegetation or vegetative litter is less erodible compared to bare soil (Swift 1984; Quinton et al. 1997; Loch 2000; Freebairn et al. 1986). The greatest reductions in soil losses occur as cover increases from 0 to 30 percent (Quinton et al. 1997; Loch 2000). Loch (2000) found exponential decreases in sediment yield with increasing grass cover, and once cover reached 23 percent, rill development ceased. At 50 percent cover, sediment losses were < 0.5 metric tons ha^{-1}, regardless of runoff rates.

As precipitation falls, the first defense that vegetation provides against erosion is raindrop interception. However, mature tree canopies can actually increase the kinetic energy of raindrop impact by aggregating precipitation into larger droplets and releasing them as throughfall to the ground (Stuart and Edwards 2006). Despite this effect, the litter layer associated with forest floors under mature trees protects the soil from raindrop impact (Stuart and Edwards 2006). The litter layer also provides organic material which can increase aggregate stability (Tengbeh 1993) and can store a large amount of water (Brooks et al. 2013). Shade provided by stems, leaves, and litter slows soil drying rates, which may increase aggregate stability compared to aggregates forming under rapid drying conditions (Tengbeh 1993).

Vegetation also increases infiltration (Loch 2000) and surface roughness via rooting and by providing a litter layer (Walsh and Voigt 1977; Woo et al. 1997). Vegetation and litter increase roughness on slopes in the form of debris dams and blockage of water movement by stems. These obstructions can increase the depth of overland flow and decrease its velocity (Hairsine et al. 1992; Yu et al. 2006; Woo et al. 1997). Increased flow depth can reduce detachment by padding the soil against raindrop impact (Hairsine et al. 1992). Gyssels and Poesen (2003) showed that rill formation decreased as grass shoot densities increased in highly erodible soils, and soil deposition occurred in meadows. Mature and dense grass stems were important in controlling erosion because the stiffer stems were able to resist the force of overland flow. By contrast, younger field crops are susceptible to being bent over by concentrated flows (Gyssels and Poesen 2003). Analogously, in the early stages of plant growth, roots are more important in controlling rill development because young shoots bend or break with heavy flow (Gyssels and Poesen 2003). Dense, heterogeneous cover is ideal for limiting rill erosion (Gyssels and Poesen 2003). Abrahams et al. (1995) found decreased infiltration and increased runoff in rangeland that had converted from primarily grasses to shrubs because the soil between shrubs was eroded by raindrop splash and rills; this occurred even though the soil was well protected directly beneath the shrubs.

Roots physically reinforce and bind soil in place, resisting erosion from concentrated flow (De Baets et al. 2006; Gyssels and Poesen 2003; Tengbeh 1993). Tengbeh (1993) found a minimum of 500 percent increase in soil shear strength when fibrous grass roots were present compared to bare soil. The increase in shear strength due to root presence depends on soil texture. Tengbeh (1993) found a clayey soil with roots had 1.7 times greater shear strength than a sandy soil with the same root density. The higher shear strength of the clay soil was attributed to stronger cohesion of the clay soil to the roots. Root growth and dieback result in more pore space and connectivity, which increases infiltration and reduces erosive overland flow (Gyssels and Poesen 2003; Loch 2000; Yu et al. 2006). Roots secrete organic binding agents



Figure 4. Standard soil erosion plots and simulated rainfall system in southern Indiana in 1968. These types of experiments were used to develop and refine the Universal Soil Loss Equation (USLE) (Photo credit: USDA Agricultural Research Service).

that increase soil aggregate stability (Tengbeh 1993; Traore et al. 2000). These exudates provide sustenance for many soil organisms that increase porosity and secrete binding agents themselves (Traore et al. 2000), thereby further increasing aggregate stability and reducing erodibility (Troeh et al. 1999).

Soil Organisms

Vegetation increases the value of habitat for burrowing invertebrates and rodents whose tunnels increase soil porosity and the formation of macropores (Loch and Orange 1997). These organisms mix material through the soil profile, transporting organic matter away from and coarse particles toward the soil surface (Pierzynski et al. 2005). Earthworms are among the most abundant (Pierzynski et al. 2005) and most studied soil organisms (Blanchart et al. 2004). Through burrowing and feeding activities, earthworms enhance the physical and chemical structure of most soils by creating macropores and transporting organic matter through the soil profile (Lee and Foster 1991). Earthworm activities increase the infiltration capacity of soil (Ehlers 1975; Shipitalo and Butt 1999) and reduce runoff (Kladivko et al. 1986). In compacted soils, earthworms decrease bulk density and increase infiltration (Joschko et al. 1989). However, earthworm castings on the soil surface and animal excavation can expose mineral soil to raindrop impact and potentially increase erosion (Binet and LeBayon 1999; Yair 1995).

Measurement of Surface Erosion

Erosion can be physically measured by erosion plots and erosion stakes or pins. **Erosion plots** are the most widely used method and consist of rectangular plots of specific size where the amount of eroded soil is collected down slope of the plot during and following natural or simulated rain events. The boundaries of the plots consist of walls of sheet metal, plastic, plywood, or concrete. A collection trough and container are installed on the downslope side to capture the runoff and sediment. The standard plot size is 6 feet by 72.6 feet (approximately 2 m by 22 m) that was used in the development of the Universal Soil Loss Equation (USLE) (Figure 4). The USLE was developed by the United States Department of Agriculture, Agriculture Research Service in 1965 as a means to predict erosion over a broad set of surface conditions and climates (Brooks et al. 2013). For more detail on the USLE Equation, see Schoonover and Crim (2015, this issue), "An Introduction to Soil Concepts and the Role of Soils in Watershed Management." Erosion can also be measured from microplots 1 to 2 m^2 in size, which are commonly used in research studies.

Surface erosion and deposition are measured at

multiple locations over time by installing **stakes** or **pins** in the ground surface. Upon installation, the height of the stake is measured above the ground surface and then re-measured at various time intervals (week, month, year) to estimate the amount of soil loss or accumulation. The erosion stakes can be arranged in various grid patterns along a slope or field to estimate erosion and deposition at different topographic positions.

Surface Erosion in Forests and Agricultural Fields

The most important factor controlling surface erosion in forests is the annual supply of litter to the forest floor (Stuart and Edwards 2006). The litter layer absorbs the kinetic energy of raindrop impact (Kochenderfer 1970) and provides organic material to the soil, which is a food source for soil organisms (Stuart and Edwards 2006). Dense root networks in forests provide soil stabilization, while root dieback increases pore space (Loch 2000). Porosity also is increased by burrowing rodents (Pierzynski et al. 2005). Consequently, forest infiltration rates are generally very high (Patric 1978; Kochenderfer 1970). Overland flow rarely occurs in forests where an intact litter layer is present (Stuart and Edwards 2006). Thus, forests experience little rill or interrill erosion (Patric 1978).

Agricultural fields commonly experience more erosion than forests mainly due to a lack of ground cover and greater amounts of exposed mineral soil. Additionally, agricultural soils tend to be more compacted than forest soils because of farm machinery traffic. Compaction collapses macropores and results in lower infiltration rates, more runoff, and greater erosion. Further, tillage (i.e., disturbing the topsoil to prepare a seed bed and provide weed control) can reduce surface residues, soil macroporosity, and aggregrate stability, thereby increasing erosion potential. Reduced tillage or no-till can help reduce erosion rates by allowing more surface residue and macropores to develop through increased soil biological activity. Since the surface of agricultural fields is irregular and has microtopography, the area is commonly drained by concentrated overland flow and rills (Pankau et al. 2012). Thus, rill erosion usually greatly surpasses interrill erosion in agricultural fields. For example, Govers and Poesen (1988) found 75 percent of eroded soil resulted from rill erosion compared to 25 percent from interrill erosion.

Erosion Control

Erosion control can take many forms in many different activities. Mechanical, physical, and biological methods all can be used to reduce erosion and control sedimentation or locations of sediment deposition. Many of these methods are generally considered under the umbrella term of **best management practices** (**BMPs**), and they are used in agriculture, construction, forestry, mining, and other land uses in which erosion is a concern. BMPs are designed to reduce erosion at optimized cost, and they are based on physical principles that influence the energy of water and the erodibility of soil (Stuart and Edwards 2006).

Managers are well aware of the benefits of vegetation for soil stabilization, so revegetating disturbed sites is a fairly common BMP (Troeh et al. 1999; Kochenderfer 1970). The revegetation process often includes soil amelioration (ripping compacted soils, fertilization, liming, etc.) and seeding followed by mulching, but also can be as simple as casting seed (Kochenderfer 1970). Vegetative species selected for erosion control usually are prolific, fast growing plants with fibrous root systems that are able to rapidly cover bare soil and hold it in place (Troeh et al. 1999). In agricultural watersheds, cover crops, such as grasses and legumes, can be planted in the fall to provide ground cover and limit erosion during the dormant season. See "Guiding Principals for Management of Forested, Agricultural, and Urban Watersheds" (Edwards et al. 2015, this issue) for more detailed information on erosion control and best management practices.

Conclusion

As sediment is the most common water pollutant worldwide, it is important to understand the dominant factors influencing erosion rates to help minimize sediment delivery to surface water bodies and protect aquatic biota. In humid climates, precipitation intensity, soil moisture,

slope steepness, slope length, vegetation, and soil organisms interact to determine a watershed's vulnerability to erosion. In forested and agricultural watersheds, BMPs are designed to limit the exposure of mineral soil to rainfall and surface runoff and thus reduce the detachment and transport of sediment. Land managers and owners can limit erosion by following two simple tenants: 1) maintain as much ground cover as possible during land management activities (farming, timber harvesting) and 2) rapidly establish ground cover following periods of active land management. Practicing these two rules will provide low-cost, effective, and long-term erosion control that will help keep working landscapes productive.

Acknowledgement

This work was supported by funds provided by the USDA Forest Service, Monongahela National Forest.

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Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 154, Pages 60-84, April 2015

Guiding Principles for Management of Forested, Agricultural, and Urban Watersheds

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Abstract: Human actions must be well planned and include consideration of their potential influences on water and aquatic ecosystems – such consideration is the foundation of watershed management. Watersheds are the ideal land unit for managing and protecting water resources and aquatic health because watersheds integrate the physical, biological and chemical processes within their boundaries. Managed forested watersheds tend to have more natural watershed functions and better water quality than other land uses. Land uses with greater amounts of soil disturbance and permanent reductions in infiltration, such as in agricultural or urban/developed settings, usually have greater undesirable hydrologic alterations and poorer water quality. Nonpoint source pollutants resulting from many forestry, agricultural, and urban activities are controlled by techniques and tools known as best management practices (BMPs). Best management practices are applied by watershed managers to large-scale landscapes, but they also are applicable to the lives of ordinary citizens. Basic BMP principles, such as controlling the amounts and duration of soil disturbance during construction around the home, applying chemicals to lawns or gardens only at needed rates and during suitable times, and incorporating techniques to encourage infiltration of rooftop and driveway runoff are important actions that anyone can take to help protect watershed functions, water quality, and aquatic health.

Keywords: *land use, nonpoint source pollution, point source pollution, erosion and sedimentation, best management practices, watershed management, roads, water quality*

In "Fundamentals of Watershed Hydrology" (Edwards et al. 2015, this issue), the definition of a **watershed** (i.e., an area of land in which all of the incoming precipitation drains toward the same body of water as a result of its topography) was introduced from the perspective of understanding hydrologic principles and cycles. A watershed provides an ideal unit for managing lands because the hydrologic cycle within a watershed drives many of the physical, biological, and environmental processes in the catchment. Thus, the watershed integrates all of the interconnected physical, biological, and chemical environmental processes (both intended and unintended) that result from (and in spite of) all of the activities occurring in the watershed. Consequently, managing at the watershed scale can make more sense than managing at other scales, such as municipalities or counties that have arbitrary boundaries.

The science of **watershed management** implements actions that maintain and enhance watershed functions that are important to the sustainability of vegetative, animal, and human communities within the watershed boundaries. Examples of watershed characteristics and functions that are impacted by watershed management include water supply, water quality, storm runoff timing and volume, physical water body characteristics, aquatic habitats and aquatic health. Proposed actions in a watershed may be modified, require mitigation, or may be rejected entirely by watershed management agencies if the potential outcomes of the proposed actions present too great a risk to individual or integrated watershed functions.

Forested watersheds typically provide the greatest number of desirable watershed characteristics and functions, including slow and moderated releases of storm runoff, cool or cold

water temperatures (from shading), quality habitat for aquatic species, low erosion rates, and high-quality water. When present, forested watersheds are often the preferred source for potable water for municipalities because the costs of water treatment are greatly reduced by the high quality of water delivered. For example, New York City saves billions of dollars by not having to filter water it receives from the Catskill and Delaware watersheds that are 90 percent forested (see http://ice.ucdavis.edu/node/133).

In this paper the discussion of watershed management begins with a focus on forested watersheds. This examination provides a baseline against which agricultural and urban land uses are described and compared. Readers who are unfamiliar with basic hydrologic concepts are encouraged to review the "Fundamentals of Watershed Hydrology" (Edwards et al. 2015, this issue) and "Soil Erosion in Humid Regions: A Review" (Holz et al. 2015, this issue) before reading this paper. Many of the concepts about the hydrologic cycle and the water budget equation, and erosion and sedimentation described in those papers, have direct application to watershed management.

Forest Management Influences on Hydrology

In the United States, much of what is currently known about hydrologic responses in forested watersheds and from forest management activities has been determined from small experimental watersheds operated by federal agencies (especially the U.S. Forest Service; e.g., Adams et al. 2004) or universities. **Experimental watersheds** have been important for understanding how forests affect the overall hydrologic cycle, especially for quantifying the effects of management on soil moisture and streamflow. In addition, the science of forest hydrology has augmented and accelerated the understanding of forest ecology since many important ecological processes are directly or indirectly dependent on moisture availability.

One of the primary techniques used to understand how forest management affects the hydrologic cycle has been the use of **paired watershed experiments** (Figure 1). The paired watershed approach compares hydrologic responses of two similar, and typically proximate watersheds, where one (the **treatment watershed**) receives a management activity (e.g., harvesting) and another (the **control** or **reference watershed**) remains undisturbed. Using data collected during several years prior to the application of the management activity, a mathematical relationship called a **calibration equation** is developed to predict the values of a hydrologic variable of interest (e.g., annual discharge, stormflow volumes, etc.) for the treatment watershed from the control watershed. Following this pretreatment period, the management activity is applied to the treatment watershed, and data are collected for several more years (i.e., the posttreatment period). Hydrologic responses for the treated watershed that would have resulted had the treatment not been implemented are predicted from the calibration equation using control watershed data during the posttreatment period. Posttreatment measured values from the treated watershed are compared to the predicted values, and the differences between observed and predicted values are attributable to the effects of the management applied to the watershed.

Every watershed is unique with respect to the combination and characteristics of the many variables that can influence hydrologic responses. However, even with the great variability and seemingly infinite combinations of topographic, geomorphic, climatic, soil, vegetative, and other factors that can influence hydrologic responses, some consistencies have been found for forested watersheds using the paired watershed approach:

1) To induce a statistically measurable increase in annual streamflow in forested watersheds, the basal area in the watershed must be reduced (usually by harvesting) by a minimum of approximately 15 to 20 percent (Stednick 1996). **Basal area** is the cross sectional area of tree stems measured at 1.4 m above the ground, and it represents the ground area occupied by tree stems (e.g., square meters of tree stems per hectare). Basal area serves as a good surrogate for leaf area, and thus is strongly correlated with the magnitude of potential transpiration and interception loss by the forest.

2) Streamflow increases resulting from basal area reduction are primarily attributable to reductions

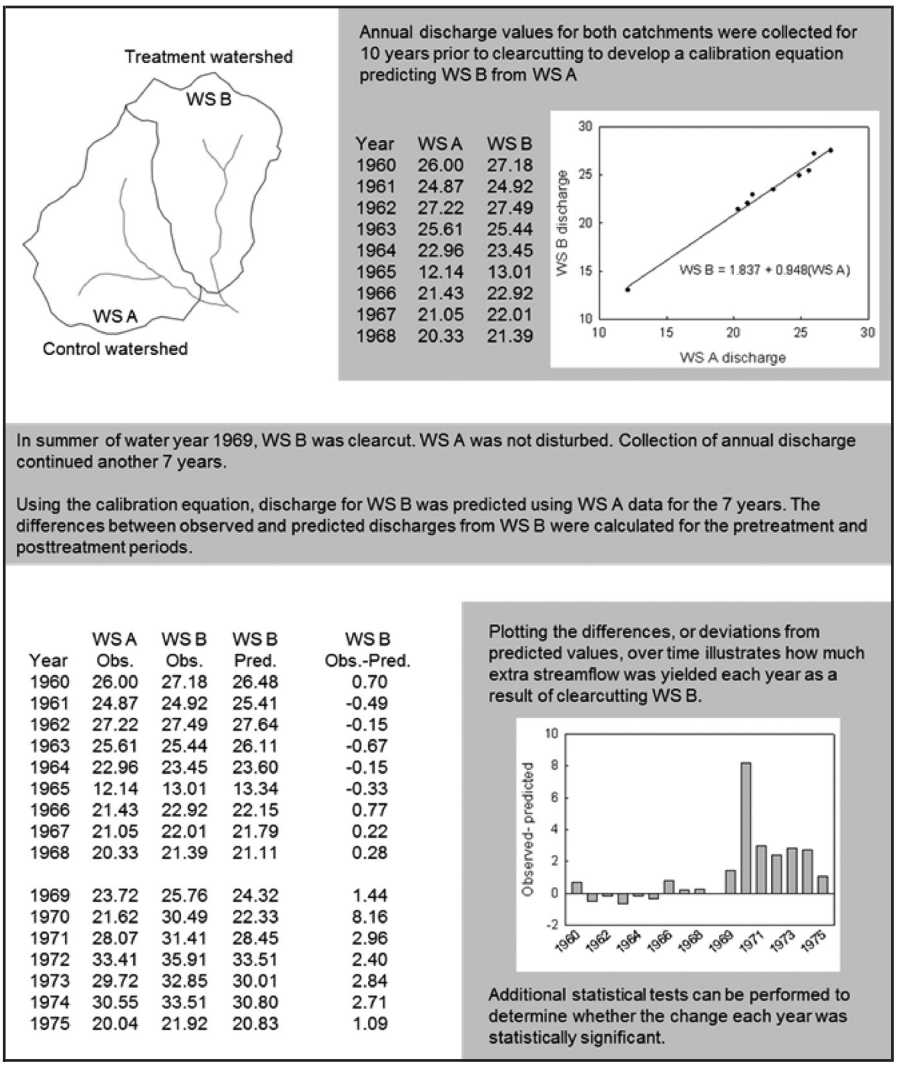

Figure 1. Steps for performing paired watershed analyses and for calculating changes in streamflow due to a treatment applied to one of the watersheds. This example illustrates the annual increases measured following harvesting and during the first 7 years of natural regeneration of the forest.

in transpiration, decreases in interception losses, and changes in soil moisture storage resulting from these two variables. Increasing solar radiation to the ground may increase evaporation from the soil and offset some of the moisture increases.

3) Annual streamflow augmentation increases in proportion to the amount of basal area removed. The greatest streamflow increases occur from clearcutting and usually during the first or second year following the harvest, but the actual maximum increases vary with the physiographic and climatic conditions (Table 1). The pattern of management or disturbances within watersheds affects the degree and duration of hydrologic changes. Even when at least 20 percent of basal area is removed, if the harvesting targets individual trees spread throughout the watershed the hydrologic response will be less than harvesting the same amount of basal area in a single block. In the former situation the residual vegetation will grow into the small openings quickly, thereby using surplus soil moisture that resulted from reductions in transpiration. By contrast, large openings have less edge so much more time is required for trees around the edge and regeneration within the opening to utilize the increased soil moisture made available from the declines in interception losses and transpiration that result from harvesting.

Table 1. Examples of streamflow increases during the first two years after clearcutting watersheds throughout the U.S. In some instances additional treatments, such as site preparation, followed harvesting.

Location	Forest Type	Watershed Size (ha)	Years after Clearcutting	Annual Increase in Discharge (mm)	Reference
Hubbard Brook Experimental Forest, New Hampshire	Northern hardwood	22	1 2	152 47	Hornbeck et al. (1997)
Great Northern Paper Co., Maine	Spruce-fir	47	1 2	310 290	Pierce et al. (1993)
Leading Ridge, Pennsylvania	Mixed hardwood	45	1 2	137 39	Lynch and Corbett (1990)
Fernow Experimental Forest, West Virginia	Mixed hardwood	30	1 2	130 86	Lull and Reinhart (1967)
Coweeta Hydrologic Laboratory, North Carolina	Mixed hardwood	59	1 2	260 200	Swank et al. (1982)
Athens Plateau, Arkansas	Pine-oak-hickory	2-5 (3 replicates)	1 2	166 388	Beasley et al. (1986, 2000)
Wagon Wheel Gap, Colorado	Aspen-conifer	81	1 2	34 47	Bates and Henry (1928)
Coyote Creek, Oregon	Mixed conifer	50	1 2	360 292	Harr et al. (1979)
H. J. Andrews Experimental Forest, Oregon	Old-growth Douglas-fir	96	1 2	462 457	Rothacher (1970)

4) Basal area reductions that increase discharge can result from management activities or natural disturbances to vegetation. While harvesting is one of the most common, and certainly the most studied causes of basal area reductions in forested watersheds, other natural disturbances that alter evapotranspiration, such as wind events or insect defoliation, also can result in increases in annual discharge. In 1938, region-wide blowdown of forest vegetation affected 6 million hectares, or 15 percent of New England. The resulting reduction in evapotranspiration increased annual discharge by 127 mm in the Merrimack and Connecticut Rivers the first year after the hurricane (Patric 1974). Multiple examples of streamflow increases from insect defoliation have been reported (e.g., Love 1955; Bethlahmy 1975; Potts 1984). Given that only portions of a watershed tend to be affected by defoliation, the magnitude of streamflow increase caused by insect defoliation during any single year is typically more like that attributable to a partial harvest than to clearcutting. However, hydrologic effects from defoliation may extend over more years than harvesting because defoliation usually continues over multiple years.

5) Increases in annual streamflow attributable to basal area reductions are greatest in regions with warm temperatures and high precipitation, but their duration is shorter than in other climates (Bosch and Hewlett 1982; Stednick

1996; Brown et al. 2005) because regeneration can occur quickly due to the favorable growing conditions. Rapid re-growth by **coppicing**, which is regeneration by sprouts that grow from still-living stumps or roots of freshly harvested trees, also contributes to shortening the time during which streamflow is increased in any climate. Throughout the United States, annual streamflow generally returns to pre-harvest levels in less than three decades after clearcutting, and often much more quickly (Troendle et al. 2010). In the humid East, measurable increases to annual discharge typically last between 3 to 10 years. By contrast, recovery in cold, snow-dominated areas of the Rocky Mountain region can be longer than the three-decade generalization. Thirty years after strip clearcutting the Fool Creek watershed, significant increases in streamflow continued to be documented (Troendle and King 1985), with estimates of full hydrologic recovery several more decades in the future (Troendle et al. 2010). These extended responses are attributed to longer periods needed for forest regrowth and changes in snowpack accumulation that resulted from harvesting.

Species conversions from hardwoods to conifers (or vice versa) via management or natural succession can significantly change streamflow yields. This change occurs because conifers intercept more precipitation (especially snow), and they tend to transpire more year-round and during the growing season due to the continuous presence of leaves (i.e., needles) and greater leaf densities compared to hardwoods in the same climatic regions (Richardson and Rundel 1998). At Coweeta Hydrologic Laboratory in the mountains of western North Carolina, two hardwood watersheds (one north-facing and one south-facing) were clearcut and planted to eastern white pine (*Pinus strobus* L.) (Swank et al. 1988). Within the first 6 to 10 years following planting of the conifer seedlings, annual streamflow increases attributable to the clearcutting and presence of the young stand were similar to what would have been expected during hardwood regrowth in those watersheds. As the conifer stands further developed during the next five years, annual streamflow declined at a rate of 20 to 50 mm per year. When the conifers reached 15 years of age, annual discharge in both watersheds was about 20 percent below what would have occurred if the watershed had re-vegetated as hardwoods (Figure 2).

Because watershed management studies have illustrated the ability to augment annual water yields by clearcutting, forest removal is sometimes considered as a possible mechanism to alleviate water shortages during droughts or in dry climates. However, the relatively short duration of those increases make supplementation of water yield by clearcutting alone impractical.

All of the hydrologic changes from forest vegetation management described so far have focused on total annual streamflow. However, understanding how stormflow changes as a result of management or natural ecosystem changes also is useful because this information includes the timing and energy of streamflow, which can impact many watershed functions.

Stormflow is generated in forested watersheds in different ways than it is in watersheds or portions of watersheds that support other types of land uses. In addition to small amounts of precipitation that fall directly into channels, water primarily reaches streams in forests through soil water and groundwater contributions. This is because forest soils generally have high soil infiltration rates due to the presence of leaf litter and the low incidence of soil compaction. Overland flow outside of channels rarely occurs in forests, except where soil has become compacted sufficiently to reduce infiltration rates substantially. Consequently, watershed management guidelines for forests and other land uses often emphasize employing management practices or implementing techniques that limit changes to soil compaction or that enhance infiltration.

Across the United States, a primary focus of hydrograph analyses has been the examination of changes to instantaneous peakflows and total stormflow, with particular attention to the impacts of forest removal on the extent or frequency of flood flows (see Edwards et al. “Fundamentals of Watershed Hydrology”, this issue for a discussion of hydrographs, peakflows, and stormflow). Statistically significant increases in peakflow and stormflow volumes have been reported for some small forested watersheds following clearcutting

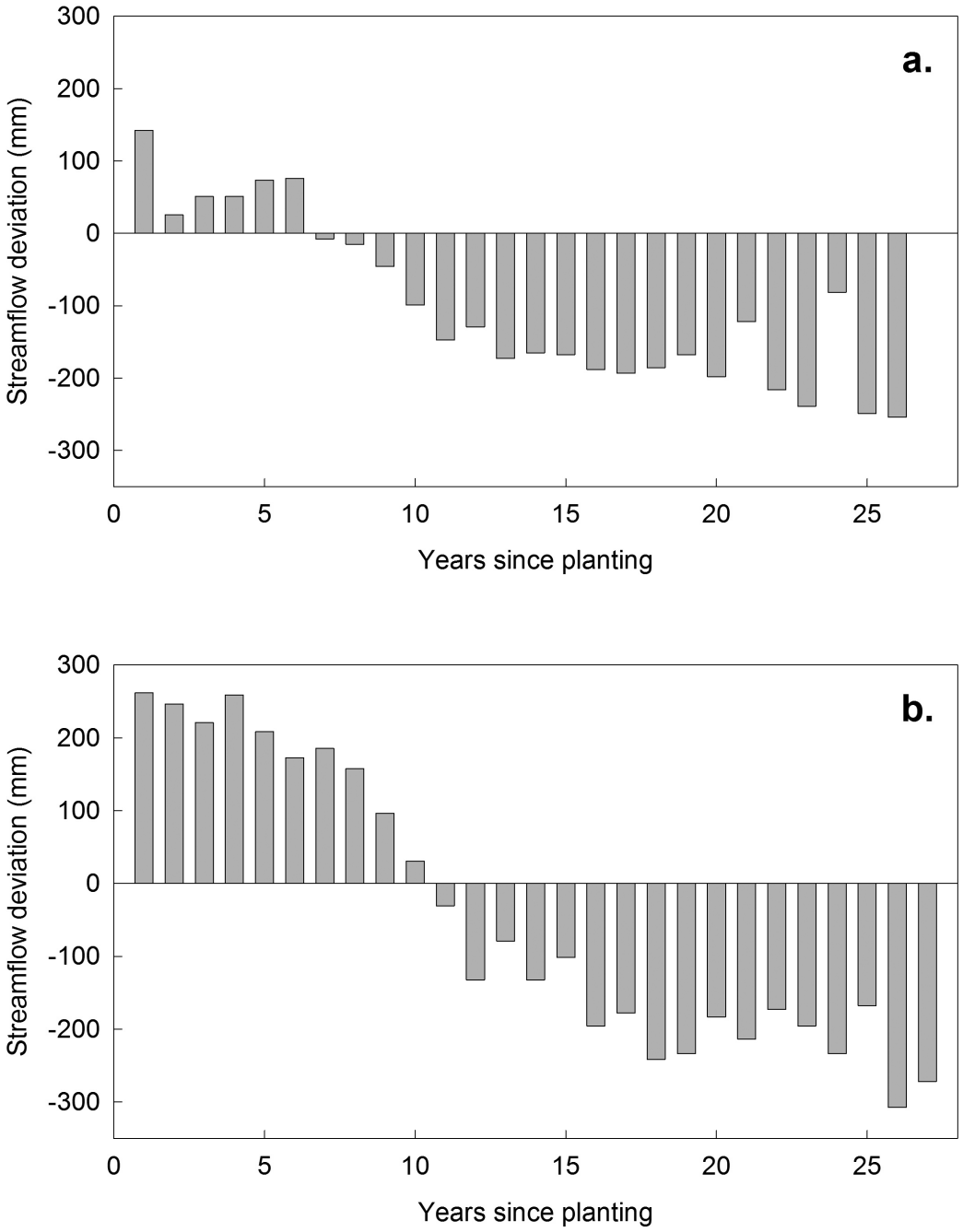

Figure 2. Paired watershed analysis was used to determine the effects of species conversion on annual stream discharge in a (a) south-facing and (b) north-facing watershed at the U.S. Forest Service's Coweeta Hydrologic Laboratory in western North Carolina. At time zero, both watersheds dominated by hardwood trees were harvested and then immediately planted to eastern white pine seedlings. Streamflow increased (as denoted by a positive streamflow deviation from predicted values) for a number of years, as typically occurs following forest harvesting due to the reduction in transpiration and interception losses. As the conifers became established on both watersheds, transpiration and interception losses eventually exceeded those levels of the original hardwood trees, and streamflow decreased below predicted levels (as denoted by negative streamflow deviations). Establishment of the conifers reduced annual discharge by at least 229 mm below what would have resulted from hardwood regrowth. Adapted from Swank et al. 1988.

(Hewlett and Helvey 1970; Hornbeck 1973; Swank et al. 2001; Troendle and King 1985), while other studies have found no measureable change in one or both of these variables (Hewlett and Hibbert 1967; Rothacher 1973; Settergren et al. 1980; Patric 1980). But even where changes have been reported, they generally have been relatively small increases and short-lived. Thus, the conventional thought in forest hydrology is that clearcutting does not change hydrology sufficiently to increase flooding. Where flooding has occurred in or downstream from watersheds subjected to intensive harvesting, stormflow increases from harvesting are considered negligible relative to the amount of precipitation received by the watershed during the storm event. However, a relatively new approach to peakflow and stormflow analyses for watersheds in the Pacific Northwest has challenged this conventional thought (Alila et al. 2009), and some new debate on this subject has emerged.

Soil As A Pollutant

Sediment, or mineral soil, is one of the most common water pollutants in the United States, and it is the most common pollutant associated with forest management. Sediment becomes a water pollutant when eroded soil is transported to waterbodies. Because it is so ubiquitous, sediment is the pollutant most commonly targeted for control during management of forested watersheds as well as other types of land management.

Erosion is a two-step process involving first soil particle detachment and then particle transport. Deposition of transported soil particles is known as **sedimentation**. Erosion and sedimentation are described in this paper only to a limited extent to support discussions herein; Holz et al. (2015, this issue) provides more in-depth coverage of erosion and sedimentation processes and the factors that control or contribute to them.

Erosion and sedimentation are natural and important processes for development of landforms as well as for maintenance of healthy channels (Leopold 1994, Swanson et al. 1988). Until the time that humans became capable of substantially changing the physical appearance of the landscape (especially with mechanized equipment), long-term erosion and sedimentation processes in combination with more catastrophic events (e.g., uplifting, volcanic activity, landslides, etc.) were predominantly responsible for controlling the morphology of natural landscapes, and the presence and locations of water bodies. Humans now have considerable influence on these variables and are responsible for elevating erosion and sediment levels above natural conditions in most water bodies throughout the world.

Concerns about sediment movement on land are tied primarily to the loss of fertile top soil at the location where the erosion occurred, but in-water deposition actually presents more numerous and important problems. Increased sediment delivery to water bodies and accelerated erosion of stream and river beds can have many negative consequences, including effects on potable water quality and treatment costs, aquatic organisms and aquatic habitats, and water body stability (Newcombe and MacDonald 1991; Wood and Armitage 1997). Toxic chemicals and organisms (e.g., parasites, bacteria, etc.) also can be bound to soil particles, and deposition of contaminated sediments in water bodies can result in a myriad of consequences for aquatic organisms and humans (U.S. Environmental Protection Agency 2004).

Fortunately, not all eroded sediment will reach a water body. Some may move very little because there is insufficient overland flow to transport the sediment, there is little slope to the ground surface so sediment movement is stalled, or the sediment becomes trapped by obstacles, known as **roughness features**, on the ground surface. Any element that can stop movement or slow the water transporting sediment can act as a roughness feature, including vegetation, leaf litter and woody material, rocks, and many types of human-placed (intentionally or by chance) features.

Once delivered to streams or rivers, only a small percentage of sediment is exported quickly through the entire channel network and lost from the watershed. This is because sediment also becomes trapped and stored in pools where water velocity slows, and behind and within in-stream roughness features, such as boulders, rocks, large logs, debris jams, etc. Sediment trapped in channels can be stored for long periods of time – storage lasting decades to hundreds of years has been reported (Madej 1987; Brakebill et al. 2010; Milius 1998).

The greatest percentages of sediment exported from watersheds result from only a few of the largest streamflow events each year (Edwards and Owens 1991; Kochenderfer et al. 1997); other events simply redistribute sediment within the channel network. Consequently, the adverse influences of elevated sediment levels in water bodies can be quite long.

Sediment storage and transport in stream and river systems that have received substantial human reconfiguration, such as straightened (aka **channelized**) and dredged channels or concrete-lined channels, is very different from that described above for more-natural channels. Streamflow velocities in channels with these types of extreme disturbances are higher due to increases in slope from straightening (Figure 3) and/or reductions in bed and bank roughness (Arcement and Schneider 1989). Higher velocities and decreased roughness will transport more sediment more quickly, thereby reducing the potential for in-channel deposition and sediment storage. Higher flow velocities and decreased roughness also result in more energy for stream bank and bed erosion. This increased energy and capacity for erosion explains why channel migration and realignment toward natural conditions continue to occur after channelization. Video illustrations of large river and small stream channel respectively, are available from the Missouri Department of Natural Resources (respectively, see http://serc.carleton.edu/details/files/19164.html and http://serc.carleton.edu/details/files/19084.html). The increased energy makes even concrete-lined or other artificially armored channels susceptible to failures (Figure 4). Substantially altered channels also provide poor habitat, feeding, and reproductive conditions for aquatic organisms, typically poor water quality, and high maintenance and repair costs, all of which argue for managing watersheds to maintain healthy, natural channel conditions.

Forest Management Influences on Water Quality

In undisturbed watersheds, hillsides and channel banks and beds provide the sources of erodible sediment. Hillside sources in undisturbed forests are limited primarily to small areas of soil that lack litter cover (e.g., small areas on steep slopes),

$$\% \text{ Slope} = \frac{\text{Change in Elevation}}{\text{Stream Length}} \times 100$$

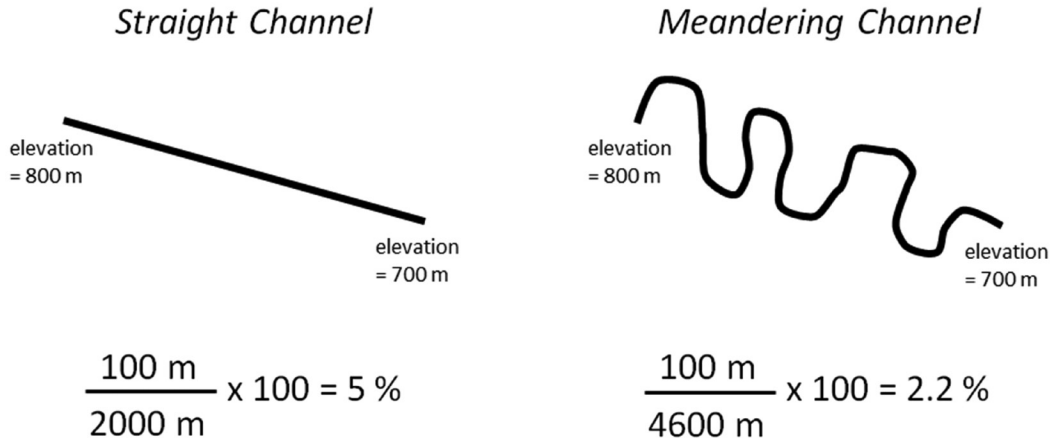

Figure 3. A stream or river's slope is calculated from the change in elevation between two points and the corresponding length of the stream channel. Consequently, when a meandering channel is straightened or channelized, the slope of the straightened channel will be greater. As a result, streamflow in the straightened channel will have a higher velocity and more energy for erosion.

animal trails, and root wads exposed by tree falls (Hamons 2007). Channel beds and banks are sediment sources because streamflow, particularly during stormflow events, provides energy to displace and transport exposed soil from the bed and banks.

Human-caused soil disturbances increase the availability of sediment sources, and thus, the potential for soil erosion in all types of land uses. Watersheds dominated by managed forest lands tend to have lower rates of erosion and sediment delivery than watersheds dominated by other land uses because there is less soil disturbance in managed forests, and soil exposure that does occur tends to be much less intense and short-term.

Roads are generally the most problematic feature relative to sediment pollution in forested watersheds. Roads contribute to soil erosion due to: soil disturbance and exposure during construction; soil that remains exposed and susceptible to erosion after construction; road slope or location; and compacted driving surfaces and drainage features and the concentrated runoff resulting from them. Roads and road effects are described in detail here because they are so ubiquitous in all land uses.

Water body crossings tend to be the most important features of road systems in terms of erosion and sedimentation. Because they occupy the area immediately adjacent to and over water bodies, they present the greatest potential to affect water quality. Historically, the focus of water body crossings in watershed management was on passing high flows, so designs considered only the size of the crossing (e.g., installing sufficiently large stream crossing culverts). Since the mid to late twentieth century, additional attention has been given to reducing sediment impacts on water quality at crossings by removing the connection between ditchlines (or ditches) and streams. Contemporary applications of the **Clean Water Act** to water body crossing designs now also include several other factors in crossing structure designs, such as improving aquatic organism passage during all ranges of flows and large wood passage during flood flows. Consequently, there are many physical and biological factors that must be considered to achieve properly functioning and safe water body crossings.

While a variety of techniques exist for building forest roads, **cut-and-fill construction** is one



Figure 4. Straightened channels often are hardened or armored with materials such as concrete to protect against channel migration back to a meandering or sinuous condition. However, the increased energy of streamflow that results from straightening, and the loss of roughness in these channels often will exceed the strength of these materials so that they eventually fail. From Ponce et al. (2004), used with permission.

of the most common types of road construction in hilly terrain or sloping landscapes (Figure 5). Cut-and-fill roads involve removing soil from the hillside from what will become most of the driving surface width, and placing the excavated material downslope of the excavated area. This side cast material is used to create the rest of the driving surface as well as the **fillslope**. If the hillside is steeply sloped, some side cast material will tend to "roll" fairly far downslope during fillslope construction. A **cutbank** on the upslope side of the road is created when hillside material is removed during excavation. **Ditchlines** also are commonly constructed along the inside edge of the road at the base of the cutbank to facilitate road drainage through pipe culverts (called **relief culverts** or **cross-drain culverts**) or similar structures constructed in or under the road and located along the road's length (Figure 5). The spacing of relief culverts generally is dependent upon the slope, or grade, of the road surface.

Once road construction is completed, erosion from the compacted driving surface can result from either raindrop impact or concentrated overland flow (see Holz et al. 2015, this issue). Erosion can be controlled in large part by paving or applying several centimeters of good quality gravel (e.g., resistant to particle breakdown by traffic). Neither covering reverses road-surface compaction, but they protect the soil surface from raindrop impact. By creating a more complex, or tortuous, path of travel and by providing roughness, gravel also reduces the slope that the water travels (analogous to how channel sinuosity influences slope in Figure 3), provides friction to slow the water, and ultimately reduces the energy for erosion of road surface overland flow. By controlling the energy of raindrop impact and overland flow, graveled roads have been reported to have 5.8 to 8.3 times less sediment losses than roads that received no surfacing with coarse fragments (Kochenderfer and Helvey 1987; Swift 1984). Paving effectively

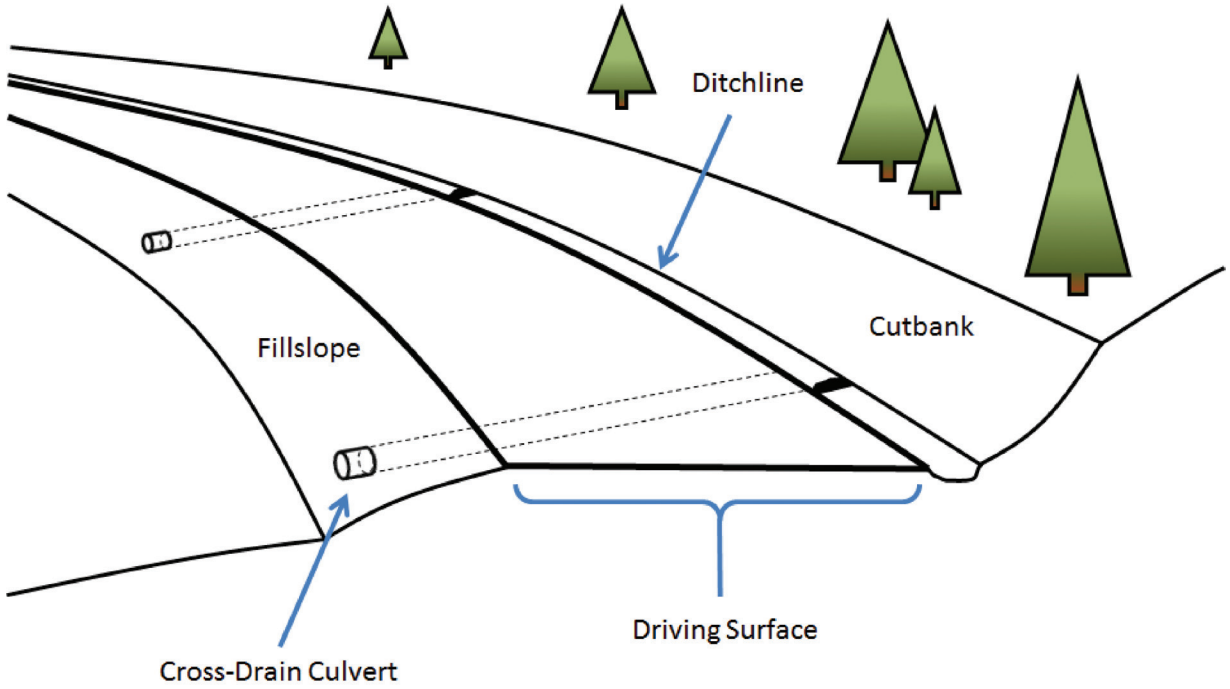

Figure 5. The major parts of a cut-and-fill road. About one-half of the inside portion of the driving surface is excavated with heavy equipment. The excavated soil is sidecast downslope creating the outer half of the driving surface and the fillslope. Road excavation also creates a cutbank. At the base of the cutbank and inside edge of the driving surface, a ditchline typically is constructed to capture water from at least part of the road surface and subsurface flow exposed by the cutbank. This runoff is carried in the ditchline until some type of cross-drain feature is encountered – in this drawing they are pipe culverts. Note that the fillslopes and cutbanks are necessarily steeper than the original hillside slope in which they were constructed. Drawing by Robin L. Quinlivan.

eliminates erosion on the road surface (Reid and Dunne 1984), but it does not slow road runoff.

Constructed cutbanks and fillslopes are steeper than the original hillsides, so in addition to being susceptible to erosion from water, they are also prone to erosion by gravitational forces. Increasing soil cover and soil stabilization on these features is critical to controlling water- and gravity-driven erosion. Typically, cover and stabilization are achieved through seeding with grass and herbaceous species and/or mulching the soil surface, and soil amendments, such as lime or fertilizers, may be applied to help hasten the rate of vegetation establishment. Natural re-vegetation might occur even without seeding, but in most climates the time required for full soil cover and stabilization is usually longer than with seeding. For major roads or particularly problematic areas around low-volume roads, organic mats (Grace 2000) or synthetic geotextiles (Theisen 1992) may be affixed to the soil surface temporarily until vegetation becomes established, or permanently if vegetation alone is not expected to be capable of providing sufficient soil stabilization.

Ditchlines themselves can be sources of sediment because they carry concentrated overland flow that can have substantial erosive energy. Ditchlines may become re-vegetated intentionally or naturally with grasses, but shallow-rooted plants can be scoured from ditchlines. Ditch cleaning or "dragging" with heavy equipment is also a common maintenance practice used to keep materials from building up and potentially clogging relief culverts, but it exacerbates ditch erosion. This practice tears vegetation from ditchlines and re-initiates elevated levels of ditch erosion. Ditch erosion can be dramatically reduced by lining ditches with moderate- to large-size quarried rock that has sufficient mass to withstand movement from the energy of the captured water. Rock-lining exploits the same erosion control mechanisms that apply to graveling road surfaces.

Even if all of the soil disturbed during road construction is successfully covered by gravel or paving, vegetation, or other materials, continued erosion from roads often remains problematic due to road drainage. **Road drainage** comes from two primary sources – overland flow from precipitation falling on the road that cannot infiltrate the driving surface, and water that becomes concentrated due to drainage features.

Overall, the key to controlling road drainage and associated erosion is dispersing water from the road in small quantities, since this will control the energy available to erode soil. Many drainage techniques have been developed toward this end, but each has its own difficulties in terms of operation and maintenance. However, most road drainage techniques result in the concentration of road runoff, through either surface features, such as **broad-based dips** used on low-volume woods roads (Figure 6a) or relief culverts under the road surface (Figures 5 and 6b). Sometimes water is drained from roads at natural breaks in the road slope, but these breaks also may discharge concentrated flow. Forest litter cover and planted grasses frequently are depended upon to provide protection against erosion by road drainage, but they provide little protection against concentrated discharge (Edwards and Evans 2004), so gully formation below the outlets of drainage features is common and can be chronic (Figure 7). Fillslopes are especially susceptible to gully formation because fillslope soil is unconsolidated. Once gullies form, further erosion and continued extension is difficult to stop without substantial effort and cost.

The volume of water that will be contributed to ditchlines is sometimes greater than anticipated due to **subsurface flow** contributions from the cutbank. During cutbank construction, large **macropores** that transport significant amounts of subsurface flow can be intersected, causing the water to emerge (Figure 8a) and be captured by the ditchline, thereby adding to road discharge (see Schoonover and Crim 2015, this issue and Edwards et al. 2015, this issue for more discussion on macropores and soil pores). The potential for exposing such macropores increases substantially if the cutbank removes the entire soil mantle (which is not uncommon in shallow soils), since subsurface flow often is concentrated above the underlying bedrock.

Landscape position can have a large influence on the likelihood that subsurface flow paths will be encountered. **Coves** in particular, and **swales** to a lesser extent, are sites of natural subsurface water accumulation and flow path development

a.



b.



Figure 6. Two types of common cross-drain features that are used on forest roads are shown. A broad-based dip (a) is simply a constructed outsloping depression in the road surface into which water drains from the adjacent road length. The 2 to 3 percent outslope of the dip sheds water off the road, ideally in sufficiently small quantities that will allow it to infiltrate into the soil. The pipe culvert (b) is installed under the road and it discharges water that collects in the contributing ditchline (also see Figure 5).



Figure 7. When water is cast off a road from a road cross-drain feature where only grasses and herbaceous vegetation are available to reduce its energy and encourage infiltration, large gullies can develop, like the one shown here at the outlet of a broad-based dip.

a.



b.



Figure 8. Several large macropores that had been major pathways of subsurface flow were intersected during the construction of a skid road in a cove (a). Substantial emergent flow was encountered (a), which resulted in surface flow running overland downslope off the road (b). Water is now routed through the watershed more quickly, surface erosion has increased, and long-term use of this area has become more challenging because of the frequency of surface flows.

because they exist in definable low elevations on the landscape (Keppeler et al. 1994, Gucinski et al. 2001). In many ways these areas behave much like subsurface stream channels in that subsurface flow can become concentrated and can result in high discharge volumes when they are intersected during road construction (Figure 8). Furthermore, coves often are source areas for surface stream channels that begin further downslope. Once subsurface flows become emergent, their volumes and velocities can be great enough to cause **head cutting**, which is the gradual migration of the top of the established channel to the source of emergent flow that occurs as the result of surface erosion. If the emergent flow and head cutting are substantial, segments of road that exist downslope between the original head of the channel and the new head can be washed out. Consequently, in many regions, road construction through coves should be avoided if possible to limit the degree to which subsurface flows are altered.

Best Management Practices

Water pollutants are classified as either nonpoint or point source based upon their origin. **Point source** pollutants are defined in Section 502 of the Clean Water Act as originating from "any discernible, confined and discrete conveyance,

including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture." Consequently, point source pollutants are associated with discharges from industrial and sewage treatment operations directly or indirectly into water bodies or groundwater. By contrast, **nonpoint source** pollution originates from diffuse sources, and it is transported by runoff and eventually deposited into water bodies, including groundwater. Sediment from forestry and agricultural operations, excess fertilizers from croplands, nutrients from livestock, oil and grease from urban runoff, lawn chemicals from residential areas, and acid mine drainage from abandoned mines are just a few examples of the many types of nonpoint source pollutants that exist.

Both types of pollutants must be considered in the management of watersheds because each can have a substantial influence on water quality and the beneficial uses of water and water bodies. Point source pollutants are controlled and regulated through permits that identify the types and set the maximum loadings or concentrations of pollutants that can be discharged into water bodies. Because discrete origins of nonpoint source pollutants are not definable, their release is controlled by the use of **best management practices**, or **BMPs**, as specified by the Clean Water Act.

Best management practices are techniques and tools used to control nonpoint source pollution. It is important to note that BMPs do not eliminate nonpoint source pollution; instead they are designed to maintain nonpoint source pollution at levels acceptable to regulatory agencies and at an acceptable cost (Edwards 2003). The EPA requires states to have an approved set of BMPs that are recommended or required for the major land uses and industries that generate nonpoint source pollutants, such as agriculture, forestry, and mining. These typically are published in BMP manuals or stormwater control manuals and are easily located using internet searches involving key words that include the state name, the activity, and the term 'BMPs' (e.g., West Virginia forestry BMPs). BMP and stormwater control manuals are reviewed and updated regularly, and new scientific findings and methodologies are considered during the revision process.

Different types of BMPs are applicable to different types of land uses. Where commonalities in activities exist among land uses, such as site access (i.e., road construction and use) similar BMPs may be employed. In other situations, BMPs may exist for activities that are unique to a given land use, such as no-till farming for agriculture.

Best management practices for nearly all activities fall into categories with the following broad objectives: limiting the occurrence of concentrated overland flow; controlling the energy of overland flow; encouraging soil infiltration of precipitation and surface runoff; capturing or detaining pollutants; providing soil cover and soil stabilization; applying chemicals at rates and times that will not result in excess losses; promoting chemical uptake or chemical retention; and retaining shade around water bodies. Note that while some of these BMPs involve flow control, their ultimate purpose is to control detachment or transport of the associated pollutant – the focus on water exists simply because of the dependency of pollutant availability and migration on water movement and the direct relationships among overland flow volume, velocity and energy.

While often not identified explicitly in BMP manuals and stormwater control handbooks, **planning** is itself a BMP; indeed, many consider planning to be the most important BMP for controlling nonpoint source pollution (Phillips et al. 2000). Well-planned activities can allow managers to prevent problems that otherwise might require implementation of additional BMPs or avoid other mitigation measures after problems result. Costs associated with planning can be much less than costs associated with other BMP implementation and mitigation measures.

Forestry BMPs

The vast majority of BMPs applied in forest management are focused on the **road prism**, which includes the entire area disturbed for the construction of the road from the bottom of the fillslope to the top of the cutbank. Road BMPs rely on practices to control erosion using the broad

approaches described previously: protecting the surface of the road; providing cover for other areas of disturbed soils (e.g., cutbanks, fillslopes, and log landings); controlling the energy and volumes of road drainage; and encouraging soil infiltration. Since the fundamentals of many of these were described previously they are not repeated here, but specific examples of these BMPs are given in Table 2.

Planning is the most important BMP for managing the effects of roads on watershed hydrology and water quality. Planning allows travel routes to be laid out away from sensitive areas (e.g., highly erodible soils, steep slopes, etc.) and allows planners to avoid or minimize the need for water body crossings.

When crossings are necessary, many construction BMPs come into play to reduce impacts to water bodies and water quality. These BMPs include crossing streams at right angles to reduce the length of the crossing and the amount of sediment that reaches the water body when fills and fillslopes are constructed in and around the crossing (Stedman 2008), eliminating connections between drainage ditches and crossings by diverting runoff onto the hillside before reaching a water body crossing, and properly installing the appropriate type of crossing to reduce undesirable changes to water body morphology (e.g., channel erosion, head cutting, etc.) or effects on aquatic organisms or habitats. While road and crossing BMPs comprise the majority of forestry BMPs, other common ones also exist. Some of these include implementing techniques that reduce land and water body disturbances by off-road equipment use and tree felling, maintain vegetation to promote infiltration of overland flow and trap sediment and other pollutants, and provide shade to protect against thermal pollution (Table 2). Each of these typically involves the establishment of strips of land along waterways in which either no disturbance is permitted or the breadth or intensity of activities is restricted to protect water quality and aquatic ecosystems from the disturbances. These areas go by a variety of names, including **filter strips**, **buffer strips**, **riparian buffers**, or **streamside management zones** (SMZs). The width of these strips and the allowable activities in them often depend upon the type of stream present in the area (perennial, intermittent, or ephemeral) or its habitat potential (e.g., trout stream). Other forestry BMPs are designed to reduce impacts from common soil-disturbing activities (e.g., site preparation, tree planting, etc.) or from activities that have a high potential to result in water pollution by chemicals (e.g., pesticide or fertilizer applications, or chemical storage)

The specific **prescriptions** (i.e., how to implement the BMP on the ground) for most forestry BMPs depend upon the physical characteristics of the landscape or feature. For example, relief-culvert spacing on roads is a function of the road grade – the steeper the road segment, the closer the spacing of relief culverts. Because each State is responsible for developing and regularly reviewing and revising its own forestry BMPs, forest managers and land owners should refer to their respective State's BMPs for the recommended or required prescriptions.

Agricultural Watersheds

To meet the food demands of a growing world population, it is anticipated that global crop production will need to double by 2050 (Tilman et al. 2011). This demand will likely be met by agricultural intensification in developed countries and increased land clearing for agriculture in developing countries. Part of the intensification process includes increasing drainage in fertile, poorly drained soils, such as Mollisols (see Schoonover and Crim 2015, this issue) of the Midwestern U.S., by installing drainage tiles. These extensive drainage networks have resulted in increased discharge from agricultural watersheds which flush excess nutrients, primarily nitrate, into streams or rivers (David et al. 2010). Elevated nutrient losses from the Mississippi River basin contribute to the hypoxic or "dead zone" in the Gulf of Mexico (Rabalais et al. 2001).

Intensive agriculture commonly results in surface water and groundwater quality impairment due to erosion of exposed mineral soil and export of nutrients not utilized by crops. Sediment and nutrient pollution from row-crop agricultural areas are considered nonpoint source pollutants and as such, are exempt from the permitting process under the Clean Water Act. Instead, voluntary BMPs,

Table 2. General categories of Best Management Practices (BMPs) and examples of each in different land uses.

General Type of BMP	Purpose of BMPs	Examples of BMPs
Protect existing soil cover or vegetation	To protect soils from erosion from raindrop impact; to maintain soil infiltration rates and avoid overland flow; to provide roughness when overland flow occurs	• Retain litter cover in forests by minimizing the area in haul roads, skid roads, and log landings • Conservation tillage or no-till in agriculture
	To protect soils from raindrop splash and soil particle detachment; to provide some roughness for overland flow	• Seed and mulch to promote grass and herbaceous plant establishment development • Geotextiles or riprap installed on highway cutbanks • Pave or apply gravel to road surfaces • Harden fillslopes at outlets of road drainage features (e.g., culvert outlets) • Cover crops
Sediment control barriers or roughness features	To capture and retain sediment	• Compost filter socks, straw wattles, silt fences, hay bales, etc. • Slash (aka windrows) from harvested tree tops installed at the base of and parallel to road fillslopes • Check dams installed in streams below crossings during construction; usually used in conjunction with pumping water around crossing area • Water and sediment control basins established in agricultural fields • Grassed waterways • Riparian buffers, filter strips, and streamside management zones along streams
Water control and drainage features	To handle and divert water in small quantities to reduce its potential for erosion and sediment transport	• Culverts, broad-based dips, or waterbars installed on roads • Road outsloping on noses of ridges to function as drainage features • Cross-drainage spacing defined by road segment grade • Water and sediment control basins established in agricultural fields • Grassed waterways
Control surface grades or provide slope breaks on roads	To manage the volume and velocity of overland flow	• Set maximum allowable grades on roads
Follow guidelines for chemical applications (herbicides, pesticides, etc.)	To reduce the potential for chemical runoff to surface waters or leaching to groundwater	• Apply chemicals when precipitation is not forecast • Apply only needed or recommended amounts of chemicals • Use chemicals away from water bodies, or adjust application method near water bodies
Provide protection zones between activities and water bodies; provide protection along water bodies	To provide a zone that will infiltrate overland flow carrying pollutants; to provide a zone between the activity and water body that can physically, chemically, or biologically keep pollutants from reaching the water body; to provide shade to water bodies; to provide sources of large wood to the water body to improve aquatic habitat; to provide woody vegetation for bank stabilization	• Retain riparian management zones, streamside management zones, forest buffers or filter strips between woods, roads, and streams, harvesting activity and streams, or agricultural fields and streams • Maintain at least a set minimum basal area or canopy cover requirement along streams for harvesting operations • Restrictions on heavy equipment use in riparian areas • In agricultural areas, periodic thinning in riparian buffers to remove nutrients stored in biomass and maintain actively growing stand for maximum nutrient uptake

such as riparian buffers, grassed waterways, and cover crops are established in agricultural watersheds to address pollution concerns (Table 2). By contrast, large animal feeding operations are a sector of agriculture that is considered a point source pollutant and is permitted by the U.S. Environmental Protection Agency. The primary challenges for large feeding operations are the handling, storage, and application of the animal manure. Manure can be land applied to row-crops and other areas as a fertilizer. However, large areas of land are needed to ensure that soils do not become saturated with nutrients that are then susceptible to leaching, which can result in surface and groundwater pollution.

Agriculture BMPs

Many different BMPs have been designed to address nonpoint source pollution issues in agricultural watersheds. Best management practices in agriculture often are referred to as **conservation practices**, and they generally are established on private farm lands through cost-share programs administered by the USDA Natural Resources Conservation Service (NRCS). The NRCS maintains a database of accepted conservation practices that have been field tested through multiple research projects. The following sections review some of the most commonly applied in-field and edge-of-field practices to control agricultural pollution.

Nutrient Management Planning. Developing a whole-farm nutrient management plan is one of the first actions taken in conservation planning and may incorporate multiple conservation practices to meet nutrient management planning goals. In general, the plans focus on optimizing the timing and rates of applied fertilizers. The overall goal is to maximize crop yields while controlling nutrient losses to the environment. At the most basic level this is accomplished by meeting but not exceeding the nutrient demands of the growing crop. A recent program promoted by multiple fertilizer, soil, and crop associations summarized proper nutrient management as the 4 Rs: applying the right fertilizer source at the right rate at the right time and in the right place (Ehmke 2012).

No-till and Conservation Tillage. Reduced tillage has become a common conservation practice in the past two decades as a means to maintain more residues (i.e., cover) on the soil surface and reduce erosion rates. The lack of soil disturbance also helps foster a richer soil biological community, including earthworms, which can increase surface soil porosity (Hobbs et al. 2008). Increased porosity allows greater water infiltration rates, which reduce the potential for surface runoff and erosion. The aforementioned sequence of events generally takes multiple years to a decade to develop. In the short term (1 to 2 years), converting from **conventional tillage** (disturbing the majority of the soil surface) to **no-till** may temporarily reduce infiltration rates due to surface crusting and compaction. However, when the soil biological community becomes re-established, soil porosity and infiltration rates increase because of the reduced soil disturbance (Haines and Uren 1990). Under reduced agricultural tillage regimes, there is an increased reliance on herbicides for weed control, which creates the potential for water quality concerns.

Cover Crops. Over the past five years, the establishment of cover crops during the dormant season has become a popular conservation practice for increasing crop yields, building soil organic matter, providing an alternative source of nitrogen, and protecting water quality. Across the U.S., producers have realized 3 to 5 percent increases in corn and soybean yields the year following cover crops (Watts 2014). Multiple research projects have demonstrated long-term increases in soil organic matter and soil organic carbon stocks with the use of cover crops (Olson et al. 2014). These increases are due to root and above-ground biomass production in the late fall and early spring. **Nitrogen-fixing legumes** (which can change nitrogen gas into plant-useable forms of nitrogen), such as hairy vetch (*Vicia villosa* Roth) can provide significant amounts of nitrogen to subsequent crops, which may help reduce synthetic fertilizer application rates. The decomposition and mineralization of cover crop residue during the growing season can provide inorganic nitrogen to crops.

Cover crops can help protect water quality via multiple mechanisms. The ground cover provided

during the dormant season helps reduce erosion rates, which are commonly elevated at that time of year. Non-legume cover crops, such as ryegrass (*Lolium perenne* L.) and cereal rye (*Secale cereale* L.) can scavenge nitrogen and phosphorus from the soil and help prevent nutrient leaching to groundwater and surface water (Dabney et al. 2001). Challenges associated with utilizing cover crops include additional costs to the producer, getting cover crops established early enough in the fall to ensure successful development, and successful termination of cover crop growth in the spring prior to crop planting.

Grassed Waterways. In humid regions of the U.S., grassed waterways have become an important conservation practice to address erosion issues associated with concentrated and channelized flow in agricultural fields. Surface runoff in agricultural fields may start as sheet flow (shallow, dispersed flow), but it generally quickly concentrates into channelized flow due to the microtopography of the soil surface. Channelized flow in fields can result in significant erosion during storm events. Wide grassed waterways can be established in channelized flow areas to reduce the energy of runoff and control soil erosion (Fiener and Auerswald 2003). Generally, grassed waterways need to be re-shaped or re-constructed after a decade because soil berms build up on their margins or channelized flow cuts around them, both of which reduce their effectiveness.

Riparian Buffers. Riparian buffers are the most common conservation practice established along the edges of fields to protect water quality. Riparian areas are transitional areas between water bodies and adjacent terrestrial areas. Riparian buffers provide many of the same benefits in agricultural systems that they do in forested systems (though the vegetation comprising the buffer may differ), including serving as wildlife habitat, providing thermal protection to cold and cool water streams, contributing woody material to streams that provide aquatic habitat, providing carbon to support aquatic food webs, and providing stream bank stabilization by the presence of extensive root networks.

Grasses, trees, or combinations of both have been planted in riparian areas to capture nutrients and sediment from adjacent agricultural fields. Riparian buffers are typically 15 or 30 meters wide. However, even narrow (9 m), remnant riparian buffers have been shown to effectively protect surface water quality (Schoonover and Williard 2003). Riparian buffers generally have high infiltration rates allowing incoming surface runoff to infiltrate and deposit sediment in the buffer. Vegetated riparian buffers also significantly reduce nitrate concentrations in groundwater, primarily through **denitrification** (conversion of nitrate to nitrogen gas in the soil and subsequent loss of the gas to the atmosphere), and plant uptake (Dosskey 2001). The greatest reductions in soil nitrate have been found in buffers where groundwater occurs at shallow depths – this is because near-surface soils are high in carbon which supports denitrification, and plant roots are able to take up nitrogen directly from groundwater (Hill 1996).

Urban Watersheds

Most U.S. citizens reside in or near cities or towns. In 2010, the U.S. population was just over 310 million and it is expected to reach nearly 440 million by 2050 (Ortman and Guarneri 2009). As the U.S. population continues to grow there will be increasing demand placed upon the country's water resources and increasing stresses placed on watershed hydrology and water quality due to the characteristics of urban environments.

The urban or developed environment is distinguished by the many types of land uses and characteristics that exist within it. For instance, some land classified as urban may be heavily commercialized, while other areas may be dominated by lower-intensity residential use or recreational use. Regardless of the specific land use, the most common indicator of urbanization is the amount of **impervious surface cover** within a watershed. The increase in impervious cover in urban areas typically exceeds the rate of population growth. For example, in Georgia a 17 percent increase in population translated to a 100 percent increase in impervious surfaces over the same time period (Ford et al. 2003).

Impervious surface cover is linked strongly to water quality, aquatic health, stream condition, and overall hydrology. Impervious cover generally is classified using one of two methods, either

Total Impervious Area (TIA) or **Effective Impervious Surfaces (EIS)**. As the name suggests, TIA includes all impervious surfaces within a watershed and is reported as a percentage of the total watershed area. Effective impervious surfaces involve only impervious surfaces that are hydrologically-connected to water bodies. For example, the area of a house roof with gutters that drains to a cistern or empties onto the surface of a lawn is considered as TIA. The area of a roof that has gutters connected to a tile network that drains directly into a ditch or stream would be considered as EIS. In the past, 10 percent TIA had been considered a threshold value at which stream ecosystems begin to degrade or show impacts from urban land use (Schueler 1994). More recent studies have shown that stream degradation begins at much lower levels of TIA, and degradation occurs progressively with increasing TIA rather than beginning once a specific threshold is reached (Schoonover et al. 2005).

Surface runoff is an important component of urban hydrology due to the large amount of impervious surfaces and their negative impact on water infiltration into the soil. As a result of reduced infiltration, there is much less groundwater recharge in urban areas compared to their rural counterparts. Overland flow delivers precipitation to streams quickly compared to the prolonged contributions of water to streams that occur from subsurface flow when soil infiltration dominates. The dominant sources of runoff into urban streams typically are roads, parking lots, rooftops, and driveways. Urban lawns often act similarly to impervious surfaces due to their high degree of compaction from mowing and other uses.

Storm hydrographs in urbanized channels typically rise and fall quickly due to the high volumes and transitory nature of surface runoff. The result is termed "**flashy**" streamflow. Much higher peak discharges occur in urban watersheds compared to watersheds with similar physical characteristics but less development. The rapid delivery of storm runoff to perennial streams results in a large percentage of the total annual flow being comprised by stormflow. In turn, baseflow in perennial streams can become reduced substantially – so much so that perennial streams can become intermittent in some instances (Korhnak and Vince 2005). Such a hydrologic shift greatly impacts stream health and characteristics. For example, many species of aquatic organisms found in perennial streams are not adapted to the temporary dry conditions that exist in intermittent streams. Even when such drastic changes in hydrology do not occur, lower baseflow levels can create challenging conditions for aquatic organisms because smaller discharges are susceptible to having or being associated with higher temperatures, lower oxygen levels, poorer habitat or less habitat variability, less food availability, and higher pollutant concentrations.

Both point and nonpoint sources of pollutants are common in urban environments (Table 3). Point source pollutants are commonly associated with discharges from commercial or industrial areas of a city. Nonpoint pollution is associated with most other forms of urban development, including residential development, and road and parking lot runoff.

Urban BMPs

Best management practices applicable to urban environments are designed to address chemical and biological nonpoint source pollutants. Many urban BMPs apply the same or similar concepts that are used in forestry and agriculture, particularly BMPs that encourage infiltration of surface runoff. Infiltration can contribute to improved water quality by reducing the erosive energy of overland flow and through biological, physical, or chemical retention or reactions that reduce pollutant transfer to water bodies.

Green Roofs. Green roofs have gained popularity over the past decade. A green roof is a rooftop that is partially or entirely covered by vegetation. They are common in both commercial and residential settings. Green roofs benefit both wildlife (habitat) and humans (aesthetics), save money through energy costs, mitigate the urban heat island effect, and play a key role in stormwater retention (Carter and Butler 2008). Green roofs can be either intensive or extensive. **Intensive** roofs typically are used on commercial buildings and can incorporate grasses, shrubs, trees, and even walking paths because the soil depth, or growth medium, usually exceeds 15 centimeters. **Extensive** roofs generally only have

Table 3. Common water quality impairments and sources associated with urbanization.

Water Quality Impairment	Potential Sources
Fecal coliform, *E. coli*, other pathogens and bacteria	Septic systems, sewage effluent, pet waste
Nutrients (e.g., nitrogen, phosphorus)	Sewage effluent, pet waste, lawn fertilizers, industrial pollution
Sediment	Channel erosion, surface runoff from developing sites
Polycyclic aromatic hydrocarbons, PCBs, pesticides	Combustion, industrial solvents, lawn runoff
Road salt	Salt/brine application for de-icing roads
Heavy metals	Automobile emissions, road runoff, old paint, corrosion, batteries, preservatives

5 to 15 centimeters of soil depth and are used in residential roofing projects where they are walked on only for maintenance. Both roofing systems provide stormwater runoff benefits by slowing the time it takes water to reach water bodies. Some roof designs have a plastic underlayment that retains some precipitation for subsequent plant growth on the roof.

Cisterns. Cisterns are regaining popularity and are being incorporated into new building designs. As in the past, cisterns are designed to collect water running off rooftops, removing some water from the stormflow hydrograph while retaining it for later use, typically for landscape watering (Jones and Hunt 2008). Although the practice might seem insignificant, a 232 m2 roof generates approximately 7,571 liters of water during a 25-mm rain event. However, there are some locations, particularly in dry climates, where cistern use or "water harvesting" requires a permit or license (Waskom and Kallenberger 2012).

Rain Gardens. Rain gardens are areas on the landscape where surface runoff naturally accumulates or areas where runoff accumulation has been incorporated into the landscape design (University of Wisconsin-Extension 2003). The drainage areas usually contain soils or growth media that drain quickly to avoid inundation, and in well-designed systems, most of the surface runoff infiltrates into the soil. Typically, rain gardens are planted with native vegetation that is adapted to alternating wet and dry conditions and that can tolerate nitrogen and phosphorus inputs, both of which can be high especially near fertilized lawns or golf courses. Like most other urban BMP designs, rain gardens interrupt and slow the travel time for surface runoff to reach surface waters.

Parking Lot BMPs. In developed areas, parking lots usually occupy the greatest amount of area, especially in commercial areas. Tremendous volumes of surface runoff are generated by parking areas, and they are a source of many types of pollutants that impact water chemistry. A 0.4-ha area of land with an impervious surface produces approximately 102,789 liters of water during a 25-mm rain event, which can quickly lead to local flooding. To lessen the impacts of impervious surfaces on stream hydrology and water quality, many parking lot BMPs have been designed and adopted across the U.S. Some of the BMPs used to reduce the negative impacts of parking lots on water quantity and quality include the use of pervious pavers, sand filters, bioswales and bioretention areas, and retention and detention ponds.

Pervious Pavers. Pervious pavers typically are designed in a grid or lattice pattern and can be constructed with cements, plastics, or even gravel mixed with a growth medium (Brattebo and Booth

2003). The holes in the pavers typically are filled with gravel, sand, or soil to allow water to quickly infiltrate. Pervious pavers are being adopted in "green" parking lots and are commonly used in spill-over lots, or those that are rarely used. They have also been adopted in residential driveways (Gilbert and Clausen 2006), fire lanes, golf cart/pedestrian paths, and other drivable green surfaces. Pervious pavers can significantly reduce runoff, but the maintenance costs and short longevity of pervious pavers can be cost-prohibitive. Pavers tend to clog easily, and their maintenance requires vacuum street sweeper use or high pressure washing.

Sand Filters. Sand filters are used to remove moderate to high loadings of pollutants, such as sediment, biochemical oxygen demand (BOD) and fecal coliform bacteria from parking lot runoff (U.S. Environmental Protection Agency 1999a). They consist of a storm grate at the parking lot surface over a sand or organic filter below the lot. They are installed during the construction of the parking lot and commonly extend along the outer perimeter of the lot. While they can be easily accessed for maintenance, the upper few centimeters of the filter material must be replaced frequently to prevent clogging.

Bioswales/Bioretention Areas. Bioswales utilize parking lot "islands" for the establishment of vegetation on soils or other materials that have high hydraulic conductivities (i.e., the soils drain quickly) (Xiao and McPherson 2011). These areas generally are designed to provide on-site treatment for the first 13 mm of stormwater runoff. Pollutants also are removed by biological, chemical, and physical mechanisms in the soil and by vegetative uptake. Bioswales are a desirable BMP because they typically take up only 5 to 10 percent of a parking lot's area and they are easily maintained.

Retention and Detention Ponds. Retention ponds, sometimes called stormwater wetlands, are areas that retain or hold a certain amount of water year-round (U.S. Environmental Protection Agency 1999b). They are designed to temporarily capture some urban runoff and release it slowly to streams. They typically have native aquatic vegetation included in their design to take up nutrients and other pollutants present in the runoff. Detention ponds also hold water during storm events and release it slowly, but they revert to dry basins during non-storm periods (Stanley 1996). Both retention and detention basins are commonly used in residential developments and adjacent to large parking lots.

Conclusion

A basic understanding of the impacts of land use/land cover on water quality and hydrology is critical for watershed planning and management. The watershed is the most appropriate level or scale for managing landscapes because it integrates the physical, chemical, and biological inputs to a given water body. Recognizing the various impacts that individual land uses can have on soils and water resources is central to controlling detrimental effects within the watershed as well as downstream.

The current era of watershed management is focused largely on nonpoint source pollutant management strategies. Unlike point source, "end-of-pipe" pollutants whose loadings are documented and quantified, nonpoint pollutant sources are much more ubiquitous and subtle, making their contributions to water quality impairment much more difficult to assess. Best management practice implementation, which begins with thorough project planning, is the primary strategy for controlling nonpoint source pollutants. While BMPs exist for major land management activities, such as forestry, agriculture, and urban development, they also are applicable in the day to day lives of all citizens. Basic BMP principles, such as controlling the amounts and duration of soil disturbance during construction around the home, applying chemicals to lawns or gardens only at needed rates and during suitable times, and incorporating techniques to encourage infiltration of rooftop and driveway runoff are important actions that contribute to protecting watershed functions, water quality, and aquatic health.

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Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 154, Pages 85-105, April 2015

The Role of Social Science in Successfully Implementing Watershed Management Strategies

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Abstract: Successful watershed management and changes in water quality conditions are dependent upon changes in human behaviors. Those tasked with managing watersheds and other natural resources often assume that people are not acting to protect or restore their resources because they lack the necessary knowledge and understanding. However, individual behaviors are impacted by a variety of social, psychological, institutional, and economic factors that need to be understood for successful implementation of watershed management strategies. This paper provides an introduction to the field of human dimensions of watershed management, an overview of social science concepts that have been found to explain water-related behaviors, and how social information can be translated into actionable items in a management plan.

Keywords: *human dimensions, community capacity, theory of planned behavior, social capital, risk, institutions, collaboration*

Human behavior is the driving force underlying many resource management concerns, but is often the component that is given the least amount of attention in the development of management plans. Instead, plans are written that assume the main barrier to changing the behaviors of individuals is a lack of knowledge regarding issues impacting water and the actions that can be taken to solve them. Overreliance on ineffective communication channels to inform stakeholders of watershed planning efforts and traditional methods of technology transfer have potentially delayed progress in achieving behavior changes. Morton (2008, 751) posits that our approach to improving water quality since the adoption of the Clean Water Act has "…one critical weakness, an assumption that a combination of regulation and a cadre of technicians can solve the problem of non-point source pollution." Over the past decade, policy makers and watershed managers have made slow but positive moves toward investing more resources in understanding antecedents to behavior change, and to incorporate that knowledge into watershed management (Prokopy et al. 2009; Davenport 2013). This article aims to provide background knowledge on the social aspects of watershed management for elected officials and policy makers, watershed managers, and citizens interested in improving water resources.

Behavior choices are predicated on a variety of social, psychological, institutional, and economic factors that need to be understood for successful watershed plan implementation. Variables informing social science theories to describe and predict the relationships among these factors and watershed projects include, but are not limited to, attitudes, value orientations, perceptions of social capital, trust, risk, and awareness. In addition, the role of institutions is central in impacting and sustaining natural resources behavior change (Ostrom 1990; Heberlein 2012). The complexity

of implementing strategies that rely upon individual behavior change for improving conditions is exacerbated by the nested and overlapping governmental boundaries that comprise the laws, rules, people, and organizations within a given watershed.

Social information can be used to understand and segment target populations to develop effective messages and policy tools to support behavior change. Management plans should include goals and objectives related to communication and behavior change that are based on social science data rather than potentially erroneous assumptions about what barriers to behavior change exist. This article provides an overview of common factors and theories in the human dimensions of watershed management, and how social science information can be translated into actionable items by those responsible for watershed plan implementation. We begin with a discussion of place, as watershed projects are place-based activities that take into account local natural conditions. Likewise, projects may benefit from understanding how people view their local watershed and community. We move through discussions of individual level variables that impact how people perceive risk related to water management, and individual level variables that can be measured to understand stakeholders and design outreach. Finally, we provide an overview of watershed management institutions and their ideal design, and offering two approaches watershed managers might use social data in planning, implementing, and evaluating watershed projects.

The Impact of Place

Several concepts are prevalent in discussions regarding place. **Sense of place** is seen as a filter influencing how individuals perceive their environment (Cheng et al. 2003; Koshollek 2010). Because of the vagueness associated with initial conceptualizations of sense of place, several additional factors have been developed to support and clarify it. The intensity of the bond that people have with places and communities is often described as **place attachment** (Simoni and Floress 2015; Wynveen et al. 2011), and people assign meaning to these areas through the experiences they have by living in them (Stedman 2003). Place attachment has been found to significantly impact the willingness of individuals to engage in behaviors to protect their place (Stedman 2002). **Place meanings** represent the value an individual places on a resource or community, as opposed to the intensity (Wynveen et al. 2011), and are "… necessary to understand the range of place-related behaviors", (Brehm et al. 2013, p 523). Variables that people associate with place include memories and experiences (Williams et al. 1992), feelings of connectedness and belonging (Cheng et al. 2003), and elements of individual and community identity (Davenport et al. 2010).

Place studies can be highly complex but are useful for natural resource managers, as understanding people's sense of place can increase the success of projects (Bott et al. 2003; Cheng et al. 2003). Understanding how place is viewed by watershed residents can help segment the population to target outreach and action (Simoni and Floress 2015). For example, researchers have found that the values held by individuals for lakes were comprised of **emotional identity** (feeling like the place is part of an individual's identity, family memories), **community character** (feeling like the resource is part of the community's identity), **natural processes** (how the resource provides ecological services), and **income** (personal economic dependence upon the resource) (Simoni and Floress 2015). Riparian owners held higher values for the emotional identity and natural process meanings than non-lakeshore owners, and those who were members of their lake group held higher values for the emotional identity and community character meanings than those who were not members. Interestingly, seasonal residents held higher values for the emotional identity meaning than year-round residents. These results highlight how place can be used to segment populations and target outreach efforts based upon their individual characteristics.

Risk Perception

Just as individuals vary in how much they value a place, they also differ in the degree of risk they perceive with regard to environmental threats. Risk focuses on threats to values or things people care

about. The study of **risk perception** focuses on the size, type, and likelihood of these risks (Slovic 1987; 2000; Slovic and Weber 2002). This field examines the ways that ordinary individuals assess risk using reasoning that is influenced by factors other than what is strictly scientific and rational (Weber 2001). For instance, many people are afraid of flying in commercial airplanes but are relatively unafraid of traveling in passenger cars where they are, on average, much more likely to be in a serious accident. Rationally, the risk of driving or riding in a passenger car is higher than flying in a commercial plane, but emotionally, many people perceive the risk of flying as higher.

Watershed managers may work with risk perceptions revolving around water quality, water quantity, flood control, and the impacts of water development on other values, such as biodiversity or scenic views (Robles et al. 2011; 2014). Managers may become frustrated when people perceive great risk to drinking highly chlorinated tap water, choosing to substitute bottled water or to install poorly maintained water filters that are actually more likely to make them sick than municipal tap water. Similarly, an individual who loves to be near a river and chooses to build a dream house in a flood plain perceives the risk of loss of life and property as reasonably small and outweighed by the value of living in a scenic spot with great recreational worth (Alhaki and Slovic 1994).

As managers work with members of the public to achieve watershed management goals, they should not expect that the public's sense of risk to valued resources equates to what a manager perceives as risky (Bennett and Calman 1999; Bontempo et al. 1997; Granger et al. 1992). Managers can instead focus on talking to people to learn what does and does not worry them (Kasperson et al. 1988; McDaniels et al. 1997; Robles Morua et al. 2014). They can learn to listen to understand key underlying values and beliefs (what the individuals hold to be true, which may be different from what managers believe to be true). By developing a sense of the broad range of existing values and beliefs related to the decision in question, managers can learn to, and then build from, these concerns and opinions to communicate their message more effectively (O'Connor et al. 1999; Robles Morua et al. 2014).

For instance, if climate change is increasing 100-year storm events necessitating enhanced stormwater management infrastructure that is expensive and has negative impacts on scenic values, a manager can choose to learn what it is that affected community members care about and believe (O'Conner et al. 1999). It may be that community members are particularly concerned about protecting a local park that will look different with the new infrastructure and that these individuals believe the construction is unnecessary because they are unaware of recent climatological data. Rather than arguing with these individuals, the manager who understands these values and beliefs could instead talk about what a 100 or 500-year storm might do to their park without the new infrastructure and perhaps show them comparisons of storm event data over time. This approach builds from an understanding of the individuals rather than from a simplistic position of trying to convince them that they are wrong (Bennett and Calman 1999; Granger et al. 1992).

It can be difficult to accommodate the differing values and beliefs that members of the same community hold regarding risks to their family, community, and environment. It would be simpler if managers could treat all community members as if they held homogeneous risk perceptions. Unfortunately, this is rarely the case. However, understanding the breadth of concerns and choosing to speak to key beliefs and values across the spectrum can make it more likely that the public will come to understand the rationale behind decisions (Bennett and Calman 1999; Granger et al. 1992). In addition, managers may come to realize that there are options of which they were unaware as they develop understandings of community values and beliefs. It is important for managers to remember that the public is generally the ultimate owner and financier of public works. A lack of technical or scientific understanding does not mean that an individual's risk perceptions are wrong; they may just be different and based on additional factors (Bennett and Calman 1999; Granger et al. 1992).

Attitudes, Norms, and Behavior

Variables associated with risk are but one approach to understanding the impact of beliefs on

actions. The **theory of planned behavior** (TPB), which explains the influence of attitudes, subjective norms, and perceived behavioral control on the intentions of individuals to undertake particular actions, also holds promise for understanding the social determinants of human behavior related to water resources, and for informing policies on watershed management. **Attitudes** toward a specific behavior can strongly influence the performance of the behavior (Ajzen 2001). Attitudes are based on **beliefs** and involve a positive or negative assessment of the performance and outcome of the behavior (Ajzen 1991; Fishbein and Ajzen 2010). In the example of lawn-watering, a person is likely to water if he or she believes watering will result in a healthy, green lawn and feels a positive attitude about this outcome. Conversely, a person facing a costly repair to a leaky septic system will likely experience a negative attitude towards fixing it. The negative attitude may be based on beliefs that the cost and inconvenience of a repair out-weigh the personal benefits of a repair. For behaviors that are within a person's control, those associated with positive attitudes are more likely to be performed than those associated with negative attitudes (Ajzen 1991; Fishbein and Ajzen 2010).

Norms and the beliefs underpinning them can similarly be strong predictors of behaviors. Norms can be viewed as the 'peer-pressure' component of behaviors because they are based on commonly-held beliefs about the expectations of important others (Babbie 1995; Fishbein and Ajzen 2010). That is, a person is likely to perform a behavior if he or she perceives strong social pressures to do so. The approval or disapproval of a given behavior by important others (e.g., friends or neighbors) affects an individual's perceptions about the performance of the behavior (Ajzen 1991; Fishbein and Ajzen 2010). For instance, a person may feel social pressures to water his/her lawn if he or she perceives that important others approve of a green lawn. A person who believes that many septic systems leak may not perceive social pressures to have his or her own leaky system repaired, particularly if others view the repair as a waste of money. Norms can strongly influence behaviors because they can be enforced formally or informally and can be very difficult to change (Babbie 1995).

The concept of control is an important factor in peoples' decision-making processes and associated behaviors. Similar to the concept of self-efficacy, perceptions about control relate to one's ability to perform a given behavior and the ease or difficulty associated with it (Ajzen 1991; Ajzen 2002; Fishbein and Ajzen 2010). **Perceived behavioral control** can have several components, including one's understanding of opportunity, knowledge, skills, time, or perception of financial resources necessary to carry out the behavior (Ajzen 1991; Ajzen 2002; Fishbein and Ajzen 2010). Control is often viewed as the behavioral determinant capable of outweighing normative pressures and attitudes because of its limiting capabilities (Ajzen 2002; Corbett 2005; Fishbein and Ajzen 2010). For instance, financial limitations may cause a person to neglect a leaky septic system, despite substantial normative pressures or a positive attitude about repairing it.

The interplay between attitudes, norms, and control are frequently examined to assess the extent to which each determines behaviors. According to theoretical models such as TPB, intentions to perform a given behavior are strong when factors related to norms, attitudes, and control all support the performance of the behavior (Ajzen 1991; Ajzen 2002; Fishbein and Ajzen 2010). The TPB is an extension of the Theory of Reasoned Action and its utility for predicting and explaining behaviors has been supported in a variety of studies (Figure 1). It has been effectively used to explain numerous environment-impacting behaviors such as littering, recycling, energy conservation, industrial pollution, and participation in landowner management programs (Armitage and Conner 2001; Cheung et al. 1999; Corbett 2002; Cordano and Frieze 2000; Harland et al. 1999; Kaiser and Gutscher 2003; Kaiser et al. 2005; Knussen et al. 2004; Russell and Fielding 2010).

Studies of residential water use typically share the objective of determining factors that predict conservation behaviors. Among those are factors that focus on socio-demographic variables such as age, income, or homeownership; however, findings tend to be contradictory and contextual (Jorgensen et al. 2009). The TPB, on the other hand, has frequently been applied in studies of conservation and its elements have consistently been shown to be effective predictors of intentions to conserve. In

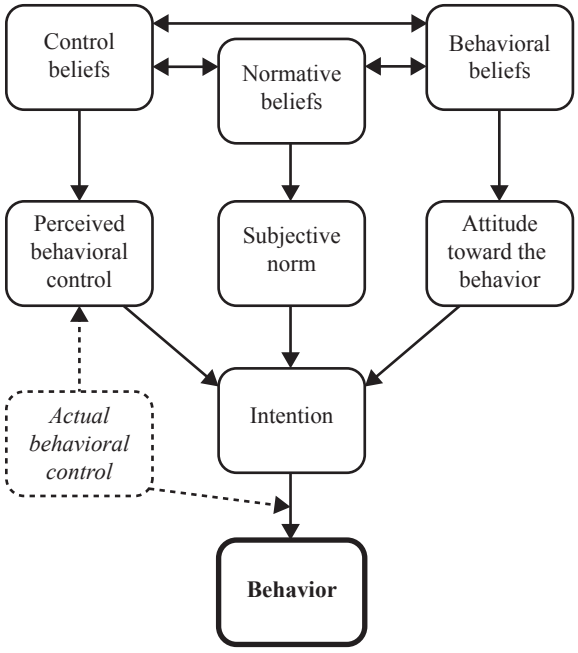

Figure 1. The Theory of Planned Behavior (adapted from Ajzen 1991; Fishbein 2010).

many cases, all three key elements (norms, attitudes, and behavioral control) positively and significantly predicted household conservation intentions (Clark and Finley 2007; Lam 1999; Trumbo and O'Keefe 2001). All three elements have also been shown to predict commercial farmers' intentions to adopt water-saving technologies (Lynne et al. 1995).

Perhaps more importantly to watershed managers, the TPB can also reveal factors that do not appear to influence intentions to conserve. For example, Lam (2006) found that the TPB was not able to explain intentions to purchase and install low-flush toilets, indicating that other factors (such as cost) may be relevant. In many studies, one TPB variable emerged as a considerably more powerful predictor of conservation intentions than others. In some contexts researchers found norms to exert the greatest influence over water use (Corral-Verdugo et al. 2002; Nancarrow et al. 2008), while others found the influence of attitudes to prevail (Armitage and Connor 2001; Clark and Finley 2007; Harland et al. 1999; Lam 2006; Russell and Fielding 2010). In other instances yet, perceived behavioral control surfaced as a very strong predictor (Kaiser et al. 2005; Lam 1999). A watershed manager who gathers data on water use through a TPB framework could therefore tailor outreach messages based on the relative influence of each of these factors as they explain the decision-making processes of the target audience. Knowing how to best appeal to water-users in a particular setting should save time and resources and lead to more effective policy formulation.

Overall, the TPB can be an important tool for watershed managers by improving their understanding of water-impacting behaviors of residents. If managers are concerned about water supply and wish to promote conservation, for instance, they could use the TPB to measure individuals' intentions to conserve based on their abilities to conserve, perceptions that important others approve of conservation, and attitudes towards conservation. The same strategy could help managers understand what motivates people to engage in behaviors that degrade water quality such as littering or dumping. By themselves, educational outreach programs intended to encourage water-friendly behaviors have been met with mixed results (Campbell et al. 2004; Gregory and DiLeo 2003; Syme et al. 2000). By characterizing how norms, attitudes, and control each influence water-impacting behaviors, watershed managers could fine-tune messages to reach the target audience more effectively than generalized attempts at 'educating the public'.

Social Networks, Social Capital, and Trust

The Theory of Planned Behavior recognizes that individuals do not make decisions in isolation. It operationalizes the impact important others can have on behavior by including subjective norms. Norms are only one part of how people impact our lives and decisions. Almost everyone will acknowledge the important role their friends, family, and colleagues play in their lives. In general, our social ties – or our social network - provide access to information (Granovetter 1973; Burt 1992), status attainment (Lin 1999), and influence our identities (Harshaw and Tindall 2005). At the individual level, **social capital** is the idea that we invest in our relations with those ties in the interest of achieving outcomes (Lin 2001). Wellman and Frank (2001) put forth that access to resources, diversity of one's social network ties,

and support systems are elements often studied from this perspective.

Establishing and utilizing social networks have been identified as important functions of a watershed group (Conley and Moote 2003; Koontz 2003; Floress et al. 2011a). Networks provide access to financial and technical resources, information, and assistance in addition to building cohesion among members of watershed groups and watershed residents. Social networks are also a significant component of the capacity individuals have to engage in behaviors to improve water quality, as noted by Davenport and Seekamp (2013). Decisions are not made in isolation, and social networks can influence behavior (Floress 2008). Social norms, often developed and maintained within a social network, are integral components of other theories of behavior change (e.g. TPB), and the means by which behavior adoption travels through networks as represented by Diffusion of Innovations (Rogers 2003).

Social capital researchers are interested in understanding how our networks influence individual outcomes and – particularly relevant in areas where collaborative watershed groups are present – group outcomes such as successful watershed planning activities (Floress et al. 2011a). Morton (2011, 41) notes that "…it is not a critical mass of people that solves problems but the critical connections among them that matter most." In addition to achievements and outcomes, others define social capital as the norms of trust and reciprocity that exist in a social structure as a result of people interacting with each other (Coleman 1988; 1990; Focht and Trachtenberg 2005; Putnam 1995; 2000; Pretty and Smith 2003). In watershed management, trust has been discussed as both a property of an individual, such as the trust one has for various agencies and organizations, and of collaborative groups. These various perspectives – individual outcomes, group outcomes, and trust – are discussed here.

Individual Outcomes

People access the resources represented by social ties to take action (Lin 1999; 2001). Other social theories note that information-seeking and the influence of the people with whom an individual associates and admires are important components in adoption of new behaviors (Rogers 2003). Thus, a person who has social network resources to help them become aware of water quality or land management problems and actions that can remediate those problems might be more amenable to changing their behavior (Floress 2008). As Morton (2011, 41) points out, watershed management is not successful because people talk about issues, but because people, "…use their power and influence to change others' beliefs, opinions, and behaviors." The types of networks individuals have access to also influence behavior when considering farmer adoption of best management practices (BMP) that improve or protect water quality (Prokopy et al. 2008; Baumgart-Getz et al. 2012). Baumgart-Getz et al. (2012) identified four types of networks that impact BMP adoption: local (interactions with neighbors and local organizations); agency (degree of connections to agency personnel); business (connections to those in agribusiness); and University Extension (connections to an Extension office). In their statistical meta-analysis, they found that local and agency networks have the largest impact on BMP adoption. Similarly, in a study of the impact of social capital on farmer behavior, Floress (2008) found that people's interaction with organizations providing information and programs about water quality and land management within a watershed has a significant impact on behavioral outcomes. Morton (2011) notes the impact family members, agency relationships, organizational membership, and peers had on conservation practices in Iowa. An important finding was that farmers who are members of more organizations are less satisfied with their current conservation efforts than those who interact more with other farmers. Essentially, interaction with those outside of producers influenced a farmer's perception that they could take additional conservation measures. This finding is supported by that of Campbell et al. (2011) who found that farmers are more likely to adopt BMPs when they participate in a watershed group.

Group Outcomes

Much effort and time have been dedicated to assisting collaborative natural resource management groups to form and persist. The relationship between collaborative groups, social

capital, and positive management outcomes is well-established, to the extent that books are dedicated to the topic (see Morris et al. 2013). Watershed groups have been seen as an answer to many of the issues inherent in top-down management, and are ideally characterized by stakeholders from different sectors sharing power in setting direction for watershed management activities (Michaels 2001; Floress et al. 2009; 2011b). The structure of a group is important with regard to what they are able to achieve. For example, Moore and Koontz (2003) found that groups tended to be comprised of agency personnel, citizen members, or both, and that each type focused on different activities (developing a watershed plan, lobbying, and addressing broad goals, respectively). Others have found that groups can be open to anyone with interest, representative of various interests identified by a leader, or restricted to those who meet certain criteria (Dakins et al. 2005) and that affiliations with organizations can impact group accomplishments (Bidwell and Ryan 2006).

Because the presence of **weak ties** (weak relationships between members of a network (Granovetter 1973)) and **structural holes** (someone in a group who provides access to resources and people outside of the group (Burt 1992)) facilitate information access, broad networks accessible within a watershed group increase a group's ability to achieve change (Floress et al. 2011a). These networks have been characterized by Schneider et al. (2003) as spanning vertical structures, such as the hierarchical structure of government; ideological dispositions used to negotiate among different interests; access to expertise (Zafonte and Sabatier 1998); and local areas. Watershed managers are more successful if they identify their desired outcomes and purposefully invite stakeholders to participate in watershed planning and implementation activities to help them achieve their aims (Floress et al. 2011a). To that end, groups should be designed to include stakeholders at both the planning and implementation stages who will provide access to people, skills, ideas, and resources that are needed for the goals the group will address (Floress et al. 2011a).

Trust

Trust – both of other stakeholders and policy makers - has been said to be vital for collaborative approaches to watershed management (Focht and Trachtenberg 2005). Building trust has been identified both as a goal of collaboration (Leach et al. 2002) and an outcome (Leach and Sabatier 2005; Lubell 2005). Leach and Pelkey (2001) found that trust was an important outcome for a group, and others have noted that trust can extend from one participant to others in the community (Hibbard and Lurie 2006). Multiple studies of collaborative groups have assessed the degree of trust group members have in each other and determined it is a necessary component for achieving environmental outcomes, but others have found that people will cooperate even in the absence of trust (Raymond 2006). Davenport et al. (2013) note that landowners will be more likely to positively assess conservation programs when they are promoted by conservation professionals who are already known by the landowner. Likewise, watershed residents who are trusted by their neighbors can facilitate behavior change in their communities (Davenport and Seekamp 2013; Fabricius et al. 2007).

Social networks, social capital, and trust are important concepts for watershed managers to consider at both the individual and group levels. With regard to individual behavior change, managers can identify highly connected people, agencies, and organizations in a community, and use those connections to influence change. At the group level, those convening a collaborative initiative should consider the types of stakeholders, problems, practices, and likely solutions that will be addressed, and form groups that will facilitate easier access to necessary resources. Finally, trust can be an explicit goal or an unintended outcome of watershed management, whether it is to increase the trust stakeholders have of those delivering conservation programs or to build trust among group participants.

Shifting from Individual Attributes: The Importance of Institutions in Watershed Governance

While much of the success of watershed management is dependent upon changes in individual behavior, **institutions** have an important role in supporting these actions (Heberlein 2012).

Institutions, according to North (1990, 3) are "the humanly devised constraints that shape human interaction." Institutions may be composed of formal rules, such as constitutions that are written and legally enforceable or informal social norms that use enforcement mechanisms outside legal and bureaucratic channels (Pahl-Wostl 2009). Institutions can also be categorized as public, private or civic (Agrawal and Perrin 2008). Institutions differ from organizations which refer to groups of people pursuing a common interest (North 1990). Formal and informal institutions and organizations constitute key components of resource regimes that mediate human interactions with various natural resources (Young 1982). The concept of **governance** is increasingly used to refer to the structures and processes through which various individuals, institutions and organizations interact in the formulation and implementation of policies (Pahl-Wolst 2009; Plummer and Fennell 2009).

In recent decades, the institutional mechanisms for resource management have been undergoing a transition from reliance on state institutions and regulatory mechanisms to decentralized and collaborative mechanisms that promote participation and interaction among institutions representing states, markets, and communities in the resource management process. This transition is particularly evident in the governance of domestic and international watersheds (Bruch et al. 2005). While the turn toward collaboration is an appropriate response to the growing interest in resource governance, and an important step toward integrating the human dimensions into resource management regimes, a more fundamental change in thinking is needed to account for the uncertainty and complexity in watershed management (Healey 1998; Pahl-Wostl et al. 2007). The true integration of the human dimensions into watershed governance institutions requires recognition of complexity and the need to prioritize learning in the resource management process. Institutions for watershed management are evolving, and could be designed to enhance efficiency, equity and sustainability of complex watersheds in the face of uncertainty.

Conventional watershed governance institutions have traditionally adopted a command-and-control approach, characterized by top-down decision-making by centralized institutions, and the use of fixed, static regulations (Karkkainen 2005). This approach to watershed management also relied heavily on technical approaches to ensuring the controllability and predictability of watersheds (Pahl-Wostl et al. 2007), and emphasized economic outcomes, particularly industrial and economic development (Healey 1998). Karkkainen (2005) has noted that the command-and control approach to watershed management assumes that sovereign states have the capacity to formulate and enforce appropriate rules. Indeed, where resources are available and resource management problems are relatively simple, the use of centralized institutions can be effective (Dietz et al. 2003). However, the use of command-and-control mechanisms often leads to several adverse consequences in the management of complex resource management problems. Centralized institutions, relying on static rules that are based on assumptions of predictability and controllability of watersheds are a poor fit for the complex and dynamic nature of watersheds. Given the dynamic and non-linear interactions among the multiple components of watersheds, such institutions lack the flexibility required for constant adaptation to changing watersheds (Healey 1998).

The issue of fit or match between the spatial and temporal scales of social and ecological systems and the institutions for resource management has received considerable attention in the resource management literature in general (e.g. Cash et al. 2006; Folke et al. 2007), and watershed management in particular (e.g. Kerr 2007). Karkkainen (2005) identifies the problem of mismatch in the scales at which decisions are made using centralized institutions and the scales at which watershed management problems occur as another shortfall of the command-and-control approach to watershed management. Watershed boundaries rarely match the boundaries of political jurisdictions within which they are managed (Davenport and Seekamp 2013). While the delineation of watershed boundaries is itself a politically contested issue (Blomquist and Schlager 2005), the reliance on sovereign states as political jurisdictions may be too small in the case of international transboundary watersheds, or too large in the case of domestic watersheds

(Karkkainen 2005). The mismatch between the ecological scales of watersheds and the jurisdictional scales of the watershed management institutions could potentially result in a lack of fit between policy interventions and the problems to be addressed (Kerr 2007). For instance, centralized institutions often adopt one-size-fits-all solutions based on generalizations that reflect poor knowledge on particular local cultures and ecosystems (Acheson 2006; Lebel et al. 2007).

A related shortfall discussed by Karkkainen (2005) is the mismatch in the resources and capacities required for the sustainable management of complex watersheds and the resources actually available to centralized institutions as single or dominant actors in watershed management. Centralized institutions often face resource constraints, such as funding and personnel shortages that render them ineffective (Lebel et al. 2007). Command-and-control approaches have also been critiqued for their inefficiency (Dietz et al. 2003), the lack of incentive to change they provide, and their poor record on the sustainable management of water resources (Acheson 2006; Darghouth et al. 2008). Additionally, centralized institutions often lead to inequitable outcomes that exert disproportionate adverse impacts on communities while offering opportunities for capture by dominant power structures (Lebel et al. 2007).

Recognition of these widespread shortfalls in the conventional command-and-control approach to watershed management has resulted in the turn toward participatory approaches such as community-based and collaborative watershed management. This approach to watershed management is consistent with the growing emphasis on **co-management** in the broader arena of resource management. Co-management refers to institutional arrangements for joint resource management involving the sharing of power, rights and responsibilities between state representatives and non-state actors, such as resource users at the local level (Yandle 2003; Carlsson and Berkes 2005). Unlike community-based conservation that emphasizes local community control over institutions and procedures for resource management, co-management necessarily involves the role of state representatives in the resource management process (Borrini-Feyerabend 2003).

The turn toward collaborative watershed management offers several benefits that represent an important step toward integrating the human dimensions into watershed management institutions. Collaboration promises to enhance equity in watershed management, both procedurally in terms of providing opportunities for adequate representation and meaningful participation as well as non-discriminatory access to justice by all stakeholders (Bruch 2005), and substantively in terms of the consideration of all interests in the search for practical solutions to shared problems (Wondolleck and Yaffee 2000). Collaboration is also associated with efficiency in the resource management process. Efficiency can result from the pooling together of resources by the multiple stakeholders, allocation of tasks according to the skill set of each stakeholder, and the avoidance and resolution of conflicts in the decision-making and implementation process (Carlsson and Berkes 2005). The collaborative approach to watershed management also promises to enhance the effectiveness of the decision-making process by enhancing the quality of decisions based on the integration of the dispersed knowledge among the diverse stakeholders, as well as building a sense of ownership and commitment of stakeholders to the successful implementation of decisions (Wondolleck and Yaffee 2000; Bruch 2005). Ultimately, collaborative watershed management provides opportunities for building the capacity of communities and organizations involved in the ongoing learning and problem-solving process, as well as enhancing the sustainability of the resource base (Wondolleck and Yaffee 2000; Plummer and Armitage 2007).

In spite of its promise, collaborative approaches to land and water resources management are frequently bedeviled with a range of conceptual and implementation shortfalls. One of the key factors accounting for failure in collaborative initiatives is the lack of political will and interest on the part of governments and their representatives to sustain collaborative processes (Berkes 2010; Akamani et al. 2015). Effective collaboration requires the willingness of governments to sacrifice power (Ruhl 1999), as well as the willingness to provide the resources, incentives and opportunities for participation (Wondolleck and Yaffee 2000).

Yet governments are often reluctant partners (Chomchai 2005), resulting in collaborative processes that sometimes lead to the strengthening of state control (Berkes 2009). Collaborative initiatives have not been successful in addressing equity issues, such as reducing poverty and empowering marginalized groups (Berkes 2009; Akamani and Hall 2015). Collaborative processes and their outcomes often strengthen the control of powerful local elite while suppressing the values and interests of less powerful actors (Reed 2008; Cinner et al. 2012). Collaborative initiatives are often constrained by the lack of adequate resources, including funding, logistics, and personnel on the part of agencies and communities (Wondolleck and Yaffee 2000). The lack of skilled personnel, such as trained facilitators and mediators in negotiation processes, could have adverse consequences on the quality of the process.

At the community level, the poor may have limited access to the media and other sources of information, limited literacy and skills for participation, and limited access to other resources required to access opportunities for participation (Chomchai 2005). The collaborative approach is also not a panacea to every watershed management problem. Individuals and organizations may not be interested when more promising alternative channels exist for pursuing their interests. The existence of multiple competing interests and organizational mandates, as well as non-negotiable positions may result in a gridlock in negotiation and consensus-building processes. Consequently, collaborative processes are often challenged by a loss of interest in sustaining such processes (Healey 1998; Reed 2008). Importantly, the promotion of stakeholder participation through collaborative approaches has been critiqued as inadequate in managing complex and dynamic watersheds due to the lack of explicit recognition of this complexity and the need for learning and adapting to change (Healey 1998; Akamani and Wilson 2011).

Designing Effective Collaborative Watershed Management Institutions

Sustainable watershed management requires innovative institutional mechanisms that can provide the awareness, interest, resources and opportunities for stakeholders to engage in collective responses aimed at building resilience and reducing vulnerabilities in the face of the multiple drivers of change to which watersheds are constantly exposed (Akamani 2014a). This section presents a set of recommendations for integrating the human dimensions into watershed management institutions while enhancing equity, efficiency, sustainability and resilience.

Creating Awareness about the Complexity of Watersheds

The conventional command-and-control approach to watershed management reflects older assumptions that separated humans from nature, and emphasized human ability to understand, control and predict natural processes (Akamani 2014b). Greater awareness among policy makers and ordinary citizens of the dynamic interdependence between the human and biophysical components of watersheds, as well as the uncertainties and unpredictability that characterize such coupled social-ecological systems, is needed to inform more sustainable watershed management policies. Such an awareness calls for watershed management policies and institutions that aim at building the resilience of the social-ecological system rather than maximizing short-term economic benefits. For instance, the emerging concept of adaptive co-management that combines the multi-level linkages of collaboration with the learning focus of adaptive management (Berkes 2009) holds promise for building the resilience of complex watersheds (Akamani 2014a).

Using Diverse Sources of Knowledge

The generation of accurate, context-specific, and policy-relevant knowledge on complex social-ecological systems is needed for enhancing success in watershed management. The reliance on reductionist science and engineering in the conventional command-and-control approach to watershed management tended to marginalize the social sciences, thus yielding knowledge that offers a partial understanding of social-ecological systems. Social and ecological vulnerabilities have resulted from policies based on such incomplete knowledge generated from reductionist science (Ludwig et al.

1993; Holling 1993; Holling and Meffe 1996). Managing watersheds from a social-ecological systems perspective calls for greater recognition of the social sciences through multidisciplinary and interdisciplinary collaboration between the social and biophysical sciences (Gelt 2000; Beschta 2000), as well as recognition of the importance of local and traditional ecological knowledge in watershed management.

Building Motivation for Collective Action

A range of economic and non-economic incentives are needed to motivate diverse stakeholders to be actively involved in collective responses to problems in complex watersheds. This might entail adopting broad watershed management goals that address the livelihood concerns of stakeholders, improving upon the quality of decision-making processes as mechanisms for building trust and social capital, and the enhancement of social learning among the diverse stakeholders. Social learning refers to learning that occurs among social groups as a result of social interaction processes (Reed 2008; Reed et al. 2010). The adequate representation of all stakeholders, early involvement of stakeholders in the watershed planning process, and the use of skillful facilitators and mediators are some of the measures that could enhance the quality of the deliberation processes (Reed 2008).

Providing Opportunities and Resources

Empowering stakeholders to be actively involved in watershed management processes will require the provision of opportunities and resources for participation. Enabling legislative and regulatory frameworks are needed to institutionalize collaborative processes and to guarantee the rights of stakeholders, particularly marginalized groups, to access information and to participate in decision-making processes. However, it is not enough to have the opportunity to participate. Stakeholders must also have the capacity to participate fully in collaborative processes (Reed 2008). This calls for various mechanisms for capacity-building, including training on how to participate in collaborative processes, and the provision of various forms of resources, such as funding and logistics. To ensure equity, special attention needs to be paid to marginalized groups who are often constrained from accessing the information, opportunities and resources for participation in collaborative processes.

Using Individual and Institutional Attributes in Watershed Management

There are multiple methods by which a watershed manager can use social and institutional information in the watershed planning and implementation processes. Prokopy et al. (2009) and Genskow and Prokopy (2011) developed a system for collecting social data for projects funded by Clean Water Act §319 funds (grants dedicated to prevention and remediation of nonpoint source pollution) based upon individual and project level data. Their system includes assessing changes in the awareness, attitudes, behaviors, and constraints of individuals targeted by watershed management efforts (Table 1). They also include a set of indicators associated with increasing the organizational capacity of watershed projects that measure the resources projects that have received 319 funds.

Davenport and Seekamp (2013) also recognized the complex and interwoven factors impacting the ability an individual has to engage in actions to protect water resources, and developed a framework that incorporates individual level variables similar to those Prokopy et al. (2009) developed, relational variables such as networks and shared definitions of resource concerns, organizational variables including engaging diverse stakeholders in collaborative processes, and programmatic variables such as coordinating goals across institutional boundaries (Davenport and Seekamp 2013). Davenport (2013) includes perceptions related to fairness and legitimacy in the Social Measures Monitoring System developed for Minnesota watershed projects. Table 2 includes a selection of variables from Minnesota's system, with the addition of risk perception.

Regardless of the framework or approach used, managers would ideally collect social information in the same manner water quality, habitat, and other environmental indicators are collected: at the outset

Table 1. Social Indicators Planning and Evaluation System (adapted from Genskow and Prokopy 2011).

Indicator Category	Outcomes	Indicators
Awareness	• Increase awareness of technical issues and behaviors	• Consequences of water pollutants • Types of pollutants • Pollutant sources • Appropriate practices
Attitudes	• Change attitudes to facilitate behavior change	• General water quality attitudes • Willingness to take action
Constraints	• Reduce constraints to behavior change	• Constraints to behavior change
Capacity	• Increase capacity to leverage resources • Increase capacity to support appropriate practices	• Resources leveraged as a result of project funding • Funding available to support practices • Technical support available for practices • Ability to monitor practices
Behavior	• Increase adoption of water quality relevant behaviors	• Percentage of critical area receiving treatment • Percentage of target audience implementing practices

Table 2. Capacity Indicators (adapted from Davenport 2013).

Individual Capacity	Relational Capacity	Organizational Capacity	Programmatic Capacity
• Awareness of problems and consequences • Concern about problems and consequences • Perceived control and efficacy for protection and restoration of water resources • Sense of responsibility for problems, consequences, and solutions • Personal norms related to behavior • Social norms related to behavior • Attitudes and beliefs • Ability to take action • Behavior adoption and change	• Inclusive social networks • Shared identity • Connectedness and trust • Positive social interactions • Collective action	• Diversity of members • Effective leadership • Access to information • Clearly defined mission and identity • Meaningful engagement • Collaborative decision making process • Conflict management • Accountability for problems, consequences, and solutions • Positive community influence • Effective engagement	• Clear goals and objectives • Adequate resources • Evidence based programs • Effective citizen engagement • Program coordination across boundaries • Program outcomes (ecological, social, economic) monitored and used for adaptation • Programs build capacity • Programs are effective in protecting and restoring resources

of projects to provide a baseline set of data and focus project goals, and throughout implementation to evaluate progress and adapt as necessary.

The process of collecting social information occurs at several scales and at different points in the planning and implementation cycle. Researchers have noted that the role of stakeholder engagement can shift over time in watershed projects given the power-sharing constraints agencies face, particularly with regard to implementation of project decisions. For instance, in projects dependent upon federal funding – particularly in agricultural watersheds – stakeholders might have a high degree of involvement in visioning, setting direction for a project, and developing goals, but very little power over how implementation projects are carried out due to the necessity of abiding by agency criteria (Floress et al. 2011b; Thompson and Floress 2012). For example, cost-share practices on agricultural lands are subject to Natural Resources Conservation Service criteria. Table 3 illustrates how participation goals, methods of collecting information, and the degree of decision-making power a collaborative group has might change over the course of a project depending on the reality of agency constraints. Other projects might have the ability to engage in co-management. It is vital that projects determine at the outset the degree of power they are able to extend to stakeholders at each stage of the planning and implementation process, and clearly communicate this information to participants. Perceptions of trust, legitimacy, and fairness can be quite negative if stakeholders expect greater power in implementation decision-making than can reasonably be afforded by watershed managers.

Table 3. Potential changes in stakeholder involvement and project activities over time.

	----------Planning Stage----------			
	Early Planning	**Mid-Planning**	**Implementation**	**Evaluation**
Goals of Stakeholder Activities	• Assess individual capacity indicators • Develop organizational and relational capacity	• Focus planning efforts • Develop organizational and relational capacity • Develop effective programs	• Collaborative group members engage in program delivery	• Determine whether plan has achieved goals – assess all capacity indicators
Project Activities	• Visioning, surveys • Focus group • Collaborative group meetings	• Collaborative group meetings • Capacity indicators used to inform implementation plan and programs	• Field days • Peer to peer networking/ neighbor visits • Other program activities appropriate to audience	• Follow up surveys • Focus groups/ interviews with group members • Institutional analysis
Stakeholder Decision-Making Control	• High – set project direction	• High – continue to set direction; share power for goal development	• Low/medium – some conservation programs have specific requirements	• Low – evaluation plan should be detailed in the watershed plan

Social Data Application Example: Eastern Marathon County Lakes, Wisconsin

This section will provide a brief overview of how a watershed project can use social data to increase adoption of behaviors. A county-wide planning process to protect 11 small lakes in Central Wisconsin was undertaken in 2010. A variety of ecological and social data were collected, including the Prokopy et al. (2009) social indicators described above (awareness, attitudes, constraints, behaviors), trusted information sources, characteristics of landowners, and perceptions of lake issues. The purpose was to develop targeted outreach strategies appropriate for the lake residents. First, the social scientist researcher on the technical team consulted with the lakes' planning grant recipient to understand the local issues. A mail survey was conducted of all landowners in the surface and ground watersheds, and audiences were segmented based upon project team input and statistical methods. Following is a description of one target audience – consumptive wildlife recreationists – and the strategies developed to impact behavior.

Consumptive wildlife recreationists made up almost 73% (n=215) of the individuals who participated in the survey. Of those, 112 owned shoreline property and 42 of the shoreline property owners had never heard of having a vegetated shoreline. Moreover, 27 of the lakeshore owners believed having vegetation along the shoreline didn't apply to their property. They noted that their biggest barriers to having a vegetated shoreline were not knowing where to get assistance, cost, and time. By using the information sources this population viewed as most trustworthy (lake groups and sportsmen's clubs) and messaging that resonates with consumptive wildlife recreationists, the project can appeal directly to the target audience, and start with a simple behavior.

One barrier to change, in this instance, is that individuals didn't know where to go for help. The first simple behavior could be to call a partner organization. Information overload should be avoided when communicating with audiences, particularly audiences relatively uninformed about watershed management issues in general and a local project in particular. Making the message and behavior relevant and easy to digest is key to successful behavior change. It was recommended that the project use mass media and lake groups to highlight the message that "shoreline vegetation makes hunting and fishing better, and there are places to help you", provide contact information for a project partner, and ask lakeshore owners to contact the organization (Figure 2). Short-term outcomes from this simple strategy would be increased knowledge of where to get help, increased knowledge that shoreline vegetation is related to fishing and hunting, and increased calls for help. Medium-term outcomes include changes in behavior (e.g. increased vegetated shoreline), and long-term outcomes would include changes in environmental conditions such as decreased pollutants entering lakes and healthier fish populations.

Conclusion

This article has made clear the importance of incorporating social science into watershed management. Much of what managers need to do in order to achieve successful implementation requires social science expertise to translate social and institutional information into actionable program activities. Much like ecological indicators, social science indicators will differ watershed by watershed. In large scale watershed projects, institutional analysis methods can be employed to understand the breadth of current program offerings and the degree to which they are coordinated with others offered in the watershed. To increase adoption of water-relevant behaviors, watershed management plans should include communication strategies that are targeted toward specific audiences, such as in the Eastern Marathon County Lakes example above.

Solving issues associated with water quality and quantity will not be accomplished with simple technical fixes. It is our hope that this article provides readers a background in the social science of watershed management, and tools and resources that can be used to understand stakeholders and make watershed plan implementation more successful. However, it is important to note that this article should not be used as a substitute for direct consultation with an expert. The best way to get

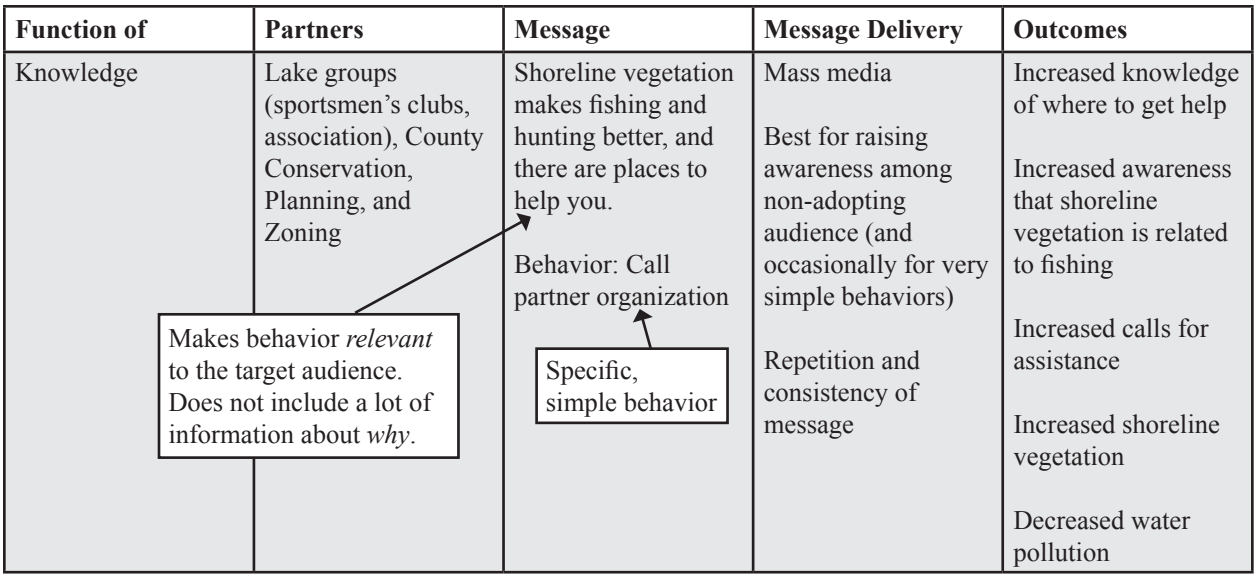

Figure 2. Where to get help: Illustration of using social data in watershed plans.

good information for use in watershed management is to consult directly with someone with expertise in this field of study. Local universities, state environmental management agencies, and private consultants usually have staff members who are able to assist watershed projects with their data collection and strategy development needs.

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A Primer on Watershed Management

Issue Editor
Pamela Edwards

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