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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

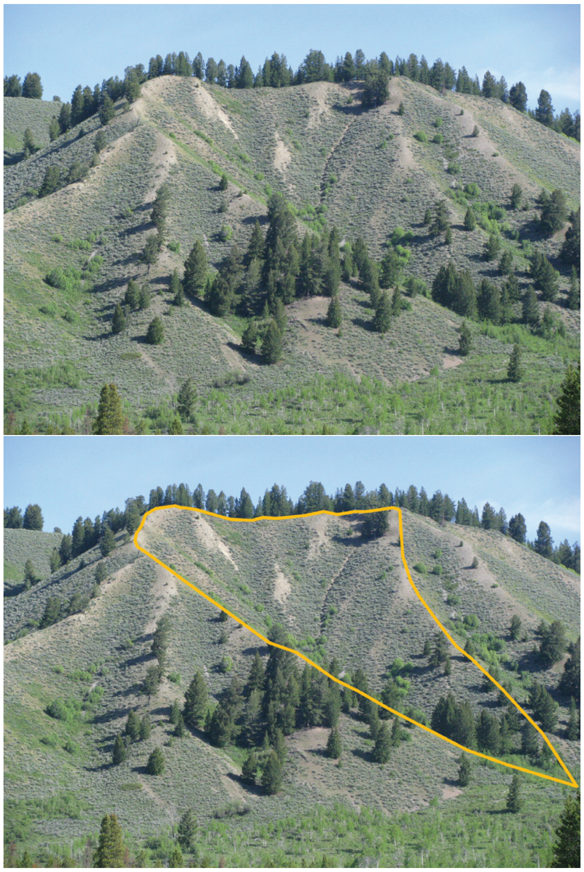

Figure 1. A small watershed in Wyoming. The watershed boundaries are the topographic high points (i.e., ridges) in the top photograph, which are outlined in yellow in the bottom photograph. Photograph courtesy of David Mince.

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,

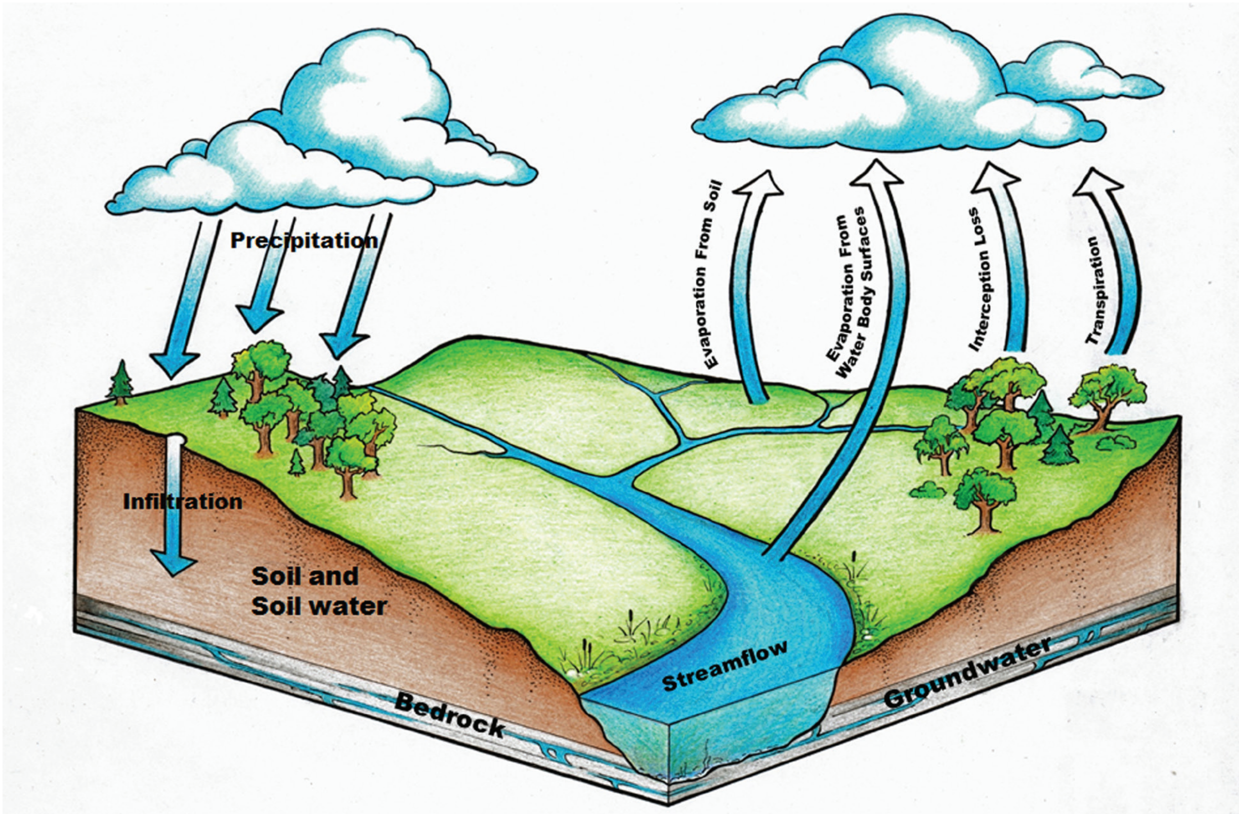

Figure 3. A simple schematic of the hydrologic cycle. Drawing by Robin L. Quinlivan.

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

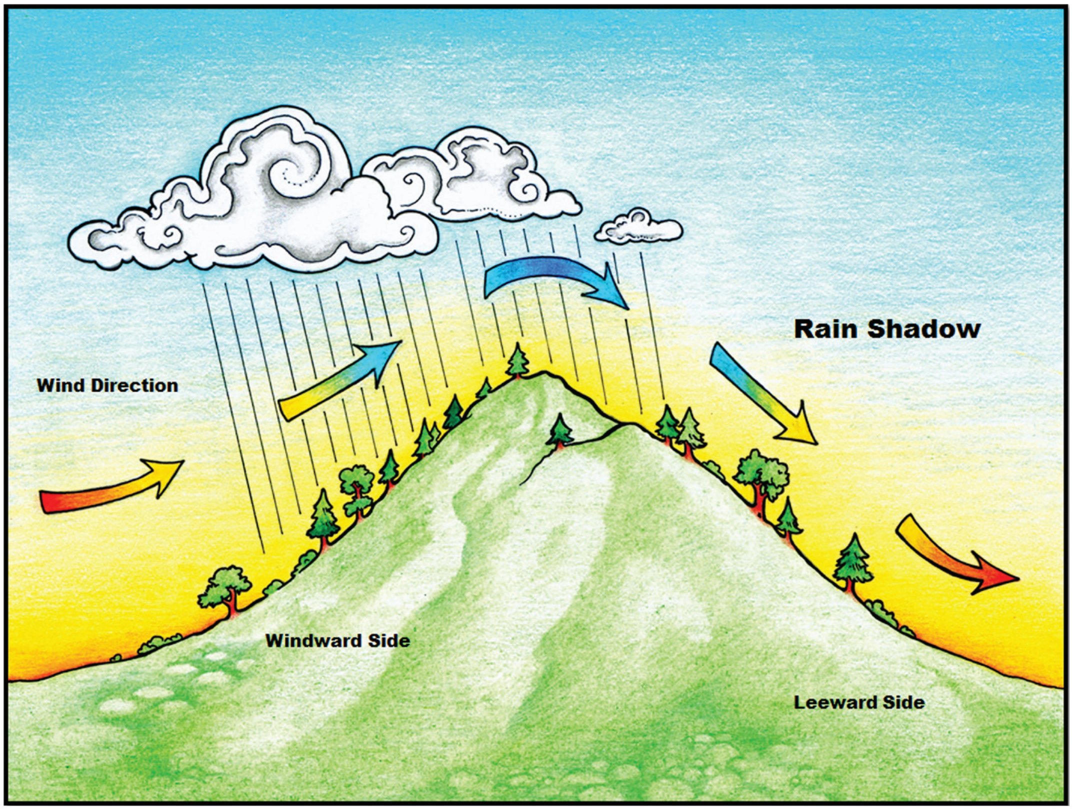

Figure 4. Effects of orographic lifting. Air currents rise when they encounter mountains, which results in the air mass cooling. Less moisture can be held by cooler air so clouds form and precipitation occurs during lifting. After the air mass crosses over the mountain, it begins to fall and warm, the 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-

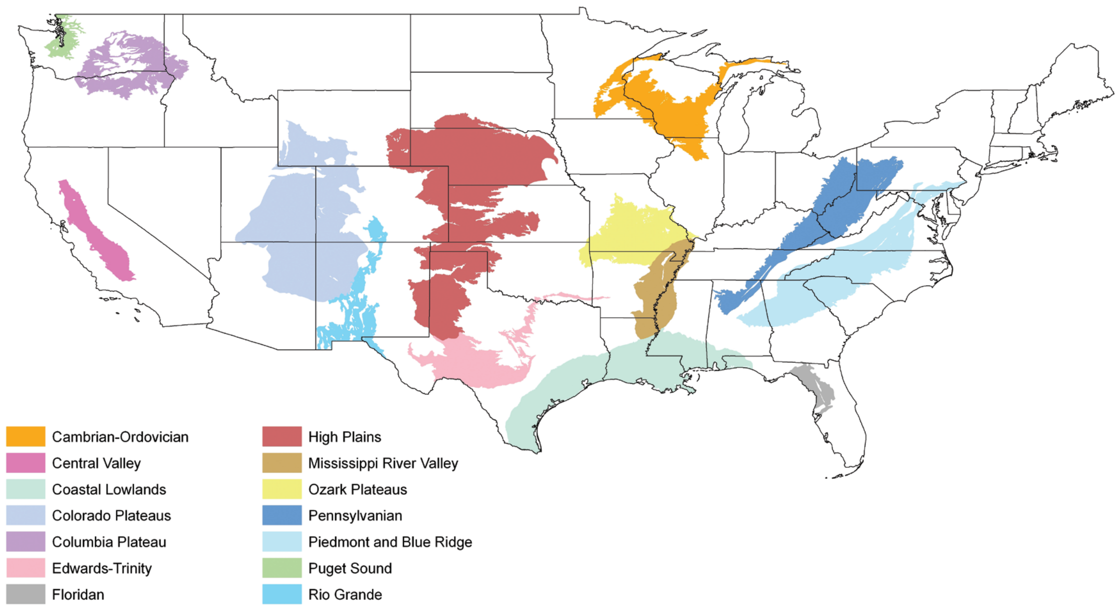

Figure. 5. Some of the major groundwater aquifers in the U.S. Most are named for their location (e.g., Floridan) while two are named after the geologic age of the rocks that host the aquifer (the Cambrian-Ordovician aquifer and the Pennsylvanian aquifer). Note the large area that each of these regional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

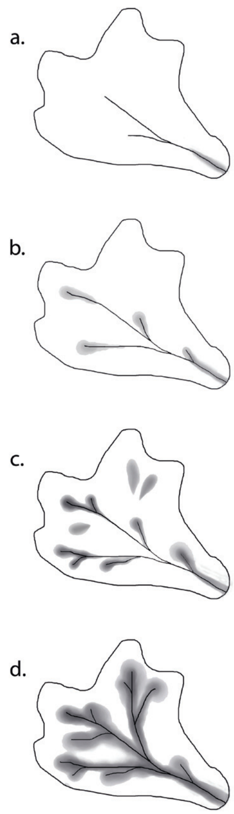

Figure 6. A schematic illustrating the progression of soil-moisture wetting and streamflow development in forested watersheds, following the variable source area concept. Shaded areas in each illustration indicate water-saturated soils. The duration of precipitation as well as the volume of streamflow 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

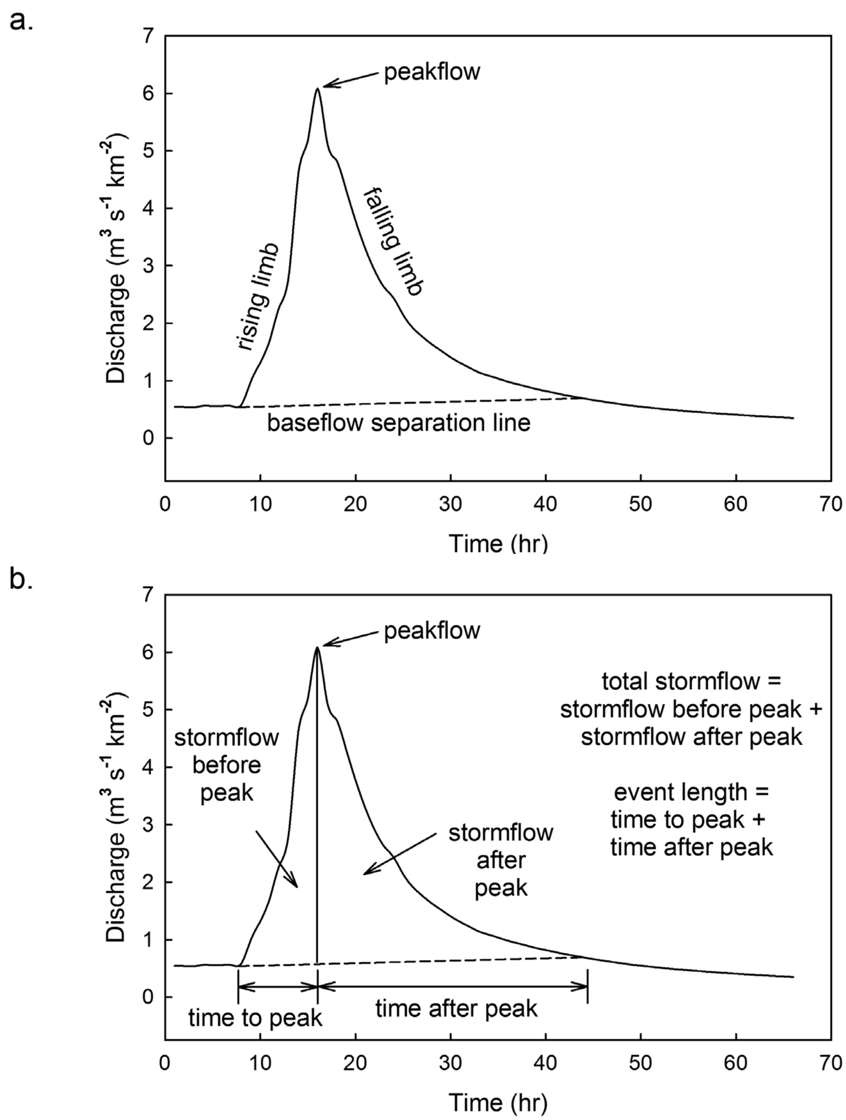

Figure 7. a.) The general components of a storm hydrograph. b.) The hydrograph variables stormflow volume before peak, stormflow volume after peak, total stormflow volume, peakflow, time to peak, time after peak, and total event length are defined from the general components and can be quantified for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

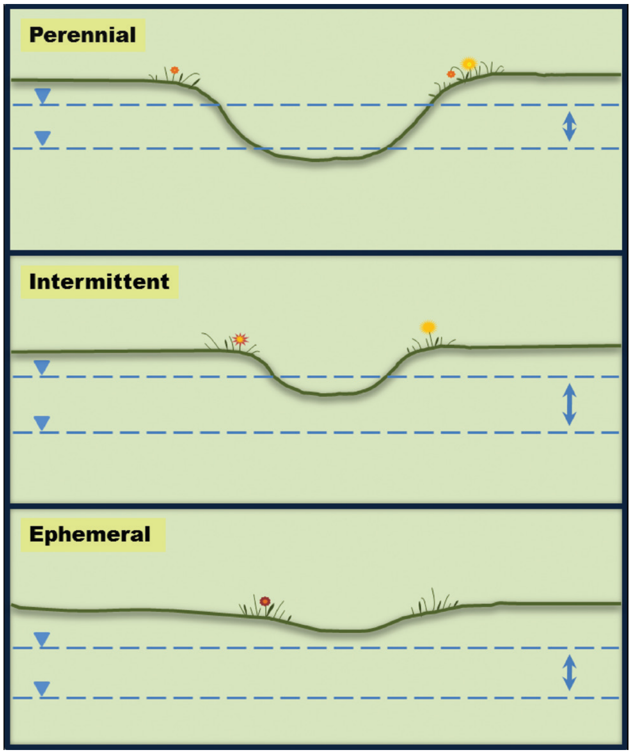

Figure 8. Channels are defined as perennial, intermittent, or ephemeral based on the duration that they receive groundwater inputs. The water table (top of groundwater) at various times throughout the year is shown by the dashed blue lines with the inverted triangles. The ground surface and stream channel 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.

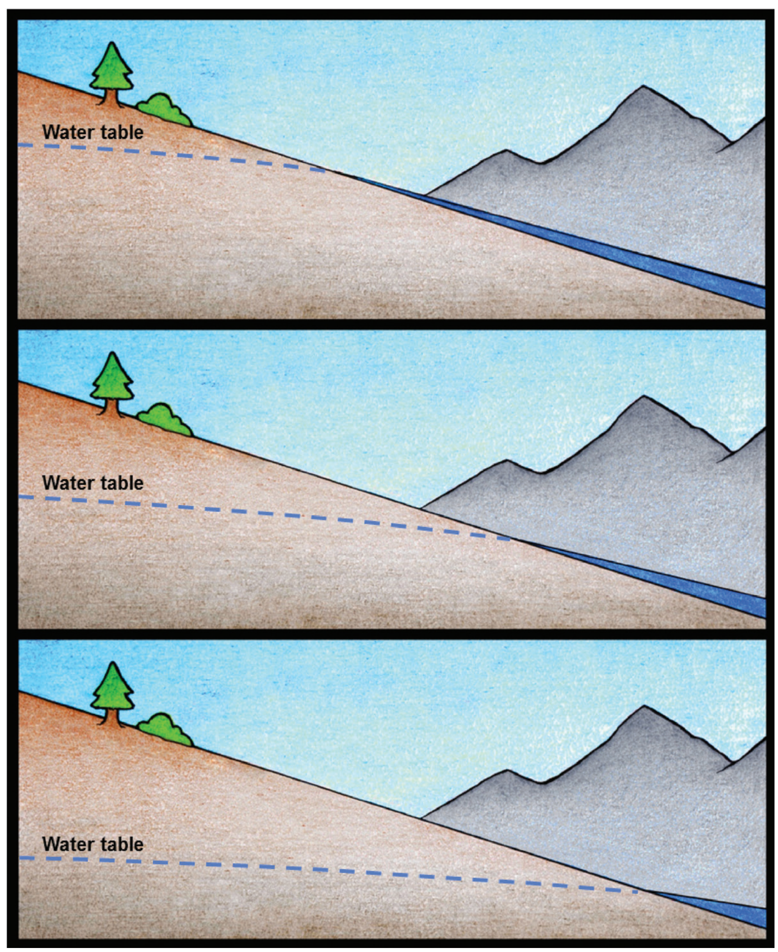

Figure 9. The position where surface flow is present in intermittent channels changes throughout the time that these streams hold surface water. When the water table (dashed blued line) is at its highest level, streamflow (solid blue area) in intermittent channels extends furthest upstream (top drawing). 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

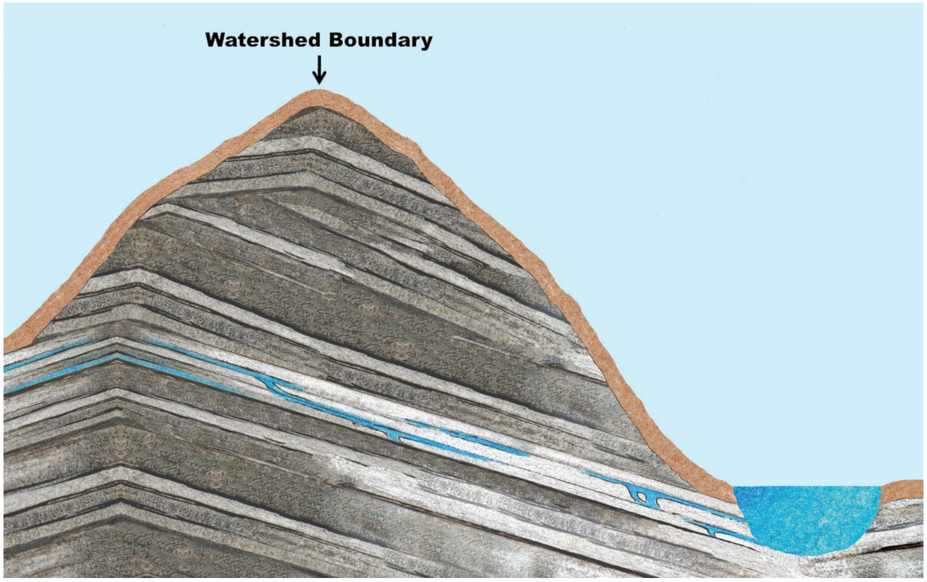

Figure 10. The dip of folded or tilted bedrock can transfer water across watershed boundaries where geologic layers are unfractured and relatively impermeable. Drawing by Robin L. Quinlivan.

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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