# 3 Watershed Basics

This chapter provides an overview of the main natural and social science disciplines and the main types of issues that come up during a watershed assessment. It discusses the watershed as a whole, as well as its component parts. Just as watersheds are naturally integrated, watershed assessments are interdisciplinary in nature. This means that components analyzed separately need to come together through integration and synthesis, as described in a later chapter.

Chapter Outline



## 3.1 Geography

Geography—the distribution of plant, animal, and human communities across a watershed—is integral to landscape and watershed assessment. Geography also encompasses the relationships among a landscape's processes (e.g., fire and human development) and features (e.g., vegetation types and dams). Underlying processes involving geological formations, hydrologic flows, and ecological transformation result in the presence of particular features, such as soil and plant types. Changes in the processes result in changes in the distributions of these features.

Geographic investigations show that people tend to aggregate around certain features of their environment. For example, many towns have grown up around the intersections of roads, year-round waterways, coastal bays, and fertile agricultural areas. At these locations, people engage in various types of social and economic interactions that may be dependent on or independent of their surroundings. These interactions are the subject of human geography.

A common tool in geography is a geographic information system (GIS), which can be available as software that plots the distribution of human and natural features and processes across a place. GIS maps show how different features (e.g., vegetation types, road alignments, general plan zones) are arrayed within a watershed. GIS can also reveal important clues as to why a particular effect is occurring—such as why one sub-watershed has more erosion than others. In the case of erosion, slope steepness, precipitation, soil types and other watershed features could indicate areas where erosion is naturally high, or high due to human activity. These clues, combined with improved management of human activities in the watershed and monitoring, can lead to improved findings by future watershed assessors.

### 3.1.1 Cumulative Watershed Effects

Many watersheds experience multiple impacts from current and historical natural and human processes. All of these processes combined are called "cumulative watershed effects" (CWE). When planning land-use activities, private parties and some agencies are required to assess the cumulative effects of their proposed actions and the actions of others in the past, present, and anticipated future on the natural functioning of watersheds.

A watershed assessment must consider the cumulative watershed effects on the watershed processes of interest. Although each individual impact may be insignificant with respect to the entire watershed, their cumulative effects may be dire. For example, changing runoff processes in a small fraction of the watershed (perhaps by converting a stand of trees to an agricultural field) or even adding a small quantity of a pollutant to a stream will not result in any detectable change at some point well downstream. However, changing many runoff processes or adding a small quantity of the pollutant at many places along the stream will produce a detectable change downstream.

## 3.2 Hydrology

Understanding the general interactions between water and the landscape is fundamental to your watershed assessment. Hydrology is the study of the occurrence and movement of water over and under the land surface. In watershed assessments, the basic hydrologic concerns are flow (volume of water per unit of time), timing (when this flow occurs), storage (volume of water in groundwater, reservoirs, lakes, or snowpack at a particular time), and quality (what's in the water besides just water). The hydrologic cycle and the water balance (an abbreviated accounting of the hydrologic cycle) are useful frameworks for thinking about how water moves through your watershed. The hydrologic cycle is a conceptual description of the ways in which water moves around the world. Water is generally moving in the hydrologic cycle, although some of it may be in temporary storage for a wide range of time periods.

*The Hydrologic Cycle*

Starting with water in the atmosphere, some of the water precipitates as snow or rain. Once on the ground or other surface, such as a leaf, precipitation in the form of snow will be stored until enough energy is available to melt the snow. The meltwater will then behave similarly to rain. Most precipitation will land on vegetation or other elevated surfaces before reaching the soil surface. Most of this "intercepted" water will drip or flow to the soil, but a small portion will be evaporated back into the atmosphere.

Water that reaches the ground surface will be absorbed, stored in small depressions, or flow downslope over the surface. The absorbed water that has "infiltrated" into the soil becomes "soil moisture". This soil moisture may remain in place, flow downslope toward a stream, or "percolate" vertically to become "groundwater". Some of the water temporarily stored in the soil may evaporate from the soil surface or be taken up by plant roots and "transpire" from the plant's leaves.

Water can reach streams and lakes via "overland flow" across the surface (minutes to hours), downslope flow through the upper layers of the soil (hours to weeks), and release from groundwater (weeks to centuries). Some water in streams may percolate into groundwater storage elsewhere along the stream channel and perhaps emerge again into the channel farther downstream. Groundwater and surface water (water in streams and lakes) are often regarded as completely distinct, but in most watersheds, a lot of water moves back and forth across the ground surface and streambeds. Some surface water will evaporate, but most of the water that has made it to a stream channel will eventually flow to an ocean (or a lake without an outlet, such as Mono Lake), where it will be available for evaporation, replenishing the atmospheric water where the cycle began.

The global hydrologic cycle can be fitted to your watershed as general concepts that describe the processes that affect the movement and storage of water through your particular watershed. When applied to a watershed, the hydrologic cycle is not a closed system, but has quantifiable inputs and outputs. These inputs and outputs, along with temporary storages, can be estimated in the simple accounting scheme of a water balance (section 3.2.1). Estimating the water balance of your watershed is a useful means of exploring its hydrology. Some of the basic components of the water balance (and hydrologic cycle) are discussed in sections 3.2.1 to 3.2.3.

In addition to describing natural hydrologic processes, your watershed assessment should consider how these processes have been altered by human activities and how the water, both in streams and underground, has been intentionally managed. Most land use alterations affect water's infiltration into the soil and evapotranspiration (evaporation from vegetation) in a small proportion of the watershed and thereby alter these components of the water balance a relatively small amount over the entire watershed. However, changing the land use of many small fractions of the watershed will eventually add up, and the cumulative effect of all those incremental effects can result in significant changes to the water balance. Engineering works, such as dams, canals, and networks of pumped wells, that allow deliberate management of water resources often change the water balance to a much greater extent than the indirect effects of land use change.

### 3.2.1 Overall Water Balance

Determining your watershed's overall water balance is useful for understanding its basic hydrology because the water balance describes the quantities of water affected by various processes in your watershed. Although a written water balance is instructive to a reader, the primary value of a water balance is to the analysts who carefully think about the hydrologic pathways and processes. There is no other thought process that yields an equivalent understanding of a watershed's hydrology. The conceptual description of the water balance is far more important than the estimated values you develop. You should expect the numerical values to be difficult to estimate and highly uncertain. Water balances are sometimes called "water budgets", although that term has the unintended implication of future prediction. A water balance or budget can be considered analogous to balancing one's checkbook—with deposits, withdrawals, and cash on hand being analogues to the key components of a water balance.

A general water balance equation starts as WATER IN = WATER OUT +/- CHANGE IN STORAGE. The basic challenge of the water balance is to fill in the details of what constitutes WATER IN, WATER OUT, and CHANGE IN STORAGE for your situation.

WATER IN is almost always just precipitation, but it could also include artificial imports of water from another watershed through canals or pipelines.

WATER OUT includes evaporative losses, streamflow, groundwater flow out of the basin, and artificial exports of water through canals or pipelines.

CHANGE IN STORAGE includes soil moisture, deeper groundwater, lakes, reservoirs, and water temporarily flowing in stream channels. The CHANGE IN STORAGE term is usually important over shorter time periods (days to months), but can often be considered negligible over a year or longer. However, you must consider whether storage is a quantitatively important term for the watershed and time period in which you are working.

An annual timeframe is perhaps most useful and easiest to work with. In most cases, change in storage over a year will be negligible, especially if you use the conventional "water year" of October 1 through September 30. In early autumn, before the rainy season has begun in California, streams tend to be at their lowest flow and soil moisture is at a minimum. So this October 1 start date begins the water year at a time of minimal hydrologic activity.

#### 3.2.1.1 Estimating a Water Balance

Water balances and many other hydrologic quantities are commonly expressed in terms of a depth of water. This is in order to control for watershed area. Hydrologic volumes (amount of water moved through waterway over a time period) are converted to depth by dividing volume by the surface area of the watershed. Flow rates vary over time, which also needs to be accounted for (see Table 3.1).

In most parts of California, the largest output of the water balance is evaporation. The term evapotranspiration (ET) is often used to describe the role of evaporation from vegetation. Good estimates of ET are difficult to develop, so in simple, conceptual water balances, ET is often the leftover quantity of water after accounting for changes in storage. For a typical, quick-and-dirty water balance calculation, estimate average precipitation over the watershed, assume changes in storage are negligible, subtract depth of streamflow out of the watershed, and the result will be ET.

Precipitation = Streamflow + ET +/- change in storage (assumed zero).
Using the streamflow number from the example in the box (rounded to 9 inches), a precipitation value of 30 inches, an assumed change in storage of 0, annual evapotranspiration would be 21 inches.

The value of the water balance exercise, even with all its inherent uncertainties, is that it provides a general idea of how much water comes into a watershed and where it goes, and it can indicate how precipitation input is transformed within the watershed. Obviously, with a more detailed water balance, these factors (e.g., fate of the water) can be estimated more precisely.

Good general reference books on hydrology for the non-hydrologist include Leopold (1974, 1993, 1997), Mount (1995), and Gordon, McMahon, and Finlayson (1992).

### 3.2.2 Surface Water

Many watershed assessments are conducted because of some perceived

**Table 3.1 An example of converting average annual stream flow to depth**

1 cubic feet per second for 1 year =
1 $ft^3$ / s x 3600 s / hour x 24 hours / day x 365 days / year =
31,536,000 cubic feet per year.

A useful (and very common) unit for water volume is the acre-foot, which is the volume of water that would cover an acre of surface area one foot deep. An acre is 43,560 square feet, so an acre-foot is 43,560 cubic feet (1 cubic foot = 7.48 gallons).

To convert the volume of streamflow above to acre-feet, divide by 43,560:
31,536,000 cubic feet per year / 43,560 cubic feet per acre-foot =
724 acre-feet per year

Finally, to convert the volume of streamflow to depth of water over your watershed, divide by the area of the watershed:

If your watershed is 1,000 acres in area:
724 acre-feet per year / 1,000 acres =
0.72 feet per year or 8.7 inches per year

problem with surface water (streams and lakes)—there's not enough of it, there's too much at the wrong time, its availability has shifted seasonally, or it is polluted, for example. Surface water also supports aquatic life—a primary issue driving many watershed assessments. Availability of surface water for supplying municipal and industrial uses, irrigation, and hydroelectric facilities is a major social and economic concern throughout most of California. Human demands for surface water resources resulted in the investment of hundreds of billions of dollars in infrastructure to store, divert, transport, and treat water from the state's streams.

The aspects of surface water typically addressed in watershed assessments are volume, timing, and quality. In most cases, water volume is not reported as sheer volume only, but rather as volume over some period of time. In streams, water is flowing—we can picture some volume of water moving past a fixed point in some amount of time. However, even where water isn't obviously flowing, as in lakes and reservoirs, the water level (and corresponding volume) go up and down, so time must be considered. Similarly, water stored as snowpacks or in the soil changes with time. But time is most obviously involved in streamflow, both at a particular moment and in changes throughout a storm or a year. Concerns about watershed condition are often raised when someone notices that the timing of streamflow appears to have shifted compared to some baseline in the past—streams seem to rise more quickly after a particular amount of rainfall, or spring snowmelt runoff seems to occur a couple of weeks earlier than it did a decade ago.

### 3.2.2.1 Streamflow Generation

A basic understanding of how rainfall or snowmelt is transformed into streamflow is important in evaluating how human activities may alter the processes that generate streamflow. There are many possible pathways by which a raindrop can reach a stream or be returned to the atmosphere without contributing to streamflow. The most direct route into the stream is for the raindrop to fall directly into the stream channel. However, stream channels occupy a small proportion (usually less than 1%) of the overall area of most watersheds, so most of the total rainfall volume falls on land. Vegetation or other surfaces cover much of the land area, so some of the rainfall is "intercepted" on leaves or other material above the soil surface and may evaporate. When rainfall exceeds the capacity of intercepting surfaces to store water, the excess drips or flows to the soil surface. Rain that arrives at the soil surface may "infiltrate" (pass through the surface into the soil), be stored on top of the soil surface in small depressions, or begin to flow downhill over the soil surface—these alternatives also interact over time and space. For example, water stored in small depressions may later infiltrate, or water flowing over the surface may infiltrate into more porous soil somewhere downslope. Some of the water flowing over the surface will collect in small channels that in turn join larger channels and eventually feed the main streams. Some of the water in the soil will move downslope below the surface and later enter a surface channel.

Human activities can alter the physical processes that generate streamflow in a variety of ways—removing or adding intercepting surfaces, such as vegetation and leaf litter, changing the "infiltration capacity" of the soil (ability of soil to absorb water), changing the storage capacity of the soil, changing the transmission capacity of the soil (ability of the soil to allow water to move through it), changing the ability of vegetation to remove water from the soil and release it to the atmosphere, changing the density of small channels that collect surface flow, for example. Compacting soil is a common result of foot and vehicle traffic that reduces the ability of the soil to absorb, store, and transmit water. As less water enters the soil, more water runs off into channels, thereby increasing streamflow over shorter time intervals than would occur in the absence of compaction. Sealing soil with concrete, asphalt, or buildings can prevent any water from entering the soil and causes almost all the rain to flow quickly to a stream. The amount or proportion of impervious (watertight) surfaces in a watershed is a common indicator of the degree to which runoff-generating processes have been altered. A watershed assessment should consider both how intense (for example, reducing infiltration capacity by 50%) and how extensive (for example, changing 30% of the surface area of the watershed) a particular alteration might be. A single parking lot may direct 90% of the rainfall that falls on its surface into a small stream, but if the lot occupies only 0.1% of the watershed area, the net impact on streamflow at the gaging station is negligible.

### 3.2.2.2 Streamflow Measurement

Streamflow is generally expressed as volume per unit of time, typically cubic feet per second. You may also see streamflow reported as cubic feet per day or acre-feet per year. Streamflow reporting must also include a particular time and geographical location. Streamflow changes from day to day (sometimes minute to minute), as well as up and down a stream channel. Knowing when and where streamflow is measured is critical to thinking about surface water.

Local water districts, hydroelectric utilities, the U.S. Geological Survey, and a few other entities measure streamflow at gaging stations, locations where the depth of water in a stream is measured and recorded at regular intervals (15 minutes is common) and where occasional manual measurements of water velocity and the area of the cross-section of the channel through which water is flowing have been made that allow a relationship to be developed between the depth and the flow. This relationship, known as a rating curve, allows calculation of the streamflow from the records of depth. A gaging station may cost tens of thousands of dollars to install and thousands of dollars per year to operate. These high costs explain the paucity of long-term streamflow records. USGS maintains the most accessible streamflow records (e.g., http://water.usgs.gov). Other streamflow records are available from the California Department of Water Resources (http://cdec.water.ca.gov/stainfo.html).

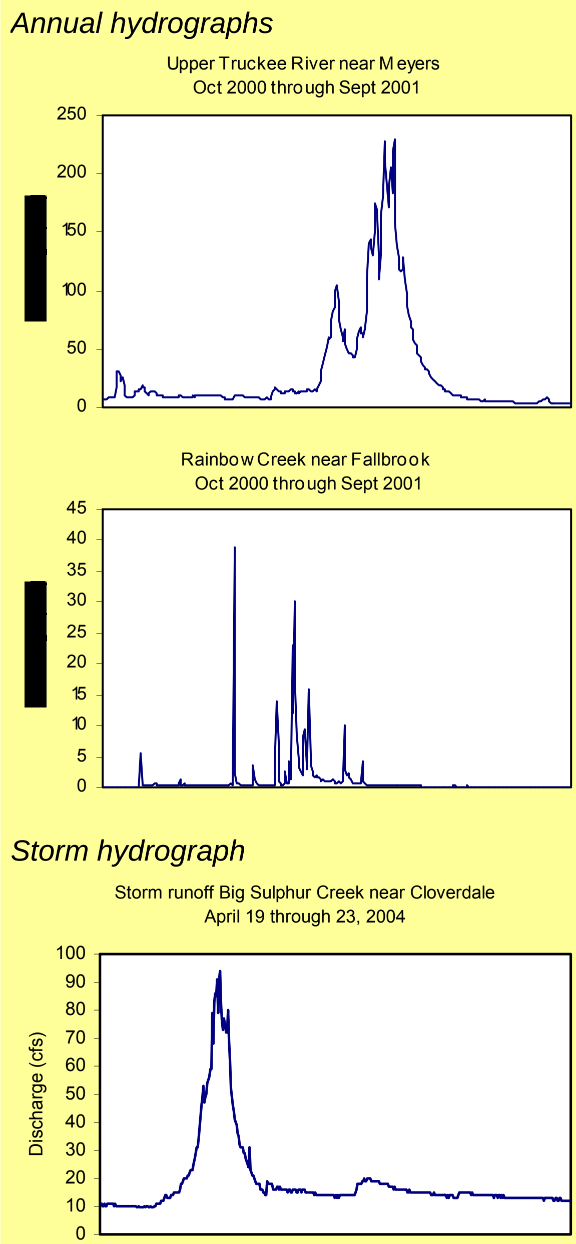


**Figure 3.1 Hydrographs**

In assessing streamflow data, important characteristics to consider include long-term averages, extremes of high and low flows, seasonal patterns, trends over time, and sudden changes (e.g., construction and operation of a diversion). A useful means of examining streamflow data to discern some of the above characteristics is plotting a stream hydrograph. Hydrographs plot streamflow over time. The most common type is an annual hydrograph (Figure 3.1) that depicts changes in flow over the course of a year. A storm hydrograph (Figure 3.1) that shows the rise and fall of a stream over a few days may be useful in assessing how your watershed responds to a rainfall input.

### 3.2.3 Subsurface Water

Water below the surface of the ground exists within the pore space (holes or voids) between or within the solid materials of the soil or rock. Subsurface water is commonly separated into one of two categories: soil moisture or groundwater. Soil moisture is found relatively close to the surface (generally within 10 feet, although there can be wide variation depending on soil characteristics and geology) and is usually in an unsaturated condition (the pores contain both air and water). In contrast, groundwater is found at greater depth and under saturated conditions (the pores contain only water or an insignificant amount of air). You may also see the terms unsaturated zone or vadose zone vs. saturated zone or phreatic zone.

#### 3.2.3.1 Soil Moisture

Soil moisture, the water in the pore space or openings between and within the solid parts of the soil, is a relatively active part of the hydrologic cycle. The water content can vary several-fold over a few hours to a few days. Precipitation that enters the soil can rapidly fill the available pore space. Irrigation adds additional water in agricultural fields. Soil moisture is withdrawn by plant roots and subsequently transpired. Water moves through the soil vertically and downslope (roughly parallel to the soil surface) and changes the localized water content en route.

Infiltration (the passage of water through the soil surface) is an important factor determining how watersheds transform rainfall into streamflow and is readily altered by human activities. The maximum rate at which water can enter the soil, known as the infiltration capacity, depends on both the physical properties of the soil and how much water is already in the soil. If the rate of rainfall is less than the infiltration capacity, then all the rainfall will be absorbed. If the rate of rainfall is greater than the infiltration capacity, then infiltration occurs at the capacity rate. The additional rainfall ponds on the soil surface and begins to flow downslope toward a stream channel. In general, the water flowing over the soil surface enters streams much faster than water flowing through the soil. Through the process of infiltration, soils greatly affect the volume of streamflow resulting from a storm, the timing of this streamflow, and the maximum rate of streamflow. In other words, soils can strongly influence the size and shape of the storm hydrograph. Infiltration can be easily changed (almost always decreased) by human activities, including compaction of soils by vehicles or livestock, removal of vegetation and leaf litter, plowing, burning, and covering the soil with an impervious surface such as concrete.

Water movement through the soil depends on the structure of the openings within the soil and the moisture content. The open space within the soil, which often accounts for 40% to 50% of the total soil volume, consists of small spaces between individual particles of soil; larger voids between clumps or aggregates of soil; tubes carved by worms, insects, and rodents; and holes left after roots have decayed. The size, shape, and degree to which these pores of various types are connected are primary influences on water movement within the soil. The rate of water flow generally decreases as the size of the pores decreases. Air within the pores restricts the flow of water, so as air is displaced by incoming water, the rate of water flow generally increases. Some soils with high moisture contents and large, well-connected pores or channels can transmit water downslope to a stream within a few hours after infiltration in a process called subsurface storm flow. Most water movement through soils occurs at a slower pace and contributes to the underlying groundwater or to a stream over a period of days to months.

#### 3.2.3.2 Groundwater and Aquifers

The term groundwater usually refers to water within the saturated zone of the subsurface where water fills all the pore space. A less formal use of the word sometimes refers to all water below the soil surface. This Manual uses the standard hydrological definition of groundwater, which is water in the saturated zone. Groundwater accounts for about 30% of California's water supply in an average year and about 40% in dry years (Department of Water Resources 2003). Even though groundwater is a slow-moving and slowly changing part of the hydrologic cycle, the role of groundwater in your watershed's hydrology and water resources management should be evaluated in your watershed assessment. Recommended introductions to groundwater hydrology include Heath (1983) and Department of Water Resources (2003).

Groundwater exists in geologic formations called aquifers that contain and transmit "significant" quantities of water. Use of the word "significant" is vague, but implies that aquifers can be used for water supply. An aquifer can be composed of hard rock or of unconsolidated materials, such as sand and gravel. Aquifers vary widely in the total amount of pore space filled with water and the degree of connectivity that allows water to flow between pores. Aquifers can be unconfined, where the water level is free to rise and fall with changes in water volume in the pore space. The top of water in the saturated zone is called a water table, and unconfined aquifers are also known as water-table aquifers. Other aquifers are confined by a relatively impervious layer that overlays the more permeable aquifer. Water in confined aquifers tends to be under pressure as a result of the confining layer acting as a cap, and the water will rise in a well that penetrates the confining layer.

Groundwater in unconfined aquifers flows from areas of higher elevation to areas of lower elevations or in the downslope direction of a sloping water table. In confined aquifers, the pressure is combined with the elevation to determine the direction and driving force of groundwater movement. Groundwater flow rates are also controlled by the aquifer's cross-sectional area permeability (capability to transmit water).

A water balance for a groundwater basin or an aquifer can aid in understanding the inflows and outflows of groundwater and the resulting changes in storage in a manner similar to a water balance for a watershed (section 3.2.1).

Groundwater storage remains fairly constant from decade to decade in relatively undisturbed watersheds that have little or no groundwater pumping. In smaller watersheds, groundwater storage may vary between seasons and between wet years and dry years. The subsurface water balance is readily affected by human activities—both indirectly and through active use and management of groundwater resources. Recharge of groundwater can be increased by excessive irrigation, filling of reservoirs, and artificial recharge with infiltration basins and injection wells. Groundwater recharge can be reduced by limiting infiltration, covering the soil with impervious surfaces, draining wetlands and lakes, reducing leaks from canals and pipes, and channelizing streams. The big variable under the control of people is groundwater extraction through wells. The number or density of wells, the depth of the wells, and the pumping rate of the individual wells all combine to control the volume of water extracted over a certain period of time. The condition of declining storage called “groundwater overdraft” occurs when more water is withdrawn by pumping than is recharged over a period of years. Groundwater overdraft has become common throughout most parts of California (Department of Water Resources 2003). As overdraft persists, pumping costs increase, wells need to be deepened or replaced, the land surface may subside and the aquifer’s storage capacity may permanently decline, remaining groundwater may become more brackish, and, in coastal areas, seawater may flow inland.

Surface water and subsurface water are thoroughly interconnected and exchange water back and forth across the ground surface in different parts of the watershed. Much of the interaction occurs within and adjacent to stream channels. At different locations along a channel and during portions of the year, water infiltrates through the streambed to recharge groundwater. At other locations and during other times of the year, groundwater may flow into the stream. Interchange of water between a stream and its bed can influence the temperature, dissolved oxygen content, and chemical composition of the stream. Interactions of groundwater and surface water can be difficult to observe and measure; the effects of these interactions on water supply and water quality need to be understood (U.S. Geological Survey 1998).

## 3.3 Climate

Regional climate exerts a controlling influence on a watershed’s hydrology by determining water and energy inputs. Precipitation provides the raw material that becomes streamflow or deep groundwater, or that is returned to the atmosphere through evapotranspiration. Energy (ultimately from sunlight) is needed to evaporate water and melt snow. Climate is usually considered the “average” weather of a region, including the variations between seasons and years and the known extremes. In conducting a watershed assessment, the most important aspects of climate to consider are precipitation, solar radiation, air temperature, relative humidity, and wind.

### 3.3.1 Precipitation

Precipitation is the water entering your watershed from the atmosphere as rain, snow, hail, and fog drip (cloud droplets captured by trees in sufficient quantity to form drops that reach the ground—it can be significant under coastal forests). Precipitation characteristics of greatest interest in assessing a watershed include annual average precipitation, variability from year to year, seasonal distribution, type (rain vs. snow), frequency of rainfall of different intensities, storm totals, and storm durations. Estimates of these characteristics can reveal, for example, how much water is available to the watershed in an average year and how that amount can vary, or whether multi-day, low-intensity storms are more typical than short-duration, high-intensity cloudbursts.

Precipitation over a watershed can be surprisingly variable, especially if the watershed covers an elevation range of more than a few hundred feet and is larger than a few square miles. Precipitation amounts from a single storm per unit area (e.g., acre) can range by two to ten-fold across a watershed. Variability of precipitation from a single storm (ignoring topographic influences) can be expected to be least in northwestern California, where most storms are widespread and can last several hours or days, and greatest in the southeastern part of the state, where highly localized thunderstorms may pass through in a few minutes. Several rain gages spread around a watershed would be desirable to assess the variability and obtain a reasonable estimate of watershed-wide precipitation. However, precipitation is routinely measured at only a few hundred locations throughout the entire state, so precipitation information for your watershed is likely to be sparse and may need to be inferred from neighboring areas.

### 3.3.2 Energy Exchange

Energy from sunlight is the driving force of the hydrologic cycle. Energy is absorbed, moved, released, and changed into different forms as water moves through the hydrologic cycle. “Energy exchange” is the common term for the various physical mechanisms involved in hydrologic processes such as evaporation and snowmelt. Most of these processes occur on water surfaces in contact with the atmosphere. Therefore, energy exchange is intimately linked to atmospheric processes and properties such as radiation, air temperature, humidity, wind, and precipitation. The physics of energy exchange are well beyond the scope of this brief introduction to hydrology, but the basics of energy on the earth’s surface can be found in any text on physical geography or hydrology. Two examples of the importance of energy exchange in the hydrologic cycle will be mentioned—evaporation and snowmelt.

Evaporation from open water or a wet surface or from within leaves of a plant (evapotranspiration) doesn’t just happen. Sufficient energy must be available and the air immediately above the surface must not be saturated (filled to capacity) with water vapor. Water loss to the atmosphere from both wet surfaces and plants (often lumped together in the term evapotranspiration) is greatest when solar radiation, air temperature, and wind speed are all high, and relative humidity is low. The amount of water loss (often termed actual evapotranspiration) is controlled by both the energy and atmospheric conditions (which can be used to calculate the potential evapotranspiration) and the amount of water available at the surface and in the soil that can be taken up by plant roots and moved to the leaves.

Snowmelt is another major result of energy exchange in the hydrologic cycle. Snow melts primarily in response to inputs of solar radiation. Properties of the snow surface, such as the size and shape of the snow grains and the presence of impurities (e.g., dust, pine needles), and the angle of the sun determine how much solar radiation is absorbed and how much is reflected. Snow melts slowly (if at all) in the winter when the surface is composed of new snow grains and the sun angle is low. Snow melts relatively rapidly in the spring when the surface is composed of large grains and debris and the sun angle is high. Another complicating factor is the conversion of sunlight (which has a relatively short wavelength) into longwave radiation. If sunlight is absorbed by a rock or tree, that object warms up and emits longwave radiation, which is completely absorbed by snow. An example of why this conversion can be important in a watershed assessment is the effect of forest harvesting. Trees shade the snowpack from sunlight. If half the trees are removed, more sunlight reaches both the snowpack surface and the trunks of the uncut trees, which in turn emit long-wave radiation to the snow. The combined effect of these changes in energy exchange is a marked increase in the rate of snowmelt. Relatively little snowmelt occurs directly in response to air temperature. The principal exception is when the air is saturated with water vapor and wind speeds are high—typically during warm storms when rain is falling on the snowpack

### 3.3.3 Climate Cycles

People have long been interested in forecasting the weather and have looked for repeating patterns or cycles in weather behavior that might offer clues about future weather. In early childhood, we recognize seasonal cycles of day-length, temperature, and precipitation. Other cycles of climate are not so easy to discern. In the late nineteenth century, geologists in Europe began to find signs of ice ages that indicated great swings of climate causing the growth and decline of continental-scale ice sheets. A few decades later, Milutin Milankovitch of Serbia calculated cyclic variations in the amount of solar radiation reaching the earth based on regular variations in earth-sun geometry. With rough intervals of 20,000, 40,000, and 100,000 years, these so-called Milankovitch cycles were later correlated with dozens of glacial advances. Over the past few decades, scientists around the world have searched for evidence of past climates in a variety of sources: sediment deposits in lakes and oceans, pollen, fossilized plankton shells, coral reefs, dust layers, tree rings, and, most successfully, in deep cores from ice sheets in Greenland and Antarctica. These various indicators of global climate, primarily air and ocean temperatures, have supported the regularity of the Milankovitch cycles, but have also suggested a complex array of feedback mechanisms involving carbon dioxide, reflection of sunlight by ice cover, sea level, biological processes, and other factors. The current consensus among climatologists seems to be that the slight changes in sunlight received at the earth's surface are strongly amplified by the other factors to trigger the cyclic ebb and flow of the ice sheets.

Besides the vast time scales of the ice ages, other apparently cyclical variations of climate have been observed within the average human life span. As the historical climate record incrementally increases, climatologists have greater opportunity to seek patterns within the record. One of the large-scale climate patterns that is widely discussed is the El Niño/Southern Oscillation (ENSO) phenomenon. Every few years, the ocean temperatures off the coast of Peru and sometimes thousands of miles to the west become unusually warm, generally beginning in December and persisting until June. This change in ocean temperature is associated with a calming of the trade winds near Indonesia and abnormally high air pressure over the western tropical Pacific Ocean and abnormally low air pressure over the eastern tropical Pacific (the Southern Oscillation part of the name). These changes in the ocean and atmospheric conditions alter the weather in regions far removed from the tropical Pacific, including reducing the number of hurricanes over the Atlantic and usually increasing precipitation in Southern California. During most El Niño winters, the jet stream and storms track across the southwestern part of the United States instead of across their more typical northern location. Because there are so many interacting factors that contribute to weather, El Niño conditions are not a sure thing for increased rainfall in California. Some El Niño years, such as 1965 and 1991, have been droughts. Conditions lumped under the name La Niña represent the opposite extreme of atmospheric and ocean circulation within the ENSO cycle.

Another large-scale ocean-atmosphere pattern recognized in the past few years is the Pacific Decadal Oscillation (PDO) that affects the northern part of the Pacific Ocean (Mantua et al. 1997). This cycle consists of two phases, apparently persisting for 20 to 30 years each. During a "positive" phase, the ocean along the west coast of North America is warm, and sea surface temperatures in the central north Pacific are cool. The relative temperature differences are opposite in the "negative" phase. The north Pacific is currently in a negative phase. The preceding positive phase lasted from 1977 to 1997.

Precipitation tends to be above-average during the negative phase in Washington and Oregon, with a less-distinct signal in Northern California. An analysis of a broad range of Pacific Northwest climate records extending over more than a century identified the ENSO and PDO cycles at five- to seven- and 20- to 25-year periods, as well as other apparent oscillations at two to three years and 50 to 75 years (Ware 1995). Still other weather patterns have been associated with 11-year sunspot cycles and 18-year lunar cycles.

### 3.3.4 Climate Change

Climate was widely regarded throughout most of the twentieth century as stable, with only minor variations around an average condition. Many climatologists held a philosophical belief that climate was self-regulating and, if perturbed (for example, by a huge cloud of volcanic ash), would "naturally" return to its average state. However, as weather records lengthened and indicators of past climates emerged from sediment and ice cores, coral reefs, and other sources, climatologists found signs of distinct trends, as well as signs of abrupt changes, suggesting that climate is not nearly as stable as was broadly accepted not long ago. In addition to the gradual swings between ice ages and interglacial warm periods over tens of thousands of years described above in section 3.3.3, recent theories suggest that average air temperatures have changed by several degrees over periods of a few decades following sudden shifts in ocean circulation (Committee on Abrupt Climate Change 2002).

Suggestions that human activities could alter the climate have been made for at least a century, but were largely ignored until the past two decades. In the late 1800s, Svante Arrhenius of Sweden calculated that the burning of coal could eventually increase carbon dioxide in the atmosphere and that doubling the concentration of carbon dioxide could raise global temperatures by 5-6$^{o}$C. In 1961, Mikhail Budyko, the famed Russian climatologist, published a warning that humans were warming the atmosphere through burning fossil fuels and other energy use. In 1971, Budyko provoked his colleagues by proclaiming that human-induced global warming was unavoidable. Two decades passed before these warnings were generally accepted in the climatology community. During the 1990s, physical evidence and modeling results rapidly accumulated for a strong case that human activities were changing the climate (Intergovernmental Panel on Climate Change 2001).

A variety of human activities that are extensive in nature, such as conversion of tropical forests, conversion of lands to desert, and production of dust and soot, are believed to affect atmospheric processes and feedback mechanisms. However, the generation of carbon dioxide from the burning of fossil fuels is the greatest and most immediate human influence on the atmosphere. Atmospheric measurements and calculations of carbon dioxide release from the quantity of oil, coal, and natural gas burned over the past century show a dramatic increase in carbon dioxide concentrations in the atmosphere over the past few decades.

Carbon dioxide, water vapor, methane, and a few other gases affect temperature in upper layers of the atmosphere by absorbing some of the longwave (infrared) radiation emitted by the earth (all objects emit radiation in these "long" wavelengths in proportion to their temperature). The gas molecules warm and re-emit longwave radiation in all directions, including back toward the earth's surface. The role of these gases in reducing the loss of longwave radiation, especially at night, was recognized 140 years ago by John Tyndall. Although these gases do not function in the same manner as the glass of a greenhouse (which traps hot air rather than radiation), the term "greenhouse gases" and "greenhouse effect" are now commonplace, even in scientific literature. Increasingly complex mathematical models of atmospheric processes have calculated temperature increases associated with increasing concentrations of greenhouse gases. Most current estimates of global average temperature rise associated with a doubling of carbon dioxide concentration relative to pre-industrial levels (280 parts per million) are in the range of 1.4° to 5.8°C (Intergovernmental Panel on Climate Change 2001). A recent modeling study using a fine-scale regional climate model suggests a temperature rise of 1.4° to 3.8°C in California for a doubling of carbon dioxide (Snyder et al. 2002).

Water supply agencies in California have been concerned about the potential effects of climate change on the state's water resources for almost two decades. Most agency and researcher attention has focused on changes to the snow hydrology of California's mountains. A recent synthesis of research results noted, "Higher temperatures will have several major effects: increase the ratio of rain to snow, delay the onset of the snow season, accelerate the rate of spring snowmelt, and shorten the overall snowfall season, leading to a more rapid and earlier seasonal runoff" (Kiparsky and Gleick 2003:9). Other expected consequences of climate change in California include increases in average annual precipitation, greater variability in precipitation, increased storm intensity, increased evapotranspiration, and changes in vegetation cover (Kiparsky and Gleick 2003). Evaluations of these and other possible hydrologic effects of climate change and how water agencies, communities, farmers, businesses, and natural systems will accommodate or respond to those effects should be included in a watershed assessment.

## 3.4 Flooding and Stormwater Runoff

Flooding is a natural attribute of rivers. Flooding is defined as flow that exceeds the capacity of the channel, i.e., when flow inundates the floodplain. A flood is a streamflow event where there is more water flowing in the stream than the channel can handle. Under these flood conditions, water spills over the streambanks onto the adjacent floodplain, which can be considered as part of the natural channel that is periodically used by the stream and that has been constructed by the stream over millennia. Floods represent the upper extreme of runoff generation and produce most of the sediment erosion, transport, and deposition within a watershed.

Stormwater runoff is the "excess" rainfall that exceeds the infiltration capacity and flows over the ground surface. It is the portion of runoff that causes the initial rise in a storm hydrograph and usually causes the peak flow in the receiving stream. In the urban context, stormwater runoff often contributes to flooding because the streets, parking lots, and storm drains generate far more (often 10 to 1,000 times more) surface runoff than would have occurred prior to development and paving. The collection and conveyance of stormwater runoff in efficient storm drains also delivers water to streams much faster than a natural channel would. Therefore, the lag between rainfall and runoff is greatly reduced, and the peak flow is usually increased. The creation of large impervious surfaces and storm drains in urban areas may generate flooding (overbank flows onto the floodplain) from much smaller storms than would have occurred in the absence of development.

### 3.4.1 Flooding Frequency

In a very broad sense, streamflow exceeds the capacity of a stream's channel and rises above its banks about every 1.5 to 2 years, on average. However, this frequency must not be considered as a consistent interval. It is better to think that streamflow will rise to the "bankfull stage" and inundate the floodplain whenever there is sufficient river flow. Overbank flow occurs every year on some rivers, and infrequently on other rivers. On average, flow rises to bankfull about 50-65 times in 100 years, or in any given year, there is a 50% to 65% chance that flow will equal or exceed bankfull capacity.

As floods get bigger, they occur less frequently. Accordingly, a magnitude-frequency relationship can be estimated on streams with long-term flow records, or more crudely estimated given flood data elsewhere in the general region. A flood of a particular magnitude is often described as a 10-year, 25-year, or 100-year event. The concept behind this type of description is that a flood of the given magnitude occurs once in the particular time period, on the average. However, the “on the average” part is often ignored, so we recommend thinking that a big flood (for example, a 100-year event) occurs 10 times in 1,000 years, or that there is a 1% chance that such an event could occur in any given year. But these ways to describe floods are merely statistical constructs. There is no physics (or physical hydrology) involved. The combination of conditions that generates large floods just doesn’t happen very often. However, there is no physical reason why two floods of some very large and rare magnitude couldn’t happen in the same year or three years apart or 200 years apart. All these statistical descriptions of flood magnitude and frequency involve an assumption of “stationarity”—that climate, landscape, channel, and measuring conditions won’t change. However, that assumption is obviously flawed, particularly as time periods of analysis lengthen.

### 3.4.2 What Causes Flooding?

Beyond the usual magnitude-frequency characterization of floods, watershed assessments must also consider the physical mechanisms of flood generation—the hydrologic processes involved in producing an overbank flow event. In general, an unusually large amount of rainfall or unusually intense rainfall is required to produce a flood. But other factors can contribute to or influence flood magnitude and timing. For example, a previous storm may have left the soil saturated or a wildfire may have reduced the infiltration capacity. Human activities may also influence factors that cause or augment flooding. For example, deforesting an area minimizes transpiration, resulting in greater soil moisture. In turn, there is less available storage capacity in the soil to absorb rainfall, and more of the precipitation quickly enters a stream channel. Construction of forest roads compacts soil and drastically reduces infiltration, which, in turn, leads to greater and faster surface runoff.

In urban areas, much of the landscape is converted to impervious surfaces (e.g., streets, parking lots, and rooftops). Most of the resulting stormwater runoff is directed into storm sewers that empty into stream channels and deliver much greater quantities of water at much faster rates than occurred under natural conditions. Urban stream channels may also be confined by levees, bridges, construction, and debris in the channel. Reduction of the channel capacity forces water to rise and spill over the banks at lower flows, which the natural channel could have handled. Very often, the floodplain is occupied by houses and various structures that reduce flow capacity and further augment flood damage.

## 3.5 Geology, Soils and Sediment in Watersheds

California’s watersheds span 11 geomorphic provinces—each with distinct geology, tectonic setting, topography, climate, soils, hydrology, vegetation, and land use history (Figure 3.2). These factors combine in complex ways, causing each watershed and each sub-watershed to be unique. This Manual describes approaches toward understanding physical processes and changes over time that alter sediment dynamics and linkages in California’s diverse watershed systems. Every watershed has a natural disturbance regime—or a combination of factors that influence how and why geomorphic processes, such as sediment erosion and deposition, change. In many cases, humans accelerate or alter these natural processes, in turn altering ecosystem dynamics that depend on these processes.

### 3.5.1 Geology

The physical character of watersheds is dependent on processes acting on the underlying material over time. The lithology (rock type) underlying a watershed influences hillslope stability, erosion processes and rates, and the background-level sediment supply to rivers. Watersheds underlain by resistant bedrock supply less sediment to rivers than do watersheds underlain by erosive material. The highly erosive Franciscan Formation, a geologic unit representative of California's tectonic history, underlies watersheds with extremely high erosion rates. The high erosion rates translate to high rates of sediment supply to rivers—the Eel River, for example, has the highest suspended sediment yield in California.

California is influenced by active tectonics (forces that deform the earth's crust) that create a diversity of watershed morphologies (shapes) such as the high relief and rugged topography in mountain ranges like the Sierra, Klamath, Transverse and Peninsular, and Coast. These tectonic forces also create lowland areas, such as the Central Valley and the San Francisco Bay-Delta Estuary. The different topography in California's geomorphic provinces, coupled with climatic and vegetative variation, lead to differences in the dominant processes of erosion and sediment transport. For example, in the Southern California Transverse Ranges, chaparral-vegetated watersheds have a semi-arid Mediterranean climate, and dry ravel (dry sliding of sediment under the force of gravity) or fluvial (channel and floodplain) processes commonly transport sediment following wildfire, while infrequent high-intensity rainfall produces debris flows (Florsheim et al., 1991). In contrast, in coastal streams in the relatively humid northern Coast Ranges, episodic erosion in forested watersheds produces sediment through processes such as debris flows, earth flows, and debris slides. Understanding the influence of watershed geology on the dominant erosion and sedimentation mechanisms throughout California is critical in distinguishing natural processes and the natural disturbance regime from anthropogenic (human-caused) disturbances and land use-caused changes.

Geomorphic Provinces of California (after Norris and Webb, 1990; Harden 1998)

**Figure 3.2 Geomorphic provinces of California**

### 3.5.2 Soils

Soils form through interactions of physical, chemical, and biological processes. They are important as a resource for California agriculture and as the growth medium for vegetation throughout the state.

A soil profile includes layers, called "horizons", of mineral and/or organic constituents of variable thickness that differ from the parent material in morphology; physical, chemical, and mineralogical properties; and biologic character (Figure 3.3).

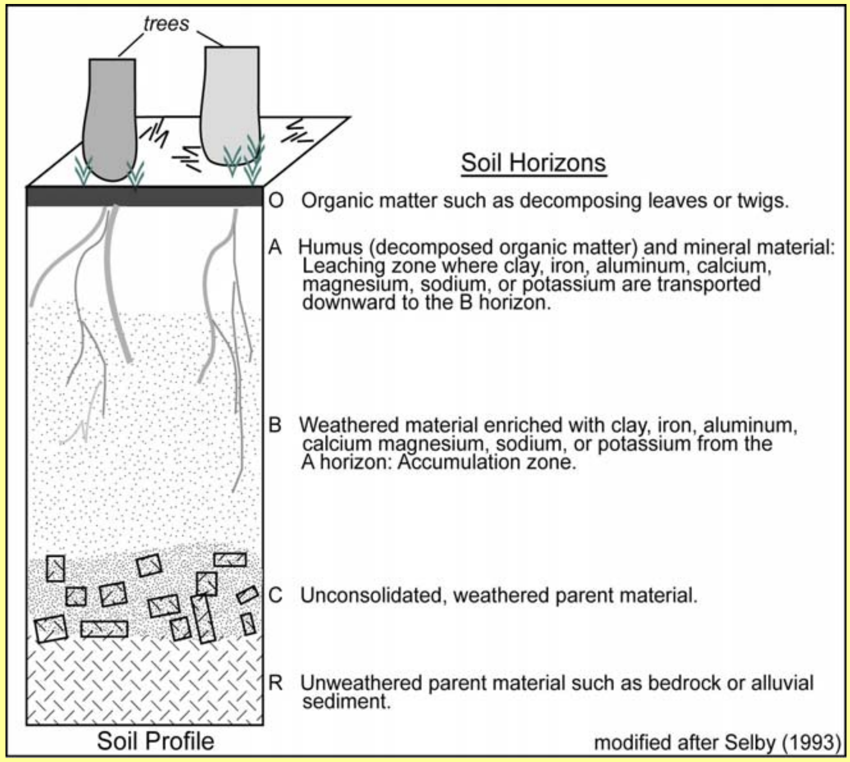


**Figure 3.3 Soil profile**

Soil development is dependent on geologic properties, such as bedrock lithology and topography, climate, vegetation and other organisms, and time. Soils exist in various degrees of development. For example, thin, poorly developed soils may not contain a B horizon (Figure 3.3), and in other locations, soils may not have formed at all.

Land use activities may accelerate surface erosion of soil where vegetation and its binding root structure are removed. In such cases, this additional contribution of fine sediment to rivers raises the suspended sediment load and turbidity, and aquatic habitat may become degraded. Other land use activities compact soils or pave them over, reducing the water's ability to infiltrate between soil particles during storms. In this case, a reduction in infiltration leads to increased surface runoff and erosion in downslope areas.

### 3.5.3 Hillslope and Fluvial (Channel and Floodplain) Processes and Morphology

Geomorphologists are scientists who study earth surface processes and landforms, including landslides on hillslopes or erosion and sedimentation in rivers. Geomorphologists take a "watershed approach" to assessment and planning that recognizes that within a watershed, everything is connected. The connectivity and linkages between hillslope and channel and floodplain systems are important in controlling the input of water, sediment, woody material, and other constituents that determine the character of river and floodplain morphology and ecology. Connectivity between hillslopes and floodplains and between hillslopes and channels provides a direct route for sediment to the fluvial system. Connectivity from tributaries to downstream channels is sometimes interrupted by dams that trap sediment, whereas increased upstream erosion from various land uses sometimes supplies too much sediment that fills in downstream pools and estuaries.

On a watershed scale, geomorphic processes are affected by upstream controls, such as climate, geology, topography, land uses, and vegetation, and downstream controls, such as changes in sea level (baselevel). Throughout the watershed, areas of erosion and sediment storage are continually in flux in response to storms that create hillslope runoff, river flow, and floods. Sediment transport, or "routing," through a watershed does not occur at a constant rate. In California, the episodic nature of hydrologic processes dictates rates of sediment erosion, transport, and deposition. So while average rates of geomorphic change are sometimes useful, predicting the possible range in magnitude of change is essential for planning purposes. For example, estimating an average magnitude and rate of channel bed erosion may describe long-term river channel changes. But actual changes occur episodically during individual events. Thus, during some storms, there may be substantially more geomorphic change than the average amount, while at other times, there may be less. This variation in rates and magnitudes of processes is a normal part of California's rivers and should be recognized and accommodated in order to minimize hazards and maintenance and to maximize habitat and safety.

#### 3.5.3.1 Sediment Erosion and Transport on Hillslopes

Erosion is a natural process that loosens and removes sediment from hillslopes or the channel bed and banks. Erosion and transport occur by physical and chemical weathering, abrasion, or entrainment of particles by running water. Hillslope erosion processes include rain splash, overland flow, incision of rills and gullies, and a broad category of processes called mass wasting, which includes landslides and debris flows. Features created by mass wasting are classified depending on whether they occur in bedrock or soil, whether they occur in unconsolidated or consolidated materials, and by their water content and rate of movement (Varnes 1958). A complete description of types of mass movement process types is contained in Selby (1993). Additional detailed descriptions of mass wasting processes are included in Ritter et al. (1995) and in other watershed assessment guides such as Appendix A of the Washington Forest Practices Board Manual (Washington State Department of Natural Resources, 1997) and in the Sediment Sources Assessment Chapter of the Oregon Watershed Enhancement Board Watershed Assessment Manual (Watershed Professionals Network, 1999).

Mass movement on a hillslope occurs when the forces resisting movement are overcome by the driving forces. This threshold may be crossed due to intrinsic processes, such as weathering over time, or by extrinsic factors, such as high-intensity rainfall. While the hillslope erosion processes that shape the landscape over time are natural, human activities may lower the erosion threshold and reduce the time it takes for sediment generated on hillslopes to reach channels.  Moreover, human activities may reduce hillslope resistance to erosion, concentrate runoff, or increases slope moisture. These responses may result from activities such as removal of vegetation and root networks, or hillslope grading for road construction. Understanding how human activities affect hillslope stability and the connectivity between hillslopes and channels is critical in watershed assessment.

#### 3.5.3.2 Erosion, Transport, and Deposition Processes in Rivers: Interactions with Morphology

As water flows in river systems, it interacts with the bed, banks, and floodplain. This interaction is affected by the size of the particles on the channel's bed, the shapes of the channel and floodplain, vegetation, and structures, such as bridges or bedrock, protruding into the channel.

During floods, flow strength increases to the point where a river gains the ability to move sediment particles on its bed, banks, or floodplain. Flow strength is an important measure of the ability of a certain magnitude of flow to move sediment. Geomorphologists measure flow strength along the interface, or boundary, between the flow and the channel or floodplain. The point where flow strength is large enough to lift particles off the channel bed and transport them downstream is called the"

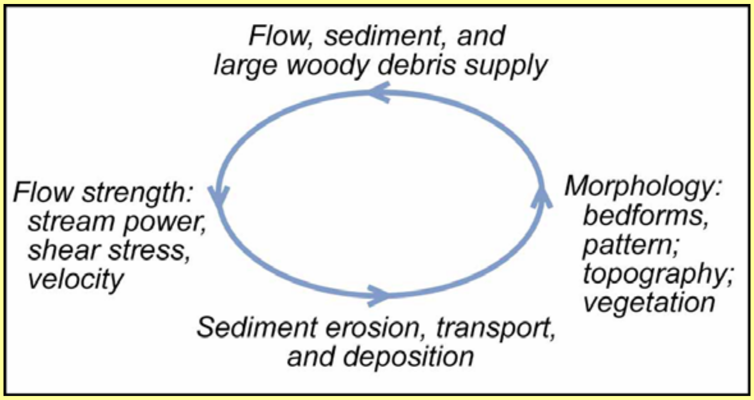


**Figure 3.4 The geomorphological cycle**

threshold of entrainment." Above the threshold, the bed material begins to move in the direction of flow. In rivers, sediment transport from upstream to downstream maintains the shape and pattern of channels, or "channel morphology," and is one of the most important processes in creating the form of the watershed landscape.

Channel bed lowering, or "incision," occurs when individual grains are mobilized from one portion of the river, but not replaced by sediment transported from upstream, or when a river's ability to transport sediment is greater than the sediment supply. Deposition occurs when the flow strength during a flood decreases below the threshold of entrainment, or when the supply of sediment is greater than the river's ability to transport it downstream.

Figure 3.4 depicts the interactions between flow, sediment, and vegetation as a dynamic cycle because each element interacts with the others, mutually adjusting to changes in the system. Stream power, shear stress, and velocity are measures of flow strength and represent the force needed to entrain and transport sediment. In turn, sediment erosion, transport, and deposition are the dynamic processes that create and maintain channel morphology. The channel's morphology and the floodplain's topography form the physical structure of habitat. Every flood has the potential to modify channel morphology and riparian vegetation, providing a supply of sediment and large woody material to downstream areas. The cycle continues as flows with the strength to entrain and transport sediment further downstream act on these elements.

The streambed itself is biologically active, providing shelter for many aquatic organisms. For example, freshwater crayfish and dragonfly larvae occupy the spaces between and beneath gravel and larger-sized sediment. A mix of gravel with small amounts of cobbles and fines (sand, silt, and clay) provide optimum spawning substrate for trout and salmon. The substrate size these organisms depend upon may differ, but those native to streams with good water quality are harmed by excessive fine-sized sediment. Streambeds covered with silt or clay-sized sediment cannot maintain the exchange of water and air from the surface to the pore spaces between the gravels. This subsurface flow is essential because it replenishes oxygen and nutrients and removes wastes. Sensitive organisms, like mayfly larvae and trout eggs, can suffocate or get trapped under finer sediment layers. Over time, the fish and aquatic insect species occupying a sediment-impacted stream may shift toward less sensitive species, like midge-fly larvae (Gordon et al. 1992)

Depending on the size of sediment particles relative to flow strength, sediment moves in channels and on floodplains along the bed (bed material load), in suspension within the flow (suspended load), and as solutes (dissolved load). Mobilization of bed material during floods maintains the quality of substrate (the base upon which organisms live) habitat for aquatic invertebrates and fish that spawn in river gravel by flushing out finer clay and silt. A critical issue in maintaining aquatic habitat is preserving the balance of coarse to fine particles. An oversupply of fine sediment, from soil erosion, for example, may cause a fining trend that overwhelms the natural processes that bring the system back to balance. Watershed assessment helps determine the natural range of variability in substrate size and can help identify the watershed conditions responsible for substrate changes over time. The disturbances caused by erosion, sediment transport, and deposition during floods are a requirement for ecological sustainability in dynamic rivers; thus, watershed assessment should consider the benefits of these natural processes and changes.

Bank erosion is a natural process that occurs due to the force of water against the bank. The rate of bank erosion depends on such factors as the resistance of bank material and the presence of vegetation. Riparian plants' root systems promote bank stability. Dynamic rivers maintain their morphology through erosion and sedimentation, and the disturbance caused by removing vegetation from one area and creating new bare patches promotes riparian succession. If these natural processes, called "disturbances" by ecologists, knock the system out of balance, other natural processes acting as feedback often restore the system to a new balanced state. These natural disturbances are essential for sustaining ecosystems. In contrast, chronic or pervasive disturbances caused by human activity may continue to cause instability over time, or may knock the system off balance to the extent that it cannot achieve a new balance.

Bank erosion is a type of disturbance that is an essential part of a functioning ecosystem, but it becomes a hazard when human activity encroaches on the width the river requires to accommodate natural processes. Human activity that removes riparian vegetation and its binding root network will accelerate bank erosion to the extent that the system may attain its former balance. Contributing to this cycle, many human interventions that are intended to stop bank erosion actually promote erosion in other areas by deflecting the force of flow or by generating turbulence around hard edges of the structure.

#### 3.5.3.3 Flooding and Sediment

Flooding (often called the "flood pulse" by ecologists) is a natural attribute of rivers. Most sediment erosion, transport, and deposition occur during floods. Flooding, defined as flow that exceeds the capacity of the channel, occurs when flow inundates the floodplain. Infrequent large floods reconfigure channel morphology and maintain or create side channels and floodplain topography. Moderate floods maintain channel bedforms and spur the

***"Dominant" Discharge***: the range of flow magnitudes that determines channel cross section width and depth (Wolman and Leopold, 1957).

***"Bankfull" Discharge***: the flow magnitude that is contained within a channel without overtopping its bank (Leopold et al., 1964).

***"Effective" Discharge***: the range of flow magnitudes that transports the majority of a river's annual sediment load over the long-term (Wolman and Miller, 1964). In a gravel bed stream, this is the discharge that transports the greatest quantity of bedload.

In some alluvial rivers, the dominant, bankfull, and effective discharge are equivalent, and generally correspond to frequently occurring flow magnitudes. However, this assumption is not valid in all rivers, for example in disturbed channels or rivers in semi-arid or arid environments.

evolution of river channel pattern. Frequent small floods sustain ecosystem function. The relation between floods and sediment in watersheds depends on the connectivity in the longitudinal, lateral, and vertical dimensions. Human activities alter connectivity in numerous ways. For example, in the longitudinal dimension, dams trap sediment and reduce supply to downstream reaches; in the lateral dimension, levees concentrate flow into one main channel and limit connectivity between rivers and their floodplains; in the vertical dimension, an influx of fine sediment in a gravel bed river infiltrates into the spaces between larger sediment particles and reduces the oxygen supply to anadromous fish eggs.

The shape of natural alluvial channels is adjusted to accommodate a range of frequently occurring floods. This range of flood magnitudes is often is simplified to a single discharge called the "dominant discharge." The dominant discharge is defined as the flow responsible for creating the characteristic width and depth of the channel and is sometimes equivalent to the flow that transports the majority of sediment over time. This important definition stems from a comparison of the magnitude and frequency of a range of sediment transporting floods conducted by Wolman and Miller (1960). The magnitude-frequency concept suggests that in many rivers, moderate sediment transporting floods that occur frequently are most effective in transporting sediment over time, in contrast to larger floods that transport large volumes of sediment, but that only occurs infrequently. Thus, a large flood that erodes and deposits sediment may alter channel morphology in the short term, whereas frequent small floods approximately equal to the flow that governs channel shape and size over the long-term. Leopold et al. (1964) found that the shape and size of many natural alluvial channels is adjusted to a flow that fills the channel from bank top on one side of the channel to the other side. They found that the "bankfull" flow has an average recurrence interval of about 1.5 years, often ranging from about 1 to 3 or more years.

The importance of these concepts to watershed assessment is the recognition that in addition to the large floods that typically receive attention, small to moderate floods are capable of channel change. In fact, floods contained within a natural channel are significant in creating and maintaining channel morphology and associated riparian and aquatic habitat as are larger overbank floods to other aspects of channel morphology and to floodplains. Altering the prevailing relationships between sediment supply, transport, and discharge magnitude, frequency, and duration will alter the shape of a channel through erosion and sedimentation processes. Care should be taken when applying these concepts to disturbed channels or to rivers in semi-arid or arid environments. For example, in an incised river, the bankfull discharge may be significantly larger than the effective discharge. In semi-arid environments where vegetation is sparse, the characteristic channel morphology may be formed during large infrequent floods rather than smaller floods that occur frequently.

### 3.5.4 Morphology

The dynamic interaction between water, sediment, vegetation, and woody material creates the shape of the channel and floodplain referred to as "morphology." Because of the continual changes in water and sediment supply and transport, morphology is not a static feature in fluvial systems. Rather, morphology is dynamic and changes in response to erosion and sedimentation during the range of flow magnitudes. Conserving and accommodating or allowing dynamic morphology is a key to preserving riparian ecosystem diversity.

Whereas the morphology (shape) of river channels along the profile from the headwaters to estuaries forms a continuum that incorporates considerable variability, classifications of these morphologies help identify the dominant processes responsible for their formation and help in the characterization of fluvial systems needed in watershed assessments. A number of books that contain descriptions of morphology and the processes that create and sustain fluvial landforms are included with the references at the end of this chapter.

*Channels*

Channels begin in the headwaters of watersheds because of springs, seepage erosion, or overland flow in gullies. Some channels begin in association with hillslope processes near ridge tops in swales called "colluvial hollows" (Dietrich et al. 1986). Headwater channels are usually steep and narrow and contain bedrock or boulders. They are directly influenced by hillslope processes. Headwater streams are extremely important ecological zones (Meyer et al., 2003) as they provide water, sediment, nutrients, and energy into the system. In forested northwest California, morphology in headwater streams is greatly influenced by large woody debris (Keller & Swanson, 1979; Montgomery et al.,1996).

The morphology along the longitudinal profile of a riverbed contains a continuum of morphology called "bedforms," (Table 3.2) which adjust to the flow and sediment supply. This bedform continuum changes longitudinally with the capacity of the river to transport sediment and as slope, particle size, and roughness decrease, and channel width and depth increase. The bedform continuum is often simplified by geomorphologists in a hierarchical classification that includes cascades, step-pools, plane-beds, riffle-pools, and dune-ripples (Montgomery & Buffington 1997) that describes the physical characteristics of the channel bed. Fish biologists use other classifications that describe the way fish utilize bedforms, e.g. riffle-pool, glide, and run.

The type of bedform present is a reflection of the location within the watershed and the physical processes active in the fluvial system. Most importantly, aquatic organisms utilize specific micro-habitats formed by bedforms, such as riffle-pool sequences, and other aspects of physical habitat, such as overhanging banks, for various portions of their life cycle. Understanding the type of bedform that is characteristic of a certain portion of a river is required before assessing the effects of human activities and before predicting the type of bedforms that may be stable during restoration of disturbed systems. Land use activities may affect the bedform continuum through alteration of channel slope, channel width and depth, particle size distributions, pool depth and frequency, and water and sediment discharge. For example, channelization often obliterates bedforms that created heterogeneity of aquatic habitat needed in functioning riparian ecosystems.

Whereas understanding the processes and physical conditions necessary to sustain characteristic river bedforms is a necessary component of watershed assessment, by itself, bedform classification does not give a complete picture of aquatic habitat in many

**Table 3.2 Types of bedforms**

Bedforms are associated with the type of bed material (bedrock, boulders, gravel, or sand) and the slope of the channel, among other factors.

***Cascade*** – bedrock or boulder bed, slope greater than 0.08;
***Step-pool*** – boulder bed, slope greater than 0.02 (<0.08);
***Riffle-pool*** – gravel bed, slope greater than 0.01 (<0.02);
***Dune-ripple*** – sand bed, slope less than 0.01.

Modified after Montgomery and Buffington (1997) watersheds. Bedforms describe the longitudinal changes in morphology of a channel. However, to understand the interactions of a river with its banks and with its floodplain (when present), geomorphologists also investigate river channel pattern, the shape of the river when viewed from above.

*River Pattern*

Classifications of river pattern usually define four endpoints in order to simplify the continuum of river morphology. Straight, meandering, and braided patterns refer to the channel, while the anabranching pattern that contains multiple channels must be considered in the context of a floodplain, described further below.

“Straight” patterns occur in channels without bends and are sometimes associated with geologic or structure control. Channelized rivers are often straightened in order to increase flow velocity for flood control, whereas, natural channels are not usually straight over long distances.

“Meandering” patterns occur in channels that contain bends that evolve through a combination of bank erosion on the outside of bends and sediment deposition on the inside of bends. These processes lead to meander migration, the movement of a channel across its floodplain through erosion and deposition. Understanding natural processes of meander migration is important in order to anticipate the effects of human interventions. For example, using hard structures, even the rock and large woody debris that are often promoted as a natural way to prevent bank erosion, inhibits meander migration and may lead to erosion in a different area as the river adjusts to its imposed pattern.

“Braided” patterns occur when flow splits around in-channel bars. Braided patterns are common in streams with high sediment loads and high slope, and they tend to be very unstable.

“Anabranching” rivers have multiple channels separated by islands (composed of the same material as the floodplain, in contrast to braided rivers, where flow splits around in-channel bars). In anabranching rivers, the dominant geomorphic process is “avulsion,” or the dynamic switching of channel location through a breach in a naturally formed or engineered levee. The anabranching pattern is typically found in low-gradient rivers with floodplains. It was common in many lowland California rivers prior to the construction of levees that concentrated river systems into single channels.

Documenting and understanding the effect of human activity on channel pattern are critical in predicting potential future river-system processes, especially in restoration activities.

*Floodplains and Estuaries*

Floodplains are integrally linked to their channel systems, and separating floodplain morphology from channel morphology is an artificial distinction. Floodplain classification is based on stream power and sediment particle size in the adjacent channels (Nanson & Croke 1992).

Floodplains contain a diverse assemblage of sediment deposited by a variety of processes that occur during floods. One process, vertical accretion, occurs as overbank flow brings fine material suspended in the water onto the floodplain. This fine material is deposited in zones of low flow strength that may occur where vegetation slows flow. Other vertical accretion processes include deposition in “crevasse splays,” or sand splays, fan-shaped deposits of sand that occur as a river breaches a natural or artificial levee, scours an area immediately adjacent to the breach, and deposits its sediment load over older floodplain sediment. Another process, lateral migration, occurs as sediment is eroded on the outside of bends and is deposited on the inside of downstream channel bends. Over time, the channel migrates in the direction of the eroding channel bank, leaving behind a bar on the inside bend, called a point bar, that continues to build in height until only overbank floods are deep enough to inundate and deposit sediment in that location. Floodplains contain a stratigraphic record documenting variability in these processes over time. Prior to their development for agriculture or other land uses, floodplain surfaces contained topographic relief that created high and low areas supporting diverse ecosystems

Many rivers in California form estuaries, a biologically rich ecotone (transition zone) where freshwater and saltwater mix in the portion of a watershed farthest downstream from the headwaters. The San Francisco Bay-Delta Estuary in California is the downstream portion of the large Sacramento-San Joaquin River watershed. Smaller California watersheds also contain important estuaries, such as the Klamath River Estuary to the north and the Tijuana River Estuary to the south, and the Navarro, Garcia, Russian, and numerous other small estuaries in between. Estuaries are affected by sediment deposition, dredging, subsidence, shoreline stabilization or alteration, and changes in upstream watershed flow and sediment regimes. For example, an increase in a river's sediment load may fill in an estuary, while a decrease in river flow may increase salinity.

### 3.5.5 Sediment Budget Framework

A sediment budget is a mass balance of sediment supply, storage, and yield over time (Reid & Dunne, 1996). Specific components of a sediment budget may be used to address the effects of natural processes or human-cause disturbances (Reid & Dunne, 1996).

The sediment budget is useful to account for watershed sediment through the relation:

$$I - O = \Delta S$$

Where I is the volume of sediment input, O is the volume of sediment output or yield, and $\Delta S$ is the change in sediment storage over a particular time period.

Sediment input, or supply, is a measure of the material produced by hillslope mass movement and upstream channel bed and bank erosion. Sediment storage is the sediment in channel bedforms and bars, the floodplain, and terraces. The output, or "yield," from a basin is a measure of the sediment leaving the watershed. The time period over which the sediment budget is relevant must be defined based on the timeframe of the input data. Because sediment erosion, transport, and deposition are dependent on the magnitude, frequency, duration, and intensity of storms, the components of the sediment budget must be placed in the context of California's episodic flood regime.

A sediment budget generally provides an order of magnitude estimate of sediment volumes produced, stored, and transported through a watershed. Although exact quantification is usually not possible, the sediment budget is a useful framework for identifying important processes and the linkages between processes that affect sediment in a watershed. The sedimentation rate and residence time of sediment in storage is critically important and can be addressed through watershed assessment to evaluate the effects of land use changes. Moreover, a sediment budget may be used to document changes in connectivity, such as loss of sediment supply following construction of a dam.

## 3.6 Water Quality

Water quality encompasses the physical and chemical characteristics of water in waterways or in water entering a waterway. Aspects of soil and atmospheric water quality are not included here, although the geochemical cycles occurring in the atmosphere and the soil and geology of a watershed are critical controlling forces in determining the quality of water in streams. Measuring water quality is important in assessing watershed condition because "changes in water quality indicate a change in some aspect of the terrestrial, riparian, or in-channel ecosystem." (Naiman et al., 1992). Water quality is one of the primary measurable, non-biological indicators of watershed condition.

This section covers legal and regulatory issues, but first provides information on key scientific concepts related to water quality. These include:

- Classes of contaminants
- Major effects of the contaminants on aquatic life
- Information on evaluation of chemical contaminants in water

Protecting or improving water quality often includes protecting and restoring natural functioning to watersheds. Activities related to understanding impacts to water quality often involve figuring out where in the watershed impacts are occurring. According to the U.S. EPA, nonpoint source pollution is "pollution from numerous widespread locations or sources that have no well-defined points of origin. The pollution may originate from land use activities and/or from the atmosphere. Examples include leaching of excess fertilizer from fields and acid rain." In contrast, point source pollution comes from a specific, identifiable source or site. In many places, nonpoint source pollution is the primary source of water quality problems.

The concept of water quality is embedded in federal (Clean Water Act, CWA, 1973) and state (Porter-Cologne Act) law, which require that state agencies and permittees meet certain standards for managing chemical inputs and other forms of pollution that might impact "beneficial uses." Beneficial uses generally refer to the "fishability," "swimmability," and "drinkability" of water, but also include protection of aquatic life and habitat.

If water quality is impaired or threatened with impairment from point or nonpoint sources, then the state is legally required to act to protect or improve water quality. The USEPA provides guidance and regulatory requirements for the state to act under the Clean Water Act while the state implements programmatic actions to achieve water quality goals. In California, the State Water Resources Control Board is responsible for managing water quality in the state's waterways, including listing waterways under section 303(d) of the CWA (http://www.swrcb.ca.gov/quality.html). Listing waterbodies means that the state has determined that there is sufficient scientific basis for calling individual waterbodies impacted to invoke their legal protection.

U.S. EPA has adopted the ambient water quality criteria, which are water quality standards for the protection of aquatic life (http://www.epa.gov/waterscience/pc/revcom.pdf). These standards can be used to evaluate water quality in the context of an overall watershed assessment. Where standards don't exist, indicators can be drawn from technical and scientific literature to inform the analysis.

The characteristics of water vary across watersheds and according to time of day, season of the year, and human activities that might affect water quality. To account for this variability, it is usually necessary to collect many samples at many times in many places in order to characterize water quality.

Sometimes waterways in a region (e.g., the Central Coast) are chosen as reference sites because they have many or all of the expected natural processes (e.g., frequent fire) and features (e.g., anadromous fish populations). Data collected from a reference monitoring site can be compared to data collected from sites of concern to establish how much the sites of concern have deviated from the natural state.

### 3.6.1 Nutrients

Naturally occurring chemicals that contribute to instream plant and bacterial growth include nitrogen-containing compounds (e.g., nitrates) and phosphorous-containing compounds (e.g., phosphates). The cycling of these chemicals, or nutrients, through terrestrial and aquatic ecosystems is a natural process that can be influenced by modifications of vegetation, soils, and rock formations; changes in the flow rate and other physical characteristics of waterways; changes in the biological conditions in waterways; and the introduction of nutrients from outside sources. Human activities usually increase nutrient concentrations, resulting in increased potential for the growth of algae and other plants in waterways. Excessive growth of algae, bacteria, or vascular plants can result in secondary impacts to dissolved oxygen concentrations and downstream organic carbon concentrations, due in part to the breakdown of plant material. When dissolved oxygen levels become too low, the normal physiological functions of aquatic animals are impaired, resulting in mortality in some cases. The U.S. EPA's ambient water quality criteria include nitrates and phosphates.

### 3.6.2 Temperature

Water temperatures must remain within a certain range in order for native aquatic organisms to maintain healthy populations and distributions. This temperature range varies from species to species, and sometimes from population to population within a species. Temperatures within a given body of water vary naturally due to seasonal and diurnal influences. The temperature of inflowing water, flow rate, wind speed, air temperature, and riparian shade influence water temperature. When natural or human processes affect these factors, temperatures may rise or fall. Relationships between landscape condition and water temperature exist, but have not been well characterized for all habitat types of California.

Temperature changes and temperatures above a certain point have particular direct and indirect effects on the health of instream aquatic communities. Temperatures above a certain point will have sub-lethal impacts (e.g., reduced growth rate, impairment of physiological function) or lethal impacts on embryonic and adult insects, amphibians, fish, and other aquatic animals. This point varies with geography and species. Rapid temperature changes can also have adverse effects. The temperature of a waterbody will affect the concentration of dissolved oxygen (colder water has more oxygen) and the instream portion of nutrient cycles

By changing the vegetative cover, hydrologic cycle, and rate and timing of instream water flow, human activities can influence the water temperatures of streams and rivers. Removal of upslope or riparian vegetation (e.g., by logging or development), for example, results in increased sunlight on the water surface, which heats the water, and increased wind speed across the water surface, which decreases the benefits of riparian shading if the air is warm (Holtby 1988). Water diversion and storage reduce instream flow, which can have serious impacts if these reductions are in the summer when the air is warm anyway. Reduced natural storage of water as snow or in shaded soils can also result in lower flows in the summer.

Water temperature can fluctuate over 24-hour periods, weather events, seasons, and climate cycles. It can also fluctuate over short lengths of a stream. These fluctuations can complicate measurements and analysis of water temperature in still and moving waters.

The mean weekly average temperature (MWAT) and the summer pool temperatures (where pools are providing cool-water refuges) are two common methods for tracking water temperature. The standards for these indices vary depending on where the waterway is in California and the species of concern. For example, in the North Coast region in 2001, the RWQCB had the following standard for temperature: "At no time or place shall the temperature of any COLD water be increased by more than 5°F above natural receiving water temperature. At no time or place shall the temperature of WARM intrastate waters be increased more than 5°F above natural receiving water temperature." (North Coast Regional Water Quality Control Board, 2001). In other regions, there may be different standards, and the basis for the standard may vary.

### 3.6.3 Suspended Material

Both organic (e.g., leaves) and inorganic (e.g., silt) material enters streams and can affect the clarity of the streams, as well as the sediment budget for a waterway or watershed. "Total suspended solids" refers to all the material suspended in the water, and "total suspended sediment" refers to just the inorganic portion. Suspended sediment is sometimes defined as including both organic and inorganic particles (Spellman & Drinan, 2001), so the use of either term must be accompanied by a definition.

Suspended sediment is a natural part of an aquatic ecosystem; as with most aspects of water quality, it is the concentration and duration that matters. Natural concentrations of suspended sediment will vary with geological and soil formations, precipitation, upstream slope steepness, and land cover. Human activities, including road construction and maintenance, logging operations, agricultural operations, housing construction, mining, grazing, and changes in flow (reservoir releases or water diversion) can result in changes in suspended sediment in-stream.

It is natural for landscapes to erode and for vegetation and other organic material to enter streams, and for these materials to become suspended or settle in response to flows. However, modifications of these processes through land and flow disturbances can cause negative impacts to aquatic communities and human uses of water. The negative impacts of excessive suspended sediment include: 1) the smothering of embryonic and larval stages of insect, amphibian, and fish species in the benthic sediment, 2) the blocking of light needed for photosynthesis by algae and vascular plants, 3) the spreading of pathogenic microbes and toxic metals bound to the surface of particles, 4) increased costs for water purification, and 5) the filling of downstream reservoirs.

Two approaches for investigating the potential for suspended sediment problems in watersheds are to: 1) monitor in-stream concentrations periodically and during and immediately following storm events and 2) develop a risk assessment or similar map-based modeling approach using information about slope steepness, precipitation, soil and geology, land cover (vegetation), and land use. Data from both approaches can be collected in the same watershed and, in combination, can reveal potential or actual impacts of suspended sediment on aquatic communities.

**Humbug Creek, Yuba River watershed**
**Photo by David Fallside**

Just as with temperature, suspended sediment concentrations can fluctuate widely over short time periods and distances. This can complicate understanding natural and human-induced erosion processes and transport of sediment through stream and river systems.

### 3.6.4 Dissolved Oxygen

Aquatic ecosystems must contain oxygen in order to sustain the lives of all animals and plants (but not all bacteria). The concentration of oxygen dissolved in water depends primarily on the temperature of the water and the waterway's elevation (which affects atmospheric pressure). Oxygen is naturally introduced into aquatic ecosystems from the atmosphere and from photosynthesis by algae and vascular plants growing in the water. Oxygen is naturally limited in the water of benthic (bottom of the waterbody) sediments because it must diffuse in from the water above, and it is simultaneously used up by respiring animals and microorganisms, as well as by chemical reactions.

There are two primary units for measuring the concentration of oxygen in water: 1) milligrams per liter, "mg/L", which refers to the amount of oxygen dissolved in one liter of water, and 2) % saturation, which refers to the proportion of the theoretical maximum concentration of oxygen that is present.

Human activities can contribute to the depletion of dissolved oxygen (DO) from waterways. For example, dams and reservoirs contribute to depletion of oxygen through microbial action in the deep water and bottom sediments. Water released from deep in a reservoir to a stream or river can be very low in oxygen. In addition, reduced flows during the summer can result in increased water temperatures, which will result in lower concentrations of oxygen and possibly excessive algal growth, which will eventually rot and further deplete the oxygen. Excessive nutrients can also contribute to bacterial, algal, and vascular plant growth, which can deplete nighttime oxygen in the benthos (bottom of the waterbody). When the excessive growth dies off, the rotting material will result in oxygen depletion in or near the benthos. Settling of fine sediments between larger gravel in benthic sediments reduces the flow of water through the gravels and hinders the replenishment of oxygen depleted by benthic organisms.

Standards for dissolved oxygen concentrations are usually based on the needs of aquatic organisms present in a particular watershed. For example, trout populations and their prey depend on oxygen concentrations >6.5 mg/L (milligrams per liter) in order to survive. Populations of warm-water fish, such as largemouth bass, will not grow at dissolved oxygen concentrations <6.5 mg/L, but can tolerate lower concentrations than cold-water fish.

California's Regional Water Quality Control Boards use two different kinds of standards for dissolved oxygen. One is a saturation standard. For example, waters must average >85% saturation in the Central Valley region. The other standard requires that concentrations be above a certain standard. For example, in the Central Valley region, dissolved oxygen be >5 mg/L for the Sacramento River at the Delta to >7 mg/L for the upper Sacramento River.

Besides causing the loss of fish and other aquatic biota, oxygen depletion can promote unwanted chemical reactions. For example, anoxic (no oxygen) or hypoxic (low oxygen) sediments are more likely to host the methylation of mercury (a chemical modification of mercury atoms) by bacteria, which allows mercury to enter the food chain through bacteria and algal food sources for aquatic animals (D'Itri, 1990).

### 3.6.5 Inorganic and Organic Pollutants

<u>I. Classes of Contaminants</u>

Contaminants are any chemical that can have an adverse effect on aquatic life if present in sufficient concentration. “Sufficient concentration” is the key phrase. In small enough quantities, most chemicals are harmless. In larger quantities, chemicals that might be essential for life can be very toxic. This well-documented pattern is the basis for the slogan “the poison is in the dose (or concentration)”. One classic example of this is the metal copper; it is an essential mineral for all living organisms, but above a certain concentration, it becomes increasingly toxic, especially to aquatic animals. Most contaminants of concern are toxic at low concentrations, typically in the parts per billion (ppb) range.

Contaminants can be divided into two major groups of chemicals: organic and inorganic. Organic chemicals contain carbon and include most pesticides, dioxins, PCBs (polychlorinated hydrocarbons), PAHs (polycyclic aromatic hydrocarbons), oil and grease, and surfactants and plasticizers (Table 3.3). The metals that are of greatest concern with respect to aquatic life are typically heavy metals, such as zinc, copper, mercury, and lead, as well as other groups of metals that include arsenic.

Aquatic contaminants can be acute and/or chronic toxicants. Acute toxicity causes mortality, while chronic exposure to lower levels of the contaminant can cause harm to the reproductive, nervous, or other physiological systems.
The U.S. EPA has developed benchmark values, those considered safe for most aquatic life, for both short-term (acute) and long-term (chronic) exposures.

II. Organic Contaminants

Organic compounds that are contaminants play no normal role in the functions of aquatic organisms. They are often designed to kill insects or other animals. Alternatively, many serve as ingredients in various manufacturing processes or are constituents of commercial products. Over time, organic contaminants will be broken down to less harmful substances. However, some can persist for decades. Those that persist for long periods of time can accumulate in the tissue of animals and be passed up the food chain. Table 3.3 contains an abbreviated list of common organic contaminants found in waterbodies,

**Table 3.3 Relevant information about classes of organic contaminants**

| Organic Chemical | Environmental Source | Effects | Special information |
|---|---|---|---|
| Organophosphate pesticides (diazinon, malathion, chlorpyrifos) | Lawns, golf courses | Neurotoxin, acutely toxic | Very water soluble, persists in water for weeks-months |
| Pyrethroid pesticides (esfenvalerate, permethrin) | Lawns, golf courses | Neurotoxin, acutely toxic, some cause chronic toxicity (reproductive harm) | Not easily dissolved in water, found in sediment, persists in sediment up to a year |
| Organochlorine pesticides | Pesticides, many such as DDT, are currently illegal to use | Neurotoxin, but also many other chronic adverse effects | Very insoluble in water, commonly found in sediment, persists for long periods (75 years) |

| Organic Chemical | Environmental Source | Effects | Special information |
|---|---|---|---|
| Polycyclic aromatic hydrocarbons (PAHs such as benzo[a]pyrene) | Combustion by-product (gasoline, wood, burning of just about any organic material) | Carcinogen, can cause tumors in fish | Insoluble in water, found in sediment, persists for decades under certain conditions |
| Dioxins | Combustion by-product involving reaction with chlorine; by-product of synthesis of some herbicides, found in bleached pulp mill effluent, incinerator emissions | Carcinogen, disrupts normal hormone function (endocrine disruptor) | Insoluble in water, persists for long periods of time in sediment if shielded from light |
| PCBs (polychlorinated biphenyls) | Hydraulic fluid, coolant, insulator, historically used in transformers, current source is manufacturing waste, currently illegal to use | Carcinogen, numerous other harmful effects | Very insoluble in water, very persistent in the sediment |
| Surfactants (detergents) | Numerous commercial/residential uses; enter water via wastewater treatment plants | Can interfere with reproduction in aquatic animals | Water soluble, are not persistent |
| Plasticizers (phthalates) | Commercial uses, makes plastics more pliable; wetting agent; found in wastewater effluent | Reproductive toxicant in fish and invertebrates | Low solubility in water, associated with sediment, persists for less than 1 month in most cases |

their sources, the type of effects they have on aquatic life, and reference information to collect additional details.

III. Metals

Metals are natural substances, many of which are essential nutrients. However, if present in aquatic ecosystems in sufficient quantities, they are harmful. Unlike organic compounds, metals are not biodegradable. Unlike organic compounds, metals persist indefinitely. They also tend to bioaccumulate, or collect, in fish tissues.

The toxicity of metals in water and sediment is complicated because normal constituents of water affect the solubility and availability of metals to be absorbed by invertebrates and fishes. Water hardness is a key factor that affects the solubility of metals. Hardness refers to the concentration of positively charged atoms (calcium, magnesium, etc.) dissolved in water. If the concentration of a metal is hardness-dependent, then special considerations must be made in assessing harmful levels in a specific water body. Another important consideration when looking at metals is that they are often found in greater

**Table 3.4 Major metal contaminants**

| **Metal** | **Environmental source** | **Hardness-dependent** | **Toxic effects** |
|---|---|---|---|
| Arsenic | Naturally occurring; used in some pesticides and herbicides, wood preservatives | No | Acute toxicity, reproductive toxicant |
| Lead | Mining, incineration of batteries, pigments | Yes | Acute toxicity, neurotixcant, impairs reproduction |
| Mercury | Fungicide; many manufacturing processes; mining | No | Methyl mercury form of greatest concern; endocrine disruptor, not acutely toxic |
| Cadmium | Used in a variety of industrial processes; most common in urban watersheds | Yes | Acute toxicity, a variety of physiological effects with long term exposure, including deformities of young |
| Copper | Mining, dormant sprays; fungicide used on boats | Yes | High toxicity with acute exposure; interferes with function of gills |
| Zinc | Mining, electroplating, roads (from worn tires), manufacturing of brass, steel, and iron alloys; dormant sprays | Yes | Acutely toxic; teratogenic with chronic exposures |
| Chromium | Numerous manufacturing processes, including tanning leather, manufacturing steel, aircraft industry | hexavalent form not affected by hardness; trivalent form less water soluble, toxicity hardness dependent | Acutely toxic, possible carcinogen |

concentrations in the sediment, bound up with other particles, than in a free (or soluble) form in the water. Over time, the bound metals in the sediment leach out into the water. Many invertebrates and various life stages of fishes live in the sediment. Consequently, it is important to examine the potential toxicity of metals in both the sediment and water column.

Table 3.4 lists key metals of concern, their environmental sources, whether the metal's concentration in water is dependent on water hardness, and toxic effects of metals.

## IV. Evaluating Contaminants in Water as Part of a Watershed Assessment

If there are land uses or activities within the watershed that might be associated with the release of contaminants, or if there is evidence within the waterway that contaminants might be a problem, there are a number of steps that can be taken to determine if contaminants are a problem.

1. Check with the Regional Water Quality Control Board, local Water Districts, Municipalities, Sanitary Districts, Regional Urban Runoff Programs, and Local Publicly Owned Treatment Works (POTWs), to determine if they have conducted monitoring within the watershed. If data already exists, independent monitoring may not be necessary.

2. Collect water to perform a toxicity test. These tests utilize invertebrates and/or fish to determine whether something in the water or sediment causes acute toxicity. Although the test is not specific for any particular contaminant, it does reflect the overall quality of the water. When possible, it is best to perform the tests with both water and sediment samples from the waterbody.

3. If the toxicity tests are positive, further analysis can be done to identify the cause of the toxicity. Toxicity identification evaluations (TIEs) can be performed to initially identify the class of contaminant responsible. For example, TIEs will differentiate between metals, certain types of pesticides, or other harmful chemicals. Once the class of contaminants is determined, a variety of analytical techniques can be used to determine the specific “bad actor(s).”

### 3.6.6 Pathogenic Bacteria

The primary bacteria types of concern in waterways are fecal coliform and enterococcal. They usually originate from deteriorating septic systems, incomplete wastewater treatment, the presence of livestock, or stormwater flooding of wastewater treatment facilities. They may also be associated with natural sources in a watershed, such as dense congregations of birds or other wildlife. Certain strains of one bacterial species, *Escherichea coli*, may cause intense gastrointestinal problems if ingested.

U.S. EPA has established standards for water quality in waterways used for recreation and as sources of drinking water. These standards are based on generalities about the consumption of water containing bacteria and the sensitivity of people potentially exposed. If waterways exceed these standards, then the state has a legal responsibility to protect residents from potential harm by notifying the public of the problem through signs and other advertising and by then identifying sources of the problem and implementing cleanup through regulatory or restoration activities. More information on this topic is posted at: http://www.swrcb.ca.gov/beach/index.html.

### 3.6.7 pH

pH is a measure of the relative acidity or alkalinity of freshwater. pH is literally the concentration of hydrogen ions in water. Hydrogen ions have a positive electrical charge, allowing them to associate with negatively charged ions, such as nitrate and chloride ions. The pH depends in part on the relative concentrations of electrically charged compounds present in the water and can therefore be affected by natural and human processes that influence the concentrations of these compounds.

In California, pH naturally ranges around neutral pH (pH = 7.0) by about 1 pH unit. Most Basin Plans for the various State Water Resources Control Board regions record a pH range of 6.5 to 8.5 as ideal for maintaining the health of aquatic communities. Violation of drinking water standards is not an appropriate indicator for pH problems because changes in pH can affect aquatic organisms before reaching a level that humans can’t tolerate.

Acid mine drainage, microbial processes at the bottoms of lakes and reservoirs, and effluent from wastewater treatment plants and industry are possible sources of pH change in a watershed. Erosion of certain geological features, such as serpentine outcroppings, can also change the pH of receiving waters. Changes in pH outside the range of 6.5 to 8.5 are usually associated with identifiable sources that can be readily investigated.

## 3.7 Aquatic Ecosystems

Although waterways constitute a small proportion of a watershed's total size, they integrate many of the human and natural processes in the watershed, and they are often the political and social focus of watershed efforts. Aquatic ecosystems include physical (e.g., temperature), chemical (e.g., nutrient concentrations), and biological (e.g., fish populations) components. The physical and chemical constituency of an ecosystem in large part determines the various plants, microbes, vertebrates, and invertebrates that live there. In turn, interactions among the various organisms determine the aquatic community structure.

### 3.7.1 Physical

Many factors in an aquatic ecosystem can be described as "physical," such as temperature, suspended and benthic sediment, and flow. Some of these are described in more detail in the water quality section (chapter 3.6).

Benthic sediment is an important component of aquatic ecosystems. While difficult to characterize, benthic sediment is critical to the health and well-being of native organisms. The structure and composition of benthic sediments determine the size of spaces among sediment particles and, in part, the rate of particle movement. Small particles result in small pore sizes, which lead to low flow rates among the particles and limit dissolved oxygen concentrations. Small particles are more easily mobilized in low flow rates, resuspending and resettling in the turbulent stream and river flows. Large particles have large pore sizes among them. They usually don't limit flows and the availability of dissolved oxygen to benthic organisms.

Measuring the proportion of benthic sediments of different sizes and the rate of downstream sediment transport are important ways to characterize stream condition. These physical measures of habitat condition often accompany studies of benthic macroinvertebrates, one biological measure of the aquatic ecosystem's condition.

Flow, the physical movement of water, impacts many other aquatic ecosystem characteristics. Low flows can result in warming of water, reduced sediment transport, and physical barriers to the movement of migratory fish. High flows can increase the rate of sediment transport, replenish depleted dissolved oxygen, and provide deeper water for fish movement.

### 3.7.2 Chemical

Most of the important chemical characteristics of aquatic ecosystems are presented in the water quality section (chapter 3.6).

Changes in stream chemistry can determine the well-being of the aquatic ecosystem. Individual organisms may not tolerate either changes in water quality (e.g., pH, dissolved oxygen, and nutrients) or the absolute values for these water quality parameters. Other organisms may be quite tolerant of wide variations in water chemistry. Changes may originate from human activities (e.g., nutrient runoff from an agricultural area), natural processes (e.g., growth and decomposition of aquatic plants), or a combination of both (e.g., excessive growth of algae due to excessive nutrient inputs. A critical part of watershed assessment is understanding the nature of water chemistry in the watershed and the causes of high or low values or changes in values for specific parameters. Many water quality standards are based on human health considerations and not on ecological effects of changes in waterbody chemistry. Therefore, standards relevant to aquatic organisms must be used when analyzing pH values in the watershed.

### 3.7.3 Biological

The biological components of aquatic ecosystems are the microbes, plants, invertebrates, and vertebrates that inhabit the water column (the water above the bottom) and the benthos (the bottom of the waterway). These grow and change relative to each other depending on the physical and chemical conditions in the waterway and can therefore indicate conditions or changes in the watershed. Understanding the natural biological condition of waterways is often challenging, as there are few "reference" waterways, that is, streams and rivers in a relatively natural state. However, many scientists use the biological composition of aquatic ecosystems to determine whether or not a watershed or waterway is deviating radically from a natural state (Karr 1981; Moyle & Randall 1996) and may be in need of restoration (Adaniya et al. 1997; Murray et al. 2001).

*Plants and Microbes*

Plants in aquatic ecosystems occur in several main forms. Phytoplankton, single-celled algae suspended in the water column, grow in slow-moving waterways and lakes. Periphyton, single-celled and multi-celled algae and vascular plants, occurs attached in films or filaments to rocks in still or moving water. Vascular plants (plants with true stems) can grow from lake, river, and stream bottoms. All these plants use nutrients and gases dissolved in the water and light from the sun in order to photosynthesize (make food using light as an energy source) and grow. Changes in flows, temperature, and nutrient availability can affect the growth of these aquatic plants. Low flows and excessive inputs of nutrients from various land uses and point sources may result in high temperatures, reduced mechanical stress (from flow), and excessive growth. Excessive growth can cause changes in pH, reduced dissolved oxygen concentrations in the bottom sediments, and production of particulate and dissolved organic carbon as the plants grow, die, and decompose.

Although fungi and bacteria may occur in the water column (millions of individual cells per liter), most of the important microbial activity occurs on the surface of or within the bottom sediments (Horne & Goldman 1994). Decomposition of plant material from terrestrial vegetation and from aquatic plants is an important process in the slower-moving major rivers and lakes, however, it may also occur in smaller waterways, such as mountain rivers, if the water is warm enough and there is sufficient material. Microbes on the surface of decaying vegetation are an important food source for invertebrates grazing or filtering food from the water and sediment (Horne & Goldman 1994). High levels of microbial activity can alter the chemistry of water within the bottom sediment and of water near the bottom. Microbial activity is one of the main reasons that water deep in lakes and reservoirs is oxygen-depleted.

Viruses are not usually thought of in the world of watershed assessment, but they are present in freshwater and can pose risks to wildlife and humans alike. Hepatitis and animal influenza viruses are just two of many pathogenic viruses that can be transmitted through freshwater, usually as a result of inputs of animal and human waste (Horne & Goldman 1994).

*Benthic Macroinvertebrates*

Benthic macroinvertebrates are the larger invertebrates (animals without backbones) dwelling at the bottom of waterways. Several major animal groups fall into this group, including insects and crustacea (arthropods), mollusks, and worms. However, most people using this term are referring primarily to the aquatic larval forms of various insects (e.g., stone flies, caddis flies, and dragonflies). Aquatic invertebrates are a major food source for many aquatic and terrestrial organisms. Their well-being can determine how well these other animals do. They are also interesting from a watershed assessment perspective because they can function as indicators of watershed condition. Certain benthic macroinvertebrates are sensitive to change, i.e., watershed degradation, and can be monitored for their presence and relative abundance to give a measure of watershed health integrated across generations of the organisms.

*Vertebrates*

Aquatic vertebrates include fish, amphibians and reptiles, mammals, and birds. The presence of individual species depends on geography, hydrology, management conditions, presence of other species, and other factors. All species, with the exception of anadromous fish, eventually rely on plant productivity within the waterway itself or on plants adjacent to the waterway that fall or are washed in. They also rely on certain aspects of the waterway's physical or chemical makeup. There are many connections between watershed landscape condition and waterway habitat condition, so impacts to aquatic vertebrates are often measured using other condition indices (e.g., physical structure of the channel, riparian vegetation, or water quality). Simplification (loss of natural complexity) of watershed and waterway conditions through habitat loss and modification (i.e., from land and water management) has led to the absence of many species from significant parts of their historic range in California.

Many watershed assessments focus on freshwater fish, usually because the fish are useful indicators of aquatic health, are listed under the federal Endangered Species Act (1973), or are of concern locally (http://www.dfg.ca.gov/whdab/html/lists.html). Most watersheds include fish, which may be viewed by the watershed assessor as another resident of the watershed, as a commercial or social resource, or as a legal problem. Anadromous ("up-running") fish migrate between different environments (i.e., the ocean and inland freshwater) to carry out particular parts of their lifecycle. Salmon (chinook and coho) and steelhead are anadromous species, spending their larval and juvenile phases in freshwater and their adult years (1-4 years) in the ocean. Their primary needs in California watersheds are unimpeded travel routes from the ocean, good quality spawning habitat (i.e., gravel bars for laying eggs), sufficient quality and quantity of rearing habitat (cool sheltered pools and riffles), and downstream transport to coastal estuaries and the ocean. Land and water management activities can impact these various life cycle needs depending on their location, type, extent, and timing of activities. Assessments of watersheds supporting these species should therefore incorporate evaluation of conditions in the waterways and on the landscape that might impact and could limit anadromous fish reproduction.

Many native fish in California lakes, rivers, and streams also deserve the attention that anadromous fish receive (Moyle et al. 1995). Their habitat requirements may be just as narrow as those of salmon. These habitat requirements are often generalized in Basin Plans as "cold-water fisheries", "warm-water fisheries," migration of aquatic organisms", "spawning, reproduction, and/or early development". For some of these requirements there are broad ranges (e.g., 35$^o$F to 70$^o$F for "cold-water fisheries"). Each species has its own ecological "niche," composed of its preferred habitat, the prey it eats, and how it reproduces. Individual fish species range in their needs, so assessing habitat conditions and the potential impacts to these conditions for many species is more complicated than for one species alone. Some common impacts to fish species are loss of historical habitat (e.g., from dam construction), fragmentation of existing habitat (e.g., from culverted road crossings), loss of prey, degradation of existing habitat (e.g., from reduced flows and excessive sediment input), competition from non-native species and diseases, and over-fishing. Measuring all of these impacts for individual fish species may seem daunting, but it is important for understanding a watershed's condition.

Amphibians and reptiles often inhabit the margins of waterways. Some species are listed as endangered or threatened, or Species of Special Concern, while others have no special designation or protection (Jennings & Hayes 1994; http://atlas.dfg.ca.gov/). Examples of native aquatic amphibians and reptiles include the Arroyo toad, Cascade frog, California tiger salamander, western pond turtle, and two-striped garter snake. Their habitat has been reduced or degraded in many places by land and water uses that affect riparian vegetation, sedimentation processes, prey availability, and habitat connectivity (usable connections among habitat areas). In some instances, they have fallen prey to invasive and/or exotic vertebrates and pathogens. Just as with fish, they rely on a particular set of physical (e.g., temperature) and biological (e.g., insect prey) conditions to survive. For individual species, these conditions could be a wide window or a very narrow one. If these conditions are altered significantly, abundance and presence will change. The job of the watershed assessor is to find out what changes are significant.

Aquatic mammals and birds often play significant roles in an ecosystem, either by physically manipulating the waterway (e.g., beavers) or by functioning as a top predator (e.g., river otters, herons). Trappers killed off many mammals in the last century. Their return has been hampered by land and water uses and by public perceptions of their role in modern waterways. Beavers may be a delightful sight to a grade-schooler, but not necessarily to the person who has to maintain an agricultural slough or diversion. Mammals' habitat needs and population dynamics (how populations of a species change over time) may be poorly understood, leading an assessor to guess at relationships between these species' habitat needs and watershed conditions and use. Aquatic birds (e.g., ducks, geese, mergansers, cormorants, dippers, herons) are in a similar boat, with few species having complete descriptions of their preferred habitats. For both birds and mammals, many general statements can be made about their habitat requirements and roles in a watershed. For example, where beavers are particularly active, they can affect how riparian areas function by cutting down riparian trees and contributing to local changes in channel structure and flow. In turn, beavers are affected by the composition of the riparian forest in terms of size and species of trees. Otters do not do very well in places where there are few smaller fish and aquatic invertebrates, which are the food for the larger fish the otters prey on.

### 3.8 Terrestrial Landscapes and Habitats

The majority of watershed area is composed of the terrestrial landscape—the uplands, hillslopes, and ridgelines. Although almost all watershed assessments discuss conditions of the landscape outside of riparian and wetland areas, very few tackle terrestrial plant communities and habitat condition, except when discussing erosion. There are many processes in the terrestrial landscape that interact directly with waterways and the riparian zone. These include erosion, nutrient cycling, input of organic material, evaporative water loss, and movement of wildlife back and forth. The condition of the upslope vegetation and soil can critically affect the capability of the watershed to retain moisture and meter surface and subsurface runoff into streams. In fact, the role of vegetation management to water supply and control is one of the original research topics of the emerging field of watershed management in the early 20th century (Colman 1953).

*Characterizing Terrestrial Plant Communities*

For botanical diversity in California, the Jepson Manual (Hickman 1993) describes 24 climatic zones and 50 geographic units contained within three floristic provinces (California, Great Basin, and Desert). Individual plant species are often grouped into communities—they often form "associations" among each other (i.e., they live together) because of similar habitat requirements or because they have a biological interaction. These communities are represented in fairly general vegetation maps (e.g., "CalVeg 2000") that show the location of plant community types. Some agencies have created more spatially refined maps for plant community types (e.g., vernal pools, wetlands, and oak woodlands), usually because human activities threaten the habitat type. Specific plans for urban area development may have even more precise maps for locations of plant community types because of legal obligations to have the information. These maps are created by on-the-ground surveying, or by using remote sensing (e.g., satellite photographs).

Most plant community location maps don't tell anything about the age of trees, the percentage of vegetation cover (how much ground is covered), and actual plant species present. One notable exception is the California Department of Forestry and Fire Protection's "hardwoods" map, which includes these types of data. Assessments in large watersheds may not have the resources to support surveys or mapping of actual plant species presence and demographics. These plant surveys might be carried out in monitoring stations or associated with specific restoration projects. Assessments of smaller watersheds, especially where there are plant communities of concern (e.g., redwood forests and vernal pools), may allow the generation of high-resolution maps. More detailed and diverse information obviously allows post-assessment decisions to have more detail and greater resolution.

*Changing Conditions*

The terrestrial landscape is undergoing constant change—there is no equilibrium or stasis in these landscapes. Both human activities and natural processes can cause changes in the terrestrial landscape. Even where the natural state has been largely converted (e.g., in urban areas), over long enough time periods, natural features have changed and will continue to change due to fluctuating climate, changing human values, and invasions by new species.

Plant communities may be replaced by another or undergo "succession" following extreme disturbance. This means that one species may take the place of another, such as the growth of chaparral following a fire that removes a conifer forest. Plant communities also age, which leads to changes in the plant and animal species that can thrive there.

A watershed assessment should measure this change as thoroughly as it represents the "snapshot" of watershed condition. While it is often difficult to predict or even to measure change, there are various indicators that are useful in assessing this dynamic state. For example, varying tree ring widths show changes in growth rates in a forest region—changes that could be related to climate, frequency of disturbance (e.g., fire), or competition with other trees. Understanding how forest complexity might have changed over a period of time will give a recent history of the physical structure of that forest and provide clues as to vegetative cover, wildlife presence, nutrient cycling, erosion, and other ecological processes.

*Wildlife*

Six hundred and forty three vertebrates occur in the state (California Wildlife Habitat Relations, California Department of Fish and Game, 1994). Assessing habitat conditions for terrestrial wildlife (here defined as all animals) or including information about individual species' presence and abundance is usually not a watershed assessment priority. However, because a watershed's area is mostly land

and not water, it makes sense to complete the description of the landscape by describing the animals that live there. Many of them are indicators of the condition of the vegetation and natural processes in the watershed. A few of them will have observable influences on the ecology of the landscape (e.g., deer). After identifying those wildlife species found in your watershed, their status can be found on lists of threatened, endangered, or species of special concern (http://www.dfg.ca.gov/whdab/html/lists.html).

One of the main data and knowledge gaps encountered in landscape assessments is a lack of easily obtainable data about the actual distribution, abundance, and population dynamics of individual wildlife species. Even such models as the California Wildlife Habitat Relations model (CWHR), which maps potential wildlife occurrences based on the presence of plant communities, rely on incomplete knowledge of habitat requirements and behavior, and they may not reflect actual species presence, let alone abundance. The California Natural Diversity Database (NDDB, http://www.dfg.ca.gov/whdab/html/cnddb.html)—the main statewide database for wildlife occurrence—relies on the voluntary submission of observations by qualified wildlife biologists. However, this database includes only species of management concern, is not based on a surveying protocol, and is biased toward areas where the number of observers is high (e.g., urban areas). Within the CNDDB, records of rare plant and animal species within your watershed boundaries (location, dates observed, ecological descriptions, legal status, population information, land ownership, data sources) can be searched for using CDFG's RareFind3 software. (http://www.dfg.ca.gov/whdab/html/rarefind.html)

The best response for a watershed assessment that lacks readily available wildlife data because of the problems listed above is to go and collect these data. This might involve collecting databases maintained by agencies that manage land (e.g., the USDA Forest Service), that build and maintain infrastructure (e.g., the California Department of Transportation), or that plan and regulate development (e.g., jurisdictions and their consultants). Developing a complete landscape assessment database might also involve hiring a wildlife biologist to conduct surveys, which is feasible for smaller watersheds (i.e., less than 10,000 acres).

Without these data, a watershed assessment will be incomplete, and analyses and decisions that affect plant community structure and wildlife habitat will be open to question.

### 3.9 Human Land Uses

Human land uses can potentially affect many aspects of the hydrologic cycle. Precipitation is the least subject to human intervention. Large-scale earth-moving operations for commercial and residential development and open-pit and mountaintop mining can change topography and geology. More commonly, watershed assessors are concerned with changes in vegetation that affect evapotranspiration, changes in surface conditions that affect infiltration, and changes in channel conditions that affect water conveyance. It is important to distinguish between temporary disturbances, from which hydrologic recovery is possible, and land use conversions, where the hydrology remains altered unless the conversion is reversed.

As with other land use changes, the proportion of the watershed altered and the proximity to stream channels determine the impacts on water quantity, timing, and quality.

### 3.9.1 Residential, Commercial, and Industrial Development

Building houses is a fundamental component of the interaction between humans and their environment. From the scale of the individual parcel to that of a town or city, the impacts to the environment and benefits to quality of life are relevant to assessing conditions in California watersheds. Residential development can occur on remote parcels hundreds of acres in size, in suburbs on the periphery of growing towns, and deep in inner cities. The development process is locally governed, is guided by state planning rules, and usually responds to a housing, political, or financial need of local communities and landowners (Fulton 1999). This use of land is sometimes called land “conversion” because of the extreme nature of the impacts (e.g., grading and covering an area with asphalt), and in sub-watersheds may be the predominant influence on natural watershed processes.

Residential development often occurs alongside commercial and business/industrial development. From a watershed perspective, these developments may have similar impacts to natural systems. From a socio-economic perspective, how these different components develop may be important. The proportion of residential to commercial/industrial development can influence traffic patterns, infrastructure development, and local economic wellbeing. For the most part, when people don’t live near work/school/community, they tend to travel by road to get to those places. In addition, as the focus of communities changes from commodity production (e.g., farming) to other economic activities (e.g., technology development), the perceived costs and benefits of certain activities on the landscape may change.

Development can have significant impacts on watersheds. Impervious cover, such as roads, driveways, rooftops, and walkways, can greatly reduce the land’s ability to absorb rainwater, resulting in increased volume and rate of stormwater runoff. Stormwater that would otherwise percolate into the soil now ends up in waterbodies, carrying a wide variety of contaminants. The amount of water entering stream and creeks often increases significantly, causing numerous changes to the shape and characteristics of the physical environment in and around the stream or creek. In general, the more that land is developed—converted from its natural state—the more likely it is that natural watershed functioning will be negatively impacted.

### 3.9.2 Agriculture

Agriculture usually converts land use in the long term, if not permanently, for the production of food and fiber. Certain alterations to watershed conditions result from this conversion. Native vegetation is replaced with actively cultivated crops of commercial value. Changes in transpiration vary with the particular crop and seasonal nature of production. Because more water is available where irrigation occurs, actual evapotranspiration generally increases. Infiltration capacity generally declines because of compaction from farm machinery. However, in some cases, active tilling may break up a naturally occurring soil layer that restricts infiltration. Depending on the nature of cultivation practices, fine sediment can also be washed off agricultural lands and into waterways. Where excess irrigation takes place, subsurface water delivery to streams may increase. This irrigation return flow (irrigation water returning to a waterway) may contain high levels of pesticides and fertilizers.

Many of the most harmful chemicals, the majority of which require permits, are used in agricultural settings. Pesticides, which persist in the environment for long periods of time, and sprays containing metals are frequently used in orchards and on row crops. If not properly controlled, these chemicals end up in water that seeps out of agricultural soils and/or stormwater and eventually drains into natural waterways. In some areas, wetlands have been artificially drained to allow for the cultivation of agricultural crops. Subsurface drains that maintain a lower water table may alter water delivery to streams by providing a faster, more efficient route for water than natural groundwater flow. As with other land uses in this section, the area affected by agricultural conversion and its proximity to streams may be more important than the intensity of hydrologic changes at the fields.

Some people argue that it is better to have land in agricultural production than have it developed for urban/suburban uses. Agricultural land use provides socially valuable open space and, if proper management practices are followed, can have limited impacts to water quality, water supply, and certain fish and wildlife habitat. To validate this perspective, it may be useful to analyze the impacts of urbanized or urbanizing areas relative to agricultural areas and both relative to less-impacted areas.

Other effects of agriculture often include leveling of floodplain topography and filling of secondary channels and sloughs. Thus, in agricultural areas today, single channel rivers are often separated from their floodplains by levees, and they lack the topographic diversity that once sustained ecosystem diversity.

### 3.9.3 Timber Management

Commercial timber management, or logging, is a land use that causes a recurrent disturbance rather than a complete conversion of land use. A forestry operation may completely change vegetation type, species mix, and age structure of the forest. However, forest management on private lands generally aims to optimize the growth and yield of selected tree species and periodically cut them—a situation not radically different in a hydrologic sense from a natural forest. On public lands, there may be a mixture of uses, including growing trees to cut them, recreation, and supporting biodiversity. Logging has dramatic impacts on the water balance of the immediate site. But as analyses increase in spatial scale, consequences to the watershed are not as obvious. Most current forestry operations do not affect a significant proportion of a watershed in a single year or decade. As with other land use changes, the proportion of the watershed logged compared to the entire watershed and the proximity of the logging to stream channels determine in part the impacts on water quantity, timing, and quality. While cutting trees in isolation may not have dramatic hydrologic consequences, the associated activities of road construction, stream crossings, yarding (collecting logs for transport), slash treatment, and mechanical site preparation may have much more serious impacts.

Forest practices on private land are regulated by the state Board of Forestry and Fire Protection and the California Department of Forestry and Fire Protection under the Forest Practices Act, the Regional Water Boards under the Federal Clean Water Act and Porter-Cologne Act, the California Department of Fish and Game, the U.S. Fish and Wildlife Service (for listed species), and NOAA-Fisheries (for listed salmon and steelhead). The state recently completely an assessment of the status, trends, and challenges to California's forest resources that also addresses timber harvesting (California Department of Forestry and Fire Protection, 2003; http://www.frap.cdf.ca.gov/assessment2003/ ).

Impacts to the watershed that have been documented to result from timber harvest include effects on sediment, water temperature, in-channel volumes of organic debris, chemical contamination, increased nutrient concentrations, the amount and physical nature of aquatic habitat, and increases in peak discharge during storm runoff. While certain of these impacts can be minimized or mitigated through the use of good management practices, the major concern today with logging in California is the potential for adverse cumulative effects at the watershed scale (Dunne et al., 2001). As a result, watershed assessment (also called “watershed analysis”) is being increasingly used as a predictive tool in the state by those responsible for management and protection of the State’s terrestrial ecosystems (North Coast Watershed Assessment Program, 2001).

The type of cutting also affects the degree of hydrologic impacts. Hydrologic impacts of selection harvests (where scattered individual trees are selected for cutting) are generally considered to be less of a problem that those of clear-cuts because the residual trees remaining after the selection logging use soil moisture and provide some protection to the soil surface (Anderson, et al. 1976).

Hydrologic processes altered by logging begin a slow recovery as young trees grow on the disturbed site. After vegetation becomes re-established on logged sites, it restores a forest cover’s hydrologic benefits, such as absorbing soil moisture for evapotranspiration, providing protection of soil from raindrop impact, adding organic matter to the soil, and supporting soil masses on slopes with their roots.

Logging can increase annual water yield to streams by reducing losses to the atmosphere. Tree removal eliminates the possibility of any interception losses (evaporation of rainfall captured on leaves) in the area previously covered by tree canopies. Cutting trees reduces transpiration in rough proportion to the areal extent of harvesting and the ability of the remaining plants to consume water. Forest soil depth and moisture storage capacity largely control the change in evapotranspiration that results from harvesting (Zinke 1987). Removing trees in shallow soils that have little moisture storage capacity impacts hydrology much less than removing trees that had access to lots of water in deep soil. The harvest area’s position on a hillslope is also important. Harvesting trees at the base of a slope near a stream will allow much of the soil water formerly used by the trees to enter the stream. However, harvesting trees near the top of a slope will probably only provide more water to the trees lower on the slope rather than to the relatively distant stream.

In addition to changes in annual water yield, timber harvesting can affect peak flows. Soil moisture is greater where trees have been removed. Accordingly, less rainfall is required to satisfy soil moisture storage before runoff may begin. This effect is most likely to have a measurable impact during small and moderate storm events and in small watersheds (Hewlett 1982). During big, intense storms, differences in soil moisture storage between cut and uncut areas are almost incidental compared to the massive amounts of rainfall that tend to overwhelm any effect of land-use change (Ziemer 1981). At the scale of larger river basins, flood peaks depend mostly on the synchronization of contributions from tributaries, which can be affected by dramatic changes in land use but are not predictable without a detailed model of the channel system. In watersheds with shallow snowpacks, timber harvesting can augment peak flows by altering the distribution of snow and the energy available for melt. More snow accumulates in open areas than in areas under forest canopy; hence, more water storage. During warm storms, greater wind speeds in forest openings compared with dense forests generate more snowmelt in the openings than under trees (Harr 1981).

Logging can increase sediment production from both surface erosion and mass movements. Tree canopy loss can allow greater raindrop impact on the soil with consequent soil displacement, but there is usually a thick layer of organic debris left on the soil after logging that absorbs the energy of falling drops. Landslides occur after harvest because soil moisture is greater in the absence of transpiration and because roots no longer help stabilize the soil after they decay. This structural support seems to be at a minimum about nine years after timber harvest, on the average, when decay of roots of harvested trees has not been compensated by growth of new roots (Ziemer 1981).

Sediment from clearcuts, logging roads, skid trails, stream crossings, and ditches may be transported to streams, rivers, and lakes by water (Swift 1988; Waters 1995) or wind (Steedman & France 2000). Nutrients may also increase in streams flowing from commercially logged watersheds (Swank et al. 2001).

Logging on public lands in most California watersheds is now almost exclusively “thinning” and “salvage” operations. Fire risk is the primary reason given for removing as many as half of the trees in any given stand. Although short-term negative impacts to wildlife (e.g., small carnivores) and natural processes (e.g., soil nutrients and water retention) have been shown to occur with these practices (e.g., Kaye et al. 1999), the longer-term effects are harder to measure, and less well-understood.

Removal of forest cover by logging results in decreased evapotranspiration (use of water by plants) and increased streamflow (Bosch & Hewlett 1982; Callahan 1990; Stednick 1996; Swank et al. 2001; Troendle et al. 2001). In one watershed study, removal of 24% of forest in small clearcuts (3-7 acres) and haul roads resulted in a 17% increase in streamflow (water volume) from the watershed (Troendle et al. 2001). This was partly due to increased peak flows during storms, but mostly due to increased duration and frequency of water release. These changes mean a net dehydration of the watershed and increased chance of “scouring” flows in the affected creeks, which may negatively impact terrestrial, riparian, and aquatic plant and wildlife communities.

### 3.9.4 Mining

Mining operations can be split into surface and underground mining. Surface mining techniques, such as dredging, quarrying, strip mining, open-pit mining, and heap leaching, are used when the mineral ores are located within a few tens of feet (sometimes hundreds of feet in giant open-pit mines) of the surface. In all cases, the removal of vegetation and topsoil accelerates erosion. If runoff is not contained, sediment yield from surface mining can be enormous.

Underground mining involves excavation of vertical or inclined shafts and/or horizontal tunnels and mechanical extraction of ore to the surface. In another type of underground mining, a solvent is injected underground to dissolve the mineral of interest, and the resulting solution is pumped out for processing. Excavation exposes tunnel walls and the extracted tailings to oxygen and water, allowing chemical reactions to occur at far higher rates than with intact rock. Mining activity also allows the products of these reactions to be leached into groundwater and streams. The surrounding rock’s mineral content and chemistry determine the potential for toxic metals (e.g., arsenic, chromium, lead, copper, etc.) and acids to be released from the site. Few areas in California have the acid mine drainage potential that is common in the Rockies.

The principal mining activity in California is sand and gravel extraction, the value of which far surpasses the combined value of all metallic minerals mined in the state (McWilliams & Goldman 1994). Because sand and gravel are critical to most types of modern construction, they are used in almost every road and building project. Utilizing aggregate sand and gravel sources near construction sites greatly reduces transportation costs, so this mining activity is dispersed throughout California.

Sand and gravel are often extracted from stream channels because deposits located within stream channels tend to have fewer impurities and are more durable than hillslope deposits. Aggregate mining in stream channels and floodplains has a variety of direct and indirect geomorphic consequences (Collins & Dunne 1990; Kondolf & Matthews 1993; Florsheim et al. 1998; NOAA Fisheries 2003). Excavating gravel or sand from a streambed changes the channel's hydraulic properties and interferes with the natural transport of sediment through the stream. For example, sediment in transport from upstream fills in the excavated area, reducing sediment supply to downstream reaches. Moreover, at the upstream edge of the excavated reach, channel slope and flow velocity are increased, and incision of the channel bed occurs, extending in the upstream direction (a process called headcutting). Thus instream aggregate extraction commonly causes channel bed erosion in both the upstream and downstream reaches. Secondary effects of the incision include loss of spawning gravels and an increase in bank height and bank erosion. Channel incision may initiate a lowering of the water table and associated losses of riparian vegetation. Gravel pits that are outside of an active channel can contribute significant amounts of sediment to a stream during mining activities, and sometimes present a flood hazard, through "pit capture." Floodplain aggregate extraction results in a loss of floodplain wetland habitat.

Suction dredging for gold in streambeds continues as an activity, more recreational than commercial, in the Klamath and Trinity river systems and in many streams on the west slope of the Sierra Nevada. While less intensive than commercial instream aggregate mining, the continuing disturbance of the streambed can potentially harm aquatic habitat, such as spawning and rearing sites for salmonids.

Watershed assessments should inventory and study both the current effects of active mines and the persistent effects of past mining. In areas once subjected to hydraulic mining, for example, some slopes may still be eroding at rates much greater than untouched hillsides, while downstream, large sediment deposits may still form unstable terraces high above a stream channel. Mercury may persist in stream channels where placer mining occurred and below ore-processing sites. Transformation of this elemental mercury to methyl mercury, a form more easily taken up by biota, introduces the toxin into the food chain and is the subject of current research. Heavy metals and other toxic leachates may be found in streams and groundwater below some mines and processing sites. Tailings piles and deposits should be checked for potential water pollutants. A good general reference on watershed impacts of mining is Nelson et al. (1991).

### 3.9.5 Grazing

Livestock grazing on California's rangelands can cause watershed impacts through changes in vegetative cover and soil conditions. When the number of animals and their access to streams and riparian are limited, the watershed impacts are modest and usually not noticeable. When the grazing pressure is great enough to restrict vegetative regrowth and compact the soil or cause direct impacts to streams and riparian areas, then the term overgrazing is descriptive. Overgrazing can remove most of the vegetative cover of an area, leaving the soil exposed to raindrop impacts, reducing infiltration, and accelerating erosion. The hooves of hundreds or thousands of livestock can also compact the soil, especially when the soil is wet. The combination of soil exposure and compaction can decrease infiltration and increase surface runoff. If infiltration capacity is severely limited on a large fraction of a watershed, the extra runoff can quickly reach streams and generate higher peak flows (e.g., Davis 1977).

Most of the concern about grazing impacts is associated with the riparian zone. Livestock gather in riparian areas for the water itself, as well as for abundant food and shade. Excessive streamside grazing that causes loss of trees, shrubs, and grasses along a stream affects the stream's shading and temperature and the stability of its banks. Without the protection of aboveground vegetation during high flows and the structural support of roots, stream banks erode back and develop shallower angles. This bank erosion eventually leads to channel shapes that are much wider and shallower than those of intact streams with vigorous riparian vegetation. Alternatively, some overgrazed streams begin an erosion cycle that results in a deep gully. When riparian areas are fenced off from other pastures and allowed to rest for a few years, the vegetation and subsequently the channels tend to recover remarkably well. A dramatic exception is where gullying has progressed to the point where the water table has been lowered, and the streamside meadows or riparian strips are literally high and dry.

The loss of vegetation cover and soil compaction also accelerates surface erosion. Many studies in the western United States have documented dramatic increases in sheet erosion and gully development in overgrazed sites compared to ungrazed sites (Fleischner 1994). The erosional effects of overgrazing add large amounts of sediment directly into the stream. The fine sediments tend to clog stream gravels and diminish spawning habitat for certain fish.

Concentrations of livestock in and around streams provide a direct pathway for nutrients and pathogens to enter the water (Springer & Gifford 1980). Animal wastes tend to be high in nitrates, a nutrient that is a water pollutant of concern. High nitrate loads promote the growth of aquatic algae, which can clog streams at low flow, as well as ponds and lakes. High levels of coliform and other bacteria have been found in streams with large numbers of livestock in adjacent areas. Good range and livestock management practices can help prevent or reduce impacts of grazing on the watershed. California recently completed a decade-long assessment of the status, trends, and challenges to California's rangelands (California Department of Forestry 2003).

### 3.9.6 Recreation

Impacts from recreational activities fall into two general categories: 1) localized effects, such as vegetation damage, soil compaction, and stream alteration that result from individuals visiting an area, and 2) large-scale effects, such as vegetation removal or conversion, creation of impervious surfaces, and engineered modification of stream channels that result from developing facilities to support recreational activities.

The individual recreational activities tend to have the greatest potential for watershed effects when they occur in and adjacent to a stream channel. Water is often a focal point for recreational activities, and streamside areas receive a disproportionate amount of recreational use within a watershed. Campgrounds, picnic areas, hiking and equestrian trails, and other facilities located near a stream provide easy access to water and contribute to degradation of riparian vegetation. As more people congregate along streams, the banks are trampled and the vegetation dies back, with impacts similar to riparian overgrazing (erosion accelerates and the channel changes form).

Off-highway vehicle use has both more intensive and more extensive effects on vegetation and soils than does non-motorized traffic, resulting in more loss of vegetation, more soil compaction, and more erosion. Operation of vehicles in stream channels kills aquatic and riparian vegetation, mobilizes sediments, and decreases channel stability.

Large-scale commercial recreational developments cause watershed impacts similar to those of other land use changes and conversions. Trees are cut down, roads and parking lots are built, topography is reshaped, drainage channels are constructed, and people congregate near water. These effects lead to changes in streamflow, accelerated erosion, and degraded water quality. Some developments require a substantial water supply, which may deplete local streamflow or groundwater. Two examples of large-scale recreational developments are golf courses and ski areas. Golf courses can transform the vegetation cover from deep-rooted species to shallow-rooted grasses requiring artificial irrigation and fertilizers. Developing a ski area involves permanent timber removal, major earthwork, extensive parking lots, and alteration of streamflow timing through snowmaking. Each of these changes leads to changes in streamflow volume, timing, and quality.

## 3.10 Water Management and Uses

Management of surface water resources occurs in the waterway and differs fundamentally from management of the landscape and resources other than water. Although land use changes and other resource management activities alter vegetation and soil properties that subsequently affect streamflow, water management avoids the intermediate steps and intentionally and directly changes the hydrologic regime. In many watersheds, this direct manipulation of the surface water alters flow, timing, and quality to such a great extent that the indirect consequences of land use change are incidental. In most cases, the measurable changes in streamflow or sediment delivery from a timber harvest or subdivision or other changes on the landscape are small compared to the hydrologic effects of dams that can store a large fraction of the annual runoff or diversions that can dry up a stream.

Management of groundwater resources is conceptually straightforward—deliberate control of input (recharge through ponds, canals, and injection wells) and output (pumping of wells). In practice, there is little true “management” of groundwater. In most areas, wells are just pumped to satisfy demand within any cost constraints, and there is no coordination or control of pumping. Groundwater management is rarely part of a watershed assessment but in many places should be. You should consider whether the topic warrants study in your watershed.

### 3.10.1 How Surface Water Is Managed

Water management includes all activities intended to change natural streamflow volume, timing, and location for the purpose of supplying water for human demands. Water is rarely available directly from nature at a desired quantity, time, and place. Great engineering works have been constructed to hold back floods, store water for the growing season, and deliver water hundreds of miles away from its source.

Dams and diversions (any structure that facilitates removing water from a stream for the purpose of transporting the water to another location) alter streamflow in a variety of ways. A stream’s hydrograph (a graph of how flow changes over time) is very different above and below a dam or major diversion.

Dams are constructed to alter streamflow timing. Water generated during the rainy or snowmelt season is captured behind the dam in a reservoir and released later to meet downstream needs (irrigation, municipal supply, hydroelectric generation, or instream flow, for example).

Depending on a dam’s size and flood reservation (management guidelines that keep part of the reservoir unfilled at different times of the year as related to the flood risk), peak flows may be entirely captured behind the dam and slowly released later in the year at a controlled rate. Smaller dams lack the capacity to have much effect on the hydrograph of large floods, whereas downstream of a big dam, there may be no indication of the floodwaters pouring in upstream. During the portions of the year when flows would be low under natural conditions, water releases from a reservoir may increase streamflow several fold above its natural level.

While dams primarily affect streamflow timing, diversions send water elsewhere, reducing natural instream flow. Individual water user's diversions not associated with large dams may have little effect on hydrograph timing except during low flow periods. However, larger water storage structures usually involve both storage and diversion.

Reservoirs dramatically change a stream's sediment transport properties. When a river enters the placid water of a reservoir, it deposits almost all the sediment it was carrying.

Streams below dams contain much less sediment than they would in the absence of the dam. Accordingly, they have an enhanced capacity to erode and transport particles from the bed and banks of the downstream channel. Progressive lowering of the riverbed often occurs below new dams. Further consequences that can result include reduction of groundwater levels and consequent loss of riparian vegetation, reduction in overbank flooding, deposition of sediments and nutrients, bank erosion, and loss of adjacent land (Galay 1983). Severity of channel lowering depends on the size of particles in the bed, channel characteristics, reservoir operation, and the sequence of flood events following construction. The alteration of sediment supply and transport changes the streambed conditions that many fish require for successful spawning. The unnatural channel and bank conditions created by the sediment alterations can also negatively impact the establishment, growth, and survival of riparian vegetation. In some cases where dams prevent high flows from scouring the channel, the stream can become choked with vegetation.

### 3.10.2 Aquatic Habitat

The aquatic system in any stream has evolved in response to the natural hydrologic regime—long-term average flows and timing, as well as extremes. Water management is designed to alter those attributes of streamflow. Impounding water behind a dam converts riverine habitat into an artificial lake. The continuity of aquatic and riparian habitat is abruptly cut by the dam and its reservoir. Organisms that migrate in the channel or along its banks may no longer move freely up or downstream. The dam greatly alters the flow of water and sediment downstream. The temperature and chemical content of water released below the dam may also be very different from the natural conditions. Such changes fundamentally alter the conditions for aquatic and riparian organisms. Inevitably, water management impacts aquatic communities with dramatic changes in community structure, species mix, and populations.

### 3.10.3 Irrigation

Providing water for irrigation is the main reason for impounding water in California, particularly in the reservoirs of the Central Valley Project. The vast majority of dams in the state were originally intended to store water from the winter wet season and release it for irrigation during the summer dry season. Irrigation requires massive volumes of water—about 33 million acre-feet each year in California (Department of Water Resources 1998). Much of this amount is diverted dozens to hundreds of miles from its source. Where farms are located adjacent to streams and rivers, the irrigation water will be diverted locally, and your watershed will include both the source and area of use. Typical water application rates range from 3 to 5 feet of water over the irrigated area. These application rates

**Table 3.5 Typical application rates of irrigation water for various crops in California. (Source: Department of Water Resources 1998)**

| Crop | Range of Applied Water (feet) |
|---|---|
| Corn | 1.5 to 4 |
| Cotton | 2.5 to 6 |
| Rice | 4.5 to 7 |
| Tomatoes | 2 to 5.5 |
| Grapes | 1 to 5.5 |
| Orchard Crops | 1 to 6.5 |
| Alfalfa | 2 to 10 |
| Pasture | 1 to 9 |

vary widely by crop and location around the state (Table 3.5). The county farm advisor and district offices of the California Department of Water Resources should have good crop water demand estimates for local conditions. If you are estimating irrigation water use within your watershed, most of that amount can be assumed to evaporate.

### 3.10.4 Hydroelectric Generation

Generating electricity from water and gravity requires a different management regime than storing water for irrigation. Although large, multipurpose water projects generate electricity in concert with releases for irrigation, projects intended primarily for hydropower release water to maximize revenue. Such projects aim to generate electricity at times when electric demand and rates are highest, such as on summer afternoons. Unlike most other sources of electricity, hydropower-generating facilities can be turned on and off relatively quickly. Below some hydroelectric powerhouses, discharges related to power demands can fluctuate drastically over a few hours. In such cases, there is usually an afterbay immediately downstream that regulates releases back into the river.

The process for the federal relicensing of hydroelectric projects under the Federal Energy Regulatory Commission (FERC) provides an opportunity to re-evaluate flow release schedules from these types of dams.

### 3.10.5 Municipal

Water storage and diversion for municipal supply influence streamflow in many watersheds. Timing of this demand differs from irrigation in that there is a base level of demand year-round, but water use for landscaping increases significantly during the summer growing season. This may stress aquatic environments during the summer, when temperatures may become too high due to reduced flows. Runoff from urban areas (e.g., for landscape irrigation) may turn seasonally dry streams into perennial waterways.

Municipal water supply utilities may be a potential partner in watershed management and restoration activities because of their need for high-quality water.

### 3.10.6 Recreation

Managing water for recreational purposes is generally interpreted as maintaining high water levels in large, multipurpose reservoirs during the summer boating season. Inevitably, there are management tradeoffs that attempt to balance irrigation, hydropower, flood management, and flat-water boating in such reservoirs. Flood control agencies prefer empty reservoirs. Irrigators, power companies, and boaters all want reservoirs filled to capacity, but the boaters prefer that level to be constant and the power producers and irrigators want to drop that level in response to their respective demands. Water releases from a dam are closely associated with the reservoir levels. The interests of different groups of recreationists conflict over reservoir management. Lake boaters and lake fishers prefer that reservoir levels remain high, but whitewater boaters and stream fishers prefer that reservoir levels drop to provide greater streamflow.

Downstream of some recently re-licensed hydroelectric projects, water releases are designed to benefit white-water boating. A significant example is the July 2000 settlement agreement on the Mokelumne River. As conditions for obtaining a new license to operate a series of powerhouses, dams, and diversions, the operator (Pacific Gas & Electric Company) will modify the operation of its system specifically to enhance recreational opportunities on the river. The agreement establishes an annual schedule of water releases at levels requested by whitewater boating enthusiasts and businesses. The agreement also includes an adaptive management program that adjusts streamflow volumes and frequency of releases based on actual use. Streamflow in the Mokelumne River is now regulated on certain days at flows desired by recreationists—yet another variation on natural streamflow. Increasing summer flows to support whitewater boating are unlikely to mimic the low-flow conditions that were naturally present before the reservoir was built.

### 3.10.7 Import and Export

Trans-basin diversions can import water into a watershed or export water out of it. Imports and exports can have major effects on the water balance. Water entering or leaving the watershed through engineered channels can also alter the timing of flows in natural channels, assuming there is some storage facility involved in the water diversions.

## 3.11 Social and Economic Setting

Watershed assessments rarely focus on human communities, or, if they do, it is usually to list the resource activities communities are involved in. There are many facets to characterizing watershed communities. Some of these are economic descriptions, how people in a watershed make money, how many people don't make very much, and the net exports or imports of commodities. Some are demographic pictures, showing more about who the people are, their ethnicity, their population centers, their age, education, and income distributions. The hardest to quantify is the part of the community picture that shows how involved people are in watershed protection activities and therefore how likely it is that particular restoration, monitoring, or management approaches will succeed if community participation is required.

### 3.11.1 Watershed Communities

Because watersheds literally cover the earth's landscape, everybody lives in one. The watersheds usually bear the name of the primary waterway, but human towns and cities only occasionally do. People may not identify with their watershed by name, but if there is any topography around, they are often aware that they are near a creek or river with a name. Certain economic, political, and social relationships depend on waterways and watersheds, for example, water diversion, county boundaries, and locations of towns and agricultural areas. The influence of the location of water on human geography is probably obvious. In the past, many towns sprang up where there was a water supply and fertile areas to grow or catch food (e.g., old floodplains and coastal areas). Now that water can be moved around in canals and pipes, and food can be imported, this is less of an issue.

Describing the interactions between human communities and watersheds is important because human activities and humans' perceptions of their environment are critical drivers in many ecosystems. Understanding how people are interacting with your watershed will provide information about potential impacts, likely future scenarios, possibilities for reduced impacts or restoring past impacts, and benefits to human communities of a naturally functioning watershed.

### 3.11.2 Characterizing Communities

If you characterize who lives in the watershed, you will have information to inform your decision making about restoration planning, the feasibility of monitoring, the need for education and outreach, and whether or not there is a constituency for watershed protection. The U.S. Environmental Protection Agency's "Community Culture and the Environment: A Guide to Understanding a Sense of Place" (U.S. EPA 2002) offers methods for this process. The guide's principles include: "holistic, place-based environmental protection efforts will lead to more effective long-term protection," "approaches [that] integrate ecological issues with local economic and social concern" help resolve or prevent environmental problems, and "tailoring environmental protection efforts to local realities and partnering with the community members leads to greater public support and involvement and, ultimately, to better environmental protection (U.S. EPA 2002). The handbook describes ways to characterize communities in terms of community capacity, demography, economics, and governing structures and provides various quantitative and qualitative assessment tools to develop a "community cultural assessment."

Another index of a community's character is the nature of its political activity. For example, Proposition 50 authorized the sale of bonds to protect watersheds and water supply. If 74% of the residents of a watershed voted against this proposition, then a watershed group planning Prop 50-funded projects might want to spend some time doing outreach and education to communities within the watershed to let them know what is happening. Information about community voting records at a watershed scale can be readily obtained with a GIS containing both the watershed boundaries and records from voting precincts. Because particular propositions can't really be called partisan in nature, they provide a politically neutral way to measure voter sentiments. There are other more direct and expensive ways to get this type of information. For example, surveying watershed residents about their preferences for watershed protection and restoration could provide important clues. If the watershed contains public lands, then the surveying should also include people outside the watershed who would then have a direct interest in management options for the watershed.

Although it may seem that information like this would only be interesting to a sociologist, the information might tell the watershed assessor a lot about likely attitudes and priorities for people in the watershed. Some of these will be obvious to a stakeholder group that represents the range of interests in a watershed, while some will be surprising. The worst-case scenario (which isn't really so bad) is that the watershed group discovers things they already knew, but now have numbers and other data to reinforce their intuitive knowledge.

## 3.12 Historic Context and Analysis

The condition of your watershed today needs to be interpreted in the context of historic changes since at least the time that European exploration and settlement began. Native American occupation appears to extend back 10,000 to 12,000 years, and their former use of the watershed is also important to understand, where possible. For some areas of California, European settlement began in the 1700s with the Spanish and Mexican occupation while in other areas, it was primarily the discovery of gold in 1849 that triggered the huge "American" influx. However, in the early 1800s, the Hudson Bay trappers came down from Oregon and extensively trapped the native beaver out of most of the state's streams where beaver could be found. Removing (or decimating) much of the population of this one aquatic mammal, which has a tendency to form woody debris dams in streams, may have had a profound effect on stream channel conditions, water storage, and hydrologic processes decades before the arrival of early settlers.

Identifying the condition and use of a watershed's resources at the time of settlement can be a type of "baseline" for your assessment, though it will necessarily be a fuzzy one. Accounts of local tribal customs may indicate the role of fire as a tool for hunting or acorn production, or the role of fish and popular fishing sites. Initial observations from the first wave of European visitors (as noted in personal diaries, army reports, etc.) can offer valuable insights into the condition of vegetation, streamflow (with extremes of drought and floods most commonly noted), and wildlife, for instance. Sometimes crude maps were drawn to identify trails or boundaries, and some useful landscape impressions or landmarks were perhaps noted (e.g., "hills covered with timber"; "creek dry"). Of course, geographic place names on old or current maps are another source of which natural resources in that area seemed to initially impress the pioneers (e.g., "Deer Creek", "Salmon River", "Dry Gulch", or "Beaver Valley")

The next step is to identify the location, timing, and the extent of changes in land and natural resource uses that could have affected the watershed's condition between settlement and the present. Such human uses include: roads, mining, logging, farming, grazing, urbanization, water development and use, hydropower, fishing, hunting, etc. Patterns of landscape disturbances also need to be described, such as the dates and size of wildfires, floods, and droughts. A chronology of events by year or decade can summarize the major changes. Old maps and landscape photographs can depict the changes even better.

Without knowing the context of land, water, and other environmental changes over time, our interpretation of the watershed's condition today could be missing the real reasons or causes. A devastating fire back in the 1920s might have altered the soil and therefore the vegetation types in one area; gravel mining to help surface a new highway in the 1960s might have rerouted the channel; a small dam built in 1900 but removed in 1970 might still be causing sediment and channel impacts. These are just a few examples of the richness in interpretation that can be gained in your watershed assessment through a good historical evaluation of natural resource uses and changes. With this understanding, then the "ah-hah!" light bulb may go on and we can become more realistic in the next phase after the assessment – what to do next.

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