STREAM AND WETLAND SYSTEMS:

PHYSICAL FORMS, ECOLOGICAL PROCESSES, AND WATER QUALITY FUNCTIONS

DRAFT REPORT

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Note:

Staff of the North Coast Regional Water Quality Control Board (Regional Water Board) is developing an amendment for consideration by the Regional Water Board to the Water Quality Control Plan (Basin Plan) for the North Coast Region. The purpose of this amendment—the *Stream and Wetland Systems Protection Policy*—will be to protect and restore the physical characteristics of stream and wetland systems, including their connectivity and natural hydrologic regimes, in order to protect beneficial uses.

This draft report has been prepared by staff and summarizes part of the scientific literature that staff has reviewed during its background research for the *Stream and Wetland Systems Protection Policy*. At this time, this draft report is being provided to the public as an informational document only. Information presented in this draft report may eventually be included in a Staff Report for the *Stream and Wetland Systems Protection Policy* to establish part of the scientific justification or basis for the amendment. However, this draft report does not present or provide the full scientific justification or basis for a specific policy and should not be interpreted as the Staff Report for the *Stream and Wetland Systems Protection Policy*.

Pursuant to California Health and Safety Code section 57004, the scientific justification or basis for any rule proposed for adoption by the Regional Water Board must undergo an external scientific peer review. Therefore, any portions of this draft report that may eventually be included in the Staff Report for the *Stream and Wetland Systems Protection Policy* to establish the scientific justification or basis for the amendment will undergo external scientific peer review at the appropriate time prior to public release of the Staff Report. This draft report has not undergone external scientific peer review.

Although staff welcomes comments on this draft report, formal public comments are not being solicited at this time and staff will not prepare formal responses to comments received on this draft report. Formal public comments will be solicited on the Staff Report when it is released and staff will prepare formal responses to comments received on the Staff Report at that time.

More information on the *Stream and Wetland Systems Protection Policy* as well as an electronic copy of this report can be found online at: http://www.waterboards.ca.gov/northcoast/programs/basinplan/swspp.html. Questions about this report or the *Stream and Wetland Systems Protection Policy* should be directed to Bruce Ho, lead author, at BHo@waterboards.ca.gov or 707-576-2460, or to Holly Lundborg, lead staff in the Basin Planning Unit, at HLundborg@waterboards.ca.gov or 707-576-2609.

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EXECUTIVE SUMMARY

This report looks at the ways in which stream and wetland systems, which include streams, wetlands and their associated aquatic and terrestrial environments, protect and enhance water quality and support the beneficial uses of waters of the State of California. This report provides the scientific background and context for the *Stream and Wetland Systems Protection Policy*, which is currently being developed as an amendment to the *Water Quality Control Plan for the North Coast Region*. This report does not propose specific policy. Rather, it supports development of water quality control strategies that utilize holistic, watershed-based approaches to address existing and potential threats to surface water and groundwater quality as a result of point and nonpoint source pollution (such as the approach proposed for the *Stream and Wetland Systems Protection Policy*).

This report draws from peer-reviewed scientific literature and local, state, and federal government agency research and guidance documents to describe the water quality functions of stream and wetland systems. This report further identifies the natural physical forms and ecological processes of these systems that are responsible for providing these water quality functions. Key stream and wetland system functions identified in this report include:

- Flood attenuation;
- Groundwater recharge and discharge;
- Surface water supply and replenishment;
- Sediment transport and storage;
- Nutrient and organic matter cycling;
- Pollutant filtration;
- Temperature and microclimate control; and
- Maintenance of plant and animal communities.

Although not a primary focus of this report, an underlying theme is that land use practices that disrupt key environmental variables and ecological processes may impair the ability of stream and wetland systems to perform water quality functions and provide beneficial uses. Activities in terrestrial environments can significantly influence watershed processes, including the transport and storage of water, sediments, nutrients, organisms, and other chemicals and materials, which directly affect the water quality of streams and wetlands and other aquatic habitats. By better understanding and recognizing these key environmental variables and ecological processes, it may be possible to implement land use management measures in ways that are compatible with stream and wetland systems, and to restore modified systems in such ways that protect and restore water quality and beneficial uses.

1. INTRODUCTION

Historically, the role of natural aquatic ecosystems in protecting water quality has not been well understood and significant degradation of these areas has occurred. For example, the number of wetland acres in California is less than 10 percent of the historic value and many of the remaining wetlands have been modified or degraded (Keeley and Zedler 1998; Traut 2005; Van Dyke and Wasson 2005; Dahl 1990; Ambrose and others 2006; Zedler and Kercher 2005). Impacts to streams also have been significant. Losses of stream riparian areas in California are estimated at 85 to 98 percent of their historic values (Riparian Habitat Joint Venture 2004). Other stream impacts, including channelization, dams, diversions, and increased pollutant loads, have impaired stream ecological processes and biological communities (e.g., Dynesius and Nilsson 1994; Kondolf and others 1996; Tockner and Stanford 2002). Activities that impact streams also may adversely affect human land uses by increasing flood damages and contributing to problems such as streambank failures, which can threaten infrastructure and necessitate expensive repairs (e.g., Booth 1991; Kondolf 1994).

As scientific understanding of streams and wetlands has increased over the last fifty years, state and federal governments have enacted laws, such as the federal Clean Water Act and California's Porter-Cologne Water Quality Control Act, to better protect these areas. Wetlands in California also are now protected under the California Wetlands Conservation Policy, which sets a goal to "ensure no overall net loss and achieve a long-term net gain in the quantity, quality, and permanence of wetlands acreage and values in California in a manner that fosters creativity, stewardship, and respect for private property" (Executive Order W-59-93). The federal government has adopted a similar wetlands policy at the federal level (Lewis 1995). However, despite these laws and policies, degradation of streams and wetlands continues to threaten water quality (Stoddard and others 2005; Ambrose and others 2006).

While billions of dollars are spent worldwide on stream and wetland restoration each year, including significant investments in the U.S. and California, restoration projects may fail without a proper understanding of the natural ecological processes that occur in and maintain these ecosystems (Bernhardt and others 2005; Palmer and others 2005). Additionally, the high cost of restoration has shown that preventing impacts by protecting intact or less degraded streams and wetlands is often more cost effective than attempting to reverse impacts later (Kauffman and others 1997; Kondolf 1998).

In order to protect and enhance the water quality of aquatic ecosystems, it is necessary to understand how these ecosystems function within their natural environments and how changes to the environment may affect the unique ecosystem services they provide. This report focuses specifically on two types of aquatic ecosystems—streams and wetlands—

and the climatic, geologic, and landscape variables that determine their physical forms, ecological processes, and water quality functions.[1]

Because other aquatic and terrestrial ecosystems—for example, groundwater basins, lakes, riparian areas, coastal and marine environments, including estuaries, and the surrounding landscapes—interact with streams and wetlands, this report also considers areas that help maintain and are maintained by streams and wetlands. In so doing, this report develops a central theme, which is that streams and wetlands are reflections of their surrounding landscapes and are significant drivers of landscape evolution. Inherent within this theme is that it is not possible to explain how streams and wetlands function if they are viewed as independent from their associated landscapes.

The terms stream system and wetland system (collectively referred to as stream and wetland systems) are used in this report to capture the concept that streams and wetlands and their surrounding landscapes are integrated ecological units. Individual stream and wetland systems are functional ecosystems that protect and enhance water quality and in which all parts—streams, wetlands, and other associated terrestrial and aquatic ecosystems—contribute to cumulative and individual measures of ecosystem health (e.g., the quality of water supplies, diversity of biotic communities, and resiliency or ability to recover from disturbance). Healthy stream and wetland systems provide water quality functions that can include fish and wildlife habitat as well as clean drinking water sources and landscapes that minimize flood damages and stream instabilities, such as streambank failures.

This report is organized into four sections. First, the watershed is introduced as the basic functional unit within which to analyze stream and wetland systems. Ecological processes at the watershed scale, including the hydrologic cycle, interactions between aquatic and terrestrial ecosystems, and biotic life cycles are described in general terms to set the stage for more specific discussions of individual systems in the following sections. Second, wetland systems are introduced as key aquatic ecosystems within the watershed that affect site-specific, watershed-level, and region-wide water quality. This section focuses primarily on the internal processes of wetlands and the ways in which watershed variables affect these processes. Next, the stream system is introduced as the dominant aquatic ecosystem within the watershed that connects the upper and lower domains and integrates watershed variables into key measures of water quality and ecosystem health. The roles of wetlands and other aquatic and terrestrial ecosystems in protecting and enhancing stream water quality are discussed, as are the roles that streams play in maintaining and improving these other ecosystems. This section connects the concept of

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[1] The term "water quality function" as used in this report is inextricably linked to the term "beneficial use" as used by the California State Water Resources Control Board (State Water Board) and the nine Regional Water Quality Control Boards (Regional Water Boards) to protect waters of the state of California under the state's Porter-Cologne Water Quality Control Act and the federal Clean Water Act. The State and Regional Water Boards have specifically recognized many water quality functions as beneficial uses and in these cases the two terms are interchangeable. Other water quality functions have not been recognized as individual beneficial uses, but as shown in this report, these functions directly support the beneficial uses of waters of the state.

individual stream and wetland systems to the broader concept of the watershed in which many stream and wetland systems combine to protect and enhance watershed- and region-wide water quality. Finally, this report concludes by briefly summarizing and discussing the concepts presented in earlier sections and their applicability to existing and emerging water quality concerns.

2. THE WATERSHED

A watershed, also known as a drainage basin or catchment, is the land area that drains to a single point in the landscape, such as the mouth of a stream. Watersheds integrate the physical forms and ecological processes that affect water quality and are the basic functional units of aquatic ecosystems (Kauffman and others 1997; May 1998; Leopold and others 1964). Watersheds can be viewed at a variety of spatial scales, from individual streams and wetlands to complex drainage networks that connect headwater streams to inland lakes and oceans. Watershed processes also can be viewed at different temporal scales, from single events to seasonal variation to longer-term patterns that extend across multiple years. In order to understand how aquatic ecosystems function, it is necessary to consider multiple watershed scales and the interactions that occur between these scales (Petts 2000; Poole 2002; Hughes and others 2001; Sedell and others 1990; Ward 1989). Furthermore, it is necessary to understand how watersheds are organized spatially and temporally within these scales because watershed conditions change across the landscape as a result of short- and long-term ecological processes (Ward 1989; FISRWG 1998; Naiman and others 1992).

Watersheds can be organized spatially along longitudinal, lateral, and vertical dimensions (see Figure 1). The longitudinal dimension refers to the direction of flow between upstream and downstream areas; the lateral dimension is the dimension that extends outward from the aquatic ecosystem into terrestrial environments; and the vertical dimension is the dimension that connects surface and subsurface flow pathways. Temporal variability in climate, geology, and landscape variables across these spatial dimensions and at different spatial scales drives ecological processes that determine watershed conditions (Ward 1989; FISRWG 1998; Naiman and others 1992). By understanding how these variables have interacted over time to shape the current watershed environment, it may be possible to predict how future land-use and management changes will shape future processes and conditions as a watershed continues to evolve (Sparks and others 1998).

This section provides a broad overview of critical watershed attributes—climate, geology, and landscape—that influence aquatic ecosystem processes at the macro-scale. Therefore, for the purposes of this section, the term watershed is used to refer to large landscapes in which multiple streams and wetlands interact and are connected through hydrologic processes. Smaller watershed scales are considered in later sections of this report, as are the roles that large-scale ecological processes play in shaping conditions at these smaller scales.

2.1 Climate

Climate controls the hydrologic cycle, which, along with geology and the landscape, drives watershed ecological processes. Key hydrologic variables controlled or significantly influenced by climate include:

1. Total annual precipitation;

2. The frequency, timing, magnitude, and duration of storms and storm peak flows;

3. The amount of precipitation that falls as snow and the timing of snowmelt;

4. Water temperatures; and

5. Water loss through evapotranspiration.

Combined, these variables constitute the hydrologic regimes of streams and wetlands in the watershed and are responsible for the development and maintenance of aquatic ecosystems (Poff and others 1997; Lewis 1995). Climatic variability between seasons, between years, and over long-term timescales also influences watershed processes and the natural physical forms, ecological processes, and water quality functions of individual aquatic ecosystems.

Mediterranean climate regions, such as coastal California, are characterized by wet winter months followed by a prolonged dry season. Although the exact durations of the wet and dry periods vary between years, the wet season generally occurs between mid-October and mid-May and is followed by seasonal drought that extends through the warm summer months and into the fall. As the dry season occurs during the time of year when evapotranspiration is highest, Mediterranean climate regions undergo annual periods of desiccation. Another feature of Mediterranean climates is significant variability in precipitation between years, such that years of higher than normal precipitation may be followed by extended drought (Gasith and Resh 1999; Bauder 2005). Although annual precipitation increases and average temperatures decrease in the northern regions of coastal California, the climate pattern remains highly seasonal (Naiman and others 1992). The seasonal concentration of rainfall and year-to-year variability in precipitation and flows means that in many ways, Mediterranean climate regions have less in common with humid areas than they do with arid ones, in which large, infrequent floods are a dominant ecological process that influences physical forms (Kondolf 1998; Kondolf and others 2001; Osterkamp and Friedman 2000; Tooth 2000; Valett and others 2005).

The consequences of this climate regime on aquatic ecosystems are several-fold:

1. Annual precipitation is concentrated during a few months of the year and a majority of annual rainfall may fall during a few large storms, making large storm events and flooding important, recurrent processes in watersheds (Gasith and Resh 1999);

2. Flood processes create temporal variability in the spatial extent and conditions of aquatic ecosystems, which increases habitat diversity (Kondolf 1998);

3. Interannual variability in precipitation provides that some years are characterized by larger than normal floods, and these large-scale natural disturbances may influence ecosystem processes beyond the single-year timeframe (Gasith and Resh 1999; Sloan and others 2001);

4. Because concentrated annual rainfall is followed by an extended dry season, many aquatic ecosystems are seasonal (e.g., intermittent streams, ephemeral streams, seasonal wetlands, and floodplains[2]) (Tooth 2000);

5. A prolonged dry season increases competition for water resources among water users, both human and non-human (Gasith and Resh 1999); and

6. Aquatic biota are adapted to predictable seasonal floods, wet-dry season fluctuations, and high magnitude infrequent flood events, and their life cycle stages, including breeding, rearing, migration, dispersal, and establishment, depend on these seasonal and interannual events (Gasith and Resh 1999).

2.2 Geology

Along with climate, geology is responsible for establishing the physical environment within the watershed, and it is necessary to understand the role of geology in shaping watershed landforms in order to understand how aquatic ecosystems function. Because current watershed conditions may, at least in part, reflect hundreds to thousands of years of geologic and hydrologic processes it is also important to consider both the short- and long-term roles of geology in determining spatial and temporal variability in the watershed (O'Connor and others 2003; Naiman and others 2000).

Watershed characteristics, including valley slope, channel slope, sediment loads, and sediment sizes are products of geomorphic processes, which are created by the intersection of geology and hydrology. As water moves through the watershed under the force of gravity, it travels over, under, and between surface and subsurface stratums. A portion of this geologic material, determined by its erodibility and the force of water, is carried by water through the aquatic ecosystem as sediment before eventually being deposited downstream. This process of erosion and deposition is responsible for developing watershed landforms, such as stream channels and floodplains. Geologic processes also influence channel gradients and the development of landforms, such as hill slopes. These landforms may further evolve as a result of mass movements and erosion (Leopold and others 1964).

The influence of geology on aquatic ecosystems varies by geologic parent material, location within the watershed, and climate. Valley slope is important in determining how water flows through the watershed and landscape position influences the hydrologic and sediment regimes of aquatic ecosystems (Naiman and others 1992; Bauder 2005). For example, steep landscapes, such as headwater regions, with unstable materials, may be characterized by episodic sediment disturbance regimes in which large storms trigger mass movements (e.g., debris slides or debris flows) that can deliver sediment to the aquatic ecosystem (Grant and Wolff 1991).

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[2] A floodplain may be defined generally as "a strip of relatively smooth land bordering a stream and overflowed at time of high water" (Leopold and others 1964, p. 317). Floodplains are discussed in more detail on page 20.

2.3 Landscape

In addition to climate and geology, aquatic ecosystem water quality reflects landscape conditions in the watershed. As landscape attributes change in space and over time, they affect the ecological processes that shape aquatic ecosystems, and it is necessary to consider aquatic ecosystems within the context of their surrounding landscapes in order to understand how they function and evolve over time (Gergel and others 2002; Décamps 1993; Reid 1998).

The watershed landscape is composed of heterogeneous habitats, or patches, such as stream reaches, individual wetlands, corridors of riparian vegetation, and communities of upland vegetation (see Figure 2). The distribution, abundance, and types of patches affect ecological processes. The scale of observation or analysis also influences the definition of individual patches, such that patches viewed at a large scale may themselves be composed of many different habitat types when viewed at a smaller scale. Therefore, the scale of observation used should be appropriate for the ecological process in question (Turner 1989; Wiens 2002; Poole 2002).

Individual patches may act as barriers or corridors for the movement of water, materials, and organisms, and interactions between patches as a result of these properties affect ecological processes (Puth and Wilson 2001; Pringle and others 1988; Wiens 2002). For example, a large stream may act as a habitat barrier for some terrestrial species, but may be a migration corridor for fish by connecting upper and lower stream reaches and habitats in the watershed. Connectivity and disconnectivity exist on a continuum and the level of connectivity or disconnectivity provided by an individual patch may vary over time and between ecological processes (Puth and Wilson 2001). For example, uplands isolate many depressional wetlands from other surface waters under normal hydrologic conditions, but may connect these wetlands to streams or other water bodies during periods of higher flows. Additionally, while uplands may provide barriers to surface water movement, groundwater pathways may provide subsurface hydrologic connectivity (Leibowitz 2003).

Landscapes include transitional boundaries, or ecotones, between patches that provide gradients in landforms and ecological processes within individual ecosystems as well as between different types of ecosystems (Kolasa and Weber 1995; Verry and others 2004; Poole 2002). Riparian areas, which are ecotones that connect aquatic and terrestrial environments, are some of the most important ecotones in the landscape and are discussed throughout this report. The National Research Council defines riparian areas as areas that are:

> …transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect water bodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence).

> Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine-marine shorelines. (Brinson 2002, p. 33)

Generally, the term riparian area refers to two types of areas in the landscape. First, riparian areas include areas that are influenced by aquatic ecosystems. Perennial and seasonal surface water flows and high water tables create surface and subsurface environments adjacent to stream channels and wetlands that are wetter than adjacent uplands. These areas support unique biotic communities, such as phreatophytic vegetation, which are plants that depend on saturated soils in the rooting zone. Second, riparian areas include areas that influence aquatic ecosystems by acting as sources of water, materials, or organisms or by buffering aquatic ecosystems from terrestrial influences. These two regions frequently overlap. For example, vegetation may be sustained by water from the aquatic ecosystem, while also providing functions to the aquatic ecosystem, such as temperature and microclimate control and input of organic material (Naiman and others 1992; Kondolf and others 1996; Tabacchi and others 1998). In this report, an area that is directly influenced by the surface or subsurface hydrology of an aquatic ecosystem is generally considered to be an extension of the aquatic ecosystem itself. Areas that provide functions to aquatic ecosystems but are not directly influenced by aquatic ecosystem hydrology are generally considered to be part of the broader landscape, although their effects on water quality may be equally as important.

3. WETLAND SYSTEMS

Research on wetlands has dramatically increased since the late-1970s (see Figure 3) and this research has revealed the important role that natural wetland systems play in protecting watershed-wide water quality (Lewis 1995). This section describes what wetlands are; identifies several of their key characteristics and ecological processes; describes how wetlands function within the landscape; and identifies the ways in which watershed variables, such as climate, geology, and landscape interact with natural wetland systems to protect and enhance water quality.

Wetlands are frequently associated with streams and other water bodies, and a thorough discussion of wetland systems by nature must incorporate processes that occur between wetlands and other water bodies. Some of that discussion is contained in this section; however, interactions between wetlands and streams also are discussed in later sections within the context of stream systems.

3.1 What Are Wetlands?

Wetlands are aquatic ecosystems that are characterized by unique hydrologic regimes that affect their physical, chemical, and biological attributes. The term wetland itself is relatively new, although other words have long been used to describe these areas (Lewis 1995). The term wetland encompasses a variety of other terms for aquatic ecosystems, including marshes, swamps, mudflats, sandflats, unvegetated ponded areas, vegetated shallows, sloughs, wet meadows, bogs, fens, playa lakes, prairie potholes, river overflow areas, natural ponds, vernal pools, and diked baylands. State and federal agencies have developed a variety of definitions for the term wetland (see Table 1), all of which reference common wetland characteristics, which include wetland hydrology, wetland substrates, and wetland biota. The National Research Council also has developed a scientific reference definition for wetlands that is independent from a specific regulatory context. The National Research Council defines a wetland as:

> … an ecosystem that depends on constant or recurrent, shallow inundation or saturation at or near the surface of the substrate. The minimum essential characteristics of a wetland are recurrent, sustained inundation or saturation at or near the surface and the presence of physical, chemical, and biological features reflective of recurrent, sustained inundation or saturation. Common diagnostic features of wetlands are hydric soils and hydrophytic vegetation. These features will be present except where specific physicochemical, biotic, or anthropogenic factors have removed them or prevented their development. (Lewis 1995, p. 59)

This definition is used here to provide a baseline by which other definitions can be compared and to avoid limiting the discussion of wetlands in this section to a particular agency or program. Most of the definitions used by state and federal agencies may be considered scientific, but to some extent these definitions also reflect the policy goals and decisions of their developing agencies. Therefore, some areas that are considered to be wetlands under one agency's definition may not be identified as wetlands under another agency's definition. While differences in the regulatory definitions of wetlands do not affect how aquatic ecosystems function in the watershed, they may limit the ability of individual agencies to address some wetlands and some wetland functions. Although such disparities exist, in general, the different wetland definitions are sufficiently similar such that the majority of concepts discussed in this section are applicable to all areas identified as wetlands under any of the state and federal agency definitions for wetlands that are listed in Table 1.

3.1.1. Wetland Hydrology

Wetland hydrology, which the National Research Council describes as "recurrent, sustained inundation or saturation at or near the surface," (Lewis 1995, p. 59), is the "driving force" that "controls the abiotic and biotic characteristics of wetlands" (Lewis 1995, p. 22). Wetlands generally have surface water depths of less than two meters, which distinguish them from deepwater aquatic ecosystems, such as lakes and many streams. Some wetlands are not regularly inundated, but contain saturated substrates for some period of time, which is the minimum hydrologic criteria that can be expected to lead to the development of characteristic wetland features, such as hydric soils and hydrophytic vegetation (Cowardin and others 1979; Environmental Laboratory 1987). Some wetlands are permanently wet, but many are non-perennial waters that are only periodically inundated or saturated during certain seasons or, in the case of many coastal wetlands, during high tides (Lewis 1995; Keeley and Zedler 1998; Euliss and others 2004). Shallow water depths and fluctuations between wet and dry periods create unique physical, chemical, and biological conditions within wetlands. These water depths and water level fluctuations also give wetlands characteristics of both terrestrial and aquatic ecosystems, which is why wetlands are sometimes described as "transitional" habitats, or ecotones (Lewis 1995; Cowardin and others 1979; Kolasa and Weber 1995).

Most wetlands undergo some form of seasonal change as a result of differences in seasonal water availability, and the specific temporal pattern of water level fluctuations in a wetland is known as its hydroperiod. Climate plays a critical role in determining this hydroperiod by controlling the amount of water available to the wetland and the timing of water availability (Lewis 1995). In Mediterranean climate regions, such as coastal California, water availability is highly seasonal and some wetland types, such as vernal pools, may be wet during the winter, but completely dry during the summer (Keeley and Zedler 1998). There also may be significant differences in wetlands between years due to interannual variability in precipitation (Keeley and Zedler 1998; Bauder 2005).

Wet-dry cycles control the direction of water flow in wetlands and in the watershed as a whole by promoting groundwater recharge or discharge, by controlling whether surface water flows are primarily into or out of wetlands, and determining whether wetlands experience a net loss of water to the atmosphere through evapotranspiration (Leibowitz 2003; Bullock and Acreman 2003; Euliss and others 2004; Elmore and others 2006; Rains and others 2005; Whigham and Jordan 2003; Winter and LaBaugh 2003; Middleton 2002; Naiman and others 1992).

3.1.2. Wetland Substrates

Sustained inundation or saturation tends to create anaerobic conditions, or a lack of oxygen, in wetland substrates, which limits the types of chemical and biological activity that can occur there. For example, although primary productivity in wetlands may be high, anaerobic conditions slow decomposition, and as a result wetland substrates tend to accumulate organic matter over time. Wetland hydrology does not always create anaerobic conditions (e.g., in wetlands where natural or artificial disturbance of substrates increases oxygen flow, or where the wetland water source contains a high concentration of dissolved oxygen), but in those wetlands where anaerobic conditions do exist, these conditions significantly influence the chemical characteristics of wetlands and the biotic communities that inhabit them (Lewis 1995). Anaerobic conditions in wetlands with soil substrates create hydric soils, which may develop specific physical and chemical indicators of wetland hydrology (Lewis 1995; Environmental Laboratory 1987). Hydric soils are a common characteristic of wetlands; however, as noted above, some wetlands do not develop anaerobic conditions and wetlands also may have non-soil substrates (e.g., rocky beaches) so hydric soils are not a universal wetland characteristic (Lewis 1995; Cowardin and others 1979).

3.1.3. Wetland Biota

Anaerobic conditions created by wetland hydrology are stressors for many plant species, and these conditions may impede or prevent such species from colonizing wetlands. Most plant species are not adapted to low-oxygen environments, and the reducing conditions in such environments also may create pH levels or chemical compounds that are toxic to many plant species. Those plants that are adapted to grow in or to withstand anaerobic conditions are called hydrophytes, and the presence of hydrophytic vegetation is commonly used to identify wetlands (Lewis 1995; Cowardin and others 1979; Environmental Laboratory 1987). Some wetlands, particularly riverine wetlands, are periodically exposed to moving water, and some plant species may not be able to tolerate the physical stresses created by these conditions. Seasonal drying of wetlands also may prevent some species from establishing. As a result, wetland plants tend to be those species that are adapted to a variety of stressors that inhibit other species (Lewis 1995; Keeley and Zedler 1998).

While wetland hydrology may create chemical conditions that are unfavorable to some organisms, this hydrology also provides necessary habitat conditions for a variety of other organisms. For example, plant species with high water requirements may only occupy wetlands as do a variety of species of aquatic invertebrates and amphibians that require standing water for all or part of their life cycles (Lewis 1995; Euliss and others 2002; Keeley and Zedler 1998). Many wetland species also are specifically adapted to wet-dry cycles, such that the timing of their life cycle stages, including breeding and rearing, correspond to the normal timing of water availability (Bauder 2005; Leibowitz 2003).

Climatic variability and disturbance are two of the primary factors that determine wetland vegetation communities (Jackson and Allen-Diaz 2006). Seasonal water availability may affect plant species composition, with hydrophytes dominating seasonal wetlands during the wet months and upland species dominating during drier periods (Bauder 2005; Keeley and Zedler 1998). Seasonal flooding may be followed by a sharp increase in plant productivity (Euliss and others 2004). Total annual precipitation also affects the distribution of wetland and upland plant species, particularly in seasonal wetlands, by controlling the degree of wetness or length of ponding. During drier than normal years, wetland species may remain dormant, while upland species dominate (Bauder 2005; Keeley and Zedler 1998). Annual precipitation also affects flood magnitudes, which impact the succession of plant communities in riverine wetlands (Naiman and others 1992).

3.2 Wetlands in the Landscape

Climate, geology, and landscape attributes, such as proximity to other aquatic and terrestrial ecosystems, influence wetland characteristics and water quality functions by controlling the specific hydrologic regimes of individual wetlands and the types of materials and organisms available to them (see Figure 4; Carter 1996; Lewis 1995; Collins and others 2006). Differences in these watershed variables create a wide range of wetland types, which correspondingly perform a wide range of water quality functions (Cowardin and others 1979; Brinson 1993; Smith and others 1995).

3.2.1. Influence of Geology

Geology controls wetland development and ecological processes by influencing the ways in which water flows into and within wetlands. Basin slope influences wetland hydrology by controlling the magnitude and timing of surface water flows to wetlands (Bauder 2005). In riverine wetlands, the influence of these flows also may be determined by geomorphic structures (e.g., stream channels, floodplains, levees, and backwater areas) within stream corridors, which provide different hydrologic regimes and chemical processes (Johnston and others 2001). Geology, topography, and landforms also influence wetland hydrology by determining factors such as wetland depth and groundwater flows (Cole and others 1997; Stein and others 2004).

Wetland depth may affect a wetland’s hydroperiod, with deeper wetlands maintaining water levels for longer periods of the year and shallower wetlands experiencing more variable flows (Brooks and Hayashi 2002). Depending on their underlying geology and their location within the watershed, wetlands may recharge groundwater basins or may receive groundwater discharge. This relationship to groundwater is an important factor in determining wetland hydrology and may affect the composition of wetland biota (Stein and others 2004; Brinson 1993; Euliss and others 2004). In vernal pools, underlying strata form impervious subsurface layers that perch water tables and create surface pools (Keeley and Zedler 1998; Rains and others 2005). Where groundwater intersects the land surface, water seepage recharges wetlands (see Figure 5). Such wetlands may be buffered against seasonal changes in precipitation if the groundwater source is sufficiently large (Brinson 1993).

Finally, geology affects soil and groundwater chemistry, which may affect biochemical processes in wetlands (Stein and others 2004). For example, groundwater often carries solutes, such as salts, which affect wetland chemistry (Euliss and others 2004).

3.2.2. Landscape Interactions

The types, conditions, and proximities of aquatic ecosystems influence flows of water, materials, and organisms into and out of wetlands. Additionally, a variety of terrestrial landscape features moderate interactions between wetlands and their adjacent terrestrial ecosystems. Terrestrial areas that influence wetland condition and transitional zones between wetlands and terrestrial ecosystems are wetland riparian areas. Other aquatic ecosystems as well as wetland riparian areas influence both the water quality and hydrologic regimes of wetlands. For example, terrestrial vegetation surrounding a wetland may influence how water flows through the landscape and may affect wetland water levels and water chemistry through processes such as nutrient uptake (Euliss and others 2004; Euliss and others 2002). Proximity to other aquatic ecosystems and access to flows from these ecosystems also affect wetland hydrology. For example, coastal wetlands, such as salt marshes, are affected by tides, while riverine wetlands rely on periodic floods for recharge (Middleton 2002; Naiman and others 1992; Greer and Stow 2003).

The watershed may supply a variety of materials to wetlands, including sediment and nutrients, which affect wetland characteristics (Mayer 2005; Euliss and others 2004; Fisher and Acreman 2004; Reuter and others 1992; Whigham and Jordan 2003). Flows from adjacent aquatic ecosystems may provide these materials as well as drive wetland biochemical processes, including denitrification and decomposition of organic matter (Middleton 2002; Bayley 1995; Junk and others 1989; Kang and Stanley 2005; Machefert and Dise 2004; Pinay and others 2002; Tabacchi and others 1990; Valett and others 2005). Other wetlands in the watershed, particularly wetlands of other types, may store or transform sediment, nutrients, or other pollutants before they reach a wetland, or may be sources of these materials, thereby influencing the water quality of the receiving wetland (Traut 2005; Fisher and Acreman 2004; Whigham and Jordan 2003).

Wetland biota reflects both conditions within the wetland itself and conditions within the broader landscape. Wetlands surrounded by forested areas may be buffered from invasion by exotic species, thereby protecting species biodiversity (Houlahan and others 2006). Other aquatic ecosystems may help replenish species in some wetlands (e.g., riverine wetlands) while in other wetlands (e.g., vernal pools) species may be protected through their relative isolation from aquatic habitats that might otherwise act as sources of predators or competitors (Middleton 2002; Zedler 2003; Leibowitz 2003). Terrestrial areas in the landscape may connect aquatic habitats or may provide habitat for wetland species, such as many amphibians, which require access to both terrestrial and aquatic ecosystems during different life cycle stages (Semlitsch 1998; Semlitsch and Bodie 2003; Trenham and Shaffer 2005). Groups of similar wetlands within a watershed or region may collectively support populations of plant and animal species that might not otherwise persist. Such wetlands collectively maintain the species pool by providing sufficient habitat and refugia to withstand disturbance, and migrants to re-colonize disturbed wetlands (Leibowitz 2003; Trenham and Shaffer 2005; Leidy and White 1998).

Finally, climate affects the degree of connectivity between wetlands and other water bodies in the watershed. Seasonal flooding within watersheds may provide periodic pathways for water, materials, and organisms to both enter and exit wetlands. Some geographically isolated wetlands may not be connected to other water bodies through surface water or groundwater pathways in normal hydrologic years, but wet years may provide intermittent hydrologic connections (Middleton 2002; Naiman and others 1992; Leibowitz 2003; Whigham and Jordan 2003; Winter and LaBaugh 2003). The degree of connectivity between wetlands and other water bodies impacts their species composition as well as their contributions to watershed ecological processes and to the water quality of other water bodies in the watershed (Zedler 2003; Leibowitz 2003; Fisher and Acreman 2004).

3.3 Wetland Water Quality Functions

Although wetlands occupy only a relatively small percentage of the landscape, they perform a variety of critical water quality functions (Lewis 1995; Dahl 1990). These functions include:

- Flood attenuation;
- Groundwater recharge and discharge;
- Surface water supply and replenishment;
- Sediment storage;
- Nutrient and organic matter cycling;
- Pollutant filtration; and
- Maintenance of plant and animal communities.

Many of these functions affect water quality within wetlands as well as the water quality of other water bodies in the watershed. This occurs because wetlands supply water, materials, and organisms to other water bodies and may be permanently or periodically connected to these water bodies through surface and subsurface hydrology. The roles of wetlands in protecting the water quality of other water bodies are briefly discussed here, but are covered in more detail later in the discussion of stream systems. The specific water quality functions of wetlands are determined by their individual attributes (see Table 2 and Table 3) as well as the interactions between individual wetlands and watershed variables such as climate, geology, and landscape. Therefore, some of the functions described here are not provided by all wetlands or are provided by different wetlands to varying degrees.

3.3.1. Flood Attenuation

Wetlands perform flood attenuation functions in watersheds during storms and periods of high flow. Riverine wetlands reduce flood peaks by absorbing and storing overbank flow for short- and long-term periods. Riverine wetlands also may reduce flow velocities by increasing contact between water and sediments over wide floodplain areas and providing resistance to flow through wetland topography and vegetation. Riverine wetlands may further decrease overbank flow volumes by promoting infiltration of water into the soil and by returning water to the atmosphere through evapotranspiration (Bullock and Acreman 2003; Naiman and others 1992). Wetlands outside the near stream environment, including geographically isolated wetlands, also may reduce flood peaks downstream. Similar to riverine wetlands, isolated wetlands absorb and store surface runoff, remove water through evapotranspiration, and slow delivery of runoff to streams through infiltration (Leibowitz 2003; Whigham and Jordan 2003).

3.3.2. Groundwater Recharge and Discharge

Wetlands may recharge groundwater basins when flooded as a result of overbank flow or after receiving water through direct precipitation or surface runoff (Bullock and Acreman 2003; Leibowitz 2003; Naiman and others 1992). Groundwater also may discharge to the surface in wetlands and support wetland communities and their associated functions. Examples of wetlands dependent on groundwater discharge include fens, springs, wet meadows, slope wetlands, and some vernal pools (Bedford and Godwin 2003; Bullock and Acreman 2003; Elmore and others 2006; Rains and others 2005). Groundwater recharge and discharge may occur simultaneously within different areas of the same wetland (Bullock and Acreman 2003).

3.3.3. Surface Water Supply and Replenishment

Wetlands store water and also may supply water to other aquatic ecosystems. Ponded water in wetlands and saturated soils support a variety of wetland plant and animal species (Lewis 1995). Although wetlands are water users that may intercept and remove water from the watershed (i.e., through evapotranspiration), they also may recharge other surface water bodies through surface and subsurface pathways, such as groundwater recharge (Bullock and Acreman 2003).

3.3.4. Sediment Storage

Wetlands remove turbidity and suspended solids from surface runoff by reducing flow velocities and providing contact with vegetation, which allows sediment to settle from the water column (Mayer 2005; Schuster and Grismer 2004; Reuter and others 1992; Nara and Pitt 2006). In addition to capturing sediment, wetland vegetation may stabilize soils and reduce erosion (Micheli and Kirchner 2002; Goldsmith and others 2001).

3.3.5. Nutrient and Organic Matter Cycling

Wetland vegetation and soils can remove nutrients from surface runoff through storage and transformation. Nutrients may be absorbed by wetland soils or used and stored by vegetation through uptake. Vegetative and microbial transformation processes such as denitrification remove nutrients from the watershed or alter the types of compounds available (Fisher and Acreman 2004; Mayer 2005; Pinay and others 2002; Reuter and others 1992; Schuster and Grismer 2004; Whigham and Jordan 2003; Traut 2005; Lewis 1995). Wetlands also produce and store organic matter, and coastal wetlands are effective at sequestering carbon (Lewis 1995; Brevik and Homburg 2004; Zedler and Kercher 2005). Storage of nutrients and organic matter in wetlands may be seasonal or temporary and wetlands also may provide sources of nutrients and organic matter to other aquatic ecosystems. Export of organic matter from wetlands may provide an important energy source for downstream aquatic organisms (Lewis 1995).

The roles of wetlands as nutrient and organic matter sinks, transformers, and sources depend on the particular nutrient and organic matter dynamics in the wetland; the degree of hydrologic connectivity between the wetland and other aquatic ecosystems; and the wetland disturbance regime (Lewis 1995; Whigham and Jordan 2003). The effectiveness of wetlands in removing or cycling nutrients and organic matter also may vary by wetland type or hydrologic regime. For example, denitrification may be most efficient in waterlogged environments, while removal of phosphorous may be more efficient in drier environments such as floodplains (Fisher and Acreman 2004).

3.3.6. Pollutant Filtration

In addition to removing sediment and nutrients from surface runoff and floodwaters, wetlands can remove other water pollutants, such as heavy metals and bacteria, from the water column (Schuster and Grismer 2004; Reuter and others 1992; Verhoeven and Meuleman 1999).

3.3.7. Maintenance of Plant and Animal Communities

The physicochemical environment in wetlands selectively excludes some species that are not well adapted to anaerobic conditions, but also provides conditions that are necessary or favorable for other species. As a result, wetlands support a number of plant and animal species that are not found in other environments, including rare and endemic species, such as fairy shrimp, California Tiger Salamander, and a number of plants (Keeley and Zedler 1998). Many species of aquatic invertebrates and amphibians depend on wetlands for all or part of their life cycles, as do a variety of birds, which utilize wetlands for breeding, nesting, rearing, drinking, feeding, and sheltering. Wetlands also provide food and habitat to fish, reptiles, and mammals (Lewis 1995; Semlitsch and Bodie 2003; Semlitsch 1998; Keeley and Zedler 1998; Stewart 1996).

4. STREAM SYSTEMS

Experimentation and observation over the last several decades has revealed that natural and restored stream systems often provide enhanced water quality benefits, resiliency, and stability when compared to their modified and impacted counterparts. As a result, stream management principles in the U.S. have gradually shifted from attempting to control streams and arrest their natural ecological processes, such as flooding, to working with or restoring these processes (FISWRG 1998; TFNBFF 2002; Riley 2003). This section describes what stream systems are; how they function within their watersheds; and the ways in which watershed variables, such as climate, geology, and landscape interact with natural stream systems to protect and enhance water quality.

4.1 What Are Streams?

Streams are aquatic ecosystems that receive and transport flowing surface and shallow subsurface water, sediment and other materials, and organisms through their associated watersheds. The term stream may be used to refer to both natural and modified or artificial bodies of flowing water and encompasses a variety of other terms for aquatic ecosystems, including rivers, canals, creeks, channels, ditches, floodways, runs, swales, tributaries, and washes.

4.1.1. Stream Hydrology

As with wetlands, hydrology is the defining aspect of streams, and the natural flow regimes of streams determine their physical forms and ecological processes (Poff and others 1997). Streams may flow year-round (i.e., perennial streams); during certain seasons or times of the year (i.e., intermittent streams); or only in direct response to precipitation (i.e., ephemeral streams). Stream flow regimes are dynamic. For example, streams may transition between intermittent and perennial waters as a result of altered landscape conditions, such as a reduction in vegetative cover, or variable climate conditions, such as wet and dry years (Greer and Stow 2003; Kondolf 1998).

Although streams are by definition landscape features that carry flowing water, it is not necessary for these flows to be perennial for streams to affect watershed-wide water quality. Intermittent and ephemeral streams account for approximately 59 percent of total stream length in the U.S., excluding Alaska, and comprise an even larger percentage of total stream length in regions with drier climates or more seasonal or variable precipitation regimes (Nadeau and Rains 2007). Intermittent and ephemeral streams may be connected to downstream perennial waters during high flow events, which have the potential to mobilize materials such as sediment, or during periods when many aquatic organisms rely on water availability or hydrologic connectivity for habitat, food sources, and movement. As a result, intermittent and ephemeral streams play important roles in watershed ecological processes and in protecting and enhancing watershed-wide water quality (Nadeau and Rains 2007; Freeman and others 2007; Alexander and others 2007; Wipfli and others 2007; Meyer and others 2007; Reid and Ziemer 1994).

4.1.2. Stream Channels

Streams form when water has sufficient power to erode sediment and create channels in the landscape. The specific shape of a stream channel is a function of its hydrologic and sediment regimes. Gravity provides the force of water, while underlying geology dictates the erodibility of sediment. Erosion occurs when the hydraulic force provided by water flows exceeds the resisting forces of the soil. If hydraulic forces are sufficiently high, they will create channels by mobilizing and moving sediment downstream or will erode sediment from streambanks or streambeds and reshape existing channels in the landscape (Leopold and others 1964; Fischenich 2001).

Although a wide-range of flows perform work on channels and contribute to channel morphology, many streams have a dominant discharge regime that is responsible for the majority of morphologic work on the channel. This discharge is sometimes referred to as the channel-forming or bankfull discharge. Bankfull discharge is the discharge at which a stream just begins to overflow its banks (i.e., the bankfull channel) onto its floodplain. In streams where bankfull discharge concepts apply, this discharge is responsible for the size and shape of the channel. For many streams, the bankfull discharge has a recurrence interval of 1 to 2 years. In other words, it is a flow that on average occurs once a year or once every other year (Leopold and others 1964; Copeland and others 2000). It is important to note, however, that concepts of bankfull discharge may be most applicable to humid climates. In areas with more arid climates or more variable precipitation regimes, including much of northwest California, larger, less frequent flows may be more important to stream morphology (Kondolf and others 2001; Kondolf 1998; Kondolf 1994; Nolan and others 1987).

Natural stream channels are dynamic in space and time and reflect ever-changing watershed conditions. Over time, channels adjust to their discharge and sediment regimes until they reach a stable or equilibrium condition. Stability in stream channels refers to the condition where stream valley slope, stream channel slope, sediment loads, sediment sizes, discharges, roughness of the stream channel, and bankfull channel widths and depths are in balance. Over short-term time scales, stable or equilibrium channels carry water discharges that have just enough energy to transport their sediment loads through the system. Under these conditions, channels do not experience excessive erosional or depositional instabilities, and characteristics such as the channel flow and sediment transport capacities and habitat (e.g., banks, bars, and pools) are maintained. Over longer periods, channels can be expected to adjust and establish new equilibrium forms as hydrologic or sediment conditions change in the watershed (Riley 2003; Leopold and others 1964).

Equilibrium conditions do not imply static channels. Erosion and deposition are natural processes that occur in equilibrium channels and these processes continually create, erode, and replace stream habitat features. For example, gravel bars in equilibrium streams may be continually eroded, but are replenished by new gravel that is deposited after being eroded from upstream areas. Additionally, meandering channels may migrate across their floodplains, while maintaining channel geometries that balance their sediment and water loads (Kondolf and others 2001; Kondolf 1994; Naiman and others 1992).

Channels that are out of equilibrium will adjust until they reach a new equilibrium state. When the sediment loads or sizes are too little to balance stream power, the excess energy causes streams to erode their beds and banks, leading to wider or deeper channels, and/or to a decrease in channel gradient or slope. On the other hand, when stream power is insufficient to carry the sediment load, streams drop their sediment in the channel. As sediment aggrades, it creates in-channel sediment bars, and may lead to the formation of multiple, migrating channels. To reach a new equilibrium, such channels may eventually need to become narrower or shallower, which will increase stream velocities and the ability of the stream to transport its sediment load by constricting flows or increasing stream gradient (Riley 2003; Fischenich and Morrow 2000; Kondolf 1994; Leopold and others 1964).

Erosional and depositional processes in channels can be beneficial when they help restore channel equilibrium following disturbance, such as floods, or when they are part of the natural cycle of creation and maintenance of channel habitat (Naiman and others 1992; Kondolf 1998). However, these processes also can be destructive, particularly when ongoing changes or conditions in the watershed prevent establishment of a new equilibrium, such as in an urbanizing watershed where stream hydrology is in flux, or when streams have been significantly modified, such as by dams, channel straightening and widening, stream channel bed elevation changes, and channel confinement such as hardening of banks. Excess deposition, or aggradation, in stream channels can increase flooding in the watershed or create unstable migrating channels and problems of bank erosion. Excess hydraulic forces or unnatural steepening of stream gradient, such as by straightening a channel and removing its natural meanders, may lead to stream bed erosion, or incision, that migrates up through the watershed, creating sediment problems downstream. In these cases, without intervention, ongoing excess erosion or deposition may disrupt stream processes and the transition to a new equilibrium state may not occur for some time (Riley 2003; Fischenich and Morrow 2000; Florsheim and others 2001; Landwehr and Rhoads 2003; Castro 2003; Kondolf 1994; Griggs and Paris 1982).

4.1.3. Floodplains

Floodplains are depositional features, which are constructed by streams and composed of alluvial sediments. Although both small and large streams may have floodplains, floodplains are more prevalent in middle and lower reaches of streams, where flows are higher and overbank flow may be a more frequent occurrence (Naiman and others 1992; Leopold and others 1964).

When a stream overflows the confines of its channel and spreads outward over the land surface, it occupies a wider surface area, which brings the stream into contact with adjacent vegetation, topographic features, and other obstructions to flow. These features provide increased roughness, which helps reduce stream velocities. As streams overflow their banks, the cross-sectional area of their discharge also increases, which leads to a corresponding decrease in water velocity. Decreased flow velocities over the floodplain may cause the stream to drop its sediment load. Deposition of sediment, or aggradation, on floodplains depends on flow dynamics, including flow velocities and sediment load sizes and characteristics. When there are high velocity flows over the floodplain, or when flows contain low sediment loads, flows also may scour, or erode, sediment from floodplains rather than depositing material (Leopold and others 1964; Riley 2003).

The processes of aggradation and scouring continually shape the landscape to create dynamic, topographically complex floodplains. Over time, under stable hydrologic and sediment regimes, floodplains, like channels, reach equilibrium conditions such that aggradation of the floodplain is balanced by scouring. Thus, under equilibrium conditions, floodplains collect and store sediments for certain periods of time before this sediment is eventually mobilized and transported downstream. In this way, floodplains are constructed and maintained by stream flows and also contribute to channel dynamics by acting as both sources and sinks of sediment. Because floodplains are geomorphically linked to stream channels and physically contain the stream during periods of high flow, they may be considered part of the stream system or part of the stream itself (Kondolf 1994; Naiman and others 1992; Leopold and others 1964). Floodplain areas also may become part of the stream channel over time as a result of processes such as channel migration, in which one or more stream channels may meander across the floodplain (Sear 1994; Kondolf and others 2001; Naiman and others 1992).

Some floodplains reflect previous hydrologic or sediment conditions in the watershed and are no longer maintained by the stream. These floodplains are referred to as abandoned floodplains, or floodplain terraces, and are located at higher elevations than their stream's current, active floodplains. Floodplain terraces are formed when streams erode their beds, or incise, thus lowering the streambed elevation (see Figure 6). An incising stream may become hydrologically disconnected from its floodplain, such that it no longer, or only infrequently, overflows its banks and interacts with its floodplain. Over time, an incised stream may construct a new floodplain at a lower elevation by eroding its banks and widening the channel (Riley 2003; Leopold and others 1964). Floodplain terraces may still be inundated during infrequent, high magnitude floods (Tooth 2000).

Floodplains and floodplain terraces are created by streams, but these areas also regulate the passage of water, materials, and organisms from terrestrial ecosystems to streams, thereby affecting stream processes. In this way, floodplains and floodplain terraces act as ecotones that connect streams with adjacent terrestrial ecosystems (see, e.g., Brinson 2002; Naiman and others 1992; Décamps 1993; Junk and others 1989). Floodplains and floodplain terraces are part of a stream's riparian areas and landscape interactions between streams and their floodplains and floodplain terraces contribute to a variety of stream ecological processes and water quality functions, which are discussed later in this section.

4.1.4. Hyporheic Zones

In addition to surface flows and processes, streams have subsurface flow components called hyporheic zones. The hyporheic zone is "the interstitial habitat beneath the streambed that is the interface between surface water and the adjoining groundwater"

(Naiman and others 1992, p. 149). Hyporheic zones are ecotones between surface water and groundwater in which stream water penetrates and interacts with sediments and connects streams to adjacent groundwater systems. Hyporheic zones vary in space and time throughout the stream system and generally become larger and more continuous in the downstream direction. They interact with floodplain aquifers and thus frequently overlap with and correspond to floodplain areas In terms of aquatic habitat volume, hyporheic zones may be many times larger than stream channels (Brunke and Gonser 1997; Naiman and others 1992; Sedell and others 1990; Stanford and Ward 1988).

Similar to floodplains, hyporheic zones interact with stream channels such that water, materials, and organisms flow from channels into hyporheic zones as well as from hyporheic zones into channels. Contributions of water, materials, and organisms from hyporheic zones to channels may be from sources that originated in the channel and were temporarily stored in the hyporheic zone or may be from upland or groundwater sources that pass through the hyporheic zone and are newly introduced into the stream. In this way, hyporheic zones are part of and maintained by the stream, but also are part of the larger system of terrestrial and aquatic ecosystems in the watershed that affects and maintains stream processes (Brunke and Gonser 1997; Naiman and others 2000; Naiman and others 1992; Sedell and others 1990; Stanford and Ward 1988; Johnson 2004; Poole and Berman 2001; Story and others 2003).

4.1.5. Stream Biota

Like wetlands, stream hydrology provides habitat conditions that support a variety of plant and animal species. Stream channels provide water sources necessary for aquatic organisms, such as fish, amphibians, aquatic invertebrates, and aquatic plants. Because floodplains are periodically inundated and often have high water tables, they frequently include wetlands and support a variety of wetland species (Junk and Wantzen 2003; Fischenich and Morrow 2000; Sommer and others 2001). Some floodplains may not be inundated frequently enough to establish wetland conditions, but are still subject to periodic inundation and may have high water tables. These conditions support a variety of unique species, including phreatophytes (Dall and others 1997; Bendix and Hupp 2000; Bayley 1995; Kondolf and others 1996; Miller and others 1995; Tockner and Stanford 2002; Dreesen and others 2002). Subsurface flows in the hyporheic zone support many species of aquatic invertebrates by providing cool oxygenated water (Brunke and Gonser 1997; Sedell and others 1990; Stanford and Ward 1998). Streams also support a variety of species that are found in the near stream environment as well as upland areas (Dall and others 1997; Kondolf and others 1996).

Vegetation supported by stream hydrology frequently is referred to as riparian vegetation, which the U.S. Fish and Wildlife Service defines as:

> … plant communities contiguous to and affected by surface and subsurface hydrologic features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, or drainage ways). Riparian [vegetation] has one or both of the following characteristics: 1) distinctively different vegetative species than adjacent areas, and 2)

> species similar to adjacent areas but exhibiting more vigorous or robust growth forms. (Dall and others 1997, p. 3)

However, the term riparian vegetation also may be used to refer to upland vegetation that is not directly supported by stream hydrology, but which affects stream conditions, such as by providing shade and microclimate control, sediment stabilization on adjacent slopes, or input of large woody debris (Kondolf and others 1996; Naiman and others 1992; Tabacchi and others 1998).

In addition to providing water levels that are required to support a variety of species, flood processes in streams create disturbance and temporal and spatial heterogeneity that affect stream communities. For example, floodplain vegetation must be adapted to withstand physical disturbance from floods or to colonize scoured soils following flooding. Flood disturbance affects the patterns of stream communities by periodically uprooting or burying vegetation and resetting the process of succession (Bendix and Hupp 2000; Baattrup-Pedersen 2005; Bayley 1995; Bunn and Arthington 2002; Décamps 1993; Dreesen and others 2002; Junk and others 1989; Kang and Stanley 2005; Kondolf and others 1996; Lite and others 2005; Naiman and others 1992; Naiman and others 1993; Nilsson and Svedmark 2002; Pollock and others 1998; Sedell and others 1990; Sluis and Tandarich 2004; Tabacchi and others 1998; Tickner and others 2001; Townsend 1989; Bravard and others 1986).

Finally, stream biota may reflect species that are adapted to using different habitats during various life cycle stages. For example, a variety of fish species live in stream channels during lower flows, but occupy floodplains during the wet season. Additionally, some species, such as anadromous fish and some amphibians utilize streams for spawning, breeding and rearing, but migrate to other aquatic or terrestrial habitats during other periods (Feyrer and others 2004; Bayley 1991; Junk and others 1989; Junk and Wantzen 2003; Ribiero and others 2004; Sedell and others 1990; Sommer and others 2004; Sommer and others 2001; Semlitsch 1998; Semlitsch and Bodie 2003).

4.2 Stream Drainage Networks

Perennial, intermittent, and ephemeral streams, as well as associated aquatic habitats, such as wetlands, form drainage networks that drain the land surface and transport water, materials, and organisms through their watersheds. In order to understand how a stream functions within its watershed, it is necessary to understand how drainage networks are organized and how upstream and downstream processes affect stream functioning within any one stream or any one stream reach (Dynesius and Nilsson 1994; FISRWG 1998; Naiman and others 1992; Naiman and others 2000; Poole 2002; Sedell and others 1990; Vannote and others 1981; Ward 1999).

Although processes in individual stream reaches are affected by a variety of factors, including local hydrology and landscape conditions, drainage networks may be divided into three general regions within their watersheds: headwater regions, transport regions, and depositional regions, which are described below (FISRWG 1998; Naiman and others 1992; Dynesius and Nilsson 1994; Kondolf 1994).

4.2.1. Headwater Streams

Headwater regions are those hillslopes where channels first begin to form in the landscape. As such, headwater streams are small streams, usually first- or second-order,[3] that have relatively steep gradients. Because they are located in the upper parts of their watersheds and receive water from a relatively small area, stream power is usually low and channel forms are relatively stable during normal flows. However, during infrequent, high magnitude storm events, headwater streams may rapidly erode and release large amounts of sediment downstream (Alexander and others 2007; Naiman and others 1992; Richardson and Danehy 2007).

Nationwide, headwater streams are estimated to comprise at least two-thirds of total channel length in watersheds (Nadeau and Rains 2007; Wipfli and others 2007; Freeman and others 2007; Naiman and others 1992). Large streams are "fed by literally hundreds of thousands of small headwater streams" (Freeman and others 2007, p. 6). A majority of headwater streams have intermittent or ephemeral flow regimes because they are located above groundwater tables or are not fed by sufficiently large groundwater basins to sustain flows year-round during dry periods. Therefore, many headwater streams are periodically isolated hydrologically from the rest of the drainage network (Winter 2007; Izbicki 2007). However, headwater streams play significant ecological roles in watersheds through periodic hydrologic connections. They are the primary sources of downstream surface water and sediment and also are significant in controlling nutrient and organic matter fluxes in downstream waters, both by contributing and storing or removing these substances (Alexander and others 2007; Naiman and others 1992; Reid and Ziemer 1994; Pinay and others 2002; Richardson and others 2005; Richardson and Danehy 2007; Wipfli and others 2007).

4.2.2. Transport Streams

Transport regions in the drainage network are comprised of medium-sized streams, usually third- to fifth-order. These streams may have moderately steep gradients and generally have enough power to transport the majority of sediment they receive from the upper watershed to downstream areas. Both erosion and deposition occur in these streams, but the dominant process, or net effect, is generally sediment transport (Naiman and others 1992).

Sediment may be temporarily stored in mid-order channels, particularly as a result of mass-wasting events, such as landslides, which form debris dams. In steep mid-order watersheds that are prone to mass-wasting, landslides may be the dominant geomorphic process that determines channel form. When debris dams breaks, stored sediment is rapidly transported downstream (Naiman and others 1992).

[3] First-order streams are streams that do not have tributaries, second-order streams are streams whose tributaries are only first-order streams, third-order streams are streams with only first- and second-order tributaries, and so on (see Figure 7).

Discharge increases in mid-order streams and these streams undergo moderate flood processes, which begin to create wider valley floors. Although the majority of sediment moves through the channel or is stored behind debris dams, some sediment may be temporarily stored on floodplains. Periodic inundation of floodplains also may support floodplain vegetation communities, including wetlands. Hyporheic zones in mid-order streams also make important contributions to stream water and water quality. Mid-order streams are more likely to be perennial streams than are headwater streams due to increased groundwater inputs that sustain flows throughout the year (Naiman and others 1992).

4.2.3. Depositional Streams

As streams converge and become wider still in the downstream direction, drainage networks transition into depositional regions. High-order streams, those that are usually sixth-order or above, begin to sort sediment into fine and coarse materials as stream gradients decrease and streams begin to meander across floodplains. Coarser materials are deposited in upper reaches of depositional regions, while finer materials are carried through to lower reaches. Flood processes tend to be more significant in high-order streams and these streams develop depositional features like floodplains and bars. Wider floodplain areas also give rise to increased hyporheic exchange between channels and groundwater systems (Naiman and others 1992).

High-order streams usually receive significant surface water and groundwater inputs throughout the year and thus tend to be perennial waters. High water availability supports corridors of riparian vegetation as well as wetlands within the floodplain. The majority of nutrients and organic matter in high-order streams comes from headwater and transport regions as well as from production that occurs on the floodplain. Therefore, water quality in high-order streams depends significantly on upstream watershed conditions as well as floodplain conditions. Whereas overland flow is an important contribution to stream water in low- and mid-order streams, high-order streams depend mostly on water inputs from upstream waters, further increasing the importance of upstream areas in determining downstream water quality (Naiman and others 1992; Richardson and others 2005; Pinay and others 2002; Pinay and others 1999; Reid and Ziemer 1994; Junk and others 1989; Brinson 2002).

4.3 Stream Water Quality Functions

Individual streams perform a variety of critical water quality functions that affect local water quality. These streams also contribute to watershed-wide water quality through their roles in the drainage network. Stream and drainage network functions include:

- Flood attenuation;
- Groundwater recharge and discharge;
- Surface water supply and replenishment;

- Sediment transport and storage;
- Nutrient and organic matter cycling;
- Pollutant filtration;
- Temperature and microclimate control; and
- Maintenance of plant and animal communities.

Many of these functions occur as a result of or are enhanced by interactions between streams and other aquatic and terrestrial ecosystems, including wetlands and riparian areas and upstream and downstream waters. In addition to wetland water quality functions, which enhance stream water quality, stream riparian areas perform a variety of critical water quality functions (see Table 4). These functions occur in conjunction with stream processes, such as flooding, as well as in riparian areas' roles as ecotones that moderate terrestrial influences on stream ecosystems. Interactions between streams and their riparian areas are described in the following descriptions of stream functions. As with wetlands, the specific water quality functions of streams are determined by their individual attributes as well as the interactions between individual streams and watershed variables such as climate, geology, and landscape. Therefore, some of the functions described here are not provided by all streams within the drainage network or are provided by different streams to varying degrees.

4.3.1. Flood Attenuation

Drainage networks perform flood attenuation functions through the short- and long-term storage of surface water and by promoting groundwater recharge. Flood attenuation functions are primarily performed by mid- and high-order streams, but also may be performed by headwater streams. Headwater streams are the primary routing mechanism for water from the upper to lower reaches of the watershed and these streams may decrease flood flows by promoting groundwater recharge and delaying water transport through temporary storage of water (Bullock and Acreman 2003; Nadeau and Rains 2007; Naiman and others 1992). Isolated wetlands in headwater areas may pond water and reduce total surface runoff through evapotranspiration and groundwater recharge (Leibowitz 2003). However, soils in headwater streams also may become saturated quickly, which may increase conveyance of rainfall through these channels to downstream waters, rather than providing upstream storage (Bullock and Acreman 2003). Although flows from headwater areas can contribute to increased flows downstream, downstream waters attenuate flood flows due to features such as larger floodplains. Therefore, the net effect of the drainage network is still to attenuate flood flows (Naiman and others 1992).

The primary flood attenuation functions of drainage networks are performed by floodplains. Floodplains receive overbank flow during periods of high flow and store water for short- and long-term periods, which slows water flows and decouples flows, thereby reducing flood peaks downstream. Contact between floodwaters and floodplain sediments, reduces flow velocities through friction. Riparian vegetation and wetlands in floodplains also reduces flow velocities by providing topographic complexity and increasing surface roughness (Naiman and others 1992; Tabacchi and others 1998; Bullock and Acreman 2003). Floodplain wetlands and backwater habitats may pond water and reduce the volume of water that moves downstream (Sommer and others 2001; Bullock and Acreman 2003; Naiman and others 1992).

By spreading floodwaters over a larger surface area and reducing flow velocities, floodplains also increase groundwater recharge and evapotranspiration, which reduces flood magnitudes. Floodplains are significant groundwater recharge zones that receive and store water in alluvial aquifers, which later sustain stream flow during drier periods of the year (Naiman and others 1992; Poore 2003; Valett and others 2005).

Riparian vegetation growing on floodplains and in uplands also reduces flood flows through evapotranspiration, which includes water losses from canopy interception and evaporation, evaporation of water that reaches the soil, and water that is transpired by vegetation (Spence and others 1996). A portion of precipitation never reaches the ground because it is intercepted by vegetation and evaporated back to the atmosphere. In vegetated areas, storage through interception is a function of plant type and form and vertical and horizontal plant community density. In a densely vegetated riparian area little rainfall will actually reach the soil surface. Consequently, while interception is usually insignificant in areas with little or no vegetation, densely vegetated riparian areas can attenuate flood peaks through the process of interception (FISRWG 1998; Dunne and Leopold 1978). Riparian areas, with their characteristic plant community structural diversity have a high evapotranspiration potential. Coniferous forests generally have the highest leaf surface-area and thereby have the greatest potential for transpiration losses, followed in descending order by deciduous trees, shrubs, grasslands, and desert shrubs (Spence and others 1996).

4.3.2. Groundwater Recharge and Discharge

As noted above, floodplains recharge alluvial aquifers during periods of high flow. In addition to slowing flow velocities, which promotes infiltration, riparian vegetation on floodplains and in upland areas increases groundwater recharge and infiltration rates by increasing soil porosity, both by providing habitat for burrowing organisms, which create pore spaces, and by protecting the soil from the direct impact of raindrops, which can lead to loss of soil pore spaces (FISRWG 1998). Undisturbed soils in riparian forests can capture, absorb and store amounts of rainfall at rates much high than disturbed soils (e.g., agriculture fields or construction sites) or grass turf or pasture (Palone and Todd 1998).

Headwater streams also provide a significant source of groundwater recharge. Because many headwater streams are ephemeral streams they are located above the groundwater table, so vertical flows tend to be in the downward direction into aquifers. Mid- and high-order streams also recharge groundwater through hyporheic zones during periods of high flow (Naiman and others 1992; Winter 2007; Nadeau and Rains 2007).

Groundwater contributions to surface flows, known as base flows, sustain stream flows in many mid-order and high-order streams, as well as some low-order headwater streams, throughout the year or during certain times of the year. Water stored in aquifers and hyporheic zones maintains base flows during drier periods of the year when stream levels drop below water tables (Naiman and others 1992; FISRWG 1998).

Groundwater recharge and hyporheic flows sustain a variety of plant and animal communities, including riparian vegetation and aquatic invertebrates, in floodplains and hyporheic zones, while groundwater discharge during dry periods is an important source of water for organisms in the stream channel (Dreesen and others 2002; Kondolf and others 2001; Brunke and Gonser 1997; Sedell and others 1990; Naiman and others 1992). Alluvial aquifers also provide water supplies for human uses.

4.3.3. Surface Water Supply and Replenishment

Streams store and transport water and also may supply water to other aquatic ecosystems. Stream flows and flood flows recharge floodplain wetlands and riparian communities, which support a variety of plant and animal species (Middleton and 2002; Kondolf and others 1996; Naiman and others 1992; Miller and others 1995). Streams also provide water for human uses both within channels and by recharging alluvial aquifers.

Headwater streams are the primary source of downstream surface water and both perennial and seasonal connectivity between upstream and downstream waters is important in maintaining water supply (Alexander and others 2007; Naiman and others 1992; Bunn and Arthington 2002). As described above, stream systems also store groundwater in fluvial aquifers and hyporheic zones, which then supply water to aquatic communities during drier periods.

Stream biota, such as riparian vegetation, are water users and therefore may reduce supplies available to other uses (e.g., through vegetative uptake and evapotranspiration) (Brown and others 2005). However, stream vegetation also performs functions that may increase the water storage capacity of stream systems. For example, vegetation provides resistance to flow, both from surface runoff and flood flows, which encourages soil infiltration and groundwater recharge. Vegetation also helps reduce erosive forces that can cause problems such as channel incision (Goldsmith and others 2001; Micheli and Kirchener 2002; Micheli and others 2004; Simon and Collison 2002; Booth 1991; Naiman and others 1992). When channels incise, water tables drop, decreasing access to water for a variety of users that depend on groundwater supplies (Brunke and Gonser 1997; Kondolf 1994; Castro 2003).

4.3.4. Sediment Transport and Storage

Natural stream channels adjust to their sediment and flow regimes to create stable channel forms that are able to move water and sediment effectively through the watershed. These channel forms help maintain a dynamic equilibrium between sediment and discharge that prevents excessive erosional and depositional instabilities, which can lead to water quality problems and the destruction of stream habitats, such as pools (Riley 2003; Naiman and others 1992).

A variety of features within the stream system store sediment for short- and long-term periods and help maintain this dynamic equilibrium. Headwater streams provide the majority of downstream sediment, but also store a significant amount of sediment in upper watershed areas. Sediment storage in the upper watershed is a product of relatively low stream power, combined with large woody debris inputs from riparian vegetation and boulders in channels, which capture and store sediment (Naiman and others 1992; Reid and Ziemer 1994; Richardson and Danehy 2007; Grant and Wolff 1991). Floodplains in mid- and high-order streams are depositional features that capture sediment during high flows, reducing suspended sediments and stream bed load (McEwen and Robbins 2003; Ritchie and others 2004; Valett and others 2005).

Deposition on floodplains is increased by riparian vegetation, which provides resistance to flow and encourages deposition by decreasing flow velocities. Riparian vegetation also helps stabilize soils in streambanks and floodplains by reducing scouring forces and increasing the sheer strength of soil through roots (Goldsmith and others 2001; Micheli and Kirchner 2002; Micheli and others 2004; Tooth 2000). Vegetation on hill slopes also stabilizes soil by reducing the direct impact of rain and runoff on soil, which can mobilize sediments, through living and dead vegetation (e.g., leaf litter); by providing soil strength through roots; and by enhancing the internal drainage of soils, which helps prevent excess soil moisture and resulting slope instabilities (Goldsmith and others 2001).

4.3.5. Nutrient and Organic Matter Cycling

Nutrient and organic matter cycling in streams happens in the longitudinal, lateral, and vertical dimensions. In the longitudinal direction, headwater streams are significant sources of nutrients and organic matter to downstream waters. Headwater streams are the primary routing mechanism for vegetative material (e.g., large woody debris) from hill slopes to downstream waters and the majority of nutrients and organic matter in large streams is transported from upstream areas (Alexander and others 2007; Pinay and others 2002; Naiman and others 1992; Reid and Ziemer 1994; Pinay and others 1999; Richardson and others 2005; Richardson and Danehy 2007). Headwater streams also are sources of aquatic insects, which provide food sources to aquatic biota in downstream waters (Richardson and Danehy 2007). Because many headwater streams are intermittent and ephemeral, nutrients and organic matter may build-up in stream channels before it is transported downstream during episodic, seasonal storms and flows that provide longitudinal hydrologic connections (Richardson and others 2005).

In addition to acting as sources of nutrients and organic matter and transporting these materials downstream, headwater streams perform important nutrient and organic matter processing functions. Because headwater streams are small, they have a high ratio of stream surface area to water volume, which increases contact between water and sediments. Similar to wetlands, this contact allows biogeochemical processes to occur, such as denitrification, which reduce nutrient concentrations. As stream size increases, contact between water and sediment decreases, and large stream channels are less efficient at removing nutrients than are smaller ones (Pinay and others 2002; Alexander and others 2000; Sweeney and others 2004; Jacobs and Gilliam 1985). Aquatic invertebrates in headwater streams also process organic matter (e.g., into fine particulate organic matter) and transform it into forms that are more easily used by downstream species (Richardson and others 2005; Vannote and others 1981). Processing of organic matter continues through the drainage network such that aquatic organisms in mid-order streams transform and export organic matter to low-order streams. In this way energy use efficiency is maximized from upstream to downstream waters as different organisms transform upstream organic matter inputs into biomass (Vannote and others 1981).

Although most transport of nutrient and organic matter in streams occurs in the downstream direction, transport can also occur in the upstream direction when animals travel from downstream to upstream waters and deposit nutrients and organic matter. For example, salmonids migrate to upstream areas to spawn before dying. This introduces large quantities of organic matter, which originated in marine environments, to medium and large rivers. Some salmonids also may spawn in small streams where they significantly influence stream nutrient dynamics (Richardson and others 2005).

In the lateral direction, nutrient and organic matter is provided by and exchanged with riparian vegetation and floodplains adjacent to channels. Surface runoff from the watershed also is a significant source of nutrients. Organic matter may be provided by vegetation in the form of large woody debris and leaf litter that falls into stream channels. These inputs are most important in headwater and mid-order channels and, per unit area, smaller streams tend to have more organic matter than do larger streams (Richardson and others 2005; Naiman and others 1992; Kondolf and others 1996). In high-order streams, vegetation input may be less important, but overland flow may provide a significant source of nutrients. Floodplains, riparian vegetation, and wetlands that receive overland flow before it reaches stream channels may moderate nutrients contributions from these flows by capturing and storing or transforming nutrients before they reach channels (Naiman and others 1992; Pinay and others 2002; Sweeney and others 2004; Wigington and others 2005; Bedard-Haughn and others 2004; Meals 2001; Jacobs and Gilliam 1985).

Floodplains and riparian vegetation and wetlands on floodplains play important roles in nutrient and organic matter cycles during flood flows. Productivity on floodplains may be high and these areas provide important food sources to aquatic biota when inundated (Schemel and others 2004; Sommer and others 2001; Sommer and others 2004; Ribiero and others 2004; Bayley 1991; Junk and others 1989; Junk and Wantzen 2003; Gladden and Smock 1990). Floodplains also absorb nutrients from floodwaters and reduce nutrient concentrations in downstream waters. Similar to in headwater streams, increased contact between floodwaters and floodplain sediments provides increased opportunities for biogeochemical processes, such as denitrification, to occur. Wetland and riparian vegetation also uptake nutrients and contribute to nutrient transformation (Groffman and Crawford 2003; Kang and Stanley 2005; Junk and others 1989; Pinay and others 2002; Schemel and others 2004; Tabacchi and others 1998; Valett and others 2005; Jacobs and Gilliam 1985). As with wetlands, alternating wet-dry cycles on floodplains create both aerobic and anaerobic conditions, which may increase decomposition of organic matter and nutrient loss through processes such as denitrification (Pinay and others 2002; Machefert and Dise 2004; Tabacchi and others 1998; Valett and others 2005).

Finally, nutrient and organic matter cycling occurs in the vertical dimension between stream channels and groundwater through hyporheic zones. Groundwater with high concentrations of nutrients or organic matter may be a significant source of these substances to streams through groundwater discharge. Hyporheic zones may filter and store nutrients and organic matter from groundwater or stream water inputs as well as provide sources of these materials to streams, such as during low flows when water stored in the hyporheic zone recharges channels (Brunke and Gonser 1997; Pinay and others 2002; Naiman and others 1992; Stanford and Ward 1988).

4.3.6. Pollutant Filtration

In addition to storing and removing sediment and nutrients from runoff and floodwaters, floodplains and riparian vegetation can remove a variety of other water pollutants, such as heavy metals and bacteria from the water column (Atwill and others 2002; Meals 2001; Tate and others 2004; Schuster and Grismer 2004; Reuter and others 1992; Verhoeven and Meuleman 1999).

4.3.7. Temperature and Microclimate Control

Streams maintain a variety of temperatures and microclimates that are needed by stream biota, such as fish and amphibians. Stream water temperatures are affected primarily by solar radiation and groundwater inputs. Increases or decreases in stream temperature as a result of solar radiation, groundwater input, or other sources are transmitted downstream so the upper reaches of a stream and the tributaries to a stream may play an important role in its thermal regime. Confluences between streams and their tributaries provide mixing zones that may increase or decrease water temperatures in the main channel as a whole or may provide local thermal refugia (Johnson 2004; Poole and Berman 2001; Shrimpton and others 2000; Naiman and others 1992; Tockner and others 2000).

Riparian vegetation that provides shade to streams may moderate local and downstream temperatures by blocking solar radiation. Generally, streams that have wider corridors of riparian vegetation are more insulated from solar radiation and have lower mean and maximum water temperatures. The effect of riparian vegetation on stream temperatures is generally greatest on narrower streams where the vegetation is able to shade the entire stream channel. Narrower streams also have lower stream surface areas with which to absorb solar radiation and, as a result, may heat up more slowly (Poole and Berman 2001; Johnson 2004; Shrimpton and others 2000; Kiffney and others 2003; Naiman and others 1992; Tabacchi and others 1998; Welsh and others 2005). Riparian vegetation also maintains stream microclimates that have higher humidity and cooler air temperatures (Johnson 2004; Welsh and others 2005). Although vegetation reduces maximum water temperatures compared to unvegetated streams, it may increase minimum temperatures by providing insulation that slows heat loss during the night. In this way, vegetation reduces diurnal fluctuations between low and high temperatures, which creates less extreme stream temperature environments (Poole and Berman 2001; Johnson 2004).

Groundwater also affects stream temperatures. Generally, groundwater is cooler than surface water because it is insulated from solar radiation. Therefore, where groundwater discharges into streams, it may create thermal refugia for aquatic species that require cooler water temperatures (Story and others 2003; Tockner and others 2000). Hyporheic zones also may moderate stream temperatures through heat exchange during different times of the day. When water temperatures are warmer during the daytime, hyporheic zone water may provide a source of cooler temperatures. During the nighttime, however, heat that was transferred during the day from the channel to the hyporheic zone may be radiated back into the channel. In this way, hyporheic zones, like riparian vegetation, help moderate stream temperatures and reduce diurnal fluctuations (Johnson 2004; Naiman and others 1992; Poole and Berman 2001; Story and others 2003).

During flooding, floodplains may provide different thermal regimes than channels, which provide habitat for different species. Topographic complexity on the floodplain creates thermal heterogeneity and a diversity of habitats. Shallower water depths on floodplains may create warm water habitats, but backwater habitats on floodplains also may be fed by groundwater discharge and provide cool thermal refugia during the summer (Junk and Wantzen 2003; Tockner and others 2000).

4.3.8. Maintenance of Plant and Animal Communities

Streams provide diverse habitats for a variety of plant and animal species and help support and maintain species biodiversity. In-channel habitats include pools, riffles, and bars and support fish, aquatic invertebrates, and other organisms. Headwater, transport, and depositional regions also provide different types of habitat structures and a diversity of habitat conditions, such as different energy sources and hydrologic and thermal regimes, which influence species assemblages (Vannote and others 1981).

Headwater streams are often located in forested areas and generally have cool water temperatures, which make them important habitat for a variety of temperature-sensitive species, such as amphibians. High organic matter inputs and low light conditions also support a variety of invertebrates. Similar to wetland biota, species that utilize headwater streams often must be adapted to periodic dry periods during the year. As a result, organisms such as fish, which require water year round or deeper water depths, may not be found in many headwater streams. However, while fish abundance is often lower in headwater streams than in other areas of the drainage network, headwater streams may provide important thermal refugia for species that require cooler water temperatures during the summer as well as rearing habitat for fish that later move into perennial channels. Headwater streams also may support distinct communities of riparian vegetation, which contribute to stream biodiversity (Richardson and Danehy 2007; Reid and Ziemer 1994).

Mid- and high-order streams may support a variety of plant and animal communities both within channels and in floodplain habitats. Stream channels provide movement corridors and dispersal systems that connect organisms, such as fish, with resources and refuges (Junk and others 1989). Floodplains also provide food sources and habitat during high flows. Many fish species utilize floodplains as rearing habitats, including rare and endangered species. Native species may be adapted to the specific timing of annual floods and require access to floodplains during certain stages of their life cycles (Ribiero and others 2004; Sommer and others 2004; Sommer and others 2001). Seasonal and permanent floodplain wetlands also may provide habitat for a variety of organisms, including migratory waterfowl (Sommer and others 2001).

Floodplains support specific plant communities that are adapted to periodic flood disturbance, including the physical force of floods and the chemical conditions created by periodic inundation and soil saturation. As with animals, plants are often adapted to the specific flood regime of a stream and the spatial and temporal pattern of disturbance helps maintain plant communities. Floodplains also tend to support high species richness due the diversity of conditions created by fluctuating water levels and flood disturbance. Although floodplains support a variety of plants that grow in upland areas, they also support many species of riparian vegetation that are only found within the stream environment (Bendix and Hupp 2000; Baattrup-Pedersen 2005; Décamps 1993; Kondolf and others 1996; Lite and others 2005; Miller and others 1995; Naiman and others 1992; Mouw and Alaback 2003; Nilsson and others 1991; Tickner and others 2001; Tockner and Stanford 2002; Bravard and others 1986).

Corridors of riparian vegetation along streams provide significant habitat to a variety of organisms throughout the watershed. Many headwater stream organisms, including water-dependent terrestrial animals, such as various species of amphibians, mammals, birds, and reptiles, rely on adjacent forested areas for habitat for at least part of their life cycles. The extent of areas utilized by these organisms varies from relatively narrow corridors to much wider areas, depending on species (Duncan 2003; Semlitsch 1998; Semlitsch and Bodie 2003; Kondolf 1996; Perkins and Hunter 2006; Spackman and Hughes 1995).

Finally, hyporheic zones provide habitat, including rearing areas and refugia during flood disturbance, for aquatic invertebrates and microorganisms that are important to food webs and biochemical processes in streams (Brunke and Gonser 1997; Sedell and others 1990; Stanford and Ward 1988).

5. DISCUSSION

As described throughout this report, the physical forms, ecological processes, and water quality functions of natural stream and wetland systems interact in space and over time to protect and enhance watershed-wide water quality. Key concepts that have been developed in this report include:

- The hydrologic regimes of stream and wetland systems, including the seasonality of flows and temporal changes in longitudinal, lateral, and vertical connectivity, create and maintain the physical forms of these systems, and drive ecological processes, which determine their water quality functions;

- The transitional zones, or riparian areas, between streams and wetlands and their associated terrestrial environments play critical roles in protecting and enhancing water quality by maintaining natural ecological processes, such as contributions of water, materials, and organisms from terrestrial environments;

- Individual stream and wetland systems contribute to the water quality of other aquatic ecosystems through permanent and periodic surface and subsurface hydrologic connections, and healthy systems perform functions that protect and enhance watershed-wide water quality throughout the year (e.g., by attenuating flood waters during the wet season and by maintaining stream base flows through groundwater discharge during the dry season); and

- Natural temporal and spatial heterogeneity in climate, geology, and landscape within the watershed and within individual stream and wetland systems support a diversity of habitats and water quality functions.

As discussed in the introduction, a majority of stream and wetland systems in California have been degraded or lost through a variety of land use practices. Although this report has not focused on the impacts of land uses on stream and wetland system conditions, an underlying theme has been that key watershed variables and ecological processes must be protected or restored in order to protect and enhance the water quality functions of stream and wetland systems.

A significant body of scientific literature shows that land use practices that alter key environmental variables and ecological processes in watersheds and stream and wetland systems can impair the ability of these systems to perform beneficial water quality functions. Such impairments impact both human- and non-human land and water users (e.g., Pinay and others 2002; Trimble 2003; Kondolf 1994; Booth 1990; Booth 1991; Booth and others 2002; Booth and Jackson 1997; Paul and Meyer 2001; Zedler 2003; Constantine and others 2005; Kauffman and others 1997; Moore and others 2005). However, the scientific literature also shows that by implementing appropriate management techniques and restoration programs, many of these impacts can be prevented, reduced, or reversed (e.g., Rice 1999; Sommer and others 2001; FISRWG

1998; Riley 2003; Gregory and Chin 2002; Breaux and others 2005; Griggs and Paris 1982).

Existing stream and wetland policies and programs in California and in the North Coast Region may be insufficient to fully protect the water quality functions of stream and wetland systems (e.g., CA SWRCB 2003; Ambrose and others 2006). To address these concerns, it is necessary to develop policies and programs that recognize the physical forms and ecological processes that create water quality functions, and to recognize the diversity of functions that these systems provide. Furthermore, it is necessary to take sufficiently broad views of the watershed and stream and wetland system landscapes in order to identify the cumulative contributions of different forms, processes, or activities that support or may impact water quality functions (Reid 1998; Benyamine and others 2004; Ambrose and others 2006).

In addition to understanding existing and ongoing impacts on stream and wetland systems, it is important to recognize potential future changes to these systems that may impact their functioning within watersheds. For example, over the next years and decades, climate change in California is predicted to increase both the frequency and severity of storms and floods during the winter, and to create water supply shortages, primarily due to a reduced snow pack and earlier timing of snow melt, during the normally drier summer months. Sea level rise as a result of climate change also will impact coastal ecosystems and water supplies (e.g., through salt water intrusion into groundwater aquifers) and may contribute to increased flooding in inland areas. Although the specific future impacts of these changes on stream and wetland system functions are unknown and may vary between watersheds, it is likely that the state will experience reduced quality and reliability of water supplies (CA DWR 2006; Traut 2005; Greer and Stow 2003; Gleick 2000). Under these conditions, the abilities of protected and restored stream and wetland systems to enhance water supply, such as through groundwater recharge, and to attenuate floods may become increasingly important.

As highlighted earlier, it is often costly and difficult, if not impossible, to restore or recreate lost or degraded stream and wetland system functions (Zedler and Kercher 2005; Zedler and Callaway 1999; Kauffman and others 1997; Kondolf 1998; Booth and Jackson 1997). By understanding how stream and wetland systems function in the watershed, it may be possible to develop appropriate management techniques that protect and enhance water quality functions; improve the success of restoration projects; and help prevent future water quality impacts or provide a degree of mitigation for impacts from continued watershed development and climate change.

FIGURES

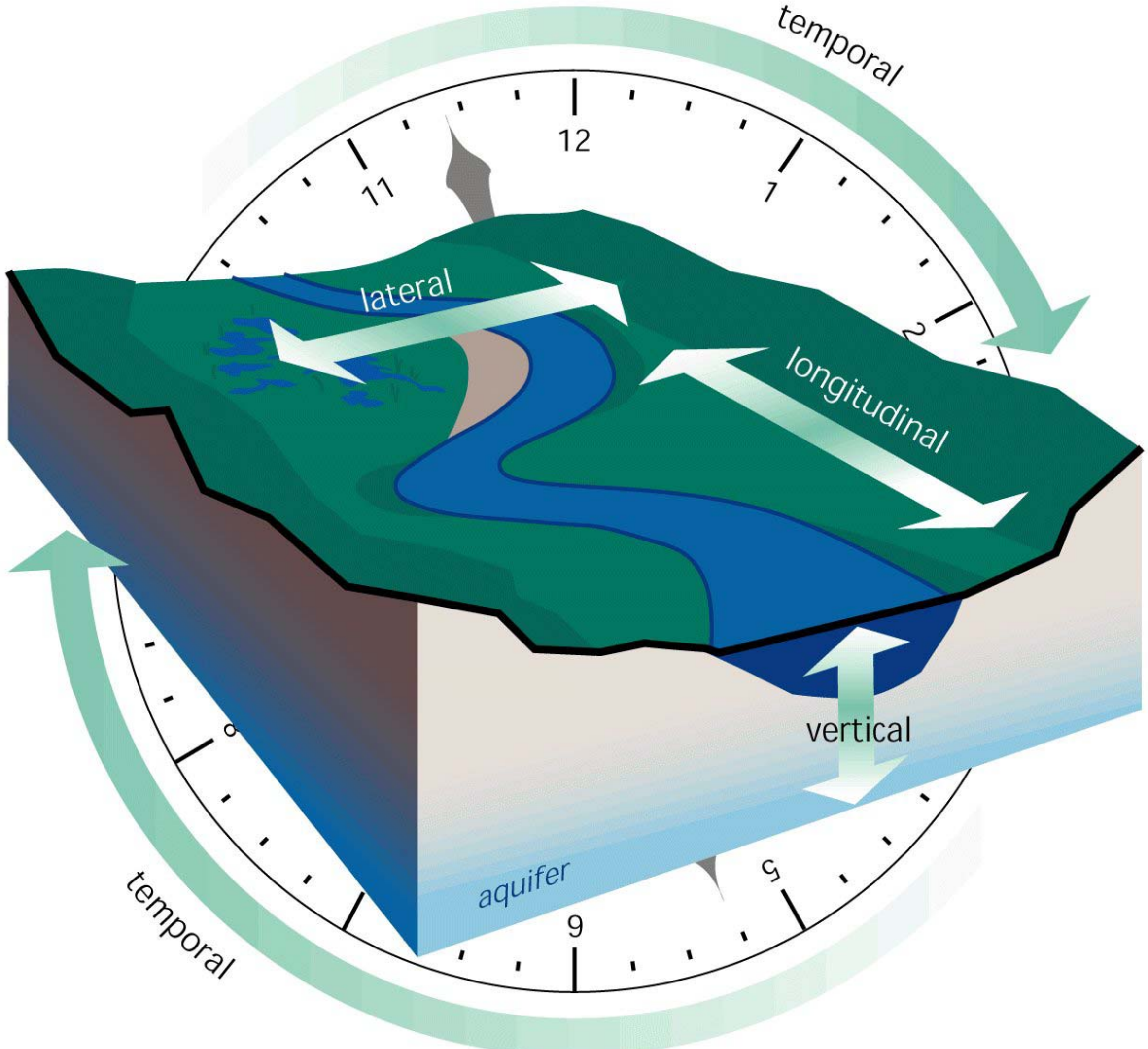

Figure 1: Four Dimensions of the Watershed
Dimensions of the stream corridor. A four-dimensional framework serves as a good starting point for examining stream corridors. (From FISRWG 1998, p. I-i)

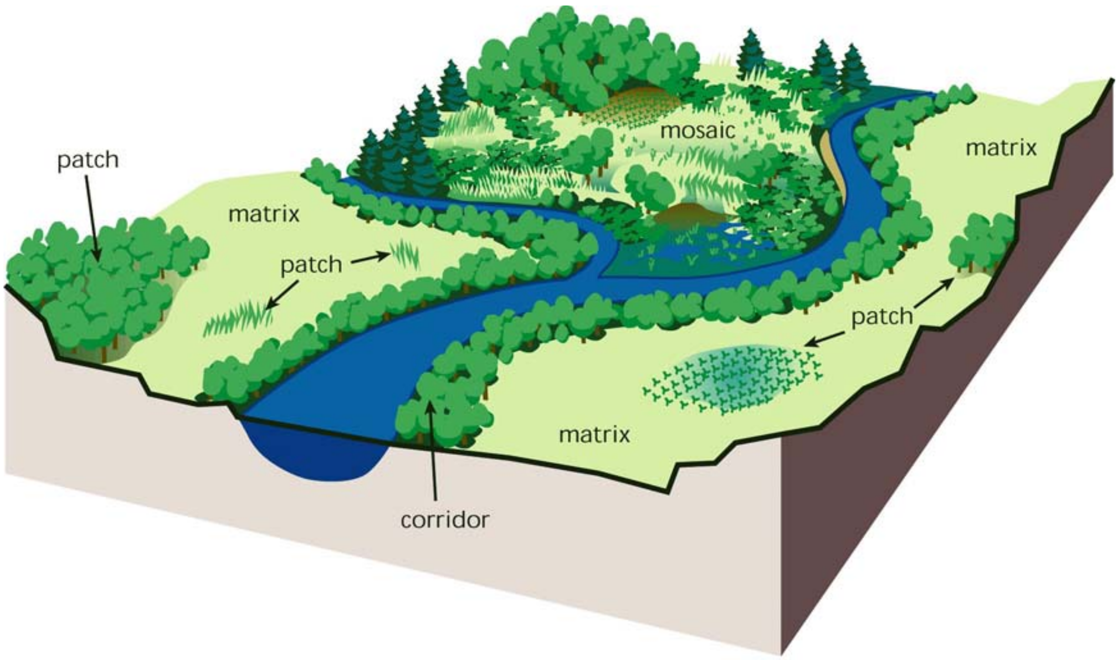

Figure 2: Habitat Patches within a River-Floodplain
Spatial structure. Landscapes can be described in terms of matrix, patch, corridor, and mosaic at various scales. (From FISRWG 1998, Figure 1.4, p. 1-5)

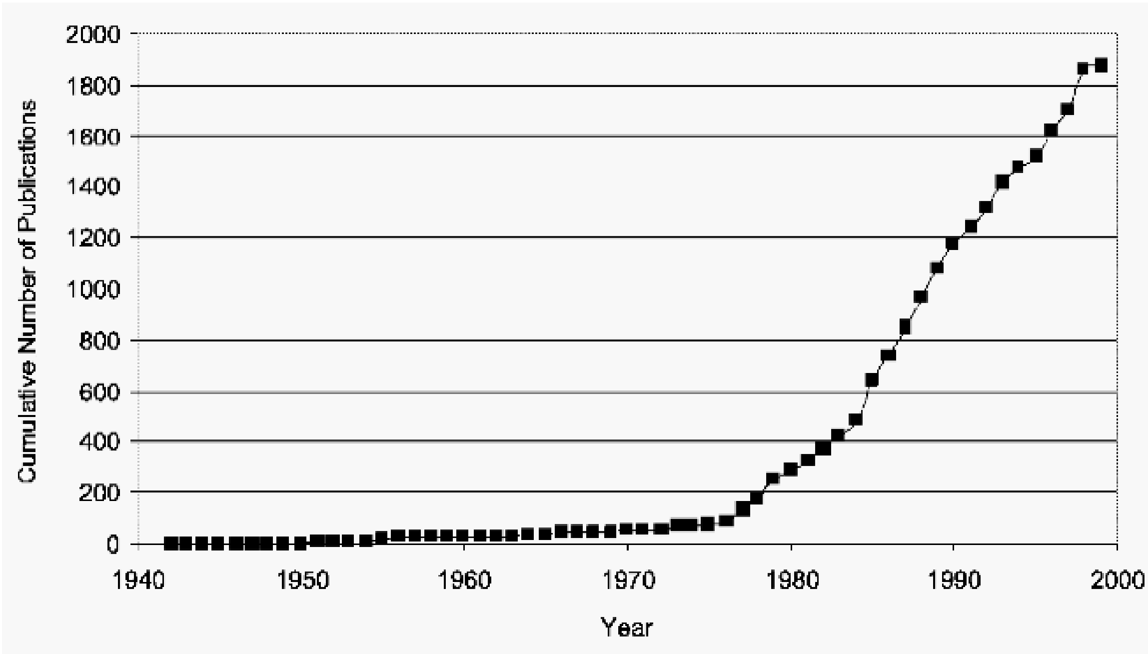

Figure 3: Cumulative Number of Riparian/Wetland Publications
Cumulative number of riparian/wetland publications, by date of publication, for the western United States. SOURCE: Koehler and Thomas (2000). (From Brinson 2002, Figure 1-3, p. 29)

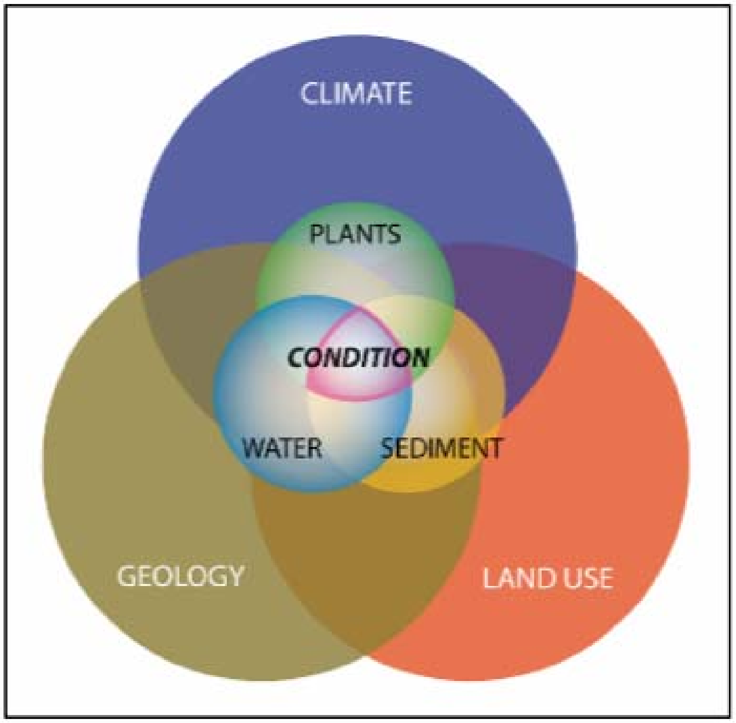

Figure 4: Influence of Climate, Geology, and Land Use on Wetland Condition
(From Collins and others 2006, Figure 2.2, p. 12)

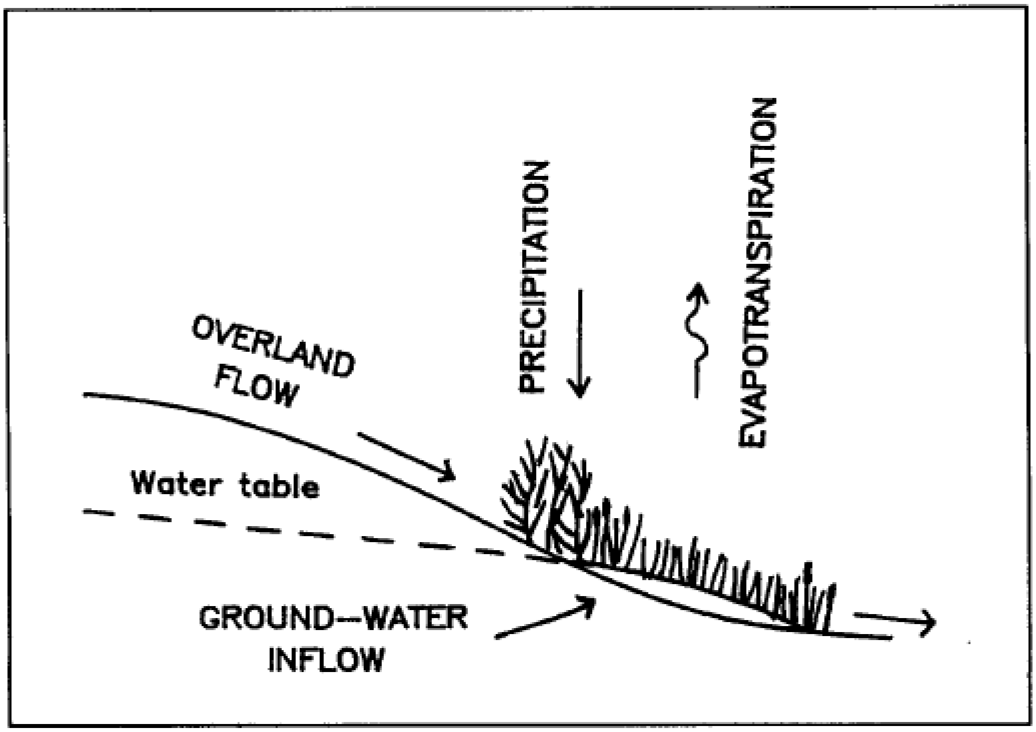

Figure 5: Groundwater Inflow to a Slope Wetland
(From Brinson 1993, Figure 2, p. 9)

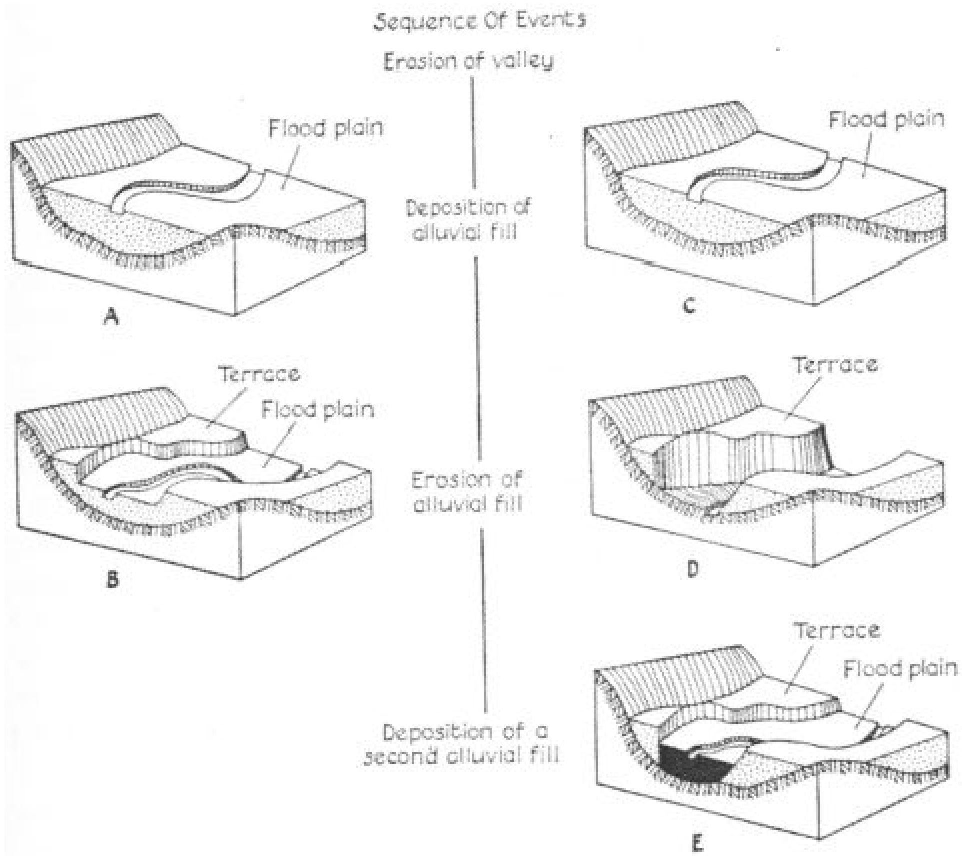

Figure 6: Development of a Floodplain Terrace
Block diagrams illustrating the stages in development of a terrace. Two sequences of events leading to the same surface geometry are shown in diagrams **A, B,** and **C, D, E,** respectively. (From Leopold and others 1964, Figure 11-11, p. 459)

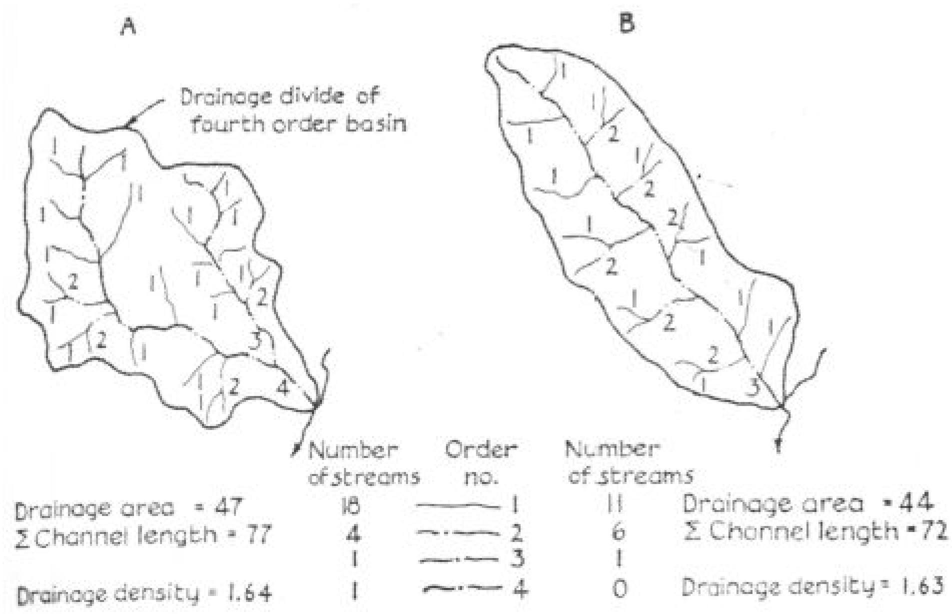

Figure 7: Stream-Order
Sketch to show order number of tributaries and other characteristics of the drainage net. Basins **A** and **B** have the same drainage density despite the different shape. (From Leopold and others 1964, Figure 5-2, p. 135)

TABLES

Table 1: Wetland Definitions Used by State and Federal Agencies in California

Agency	Definition	Source
California Coastal Commission	Lands within the coastal zone which may be covered periodically or permanently with shallow water and include saltwater marshes, freshwater marshes, open or closed brackish water marshes, swamps, mudflats, and fens.	Cal. Pub. Res. Code § 30121
California Coastal Commission	Land where the water table is at, near, or above the land surface long enough to promote the formation of hydric soils or to support the growth of hydrophytes, and shall also include those types of wetlands where vegetation is lacking and soil is poorly developed or absent as a result of frequent and drastic fluctuations of surface water levels, wave action, water flow, turbidity or high concentrations of salts or other substances in the substrate. Such wetlands can be recognized by the presence of surface water or saturated substrate at some time during each year and their location within, or adjacent to, vegetated wetlands or deep-water habitats.	14 CCR 13577(b)
California Department of Fish and Game	Lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water…Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year. (Source: Classification of Wetlands and Deepwater Habitats of the United States; FWS/OBS 79/31; December 1979) The lower limit of a wetland is established at a depth of two meters (6.6 feet) below water; however, if emergents, shrubs, or trees grow beyond this depth at any time, then the deepwater edge of such vegetation is the boundary. Examples of wetland areas include swamps, freshwater marshes, bogs, vernal pools, wet meadows, wet pastures, springs and seeps; portions of lakes, ponds, rivers and streams; and all other areas which are periodically or permanently covered by shallow water or dominated by hydrophytic vegetation or in which the soils are predominantly hydric in nature.	CA DFG 1994, pp. 5-6
U.S. Army Corps of Engineers	Those areas that are inundated or saturated by surface water or ground water at a frequency and duration sufficient to support, and that	33 CFR 328.3(b)

	under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.	
U.S. Department of Agriculture Natural Resource Conservation Service	The term "wetland", except when such term is part of the term "converted wetland", means land that— (A) has a predominance of hydric soils; (B) is inundated or saturated by surface or groundwater at a frequency and duration sufficient to support a prevalence of hydrophytic vegetation typically adapted for life in saturated soil conditions; and (C) under normal circumstances does support a prevalence of such vegetation.	Food Security Act of 1985 (16 U.S.C. 3801[a][18])
U.S. Environmental Protection Agency	Those areas that are inundated or saturated by surface water or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.	40 CFR 230.3(t)
U.S. Fish and Wildlife Service	Lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water…Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year.	Cowardin and others 1979, p. 11

Table 2: Expected Relationships among Wetland Attributes and Wetland Water Quality Functions
(From Collins and others 2006, Table 2.3, p. 16, with minor modifications)

Water Quality Function	Wetland Attributes[4]												
	Landscape Context		Hydrology			Physical Structure		Biotic Structure					
	Landscape Connectivity	Buffer	Water Source	Hydroperiod or Channel Stability	Hydrologic Connectivity	Structural Patch Richness	Topographic Complexity	Organic Matter Accumulation	Number of Plant Layers Present	Number of Co-dominant species	Percent of Invasive Co-dominants	Horizontal Interspersion and Zonation	Vertical Biotic Structure
FUNCTIONS RELATED TO HYDROLOGIC PROCESSES													
Short-term storage of surface water	X	X		X	X	X	X					X	X
Long-term storage of surface water	X	X		X	X	X	X					X	X
Storage of subsurface water			X	X	X		X	X					
Moderation of groundwater flow or discharge	X	X	X										
Dissipation of energy						X	X	X	X			X	X
FUNCTIONS RELATED TO BIOGEOCHEMICAL PROCESSES													
Cycling of nutrients	X	X		X	X	X	X	X	X	X	X		X
Removal of elements and compounds	X	X		X	X		X	X	X			X	
Retention of particulates				X	X	X	X	X	X	X		X	
Export of organic carbon				X	X			X	X		X	X	X
FUNCTIONS RELATED TO HABITAT													
Maintenance of plant and animal communities	X	X		X	X	X	X		X	X	X	X	X

[4] For descriptions of the wetland attributes listed in the table, see Collins and others 2006.

Table 3: Wetland Functions, Descriptions, and Associated Values
(From Smith and others 1995, Table 2, p. 24, with minor modifications)

Water Quality Function	Description	Associated Benefits, Products, and Services
FUNCTIONS RELATED TO HYDROLOGIC PROCESSES		
Short-term storage of surface water	The temporary storage of surface water for short periods.	Onsite: Replenishes soil moisture, import/export materials, conduits for organisms. Offsite: Reduces downstream peak discharge and volume and help maintain and improve water quality.
Long-term storage of surface water	The temporary storage of surface water for long periods.	Onsite: Provides habitat and maintain physical and biogeochemical processes. Offsite: Reduces dissolved and particulate loading and help maintain and improve surface water quality.
Storage of subsurface water	The storage of subsurface water.	Onsite: Maintains biogeochemical processes. Offsite: Recharges surficial aquifers and maintain baseflow and seasonal flow in streams.
Moderation of groundwater flow or discharge	The moderation of groundwater flow or groundwater discharge.	Onsite: Maintains habitat. Offsite: Maintains groundwater storage, baseflow, seasonal flows, and surface water temperatures.
Dissipation of energy	The reduction of energy in moving water at the land/water interface.	Onsite: Contributes to nutrient capital of ecosystem. Offsite: Reduced downstream particulate loading helps to maintain or improve surface water quality.
FUNCTIONS RELATED TO BIOGEOCHEMICAL PROCESSES		
Cycling of nutrients	The conversion of elements from one form to another through abiotic and biotic processes.	Onsite: Contributes to nutrient capital of ecosystem. Offsite: Reduced downstream particulate loading helps to maintain or improve surface water quality.
Removal of elements and compounds	The removal of nutrients, contaminants, or other elements and compounds on a short-term or long-term basis through burial, incorporation into biomass, or biochemical reactions.	Onsite: Contributes to nutrient capital of ecosystem. Offsite: Reduced downstream loading helps to maintain or improve surface water quality.

Water Quality Function	Description	Associated Benefits, Products, and Services
Retention of particulates	The retention of organic and inorganic particulates on a short-term or long-term basis through physical processes.	Onsite: Contributes to nutrient capital of ecosystem. Offsite: Reduced downstream particulate loading helps to maintain or improve surface water quality.
Export of organic carbon	The export of dissolved or particulate organic carbon.	Onsite: Enhances decomposition and mobilization of metals. Offsite: Supports aquatic food webs and downstream biogeochemical processes.
FUNCTIONS RELATED TO HABITAT		
Maintenance of plant and animal communities	The maintenance of plant and animal community that is characteristic with respect to species composition, abundance, and age structure.	Onsite: Maintains habitat for plants and animals (e.g., endangered species and critical habitats), for rest and agricultural products, and aesthetic, recreational, and educational opportunities. Offsite: Maintains corridors between habitat islands and landscape/regional biodiversity.

Table 4: Riparian Area Functions, Descriptions, and Associated Values
(From Brinson 2002, Table 2-3, p. 124, with minor modifications)

Water Quality Function	Indicators that Functions Exist	On-site or Off-site Effects of Functions	Goods and Services Valued by Society
FUNCTIONS RELATED TO HYDROLOGY AND SEDIMENT DYNAMICS			
Stores surface water over the short term	Floodplains connected to stream channel	Attenuates downstream flood peaks	Reduces damage from floodwaters (Daily, 1997)
Maintains a high water table	Presence of flood-tolerant and drought-intolerant plant species	Maintains vegetation structure in arid climates	Contributes to regional biodiversity through habitat (e.g., forest canopy) provision (Szaro, 1991; Ohmart, 1996; James et al., 2001)
Accumulates and transports sediments	Riffle-pool sequences, point bars, and other features	Contributes to fluvial geomorphology	Creates predictable yet dynamic channel and floodplain dynamics (Beschta et al., 1987a; Klingeman et al., 1999)
FUNCTIONS RELATED TO BIOGEOCHEMICAL PROCESSES			
Produces organic carbon	A balanced biotic community	Provides energy to maintain aquatic and terrestrial food webs	Supports populations of organisms (Gregory et al., 1991; Meyer and Wallace, 2001)
Contributes to overall biodiversity	High species richness of plants and animals	Provides reservoirs for genetic diversity	Contributes to biocomplexity (Szaro, 1991; Naiman and Rogers, 1997; Pollock et al., 1998)
Cycles and accumulates chemical constituents	Good chemical and biotic community	Intercepts nutrients and toxicants from runoff	Removes pollutants from runoff (Bhowmilk et al., 1980; Peterjohn and Correll, 1984)
Sequesters carbon in soil	Organic-rich soils	Contributes to nutrient retention and to sequestration of carbon dioxide from the atmosphere	Potentially ameliorates global warming (Van Cleve et al., 1991)

Water Quality Function	Indicators that Functions Exist	On-site or Off-site Effects of Functions	Goods and Services Valued by Society
FUNCTIONS RELATED TO HABITAT AND FOOD WEB MAINTENANCE			
Maintains streamside vegetation	Presence of shade-producing forest canopy	Provides shade to stream during warm season	Creates habitat for cold-water fish (Beschta et al., 1987b; McCullough, 1999)
Supports characteristic terrestrial vertebrate populations	Appropriate species having access to riparian area	Allows daily movements to annual migrations	Supplies objects for bird watching, wildlife enjoyment, and game hunting (Green and Tunstall, 1992; Flather and Cordell, 1995)
Supports characteristic aquatic vertebrate populations	Migrations and population maintenance of fish	Allows migratory fish to complete life cycles	Provides fish for food and recreation (Nehlsen et al,. 1991; Naiman et al., 2000)

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