Confluence:
A Natural and Human History of the Tuolumne River Watershed

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Preface and Acknowledgments

In the spring of 1983, Dennis Johnson who was then the head of Outdoor Adventures UC Davis proposed that the UC Davis Geology Department begin running educational field trips on the Wild and Scenic section of the Tuolumne River. Geologists are notorious for saying yes to all opportunities to go into the field and being durable under unpleasant conditions. Since it was an El Niño year, the spring runoff was epic, and so was the field trip. Since that first trip, the Geology Department and then later, the Center for Watershed Sciences, have been running field trips down this river with Outdoor Adventures, acquainting students and faculty with the natural history of this wonderful outdoor laboratory.

What was missing for these great educational field trips was an accompanying text and a field guide. In winter 2009, a small group of graduate students and researchers got together as part of a class to write this book. The 13 chapters that make up this text were designed by students and, with the exception of the first and last chapters, written by the students. Since it was part of a class, they had only 10 weeks to complete the whole thing. Then, during the spring of 2009, a mix of graduate and undergraduate students got together as part of a class entitled Ecogeomorphology to develop a field guide and a conceptual model for the ecology and geomorphology of the Wild and Scenic section of the Tuolumne. Dr. Peter Moyle and I co-taught this class full of wonderful students. Their guide accompanies this book.

There are two important caveats about this text. Since it is an electronic manuscript, it is a living document that will be updated, added to, and corrected by future students. Expect numerous revisions to version 1.0. Second, it is a student product, remarkably enough completed in just ten weeks. There are errors in it and we appreciate hearing about them so that we can correct them for future versions.

It is vitally important that a number of groups and people receive thanks. First and foremost, all costs for this work, including all of the field trips, were supported by the Roy Shelmon Chair in Applied Geosciences. Thank you Dr. Shlemon for all of your support over these many years. Jordy Margid and Ali Greckho of Outdoor Adventures UC Davis provided all logistical support and good humor. For more than a quarter of a century, Outdoor Adventures has been helping in this regard. Maggie Dowd and the staff of the Groveland Ranger District of the Stanislaus National Forest have been exceptionally helpful and supportive of this effort. Janice Fong of the UC Davis Department of Geology helped with a number of illustrations in this text (but not all, and certainly not the ugly ones). And finally, a special thanks to Patrick Koepele and The Tuolumne River Trust for encouraging the development of this manuscript, helping to distribute it, and helping protect and restore the Tuolumne River. Thanks to all.

Jeff Mount. Summer, 2010

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> ***"After ten years spent in the heart of it, rejoicing and wondering, bathing in its glorious floods of light, seeing the sunbursts of morning among the icy peaks, the noonday radiance on the trees and rocks and snow, the flush of alpenglow, and a thousand dashing waterfalls with their marvelous abundance of irised spray, it still seems to me above all others the Range of Light"***
>
> ***John Muir***

CHAPTER 1: THE TUOLUMNE RIVER AND ITS WATERSHED

JEFFREY MOUNT

INTRODUCTION

When each of us visits the Sierra Nevada or its adjacent valleys, our focus is place-based. That is, our visit is wrapped around a particular location, attribute or experience. Rarely do we consider our location within the broader context of the Sierra and its many physical, biological, economic and cultural connections. The hiker who sets out across the glacier-scarred hills of Tuolumne Meadows is unlikely to draw a connection between the sculpting of this barren landscape and the fertile soils surrounding Modesto. Unless their guides tell them, the squealing rafters bouncing down Clavey Falls on the Tuolumne River are unaware of the complex pathways that water, under the relentless pull of gravity and money, took before it carried them down the river. The farmer in the foothills contemplating whether to convert his land to a vineyard or hang on and keep grazing cattle, rarely thinks about the 600 million years it took to assemble his watershed or how climate change may undo his efforts in the next generation or two. And the picnickers on the banks of the lower Tuolumne River, watching as the remnants of a once great salmon run struggle to hang on, give little thought to the historic role that these fish played in linking the entire watershed to the Pacific Ocean. All of these experiences have three things in common. Each is place-based, each place is linked in space and time to other landscapes, and all fall within a single watershed.

This book diverges from the usual place-based approach to describing the natural and human history of the Sierra Nevada. Instead, the book emphasizes the historical and current connections inherent to Sierran landscapes and ecosystems, and how human activity affects, and is affected by them. The landscape feature that provides the best vehicle for this kind of exploration is the watershed: a geographic area where rainfall and snowmelt collect to flow to a common point or outlet (outside of the US these are called *catchments*). The movement of water through a watershed, along with sediment, carbon, nutrients, plants and animals, form the broad connections. We take advantage of this movement, whether for economic reasons or simply for pleasure, and in so doing, change these connections, often with unintended consequences over great time and distance. Understanding these connections is, of course, a necessary step to managing them.

This book uses the Tuolumne River watershed to illustrate how watersheds in the Sierra Nevada and Central Valley connect in space and time. The Tuolumne is an ideal case study for several reasons. From its high peaks in Yosemite National Park to its rich alluvial floodplains, it has all of the physical and biological characteristics of west slope Sierran watersheds. In addition, its long history of human uses are explored, from Native Americans who managed the landscape for thousands of years, to gold miners, loggers and farmers who changed the land with astonishing rapidity, to the Sierra's most storied and ongoing dam controversy at Hetch Hetchy. Finally, the Tuolumne watershed's future, under climate change and population growth, represents the future challenges that will be faced for the entire Sierra Nevada.

What is, and is not, in this book

The information in this book is presented in five general sections. The first, this Introduction, provides a basic description of the watershed and introduces the concept of watersheds as continua. Chapters 2-4 describe the geologic process involved in building the watershed as well as the current climate and hydrology. Chapters 5-8 examine the ecology of the watershed, both aquatic and terrestrial. Chapters 9-12 focus on the human history of the watershed and how it transformed the hydrology and ecology. Chapter 13 provides a brief, speculative look into the future for the watershed under climate change. Finally, an appendix to this book provides a visitor's guide to the ecology, geomorphology and hydrology of the most frequently visited whitewater rafting stretch of the Tuolumne River: Meral's Pool at Lumsden Road to Ward's Ferry Bridge.

This book was developed by students and staff connected with the Center for Watershed Sciences at the University of California, Davis and with a course entitled Ecogeomorphology, taught by Professors Jeffrey Mount and Peter Moyle. The book is NOT a typical academic treatment, involving in-depth technical summary and analysis with an exhaustive list of references. Instead, and in a break from academic tradition, this book is non-technical, with the objective of introducing some basic concepts of geology, hydrology, and ecology using the Tuolumne as the case study. In this way, the book is intended to be accessible to all, visitors and residents alike, regardless of technical background or training.

THE TUOLUMNE IN CONTEXT

The Sierra Nevada—John Muir's Range of Light—is the west's most important mountain range. The range stretches more than 400 miles along the eastern edge of California, and includes a portion of northwestern Nevada (Figure 1). By global standards, it is not a large mountain range, nor is it particularly tall. However, it is one of the most important since it provides so much to the state of California: home to 36 million people and the world's seventh largest economy. Today, the Sierra Nevada and its snowpack supply roughly 60% of the water used in California. Sierran waters are transported to the Central Valley, San Francisco Bay area and southern California, serving more than 28 million people, while irrigating more than five million agricultural acres. The water of the Sierra is captured by more than 400 dams and diversions, and routed to its many users through one of the world's most complex water distribution systems. Before the water leaves the Sierra, its potential energy is converted to electricity, supplying up to 15% of the state's demand. As the water emerges from the mountains the water is bought, sold, haggled over and, to quote Marc Reisner, "stolen fair and square." Without the Sierra Nevada and its most precious ecosystem service, California could not sustain the population and economy that it does today.

Figure 1.1 The Sierra Nevada range and its watersheds

The Sierra Nevada, of course, is much more than just a source of water. Up until recently, it supplied the state with abundant timber, the vast majority of the state's gold, grazed millions of head of cattle and sheep on its meadows, and fed millions of people all over the world from the fertile floodplains of the adjacent Central Valley. Prior to the gold rush it supported tens of thousands of Native Americans who thrived off of the unique biodiversity of its rich ecosystems. And most relative to today, the Sierra has been a source of inspiration and recreation to visitors from all over the world. With more than 50 million visitor days annually, it is a well-used and well-loved mountain range.

Although considered a single mountain range, the landscapes, climates, plant and animal communities of the Sierra vary enormously. Altitudinal gradients are strong in the range, with desert-like conditions and hot, dry summers at the base to alpine conditions with short summers and year-round snow at the highest elevations. Latitudinal differences are also profound, with a relatively wet, low-elevation range at its northern tip in the Feather River watershed grading to a dry, high elevation range at its southern terminus in the Kern River watershed.

The variation within the Sierra is captured in the differences between its many watersheds. There are 24 large watersheds in the Sierra: 16 on the west slope and eight on the east slope. On the west slope, 12 of these aggregate into one large watershed that flows into the Sacramento-San Joaquin Delta, the hub of California's water system, and eventually into San Francisco Bay. The remaining four drain into the Tulare Basin, which connects to the San Joaquin River only during very wet years. The east slope watersheds are all internally-drained, never making it to the Pacific Ocean, except for water piped from the eastern Sierra to southern California as part of the Owen's River Aqueduct.

The Tuolumne is the largest watershed in the San Joaquin system. At more than 1600 square miles it is larger than the state of Rhode Island. It begins at Mount Lyell and Mount Dana in Yosemite National Park at over 13,000 feet, well-above tree line, and ends at its confluence with the San Joaquin River, 50 feet above sea level on the Central Valley flood plain. Its size and orientation allow it to wring a great deal of water out of Pacific storms and collect it into a very large river. Roughly 1.8 million acre-feet of water per year run off the watershed as an average.[1] This water supplies the needs of 2.4 million people in the Bay Area and 550,000 people within the watershed itself. Its waters irrigate more than 300,000 acres of prime agricultural land and support a complex but degraded ecosystem, both within the watershed and in the Delta downstream. Its two hydropower systems, Hetch Hetchy and New Don Pedro, supply roughly 1.5% of the state's annual demand for electricity. The middle and upper watershed receives more than a million visitors (most via Yosemite National Park) every year, and boasts the most sought after wilderness area in the world and the crown jewel of Sierran whitewater runs. It is not only one of the most important watersheds in the Sierra Nevada, it is a vital component of California's diverse physical, cultural and economic landscape.

BACKGROUND: WATERSHEDS AND THE RIVER CONTINUUM

Watersheds and their rivers are often viewed as fixed in both space and time. With the exception of the easily observed hydrologic changes that take place each season, processes that shape watersheds tend to operate at a range of scales, often out of sync with our life spans or our ability to perceive. Yet all watersheds are on some trajectory of change, driven by a complex

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[1] An acre-foot of water is equal to 43560 cubic feet of water or approximately 326,000 gallons of water. An acre-foot is enough to supply two to four households with water for one year.

mix of physical, chemical and biological processes. The watershed, its river, and its biota all reflect this. In this section, the overall processes that shape watersheds are reviewed and a unifying principle—the notion of watersheds and their rivers as physical and biological continua—is presented.

Drivers of Change

The character of a watershed, including its topography, hydrology, and biota, are the product of three quasi-independent processes or features: geology, climate and tectonic setting. These processes, which are explored in more detail in Chapter 2-4 of this book, are described as quasi-independent because there is some feedback between them.

The geology forms the physical template for any watershed. The composition and distribution of the rocks that underlie a watershed influences the evolution of the channel network and hillslopes, principally through differential resistance to weathering and erosion. The atmosphere, in association with plants and the soil microbes that support them, is constantly breaking down the minerals that make up rocks. This weathering process leads to the formation of soils and dissolves some minerals. Water mediates this process, carrying away the products of mineral dissolution and erosion. This is where differences in climate come in. The warmer and wetter the climate, the more intense the weathering and erosion processes.

The relentless weathering and erosion of the rocks that underlie a watershed will, if uninterrupted, remove everything, wearing it down to a smooth plain. Opposing this are the tectonic forces that cause the rocks of the watershed to bend, break, and push up to form mountain ranges, or subside to form valleys. The tectonic setting—meaning the location of a watershed within a tectonic plate—dictates the location and rates of this rearrangement of the land. The contest between the tectonic forces and the climate, mediated by the geology, dictates where a watershed occurs, how it evolves through time, what its soils are like, as well as its plant and animal communities.

There are feedbacks between these seemingly independent forces. The tectonic setting and the geology are typically closely related, particularly if the rocks are relatively young. The tectonic setting also affects the climate because mountains, in the way they alter the flow of the atmosphere, increase the amount of precipitation that falls locally. Tectonic uplift of a mountain range also increases instability of hillslopes and enhances the ability of water to erode the landscape. In this way tectonic forces, through feedbacks, accelerate the removal of the mountains that they build, with that removal taking place in the watershed.

Finally, the workhorse of a watershed is its river. Pulled by gravity, the water that flows across the surface of the land or passes through it as groundwater collects in the network of channels that drain the watershed. This plumbing system not only carries away the water, but also the by-products of weathering and erosion, either exporting them from the watershed or storing them as alluvium in valleys. And the rivers themselves, in the way they incise the land, act as an agent of erosion that sculpts the watershed. The rivers, in their shape and behavior through time, are the ultimate expression of the interactions and feedbacks between the geology, climate and tectonic setting of a watershed.

Physical Continua

The work that a river does in a watershed, involving transporting the products of weathering and erosion to the sea, is not done equally, everywhere. The small tributaries that occur in the headwaters are vastly different than the large river seen near the mouth. However, the products of these headwater streams are aggregated and passed downstream to larger tributaries, which in turn aggregate and pass these products, and additional products supplied by local hillslopes, to the mainstem. This progressive downstream handoff forms a fundamental physical continuum.

The physical continuum of large watersheds like those found in the Sierra can be broken into three general zones with diffuse boundaries (Figure 1.2). The headwater portions of most watersheds can be viewed principally as a source zone. The high relief of the headwaters and high relative precipitation make this zone a source for both water and sediment. In this setting, hillslope processes dominate the character of the streams. The middle zone in most watersheds is a transfer zone, with only modest contributions of water and sediment from adjacent hillslopes due to lower relief and lower precipitation rates. The river channel is not as steep in this zone and the canyons not as narrow, allowing for local, short-term storage of sediment in river channels and even occasional valleys. The lowermost reaches of a watershed are commonly a storage zone. Here, the lower gradient of the river and its emergence from the confines of its canyons cause it to spread out, depositing or storing sediment on the floodplain. In many cases, these broad floodplains also store large quantities of water, both on the surface and in the subsurface.

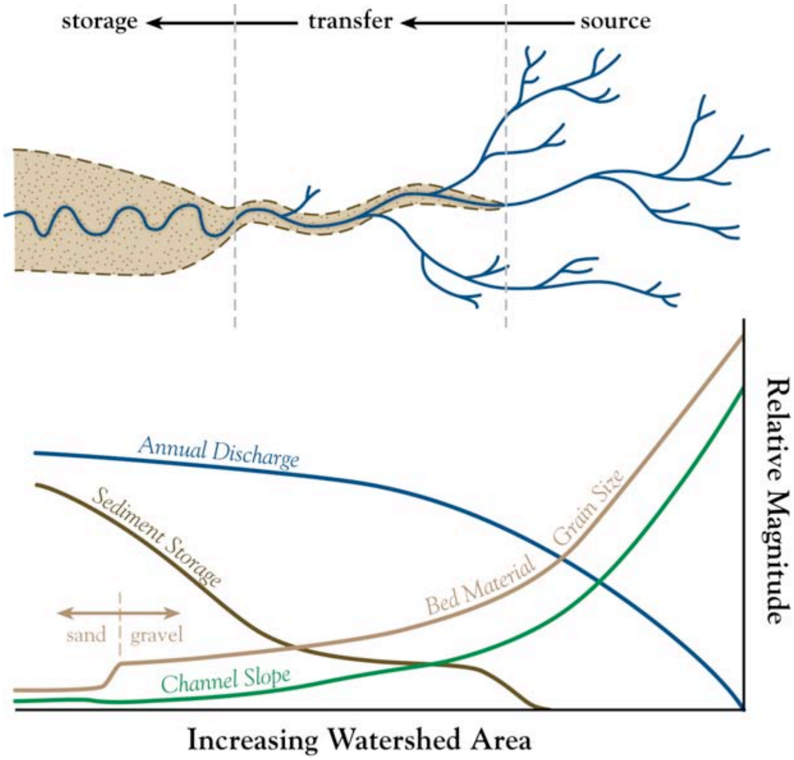

Figure 1. 2 The Tuolumne River Watershed depicting the source zone, transfer zone, and storage zone and the relative magnitude with increasing watershed area.

Although the concept of a physical continuum is appealing, it only works when the watershed is viewed broadly. When viewed closely, there are numerous discontinuities in the continuum. The most prominent of these occur where geology or tectonic processes create sharp changes in the landscape or, more commonly, where tributaries join the mainstem. Depending upon the relative size of the tributary, and the conditions that govern sediment production within it, this can lead to abrupt changes in the character of the mainstem as large volumes of water and sediment enter it from a single point.

Biological Continua

The biology of a watershed can be broken up into two general classes: terrestrial and aquatic. The plants and animals that colonize the hillslopes of the watershed make up the terrestrial communities; conversely the plants and animals that occupy the rivers, lakes, and wetlands make up the aquatic communities. A transition between aquatic and terrestrial communities, known as the riparian zone, occurs along the edges of rivers and streams throughout a watershed.

The physical gradients within a watershed along with the species interactions drive the formation of continua in the plant and animal communities as well. For the terrestrial communities outlined in Chapter 8, the gradients in soil moisture, soil types, hillslope orientation, temperature, elevation, fire, competition and disease, drive the formation of complex mosaics of forests, shrublands, and grasslands that cover a watershed. Continua for the aquatic communities and their adjacent, closely-linked riparian communities are even more pronounced with distinct differences between those located within the source, transfer, or storage zones. These differences, which are described in detail in Chapters 5 and 6, reflect remarkable adaptation and specialization on the part of plants, insects, amphibians, and fish to the physical continuum and the contributions made to aquatic communities by terrestrial communities.

THE TUOLUMNE CONTINUUM

The Tuolumne River and its watershed contain unique physical and biological continua. These continua record connections across the landscape, driven principally by the hydrological cycle and the movement of plants and animals, and are under constant adjustment at a range of scales, both in space and in time. To simplify this complexity and for the purposes of description in this text, we have broken up the watershed into source (upper), transfer (middle) and storage (lower) areas, following the pattern seen in most large watersheds (Figure 1.3).

The Upper Watershed: Source

The upper portion of the watershed, from roughly 4000 ft. to 13,000 ft. in elevation, serves as the principal source area for the Tuolumne River. This is the area of the watershed that receives abundant precipitation, most of it as snow. The rugged landscape, with its high relief amplified by glaciers, volcanic eruptions and rapid tectonic uplift, drives the water over the land and into the drainage network. Its granitic, poorly-developed soils and erodible slopes provide most of the sediment that enters into the drainage network. In the subalpine and montane portions of the source area, the watershed is heavily forested, with a mix of pine and fir. These forests and their interspersed meadows provide plant material to the rivers, as well as contributing nutrients. Almost everything the area generates is exported to the river, lost to the atmosphere, or lost through the movement of plants and animals out of the basin.

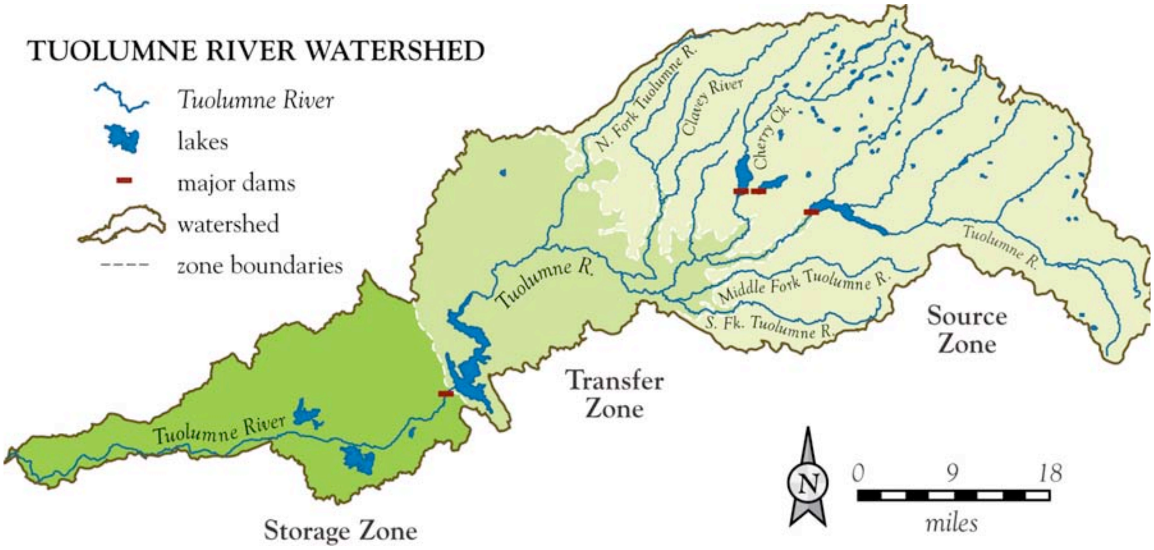

Figure 1.3 The source, transfer and storage zones of the Tuolumne River

The Middle Watershed: Transfer

The middle of the watershed, between roughly 170 ft. and 4,000 ft., is the transfer area of the watershed continuum. Water, sediment, nutrients, and carbon—both as wood and dissolved in the water—supplied by the source area of the watershed and, to a lesser extent, from its own hillslopes, transit through this portion, often with temporary storage. The river, with its lower gradient and widening canyons, has local accumulations of sediment, allowing for the development of gravel and sand bars, along with riparian plant communities. With strong temperature and moisture gradients as well as a complex mix of soils, the terrestrial plant and animal communities are the most diverse within the watershed, grading from oak/savannah to chaparral, to mixed hardwood/pine to pine forests. A distinctive aspect of this transfer zone is the abundance of large tributary inputs to the river. From the top of the transfer zone to the bottom, the major tributaries such as Cherry Creek, the South Fork, Clavey River, and the North Fork all join the Tuolumne River, more than doubling its watershed size and discharge. Each of these tributary junctions forms an important discontinuity in this zone.

The Lower Watershed: Storage

At approximately 170 feet in elevation, the Tuolumne River and its watershed passes into the Central Valley, eventually joining with the San Joaquin River. As the river emerges from the canyon it spreads out, losing its ability to transport sediment and spreading the water, carbon and nutrients across the floodplain. This process, which has been active off and on for millions of years, has built a large alluvial fan that stores some of the products supplied by the upper and middle watershed. Rather than topography, hydrology and biology based mostly on deconstruction, this portion is based on construction by the river and accumulation of the goods eroded from above. Before being cleared for agriculture, this constructed landscape supported a rich mixture of productive river, wetland, floodplain, riparian forest, and grassland plant and animal communities.

Enter the Humans

The upper, middle and lower portions of the Tuolumne watershed form a continuum with downstream and downslope handoffs of water, sediment, carbon and nutrients. The biology of the watershed reflects adaptation to this continuum, including the significant variations in conditions that occur through time.

Then, enter the humans. The Native Americans intensively managed the landscape with fire and, through their hunting and gathering practices, actively managed the plant and animal communities. Ten thousand years of such management profoundly shaped the distribution, abundance, and spatial organization of the ecosystem. The miners and those who supplied them came to the watershed in droves during the California Gold Rush, completely transforming its middle and lower reaches. During and shortly after the Gold Rush, agriculture converted the entire floodplain to a network of highly productive farms. Grazing rapidly expanded throughout the watershed shortly after the Gold Rush. The mix of cattle and sheep drastically changing all of the plant communities that supported grasses, from the oak woodlands of the foothills the the alpine meadoes of the uppermost watershed. Logging of the forests, both public and private, and the subsequent management of these forests to suppress fire, changed their species composition and their health. Dams, for hydropower and water supply, were constructed at each of the zone transitions: the Hetch Hetchy system at the transition from the source zone to the transfer zone, and the La Grange and New Don Pedro Dams at the transition from the transfer zone to the storage zone. Each facility transformed the hydrologic cycle, fundamentally altering the movement of water, sediment, carbon and nutrients throughout the watershed.

For the last 12,000 years human ecology has been inseparable from the natural ecology of the Tuolumne River and its watershed. Humans have changed the watershed and, in turn, the watershed has altered human behavior. The consequences of these changes have, depending upon one's view, ranged from the benign to the beneficial to the disastrous. With a rapidly changing climate and growing population, even more changes are in the offing. Yet all of these changes and management challenges have a common thread. They all involve altering the physical and biological continuum and its connections within the watershed and then managing or ignoring the consequences. It is at the interface of these changes, challenges, and management that the future of the Tuolumne River watershed will unfold.

SUMMARY

The watershed of the Tuolumne River is the most significant within the San Joaquin River. Covering more than 1600 square miles it supplies water and electricity to millions of Californians, feeds millions of people around the world, and draws millions of recreationists to its wilderness and its whitewater. The watershed itself is a continuum of linked physical and biological processes. Its high elevation headwaters form a key source zone where most of the water and sediment are generated, along with nutrients and carbon. This material is routed to a transfer zone that occupies the middle elevations of the watershed. This zone acts as neither a major source nor a sink for material, but simply passes it to the lower watershed. At the low elevations of the Tuolumne watershed, the river becomes unconfined, spreading across a large alluvial fan. Here, large volumes of sediment and, to a lesser degree, water, nutrients and carbon, are stored, forming some of the richest agricultural soils in the region.

The biology of the watershed reflects this continuum in processes, with native plant and animal communities adapted to the high variation in conditions in space and time. Humans have been managing this continuum for at least 12,000 years. Native Americans managed the landscape with fire in order to enhance the production of desirable plants and animals. From the Gold Rush on, Californian's have managed all aspects of this continuum, with mixed results.

GENERAL READINGS

Laws, J. M., 2007, *The Laws Field Guide to the Sierra Nevada.* California Academy of Sciences, San Francisco.

Mount, J.F., 1995, *California Rivers and Streams: The Conflict Between Fluvial Process and Land Use*. University of California Press, Berkeley, 390 p.

Moyle, P.B, 1993, *Fish: An Enthusiasts Guide*. University of California Press, Berkeley, 283 p.

The University of California Press has a series of Natural History Guides that do an excellent job of summarizing both human and natural history in California and in the general Sierra Nevada. For those interested in Sierran natural history the UC Press guides you should own include:

A Natural History of California, by Allan Schoenherr
California Forests and Woodlands, by Verna Johnston
Field Guide to Freshwater Fishes of California, by Samuel McGinnis
Geology of the Sierra Nevada, by Mary Hill
Glaciers of California, by Bill Guyton
Introduction to California Mountain Wildflowers, by Philip Munz
Introduction to California Spring Wildflowers of the Foothills, Valleys and Coast, by Philip Munz
Introduction to Fire in California, by David Carle
Introduction to Water, by David Carle
Mammals of California, by E. W. Jameson, Jr., and Hans J. Peeters
Sierra Nevada Natural History, by Tracy Storer, Robert Usinger and David Lukas
The Natural World of the California Indians, by Robert Heizer and Albert Elsasser

All of these titles can be reviewed and purchased at:
http://www.ucpress.edu/books/cnhg/complete.php

CHAPTER 2: ASSEMBLING THE WATERSHED

ANDREW NICHOLS, JEFFREY MOUNT, AND NAOMI MARKS

Introduction

As noted in the introduction of this book, the character of a watershed, including its topography, hydrology, soils, plants and animals, are ultimately derived from three key independent drivers: geology, tectonic setting and climate. The geology of a watershed—that is, the rocks or alluvial deposits (pieces of rock moved by water) that underlies the landscape--forms the template that water flows across and through. The shape of this template is largely determined by differences in resistance of rocks to erosion and weathering which, in turn, control the rates of river incision and hillslope evolution. This physical template for the watershed upon which erosive and weathering forces act is assembled by historic tectonic forces and actively altered by present tectonic forces. The tectonic setting, or its location on a tectonic plate, dictates the magnitude and patterns of this process. Finally, the rain and snow that falls on a watershed, coupled with an oxidizing atmosphere and plants that accelerate weathering to form soils, acts to tear down the rocks that tectonic forces are pushing upward and export the by-product from the watershed via the rivers. This atmosphere-earth contest shapes the evolution of watersheds and gives each its unique character.

When you walk, drive or paddle through a watershed, or simply visit it via a map, the landscape that you see represents a moment in time in the evolution of that watershed. Incessant change in climate and tectonics insures that the watershed of the past was not the same as the watershed of today, while the watershed of tomorrow will be different than both. The Tuolumne River watershed offers an ideal case study of how geology, tectonics and climate control watershed evolution. In this chapter, we explore the long history of the watershed, including the assembling of the rocks that underlie the watershed. Succeeding chapters examine the contest between climate and tectonic forces that resulted in its current configuration, and the climate and hydrology of today.

Background: Plate Tectonics, the Unifying Theory of Geology

The geologic history of the Sierra Nevada is encapsulated within its rock record. This record has three basic components to it. First is the age of the rocks, which gives us the timing of major geologic events. Age can be determined directly using geochemical techniques, or indirectly through fossils and correlations with rocks that are well-dated elsewhere. Second is the origin of the rocks. For example, sedimentary rocks such as limestone and sandstone record the deposition of sediments under specific environmental conditions (deep in the ocean or in a river), metamorphic rocks record the recrystallization of rocks due to increases in temperature and pressure as they are buried, and igneous rocks record cooling of molten rocks (or magma), whether rapidly cooled following eruption on the Earth's surface, or slowly cooled in the depths below (Table 1.1). Finally, there is the history of events that have impacted a given rock since its time of formation. Rocks are bent to form folds, broken to form faults, and, depending on their tectonic location, can be moved great distances. These three components—age, origin and history—are the essential elements of the rock record of the Sierra Nevada and the Tuolumne River.

Rock Type	How the rock is formed (i.e. *origin*)	Examples
Igneous	Cooling of molten rock inside the Earth (*plutonic*) or on the Earth's surface (*volcanic*)	*Plutonic* : Granite, diorite, gabbro *Volcanic* : Rhyolite, andesite, basalt
Sedimentary	Accumulation of sediments or precipitation of crystals from aqueous solution	Sandstone, shale, limestone, conglomerates
Metamorphic	Intense heat and/or pressure change a rock from one form (*parent*) to another	Schist, gneiss, quartzite (*sandstone)*, slate (*shale*), marble (*limestone*)

Table 1.1 Types and origins of the different common types of rock

The long and complex geologic history recorded in the rocks of the Sierra Nevada reflects the region's tectonic setting. For more than 600 million years, California has been at or near the edge of the North American tectonic plate. As a brief background, the surface of the earth can be divided up into seven major (and several minor) tectonic plates that are in constant motion. These plates, which are relatively rigid, make up the lithosphere, which includes the earth's crust and the upper portions of its mantle (Figure 2.1). These rigid lithospheric (or tectonic) plates glide around on a soft asthenosphere. The plates vary in thickness and composition, depending upon their age and the type of crust that caps them. On the continents, the crust is of relatively low density, is rich in silica and alumina, and is thick, typically around 25 miles or more. In contrast, the crust that underlies oceans is high density, is rich in iron and magnesium, and is thin, typically around 6 miles in thickness. This contrast in thickness and density controls much of the topography of the earth. The continental crust, being more buoyant, underlies most of the terrestrial surface of the earth and the shallow continental shelves, while oceanic crust, being thin and dense, underlies the ocean basins.

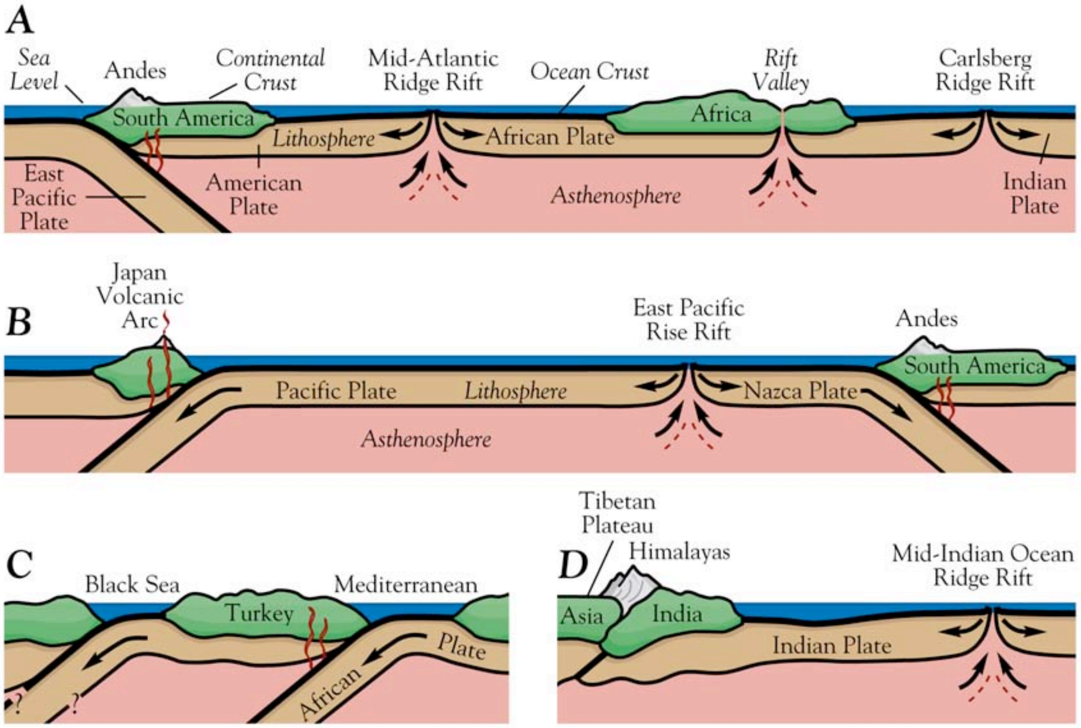

Figure 2.1. Generalized diagram depicting the structure of the Earth's crust and mantle at the major types of lithospheric plate boundaries. (Mount, 1995).`

Since the tectonic plates of the Earth are in constant motion, they are also constantly interacting with each other. These interactions at plate boundaries are where most of the geologic excitement occurs. The composition of the crust at these boundaries—continental or oceanic—dictates the dynamics of the plate interactions and the associated origin and history of the rocks. Plate interactions can be grouped into three general types: divergent, convergent, and transform (Figure 2.1).

Divergent Plate Boundaries: Where an edge of a tectonic plate is pulling away from adjacent plates, it is known as a divergent boundary. The divergence of two plates creates a void that is typically filled by upwelling magma (*molten rock*) to form new crust that is oceanic in character (thin, dense). Where plates have been pulling apart for long periods of time, they form great ocean basins such as those seen in the Atlantic and the eastern Pacific, with long submarine ridges occurring where new oceanic crust is forming. In contrast, new plate boundaries often form through the break-up of continents, a process known as continental rifting. In the initial stages of continental rifting, large valleys, such as the East African Rift Zone and its northward extensions, the Red Sea Rift and the Gulf of Aden begin to form. As rift valleys expand, oceans, floored by oceanic crust, are created. In this way, geological processes occurring at divergent boundaries increase the size of tectonic plates through addition of new oceanic crust.

Convergent Plate Boundaries: When two rigid lithospheric plates collide, something must give. When thin, dense oceanic plates meet more buoyant continental plates, the soft and plastic (moldable) underlying asthenosphere allows the denser oceanic plate to slide – or *subduct* – underneath the continent (Figure 2.1). This subduction process can also occur when two oceanic plates of differing density converge. As the subducting plate slides deeper into the hot asthenosphere it begins to melt, initiating the first of a series of geological processes that will dramatically alter the plate above.

The location where one tectonic plate slides beneath another is known as a *subduction zone*. These remarkable locations of plate convergence are characterized by enormously deep oceanic trenches, where large earthquakes are common and prolific amounts of sediment are deposited. As the downgoing plate slides deeper into the asthenosphere, sediments and volcanic rocks resting on top of the plate are scraped onto the overlying plate. What is not scraped off is melted as it moves deeper into the Earth's hot interior and is effectively recycled. The water that is carried deep into the earth in a subduction zone lowers the melting temperature of the surrounding rocks. This leads to the formation of magma at and above the subduction zone at depths where the ideal combination of heat and water melt rock. Because the molten material is less dense than the surrounding rocks, large concentrated volumes of magma rise up and collect in the plate above, cooling and eventually crystallizing into a body of rock called a *batholith*. Rock types in batholiths will vary depending on whether oceanic crust subducts under continental or oceanic crust. When oceanic crust subducts beneath a continent, the resulting batholith is rich in *granite*, reflecting the silica- and alumina-rich overlying crust. Conversely, if only oceanic crust is involved in the subduction process, the underlying batholith will be dominated by *gabbro*, an igneous rock rich in magnesium and iron, reflecting the composition of both the subducting and overlying crust. Commonly, pools of either gabbroic or granitic magma are able to reach the Earth's surface through fractures and weaknesses, creating large linear chains of volcanoes. When these volcanic chains are located on a continent, such as in the Andes of South America or the Cascades of California, Oregon and Washington, they are referred to as *continental arcs*. When formed over oceanic crust, chains of islands, similar to what we see today in Japan or the Aleutian Islands, are created and referred to as *island arcs*.

These subduction-related geologic processes dominate much of the geology seen along the world's convergent plate boundaries. However, the most dramatic of tectonic events at convergent plate boundaries occurs when something refuses to subduct. Occasionally, island arcs or other objects (known as *terranes*) will collide with and be added to the edge of a continent. This process of adding (or *accreting*) terranes is akin to an object riding on an escalator and being deposited at the end as the belt dives underneath. The stresses involved with this slow and continuous accretion impact the continent well inland from its edge, leading to significant mountain building events known to geologists as *orogenies*. The most extreme example of this is where two large continental plates collide. The size, low density and thickness of each continental plate ensure that neither will give way in the collision, leading to the greatest orogenies. The formation of the Himalayas, the world's tallest mountain range, is a product of the ongoing collision between the Asian and Indian continents. These collisions and accretions, in conjunction with the formation of chains of volcanoes, are the reason that mountains (volcanic or otherwise) usually lie at the edge of convergent plate boundaries.

***Transform Plate Boundaries*:** The formation of new crust at divergent boundaries is balanced by the subduction and melting of crust at convergent boundaries. If it didn't, the earth would be either expanding or contracting, which it is not. However, given the complex geometry of plates moving on a spheroid like the earth, some plate interactions will involve only sliding past each other, neither creating nor destroying crust. Known as transform boundaries, the grinding interaction between plates applies a great deal of stress to the tectonic plate edges. This stress is accommodated or released through the formation of large fault zones, typically dominated by one very large fault connected to many smaller ones. The motions of these faults can lead to the formation of both mountain ranges and valleys, all oriented roughly parallel to the plate boundary.

The geologic history of the Sierra Nevada and the Tuolumne watershed, as read through the age, origin, and history of its rocks, is largely a story of an evolving plate boundary at the edge of the North American continent. The rocks of the Tuolumne River watershed reflect all three types of plate boundaries—divergent, convergent and transform-- over the past 600 million years (Figure 2.2). The bulk of this history reflects numerous subduction zones and terrane accretions at a convergent boundary as the dominant theme, culminating with the development of the transform boundary of today that we know as the San Andreas Fault. In brief, the Sierra Nevada began as a sedimentary plain on the margin of the Pacific plate. The early mountain building began as the result of the Pacific plate subducting beneath the North American plate which resulted in four major terrane accretions, periods of volcanism, dramatic uplift, and large granitic batholiths forming beneath the growing mountain range, now exposed by glaciation.

Early History (600 to 300 million years ago)

During the Late Precambrian until the Middle Paleozoic (Figure 2.2), California lay at the edge of the North American continent, much as it does today. The difference, however, is that while today the continent abruptly ends at an earthquake-riddled transform boundary between the North American and Pacific tectonic plates, for approximately 300 million years beginning in the Late Precambrian, these two tectonic plates met at a divergent plate boundary located some distance away from the edge of the North American continent. In this way, California lay under a shallow sea that extended along what is known as a *passive continental margin*. This extensive, low-gradient plain was similar to the present-day eastern seaboard of the United States and devoid of the earthquakes and volcanoes we see today along the western edge of North America. Extending from present-day Idaho, through Nevada and into southern California, the shelf that formed along the seaward edge of the continent received vast quantities of sediments from the large rivers that drained westward from the flat continental interior. Because North America lay across tropical equatorial latitudes at the time, this continental shelf alternated between accumulating sandstones and mudstones during cool/wet periods, and limestones and other chemical sediments during warm/dry periods. The deposition of sediments at this continental margin dominated geological processes until approximately 300 million years ago (ma) during the Middle Paleozoic Era, when the margin transitioned to an *active* state dominated by processes associated with a convergent plate boundary located under the ocean off the continent's edge. Convergence certainly created periodic uplift during this period. However, the "big story" is the lateral accretion of material, because after the mountains have come and gone (through erosion), all that is left to see is the remnant rocks.

The bulk of the geologic record from this period of time is preserved in thick sedimentary rock sequences scattered around the Great Basin, southern California, and the east slope of the Sierra Nevada. Within the Tuolumne watershed today, rocks of this age are scarce, having been melted during the later intrusions of the granitic magmas that ultimately came to form the granites of the High Sierra we see today. The rocks that record this early passive continental margin are referred to as "roof pendants" and preserved in a small region in the uppermost part of the Tuolumne watershed (Figure 2.3). The subsequent emplacement of the surrounding granite recrystallized these sedimentary rocks, turning them into metamorphic rocks.

Accreted terranes of the foothills (300 ma to 140 ma)

During the middle of the Paleozoic Era, the North American and Pacific tectonic plate boundary transitioned into a convergent boundary dominated by subduction-related tectonics. Periodically over the next 160 million years, this altered tectonic setting allowed new rocks to be added to the continent through a process known as *accretion*. During this period, geologic objects (or *terranes*) at times collided with western North America. These collisions not only added rock to the continent, but the heat and pressure associated with the collisions altered (*metamorphosed*) the existing rocks as they were squeezed and shuffled into long-vanished mountain ranges. The rocks associated with this complex period in the geologic history of California are represented by a diverse suite of igneous, sedimentary and metamorphic rocks that make up much of the Sierra Nevada foothills. Lumped together, these rocks are known as the Foothills Metamorphic Belt. However, geologists separate this group into individual groups (known as *terranes*) based on differing geologic histories. In some cases the terranes are *exotic*, meaning that they have been transported great distances before being added to the continent's edge. In other cases, terranes were formed in close proximity to where they are now – not quite exotic, but terranes nonetheless. Regardless of origins, either close to home or far afield, these terranes occur all along the western margin of North America, from Mexico to Alaska. As noted in the background to this chapter, most of these terranes are emplaced, or accreted, through the process of stacking them against the continent through subduction. However, following accretion many terranes have been moved great distances by faults (such as the New Melones and Bear Mountain Fault Zones in the Tuolumne River watershed – Figure 2.3) that parallel the continental margin.

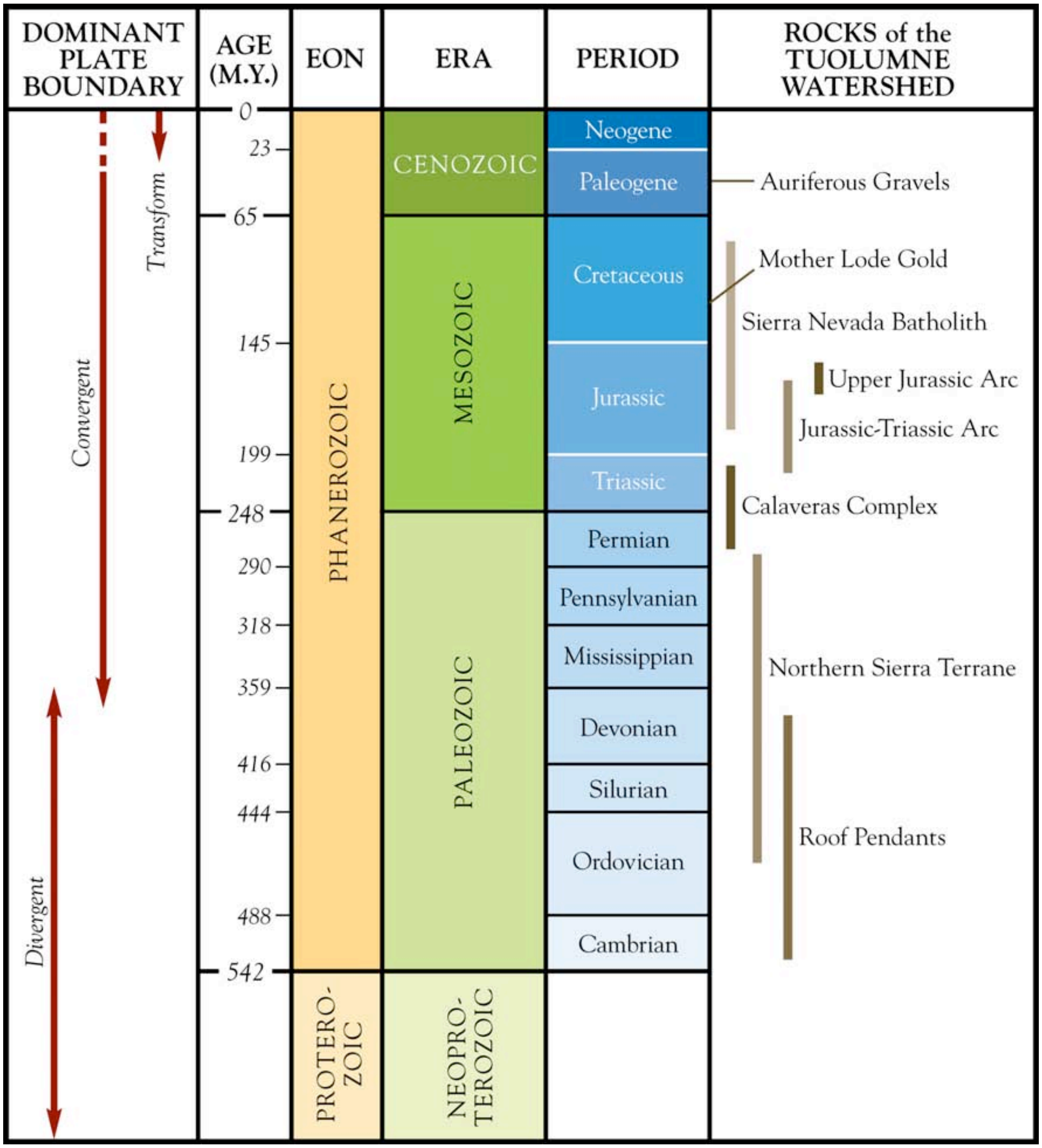

Figure 2.2. The timing of divergent, convergent and transform margin tectonics, and the rocks that remain in the Tuolumne River watershed to record these tectonic processes.

Teasing apart the age, origin and history of the rocks that make up terranes is complex business. The rocks have typically been bent, broken and recrystallized, and rocks of very different ages have been interleaved by faulting. Thus, it should be no surprise that geologists are still arguing over the designation and history of terranes in the Sierras. Some terranes are not considered exotic at all, but instead formed close to their current location. In the vicinity of the Tuolumne River, principally within the foothills, there are four main terranes that can be seen and whose origins we explore in depth below (Figures 2.3). From east to west, these include the Northern Sierra Terrane, the Calaveras Complex, the Jurassic-Triassic Arc, and the Upper Jurassic Arc.

Northern Sierra Terrane**:** The easternmost and oldest terrane of the Sierra Nevada Foothills in the vicinity of the Tuolumne River consists of an amalgamation of rocks of ages spanning from the Ordovician to the middle Jurassic. Known in recent literature as the Northern Sierra Terrane, but usually referred to as the Shoo Fly Complex, this terrane was added to the continent as early as the Permian or as late as the mid-Jurassic, though this remains subject to vigorous debate amongst geologists. The oldest rocks of this terrane are sedimentary deposits that formed seaward of the western edge of North America in a deep ocean basin. These sediments contain fossils of marine organisms that give ages from the Ordovician-Silurian period, and appear to have derived some of their overlying sediment from the nearby continent. Overlying these are the remnants of at least three island arcs of different age, similar to the island arc system that forms Japan. The accretion of this long-lived stack of material, a violent if slow process, caused extensive deformation and recrystallization of the terrane sediments, converting them to metamorphic rocks. In the vicinity of the Tuolumne River watershed, later intrusions of granite largely destroyed the record of the Northern Sierra Terrane. However, a pocket of these rocks can be found north of Jawbone Ridge within the Clavey River drainage basin (Figure 2.3).

Calaveras Complex: One of the most distinctive, and often visited terranes exposed in the Tuolumne River Basin is the Calaveras Complex. Seen (or as geologists like to say "cropping out") throughout the central portions of the watershed, the Calaveras Complex is the most prominent group of rocks encountered on the Wild and Scenic stretch of the Tuolumne River visited by whitewater rafters. Lying just west of the Northern Sierra Terrane (Shoo fly), the Calaveras complex is the second terrane to have "docked" onto the edge of the North American continent during the middle of the Jurassic period. A well known fault—the Shoo Fly Thrust—marks the boundary between the two terranes. The complex consists of rocks of starkly different ages and origins. The most prominent rocks are dark cherts, metamorphosed muds (argillites) and volcanic rocks, which formed during the Triassic and early Jurassic in a relatively deep ocean adjacent to an oceanic island arc. Embedded within this suite of rocks are much older blocks of marble, which are metamorphosed limestones that formed in shallow reefs during the Permian period. These rocks slid into the deep ocean millions of years after they were formed and were mixed with the cherts and argillites. The rocks of the Calaveras Complex have been intricately folded and broken by tectonic forces, creating a mixed pile of material known as a *mélange*. The process of making a mélange is associated with the stirring of relatively soft sediments that occurs as the sediments are scraped off of a subducting plate at a subduction zone.

There is some disagreement among geologists about how far the Calaveras Complex travelled before it was accreted to the North American Continent. Some view it as having travelled a great distance, qualifying it as an exotic terrane. Others feel as though it formed adjacent to the edge of the continent and was simply deformed, in place, at a subduction zone along the margin of the continent. Regardless, by the middle Jurassic Period, the Calaveras Complex had been pushed against the Northern Sierran Terrane and locked into place.

***Jurassic-Triassic Arc*:** The western boundary of the Calaveras Complex is defined by a large fault zone containing the Sonora and the Melones Faults. West of that fault a belt of metamorphic rocks defines a new terrane: the Jurassic-Triassic Arc (Figures 2.3). This belt represents an extremely diverse group of metamorphic rocks as old as late Paleozoic and as young as mid-Jurassic, with most rocks Triassic through mid-Jurassic in age. This complex group of rocks originally made up another arcuate chain of volcanoes built on top of oceanic crust and eventually accreted onto the edge of North America. Visible today are the metamorphic remnants of a group of volcanic and sedimentary rocks formed within and around these volcanoes, including pieces of oceanic crust, ocean-bottom sediments, volcanic flows and the gabbroic magma chambers that fed them. Included within this mixed-bag of rocks is serpentinite – the state rock of California known for its dark green color and waxy appearance. Serpentinite represents the metamorphosed remnants of dense, magnesium-rich mantle rocks, known as peridotite, underlying oceanic crustal rocks. During subduction, this peridotite was subjected to high pressures and temperatures, metamorphosing the rock into the less-dense serpentinite as it was thrust up onto the edge of the North American continent. The ages of the igneous rocks that make up this terrane suggest that it was an active volcanic arc in close proximity to the continental margin and traveled a short distance to its eventual resting place. The western margin of this terrane is the Bear Mountain Fault Zone. This fault extends from the region of the Tuolumne River all the way north to Oroville. An earthquake along this fault zone near Oroville in 1975 was thought to be caused by the weight of Oroville Reservoir. This spawned concerns over the placement of the Auburn Dam on the North Fork of the American River. These concerns coupled with concerns over cost and environmental impacts, lead to the project's abandonment in 2008.

***Upper Jurassic Arc*:** The fourth and youngest belt of metamorphic rocks in the Sierra Nevada foothills lies west of the Bear Mountain Fault Zone and underlies the eastern portions of the Central Valley. This belt of rocks, termed the Upper Jurassic Arc, is particularly important because it records the beginning of subduction-related processes leading towards the eventual creation of a continental volcanic arc in the Sierra Nevada and the underlying granitic batholith. Until this point, terranes accreted to the North American continent largely reflected collisions between oceanic island arcs and the continental margin. However, the Upper Jurassic Arc and its thick sequences of dark-colored slates and sandstones largely record a different process - that of scraping a huge wedge of metamorphosed sediments onto the continent. In this way, it is less a terrane and more a deposit that formed where it is today. These metamorphic rocks were created from sediments that had been eroded from the North American continent and deposited in the deep offshore trench marking the location of a large subduction zone that underlay the current location of California's Great Central Valley.

Building the Granitic Spine

The formation of the Upper Jurassic Arc in the westernmost foothills signaled a major transition in the tectonics of California and the Sierra Nevada. At this time the subduction zone that had been active off and on since the middle Paleozoic Era moved westward, and continued

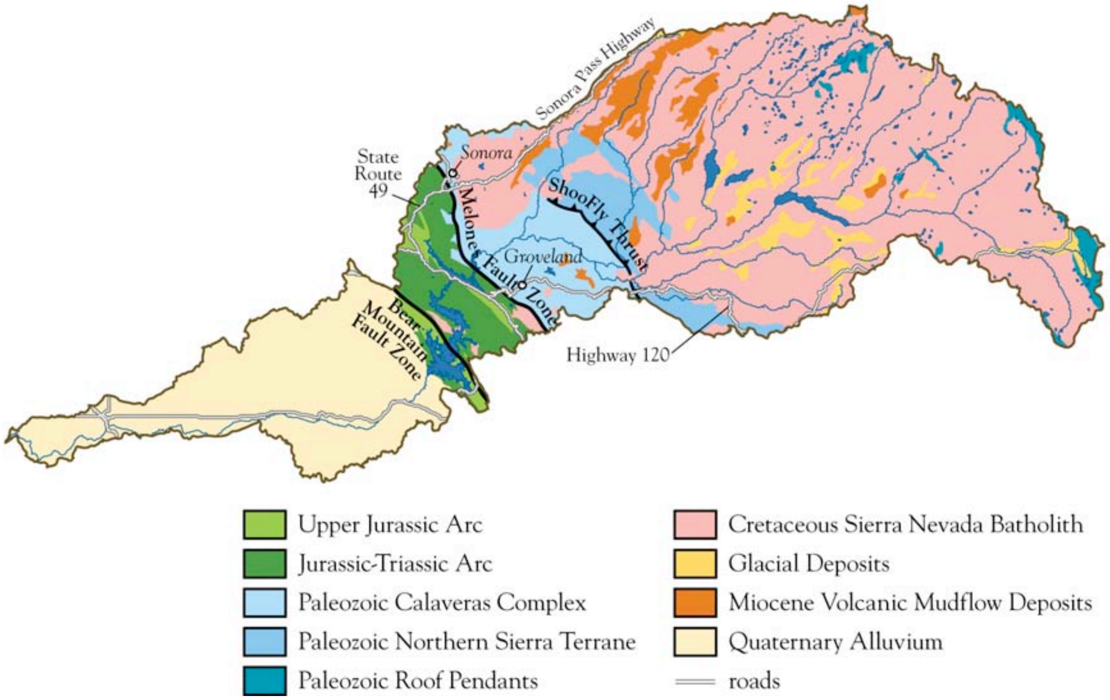

Figure 2.3: Generalized geologic map of the Tuolumne River Basin (based on California Division of Mines and Geology geologic maps).

to subduct oceanic crust of the Farallon plate beneath the continent in the vicinity of the present-day California Coast Ranges. The subducting slab, with its high water content, reached the ideal depth and temperature for dramatic melting of the crust in the vicinity of the crest of the present-day Sierra Nevada. At the surface, a very large Andean-style continental volcanic arc was created, in a mountain building event known as the Nevadan Orogeny. Meanwhile, 6-9 miles below the surface of the earth, slow cooling of these unerupted magmas formed the Sierra Nevada's most iconic and voluminous rock type: granite.

Making Granite

Granite dominates the Central and Southern Sierra, forming the spine of the mountain range. More than half of the Tuolumne watershed is underlain by granitic rocks (Figure 2.3), which controls aspects of the watershed hydrology, soils, and water chemistry. The granite seen throughout the Tuolumne River basin did not form all at once. However, it did form over a relatively short period of time. Most of the granite is Cretaceous in age, reflecting a roughly 60 million-year period, ending around 85 ma, when concentrated granite formation took place over the subduction zone.

Magma bodies that form deep in the earth are called *plutons.* They differ from basaltic rocks in that they cooled subsurface and were later exposed through weathering and glaciation. Plutons are typically balloon-shaped and, depending on the rock which has been melted, have unique chemical and mineralogical compositions. As these plutons rise toward the surface, they join with other plutons to form an amalgamated body of granite known as a *batholith.* The Sierra Nevada Batholith is the largest regional concentration of granite in the world.

The iconic status of Sierran granite is largely derived from the large, multi-colored monolithic granite structures seen throughout the mountain range (and revered by rock climbers throughout the world) and the unique "salt and pepper" look of its constituent minerals. As molten rock rises toward the surface, it is subjected to less pressure and it begins to slowly cool within the confines of the rock it intrudes into. As the decline in temperature and pressure occurs the melt becomes chemically saturated with respect to certain mineral phases, such as hornblende and plagioclase. Individual minerals begin to nucleate and then grow in this saturated environment. Because these minerals selectively remove some elements from the melt, the melt becomes relatively enriched in other elements. As the magma continues to cool and depressurize, this cycle continues with new mineral phases forming and thus further altering the composition of the surrounding melt. The end result of this process is the formation of a mixture of minerals, with quartz typically being the last to form, of different sizes and compositions that ultimately solidify to create the multi-colored granite seen throughout the Sierra Nevada. This is complicated by continued formation of new bodies of magma that intrude into or assimilate older, solidified or partially solidified plutons. This assimilation process changes the chemical composition and resultant mineralogy of the younger pluton. This chaotic period of magma intrusion and pluton assimilation deep below the Earth's surface is responsible for the exceptional local variability in the composition of Sierra Nevada Batholith.

Mother Lode Gold

As discussed in Part 3 of this book, gold has defined the human occupation and much of the human alteration of California. The Tuolumne watershed is no exception to this. Tuolumne County yielded the third largest total recorded gold production of all California Counties. The exploitation of gold in the watershed hastened the displacement of Native American, and ultimately dictated the location of roads, towns and water supply systems.

The occurrence of gold in the Tuolumne watershed is not a random accident. Many geologic factors, including terrane accretion and the building of the Sierra Nevada Batholith, worked together to control location and abundance of gold. In the Tuolumne watershed, gold occurs both as placers (gold among gravels) and as lode deposits (gold found in hard rock veins). In this section, we review the processes that formed lode and placer gold.

Mother Lode Host Rocks and the Melones Fault Zone

The Mother Lode vein system that was the target of so many hard rock mines is intricately linked to the terranes of the Foothills Metamorphic Belt and the faults that both bound them and occur within them. At the time of its formation in the Late Jurassic, the Melones Fault Zone, which juxtaposes the Calaveras Complex and the Jurassic-Triassic Arc terranes, reached deep into the earth into the vicinity of the newly developing Sierra Nevada Batholith. Fluids rich in CO_2 that were associated with the cooling, crystallizing magma 6-9 miles below the surface, rose upward along the Melones Fault Zone. These fluids, which were of high pressure and temperature, may have expanded the fault zone, enhancing their pathway toward the surface. Reactions between gold-bearing, CO_2-rich ore forming fluids and the oceanic arc-related rocks within the foothill terranes led to the precipitation of quartz, carbonate, mariposite (Cr-rich muscovite) and gold.

It remains surprisingly unclear just what or where the source rocks for the gold might have been. It is apparent that the gold resulted from CO_2-rich fluids released in some association with the emplacement of the Sierra Nevadan Batholith. However, it is also likely that the gold is not from granitic plutons, but rather from previously metamorphosed rocks of the accreted terranes, and was leached from these rocks and brought to shallower depths by these fluids. Age and geochemical data indicate that the ore forming solutions precipitated a mix of quartz, carbonate and gold at temperatures of 480 to 840°F, 1-6 miles below the surface. Uplift and erosion of the Sierras (discussed in Chapter 3), brought this gold close enough to the surface to exploit it.

Geology of Placer Gold

Placer gold occurs as particles of gold found in streambed sand, gravel, and silt. It frequently occurs in the placer deposits as a native metal, uncombined with other elements. Gold has a high density, sixteen to nineteen times heavier than water and five to six times heavier than stream gravels. Much of the gold found in the Sierra Nevada placers is actually electrum, a natural amalgam of gold and silver. Electrum is somewhat less dense than pure gold, but is still 5 to 7 times heavier than the streambed gravels in which they are found. Coarser gold nuggets could be found at the bottom of streambed channels, often in contact with the bedrock. The finer grained gold dust is more widely distributed with the stream gravels, but due to its mass, naturally concentrates in the lower parts of the streambed.

Sierran placer gold comes from gold-bearing quartz veins in the metamorphic bedrock of the Sierran foothills. The gold is liberated from the host rock through weathering and erosion, and is transported downslope and downstream via gravity and running water. Because the transport of placer gold is gravity and fluid driven, larger nuggets will be found in reasonably close proximity to the outcrops from which they eroded, whereas extremely fine-grained gold dust can travel much further downstream.

The original quartz-gold veins were emplaced in the bedrock of the ancestral Sierra Nevada about 130 million years ago during the end of the Jurassic period. Emplacement was followed by 65 million years of intense uplift and erosion until the ancestral Sierra topography, Cretaceous rivers and their tributaries efficiently concentrated much of the gold that had weathered out of the bedrock, and concentrated it into rich zones called “pay streaks” by the miners. By the beginning of the Tertiary period, an increase in erosion and sedimentation associated with uplift coincided with the deposition of tremendous amounts of volcanic debris that blanketed much of the Sierra Nevada. Gold from the original placer deposits was eroded out of its original streambeds and redeposited further downstream, then often covered with Tertiary volcanic deposits.

The uplift of the modern Sierra Nevada within the last several million years precipitated a resurgence of deep erosion, the likes of which had not been seen since the Cretaceous (see chapter 3). The spectacular canyons and innumerable tributary ravines that make the modern Sierra landscape so distinctive were incised during this period of dramatic uplift and erosion. The deep channel erosion cut many of the Tertiary auriferous, or gold bearing, gravel channels and remobilized much of the gold. These most recent, remobilized placers were the deposits discovered in 1848 and exploited in the early years of the Gold Rush. It was not until the early 1850s that the remnants of the Tertiary placers were identified.

Summary

The rocks of the Tuolumne River tell the story of the watershed's evolution. The age, origin and history of the rocks that make up the geologic mosaic of the watershed, tell a four-part history of watershed assembly. The oldest rocks, preserved in the uppermost portions of the watershed near the crest of the Sierra, record a time when the current west coast of North America was flanked by a continental shelf along a passive continental margin. Three of the terranes that make up the Foothill Metamorphic Belt record mid-Jurassic westward growth of the continent in the geologic equivalent of a pile-up as volcanic arc-related rocks were plastered onto the continent during subduction. In the Late Jurassic, a fundamental shift occurred in the convergent margin, with a westward shift in the subduction. The early stages of this shift led to the formation of the Upper Jurassic Arc, the westernmost terrane in the Foothills Metamorphic Belt. The shift led eventually to the formation of the iconic rock of the Sierra Nevada, granite. Cretaceous subduction, up until 85 ma, created concentrated melting deep in the earth in the area of the Sierra Nevada. This melting formed an Andean-style arc and the vast Sierra Nevada Batholith. During this time, gold managed to find its way into the Foothills Metamorphic Belt along faults that cut through and bounded the various terranes.

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CHAPTER 3: EVOLUTION OF THE MODERN TUOLUMNE RIVER WATERSHED

JEFFREY MOUNT

INTRODUCTION

The geologic template that makes up the Tuolumne River watershed took almost 500 million years to put together. This long history is often forgotten when viewing the watershed today. Yet these events have played a key role in how the watershed has evolved, principally by controlling the rates and products of erosion and soil formation as the Sierra Nevada was formed. But assembling the underlying rocks is only half of the story. The evolution of the watershed—the earth-atmosphere contest described in the introduction to this book—is itself a long, complex history (Fig. 3.1). In this chapter, the major elements of this history are reviewed, including how geologic and climatic events have left indelible imprints on the watershed today.

EXPOSING THE GRANITIC SPINE

The geologic template of the Tuolumne, including its iconic granite in the headwaters and its gold-bearing terranes in its foothills, all reflect rock-forming processes that took place at great depth below the surface (See chapter 2). When you walk the glacially-polished granites of Tuolumne Meadows, you are standing on rock that formed from a melt some 6-9 miles below the surface. To get these granites to the surface, you had to erode a lot of overlying rock. This required prodigious uplift of the mountain range and, most important, synchronous weathering, erosion, and removal of this material from the mountain.

The stripping off of 6-9 miles of rock at the crest of the ancestral Sierras involved a collaboration between tectonic forces and climate. Although granite-forming subduction ceased around 85 ma, the western margin of North American was still undergoing convergence with the tectonic plate that underlay the ancestral Pacific Ocean. This compression led to dramatic and rapid uplift of the ancestral Sierras and the regions to the east in Nevada. At the same time that these forces were pushing the mountain up, the precipitation that was falling on the Sierras during the warm, wet climate that dominated North America during that time, was able to keep up with this uplift by eroding deep into the evolving mountain range. Based on multiple lines of geologic evidence, the bulk of the uplift and exhumation of the Sierras took place in the 10-20 million years following cessation of the formation of granite. This is a lot of rock to weather, erode, and transport off the crest of the mountain range in a relatively short period of time. It is important to note, however, that there is a feedback between climate and tectonics in mountain building events. As mountains are pushed up, they change their own climate, increasing precipitation as air is forced up and over them (chapter 4), enhancing their own erosion. Alternatively, high rates of erosion and removal of the mass of a mountain can, in turn, accelerate the rate of uplift, much in the way a ship floats higher as freight is removed. This feedback allows for both the rapid uplift of a mountain range and its rapid erosion.

Perhaps more significant is the mass of material that was removed from the Sierras. A mountain range that is roughly 400 miles long and sheds as much as 6 to 9 miles of overlying rock must have left a deposit somewhere. Today, the Cretaceous sediments that were swept off of the ancestral Sierran arc underlie the Great Central Valley. These deposits form a thick prism of sandstone and shale that gives a geologic record of the timing of uplift and erosion of the Sierras. Additionally, the deposits and their fossils, give a clue to the environmental conditions at the time. These deposits are the product of numerous westward-flowing large rivers that dropped their Sierran-derived loads in deltas along a Cretaceous shoreline that hugged the eastern edge of the valley. At least one of these rivers formed a delta that underlies Modesto, and was the ancestral Tuolumne River. To date, there is no direct evidence that the present channel of the Tuolumne is the same as the Cretaceous Tuolumne. We only know that a river was there at the time and that the modern Sierras with its axis parallel to the western margin of North America had begun to form.

This episode of dramatic uplift and erosion in the late Cretaceous continued off and on until the Eocene (see map, Figure 2.4), roughly 50 million years ago. This was a particularly tumultuous time in the western United States, with mountain building events stretching as far east as the Rockies and south into the area of the Grand Canyon. This long, somewhat diffuse tectonic event is known as the Laramide Orogeny. Evidence throughout the Sierras indicates that by the close of this event, the rivers that had helped erode the ancestral Sierras had expanded themselves eastward into Nevada, Utah and perhaps even Idaho, forming very large watersheds that continued to feed sediment into the Central Valley.

The Tropical Tuolumne River Watershed

Approximately 50 million years ago, during the Eocene Epoch, the dramatic uplift and erosion of the Sierra Nevada began to slow, leading to the development of a more subdued mountain range backed by a high plateau to the east. To most, the Eocene Epoch is known for the rapid evolution of mammals, including the appearance of *Eohippus*, the ancestor of modern horses. For the human occupation of California and the Tuolumne River, however, the Eocene Epoch played a critical role because of its deposits of gold.

Globally, the Eocene Epoch is notable for a period of intense warming. California was no exception to this. Throughout the foothills of the Sierra sediment deposits and fossil soils indicate that an extended period of wet, tropical conditions prevailed, replete with vegetation that we would think of as jungle-like. Large river systems continued to drain westward out of the vicinity of Nevada, Utah and Idaho during this time. Most importantly, the channels that these rivers flowed through carried modest amounts of gold. Remnants of these channels can be found in small outcrops in the Tuolumne River watershed, indicating that an Eocene-age river ran close to the present course of the river. The abundance of these deposits—known as "auriferous gravels"--increases to the north, with the largest occurring in the Yuba, Bear and American River watersheds. These 50 million-year-old deposits helped shape California's human occupation and transformation. Hydraulic mining between 1852 and 1884 washed vast quantities of this material into the Central Valley and San Francisco Bay, clogging the rivers and increasing flood damages. This led to the first environmental lawsuit when the farmers of the valley sued the miners, leading to an injunction against hydraulic mining in 1882 and an outright ban on it in 1884. In response to the filling of the rivers with sediment, the U.S. Army Corps of Engineers built the flood control project that we see today in the Central Valley.

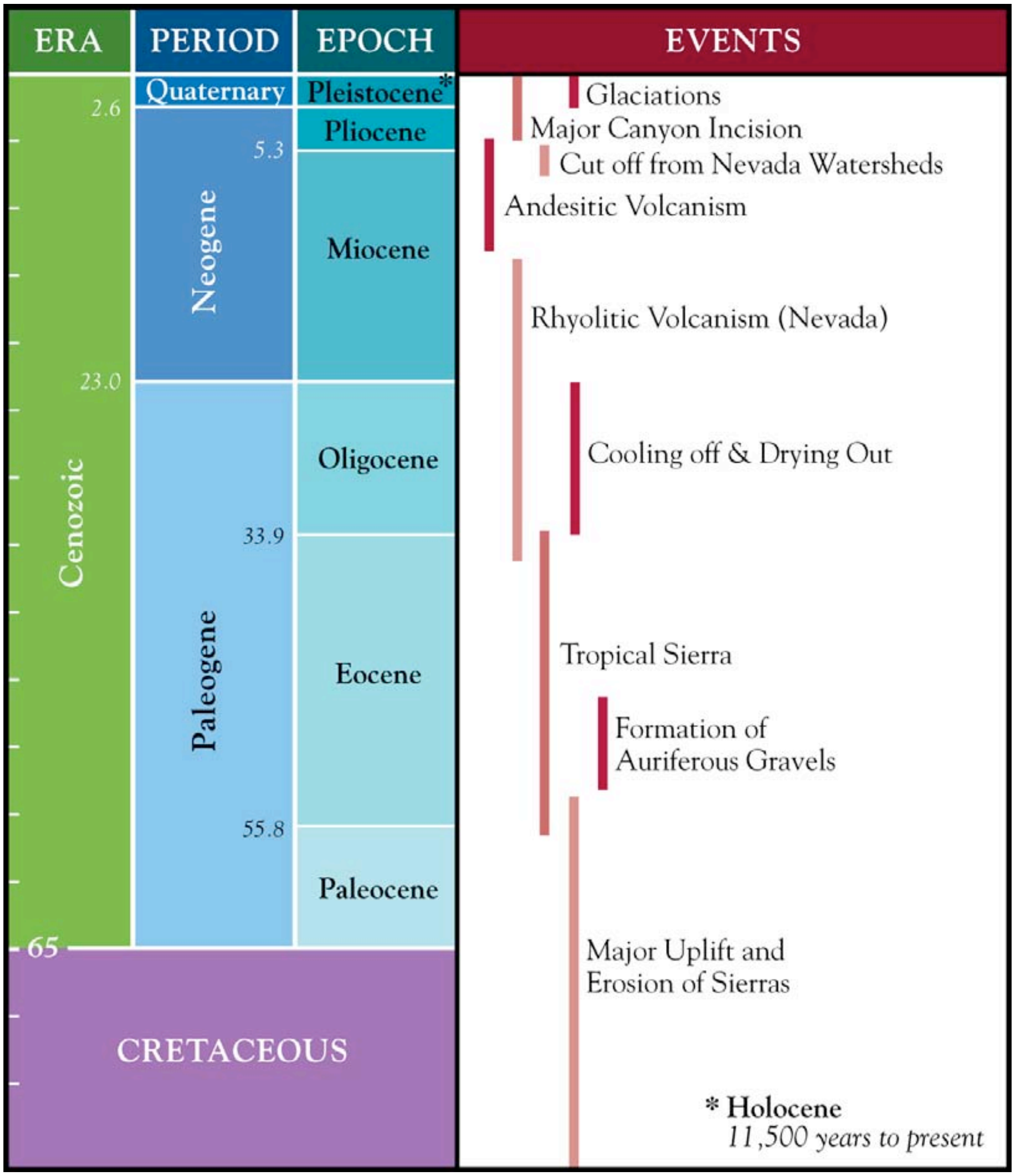

Figure 3.1. General time column of the Late Cretaceous and Cenozoic outlining major events that impacted the Tuolumne River Watershed. From various sources.

Drying Out and Cooling Off

At the end of the Eocene and the beginning of the Oligocene there was a global cooling event. This brought significant changes to California's climate, with an extended period of drying out and cooling off. During this cooling, the land to the east of the Sierra began to change. Large, explosive volcanic eruptions occurred in Nevada, forming ignimbrites: silica-rich volcanic flows that can move very fast and very far. Although sourced in Nevada, these ignimbrites were able to travel into California through the river canyons that dissected the ancestral Sierra Nevada. Deposits of these ignimbrites can be found to the north of the Tuolumne River watershed. During this period, the Sierras continued to uplift and erode, albeit not at the pace seen in the Cretaceous. Despite this uplift, the rivers maintained their connection to the interior east of the Sierras by carving deep canyons.

The Miocene Sierras/Cascades

Geographers today separate the Cascades from the Sierra Nevada. However, in relatively recent times (geologically-speaking) the Sierra Nevada was indistinguishable from the rest of the Cascades. The Cascade Mountain Range extends from southern British Columbia to Northern California. This range's most distinctive characteristic is its numerous volcanoes. This chain of volcanoes is forming to the east of the Cascadia subduction zone where the Juan de Fuca plate slides eastward beneath North America. As described in Chapter 2, subduction of the Juan de Fuca Plate is causing melting of the lithosphere above the down-going slab. This melting forms magma that rises to the surface and erupts as volcanoes.

Mount Lassen, at the northern tip of the Sierras, is the southernmost active volcano in the Cascades, coinciding with the southernmost occurrence of subduction beneath the North American continent. During the Miocene, 5 to 20 million years ago, the southern margin of the subduction zone was much further to the south than today (Figure 3.2). Subduction was occurring beneath the entire Sierras during this time causing extensive Cascade-like eruptions all along the crest. At the same time that these eruptions were taking place, the Great Basin to the east of the Sierras was expanding and stretching, as if being pulled apart in an east-west direction. This stretching, which continues today, led to the formation of the distinctive, north-south oriented valleys and mountain ranges immortalized by John McPhee in his book "Basin and Range". Owens Valley, just to the east of the uppermost Tuolumne, is the western edge of the Basin and Range. This extension also dismembered the large watersheds that had previously crossed Nevada and the Sierras, severing their historic connection to the Pacific Ocean.

During the Miocene, andesitic lavas erupted from a series of fissures near the crest of the present Sierra Nevada and dominated the landscape, completely filling and plugging river canyons and mantling the crest with a mix of volcanic flows, volcanic mudflow deposits (known as *lahars*), ash deposits and river deposits rich in volcanic material. The remnants of these eruptions can be seen on many of the mountain passes to the north of the Tuolumne watershed.

Some of the more spectacular examples of the Miocene Cascade/Sierran geology occurs in the Stanislaus watershed, just north of the Tuolumne and can be seen in the foothills on the drive into the basin on highway 108. Distinctive flat-topped ridges occur throughout the lower Stanislaus region, including the aptly named Table Mountain. The flat ridge tops are a clue to their unique origins. During the Miocene eruptions, lavas commonly flowed into and down the numerous river canyons that dissected the watersheds. Large floods, formed by melting snow and rain, also carried volcanic material down these canyons, often reaching all the way to the floor of the Central Valley. When this mix of laval flows, lahars and flood debris cooled or compacted, it formed a deposit that was substantially more resistant to erosion than the surrounding metamorphic or igneous rocks, particularly the relatively soft metamorphic rocks of the foothills. As the landscape lowered in response to continued uplift and erosion of the Sierra the more resistant volcanic channel deposits where exhumed, forming ridges instead of canyons. Known as "inverted topography', this distinctive feature can be seen best in topographic or geologic maps where the flat-topped ridges are sinuous in their pattern reflecting the pathways of the ancient river valleys. Interestingly, some of the gold that was taken out of the region came from the base of these fossilized valleys, where gold placers were entombed by the volcanic debris.

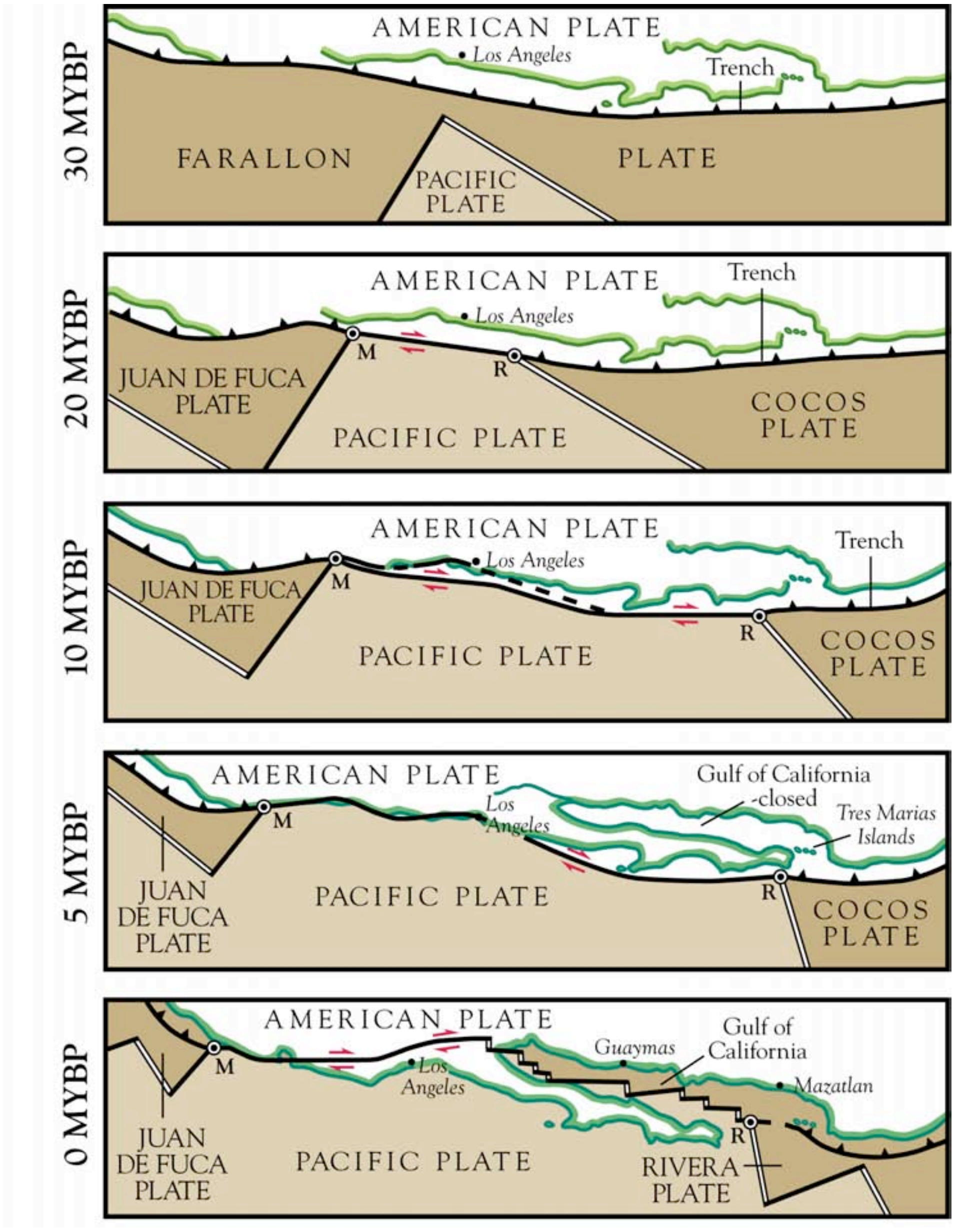

Figure 3.2 Evolution of the California margin for the past 30 million years. The barbed lines show the position of the subduction zone, with the barbs pointing toward the overriding plate. Volcanoes, formed along the crest of the Sierras in response to subduction. Collision of the East Pacific Rise caused the margin to shift to a transform (the modern San Andreas Fault), progressively shutting off volcanisms as the transform fault expanded. From Mount (1995).

Within the Tuolumne River watershed, the evidence of these eruptions is scattered and indistinct, yet the eruptions appear to have played an important role in the evolution of the watershed. The voluminous eruptions in the Stanislaus watershed completely filled its canyons, eventually spilling over the watershed divide and into the adjacent Tuolumne River canyons. These flows and lahars filled most of the mid-elevation tributaries that drain the divide between the Stanislaus and the Tuolumne.

These deposits are a distinctive feature of the geologic map (Figure 2.4) and trace the historical tributary patterns. One of these tributaries, near the site of the current Rancheria Creek appears to have been a major conduit for volcanic flows that eventually reached the mainstem of the river in the vicinity of Hetch Hetchy reservoir. These flows then filled the ancestral Tuolumne River canyon, continuing downstream past the present town of China Camp. Remnants of these flows can be found today, and give us a glimpse into the historic topography of the watershed.

Because they were plugged during the Miocene, the present canyons of the Tuolumne River, from the Grand Canyon of the Tuolumne until the river emerges into the Central Valley are all “new”. The evolution of the Grand Canyon of the Tuolumne is shown schematically in Figure 3.3. As with the formation of inverted topography in the Stanislaus drainage, the Tuolumne River, unable to downcut through the tough volcanic rocks that filled its canyons, began to erode the softer granite and metamorphic rocks adjacent to the channel, rapidly downcutting and forming the new channel that is carving the canyons we see today. The location of many of the new channel segments are not simply a product of random erosion processes. The character of the bedrock itself controlled the location of channel formation and downcutting. For example, in the vicinity of the Grand Canyon of the Tuolumne the channel location appears to have been controlled by the orientation of fractures within the granite. During incision, the river took advantage of the weaker rock along these fractures. Fracture control of river orientation can be seen throughout the upper watershed.

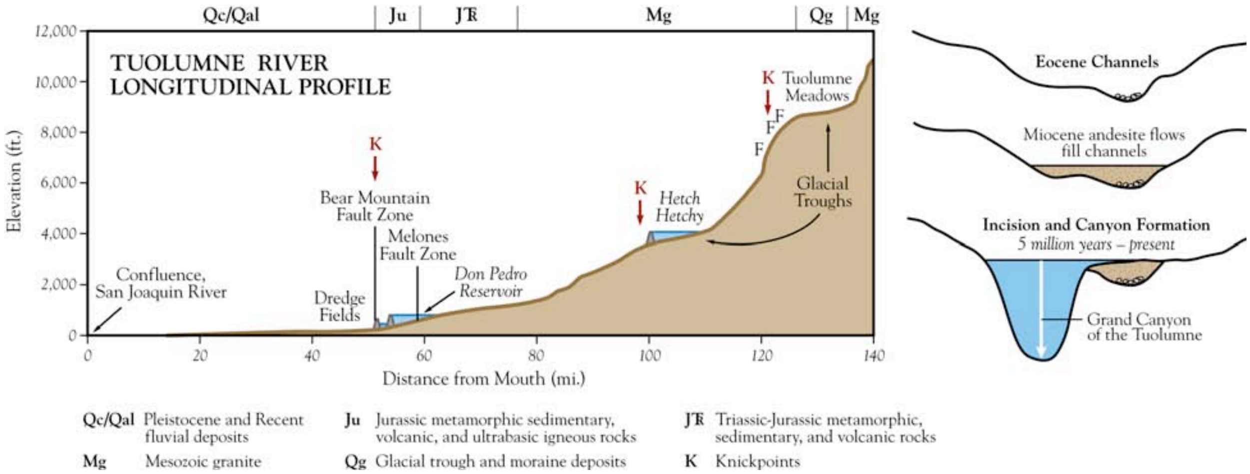

Figure 3.3 Longitudinal profile of the Tuolumne River indicating geologic units that river is incising into and knickzones (K) and major waterfalls (F). Evolution of the Grand Canyon of the Tuolumne in the vicinity of Hetch Hetchy illustrates andesitic filling of broad shallow channel followed by lateral movement and incision to form the present canyon. From Mount (1995).

Remnants of the Miocene river can be seen on the drive up highway 120 toward Yosemite. It has been speculated that the very distinctive, broad valley that occurs east of Groveland in the vicinity of Casa Loma is the historic channel of the Tuolumne. The occurrence of the andesitic rocks and the odd occurrence of a valley high on a hillslope adjacent to the river should be the visual clue.

There are two additional important points about the Miocene in the Sierra Nevada. First, the end of volcanism in the Sierras came as the subduction zone that was driving the formation of the arc was cut off by a northward expansion of the San Andreas fault (Figure 3.2). When the convergence between two plates becomes increasingly oblique, a lot of the convergence starts to be accommodated by the development of faults that slide blocks horizontally, or parallel to the plate margin, rather than plunging them beneath the continent at a subduction zone. The northward expansion of the San Andreas system from the Miocene to the present reflects the decreasing angle of convergence between North America and the plates underlying the Pacific. Once subduction was shut off by this transition, volcanism was shut off as well. This process will eventually shut off volcanism that is forming Mount Lassen and Mount Shasta as well as the San Andreas continues to expand northward.

Second, despite more than a century of geologists crawling around on the Sierra Nevada, they are still arguing over whether the range is “young” or not. The rugged topography of the Sierra, with its deep canyons and craggy peaks, naturally leads to the assumption that it is a new landscape and must be rapidly and recently rising. Indeed, conventional wisdom just a decade ago was that the Sierras, as a large mountain range, formed in the last five million years. Yet evidence from diverse sources of geologic information indicate that the mountains have been a substantial edifice for some time, even though rivers managed to make it from the interior to the Central Valley. In Nevada and Arizona, the Miocene fossil plants, along with the chemistry of tooth enamel of fossil mammals and weathered volcanic glass in soils, all suggest that weather in the Great Basin was significantly impacted by a large mountain range in the vicinity of the Sierras. That said, a spate of recent studies using cosmogenic nuclides to calculate rates of erosion and geodetic surveys to estimate rates of uplift indicate that the river channels of the central and southern Sierra may be responding to a pulse in uplift within the past few million years. One manifestation of this is the formation of the numerous inner gorges in the region. Inner gorges, which are steep, narrow gorges flanked by more gentle topography, form through rapid channel incision and canyon formation that is not matched by hillslope erosion. In this way, the more gentle slopes are attempting to “catch up” to river incision. Inner gorges, around the world, are a common phenomenon associated with recent, rapid uplift.

GLACIERS, FAULTS AND FRACTURES: THE FINISHING TOUCHES ON THE MODERN WATERSHED

Although the Tuolumne watershed is the product of 85 million years of evolution, the Pleistocene Epoch, lasting from 2.5 million years ago to 12,000 years ago, left the most recognizable impression. Globally, the Pleistocene is characterized by a period of extraordinary change, including growth of continental ice sheets and mountain glaciers, 300 foot changes in sea level, wild swings in temperature, and perhaps most significantly, the rise of hominids in East Africa and the eventual appearance of modern humans, nature’s most powerful ecosystem engineers.

The Pleistocene (and to a lesser extent, the Pliocene, the epoch that precedes the Pleistocene) brought cooling to the Sierra Nevada and triggered the formation of large glaciers. Glaciers are thick accumulations of ice that flow downhill under the influence of gravity. They are distinguished from permanent snowfields and other accumulations of ice and snow by the fact that they are long-lived and thick enough (usually thicker than 120 ft reaching up to several miles) that their mass causes them to move downslope, albeit very slowly. The movement of a glacier is driven by internal deformation of the ice under pressure and the common occurrence of water at the base of the glacier that lubricates its movement.

Glaciers are just as dynamic as rivers, although on a different time scale. The sculpting of the Tuolumne watershed during the Pleistocene is a product of the periodic expansion and contraction of the glaciers. Most glaciers, at any period in time, are adjusting to the processes that form the glacier--such as accumulation of snow, which converts to firn (compacted snow from past seasons recrystalized into dense granules) and then to ice--and the processes that destroy a glacier, collectively known as ablation. On every glacier there is an equilibrium or firn line. Upslope of this line, there is net accumulation of ice, below this line net loss, with the intensity of accumulation or loss increasing with distance from the equilibrium line. In this way, high rates of ice accumulation at the head of the glacier, where it is typically colder and more snow falls, helps push the ice downslope below the equilibrium line (Figure 3.4). Formation, expansion, contraction and eventual extinction of glaciers are controlled by two interacting factors: precipitation and temperature. To form glaciers you need to couple high precipitation rates with low temperatures. Without both, no glaciers form. For example, we think of the Arctic as ideal for the formation of glaciers. Yet the Brooks Range, the dominant mountain range in Alaska's arctic, has only a handful of small glaciers. This is because precipitation rates are too low for glaciers to form, despite the seemingly ideal conditions.

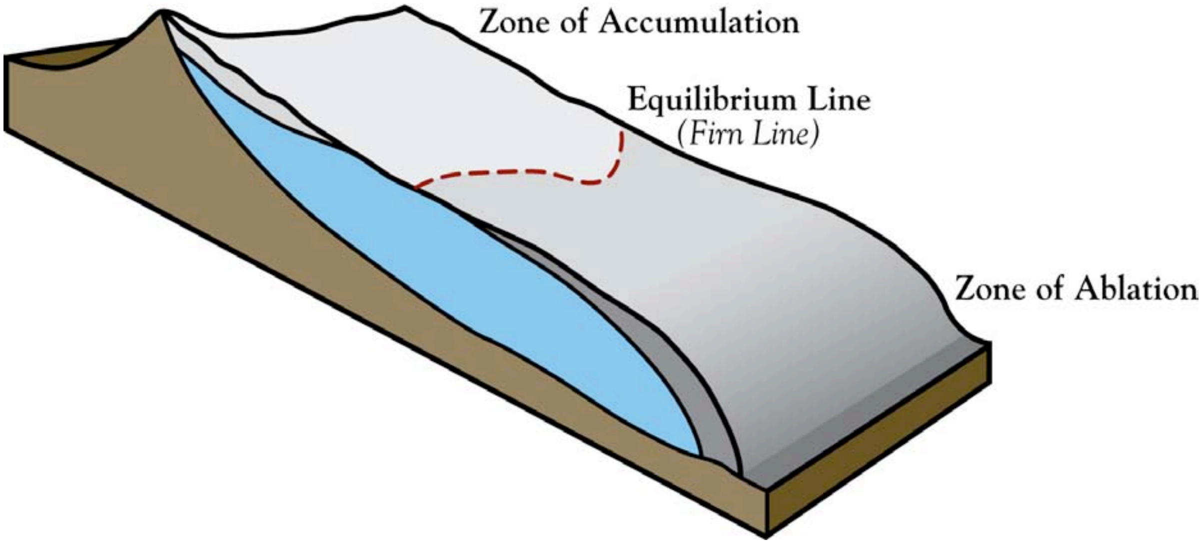

Figure 3.4 Diagram depicting equilibrium or *firn* line of a glacier that delineates the zone of accumulation (above) from the zone of loss due to melting and ablation.

The dynamic balance between precipitation and temperature drove the Pleistocene glaciation of the Sierra and the shaping of the Tuolumne watershed. Recent modeling of glaciers that occupied nearby Kings Canyon suggest that during the Pleistocene, the average annual temperature of the southern Sierra Nevada was roughly 10°F cooler than today and the average precipitation rate was double. Considering that much of the high elevation of the southern Sierras receives an average of more than 60 inches of precipitation per year today, the Pleistocene must have been a very wet period (fossil evidence suggests that it also was occasionally quite dry). However, given the relatively southern latitude of the Sierra's glaciers, and their proximity to warm maritime air, they were susceptible to subtle changes in temperature or precipitation. For this reason, the record of Pleistocene glaciation in the Sierras is complex, with at least four episodes of major glacial advance and retreat, and possibly three or four additional smaller ones. Of the four to six major glaciations of the Tuolumne watershed, two have left the most recognizable signatures: the last glaciation during the late Pleistocene, the Tioga, and the much larger glaciation that preceded it, the Tahoe.

With the exception of a few small, fast-shrinking glaciers on the peaks in the uppermost watershed, the glaciers that shaped the Tuolumne were gone by the end of the Pleistocene, when the Sierras warmed and became drier. What is left behind today is the record of the remarkable power of ice to shape landscapes, both through erosion, whether by ice or by meltwater rivers, and through deposition of the prodigious amounts of rock that are excavated and transported by glaciers.

The glacial geomorphology of the Sierra Nevada has been studied for more than a century. The Yosemite Valley of the Merced watershed, just over the ridge from the Tuolumne, has drawn some of North America's best geologists to it to tease out the landscape signature of the numerous advances and retreats of the glaciers. These same geologists spent considerable time and energy in the headwaters of the Tuolumne. Here, the topography exhibits classic features of montane glacial processes.

In the uppermost portions of the watershed, above the Grand Canyon of the Tuolumne River, thick alpine ice fields developed during the Pleistocene. During the last large glaciation event, these ice fields reached thicknesses greater than 2000 feet, forming a cap on the crest of the Sierra. The erosive power of the thick ice sheets can be seen in the distinctive gentle-sloped valleys and meadows and the rounded granite hilltops of the upper watershed. In unglaciated watersheds elsewhere in California, the headwaters are typically the steepest (the Klamath is a notable exception). Not so in the Tuolumne, where the low gradient of the headwater streams, such as the Dana Fork and Lyell Fork, reflect extreme ice thicknesses and glacial erosion.

The alpine ice fields of the upper watershed pushed ice downslope under the force of gravity. As they did, ice was funneled into pre-existing valleys, creating valley glaciers. These valley glaciers formed the spectacular canyons of the watershed that lie generally above 4000 ft. Since the path of the mid-elevation Tuolumne River was set in stone in the Miocene, glaciers did not technically form the Grand Canyon of the Tuolumne. Rather, the large valley glaciers that periodically filled the valley expanded its width and depth. The long profile of the river (Figure 3.3) shows well the effects of the glaciers. Note the steep transition from the low-gradient meadows of the upper watershed to the Grand Canyon of the Tuolumne. This transition is where the alpine ice fields fed into the canyons. This step-like transition was presumably caused by glacial plucking of the bedrock as the ice flowed down into the expanding canyon. This plucking is the cause of the numerous spectacular waterfalls on the Tuolumne in this portion.

Interestingly, the Grand Canyon of the Tuolumne is a V-shaped valley, rather than U-shaped like its better known neighbor, Yosemite Valley. V-shaped glacial valleys are common, and typically reflect geologic, rather than purely glacial controls on valley downcutting or enlargement. In the case of the Grand Canyon of the Tuolumne, the regional fracture pattern's control on downcutting may have contributed to its V shape.

In the last five million years, rain, melting snow, and glaciers have been stripping off the carapace of Miocene volcanic rocks that covered the Sierra, eroding hillslopes of granite and metamorphic rocks, and carving the deep canyons of the middle portions of the watershed. These processes were aided by the continuous uplift and westward tilting of the mountain range. Just as in the Cretaceous unroofing of the Sierran granite, the post-Miocene erosion and formation of the modern day Sierras produced prodigious amounts of sediment. Where is it today?

Glaciers are nature's best bulldozers. During glacial advance, rock is plucked off of valley walls and floors and commonly ground into fine sediment or entombed in the ice. A large volume of material falls off of valley walls or is delivered by tributaries and is deposited on top of the glacier, moving downslope like a conveyer belt. When the balance between temperature and precipitation shifts and the equilibrium line of glaciers moves upslope, glacial retreat begins. This melting of the glacier and its retreat releases large volumes of sediment to the watershed. Along the margins of the glacier and at its retreating terminous, sediment is abandoned by the glacier and large moraines can form. These moraines are recognizable by their mix of fine and coarse alluvial material, often perched along the ridges or valley walls (Figure 2.4). However, most of the sediment generated by the glacier is exported from the watershed by its river.

In the middle portions of the watershed, below the advancing and receding glaciers (below Hetch Hetchy), but above the San Joaquin Valley floor, the Tuolumne River is confined to narrow canyons. As described in the Introduction to this book, this portion of the watershed today is effectively a pass-through reach, neither contributing nor retaining much of the material provided by the watershed. This has been the case ever since the Miocene and, for that matter, probably since the Cretaceous. During glacial retreat, when the sediment was released into the river and onto the landscape, confinement of the river to its steep channel gave it sufficient stream power to move all of this sediment out of the foothills. There are no significant glacially-derived river deposits in the middle portion of the watershed, with the exception of some small alluvial valleys.

When this flow of sediment and water left the foothills and emerged into the valley, things changed. As background, over time, every river exhibits two characteristics that define how much and what kind of sediment it can transport. The competence of a river is the largest material that can be moved. The capacity of a river is the total amount of material that it can transport, from fine clay to large boulders, over a specific interval of time. Rivers with high capacity and competence tend to be steep, have high flows, and are confined to narrow, deep channels. Thus, the ability of the Tuolumne to move sediment out of its middle reaches stemmed from its steepness and narrowness. However, just below La Grange dam, at the base of the foothills, the river emerges abruptly into the San Joaquin Valley. Being no longer confined by canyon walls and entering a low-gradient valley, the river loses capacity and competence, dropping its sediment and forming a large alluvial fan. The loss in competence is more dramatic than loss in capacity as the river emerges from its canyon. Thus, coarse grained sediment, like cobble and gravel, tends to be dropped at the head or apex of the fan while finer-grained sediment is carried farther down the fan and deposited on floodplains. This is why the gold and aggregate mining sites of the lower watershed are all located near the head of the fan.

Alluvial fans like the Tuolumne fan are heavily influenced by changes in sediment supply and discharge that emerge from the watershed. During periods when there is high sediment supply relative to discharge, rivers will build their alluvial fans, both vertically and laterally. Conversely, during periods when sediment supply is low relative to discharge, the river will incise or cut down into the fan. When this incision occurs, the floodplains of the previous growth cycle are abandoned and left to form soils disconnected from the river. In this way, fans can experience alternating cycles of growth and incision/soil formation.

The advances and retreats of the glaciers in the headwaters have controlled the construction of the Tuolumne River fan. Geologists and soil scientists who have studied the fan and those of its neighbors, the Stanislaus and Merced, have been able to identify at least three major episodes of alternating fan growth and incision/soil formation during the Pleistocene. From oldest to youngest, the sedimentary formations and soils formed by cycles of glacial advance and retreat are known as the Turlock Lake, Riverbank and Modesto Formations. The rich agricultural land of the Tuolumne fan and the east side of the San Joaquin Valley owes its origins to these events.

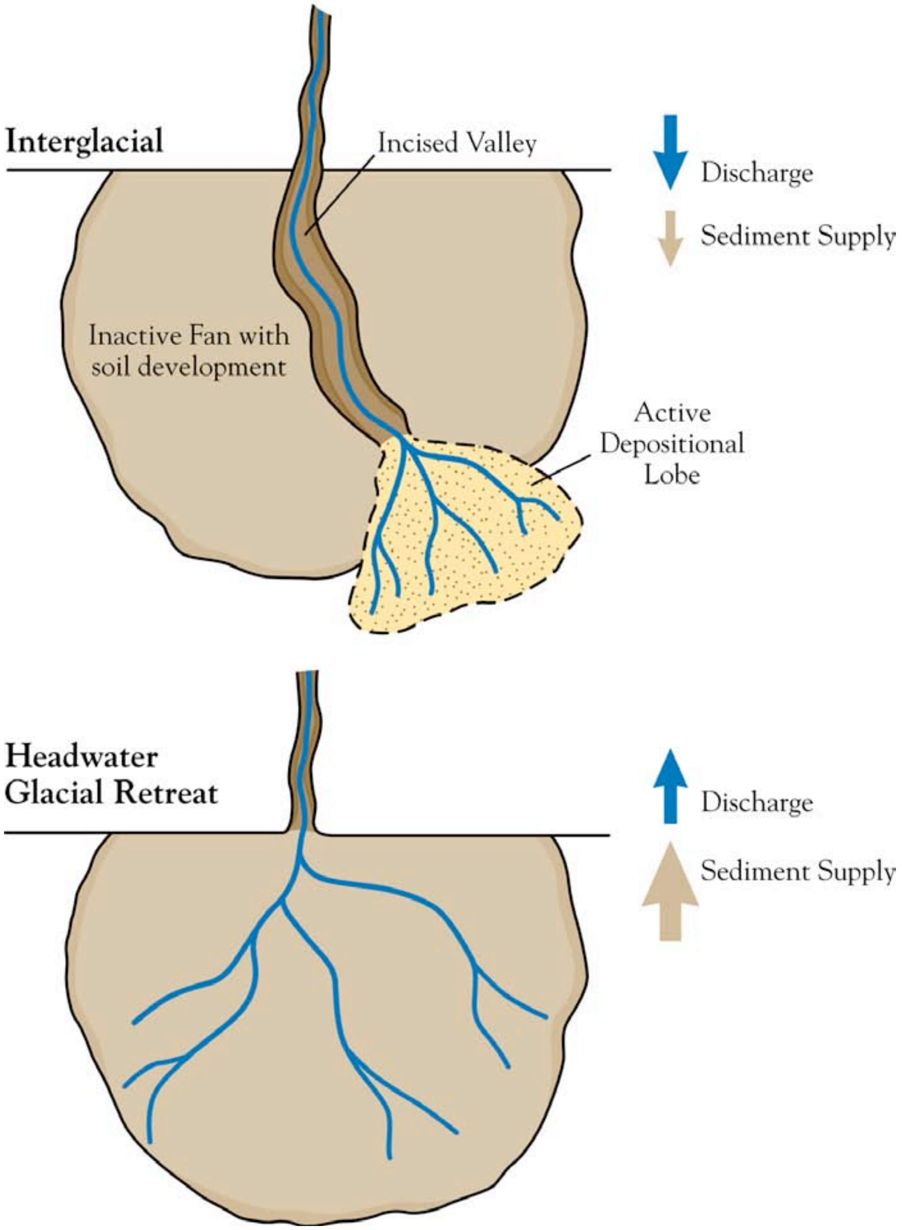

Figure 3.5. Schematic diagram of the growth of the Tuolumne River alluvial fan during interglacial periods when discharge is moderate and sediment supply is low or declining (leading to incision) and during periods of glacial retreat when discharge is high but sediment supply is relatively much greater. During this period channels distribute sediment across the fan, causing it to grow vertically.

The Holocene

The Quaternary Period is divided into the Pleistocene and the Holocene. The Holocene encompasses the last 12,000 years of earth history, leading up to today. Around the world, the close of the Pleistocene was marked by rapid warming, melting of continental glaciers and associated rapid rise in sea level. In this way, global warming has been occurring for more than 10,000 years and is nothing new. It is just that humans and their greenhouse gasses are accelerating the pace toward a very warm and uncertain future. Indeed, there is a movement afoot in the geologic community to identify a new

Epoch, called the Anthropocene, identified as that period of time when human activity significantly modified the earth's biology and climate.

Given the lack of volcanoes or large glaciers and a general reduction in precipitation, the Holocene epoch in the Tuolumne River watershed is, by comparison to the Pleistocene or the Miocene, a bit dull. No major landscape changes have occurred in the Holocene in part because of its benign climate and its relatively short interval of time. As is discussed in the following chapters, the native plant and animal communities of the Tuolumne, many of which are relicts of the Pleistocene, are all adapted to the Mediterranean climate of the past 12,000 years. During this period there have been some modest changes in climate, albeit not on the scale of the Pleistocene. For example, during the middle parts of the Holocene, between roughly 8,000 and 3,000 years ago, the Sierras were warmer and drier than today, with a very high frequency of fires. More recently, from roughly 900-1300AD, California experienced several spectacular droughts, including one that appears to have lasted for a full century. These occurred during what is known as the Medieval Warm Period, which has been recognized as having severely impacted the west. Even more recently, the Medieval Warm Period was followed by the Little Ice Age: a period from roughly 1500-1850 AD when there was significant cooling and an increase in wetness in the Sierra. All of these periods saw modest changes in vegetation type and cover. But by all comparisons, the Holocene is dull compared to the wild climate of the Pleistocene.

SUMMARY

The transition from watershed foundation to evolution took place after the cessation of granite formation. In a period of less than 20 million years, more than 6-9 miles of rock were eroded off of the Sierra Nevada and deposited within the Great Central Valley. The ancestral Tuolumne watershed appeared at this time. Between the Cretaceous and the Miocene, the Sierras became a gentle, occasionally tropical landscape connected by rivers to the interior. During the Miocene, between 5 and 20 ma, the Sierras looked much like the Cascades, with large eruptions of volcanic material near the crest. During these eruptions, the pulling apart of the Great Basin and uplift of the Sierra cut off the riverine connection to the interior. The Tuolumne watershed was overwhelmed by these eruptions that spilled out of the Stanislaus watershed, plugging the canyons with erosionally-resistant volcanic rock. A "new" set of canyons and tributaries formed adjacent to the ancestral canyons, with orientations and locations controlled by the fabric or the bedrock, assembled more than 100 million years before.

The most striking feature of the watershed derives from its glacial history. Beginning 2.5 ma, the Sierras began to grow glaciers as the right mix of higher precipitation and lower temperatures allowed for the net accumulation of ice. At the uppermost elevations, thick alpine ice fields sculpted the smooth mountains and meadows that are a hallmark of the watershed. Farther down the mountain, valley glaciers expanded post-Miocene canyons, creating the Grand Canyon of the Tuolumne. And in the Central Valley large volumes of glacially-derived sediment were deposited during periods of glacial retreat in alluvial fans.

The Holocene Epoch of the watershed has been, by all measures, less dramatic than the previous epochs. That is, until the Europeans showed up.

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Chapter 4: Climate, Hydrology, and the Watershed

GERHARD EPKE, SARAH NULL, AND SABRA PURDY

INTRODUCTION

The Tuolumne River watershed drains 1,900 square miles of the Sierra Nevada and the Central Valley as it flows west towards its confluence with the San Joaquin River. The 150 mile long journey begins in alpine headwaters, at more than 13,000 feet elevation in Yosemite National Park. From the open, treeless expanses of these elevations, the river flows through the largest sub-alpine meadow system in the mountain range, Tuolumne Meadows, and then it passes into a succession of deep canyons until it reaches the eastern edge of the Central Valley. All along its length tributaries enter the river, contributing water and sediment, increasing its size and power. For its last 50 miles across the Central Valley, the Tuolumne's surroundings change dramatically. As it emerges from the confines of its canyons, it spreads out across an alluvial fan, eventually adding its waters to the flow of the San Joaquin River. By the time the San Joaquin reaches its confluence with the Tuolumne, it has collected flows from the Merced River, the Tuolumne's neighbor to the south, and numerous other small watersheds from the west side of the Central Valley. Prior to the damming and diverting of the Tuolumne, its addition increased the San Joaquin flows by half. These combined flows spread across the San Joaquin floodplain annually during the winter floods and the spring snowmelt, part of an immense riparian forest complex, eventually wending their way into the Sacramento-San Joaquin Delta, and the San Francisco Bay.

As the preceding chapters of this book discussed, the physical characteristics of the Tuolumne River and its watershed are a product of the interaction between the geology, tectonic setting and climate. This chapter describes the climate of the region and explains how it controls hydrologic processes within the Tuolumne watershed. These processes exhibit strong seasonal and elevational climate gradients that, in turn, influence the distribution and type of terrestrial and aquatic ecosystems and the human interactions within the watershed.

The Mediterranean Climate

The climate of the Tuolumne River watershed, along with much of Central and Southern California, is characterized by strong seasonal variation, particularly in precipitation. Cool, wet winters give way each spring to warm, dry summers. An annual drought, from May to November, is a signature of the climate of Central and Southern California. This type of climate, referred to as Mediterranean for its occurrence in regions surrounding the Mediterranean Sea, is surprisingly rare in the world and occurs only on the western margin of landforms at similar latitudes, such as in South Africa, Australia, and Chile. In California, the dominant direction of atmospheric circulation is from west to east, driving air from the Pacific onto and over the complex topography of the state. Our regional and local climate, and that of the Tuolumne, reflects the interaction of atmospheric circulation with California's rugged landscape. Climate and its interaction with landscapes also drives the hydrologic cycle, which explains how water is distributed in the atmosphere and moves on or through the earth. In general, when water is exposed to the air and solar energy, it evaporates from liquid to gaseous form, dissipates upwards into the atmosphere, and falls back to the earth as precipitation. Precipitation which is not re-evaporated can be temporarily stored as snow or ice, groundwater, or flow back into the ocean (Figure 4.1). Globally, the volume of water in each phase of the hydrologic cycle remains fairly consistent, only changing significantly during glacial-interglacial cycles.

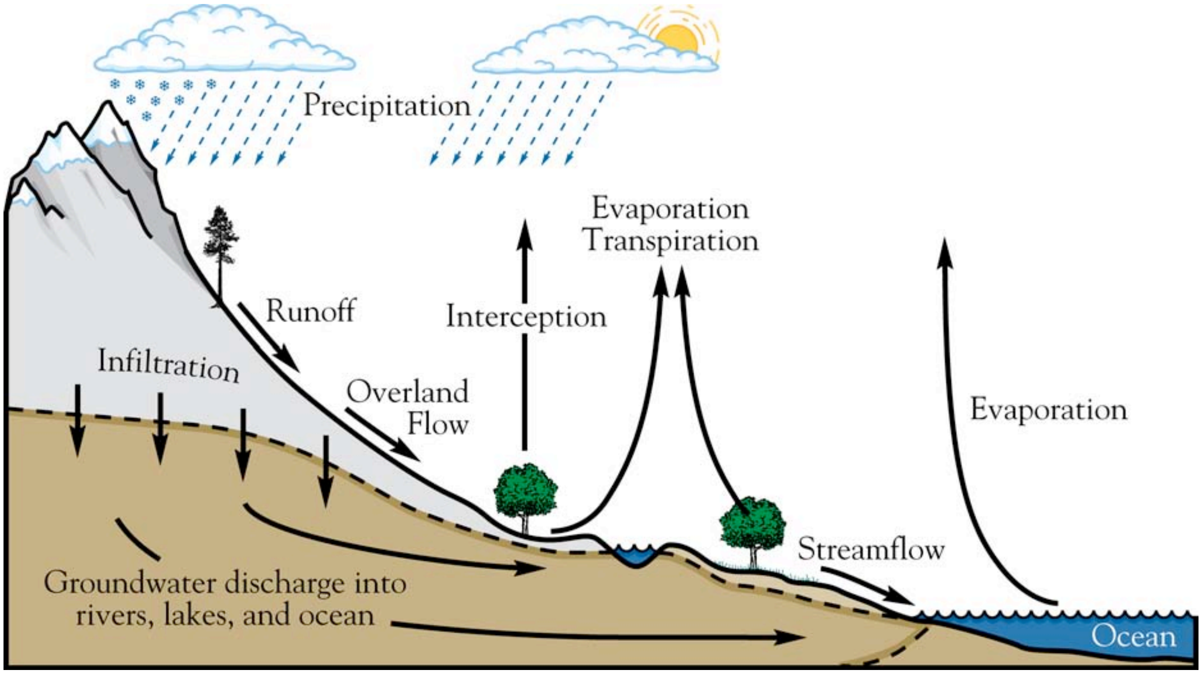

Figure 4.1 The Hydrologic Cycle from Mount 1995

Seasonal and annual variation in precipitation in California is driven principally by the location of high and low pressure areas in the Pacific Ocean. The temperature of sea water at the surface tends to control the intensity and location of these areas which, in turn, steer storms as they approach the west coast of California. In the summertime, the northern Pacific Ocean is warmed more evenly, and a high pressure system known as the 'Pacific high' establishes itself off California's coast. This stationary high pressure system steers storms far to the north, leaving California dry all summer. During winter months, on the other hand, the northern Pacific Ocean receives much less sunshine and the Pacific high shifts south and is reduced. This results in winter storms, which build in the northern Pacific and sweep east across the state bringing widespread precipitation. In drought years, the blocking high pressure system will not dissipate fully during the winter, steering vital winter storms away from California and into Washington and British Columbia. Conversely, in very wet winters, this blocking high reappears only rarely, allowing Pacific storms to sweep into California frequently. In most years, the bulk of the winter precipitation falls in just seven storms. A wet winter is typically characterized by just a few storms above the average, with a dry winter a few storms below the average. In general, there is enormous inter-annual variability in precipitation. California weather swings back and forth between extremes and only rarely do we get an average ("normal") precipitation year. Table 1 indicates the water year type by year and water yield. Note that in the thirty years shown in this table, there are only two years that are classified as "normal" water years.

The wettest years in both southern and northern California are commonly associated with regional changes in sea surface temperatures in the equatorial Pacific Ocean. These changes are called ENSO events, for El Niño, Southern Oscillation, or El Niño for short. During El Niño events, a decrease in the east-to-west trade winds allows an area of very warm water to shift eastward from the Indian Ocean and western Pacific to the eastern Pacific off of Peru. This shift pumps warm water into the atmosphere, changing circulation patterns around the globe. When strong El Niño patterns occur, typically once a decade, California will often (but not always) have very wet winters. All the records in the Tuolumne

River watershed for annual precipitation and thickest snowpacks are associated with El Niño events. The first and second wettest years on record in the watershed, 1983 and 1998, are both El Niño years.

Table 1. Thirty years (1969-1999) of data showing acre-feet of water yield and the associated water year type. Note there are only two years, 1972 and 1979 that are classified as "normal."

Year	Acre Feet of Yield	Water Year Type
1969	3,858,598	Extremely Wet
1970	**2,903,749**	Extremely Wet
1971	1,696,685	Normal
1972	1,228,740	Dry
1973	2,066,837	Wet
1974	2,306,285	Wet
1975	2,066,348	Wet
1976	699,777	Critically Dry
1977	454,334	Critically Dry
1978	2,932,759	Extremely Wet
1979	1,957,501	Normal
1980	3,040,767	Extremely Wet
1981	1,130,446	Dry
1982	3,810,491	Extremely Wet
1983	4,639,714	Extremely Wet
1984	2,544,881	Wet
1985	1,281,836	Dry
1986	3,028,685	Extremely Wet
1987	750,286	Critically Dry
1988	843,629	Critically Dry
1989	1,362,947	Dry
1990	894,134	Critically Dry
1991	1,160,524	Dry
1992	870,146	Critically Dry
1993	2,581,784	Extremely Wet
1994	1,136,409	Dry
1995	3,939,017	Extremely Wet
1996	2,348,979	Wet
1997	3,245,211	Extremely Wet
1998	3,348,765	Extremely Wet
1999	2,127,404	Wet

It is a common misperception that high annual amounts of rain and snow are associated with years of intense flooding. Although there are often floods in the Tuolumne watershed during El Niño events, they are not unusually destructive. This is because during El Niño years, a greater proportion of the precipitation falls as snow, rather than rain, delaying runoff and reducing the impacts of flooding. Most flooding during these years is associated with late spring snowmelt. In contrast, large floods, particularly in the last 60 years, have occurred in years of relatively average or even below average precipitation. These floods are associated with a unique and poorly understood phenomenon called "atmospheric rivers."

Atmospheric Rivers

Most of the cool, snowmaking storms of California's winters originate in the northern Pacific, often near the Gulf of Alaska, and sweep from the northwest to the southeast across California. Less frequently, slow-moving, elongate southwest-northeast oriented fronts develop that tap into warm, subtropical air from the western Pacific. Known colloquially as the "Pineapple Express", these storms look and behave more like a river than a typical storm front. The stationary fronts move prodigious amounts of warm, moisture-laden air into California, often over a period of several days. The warmth and intensity of these storms leads to large amounts of rain, with proportionally less snow. This results in "rain on snow events," which liberates vast volumes of water that had been stored as snow in a short period of time. This phenomenon is responsible for the largest floods on record in California. Great floods in the Tuolumne watershed—1955, 1964, 1986, 1997—are all associated with this unusual weather phenomenon.

Orographic Effects

The Tuolumne River watershed experiences the same seasonal weather patterns as the rest of California, but the presence of the mountain range and orientation of the watershed itself cause significantly more precipitation to fall here. Moreover, precipitation does not fall equally or in the same mix of rain versus snow across the watershed. This variation is caused by the interaction between the topography in the watershed and the moist Pacific air masses that move across it.

When the west-to-east flow of Pacific air encounters the Sierra Nevada, the mountain range forces it to rise (Figure 4.2). As it rises, it cools and becomes less dense, decreasing the amount of water vapor that the air can hold. This causes condensation which forms clouds, and as the process continues, eventually precipitation. This produces the dramatic increase in total precipitation in the watershed with increase in elevation (Figure 4.3). Depending upon the temperature of the air flowing into the watershed the precipitation falls as rain in the low elevations and changes to snow in the upper elevations. For every watershed in the Sierra there is an elevation where roughly half of the annual precipitation falls as snow, with higher elevations dominated by snow. In the Tuolumne watershed, this occurs at approximately 5000 ft. However, as discussed later in this book, this elevation has been rising for the past 50 years as the climate of the Sierras has been warming.

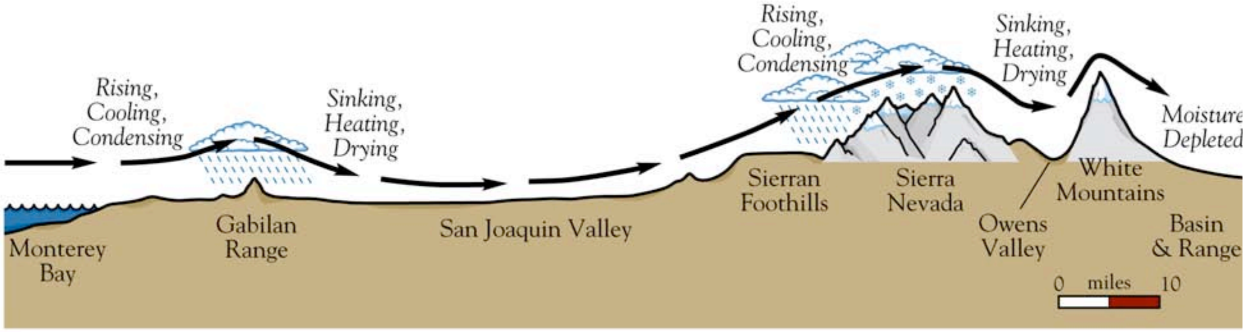

Figure 4.2 The Orographic Effect in California from Mount 1995.

Orographic effects also lead to localized areas of relatively low precipitation on the lee side of ranges. Air forced upward over a mountain range will lose water vapor, in effect wringing itself out. As that air passes over a ridge crest and sinks, the increase in pressure and temperature increases its capacity to hold water. Warmer air can hold more water vapor than cooler air, and thus the lee side of ranges in effectively in a *rainshadow.* This *rainshadow* effect will produce relatively low precipitation in some of the larger valleys, such as Tuolumne Meadows, that are sheltered by large ridges, and contributes to the high desert climate on the eastern side of the range and into the Great Basin (Figure 4.2).

During the summer, the highest reaches of the watershed receive small amounts of precipitation from afternoon thunderstorms while the rest of the state is hot and dry. These are associated with moist air that often flows into the watershed from the south or west up the river canyons from the hot plains of the Central Valley. Warming during the day causes the moist air to rise, often forming dramatic cumulonimbus clouds at the higher elevations that build throughout the day, leading to afternoon thundershowers. This type of precipitation, and the lightning-ignited fires that occasionally accompany it, are important summertime phenomena in the upper watershed.

The Flow Regime

The hydrologic cycle of the Tuolumne watershed, including the complex pathways of water, drives flow conditions within the watershed's rivers and streams. Reflecting the diversity of precipitation patterns in space and time and the complex topography and geology of the watershed, flow within the rivers and streams is highly variable. This variability, including the magnitude, timing, duration and frequency of different flow conditions, is called the flow regime.

The flow regime of a river or stream is recorded in its hydrograph: the plot of discharge (measured as volume per unit time, such as cubic feet per second) versus time (Figure 4.3). The hydrograph is, in essence, the EKG of the watershed, recording how long it takes for precipitation to make its way to some point of measurement. There is great art and science in deciphering a hydrograph, including how human activities in a watershed alter the hydrologic cycle.

For the typical Sierran watershed, the hydrograph can be broken up into components that record seasonal changes in precipitation timing and type, and various sources of water (Figure 4.3). As a matter of convention, and reflecting our seasonal drought, water managers in California define the water year as beginning October 1st and ending September 30th. For the first six months of the water year, the hydrograph mirrors the storms that inundate the watershed. The abrupt rise in flow that occurs with each significant storm is the signature of water falling on the landscape, saturating the soils, and rapidly running into the river. The relatively slow recession of flow following each storm records the slow draining of the saturated landscape. In the spring, usually beginning in April and peaking in late May, there is a sustained period of runoff associated with the melting of the snowpack in higher elevations. Because this melt typically occurs after the rains have stopped, it declines slowly over the course of many weeks with few, if any, abrupt changes. During this late spring/early summer decline in flows, the discharge of groundwater, recharged over the course of the winter and spring, becomes a progressively greater part of the total flow, slowing the rate of flow decline. Then, over the course of the summer, groundwater discharge, known as baseflow, keeps the rivers and streams flowing even when there is no rainfall or snow melting in the basin. This pattern of change repeats itself year-in, year-out, albeit with great variability between wet and dry years. This pattern, including its variation between years, is the watershed's flow regime.

The biota of the Tuolumne watershed, including all the terrestrial and aquatic plant and animal communities, have spent millennia adapting to the natural flow regime of the Tuolumne and its associated hydrological processes. The conversion of the lower half of the watershed to an entirely regulated system with a highly altered flow regime has had profound and detrimental impacts on the ability of the species adapted to the historical hydrograph to function. This poses major challenges for managing the Tuolumne River and its watershed (see later chapters of this book).

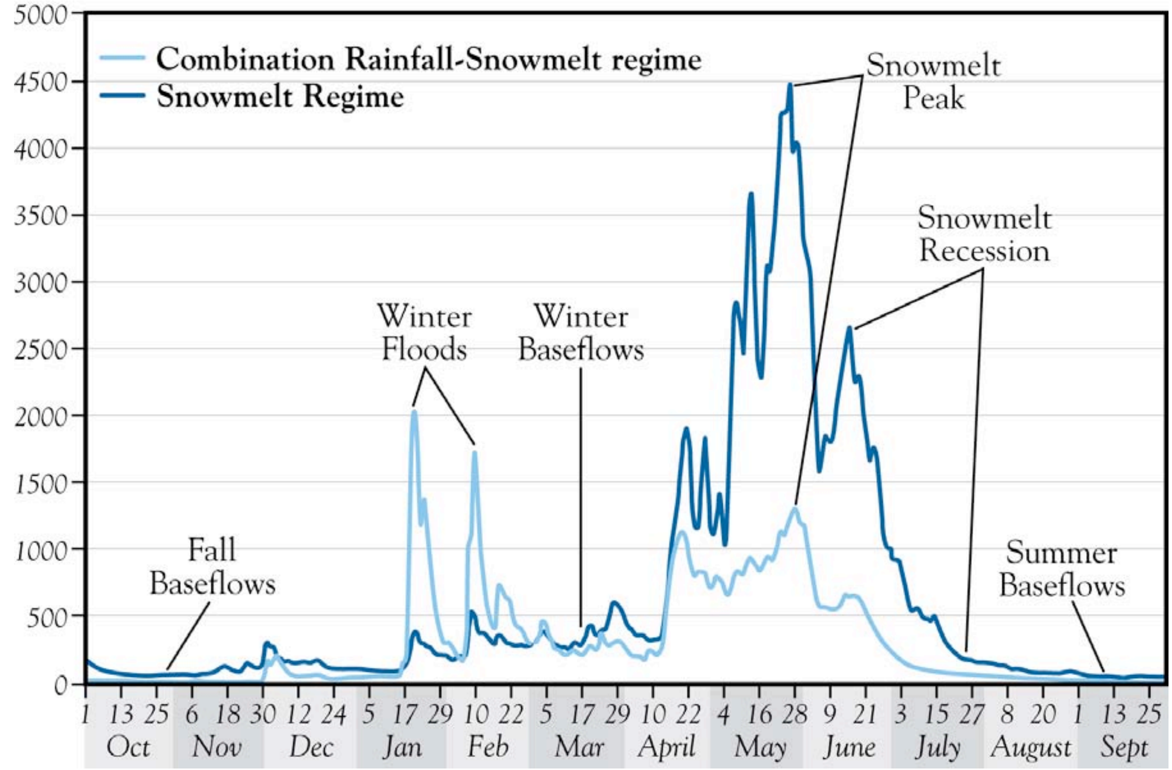

Figure 4.3 Hydrograph Components for a Snowmelt-dominated and Combination Rainfall/snowmelt Flow Regimes similar to the Tuolumne River, Cherry Creek, and Eleanor Creek. Water Year 1999. Combination Rainfall-Snowmelt regime from the Clavey River; snowmelt regime from the Pohono Bridge, Merced River. From McBain and Trush 2006.

Climate and Hydrology of the Upper Tuolumne Watershed

The upper Tuolumne River watershed is the hydrologic engine of the watershed. The orographic lift created by the 13,000 ft ridges of the upper watershed allows it to wring the maximum amount of moisture possible out of the winter storms that pass over it. With the exception of the large meadow systems (described below), an unusual anomaly in the upper watershed, the relatively thin soils do not retain much water. Additionally, the groundwater systems within the granite of the upper watershed have limited storage capacity. This combination of high precipitation, thin soils and limited groundwater leads to very high runoff, making it the most important source of water in the watershed.

The climate and hydrology of the upper watershed are almost entirely defined by snow. At elevations above 8500 ft, snow covers the landscape for more than half of the year. Snow accumulation begins as early as October in the watershed, reaching its peak around April 1st. However, snowfall has been recorded in every month of the year in the watershed, including the warmest months of July and August. Water watchers focus less on the depth of snow than on its snow water equivalent or SWE (Figure 4.4). This is simply a measure of the depth of water that would be formed by melting the snow in place and is an indication of the amount of water that is likely to be available for runoff in the spring.

As any alpine skier knows, snow and the underlying snowpack, evolve over the course of a season. During the coldest parts of the winter, snow accumulates as powder, with very low SWE relative to its depth. With multiple snowfalls, including intermittent days of warming and melting, the snowpack compacts and the ice crystals change shape, leading to progressive increases in snowpack density (sharp changes in density can lead to high avalanche hazards). By April 1st in most years, the snowpack reaches it greatest SWE. Water is then lost from the snowpack through melting, leading to runoff or groundwater recharge, or through sublimation, where the snow is lost to the atmosphere as vapor.

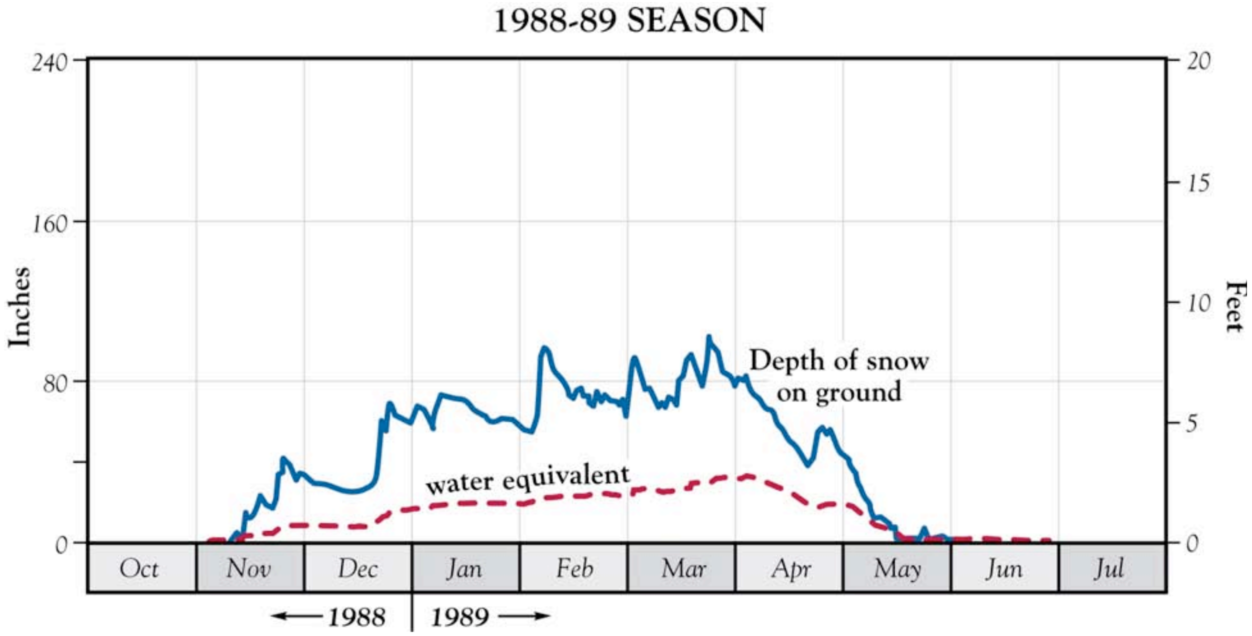

Figure 4.4 Annual Snow Depth and Snow Water Equivalent in the Feather River drainage during severe drought. From Mount 1995.

Melting of the snowpack is controlled by the length of day and air temperatures. Both combine to cause the pack to "ripen" in the spring. This occurs when the daytime melting and nighttime refreezing of the pack causes it to warm to roughly 32°F throughout. At the point where the pack has both ice and liquid water within it, it is ripe and the melt begins. Water that flows out of the pack typically flows along the base of the pack and through the saturated soils that immediately underlie it, and then into streams. A portion of the melt moves into groundwater, delaying its eventual movement into the streams.

Meadow Hydrology

As noted in the preceding chapter, the unique topography of the upper watershed is the product of a large ice cap and glaciers that formed during the Pleistocene epoch. Deep scours created by moving ice were filled by sediment during and after the retreat of the glaciers. The accumulation of this sediment in these depressions formed the high mountain meadows that occur throughout the Sierras. The largest of these—Tuolumne Meadows—occurs high in the Tuolumne watershed.

Hydrologically the meadow behaves like a wetland, or water capacitor. Meadow soils typically have a large water holding capacity, and as snow melts in spring, a large portion of that water goes from being stored on the soil surface as snow to infiltrating into the soil and being held there until stream levels drop and draw the water out. As large pulses of water flow through the meadow and overtop the stream banks, the vegetated surface of the meadow slows the flows, gathering more water into the soil and attenuating the flood pulse downstream. Over the course of the summer, the meadow soil slowly releases its accumulated water back into the stream as outflow. The low gradient of the meadow also creates the typical large meander bends that slow the water and allows the further absorption by side channels and backwaters.

The Grand Canyon of the Tuolumne

As the river leaves Tuolumne Meadows, it enters a steep, narrow gorge which extends twenty miles and falls four thousand vertical feet to Hetch Hetchy. This portion of the river is called the Grand Canyon of the Tuolumne, and it represents a significant shift in the river's character. Whereas the river spread out into close contact with its surroundings in the meadows, here it churns straight downhill bounded on both sides by steep granite walls (see chapter 3 for more details).

From Tuolumne Meadows all the way to New Don Pedro Reservoir, rivers and creeks draining the northern reaches of the watershed consistently converge with the Tuolumne. These parallel tributaries run roughly northeast to southwest. They drain progressively lower elevations and exhibit progressive shifts in character and water contribution per catchment area. The first few of these, such as Return, Paiute, and Rancheria Creeks, originate in the Sawtooth Range at the northern boundary of the park and flow into the Tuolumne between Tuolumne Meadows and Hetch Hetchy. Like the Tuolumne's headwaters, these tributaries are cold and clear and steep and contribute a larger comparative volume of water than watershed of a similar size at lower elevation.

After tumbling 4,000 feet down through the Grand Canyon of the Tuolumne, the river's gradient flattens out on another glacial bench at Hetch Hetchy Valley. This bench, though, is very different from Tuolumne Meadows. It is surrounded on two sides by sheer vertical walls and on a third by the O'Shaughnessy Dam. Before it was dammed in the early part of last century, the Hetch Hetchy Valley looked much like Yosemite Valley, with a meandering alluvial channel flowing through wetlands and meadows. This change in plumbing of the watershed and other continued controversies are discussed in more detail in chapter 12.

Climate and Hydrology of the Foothill Region

For 50 miles below Hetch Hetchy, the river flows through a deep, relatively straight and narrow bedrock canyon at a consistent gradient all the way to the edge of the Central Valley. This transfer zone, where little water or sediment is stored for any length of time, evolved from the interplay of mountain uplift and channel incision amplified by the processing of postglacial outwash over the past several million years. This zone, which occurs in all of the major Sierran watersheds, has its own unique climate and hydrology.

The climate of the foothills region reflects the strong orographic influence of the mountain range. In the lowermost portions of the region, annual precipitation is relatively low, commonly below 20 inches per year. If you compare that to the vicinity of Hetch Hetchy, precipitation has more than doubled and, in some cases, even tripled (Figure 4.4). The orographic gradient in precipitation is also matched by strong gradients in temperature, with mild winters/hot, dry summers at the lowermost elevations and cold winters/mild, dry summers at the uppermost elevations. These gradients are superimposed on the more complex geology of the foothill region, leading to a mosaic of diverse soil types. This physical diversity, in turn, leads to the greatest biodiversity within the watershed, ranging from montane forests to chaparral to oak savannah.

Lying below the rain/snow line, precipitation in the foothills region is dominated by rain, with accumulations of snow a rarity. The dominance of rain changes the hydrology of local creeks and groundwater. The steep topography and relatively thin soils of the foothill region leads to rapid runoff during intense rain events. Like the upper watershed, there are no major alluvial aquifers to store large amounts of water. In this way, this portion of the watershed "sheds" it water relatively quickly during the winter, and during the hot May-November annual drought, dries out quickly.

Vegetation and Hydrology

The annual drying out of the foothills region is mediated, in part, by the plant communities that have adapted to these unique conditions. Plants play a central and often dominant role in the hydrologic cycle. Their internal mechanism of using roots to absorb water from the soil, transferring it up to their photosynthetic tissues, and losing it to the atmosphere as they absorb CO_2 is called transpiration. Different species of plants can transpire at very different rates depending on water availability. Riparian plants, for instance, often have limitless supplies of water and transpire enormous amounts of water per day, while other species living on dry, south-facing slopes and on ridge tops are suited to more desert-like conditions and vary their uptake of soil moisture and stringently regulate their releases of H_20 gas depending upon conditions. Plants also affect water movement aside from their metabolic functions. Vegetation physically intercepts precipitation before it touches the ground. Even after it saturates the leaves and drips down, other canopy layers, grass and litter layers often intercept the water again. While some of this water flows down the stems and trickles through to the ground, most of it ends up evaporated back into the atmosphere. The combination of transpiration, interception, and evaporation creates a significant hydrologic pathway that returns a great deal of water back into the atmosphere (Figure 4.1). This is the principal reason that in most Sierran watersheds between one-third and one-half the precipitation that falls from the sky never makes it into the rivers.

Tributaries

The hydrology of the Tuolumne River in the foothills region is dominated by rainfall, and its rapid runoff from the land, coupled with the accumulation of large flow increases from tributaries. These tributaries convey water and sediment from various portions of the watershed, both within the foothills region and, for the larger tributaries, from the upper elevations. Five major tributaries and numerous smaller ones join the Tuolumne River in the 50 miles that make up the foothill reach (Figure 4.5). These tributaries, in aggregate, constitute roughly two thirds of the entire watershed. Since most of the watershed's perennial streams are in the foothills, this comprises a large percentage of the Tuolumne's total aquatic habitat.

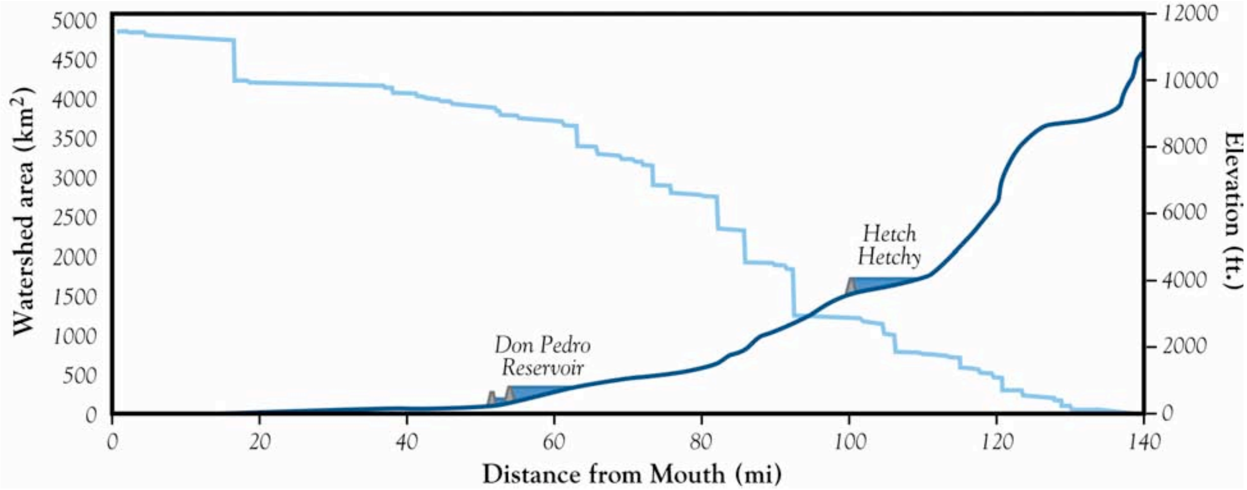

Figure 4.5 Tuolumne River longitudinal profile and corresponding watershed area drained. Note large increases in watershed area at each tributary junction.

Eleanor Creek and Cherry Creek: These tributaries drain the northern portions of the Tuolumne watershed. They each have high elevation headwaters and gain a significant contributing watershed area with many smaller creeks subsidizing the flow of the larger streams. Numerous shallow glacial lakes occur in the headwaters of both creeks. They are dominated by snow in the upper watersheds, but become primarily fed by rainwater in the lower reaches. They each have a significant reservoir on them now, part of the larger Hetch Hetchy hydropower and water supply project.

Middle and South Fork of the Tuolumne River: These forks originate in the western portion of Yosemite National Park, near the highway 120 entrance, at around 8,000 feet. The relatively low elevation headwaters mean that a significant portion of these forks' annual precipitation falls as rain and that flows are reduced earlier in the summer as compared to their higher elevation neighbors. Nearly all of the Middle and South Forks are heavily forested, which contributes to the character of the rivers, including primary production, temperature, and flow. They converge shortly before entering the Tuolumne River and are the only significant tributaries to enter from the south.

Clavey River: The Clavey is the best known and perhaps most fought-over tributary of the Tuolumne River (see chapter 12). The tributary is second in size only to Cherry Creek. The Clavey's headwaters are located at approximately 9000 feet at Lilly and Bell Creeks. As one of only three major undammed rivers in the Sierra Nevada (the other two are the Cosumnes River and South Fork of the Merced), the Clavey retains much of its original hydrologic character and acts as an important reference for how the nearby regulated rivers must once have behaved. It is an ecological refuge for many of the native fishes and amphibians of the Sierra that have otherwise been extirpated from more developed rivers (see chapters 5, 6, and 12).

North Fork Tuolumne: Of the six significant tributaries of the foothill region, the North Fork is the lowest in average elevation, headwater elevation, and the elevation of its confluence. It is a relatively long tributary that originates around Pinecrest Lake, at about 5,500 feet. Lying almost entirely below the rain/snow line, the tributary's hydrology is dominated entirely by rainfall and groundwater discharge. On its way to the Tuolumne, it flows along the boundary with the Stanislaus watershed for ten miles before it turns south and flows another ten in its own deep valley. The close proximity of the Stanislaus watershed boundary and the many geologic upheavals in the area suggest that the North Fork Tuolumne may have been part of the Stanislaus watershed at some points in its evolution, but was captured by the Tuolumne watershed in recent history. Its relatively warm temperatures and low gradient, along with livestock grazing in its watershed contributing an excess of nutrients, makes this a warm, highly productive stream.

The aggregation of large tributaries and the shift from snow-dominated to rain-dominated precipitation creates a complex hydrograph for the Tuolumne River in the foothill region (Figure 4.6). In contrast to the upper watershed where snowfall predominates, in the foothills the rivers rise during winter storms, occasionally dramatically so. During the spring, when rainfall ceases, flow on the Tuolumne peaks due to snowmelt in the upper watershed and groundwater inflow from both the upper watershed and the foothills. Small, ephemeral tributaries fed solely by groundwater during the spring and summer decline rapidly, contributing little flow to the mainstem Tuolumne. Prior to the construction of the Hetch Hetchy system, the mainstem Tuolumne would continue to drop in flow throughout the summer to very low flows in the fall after snowmelt ceased and groundwater in the basin was depleted. Today, however, these baseflows are augmented by reservoir releases that keep the foothill mainstem reach artificially high and, on a daily basis, highly variable. Further, flow regulation has reduced the frequency and magnitude of high flow events as shown in Figure 4.7, which contrasts unregulated vs. regulated flows for the 1994 water year.

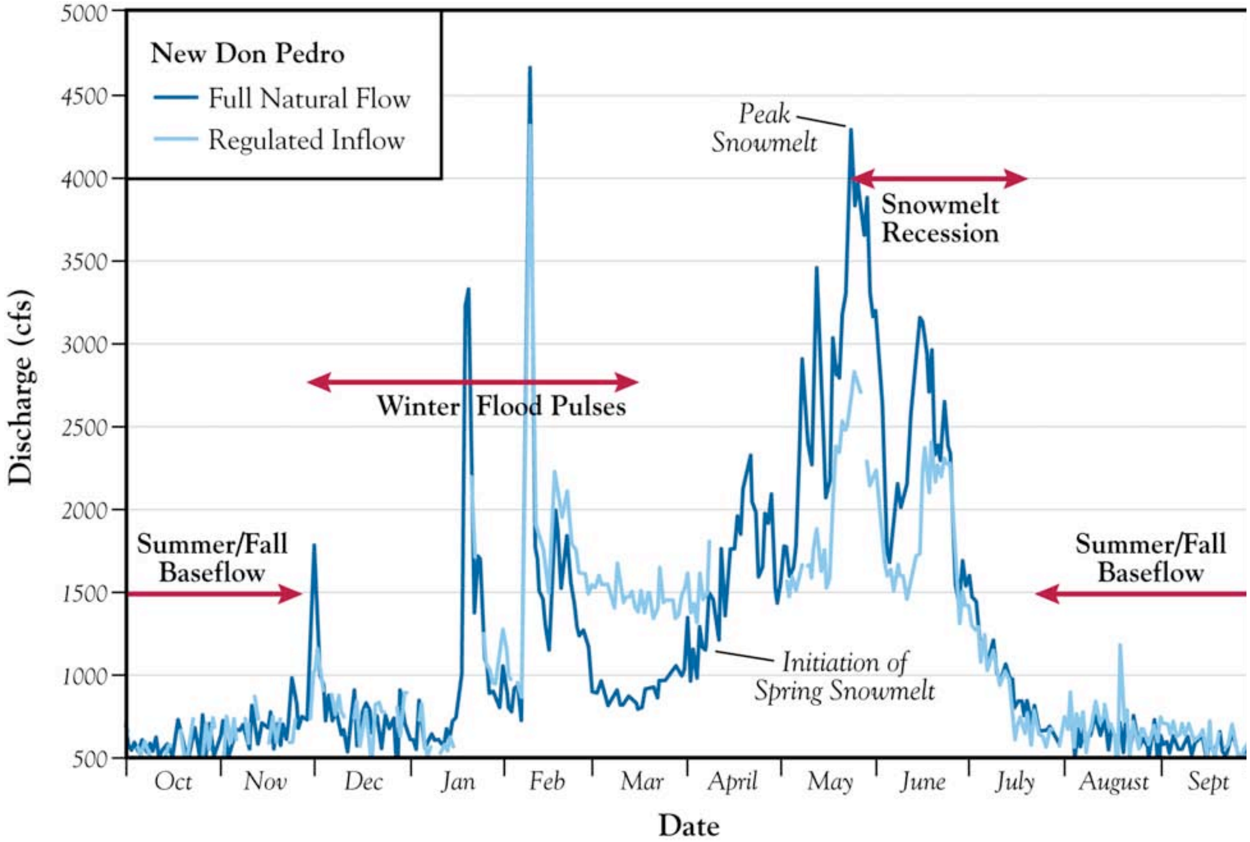

Figure 4.6 Hydrograph for the lower Tuolumne River watershed in the foothill region, where nearly all precipitation is in the form of rain. Blue represents the historical unimpaired hydrograph, while green represents the current, hydrograph under regulated flows. Note the differences in the timing, duration, and magnitude of runoff events. From McBain and Trush 2000.

The Lower Tuolumne Watershed

As the Tuolumne River emerges from the bedrock confines of the foothills and flows its last 50 miles across the Central Valley to its confluence with the San Joaquin River, its hydrologic and climatologic character changes dramatically. Through seasonal flooding and dynamic channel forms and locations, the river historically exerted a strong, intimate, and extremely complex relationship with its landscape here. This expression of the river, such as the flat, fertile ground, water and vegetation, drew people to settle along the banks, but, predictably, this ultimately lead to a conflict of interest between the humans and the natural hydrology. This conflict has lead to significant alteration of those very natural processes and the environment that drew them in the first place.

Historically, when the Tuolumne entered the Central Valley its lateral constraints were the bluffs at the eastern edge of the valley and the river's own natural levees and banks. This reach had few tributaries and receives much less precipitation than the rest of the watershed, but water from upstream funneled down to this reach and spread out over the land during high flows. There was a great deal of channel meandering, and aerial photos from the 1930s indicate a vast riparian complex with many abandoned channels, oxbows, newly exposed cut banks, and aggrading point bars. Coarse sediment from the middle reaches and above supplied spawning habitat for salmon. The dynamic nature of the river created considerable habitat heterogeneity and provided multi-aged stands of riparian forest.

Seasonal Flooding

Today the word ‘flood’ carries a strong negative connotation, but technically a flood is simply when a river rises above its banks, which, in most natural systems occurs annually. With the hydrograph of the lower Tuolumne River, and indeed all the lower Sierran rivers, this meant that large winter storms moved and scoured everything around and then sustained spring floods from snowmelt inundated the surrounding landscape. Over time, sediments deposited to form natural levees and floodplains along the channels. Large riparian forests grew up along the banks, and the river moved constantly through and around them. The spring snowmelt and baseflow recession coincide with warmer temperatures, insects hatching, plant growth and reproduction, spring spawning of fishes, and the passing of migrating waterfowl. The low gradients across the floodplains and over the remaining distance to the ocean meant that lots of organic matter, nutrients and water were stored and recycled here, which is why it is referred to as a sink. A seasonal pulse of water, fine sediments, and nutrients did, and still do, leave the watershed and join the San Joaquin, Merced, Stanislaus, and other creeks from the Sierra foothills and eastern Diablo Range to flow through the delta and out the Golden Gate.

Currently, with the irrigation demands of industrial agriculture being met either through river diversions or groundwater pumping, there has been a 60% reduction in the flows present in the lower reaches. Most of the Tuolumne river water ends up evaporated or transpired off of fields and in the atmosphere. The ground below the lower Tuolumne River was historically saturated every winter, forming a distribution of springs, wetlands and vernal pools in the winter and spring. Water flowed into and out of the river from below in complex ways that depended on the underlying sediments. Today, though, generations of farmers have pumped groundwater from the area to the extent that the saturated water table is now far below the surface and much of the water that remains in the river channel at this point sinks away into the ground.

Today, the top 20 miles of the lower Tuolumne reach are buried under two consecutive reservoirs; New Don Pedro and La Grange. After this point the river flows undammed through Modesto to the San Joaquin, but it suffers from reduced flows, reduced variability in flow, reduction in the magnitude, frequency and duration of flooding, increased fine sediments and contaminants, decreased coarse sediment inputs (these are entrained behind Don Pedro and La Grange Dams), degraded bed morphology, and a loss of floodplains to name a few. Urbanization, agriculture, and the need to protect human endeavors from floodplain processes have generated a highly regulated, constrained river whose self-sustaining processes can no longer function. As discussed in some subsequent chapters, these physical alterations are profound and have disrupted the natural ecosystem processes that existed here beforehand that were essential to the productivity and “health” of the ecosystem. The detrimental effects of a century of dams, diversions, mining, dredging, and agriculture are extensive and have resulted in the loss of an estimated 98% of the riparian habitat and the decline of the majority of native species dependent on the aquatic and riparian ecosystems, including the iconic but embattled chinook salmon (see chapter 6).

Restoration

The impacts have been recognized by state and federal agencies and the FERC relicensing settlement agreement for the New Don Pedro project requires an ambitious restoration program for the lower Tuolumne River below La Grange. The restoration plan is primarily based on reinstituting or restoring the hydrologic variability that has been lost by flow regulation, overallocation, and channel alteration. The restoration project aims to increase the number of naturally spawning fall-run chinook salmon in the river through implementing a more dynamic approach to water releases to mimic natural flows, restore the channel where appropriate, provide the river with access to its floodplains, and augment spawning gravels. Restoration of the river to pre-gold rush conditions is impossible due to economic, societal, and infrastructural constraints, but major improvements are underway to provide rehabilitation to the 50 miles of the Tuolumne River below La Grange Dam.

After more than a century of intensive and extractive use, the restoration efforts currently underway are sorely needed. The scope and size of the project coupled with diverse public and private stakeholders, and the constraints of a working landscape are a formidable challenge. However, the very fact that these efforts have been undertaken indicates a profound shift in how we think about the value and purpose of rivers. It remains to be seen whether the attempted rehabilitation of long-absent ecosystem processes will be successful in the lower Tuolumne River, but it is an ambitious and important endeavor nonetheless.

From its pristine origins on the spine of the Sierra, the Tuolumne River begins an evolution. Its character changes based on the physical and ecological gradients it passes through, as well as see it transition from an unconfined, wild river, to a meticulously controlled working river. From Hetch Hetchy to the San Joaquin confluence, the Tuolumne River demonstrates the full range of what is possible on Sierra Rivers.

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Chapter 5: Terrestrial Ecosystems of the Tuolumne River Watershed

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INTRODUCTION

Ultimately, two factors control the distribution and composition of plants and animals in the Sierra Nevada: fire and water. The seasonality of the Mediterranean-montane climate with its hot, dry summers, and cool, wet winters strongly shapes the community structure, behavior, and adaptations of the Sierran flora and fauna. Most specifically, a stark elevation gradient governs the distribution and abundance of plant species from the Central Valley floodplains to the Sierran crest alpine zone by altering the availability of water through both space and time. While the high Sierra receives the majority of annual precipitation in the watershed, predominantly in the form of winter snow, the lower elevations often operate at a water deficit subsidized by water flows from the upper watershed, most reliably from spring snowmelt. The plant water deficit creates conditions ripe for wildfire, a natural and important disturbance of foothill and mid-elevation vegetation communities. As such, plants have developed a number of life history strategies, such as serotiny, to survive and thrive in this challenging landscape. Similarly, other organisms such as fungi and animals have developed adaptations and life history strategies to create a unique, and biodiverse, set of interdependent ecosystems within the Tuolumne River watershed.

INTRODUCTION TO TERRESTRIAL ECOSYSTEMS

There are two broad categories of life strategies for plants and animals, 'specialists' and 'generalists,' with many species using a combination of strategies. Specialists have adapted over evolutionary timescales to a fairly narrow set of environmental conditions. For example, animals that are specialists often live year-round within one biome, and have specific life history strategies to handle seasonal fluctuations in climate, and ultimately food and water availability, according to their niche. Plants that are specialists have evolved to occupy very specific – often harsh – climatic or edaphic conditions, such as alpine conifers or serpentine endemics. Generalists, on the other hand, are able to thrive in multiple temperature zones and have broad diets, utilizing available food resources, and are flexible in other life history needs, such as germination, nesting, or denning requirements. Animal generalists may migrate between biomes depending upon food availability and weather conditions, whereas plant generalists are often considered "weedy" and unfortunately these species when found in the Tuolumne watershed are often non-native to California.

Structural components of vegetation

Distinct groupings of vegetation communities are called biomes, while the transition zones from one biome to another are called ecotones. With the Sierra Nevada range oriented approximately north to south, biomes and less distinct ecotones are arranged laterally (west to east). These zones can vary locally due to specific geologic, topographic, and climatic conditions. The Tuolumne River watershed itself is positioned longitudinally on the western slope of the south-central Sierra Nevada, and the biomes give way one to another via ecotones as elevation changes.

Within the communities themselves, there are distinct vegetative layers in the vertical plane (e.g. from the top of the canopy to the forest floor). In the 'forest' biome, these layers are termed: emergent, canopy, understory, shrub, forbs, and forest floor layers. In forests, emergents are the tallest trees and will extend above the canopy layer. The canopy is the conifer (cone-bearing tree) layer where the dominant trees form an upper limit; this layer's upper boundary is sun-exposed, so the trees themselves must be sun-tolerant. Trees of the understory are shade-tolerant and can thrive under the canopy, or are immature canopy trees waiting for forest gaps to develop so that they can grow to fill in the canopy. The shrub layer consists of small woody plants that maintain their structure (but not necessarily their leaves) above ground in winter. The forbs (soft-stemmed flowering plants) and grasses layer are composed of annual or perennial ground plants that emerge directly from the soil each spring. The forest floor layer is the decomposition zone where fungi and insects recycle organic materials back into the nutrient cycle.

An additional level of complexity is present in the horizontal plane, where patterns of densely vegetated versus open forest areas, tree size, species, and local topography are important structural components of the ecosystem. Some factors of this complexity include local variations in soil, moisture, and nutrient conditions; whether an area is exposed to sun, shade, or wind; forest density edge effects versus interior forest; temperature; and precipitation amount (annual), duration and intensity (per storm event), and form (rain or snow). Two very specialized habitats, meadows and riparian corridors, are interspersed in small quantities across all biomes and ecotones. Meadows can be found throughout the Sierra Nevada and range from very wet to very dry. Generally dominated by shrubs, forbs, and grasses, meadows provide open space for animals to graze and hunt, and support a unique floral and faunal community. Riparian corridors are confined to the edges creeks and rivers, where soil moisture often dictates which plant species are present. Both of these zones are highly productive, providing food and water to myriad animal species, as well as providing conditions necessary for specialized plants to thrive.

Succession, defined as a predictable change in species composition and community structure over time or space, can occur through a number of pathways and at multiple timeframes. Early succession usually begins with a type of disturbance such as flooding, fire, glacial retreat, or volcanic activity that provides a bare substrate to be colonized by plants. Fire is one of the dominant drivers in ecosystem succession in the Sierra Nevada. In forest settings, smaller fires clear underbrush, leaving the dominant trees intact. Larger fires, on the other hand, may kill many acres of trees, leading to bare soil surfaces with nutrients from the dead trees available for use by opportunists, though in many cases, nutrients are washed into local streams when the barren soil erodes. Fire opportunists include grasses and shrubs that were suppressed by lack of sunlight when a closed canopy was the dominant forest structure. The fires 'reset' the ecosystem back to a 'beginning' stage, so that conifers are no longer the dominant species or community structure. It may take 50-100 years for conifers to return to their dominant state after a catastrophic fire. In the ensuing years, other species are able to fulfill their lifecycles until the regenerated conifers suppress them.

Competition is another important driver of species composition and community structure. Competition is a struggle between individual plants or animals for the same resources. For plants, succession after fire describes a competitive arc where one species replaces another over time. The vertical structure of vegetation is a product of competition, where some species are able to thrive only in high light conditions such as in the canopy, whereas others manage to establish in low light conditions in the understory. Animals also face this competition. Some animals leave their parents to find their own territory once able to fend for themselves. If they are not able to establish a big enough space to survive in, they will die. Other animals live together more cooperatively, but still hunt for themselves.

The Sierra Nevada is an imposing boundary to plant migration, and during the last ice age (~10,000 years ago), California was bounded by glaciers to the north and east, and by desert to the south. This effectively isolated the plant species of California, which allowed them to develop on their own evolutionary trajectory. Today, there are many endemic (distinct species found nowhere else) plants (from conifers to grasses) that grow exclusively in California. Plant migration is another succession strategy that is evident today due to relatively rapid increases in temperature (~1°F worldwide in the last 150 years) due to climate change. As temperatures increase, plants and animals have adjusted by migrating northward or upward in elevation, as well as budding earlier, giving birth earlier, and coming out of hibernation earlier.

Forest Life Cycle

Terrestrial plants obtain the energy and nutrients necessary for life above and below ground. Above-ground, plants use stems, leaves or needles, and buds along with the sun's energy to obtain carbon by absorbing carbon dioxide (CO_2) molecules from the atmosphere. This process, photosynthesis, converts light energy to chemical energy (food), by metabolizing simple CO_2 into complex carbohydrates. A by-product, oxygen (O_2), is expelled by plants into the atmosphere, thereby creating the conditions necessary for the biotic processes of other life forms, namely animals. Below ground, plant root systems absorb water and dissolved nutrients that are made available by mineral (rock and soil) weathering. Conifers – which are by far the dominant Sierran tree type - also absorb nutrients through symbiotic relationships with mycorrhizal fungi (see Fungi side box) that intertwine with their root systems.

Almost all terrestrial plants are considered autotrophs (can make their own food/energy) and are referred to as producers, because they are able to build tissue that is available for other species to use. All animals, on the other hand, are heterotrophs (obtain food/energy by eating other organisms) and are referred to as consumers. Animals, including humans, cannot synthesize the Sun's energy and CO_2 like plants do, and thus require an external supply of energy in the form of eating plants or animals.

Box 5.1
Fungi

Fungi are a special type of heterotroph (organisms that derive energy from other organisms). They are called saprophytes (decomposers), and are neither plant nor animal. They live below ground and occasionally become visible by fruiting into mushrooms or mold above ground. To obtain nutrients, fungi break down complex organic material - dead plants and animals - into simple organic materials. Once broken down and absorbed by fungi and conifer alike, other plants recycle the remaining nutrients. Some fungi live in soil and dead materials, breaking down those materials for food. Other fungi have symbiotic (for mutual benefit) relationships with the root systems of most plant species, and obtain their complex organic materials indirectly via plant photosynthesis. In return, the tiny strands of fungi interwoven with plant roots increase the surface area of root systems and facilitate absorption of water and nutrients from the soil. Fungi in symbiotic relationship with plant roots are called mycorrhizae (fungus roots). Studies show that a major factor in plant biodiversity, community composition, and ecosystem productivity is the below-ground diversity of mycorrhizae fungi. These important associations are found throughout all forest biomes, including the Sierra Nevada.

Animals

Animals, from the smallest insect to the biggest mammal, obtain the necessary building blocks for life through ingestion of plants, animals, water, and nutrients. Over 300 animal species live in the Sierra Nevada for all or part of their life cycles. Those that stay year-round may hibernate. Others migrate into the Sierra in spring and summer and move south or down in elevation for milder winters. Within the animal kingdom, some are herbivorous, eating only plants. This group is considered primary consumers because they obtain food directly from the producers. Some animals are carnivorous, eating only other animals. Some of these animals are secondary consumers, eating other animals that eat vegetation only, while tertiary consumers eat other carnivores. Many animals are omnivorous, eating plants and animals according to availability, and therefore may move from one consumer group to another. One other category of consumers are the decomposers that break down dead organic materials into carbon molecules that can be recycled back into the ecosystem.

The producer-consumer dynamic can be thought of as a food web, which can be shown using a simple graph of how animals survive depending on what type of food they consume (Figure 5.1) These webs can be very complex depending upon how many types of food an individual animal utilizes. An example of a food web goes like this: a plant (the producer) is eaten by an herbivorous insect (primary consumer), and then is eaten by a bird (secondary consumer). The bird is hunted by a raptor (a predatory bird), and is killed and eaten by this tertiary consumer. Another example: a squirrel (herbivorous primary consumer) eats pinecone seeds (conifer as producer); the squirrel is hunted and killed by a coyote (secondary consumer). The coyote may be hunted and killed by a wolf (tertiary consumers). The wolf is a primary predator of these ecosystems, and thus is not hunted by other animals. Because there is a loss of energy at each transfer (efficiency is not 100%, digestion is unable to extract all of the energy contained in the food consumed), there are always fewer tertiary consumers than secondary consumers, and so on down the food chain.

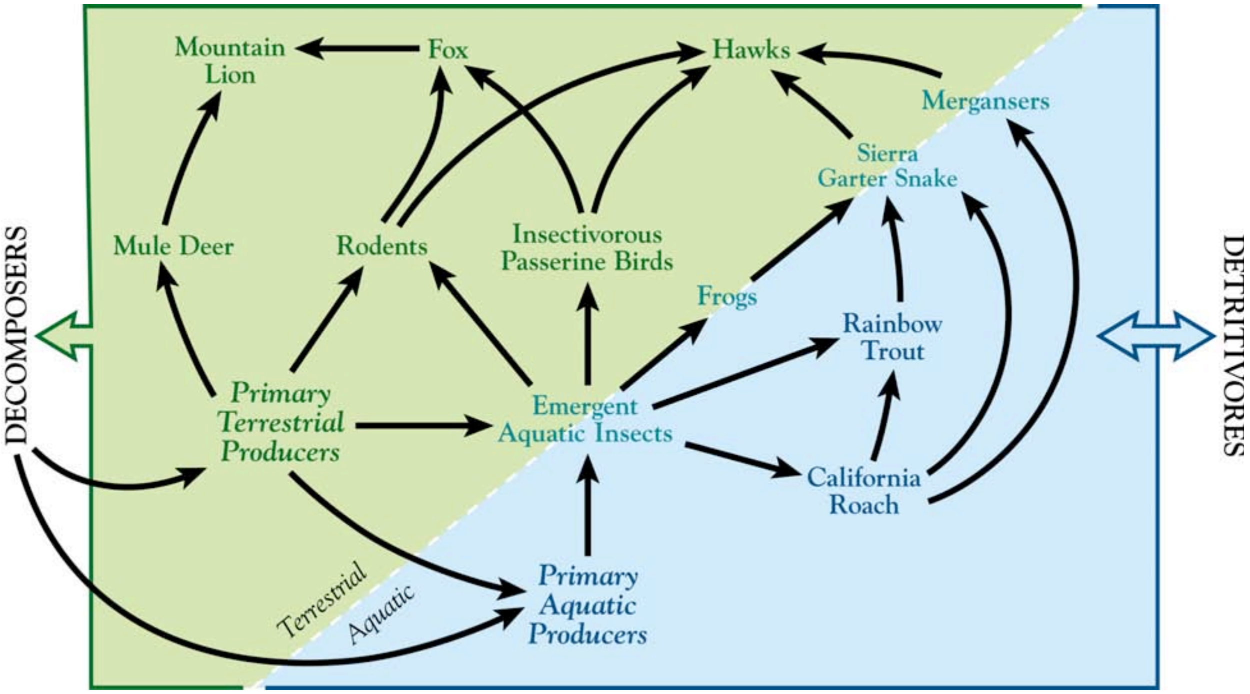

Figure 5.1 Links between the aquatic and terrestrial food webs on the Tuolumne River.

Conifers

Conifers (from the Latin *conus*, 'cone' and *ferre*, 'to carry') extend across vast expanses of the Sierra Nevada, from the foothills to tree line, and are by far the dominant plant species in the Sierra

Nevada forest ecosystem. Conifers belong to the plant group of gymnosperms, which means 'naked seed.' Although each species may inhabit specific geographic ranges, conifers as a whole are generalists of the highest order, dominating huge swaths of land on all continents except for Antarctica. The life history of conifers and other plants within the forest is cyclical based on seasonal temperatures, water availability, light conditions, and fire cycles. Conifers are evergreen and keep their needles year around. This adaptive strategy allows them to photosynthesize even in winter months, thus maintaining a steady supply of carbohydrates. The reproductive seeds of conifers are housed in cones rather than in flowers like angiosperms (plants where seeds sit inside ovaries). Seed cone production can vary greatly between species and between years, depending on environmental conditions. Most conifers produce pollen (male sperm cells) and seeds (female egg cells inside the cones) on the same tree, and pollen is dispersed by wind to neighboring trees in spring. Once fertilized, the seeds inside the cones mature throughout the summer, and generally in the fall the cones spread their protective scales to release the seeds. Seeds are dispersed by two main avenues; either the seeds are very light and thus disperse by wind, or seeds are much heavier and are locally dispersed by gravity or through collection and storage by birds, squirrels, and other rodents. This seed dispersal forms a seed bank, where they lie dormant, waiting for an environmental cue to germinate. This process occurs in one form or another in most plants. Fertilized seeds germinate when conditions are favorable, and may be viable for longer than a year as they wait for optimal conditions, such as fire (see serotiny box). Upon germination, seedlings must establish quickly or die; most die. But under certain conditions, open space and sunlight in the case of Lodgepole pine (*Pinus contorta*), or shelter close to the parent tree in the case of red fir (*Abies magnifica*) and the endemic Giant Sequoia (*Sequoiadendron giganteum*), will promote seedling establishment. Those that establish may grow to maturity and depending on the species, reproduce and live for up to hundreds of years.

Box 5.2

Serotiny

Serotiny is a specialized cone behavior, where seeds are not released by the cone upon fertilization. Instead, a resin seals the fertilized seeds inside the cone, which can remain closed for years until the cone is burned or heated during a fire. A moderate fire will melt the resin but not harm seed viability. This trait may be an evolutionary tactic to protect seeds from frequent fires, and a strategy that allows seedlings to take advantage of readily available nutrients and light on the burned forest floor directly after a fire. Seeds up to 20 years old have germinate immediately upon dispersal after a fire. Many conifers do not utilize serotiny as a strategy, while others depend solely on serotinous behavior for seed dispersal, and the degree to which serotiny plays a role in seed dispersal varies within some species. Lodgepole pines can produce serotinous and non-serotinous cones on the same tree, making its reproductive strategy highly adaptive.

Many seeds never find optimal conditions for germination; most are eaten, others decompose. Both fates benefit aspects of the forest ecosystem, but not conifer regeneration. Thus, most plants have evolved to produce an excess of seeds to bolster the probability of seedling establishment. Empty fir (*Abies* spp.) and spruce (*Picea* spp.) cones will shed to the ground by fall. Spent cones from pine (*Pinus* spp.) trees, Giant Sequoia, and most cypress (*Cupressus* spp.) and juniper (*Juniperus* spp.) trees will shed to the ground the following fall. The accumulation of years of shedding cones and needles creates a spongy layer of organic materials beneath the conifers, with partially decayed materials at bottom and the newest layer on top. This layer can accumulate to great thickness, providing homes for rodents, some ground-nesting birds, and shelter for deer, among other animals. The nutrients present in this material decompose slowly, returning to the soil decomposed by fungi, and taken up by the conifer's own root system.

A mature conifer can die in a variety of ways. Little is known about 'old-age' conifer mortality, but individual trees can die at any time, and might remain standing in an upright position until the root system decomposes enough for the tree to topple over. These upright, dead conifers called snags provide shelter, nests, and nutrients for a wide variety of animals, particularly birds. Windstorms can blow live or dead trees over, knock tops off, and shear branches. In addition, trees naturally shed branches, bark, needles, and cones on a periodic basis. Landslides and avalanches clear everything in their paths. Along rivers and streams flooding can erode channel banks and whole trees can fall or slump into or across the channel. Infestations of beetles or bacteria, such as the lodgepole needle miner (*Coleotechnites milleri*) associated with the lodgepole pine, can kill whole stands. Fire, caused by lightning strikes, can kill and scorch huge swaths of forest, or affect just the one tree. These natural processes create abundant amounts of available organic materials, which provide myriad ecosystem services within the forest.

On the forest floor, dead wood provides ecological and structural functions including shelter, microclimates, and food resources, to a vast assortment of organisms. Under moist conditions, a downed tree can act as a 'nurse log' for regenerative growth of itself or another conifer. Bark beetles (*Scolytidae* spp.) and wood borers (Buprestis aurulenta) tunnel into live and dead wood. Harvestmen spiders (*Taracus* spp.) and carpenter ants (*Camponotus* spp.) also colonize dead wood, scavenging organic materials and hastening the decomposition process of the tree from the inside out. Amphibians such as salamanders (*Batrachoseps and Ambystoma* spp.) and newts (*Taricha torosa*) find shelter under or in moist dead wood, where localized high humidity offers moist conditions necessary to keep their skin hydrated. They also have a built-in food source courtesy of the beetles, spiders, and ants. Fungi, the only organisms able to fully break down wood, occupy a downed log for years while decomposing the wood, allowing its nutrients and carbon to be recycled. Many species ofbirds, as well as mammals from mice (*Peromyscus* spp.) to black bears (*Ursus americanus*) utilize dead wood as a food resource and as shelter.

BIOTIC COMMUNITIES OF THE TUOLUMNE RIVER

Plant and animal life abounds from the heights of Sierran peaks to the Central Valley floor, an elevation difference of over 13,000 feet in the Tuolumne River watershed. The life strategies of these terrestrial species are strongly influenced by temperature and soil moisture gradients, which are governed by elevation and topographic location (such as a ridge, canyon, or sun aspect) within the watershed. At the lowest elevations of the Central Valley, grasslands once thrived and floods spread widely across floodplains adjacent to river channels. In the foothills, oak woodlands and chaparral forests continue to dominate the landscape. As precipitation increases with elevation, vast expanses of montane and sub-alpine conifer forest support a large variety of plants and animals. Forests make up ~70% of the vegetation communities of the Tuolumne River watershed. At the highest elevations in the alpine zone, temperatures become so cold that most terrestrial species cannot live there year-round.

Alpine/Subalpine Zones

Elevations above ~8000 feet are home to the plants and animals that can tolerate cold temperatures for many months each year. In the alpine zone, snow can persist in shaded granite crevasses until early fall; snow will come again shortly thereafter. The transition between subalpine and alpine is the most visible ecotone, as erect whitebark pine (*Pinus albicaulis*) give way to krummholz (i.e.

stunted due to environmental conditions) whitebark pine, and eventually no conifers grow at all. Erect whitebark pines can grow up to 40' tall in protected lower elevations, but by 12,000 feet, they survive the winds and temperatures only by growing ever smaller and more gnarled, until they lay horizontally in matted patches. These hardy survivors accumulate growth in very thin rings and so have little girth. Even under such harsh environmental conditions they can live up to 1000 years. Finally, conditions are such that only wildflowers, forbs, grasses, and mosses are capable of completing their reproductive cycles during the short growing season (as little as 20 days). Another treeline species, the Bristlecone pine (*Pinus longaeva*), is restricted to the White Mountains just east of the Sierran Crest, but as the oldest living individual organisms on Earth (at almost 5000 years old) they are iconic sentinels to the evolution of montane ecosystems.

The animals of the subalpine/alpine zones are specialists. For example, the Clark's nutcracker (*Nucifraga columbiana*) obtains much of its food by cracking open whitebark seed cones, eating some and storing others for later. The nutcrackers bury seeds strictly for themselves, but invariably some seeds are buried in locations favorable for germination and seedling survival, forming a mutualistic (each species benefits) relationship between plant and animal. Another resident, the alpine pikas (*Octotona alpina*), are small (up to 7 inches in length) mammals closely related to rabbits. They spend the short growing season stockpiling small mountains of dried herbaceous plants to consume while overwintering; they do not hibernate. They gather so many herbs that other small rodents tend to overwinter with the pika, eating a share of the stockpiled food, Deer will browse remaining dried grass piles when other food sources become scarce as winter wanes. Pikas live among granite slabs; close enough to a meadow to forage, far enough away to live in relative safety. They sound a loud whistle to warn of approaching danger; when hiking in the high Sierra these warnings often precede a hiker – with a sharp eye, the rear ends of pikas can be seen as they retreat into the granite slabs and out of danger range. Pikas tolerate cold much better than hot, rarely surviving if exposed to temperatures above 75°F.

Yellow-bellied marmots (*Marmota flaviventris*), the other ubiquitous creature of the alpine zone, are large rodents (up to 20 pounds) related to squirrels, and are highly social. They are omnivorous, eating massive amounts of grasses and herbs, as well as insects, spiders, and worms in the spring and summer to build up thick layers of fat to get them through 6-9 months of hibernation. Red foxes (*Vulpes vulpes*), coyotes (*Canis latrans*), eagles, and hawks roam freely into the alpine zone, hunting for a pika, marmot, or whitetailed jackrabbit (*Lepus townsendi*), but make their homes in lower-elevation subalpine zone habitats. These predators are carnivorous generalists, ranging across habitat zones, willing and able to catch and eat any other animal, not restricted to a specific habitat or diet.

Meadows

Meadows could be considered the 'dinner tables' of the mountains because they provide both food and moisture to animals. Meadows are generally treeless but are full of forbs, grasses, and woody shrubs. Meadows occupy just a fraction of the forest landscape (less than 1% of the Sierra Nevada), but are hotbeds of biodiversity and high productivity. Plant species that cannot flourish under the forest canopy because of light, moisture, or nutrient conditions may thrive in meadows instead. The high concentration of forbs and grasses is extremely important to herbivorous animals and to the carnivores that prey on the herbivores. Butterflies, moths, bees, and other insects depend upon the yearly profusion of wildflowers as a primary food source, while the wildflowers rely on the insects to assist in their reproduction by pollinating the flowers. Various birds use the meadow for hunting, nesting, or foraging. Forbs, sedges, and woody shrubs thrive in meadows where subsurface water is available year-round. These meadow plant communities support a large number of insects, birds, and mammals, many year-round but even more during the seasonal flush of spring and summer growth. Sedges (*Cyperaceae* spp.), rushes (*Juncaceae* spp.), grasses (*Poaceae* spp.), woody willow shrubs (*Salix* spp.), and annual wildflowers dominate wet meadows. Sedges have grass-like leaves and triangular stems. Rush's stalks are slender and rounded and come to a delicate needle-like point at the end that turns brown as the summer progresses. Mountain meadow grasses can be identified by a round, hollow stalk with leaves that originate from a node along the stalk.

Meadow moisture can range from wet, to moist, to dry. Wet meadows are generally shallow, flat depressions in the landscape supported by perennial streams. Winter snows accumulate because of the slightly concave topography and in the spring surrounding uplands drain snowmelt to the meadow. The combination of a relatively flat area along with deeper soils and vigorous plant growth make high elevations wet meadows valuable water storage and flood reduction zones. Conifers are generally excluded from the open space of a wet meadow because their roots do not tolerate the low oxygen conditions of inundation. In all but the lowest snowfall years, groundwater is generally available through summer, thus providing more succulent green vegetation for herbivores for many months of the year.

Moist meadows may be spring-fed or have an ephemeral stream running through it. Some meadows of this type have experienced rapid encroachment by conifers. While it is unknown exactly why encroachment is occurring, it may be that fire suppression policies have had unexpected consequences; what may once have been maintained as open meadow via deliberate fires in Native American times might now be turning into young forest. Other reasons for encroachment include drops in the water table due to erosion and incision from land use practices, and forest management that promotes denser stands that were historically present with higher evapotranspiration rates depleting the water table.

Dry meadows may be located on slopes or convex portions of the landscape and have thin soils that cannot support trees, but they still capture soil moisture in the springtime from the melting snowpack. Additionally, dry meadows can result from degradation of one of the moister meadow types and a concurrent drop in the water table. This landscape supports annual grasses and forbs long enough for them to grow and reproduce. By mid-summer the shallow subsurface holds little moisture and although vegetation is dry, it is still edible and utilized by herbivores.

Migratory birds, such as the endangered willow flycatcher, return from over-wintering in Central and South America at the end of snowmelt. Aptly named, the flycatcher nests in willows found in wet meadows or in the riparian corridors of forest streams, and catches flying insects emerging from the meadow stream to feed their young. Mountain voles (*Microtus monanus*) and their cousins, the deer mouse (*Peromyscus maniculatus*) are year-round inhabitants of all types of meadows.

Tuolumne Meadows, at ~8500 feet, is a world-renowned example of a subalpine meadow surrounded by Lodgepole pine (*Pinus contorta* ssp. *marrayana*) forest (Figure 5.2). The Lodgepole pine often exists in monotypic (single species) stands within the subalpine zone, interspersing with mountain hemlock (*Tsuga mertensiana*) at higher elevations and red fir at lower elevations. Tuolumne Meadows is nestled amongst fractured granite and forest, a great expanse roughly 10 by 15 miles of sedges, grasses, rushes, forbs, and wildflowers carpet the meadow floor by early spring. Through early summer, wildflowers bloom with abandon, casting color everywhere amid the herbaceous greenery. The Tuolumne River, created by a confluence of Dana and Lyell forks, runs through the meadow providing an abundant supply of water, while the meadow itself provides nourishment for the foraging herbivores. John Muir described the Tuolumne high country meadows as "flowery carpeted mountain halls."

Figure 5.2 The sub-alpine zone of the Tuolumne River watershed in the low gradient reach passing through Tuolumne meadows surrounded by Lodgepole forest. Note the incursion of young Lodgepole pines into the meadow in the foreground. Photo by Dan Anderson.

Box 6.3

Wildflowers

Wildflowers are an abundant and integral component of the forb and grass forest layer, easily noticed because their flowers come in so many colors. Annuals (forbs that regenerate yearly through seeding) spread their seeds by the end of the summer, overwinter in the soil, then germinate and sprout in early to late spring and quickly blossom to flowers. The flowers may stay vibrant for as little as 1 month and up to 4 months – long enough to spread pollen via wind or attract pollinators, to complete the reproductive cycle. Insects such as bees, ants, moths, and beetles, as well as birds and bats (the only flying mammal) gather nectar from the pistil (female ovaries) from individual flowers for food. Pollen (sperm cells) is located on the stamens (male reproductive organ) of the flower. Pollen is generally not mobile, and so relies on animals to gather nectar and incidentally carry pollen from plant to plant. Wind spreads pollen, and is the primary pollination mechanism for many species such as grasses and fir (Abies spp.) trees. Perennial wildflowers sprout from dormant roots in early to late spring, while annuals sprout anew from a seed every year. Wildflowers grow sparingly within the forest itself mainly because of competition for light from the overstory. But, some manage to flourish by taking advantage of moist soil conditions, shade, and fewer herbivores grazing in the area. Wildflowers in meadows proliferate, growing thickly and vigorously in the deeper, moist soils with abundant light. These plants are more likely to be eaten by herbivores along with the sedges, grasses, and rushes that also dominate the meadows. A few favorite wet meadow wildflowers are the perennial western asters (Aster occidentalis), blue lupines (Lupinus polyphyllus), and yellow butterweeds (Senecio douglasii).

Animals that patrol the Tuolumne Meadow and adjacent forest for food are careful to stay mostly out of sight, but their tracks tell much about their habits to an educated observer. In winter, pine marten (*Martes americana*), weasel (*Mustela erminea*), white-tailed jackrabbit (*Lepus townsendii*), coyote (*Canis latrans*), Douglas squirrel (*Tamiasciurus douglasii*), Belding's ground squirrel (*Spermophilus beldingi*) and abundant other tracks are visible to the experienced eye. Martens, weasels, and coyotes are carnivorous – hunting the herbivorous jackrabbits, squirrels, mice, and voles of the meadow throughout the year. The Belding's ground squirrel makes its home in the meadow, digging large burrows belowground to accommodate 10-200 members of the group. They hibernate about 8 months a year, with low activity possible as needed during winter, and emerge in late spring. They must double their body weight with thick layers of fat to survive the long winter. Omnivorous, they prefer flower heads, grasses, and seeds but will eat insects, bird eggs, and small mammals as well. Weasels are just the right size to infiltrate the burrows and steal a baby ground squirrel for dinner. Pine martins do not hibernate, and hunt mice, which also do not hibernate, throughout winter. Although now uncommon, badgers (*Taxidea tasux*) do not hibernate. Prodigious diggers, they can swiftly excavate and kill a squirrel hiding or hibernating 1-2 feet underground. Birds that overwinter include mountain chickadee (*Poecile gambeli*), red-breasted nuthatch (*Sitta canadensis*), brown creeper (*Certhia americana*), red crossbill (*Loxia curvirostra*), and Clark's nutcracker. Birds hunt for insects in tree bark and soils even in winter. In summer, other animals, particularly birds, migrate upward in elevation or northward in latitude to utilize the meadow.

Montane Forests

The term 'mixed conifer forest' is often used to describe large swaths of mid-elevation forests of the Sierra Nevada; here the term montane forest is used. This forest biome predominates at elevations between ~3000-10,000 feet and includes white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), sugar pine (*Pinus lambertiana*), incense cedar (*Calocedrus decurrens*), and California black oak (*Quercus kelloggii*). Red fir (*Abies magnifica*) and Lodgepole pine intermingle between the lower elevations of the subalpine forest and the upper elevations of the montane forest. This ecotone can be found above Hetch Hetchy in the Tuolumne River watershed. Jeffery pine (*Pinus jeffreyi*) can be found in volcanic terrain at higher elevations, and are in abundance in the Clavey River sub-watershed, where volcanic bedrock and soils are common. White fir, red fir, and Jeffery pine intermingle as elevations decrease. Canyon live oak (*Quercus chrysolepis*) is common on very steep, rocky slopes. Ponderosa pine, sugar pine, and California black oak form an ecotone at the intersection of the lower montane forest and upper oak woodlands or chaparral forests.

Sugar pines are the largest of all conifer species . They grow over 200 feet tall and cones can measure up to 24 inches in length, yet light, delicate winged seeds float through the air in early fall in cone-bearing years. An invasive disease from France, the White Pine Blister Rust (*Cronartium ribicola*), threatens the sugar pine. The rust spreads via wind born fungal spores to gooseberry and currant plants, where the spores await moist climatic conditions. In 'wave' years, spores spread back to the sugar pines, infecting new trees. This majestic conifer may be driven to extinction.

Quaking aspen (*Populus tremuloides*) is a widespread deciduous tree species found across North America. The Clavey River sub-watershed is home to the largest stand of quaking aspen in the Sierra Nevada, encompassing 125 acres at Bell Meadows in the upper montane forest. Because of the aspen's geographic distribution, it can be considered a generalist. However, they also exhibit specialist adaptations. Aspens thrive in moist soils, but do not tolerate standing water very well. They are shade intolerant, so as conifers begin to encroach on an aspen stand, the conifer will out-compete the aspen for the available resources, and aspen will slowly die out. Aspen are fire-adapted and can resprout from its root system after a fire.

Box 8.4

Snow Plant

A unique flower, the snow plant (Sarcodes sanguinea), has a symbiotic relationship with mycorrhizae fungi and a parasitic (extracts nutrients or usurps living space while giving nothing in return) relationship with conifers of the montane biome. Because it lacks chlorophyll, it does not photosynthesize. Instead, its nutrients come from organic materials that the fungi are decomposing, as well as complex carbohydrates supplied indirectly from the conifer to the mycorrhizae to the snow plant. This occurs because its root system - much, much smaller than that of a conifer - is also entwined with mycorrhizae. Thus, the plant always grows under or very near conifers so it can redirect some nutrients from both conifer and fungi. It is variously called a saprophyte (deriving nutrients from decaying materials in soils) or mycotrophic (deriving nutrients from mycorrhizae). Its stem, leaves, and flowers are all colored the same variation of red. Its flowers are bell shaped and hang off of the stem drooping downward. Its leaves are arranged all along the stem and look a bit like overgrown asparagus heads (the fleshy scales from the top of the plant that we eat along with the stems). It can stand, up to 18 inches tall.

Birds proliferate in the montane forest biome. Many birds migrate into the forest and mountain meadows in spring and leave for southern locales in fall. Western tanagers (*Piranga ludoviciana*) and red-breasted sapsuckers (*Sphyrapicus ruber*) exemplify this behavior, whereas the migration of the mountain quail (*Oreortyx pictus*) is unique. Although quail are capable of full flight, they prefer to run or walk whenever possible, including during their annual migration from the Sierran foothills to the montane forests and back. If you keep a sharp eye out, they can often be seen alongside roads, running for cover when startled. Birds such as the pileated woodpecker (*Dryocopus pileatus*) live in the montane forest year-round. This bird facilitates the decomposition process in live trees. It uses its strong beak, neck, and body to drill holes for nesting and to break up bark and wood tissue as they hunt for insects to eat. Pileated woodpeckers mate for life and defend a territory of about 0.4 square miles by drumming on snags around the perimeter of their space. Eggs hatch about 18 days after being laid in the spring. The fledglings fly about a month later and are taken care of through their first summer before flying off to establish their own territories.

The mule deer (*Odocoileus hemionus*) is the only deer species native to the Sierra Nevada, and is endemic to California. They are herbivores, migrating into the lower montane forest and foothills in the winter, and browsing in the lush montane meadows in spring and summer. They eat forbs, grasses, berries, and acorns in season, and subsist on conifer needles and twigs in winter. They live just inside the forest along the edges of meadows, never far away from water or food. Grizzly bears (*Ursus arctos horribilis*), gray wolves (*Canis lupus*), and mountain lions (*Puma concolor*) were historically the primary predators of the mule deer, while coyotes, black bears, bobcats (*Lynx rufus*), and eagles might take down a fawn or weakened elderly deer. Today, the mountain lion is the primary predator; the grizzly is now extinct in the Sierra Nevada, and gray wolves have not adapted to human populations as well as mountain lions and have been extirpated from California. Because of the lack of top predators, the mule deer population increases quickly each spring and summer when fawns are born. But in winter when food grows scarce, too many deer force a cycle of starvation, which kills old and weak individuals. Instead of predation, food availability maintains the population balance. Mountain lions roam quietly but widely throughout the montane and foothill forests in search of food. At upper elevations, they hunt from rocky ridge tops, the better to see whether unsuspecting food sources – from mice to deer - are busy in the canyons and meadows below. Lion kittens are born from early to late summer, with mother caring for them into their second year. Lions must learn to hunt with silence and stealth because their primary food source, the mule deer, is equipped with big ears and noses specifically evolved to protect them from creeping predators. A mountain lion must hunt successfully enough to remain healthy, and will resort to small mammals when needed.

Riparian corridors represent the interface between water and land, where the hydrologic cycle regularly influences geomorphic and ecological processes. Comprising at most 1% of a mountain landscape, the riparian corridor supports disproportionately large numbers and densities of plant and animal species, due largely to availability of water and high soil moisture. Riparian plants depend on a sub-surface hydrologic connection to the stream channel, and this dependency is the limiting factor for riparian width. In steep canyons, this strip may be just a few feet wide or even nonexistent when bedrock predominates, but as the canyons widen into valleys, the corridor can become much wider.

Hydrophilic (water loving) vegetation, including alder (*Alnus* spp.) and willow (*Salix* spp.), are ubiquitous along streams from the valley floor to high elevations in Sierra Nevada watersheds, including the Tuolumne River. Riparian trees are generally deciduous (sheds its leaves and is dormant in winter) and require a minimum-length growing season. White and red alder trees (*Alnus rhombifolia* and *Alnus rubra,* respectively), western sycamore (*Platanus racemosa*), and willows are common in the riparian corridor. This swath of dense vegetation along both sides of the river, and the river itself, act as a passageway for migration up- and down-watershed for all sorts of plants and animals. Animal species using these river commons include raptors such as bald eagles (*Haliaeetus leucocephalus*), red-tailed hawks (Buteo jamaicensis), and great horned owls (*Bubo virginianus*), small carnivores like fisher (*Martes pennanti*) and American marten (*Martes americana*), migratory herds of endemic mule deer (*Odocoileus hemionus*), and the American dipper (*Cinclus mexicanus*), the only songbird native to North America that regularly enters the water for its food. This specialist flies low over river channels in the Sierra Nevada, diving into the river and walking along the river bottom hunting for aquatic insects. Adaptations designed to optimize their unique ability to forage for food under water on the channel bed include a thick coat of feathers, a low metabolic rate, and extra oxygen-carrying capacity in its blood. Dippers are year-round residents, nesting near water and diving for aquatic insects in ice-free rivers throughout the winter.

Foothill Woodlands and Grasslands

As the mountain descends below 3000 feet in elevation, the lower montane ecotone of ponderosa pine, black oak, and sugar pine gives way to the foothills biome dominated by oak woodlands, grasslands, and chaparral habitats. Oak species found in this zone include black oak, blue oak (*Quercus douglasii*), interior live oak (*Quercus wislizenii*), and the endemic valley oak (*Quercus lobata*). In recent decades, up to 20% of oak woodlands have been destroyed because conventional wisdom thought that removal would improve grazing. Indeed, upon removal grass densities initially increased for 1-2 years, but before long it became evident that oak removal was a mistake. Oaks are widely spaced because subsurface moisture is limited in the hot, grasslands environment; oak roots radiate expansively to gather enough moisture and nutrients to survive. Oak trees are essentially individual islands where local nutrients and moisture rally to support small, self-contained ecosystems. The loss of these islands and the nutrients cycled through them led to a decrease in grass productivity after the initial flush. With regard to grazing, another unintended consequence of oak removal was that grasslands without trees mean cattle have no shade. Oak woodlands are also removed for development of land for agricultural purposes, and to make room for housing tracts as Central Valley towns expand.

Oak woodlands (Figure 5.4) are home to more native species than any other Sierran biome – with up to 85 species of animals using the foothills at some point in the year; seasonal visitors include migratory birds and upland animals that use the foothills for overwintering. Acorns produced by oak trees feed numerous animals, including the acorn woodpecker (*Melanerpes formicivorus*), western scrub jays (*Aphelocoma californica*), mule deer, western gray squirrel, and even the black bear (*Ursus americanus*). According to research, oak communities more than 500 miles apart can exhibit synchronous reproductive behavior, producing abundant amounts of acorns in the same year, a phenomenon known as masting. Because so many species depend on acorns as a food source, it is thought that masting behavior helps to overwhelm the acorn eaters with so much food that once collected and stored some acorns will be forgotten, allowing the germination and establishment of oak seedlings. Unfortunately, grazing, invasive grasses, and artificially large deer populations dramatically reduce the chances of survival of a seedling. The invasive grasses prove to be tough competition for water and nutrients, while grazers do what they do best – eat plant materials, particularly young leaves.

Figure 5.4 Oak woodland and grassland along Tuolumne River in the foothills reach. Grey Pine is also present.

Wildflower species of the foothills have suffered less from invasive species than native grasses have. California poppies (*Eschscholzia californica*), the endemic goldfield flowers (*Lasthenia* spp.), and Johnny jump ups (*Viola douglasii*) are just a few of the many beautiful wildflowers that make an entrance in early spring when the soils are still moist. California poppies, the state flower of California, are well adapted to the drought conditions of the Central Valley and foothills. Their rich golden flowers open in sunlight and close at night or in cold, windy weather. Grasses that co-dominate with oak woodlands, as well as grassland expanses on the valley floor, are no longer dominated by native perennial species. Instead, annual European grasses introduced to California by early Spanish missionaries predominate, such as wild oats (*Avena* spp.) and foxtail brome (*Bromus rubens*). Introduced annuals germinate faster and send roots deeper than the native perennials, thus taking up much of the available water and nutrients each growing season. Native grasses have suffered tremendous habitat losses by being out-competed by the European grasses. Even more devastating to grasslands habitat is the conversion of grasslands to agricultural lands, although at higher elevations in the foothills less development has occurred. Wide expanses of oaks dotting the 'golden hills of California' are still very beautiful from afar and still very much evident to a freeway traveler. Yet, few people think about the fact that the 'golden hills' are, in reality, invasive grasses that dry out during the Mediterranean-climate-driven drought conditions from May to October every year.

The endemic foothill (or gray) pine (*Pinus sabiniana*) lives along the upper edges of oak woodlands and among chaparral. This pine grows in small clusters and often sprouts multiple trunks at ground level. The Miwok and Yokut Indian tribes called this tree the ghost pine because of its silvery gray appearance, and harvested the delicious seeds (pine nuts) from the cones. In addition they cut open still-green cones, extracted, and ate the tender cone 'heart.' This foothill pine can grow on canyon walls or on grassy foothills, and is sometimes associated with reddish serpentine soils (derived from the metamorphic rock serpentinite, the official CA state rock). Serpentinite rocks are greenish in color and feel waxy when touched, and contain high levels of nickel, chromium, cobalt, and iron (the iron turns reddish when exposed to oxygen – basically 'rusting,' thus the reddish soils). Serpentine soils are generally thin, hold little water, and have little calcium, potassium, or nitrogen, three important nutrients vital to plant health. Plants that survive on these soils are often dwarfed due to nutrient stress, water stress, and heavy metal exposure. However, the foothill pine is indiscriminant in terms of what soil it grows in, and appears to thrive in serpentine soils just as well as it does in other soils. Plant species that have the ability to grow on or off serpentine soils are called *bodenvags,* a German word meaning 'indifferent.' Although the foothill pine has a fairly narrow geographic range, it has adapted to a variety of environmental conditions, thus a classification of generalist fits the life strategies of this tree. Rosaceae is a ubiquitous foothills plant family containing many chaparral shrubs, some of which are also *bodenvags.These* include the chamise (*Adenostema fasciculatum*) and toyon (*Heteromeles arbutifolia*) shrubs. The foothill pine has an affinity for chaparral, and grows in clusters throughout chaparral as an emergent forest layer along with the California scrub oak (*Quercus berberidifolia*).

Chaparral Ecosystems

The term chaparral applies to a broad category of woody shrubs that often grow no more than about 8-10 feet tall, although 100-year-old manzanita (*Arctostaphlos* spp.) have been measured at a height of over 30 feet. Many chaparral species are endemic to California. These shrubs grow in vast thickets with generally closed canopies, forming the canopy layer of this biome. Chaparral stands are common in the Tuolumne River watershed from approximately 1000 to 3500 feet in elevation, along with oak woodlands. They are bushy with waxy leaves and sunken stomatal openings (that allow CO_2 to enter and water vapor to exit) that slow evapotranspiration (the release of water vapor by plants) in this hot, semi-arid climate. Chamise, toyon, deerbrush (*Ceanothus integerrimus*), manzanita, and scrub oak are common chaparral species of California. Chaparral stands live only in Mediterranean climates, and thrive in these biomes across the world (Chile, Southwestern Australia, South Africa, and the European Mediterranean). They are specialists that thrive in the right environment, limited by temperature and moisture conditions. They like it hot and dry for the most part. Sprouting starts in January after the rains in late November-early December, with flowering and seeding by March-April. Dormancy begins in the summertime until the rains come again and the cycle starts anew.

Chaparral is highly adapted to fire. Depending upon the species, following a fire, chaparral species either resprout directly from their root systems or they have a serotinous seed bank that sprouts once fire has prompted the seeds to germinate. Some species utilize both adaptations. Yet chaparral can apparently thrive for centuries without fire. Old-growth chaparral has been aged to over 150 years without any fire scars, using dendrochronology (tree-ring dating). Some dormant chaparral seed banks can germinate even after 100 years between fires. Even though chaparral germinates directly after a fire, if a high intensity fire has completely burned the chaparral forest, it may take up to five years for the stand to grow tall enough to dominate the flora (plant life) again. In the meantime, grass and forb seed banks will sprout and complete their lifecycles in the years between fire occurrence and subsequent canopy closure by the chaparral. This behavior is an apparent evolutionary adaptation by the forest floor layer species. After succession is reset by fire, chaparral generally takes over for several decades until oaks and conifers take over and shade it out. These species have adapted so that once every 10 to 100 years, their seeds are ready to take advantage of the right environmental conditions for them to thrive, even if just for a short time.

A mixed stand of chaparral, foothill pine, and scrub oak supports a number of animal species, including the wrentit (*Chamaea fasciata*), a chaparral specialist not found in other biomes. The wrentit is a small and elusive bird, generally heard but not seen. They mate for life and live together in close communities. They forage on chaparral insects such as ground dwelling beetles (Tenebrionidae), ground and shrub dwelling ants, bumblebees (*Bombus* spp.), butterflies, moths, wasps, and flies. These insects are important pollinators for many plant species, and are a food source for birds, thus forming one of the many food webs of the Sierra Nevada. The western scrub jay (Aphelocoma californica) makes its home in chaparral forests, gathering nuts, seeds, and berries and storing them for wintertime. The jay is an omnivore, so they eat insects, frogs, and lizards when available. The California quail overwinters in chaparral and breeds in the spring before walking their brood upslope into the montane forests in summer. Gray foxes (*Urocyon cinereoargenteus*) and bobcats utilize chaparral in winter and range high into the montane forest in spring and summer. Both predators hunt brush rabbits (*Sylvilagus bachmani*), deer mice, and California ground squirrels (*Spermophilus beecheye*) in the chaparral forest.

Floodplains

At the confluence of the Tuolumne River with the San Joaquin River, and in the millennia prior to intensive land use and resource extraction, seasonal wetlands dominated the valley. These wetlands were located around each Sierran river confluence with the San Joaquin River. Today, remnants of these wetlands are called the Pacific Flyway, the west coast route taken by millions of migratory bird species on their way to and from mating sites in the north and overwintering sites to the south. Remnant seasonal wetlands in California constitute just 10% of their former area. Agricultural fields now blanket the vast majority of the valley, still providing some refuge for migratory birds.

Prior to grazing and agricultural disturbance, endemic bunchgrass, clover, and wildflowers stretched across the Central Valley at the height of spring bloom. Today, along roadsides and field edges, non-native grasses such as oats and rye can be found. European grasses were brought to the valley by herders with bags of seed at the ready to ensure success for their cattle and sheep.

Figure 5.5 View of the Tuolumne River looking downstream near Merrill's Pool. Chaparral covers the south facing hillside in the background while gray and ponderosa pines edge the river near the rapid. Mixed riparian shrubs and grasses occur in the north facing foreground. Photo Sabra Purdy

In the floodplain on the valley floor, the narrow ribbon of river supports the most diverse habitat zone in the valley. Cottonwoods (*Populus fremontii*), valley oak, the endemic California box elder (*Acer negundo var. californicum*), the endemic California buckeye (*Aesculus californica*) and black walnut (*Juglans nigra*) trees form the canopy layer along the river, while willows and alders occupy the understory (Figure 8.5). Vines such as the California blackberry (*Rubus ursinus*) and wild grapes (*Vitis californica*) occupy the shrub layer. All species (except the oak – they are opportunists) are dependent on moist conditions for vigorous growth, and so live directly adjacent to the river in the riparian corridor. Cottonwoods are specialists in this environment; their seeds are light-weight, drift easily on wind and water, and are dispersed in early to mid-spring to take advantage of snowmelt flows (an evolutionary adaptation). Seedlings sprout on gravel bars. Seedling roots follow the recession (lowering) of snow-melt flood, and can grow quickly and effectively as long as water depths do not recede too quickly. River regulation has adversely affected cottonwood regeneration, because winter snowmelt flows are captured in reservoirs rather than flowing downstream. Cottonwoods have not yet adapted to this water regime change – and may die out in the Tuolumne River watershed before such an evolutionary process can take place. There are few young cottonwood trees these days; much research is being done to determine if regulated flows can be pulsed correctly during the critical sprouting phase in spring. What is clear is that humans have dramatically altered the annual winter snowmelt flow regime. The cottonwoods left today must reproduce within their lifetimes (~100 years) for the population to remain viable.

Figure 5.5 Lower Tuolumne River with riparian forest growing and access to the floodplain. Photo from Department of Water Resources.

For myriad animals, the river is essential to their survival. Hot, dry summers necessitate that animals either migrate to cooler climates, or have a steady water source. In the days before agriculture, the endemic tule elk (*Cervus elaphus nannodes*) and grizzly bears were the megafauna species of the valley. Grizzlies are now extinct in California, while small populations of tule elk live on a few reserves in the state. The American kestrel, a bird of prey, is an inhabitant of the floodplain, and stays well-fed by capturing ground mice, gophers, snakes, and an occasional squirrel.

Landscape alterations

Fire Regimes

California's plant and animal ecosystems have evolved with fire as an integral part of the ecosystem. Recall from earlier in this chapter that at the highest elevations, lightning strikes hit on average once per square mile per year, while in the foothills strikes occur at an average rate of once per 3-6 square miles per year. Tuolumne River watershed area above New Don Pedro is ~1500 mi^2, so one can expect 300-1500 lightening strikes across the whole watershed over the period of a year. While not every lightening strike results in fire, fires are one of the main drivers of ecosystem demise and regeneration in Sierran watersheds.

Fires can be thought of as individual events, but at longer time scales they are repeated events that exhibit patterns based on the topography, climate, and vegetation of an area. Fire patterns have created vegetation patterns that are adapted to frequent fire. Individual fires have physical characteristics, such as size, behavior, and burn patterns. A fire's effects on plant ecosystems include complete death, partial burning, scorching, elevated temperature exposure without burning, and smoke inundation. The vertical and horizontal structure of the forest, along with species composition, vegetation moisture content, air temperature, and amount of biomass all play a part in a fire's severity, intensity, extent, and continuity (Table 5.1). Animals are also affected by fire; they can die or be injured due to exposure to high temperatures and smoke. Mobility is an advantage for some animals, but many animals are not able to move quickly such as beetles and ants. These creatures must burrow in place inside of tree bark or in the ground; if temperatures exceed their survival thresholds, they die. For bark beetles, if a tree dies, the beetles most likely die too. Ground dwelling ants may survive if their nests are more than a few inches belowground. Dry soils are excellent insulators, with temperatures decreasing at a rate of over 200°F per one inch of soil depth. Different types of fire have different temperatures. For instance, a chaparral fire temperature can be as high as 1200°F, but 1 inch below the soil surface temperatures fall to just 400°F. A grass fire burns cooler; it may have high temperatures of 500°F, with temperatures less than 200°F one inch below ground surface.

Table 5.1 Fire Regime Characteristics of the Tuolumne River Watershed Biomes

TEMPORAL	
Seasonality	Most fires occur May-October, during the Mediterranean drought season
Fire Return Interval	-Pre-fire suppression, 0-20 years on average -Post-fire suppression, >>20 years on average
Weather	Temperature, relative humidity, wind, precipitation, and atmospheric stability influence fire behavior by regulating fuel moisture levels and the rate of spread of the fire
SPATIAL	
Size/extent	Localized, small to stand-replacing, large areas
Spatial complexity (continuity/patchiness)	Fuel consumption and spread patterns are influenced by vegetation structure, moisture, topography, and weather conditions. Fire complexity can range from moderately patchy, to complex and widespread, to completely burned.
MAGNITUDE	
Intensity	Depends on how fast the fire moves, how much vegetation gets burned, and how hot the fire is; can range from low to moderate to severe.
Severity	Severity is a term used to assess the alteration or disturbance of a fire on the ecosystem, often estimates as percentage of plant death.
Fire Type	-Ground fires occur mostly in grasslands and can burn organic materials in soils. -Surface fires burn understory, shrub, and forest floor layers, and may burn into the canopy. -Crown fires occur when thickets of smaller fuels in surface fires ignite the canopy layer. If the canopy layer is dense enough, the fire will spread from tree to tree.

Conifers, understory trees, shrubs, grasses, and wildflowers all have specific life strategies in response to fire (Table 5.2). Conifers have thick bark to insulate them, and their burnable materials (limbs, needles, and cones) are often high above the ground. As long as fire does not reach the canopy and become a crown fire, these trees will most likely survive. Survival may not be the case for younger conifers with less bark and height. Understory, riparian trees, and shrubs have different fire strategies compared to conifers. They have thinner bark and are often not as tall, so they may suffer more casualties in a low to moderate severity surface fire. Their survival strategies are to resprout from branches, trunks, or root systems. Because soils are such good insulators, root systems can survive as long as a slow burning ground fire does not find thick organic soil materials to settle in to. Grasses and wildflowers rely on deep root structures for perennial species, and annual species rely on seed beds in the soils. This wide range of survival strategies is greater in plant communities with recurring fire regimes, such as California's Mediterranean climate.

Table 5.2. Forest species adaptations to fire			
Survival Adaptations			
Species	*Adaptation*	*Function*	*Response to fire*
Conifers (pine, fir, cedar, sequoia)	Thick bark	Protects inner tissue from heat	Resistant to burning, depends on fire intensity and severity
Alder, buckeye, madrone, cottonwood	Sprouting	Regrowth from roots	Stimulates sprouting
Oak	Sprouting	Regrowth from dormant buds on limbs	Stimulates sprouting
Recolonization Adaptations			
Species	*Adaptation*	*Function*	*Response to fire*
Conifers (pine, fir, cedar, sequoia)	Serotinous cones	Seeds are protected until nutrients released during a fire are available for use by seedlings	Cones open, seeds germinate in advantageous conditions with newly available nutrients from burned organic materials
Alder, cottonwood, willow	Water dispersed seeds and stems	In areas where nutrients become available, stems can sprout buds and roots; seeds can germinate quickly	Stimulates sprouting of stem or seeds
Deer Brush, scotch broom	Enhanced fruit and flower production	Increased productivity effort up to a few years after fire	Stimulates sprouting and germination
Manzanita	Seeds resistant to heat, buried in soils	Seeds require fire to germinate	Stimulates germination
Perennial and annual grasses	Deep root systems	Most fires are not hot enough to kill root systems	Stimulates resprouting

Native American Fire Regime

Many Native Americans tribes in California used fire extensively and with great skill as a habitat management tool to control vegetation patterns in forests, riparian corridors, chaparral, oak woodlands, grasslands, and meadows. Fires were important in maintaining a clear understory in forests, which allowed easier passage and greater visibility while hunting. Willows growing along riparian corridors were valued when long and straight so they could be used for baskets; these shoots were managed by fire, growing long and straight after fires. Chaparral was burned to provide room for native perennial bunchgrasses to grow. One bunchgrass species, deer grass, was highly valued in basket making. To weave one cooking basket, up to 4,000 deer grass flower stalks were needed. Oak woodlands were burned in order to control pests from infesting acorns that were so valuable as a food source. Grasslands were burned to enhance native grass growth and to enhance food for wildlife. Meadow edges were burned to keep conifers from encroaching into the wet meadow. With fire, Native Americans in California maintained plant food sources, increased forage for wildlife, recycled nutrients for enhanced plant growth, decreases plant competition.

It is conjectured that about 20% of California lands were heavily influenced by the Sierra Miwok fire management techniques, including Hetch Hetchy and Yosemite Valleys. Fires were set on nearly an annual basis to clear brush from the chaparral and maintain the open, park-like setting in the forests and meadows that early settlers spoke of. In the black oak-ponderosa pine ecotone of the lower montane – upper foothills forest, the Sierra Miwok, Western Mono, Mono Lake Paiute, and the Foothill Yokuts worked in concert using fire to manage for mushrooms, acorns, grasses, brush elimination, rapid branch growth, and pest control.

European Settlement Fire Regime (~1600-1850)

When Europeans entered California, the use of fire by Native Americans was evident from visible smoke plumes as stated in early explorer’s journals. Those who came spread human-borne diseases, invasive seeds, and subjugation of the Native Americans. The repercussions of European settlement proved to be devastating to the Native Americans and their way of life. Oral traditions dictated that institutional knowledge was passed on through story and applied experience, but as disease, starvation, and fighting decimated tribal populations, a tremendous loss of institutional knowledge and societal structure occurred. The effect of the loss of management on forest structure was immediate. Euro-American settlers failed to understand the importance of the Native Americans’ knowledge with devastating results.

By the late 1700s, Spanish missions established along coastal California brought more change, in the form of cattle. By 1860 there were close to one million each of beef cattle and sheep. Range quality was quickly declining because native bunchgrasses were not adapted to survive continuous grazing. Since sheep have an indiscriminate palate and will eat just about anything, sheep became the grazing livestock of choice. By 1880, California wildlands supported over 5 million sheep. As range quality from the valley to the subalpine forests declined, introduced annual grasses moved in where native perennials suffered from grazing. Invasive grasses sprouted, flowered, and dried earlier, grew in more continuous fields, recovered from fire faster than the native bunchgrasses, and quickly out competed the native plant species. The replacement of perennial grasses to annuals led to an increase in fire size and return interval, particularly in the floodplains and foothills where grasslands were prominent.

Fire Suppression as Policy (From ~1910 to present)

Modern ecological studies of fire return intervals have shown that fire regimes shape landscape heterogeneity in terms of vegetation types and age class patches. With fire suppression, landscapes have become more homogeneous, thus lowering the diversity of vegetative and animal species, particularly those that that need fire as a part of their life strategy. In the past 100 years, fire suppression policies have triggered a wave of forest competition and succession. Because fire has been suppressed, white fir and incense cedar have increased in number, growing tall and shading out ponderosa and California black oak seedlings that need open space and sunlight to establish. Understory and shrub species intolerant of shading, particularly montane manzanita (*Arcotostaphylos* spp.) and ceanothus species have also been suppressed. In their place shade-tolerant understory trees and shrubs such as mountain dogwood trees (*Cornus nuttallii*), hazelnut trees (*Corylus conruta*) and thimbleberry bushes (*Rubus parviflorus*) have become more common. This type of succession from one dominate forest type to another can be a natural process and is often driven by fire. The loss of fire has altered the forest in ways that cannot sustain forest structure in the long term.

Today, limited prescribed burns are being used to eliminate white fir and incense cedar from small areas in an attempt to restore the forest to more natural conditions, by helping ponderosa pines and California black oak to reestablish in open-canopy locations. Another unintended consequence of fire suppression policies is the spread of Annosus root rot (*Heterobasidion annosum*), which infects dense clusters of conifers. Its spores spread via wind to fresh wounds or tree stumps, and thus is particularly invasive in logging areas. Once infected, a tree dies quickly but is left standing as a snag. Beetles, such as the eyed elater (*Alaus melanops*), and fungi will move into the dead wood and begin the decomposition process all over again. Root rot may be anthropogenically (human induced) driven, which may not occur if a natural fire cycle was present and logging was not occurring.

Lodgepole pine may be more affected by fire than either white fir or red fir, which may lead to greater or lesser degrees of fire severity depending upon the dominant conifer species. Lodgepole pines proliferate at higher elevations, so while fires may be less frequent, they appear to be more severe. This may be one reason why Lodgepole pines have both serotinous and non-serotinous cones. Weather plays an important role in fires. Relative humidity (amount of water vapor in the air with respect to total amount of water vapor the air can hold at a certain temperature) of individual trees as well as overall humidity can be an indicator of how severely a fire may burn. The higher the relative humidity and the lower the temperature, the less severe the fire. Wind speed and direction also play large roles in fire spread and severity. A lower wind speed generally results in a slower spread time, but a higher scorch height, as fire that is not moving may burn longer in one area. Length of time between fires, rather than the number of times an area has burned in the past, is another indicator of fire severity. The longer an area has accumulated combustible fuels, the higher the burn severity when the area does burn.

Based on fires studied in Yosemite and Kings Canyon National Parks, fires may be self-limiting in red fir, white fir, and Jeffery pine forests if the interval between fires is 11-17 years. The ideal fire return interval is an important consideration for today's forest management. An additional result of fire suppression over the past 150 years is a greater proportion of shade tolerant trees such as red and white fir. In many areas, aspen stands have been shaded out by newly dominant stands of fir. Lodgepole pine forests, on the other hand, do not appear to have this same capability of a type of self-regulation in terms of fire severity. Recall that Lodgepole pines grow mostly in 'pure' stands, and may use serotiny as a fire adaptation, where fire triggers seed germination. Red and white fir and Jeffery pines, on the other hand, do not exhibit serotiny and may rely more heavily on thick bark and limbs high above the ground, such that surface fires don't reach the crowns. These adaptations work best when fire occurs often enough to keep the understory biomass low. Study results that indicate a threshold where lower fire severity may be possible holds great potential for proactive management decisions.

Today, forest managers more fully appreciate that suppression has dramatically increased fuel loads resulting in more severe fires, and have shifted the structure and species composition of the forest. Thus policies have shifted away from fire suppression in some cases. However, there is ever increasing development in the foothill region and increasingly, forest management policies remain in place to defend man-made structures at the urban-forest interface. Fires that threaten property are actively defended at an astronomical cost. Forest understory thinning projects and prescribed fires are used in the effort to lower fire threats and to maintain healthy forests without too much fire. However, these treatments are tremendously costly and the vast geographic area (more or less the entire Sierra Nevada) possessing dangerous levels of fuel accumulation far outstrips the amount of resources allocated for thinning projects. Logging is frequently permitted on thinning projects to offset the cost. The cost of these treatments is high, so logging is often permitted as a payment for thinning.

Ecological Trends

Grazing, mining, logging, agriculture, and fire suppression have dramatically altered biomes, ecotones, and forest stands within the Tuolumne River watershed. Grazing negatively affects watershed hydrology, stream morphology, soil integrity, and vegetative health. Mining destroyed streambeds and mountainsides, diverted water from streams, meadows, and riparian corridors, and sent massive amounts of gravels downstream through the fluvial corridors (chapter 10). With the gold rush, the demand for wood products increased exponentially (chapter 11). Ponderosa pine and sugar pine were favored species, but many other conifers were logged also. Sawmills sprang up next to each gold rush town, but the work continued to be difficult until the transcontinental railroad brought easily accessible steam power into the heart of the Sierra. Soon, steam donkeys were skidding huge conifers from the mountainsides, railroad spurs were built so that the logs could be moved to steam-powered sawmills, and the transcontinental railroad was shipping lumber to market. While some people initially came to California to search for gold, shopkeepers, farmers, and laborers followed with the intent of providing services for the miners. Floodplains and grasslands were developed for agricultural production, making the San Joaquin Valley farming the 'breadbasket' of America today. Alteration of land has progressed from building levees to keep floodwaters in the river channel, to draining wetlands, to building dams to control water flow and provide water for irrigation canals. Floodplain grasslands, oak woodlands, riparian corridors, and wetlands have disappeared as agricultural fields have taken over the landscape. And lastly, fire suppression throughout the watershed has led to dense thickets of woody materials just waiting for a lightning strike to start a fire. High biomass per unit area leads to higher severity fires, which ecosystems are not adapted to like they are to low and moderate intensity fires. Fire suppression requires a vast amount of time and money, yet fires in the Sierra are inevitable. Forest managers have become proactive in thinning and setting controlled fires to lower the risks of catastrophic fires, but current fuel load far exceed the amount of thinning performed on an annual basis and the risks of catastrophic fires in the Sierras continue to increase.

For at least the past 150 years, small, systematic trends in temperature (upward) and moisture (downward) have been driven by greenhouse gas emissions from industrialization. Organisms respond more broadly to seasonal shifts rather than to temperature and moisture directly. These broad yet subtle environmental shifts have resulted in modifications in timing events, range, and abundance of numerous species. Studies show that birds, fish, amphibians, insects, reptiles, and mammals have shifted breeding, hatching, hibernation, and feeding patterns in response to these systematic trends. Egg laying by amphibians, flowering time of non-woody plants, peak flight date of birds, bud-break of trees, and hibernation timing of marmots have all changed. Spring events have shifted 2-5 days earlier on average per decade for the past 20-100 years, while autumn events such as leaf fall, departure time of migrant species, and hibernation are delayed 0.5-1.5 days per decade. Species have migrated upward ~20 feet in elevation per decade due to temperature cues or by changes in food sources also brought about by temperature cues. Tree lines have shifted upwards in elevation, and sub-alpine shrubs, forbs, and grasses are migrating into the alpine zone. Broad ecosystem changes can be seen from a plant perspective as grasses, wildflowers, shrubs, and trees bud or flower a few days to a few weeks earlier in the year. Animals follow suit in order to take advantage of seasonal events tied into their life cycles.

As detailed throughout the chapter and summarized above, human-induced alterations have resulted in the introduction of invasive species, excess sedimentation, loss of old-growth mature forest, and high levels of biomass that create potentially dangerous fire conditions, as well as high levels of general ecosystem disruption across much of the watershed. Species have suffered individually due to dramatic landscape alterations, and overall population losses have resulted because of intensive land use changes. Plant and animal specialists often have more trouble adapting to dramatic changes in environmental conditions than generalist species. Ecotones and biomes are gradually shifting upwards, with animals following shelter, food, and forest structure necessary for their life strategies. When visiting the Tuolumne River watershed, it is evident that humans have had a colossal impact on forest processes. Nevertheless, conifers continue to dominate the landscape, riparian corridors and meadows still serve valuable ecosystem functions, many plant and animal species continue to thrive across the Sierra Nevada. Evolution and adaptation continue in the face of changing conditions. While the challenges facing the communities of the Tuolumne watershed are great, the inherent resiliency and adaptability of the system helps it weather the storm of human-induced changes, resource extraction, and climate change. Fire and water remain.

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CHAPTER 6: AQUATIC ECOLOGY OF THE TUOLUMNE RIVER

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INTRODUCTION

The climatic and hydrological setting of the Tuolumne River has shaped the evolution of living things within the system. Like most stream ecosystems, the Tuolumne contains a gradient of environmental conditions that influences the composition of the biological community. Changes in the physical conditions of the Tuolumne River, such as temperature, extent of riparian cover, exposure to the sun, gradient, magnitude and timing of flood events, depth of water, and width of channel all affect the biological community, and, subsequently, overall ecosystem structure and function. In addition, the overarching climatic influences discussed in chapter 4 provide another gradient of factors along the course of the river. This continuum of conditions and interactions shapes and defines the biological communities both within and adjacent to it. The subsidization of the river with organic matter, nutrients, sediment, and water from the surrounding uplands is reciprocated by the disproportionate importance of the riparian zone to the overall landscape and the biota living within it.

To demonstrate the different influences of factors such as elevation, stream gradient, and stream order on the biotic system, we split the Tuolumne River into three distinct sections: the headwater reach (from Lyle/Dana fork to Hetch Hetchy meadow), the middle reach (Hetch Hetchy meadow to La Grange), and the lower reach of the river (La Grange to its mouth) (Figure 6.1). Each section of river differs in terms of its physical organization and structure. This in turn shapes the types and life histories of the plants and animals living within that section of the river. Further, each reach of the Tuolumne is intrinsically linked to the ecological processes occurring upstream. Within this context, we discuss how aquatic food webs are structured and connected within the different reaches of the river and how the development of the river for hydropower, water delivery, as well as agriculture and urbanization in the lower watershed has altered the character and function of the aquatic system.

Introduction to Aquatic Food Webs

Food webs are the network of feeding relationships and interactions between different organisms. Food webs are inherently complex because they attempt to trace and categorize all of the relationships between the living things in an ecosystem. Simplistically, these relationships are often organized into hierarchical tiers. These tiers are referred to as “trophic levels.” However, in nature these levels are rarely distinct or static. Rather, organisms exhibit complex and changing relationships and interactions. The resulting schematic is a web-like jumble of arrows showing connections between the various members of the web (Figure 6.1).Like terrestrial food webs (see chapter 5), aquatic food webs are made up of interactions (transfer of energy) between primary producers (e.g., algae and plants) which convert solar energy into food, primary consumers (e.g., things that eat algae and plants), and of predators (secondary consumers) that eat the primary consumers. The web can be further expanded by predators that consume other predators which are called tertiary consumers. Another component of the food web are the detritivores which consume decaying organic matter from both plants and animals, a function that aids in decomposition and nutrient cycling. Because detritivores tend to be indiscriminant as to what trophic level they are consuming from (eating both plant and animal matter), and often being consumed by primary consumers, they significantly add to the complexity of energy pathways in the aquatic food web. The type of primary production in a given reach (i.e., allocthanous vs. autochthonous), along with other physical factors, defines the nature of the consumers it supports due to the physical adaptations such as mandible shape, body morphology, or behavioral habits that allow the process the different types of material. Benthic macroinvertebrates play the primary consumer role in stream food webs, bridging the gap between primary producers and secondary consumers/predators (i.e., amphibians and fish). Macroinvertebrates consist of several different types of animals including aquatic insects, gastropods (snails), annelids (earth worms, leeches), bivalves (clams), and crustaceans (crayfish). During their prolonged aquatic life stage, stream insects take a larval form before metamorphose into a terrestrial adult. Aquatic insects feed on primary producers, such as algae, and are consumed by fish, amphibians, and even other invertebrates (secondary consumers).

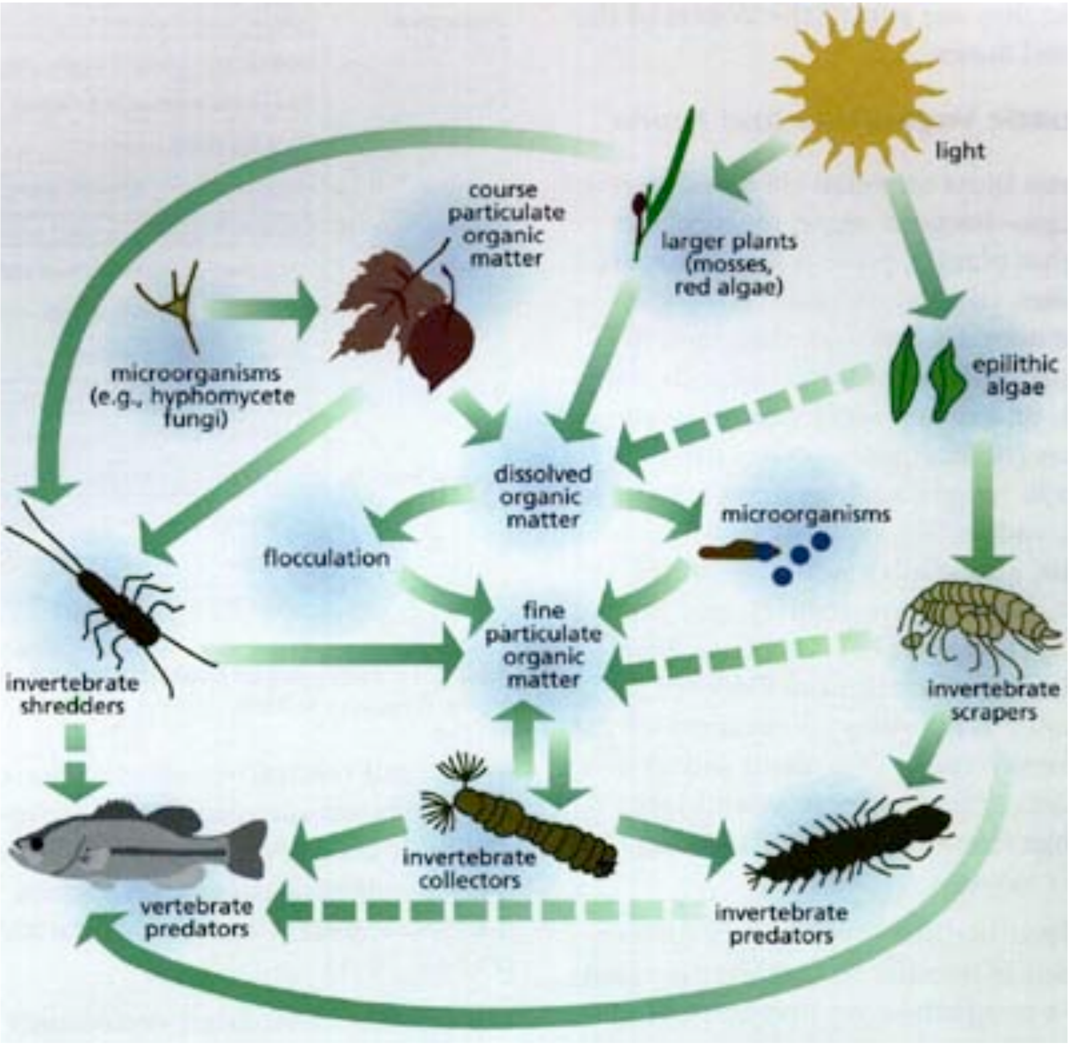

Figure 6.1 A simplified aquatic foodweb depicting the flow of energy from the sun as it moves through the different trophic levels. In this diagram the vertebrate predator (the fish) is the top predator, but there may be further additions if other predators consume predators (i.e. an otter eats the fish and is subsequently consumed by a mountain lion, which would link the terrestrial foodweb to the aquatic). This diagram also includes microorganisms such as fungi and microorganisms that process decaying organic matter that can be from any trophic level, thus perpetuating the energy flow in the system. Image from the USDA Forest Service www.fs.fed.us/.../images/eco-images/foodweb2.jpg

Allochthonous vs. Autochthonous Production

Carbon is the currency that all life forms are based on. Primary producers capture solar energy and carbon dioxide and convert them into starch and sugars, making them autotrophs or self-feeders. Non-photosynthesizing organisms (i.e., fungi and animals, called heterotrophs) must derive their energy from the primary producers or something that has consumed a primary producer. The origin of these carbon sources can be from either autochthonous or allochthonous production. Autochthonous production occurs when stream resources are derived from within the stream (i.e. algae), whereas allochthonous production refers to those resources derived externally from the stream (i.e. terrestrial leaf litter, woody materials).

The specific type of production in a given ecosystem largely depends on factors such as water temperature and depth, light penetration, nutrient availability, surrounding terrestrial conditions and variability of the flow regime. Generally, in the higher-gradient headwater portions of a stream, most carbon is allochthonous, originating from leaves falling into the stream. Algae production is low due to cold temperatures, scouring flows from high gradients, and low availability of nutrients typical of headwater streams. Lower in the system, enough nutrients have accumulated and the water has warmed sufficiently that production becomes predominantly autochthonous, consisting more of algae and aquatic vascular plants known collectively as macrophytes. While we see an overall gradient of change in the types of carbon production from the headwaters (more allochthonous) to the Central Valley floor (more autochthonous), both types are present throughout. For example there is algae production occurring in many of the reaches of Tuolumne Meadows and the historical allochthonous inputs of the extensive valley floor riparian forests would have been considerable.

THE REACHES OF THE TUOLUMNE RIVER

The historical conditions of the Tuolumne watershed are not precisely known. In the early days of the gold rush, major anthropogenic impacts took place on nearly every tributary and reach of the watershed in the gold country (the middle and lower reaches). Water diversions, dams, panning, sluicing, and digging up the streambed in search of gold were certainly a massive disruption to the historical condition and function of the local streams. While the impacts decreased further upstream in the watershed, by the 1860s, there was considerable grazing activity in the headwaters of the Tuolumne River. Because of the dearth of information on the pre-settlement condition, we can only make an educated guess about the historical conditions of each of the three reaches based on the notes of settlers about their surroundings and the condition of more remote places in the Sierra that have not experienced as much disturbance from human activities as the Tuolumne to infer the conditions of the historical Tuolumne. The later hydropower development boom created abrupt separations between the river's reaches which formerly functioned as a continuous unit. This separation drastically altered the Tuolumne's hydrograph (see chapter 4) which caused significant changes in the aquatic communities of the Tuolumne River resulting from the construction of dams.

Headwaters

The headwater reach of the Tuolumne River is partially characterized by its steep gradient, stable channel morphology, and coldwater habitat. In the highest reaches of the headwaters, small trickling creeks begin on the rocky, exposed sides of the surrounding peaks, with tiny alpine meadows often the only productive areas in an otherwise austere setting. These meadows can occur in small flat depressions where sediment has gathered, or on steeper slopes where seeps and springs coming through the hillslope system ooze to the surface and allow typical wetland plants such as sedges and rushes to take hold. Much of this part of the watershed is locked under snow and ice for six to eight months out of the year and large snowfields and remnant glaciers on Mt. Lyell and the surrounding peaks feed the river in the summer months. It is a difficult landscape for any organism to make a living in. For the vast majority of the year, water is locked up as ice, as if the plants existed in a frozen desert. All production ceases during this time and the plants become dormant to cope. The majority of the plants in this area are tough perennials that can reproduce via creeping root rhizomes and clones. There is then an abrupt shift in conditions when the spring runoff begins and water is bountiful to the point of excess. During this time, the tiny alpine meadows are sodden and any plant living there must be able to handle having its roots fully inundated and be able to cope with the difficulties of a low oxygen environment (plants, like animals, need to take in oxygen through their roots and special adaptations are required for living in wet environments). The animals that make their living in this zone are also hardy and adapted to a harsh and changeable environment. They must be able to withstand many months frozen and dormant and then cope with the period of high run off and inundation, followed by a decline in flows and significant drying in the small meadows and tarns that dot the alpine landscape. The brief summer months are the time of productivity and all food production, reproduction, and growth must be accomplished during this brief time. By late summer, water is again hard to come by and plants return to dormancy to wait out the long winter under the ice. Animals too must either become dormant or migrate downslope to more hospitable environments. Historically, these upper reaches were fishless and the top aquatic predators were amphibians such as the mountain yellow legged frog (*Rana muscosa*), the Yosemite toad (*Bufo canorus*), and the Mt. Lyell salamander (*Hydromantes platycephalus*) (see chapter 8 for more on these species).

As it continues down slope, the river is characterized by dense riparian vegetation of willows and conifers punctuated by narrow rocky gorges. The Lyell and Dana forks of the river confluence near Tuolumne meadows, flowing through areas of exposed bedrock, cascades, deep pools, and rushing rapids. The open expanses of subalpine meadows in Tuolumne Meadows, unusual for headwater reaches, represent a discontinuity in the otherwise steep and narrow upper Tuolumne River. Historically, there would have been dense riparian shrubs lining the banks of the river as it meandered through the meadows, though today, much of the river and its banks are open and somewhat eroded, a relic of the heavy grazing that took place in this area before it became a national park in the late 19th century. Historically, during the high spring runoff, the river overtopped its banks and spread out onto the floodplain of the meadow. This, in combination with many pools of standing water left from melting snow, provided an ephemeral but vital habitat. The warm standing water was colonized by algae, zooplankton, and aquatic insects. Standing puddles in meadows are the essential breeding habitat for Yosemite toads, whose tadpoles must rear for approximately six weeks (food and temperature dependent) in these risky ephemeral habitats before metamorphosing into tiny adult toads. The hydrologic function of this habitat is one of a seasonal wetland, similar to the vernal pools of the Central Valley floor.

Little sun penetrates the canopied forests and narrow gorges of the upper watershed. This, in concert with low nutrient availability naturally meant that the bulk of the carbon in this area came from terrestrial sources (e.g., leaf litter, pine needles, woody debris, and senescent grasses). Algae and aquatic plants (macrophytes), were essentially limited in their overall contribution to the food web in this reach, and were most abundant in the meandering reaches of the meadows and in portions of tiny headwater streams trickling into the Lyell and Dana Forks of the river. The large size and indigestibly woody composition of the organic matter found in this reach favored shredding invertebrates, which, with the help of microbes as decomposers, likely represented the dominant functional feeding group in the Tuolumne River's headwater section (see Box 6.1 on functional feeding groups).

Box 6.1

Functional Feeding Groups and body morphology

Aquatic insects can be separated into several functional feeding groups depending on how they acquire resources for growth and survival. Functional feeding groups are generally categorized as shredders, collector filterers and gathers, scrapers, and predators. Shredding insects generally dominate in areas that have predominantly allochthonous production (e.g. the upper watershed). The relatively large size of the materials they consume such as terrestrial leaf input and woody debris is categorized as coarse particulate organic matter (known as CPOM). Eating CPOM requires morphological adaptations such as large mandibles. Since the reaches that typically have greater allochthonous inputs than autochthonous production are also usually higher in gradient, shredders are often adapted to cope with fast water environments possessing features such as compressed bodies, hooks on feet or abdomens, or the tendency to build fixed retreats in the rocky stream bottom. As shredders process CPOM, it becomes transported downstream as fine particulate organic matter (FPOM). In turn, FPOM becomes a vital resource for several downstream insects that collect, gather, and filter this material.

Collector/filterers and gatherers tend to dominate in areas that are downstream of areas of major allochthonous inputs and the shredders that process it. They generally dominate in areas that are lower in gradient and have finer substrate. Their morphological and behavioral adaptations include building elaborate nets or possessing filtering hairs on the forelegs to filter FPOM out of the water column. Scrapers have evolved specialized mouthparts to remove algae directly from rocks. They are more numerous in reaches with increased autochthonous production, thus in general increase lower in the watershed, but they are also prevalent in reaches with lots of solar radiation, low velocities, and shallower water, all of which support the growth of algae. Predatory invertebrates occur within all of the reaches of the river, though the species will change according to habitat, location in the watershed, and water quality.

Shredding insects, such as stoneflies from the families Neumoridae (forestflies) and Pteronarcidae (salmonflies), require cold oxygenated water and coarse particulate organic matter (CPOM) as a carbon resource, and thus thrive in the headwaters of the Tuolumne River. Similarly, shredding caddisflies, including the lepidostomatids and limnephilids, also did well in these habitats, and were particularly common in small oxbows and potholes in the meadow habitats). In shredding the coarse and fibrous allochthonous materials of the upper reaches, the tattered bits of organic materials were released for use by the other functional feeding groups. Collector/filterers and scrapers were certainly present to take advantage of this, but their distribution and abundance were limited. Predators such as perlid stoneflies and megaloptera stalked other aquatic insects and fast moving upper reaches, while in the slower moving reaches and backwaters were dominated by odonates (dragon and damselflies), dyticid beetle larvae (larval predacious diving beetles) and hemipterans (true bugs) that made their living preying on other insects and tadpoles. Tadpole hunting snakes such as terrestrial and aquatic garter snakes (*Thamnophis sirtalis* and *T. couchii*) were common predators once again connecting the aquatic food web with the terrestrial.

The challenging conditions for survival in the aquatic environment of the upper headwaters meant that these reaches naturally contained less species diversity than more hospitable reaches downstream. The plants and animals able to persist in the headwaters were particularly well adapted to survive the long freeze of winter punctuated by an immense burst of productivity during the brief summers. Competition for scarce nutrients in the fresh snowmelt waters drove many interactions and the organisms best adapted to withstanding the difficult abiotic conditions as well as efficiently using the available resources dominated.

Figure 5.3 Caddis Fly larva (L) and cases (R) from the family Limnephilidae. Photo Adam Clause

Today, the upper Tuolumne remains the least altered of the three reaches. Carbon inputs are still predominantly terrestrial in origin, shredders dominate the invertebrate community, and the strong seasonal influences of ice and snowmelt shape the overall structure of the aquatic community. However, there are several major differences in the current aquatic ecosystem. Heavy grazing in the late 19th century has left its mark on the meadows of the Tuolumne headwaters. Many of the stream banks still bear erosion scars from that time, and the river is visibly incised into its channel in many locations resulting in a lowered water table throughout the meadow. This has impacted the critical floodplain habitats and processes of the meadows. In particular, stream bank erosion and subsequent incision result in shorter, less frequent occurrences of standing water on the meadow floodplain. This can have profound impacts on animals such as the Yosemite toad, whose tadpoles race against time to develop before the ephemeral breeding habitats dry up. It is not uncommon to come upon dried up tarns or puddles in the Tuolumne Meadows area with a slick of dried up tadpoles on the bottom. Additionally, development in this area of the park for tourism and recreation has added a small but significant amount of nutrients into the river and boosted autochthonous production of algae and phytoplankton considerably. By far the most significant alteration of the upper Tuolumne aquatic food web is the ubiquitous stocking of fish in historically fishless waters. This has profoundly altered the interactions, pathways of energy through the community, and the community structure itself. In large part, the decline of the mountain yellow-legged frog throughout its range in the Sierra Nevada is attributed to an inability to cope with novel predators in the ecosystem (see chapter 8). The installation of the O'Shaughnessy Dam at the bottom of the headwater reach represents a major change to the hydrologic patterns that governed the reach, creating a large lake where a large complex of wet meadows once existed. The changes of flow, sediment distribution, temperature, and habitat type have all been considerable. Overall, the headwaters remain the least impacted by human endeavor of the three reaches we examine, but there have most certainly been some profound impacts the function and organization of the aquatic system over the past century.

The Foothills

Downstream of Hetch Hetchy Valley, the Tuolumne River enters a transition zone from a high gradient, predominantly conifer-forest canopy system to a noticeably wider stream corridor of lower gradient. The character of the forest has changed to a complex mix of conifers, oaks, grassland, and chaparral—a heterogeneous landscape shaped by small differences in moisture, aspect, light, and soil types. Fire played a major role in the structure of the forest and frequent low intensity burns were a major source of nutrients to the river. The current fire regime has become rarer but more catastrophic due to a century of fire suppression (see chapter 5) and big fires can result in major landslides, huge nutrient and sediment pulses, and slow regeneration of the forest, all of which impact the processes taking place in the river. The more open nature of the river canyon (albeit still confined by steep foothills) and the nutrients moving downstream from the headwaters provide the right conditions (high nutrients, exposure to the sun) made this reach far more productive in terms of algae and phytoplankton (autochthonous production). The river makes its way from Hetch Hetchy Valley and winds its way down the canyon. Steep, fast-moving rapids pour over boulders, frequently at the mouth of tributary streams, but long pools and runs are also plentiful, providing many types of habitat such as eddies behind boulders or downed wood, shallow backwaters where juvenile fish rear, deep pools with plenty of cover, and shallow rock gardens. Algae and periphyton anchor themselves on rocks or emergent plants, particularly in the late summer months when the river is low and warm. Considerable terrestrial inputs continue from the riparian edge and upslope, making it highly productive and supporting a diverse aquatic community. Numerous species of fishes historically used this stretch of the river, the presumed barrier to migration being upstream at Preston Falls (see chapter 7). This section of river historically supported a robust population of spawning Chinook salmon and Steelhead trout, as well as a diverse assortment of native minnows and suckers. Marine-derived nutrients from decaying salmon carcasses played an integral role in bringing nutrients to the foothill reach subsidizing the riparian forest (one can find the signature of marine-derived nutrients in older trees using stable isotope analysis). Carcass material supported all levels of productivity, including the riparian zone and nearby terrestrial consumers through the direct consumption, drifting to adjacent habitats, or as substrate for algal colonization. This section of river was largely defined by the heterogeneity of its resources, habitats, and productivity, resulting in a highly diverse aquatic community.

Aquatic insects such as glossosomatid caddisflies and heptageniid mayflies exploited algae crops by scraping and consuming directly from substrate. Several dipterans (true flies), such as simuliid black flies, attached themselves to macrophytes or sediments in order to filter passing FPOM. Others, such as emphemerellid mayflies, found refuge from swift currents within macrophyte beds or behind large gravels, where they filtered and gathered fine particles from the water column. A wide range of habitats and abiotic influences (water temperature, depth, substrate size) and diverse assortment of macroinvertebrates further suggests that the historical fish assemblage of this section of river was similarly robust. The foothill yellow-legged frog (*Rana boylii*) was a common amphibian in the foothill reaches and was well adapted to the hydrologic regime defined by the snowpack above, fine tuning its breeding cycles to the spring runoff. The native fish and amphibian communities that were historically present in this reach have largely been replaced by stocked sport fish such as brown and rainbow trout (*Salmo trutta* and *Oncorhynchus mykiss*) as well as more warm water fishes such as small-mouth bass and catfish that have made their way up the river from Lake Don Pedro below (see Box 6.2 on reservoirs).

The biggest change that has affected the foothill reach is the presence of O'Shaughnessy, Cherry, and Eleanor Dams upstream and the terminus of the foothill reach at Lake Don Pedro downstream. Although channel stability has remained largely intact, a decrease in the residence time of water and increased bed mobility associated with dam releases has made it more difficult for algae and other primary producers to establish. Daily fluctuations in flow stemming from power production and recreation flows represent a novel hydrograph that is difficult for many of the river's inhabitants. The ramping rate is often very rapid—the river can go from a trickle to several thousand cfs in a matter of hours. Much of the prime edge habitat fluctuates between drying out and inundation on a daily basis, a process that is highly detrimental to invertebrate populations, amphibian eggs, algal production, and juvenile fish. Stranding is a common problem throughout this reach as is its antithesis, scouring flows that flush the eggs and larvae of juvenile insects, amphibians, and fishes downstream. The rapid fluctuations also impact primary production by scouring already stressed plants, periphyton, and algae, reducing their capacity to grow and support the community. In addition, the impoundments on the Tuolumne River and its tributaries (including Hetch Hetchy, Cherry, Eleanor, and Don Pedro Reservoirs) have effectively severed the river continuum by interrupting transport of nutrients and organic matter downstream. Similarly, sediments originating in the headwaters (critical components for macroinvertebrate habitat and fish spawning) cannot bypass the reservoirs, resulting in the loss of beaches and backwater habitats from daily fluctuating flows. For this reason, organic material production (CPOM and FPOM) and sediments from large unregulated tributaries, such as the Clavey River, have become increasingly important in sustaining the current community. These unregulated tributaries also provide a refuge for the aquatic communities in the watershed. They represent a place where the hydrologic and biotic processes that were historically present can continue. These areas are particularly important conservation targets and will become more so in the future as climate change further alters the structure and function of the watershed.

Box 6.2
Reservoirs

Reservoirs are similar to streams in that they form a continuum of changing habitats, primary producers, and animals from the inflowing streams to the dam. However, reservoirs usually have much slower currents and are deeper than the rivers they have flooded. As a result, reservoir water often becomes stratified during spring and summer, with a warm shallow layer floating on top of a deep cold layer. These habitats are shaped in part by climate and whether the dam is built high up in the watershed or close to the river's mouth. Coupled with the inevitable introduction of exotic fishes, reservoirs contain biological communities that are much different than those found in rivers.

The changes in water velocity and sediment size seen in rivers are often all present but compressed within the reservoir. If the dam is located in the middle or upper reach of a river, the streams that enter the reservoir often have steep gradients. As a result, the inlets of a reservoir frequently have relatively fast currents where only coarse-grained sediment such as pebbles can deposit. As the inlet streams' water moves further into the main body of the reservoir, it rapidly loses speed and all but the smallest sediment falls out of suspension and settles onto the reservoir floor. Consequently, the size of sediment and the velocity of water both decline from the inlet streams to the dam.

The makeup of the primary producer community follows the changes in sediment and water velocity. Just as coarse material settles out where inlet streams enter the reservoir, so too does leaf litter and waterlogged wood. Additionally, inlet areas are usually shallower than the main body of a reservoir and thus have a greater bottom area that receives light; as a result, algae growing on sediment and organic material are most common at the mouths of feeder streams. Consequently, the primary consumer community near inlets tends to be dominated by bottom-dwelling aquatic insects (e. g., mayfly nymphs, caddis larvae). However, further into the reservoir the bottom is generally too deep for the sun's light to reach, and the cold depths are relatively unproductive. Thus, phytoplankton (free floating algae) dominates the primary producer community of reservoir main bodies. In turn, these algae are fed on by zooplankton (small free floating invertebrate predators), the dominant primary consumers of the reservoir's main body. Hence, just as water velocity and sediment sizes change from the inlet streams to the dam, so too do the biotic communities, with bottom-dwelling algae and insects giving way to floating algae and zooplankton.

The presence of Lake Don Pedro at the base of the foothill reach represents perhaps the most serious discontinuity separating the physical and biological processes of lower watershed from the middle and upper watershed. Though the middle and lower reaches have effectively been separated from one another since La Grange dam was constructed (the first crude versions were built as early as the 1850s and fish migration was almost certainly blocked by the 1860s), Don Pedro is a significant impediment to the historic continuum of sediments, nutrients, and flow. Further, the water quality in Don Pedro declines significantly as compared to the high elevation reservoirs above. The numerous impoundments on the river each represent a break in the continuity of processes and production as well as control the hydrologic processes below it. In this way, each reach between dams is effectively disconnected from both the reaches above and below representing autonomous sections of river controlled by the upstream impoundment. This loss of continuity has profoundly altered the organization and community structure of the food webs of the middle and lower reaches.

The Valley

The downstream section of the Tuolumne River, from below La Grange to its confluence with the San Joaquin River, was characterized by a sudden emergence of the river from the foothills into the broad flat plain of the Central Valley. At the transition, the gradient drops rapidly and the river became wide and slow. The river meandered back and forth across the floodplain bounded only by the occasional bluff, a remnant of the great inland sea that covered the Central Valley in millennia past. The water retained the fine sediments it held in suspension on the long journey out of the mountains, and only here did the velocity of the river slow enough to allow the sediment to begin to settle out. The turbidity of the water inhibited sunlight penetration and thus autochthonous production, making this reach much more dependent on upstream organic matter traveling down and once again, terrestrial inputs of carbon. The extensive riparian complexes of cottonwoods, willow and valley oaks provided a huge input of leaf litter and wood, which would rapidly settle to the bottom in a thick mat of organic matter to be consumed mostly by microbes tolerant of the anoxic conditions in the many attendant backwaters, sloughs, and marshes. The lack of hard bank material on the alluvial plain allowed the river to meander freely, leaving a network of remnant channels, oxbow lakes, and braids that supported a unique aquatic community. The defining character of this reach was seasonal flooding. The broad floodplain of the valley floor allowed the river to spread out and release the energy and power it gained while creating a much larger aquatic complex than just the river bed. Winter storms and spring snowmelt runoff fed this large seasonal wetland, after which the river was reduced to a warm trickle in the hot summer months.

The community adapted to this type of environment favored those able to cope with a constantly changing environment that fluctuated between the sodden world of the spring flood and the hot, anoxic waters of the Central Valley summer. The macroinvertebrate community was dominated by those able to directly filter material from the water column, did not require cold or highly oxygenated water, and could tolerate turbidity. Aquatic insect communities were typically dominated by several dipteran families, such as non-biting midges (Chironomidae), biting midges (Ceratopogonidae), blackflies (Simuliidae), and mosquitoes (Culicidae). Also present in this reach were many non-insect invertebrates tolerant of sediment and low dissolved oxygen such as snails, annelid worms, and leeches. These invertebrates were uniquely adapted to process fine organic matter drifting down from the upper reaches. The aquatic communities in this reach were highly resilient to disturbance events such as periodic flooding. Additionally, these macroinvertebrates exhibited rapid generation times, allowing them to swiftly reproduce and colonize new habitats post flood disturbance or make use of ephemeral habitats. Other functional feeding groups, such as shredders and scrapers, existed as well, but were probably subordinate to the filterer/gatherer groups because of the low oxygen environment. The floodplains adjacent to the river would be repeatedly inundated over the course of the wet season. Much like the meadows of the upper reaches, this transient habitat was incredibly productive, filled with phytoplankton blooms, hoards of zooplankton, and aquatic insects. Floodplains played a crucial role in the life history strategies of many native fishes such as chinook salmon and steelhead, as well as Sacramento splittail and Sacramento perch all of which took advantage of the incredible productivity of the temporary floodplain habitat. On the floodplain, juvenile fishes grew at an astonishing rate gaining the strength and size to better survive the hazardous outmigration to the ocean. When the floodwaters receded, some of the carbon from the floodplain returned to the river with it, while fresh sediments and nutrients were deposited on the floodplain creating the famously productive soils of the Central Valley.

Human development in the lower reaches followed rapidly on the heels of gold discovery in the foothills. Major changes to the river corridor occurred almost immediately. The explosion of mining activities upstream put vast amounts of silt and sediments into the river, burying prime habitat for invertebrates, fish spawning, and inundated the area with scouring flows of mud and silt. At the same time, the demands of the mining communities for food led to a boom in agriculture (see chapter 11) which precipitated major changes in the aquatic ecosystem. Almost immediately, farmers began clearing the riparian forests, draining wetlands, diverting water, and building levees to contain the powerful seasonal floods that threatened crops and towns. Today, the valley reach of the Tuolumne River is drastically different than it was 150 years ago. Recent estimates indicate that upwards of 95% of the riparian forest has been lost to urbanization, levee building, and conversion to crop lands. The disconnection of the river with the floodplain and the discontinuities created by the upstream dams have resulted in greatly diminished capacity to support aquatic life.

One of the most problematical changes has been the dam at La Grange. As mentioned above in the foothill reach, La Grange Dam effectively stopped all migration of fishes, most likely beginning in the early 1860s. This effectively extirpated the spring run Chinook salmon which presumably migrated all the way up to the barrier at Preston Falls in the foothill reach to over summer before spawning in the fall. Fall run Chinook salmon, which could spawn in the lower watershed due to their life history strategy of entering the river in the fall with the first rains, were still able to eke out a living in the valley reaches below La Grange. However, the emplacement of the dam did not just stop fish migration. The valley reach was completely cut off from gravel and sediments from the upper watershed. However, high flows in the winter time, while regulated, were often still large enough to mobilize gravel in the stream bed below the dam resulting in a loss of the substrate needed for successful spawning in salmonids. This negatively impacted invertebrate habitat as well and fundamentally changed the shape and bed structure of the river. Overall productivity in the valley reach plummeted with the loss of the riparian forest and the disconnection to the floodplain. An incredibly complex and diverse system was irretrievably reduced.

The Tuolumne River has become a working river. Numerous dams for water storage and hydropower confine the river, while the vast majority of its flows are spoken for either for urban or agricultural consumption. Aggregate mining pits along the river in the valley reach have further altered channel morphology, sediment distribution, and host a bevy of predatory non-native fishes and noxious aquatic weeds. Introductions and invasions by voracious predatory centrarchids (largemouth bass, sunfish, and crappie) are increasingly detrimental to historical food web dynamics because they prey on native fish with cascading effects to other trophic levels. Agricultural fields and the mushrooming urban development typical of the Central Valley impinge upon the river. While these many impacts have proven detrimental to the community structure and function of the lower river, the problems of the river have not gone unrecognized. As discussed in chapter 4, a serious effort aimed at restoring a number of hydrologic and geomorphological processes in the lower Tuolumne is currently under way, with the main focus being on improving spawning habitat for fall run Chinook salmon. While it is evident that the human uses of the river will largely continue as they have, there is a concentrated effort to make the remaining habitat function as best it can to protect the remaining biotic integrity.

Significant changes to the habitat structure of the Tuolumne River have substantially altered its biotic community. These changes, along with introductions of non-native trout and invasions of several warm water fish, have restructured the Tuolumne's aquatic food web from top to bottom. Restoring the system's natural biotic processes and food web dynamics to a pre-European settlement state are unrealistic. However, there are a number of management actions and strategies that could protect and improve the condition of the river. First, continued protection of the headwaters areas in Yosemite National Park and restoration of historical and current impacts, in particular in Tuolumne Meadows, from grazing, recreation, and roads will aid in improving water quality, water storage, and flood impacts. In the foothill reach, large unregulated tributaries will play an increasingly important role in reestablishing the river continuum by providing sediment necessary for the lifecycles of several macroinvertebrates and fish and through the direct transport of resources to mainstem channels. Similarly, tributaries provide habitat heterogeneity, thermal heterogeneity, and refuge from hydropower generating flows—all of which contribute to a more biologically diverse food web. Tributaries provide a link to the Tuolumne's past by providing habitat variability and encouraging the establishment and colonization of native species. In addition, it is vital that the hydrological processes that historically occurred be reinstated as much as possible by releasing flows from the dams in such a way that they mimic the natural hydrograph below Hetch Hetchy, Cherry, Eleanor, New Don Pedro, and La Grange Reservoirs. This includes providing flows that represent seasonal floods in the appropriate season and trying to mask the effects of daily ramping for hydropower production to reduce the stress to the aquatic community. In the valley reach, it will be of particular importance to reconnect the Tuolumne River with its historical floodplain habitat to allow the historical processes that shaped the aquatic community to persist, albeit in a diminished form. Also required is an effective invasive and introduced species management plan for the restoration of the native fish assemblage and overall ecological recovery. In conclusion, the aquatic communities of the Tuolumne River are dependent on the physical processes that have become so altered by human endeavor over the past 150 years. While a total restoration is not feasible, we can manage the river in such a way as to maximize its productivity both for human uses and the function of the aquatic community.

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Chapter 7: Fishes of the Tuolumne River Watershed

MANDI FINGER AND SABRA PURDY

INTRODUCTION

California possesses a diverse and unique fish assemblage. However, the current state of California's fish assemblage is profoundly altered from its historical condition. These changes have occurred due to a number of factors, but the most obvious include dams and diversions, changes in habitat quality, and the introduction of non-native fishes stocked for sport. While there have been major changes, most of California's native (and often endemic) species still persist; a tribute to their inherent adaptability and hardiness. However, the native fishes of California face a tough battle; they must contend with shrinking habitats, over-allocated water, competition and predation from non-native species, and human encroachment in nearly every habitat. It is unlikely that the remarkable native fish fauna of California is fully appreciated.

The Tuolumne River watershed ranges from the alpine peaks of the Sierra Divide to its confluence with the San Joaquin River. We have divided the Tuolumne River into three sections, the upper watershed (above Hetch Hetchy), the middle watershed (between La Grange and Hetch Hetchy Reservoirs), and the lower watershed (below La Grange to the San Joaquin confluence). Because of the rapid elevation gain on the west side of the Sierras, native fish historically inhabited only the lower two reaches. This chapter describes the historical assemblages and unique characteristics of California's native fishes. It also contrasts the assemblages' historical context, before European arrival, with the changes that have occurred to fish fauna post-European settlement.

Fishes and fish assemblages of the Central Valley in California

The Central Valley of California is a center of speciation for fishes. It is geographically isolated from the north, east, and south by mountain ranges and the sole outlet is through the Sacramento/San Joaquin Delta into San Francisco Bay. This creates an area of unique geomorphology, climate, and hydrology that has shaped the adaptation of the fishes present. There are 17 endemic fish species within the Sacramento-San Joaquin watersheds, and many more distinct subspecies as well as runs of anadromous fishes (those that migrate into fresh water to spawn). The Tuolumne River lies in the Central Valley sub-province, one of seven zoogeographic sub-provinces that divide the Sacramento-San Joaquin Province in California. Each of these provinces is sufficiently isolated to possess a distinct fish fauna.

The Mediterranean climate and unique geology of California, have led to native fishes in California having certain characteristics in common. The various fish assemblages of the Tuolumne River demonstrate these characteristics (Box 7.1).

Box 7.1
Common Characteristics of Central Valley Fishes

- *Long lives (often >10 years), large body sizes and high fecundity (ability to reproduce). This allows adults to "wait out" periods of poor environmental conditions, such as drought or floods.*
- *Assemblages in middle and upper reaches of rivers include few species, but high morphological diversity and niche portioning between species to take advantage of different habitats and food sources.*
- *Many species are opportunistic and will utilize ephemeral habitats as they become available (i.e. floodplains for rearing or predator avoidance).*
- *Most species do not care for their young, instead they produce as many offspring as possible.*
- *Juveniles often use different habitats and foods than adults in order to avoid predation and competition.*
- *Fishes in CA are adapted to environmental extremes, either avoiding or tolerating poor conditions. Characteristics range from anadromy, to high tolerance of variable temperatures, salinity, and levels of dissolved oxygen.*
- *Many California fishes are able to colonize new habitats quickly through dispersal mechanisms such as a high degree of "straying", or wandering away from natal habitats.*

Before damming and other human impacts, the waters in the Tuolumne River above Preston falls (50 miles upstream of New Don Pedro dam) were fishless. Below the falls, there were four overlapping fish assemblages as described by Moyle (2002), (Figure 7.1). They included the 1) rainbow trout assemblage, 2) California roach assemblage, 3) pikeminnow-hardhead-sucker assemblage, and in the lowlands, deep-bodied fish assemblage. Nearly all of the fishes could use the lower reaches, at least at certain times of the year, but as gradients increased and water temperatures decreased in the foothills, only the strongest swimmers and cold-water loving individuals populated the river. Therefore the lower elevations possess greater species and habitat diversity leading to overlapping assemblages, while the upper reaches are dominated by just a few species. There was considerable blending of assemblages throughout the lower reach of the Tuolumne and species coexisted by utilizing different microhabitats and migrating seasonally to take advantage of ephemeral habitats such as floodplains and small streams. Some species such as rainbow trout or California roach may be dominant in one habitat, but only be a minor part of another. In addition, some species, though more common in some assemblages might still be present in all of the assemblages, such as Sacramento pikeminnow and Sacramento sucker, which can be found in nearly all of the accessible habitats of the Tuolumne River.

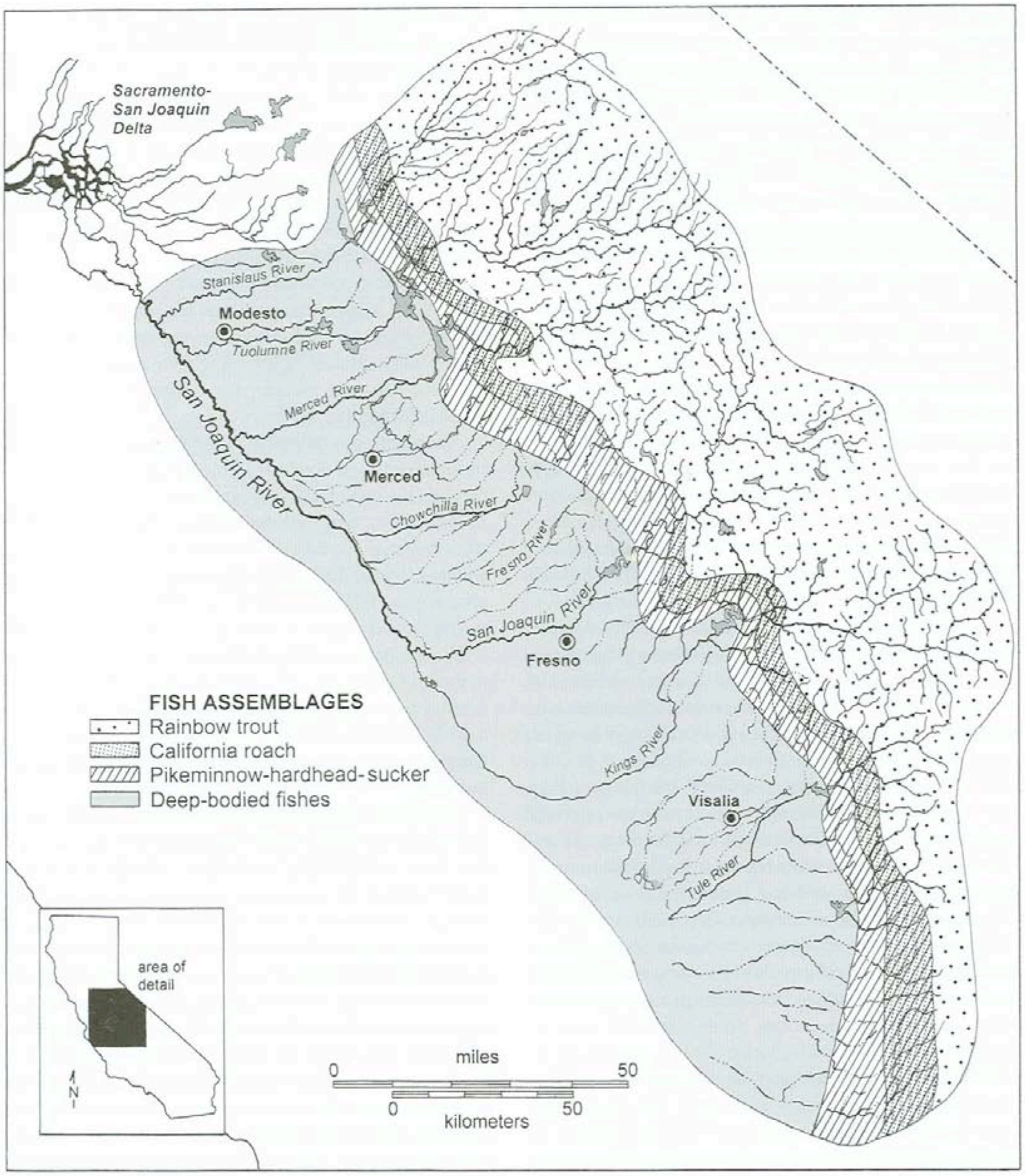

Figure 7.1 Fish assemblages of the San Joaquin River drainage. The deep-bodied fishes assemblage is included in the lower reaches of the Stanislaus, Tuolumne, and Merced Rivers due to alterations of habitat including in-channel gravel pits, dredging pits, and other artificial habitats that contain alien fishes. Each of these rivers has upstream impoundments and have been increasingly managed to benefit the spawning, rearing, and migration needs of native fishes. From Moyle 2002.

Rainbow trout assemblage

Historically, the rainbow trout assemblage occurred in the middle reach of the Tuolumne River, from below Preston Falls to roughly New Don Pedro dam. Rainbow trout, (*Oncorhynchus mykiss*), the fish that characterized this assemblage were found in areas with cold, clear water with high stream gradients. The waters were permanent, with boulders, cobbles and bedrock as sediment, some pools and plenty of riffles. There were not many aquatic plants, but undercut banks and plentiful riparian vegetation provided shade and cover from predators. Rainbow trout were dominant here, but riffle sculpin (*Cottus gulosus*), and Sacramento sucker (*Catostomus occidentalis*) were also permanent residents in the upper-middle reach of the Tuolumne.

The Rainbow trout is a highly successful species of *salmonid*, (*see special box on salmonids*) the family of fishes that includes trout, salmon and whitefishes. Rainbow trout exhibit a wide variety of morphology and life history strategies, and are among the most physiological tolerant of salmonids. In the Tuolumne River, as with elsewhere in California, they were derived from coastal rainbow trout, which migrated from the ocean and gave rise to resident forms in the upper reach of the river. Typically, most fish spend their lives in a short stretch of a stream, mature in their second or third year, and spawn 1-3 times, usually in the spring (February-June). When spawning, females dig a redd, or nest, with their tail in gravel that has good oxygen flow. When fry hatch 2-3 weeks later, they spend time in the shallow water near the shore, gradually moving into deeper water as they grow. Rainbow trout mostly eat aquatic and terrestrial insects that drift in the water column, but are opportunistic and may consume frogs and fish. Adults are territorial and aggressive, but coexist with other fishes as the dominant predator.

In the rainbow trout assemblage, both anadromous and non-anadromous rainbow trout juveniles occupied cold, fast water at higher elevations where riffles predominated. In addition, spring-run Chinook over-summered in the upper reach with rainbow trout and steelhead. These salmonids co-occurred by selecting different microhabitats in the river, trading off risk of predation and competition for abundance of food sources. Smaller salmonids are more susceptible to predation by other fish, as well as avian predators, such as kingfishers and herons.

Riffle sculpin were common in the rainbow trout assemblage. While rainbow trout mostly fed on drifting terrestrial and aquatic insects, riffle sculpin fed on benthic invertebrates such as caddisfly and mayfly larvae. They eat salmon eggs and fry if given the opportunity, as well as the occasional juvenile trout. Sculpin are typically small, bottom-dwelling fish, have large flattened heads with very large jaws, fan-shaped pectoral fins for grasping the substrate, and an absence of a swim bladder, which helps them remain on the bottom in fast flows. They are dark in color, blending in with the substrate to avoid predators and hide from their prey, which they ambush. Riffle sculpin reach sexual maturity at two years, with females depositing eggs on the underside of rocks in swift riffles or inside cavities of submerged logs. Males guard the embryos, as well as yolk-sac fry. Sculpin can be fairly aggressive toward other benthic fishes, which they prey upon or displace.

Sacramento suckers were associated with this assemblage, and like sculpin are benthic feeders, but eat algae, detritus and associated small invertebrates; and rainbow trout will often follow them while they forage, hoping to eat invertebrates stirred up by the sucking. Sacramento suckers will be described in more detail below.

Box 7.2

Salmonids

The family Salmonidae contains fishes that are native to the pacific side of the Northern hemisphere including salmon, trout, char, grayling and whitefish. Salmonid characteristics include a fusiform (torpedo-shaped) body, a forked tale, adipose fin, and juveniles generally have lateral parr marks that fade as they grow.

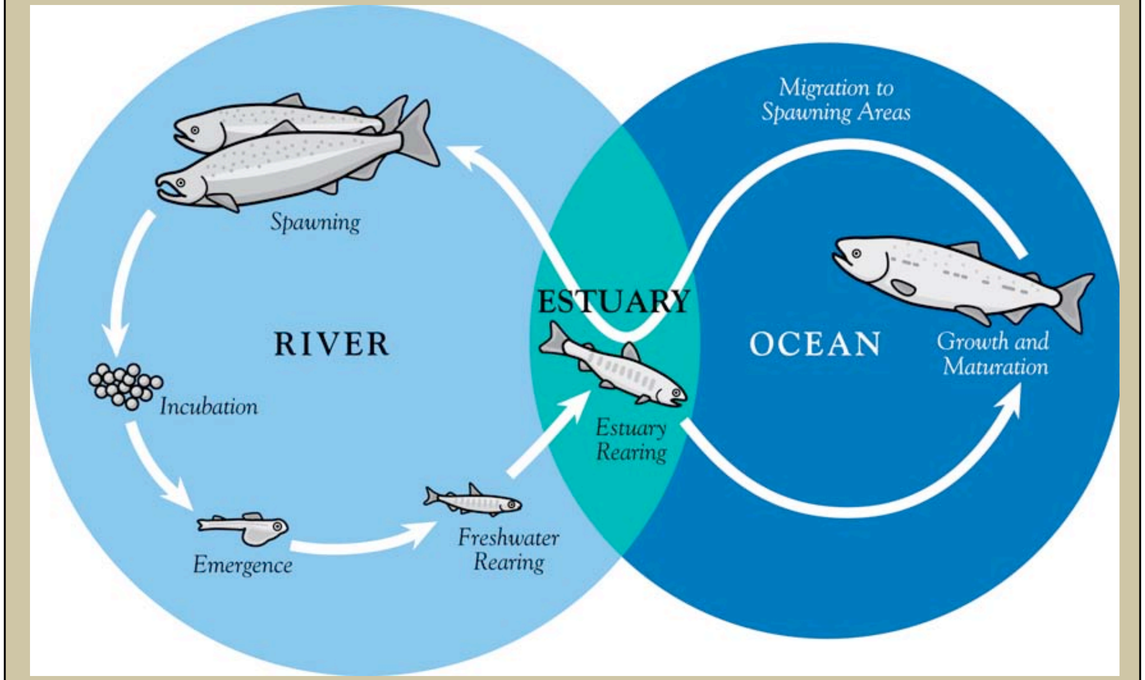

Figure 7.3 Salmon life-cycle.

Salmonids are popular with anglers as well as commercial fishermen, and many species are cultivated in hatcheries, helping humans distribute them throughout the world. Salmonids are strong swimmers and can rapidly colonize new waters as geology changes as long as there is cold, well-oxygenated water, and spawning habitat. Salmonids readily adapt to a variety of conditions such as alkaline terminal lakes, tiny headwater streams, large coastal rivers, and even intermittent streams. Salmonids exhibiting anadromy (Box 7.4) have a wide array of life history strategies, and have a remarkable ability to find their way back to their natal stream (or hatchery). However they also display a five to ten percent rate of "straying" which occurs when they spawn in areas other than where they hatched, an adaptation that allows them colonize new areas. In addition, anadromous forms can give rise to land-locked forms, such as steelhead giving rise to resident rainbow trout, or coho giving rise to kokanee. This flexibility in life history means that salmonids can take advantage of good river and ocean conditions, or avoid habitats where conditions may be poor.

Pikeminnow-hardhead-sucker and California roach assemblages

Species richness and ecological structure in the lower middle reach of the Tuolumne River were greater than in upstream portions, because the associated habitats were more complex, the gradient was lower, and the water was slower-moving. This meant that species without the swimming ability to colonize upstream portions could colonize these habitats and co-occur by taking advantage of different microhabitats. In the middle reach, two fish assemblages historically co-occurred it the Tuolumne River, though in different habitats: the California roach assemblage and the pikeminnow-hardhead-sucker assemblage. Both were dominated by the family Cyprinidae, or minnow species, a common family but with a high degree of speciation in the Central Valley due to long-ago geologic isolation and limited ancestry. In California cyprinids tend to live longer and grow bigger than cyprinids elsewhere, and are a common member of the fauna. In addition, many of the most successful invasive fishes in California are cyprinids. Part of cyprinids' success is due to adaptations such as 1) excellent hearing 2) production of a "fear substance" released by injured fish that alerts other fish in the area to danger 3) highly specialized pharyngeal teeth (teeth inside the throat) 4) very high fecundity, and 5) the tendency to shoal and school.

The pikeminnow-hardhead-sucker assemblage (Figure 7.3) occurred in the narrow elevational band of about 27-450ft above sea level in the main-stem and larger tributaries of the Tuolumne River. These streams had perennial summer flow, deep rocky pools and shallow, wide riffles. The water quality was high, with lots of dissolved oxygen, high clarity, medium summer temperatures and plenty of riparian vegetation and stream meanders that created a complex habitat. The most abundant fishes of this assemblage were Sacramento pikeminnows (*Ptychocheilus grandis*) and Sacramento suckers. Hardhead (*Mylopharodon conocephalus*) also occurred, but mostly in the cooler waters with deep, rocky-bottomed pools (Figure 7.4). Other assorted native fish found here included tule perch (*Hysterocarpus traski traski*), California roach (*Lavinia symmetricus*), riffle sculpin, and rainbow trout, though these last two became less common or were only present seasonally as water temperatures rose and stream velocity slowed.

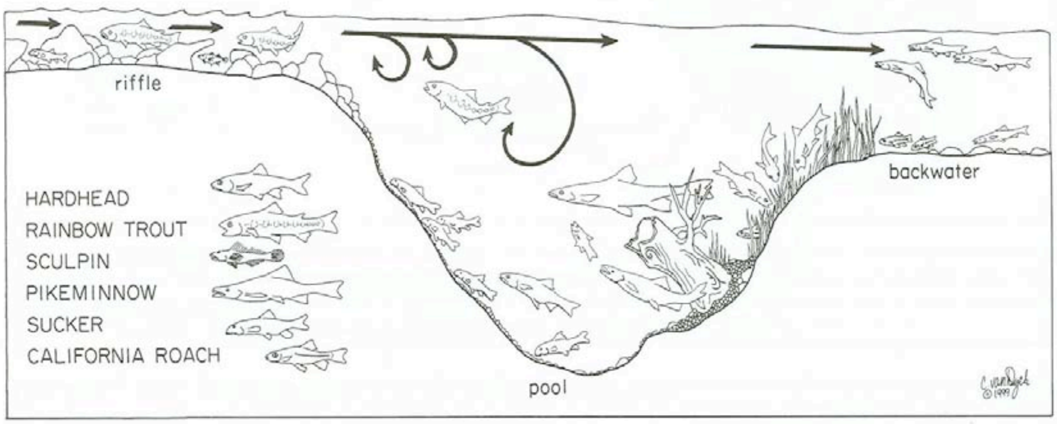

Figure 7.4. Cross section of a pool containing the Pikeminnow-hardhead-sucker assemblage in the Sacramento-San Joaquin drainage. Note the habitat partitioning driven by body morphology and prey preference. From Moyle 2002.

In addition to resident rainbow trout, anadromous salmonid adults and their juveniles were seasonally a part of this assemblage. Spring-run Chinook and steelhead spent summers in permanent areas with deep pools and cold water in the middle reach of the Tuolumne River before spawning high in the middle reach in autumn. Fall-run Chinook salmon adults moved upstream in the fall to spawn in the lower reach, with their juveniles predominantly migrating to sea in spring.

Sacramento suckers (family Catostomidae) are closely related to Cyprinids and share many of their characteristics. Besides the Tuolumne River, they were found throughout the Sacramento-San Joaquin watershed. Sacramento suckers were (and still are) successful due to their use of little-exploited food sources, their strong swimming ability, and their tolerance of a wide variety of environmental conditions ranging from the brackish waters of the estuary to the higher reaches with the trout. They are specialized bottom-feeders, with a vacuum cleaner-like sucker mouth with fleshy lips, and a flattened belly (Figure 7.4). They spent their time on the bottom, feeding on detritus, algae and small invertebrates, often moving into faster-moving water at night to feed avoid avian predators such as kingfishers that hunted during the day. Juvenile suckers and other young cyprinids such as hardheads spent time at the stream edges, with the smaller fish remaining closer to the edges to avoid being eaten by larger fish.

Sacramento pikeminnows were the top predator in the middle and lower reaches of the Tuolumne River and throughout the Central Valley. They are large, long-lived, highly fecund, slow growing, predatory cyprinids. Pikeminnows had large mouths with sharp pharyngeal teeth (located in the throat arch) adapted for eating other fishes , though juvenile pikeminnows preyed on smaller items such as aquatic insects. Sacramento pikeminnows prefer warmer, slower-moving water with deep pools, undercut banks and overhanging vegetation. They dominate the large pools, and fed at dusk and dawn by charging and using their large mouths to engulf their prey

Hardhead were another large minnow species typical of this assemblage. Larger hardhead spent time in deeper water and large pools, and had a broad diet that included algae and invertebrates. Hardhead required good water quality with high dissolved oxygen content. Rainbow trout were also present, but preferred riffles and cover (logs, undercut banks, behind rocks) defending their feeding territories from other fishes. Sculpin occurred, mostly in the riffles, hunkered down against the bottom waiting for prey. In addition, Tule perch were presumably present, feeding in the faster water but spending the rest of their time in pools and around aquatic vegetation.

California roach assemblage occupied the smaller, warmer tributaries that flowed through oak and pine woodlands in to the larger main-stem Tuolumne River (where the pikeminnow assemblage dominated). Some of these smaller streams dried up in the summertime, confining fish to warm, stagnant pools. In springtime, these same tributaries had cold, swiftly moving water, and were periodically flooded. The California roach was the most abundant permanent resident of this assemblage, though fishes from the pikeminnow assemblage and the rainbow trout assemblage were seasonally present. Small-bodied roaches could be found in extreme conditions such as those with high temperatures and low dissolved oxygen, as well as cold, clear, and well–aerated conditions, but did not tolerate high salinities. In addition, they are ecological opportunists, present in a variety of habitats, feeding on variable foods, and coexisting with many other species. Other fishes such as suckers, pikeminnows and other native minnows migrated upstream to spawn in these tributaries in spring. In the Red Hills Area of Critical Concern, there is a morphologically and genetically distinct subspecies of California roach called the Red Hills Roach, which is found only in serpentine habitat in Horton Creek and other small streams and drainages southwest of Jamestown.

Box 7.3
Red Hills Roach

The Red Hills Management Area consists of 7,100 acres (slightly more than 11 square miles) of public land located near the intersection of State Highways 49 and 120, just south of the historic town of Chinese Camp in Tuolumne County. Elevation ranges from 750 to 1750 feet above sea level.

The entire Red Hills Management Area has been designated as an Area of Critical Environmental concern (ACEC) to protect several rare plant species that grow in the unusual serpentine soils, to protect bald eagle wintering habitat, and preserve habitat for the rare endemic subspecies of California roach known as the Red Hills roach (Hesperoleucus symmetricus).

The Red Hills has no perennial streams, but it has a number of intermittent streams that have spring fed reaches and pool, used by the Red Hills roach. The roach is abundant in several of these permanent pools along the intermittent streams draining into Six Bit Gulch and Poor Man's Gulch. Like other California roach, fish survive in the warm shallow water in these permanent pools during hot dry summers until spring when they move upstream to spawn. Research indicates that the Red Hills variety of California roach is genetically and morphologically unique making them noticeably different from other California roach populations. One of the unique morphological characteristics is a chisel lip that is used to scrape algae, a major food source, off submerged rocks.

Up until 1996 the U.S. Fish and Wildlife Service had recognized the Red Hills roach as a candidate (category 2, now eliminated) for listing under the Endangered Species Act. The isolated nature of the population of the Red Hills roach due to past and continuing habitat degradation as well as their limited range, has led some researchers to be concerned about the roach's long-term survival. The presence of a number of introduced fish species such as green sunfish, largemouth bass and mosquito fish may limit the roach population by predation and/or competition.

Deep-bodied fish assemblage

The lowest reaches of the Tuolumne River contained the deep-bodied fish assemblage. The water was warm, slow-moving, and meandered through oxbow and floodplain lakes, swamps and sloughs. Deep-bodied fish, such as tule perch, Sacramento perch, thicktail chub and juvenile fishes of many species lurked in weedy, backwater areas, while adult cyprinids such as hitch, blackfish and splittail occupied the open water. Some populations of pikeminnows and suckers spent much of the year here, migrating upstream to spawn in spring. Adult and juvenile anadromous salmon and steelhead were an important component of this assemblage, either spawning in the lower reaches (fall-run Chinook), passing further upstream to spawn, or out-migrating to the ocean (juvenile salmonids).

As in the assemblages upstream, cyprinids dominated in the lowlands. Hitch was a common cyprinid found in the lower reaches, common in lakes, sloughs, and slow-moving rivers. Hitch are so closely related to California roach and Sacramento blackfish that they produce fertile hybrids. Hitch performed mass spawning migrations in the spring when the flows increased, traveling to rivers, sloughs, ponds, and tributaries. Females were highly fecund, laying eggs that swelled to four times their size after being released, lodging in the substrate. Hitch were once so abundant that they were an important food source for Native Americans of the Yukot tribe**.**

The thicktail chub (*Gila crassicauda*) is now extinct, but once inhabited Central Valley lowland habitats, including the lower reach of the Tuolumne River. Their bones are the most abundant fish remains in Native American middens along the Sacramento River, indicating that thicktail chub were very abundant. The morphology of thicktail chubs indicates that they were carnivores, feeding on small fish and large aquatic invertebrates.

Thicktail chub, Sacramento blackfish and Sacramento splittail spawned in floodplains, attaching their embryos to the submerged vegetation. Floodplains were composed of dense riparian forest, wetlands, and ephemeral floodplains that were inundated during winter rains and spring snowmelt. These areas were excellent habitat for juvenile fishes of many species, due to the abundance of zooplankton such as copepods and daphnia. Juvenile salmon moving downstream to the ocean would also use the highly productive floodplains to rear and avoid predation.

With the winter rains, Sacramento splittail adults moved upstream into flooded riparian areas and the lower reaches of rivers to forage before spawning and laying eggs on the floodplain. Rising flows were the major trigger for splittail spawning, but increases in water temperature and day length may also have been factors. Sacramento splittail are adapted to the erratic climatic cycles of California, and concentrate their reproductive effort in wet years when conditions are better for the next generation. Splittail are highly fecund, and are fractional spawners, with individuals spawning over a period of several months in response to changing river conditions. After emergence, most larval splittail remained in flooded riparian areas, feeding among submerged vegetation before moving off floodplains into deeper water.

Tule perch, an endemic subspecies, were widespread throughout lowland rivers and creeks in the Sacramento-San Joaquin watershed. Tule perch inhabiting rivers could usually be found within beds of emergent plants, in deep pools, and near banks with cover. They required cool, well-oxygenated water for persistence, but had remarkable salinity tolerance.

The only fish in the Centrarchidae family (sunfishes) native and endemic to the Central Valley was the Sacramento perch (*Archiplites interruptus*). It is ironic that there is only one endemic centrarchid in California, because centrarchids, such as bass and sunfishes represent some of the most egregious invasive species in California today. Sacramento perch are medium-sized, fecund, long lived (up to nine years) fish. Along with the Sacramento Pikeminnow, Sacramento perch were the dominant piscivorous fishes of the Central Valley and were historically present in great numbers. Sacramento perch are frequently associated with beds of rooted, submerged, and emergent vegetation. They are adaptable, tolerating more extreme environmental conditions than other fishes including high turbidity, high temperatures and elevated salinity and alkalinity concentrations. Like many other species of sunfish, males create nests out of shallow pits in substrate ranging from silt to gravel which they defend until larvae leave the nest. Sacramento perch prey on small crustaceans, copepods, insect pupae and larvae, other fish including their own young-of-the-year, and aquatic insects.

Anadromous fishes

The Chinook salmon (*Oncorhynchus tshawytscha*) was historically the most abundant anadromous fish in the Tuolumne, though steelhead and lamprey also occurred. The Tuolumne River had two major runs of Chinook: the fall-run and the spring-run, which were distinguished by run timing, spawning location, and degree of sexual maturity at the start of the spawning migration. A characteristic Chinook adaptation was a high rate of straying, or returning to a habitat other than the natal habitat. This allowed them take advantage of new habitats and survive difficult conditions in established habitats. Fall-run fish spawned and died in the lowland areas of the Tuolumne River after entering the fresh water in early fall as sexually mature adults. Juvenile fall-run Chinook usually spent less time in fresh water (3-12 months) before entering the ocean. The juveniles emerged in the springtime, moving downstream to estuaries to grow before entering the ocean. It is believed that in the Central Valley, fall-run Chinook numbered over a million spawners in some years.

Box 7.4

Anadromy

Anadromy is a common life history adaptation among fishes that involves migration between the rivers and the ocean in order to take advantage of both habitats. It is common in a variety of fishes, but is particularly common in salmonid species. Anadromous fishes spawn, hatch, and rear in rivers, then migrate to the ocean to take advantage of the high productivity that allows them to grow much larger than they would if they remained in the river. Once they reach maturity, they reenter their natal rivers and spawn near where they themselves were born. Salmonids apparently use a combination of cues that includes scent (each river has a distinct chemical signature that salmonids can discern), as well as the magnetic pull of the earth and the path of the sun.

California represents the southern limit of west coast anadromous salmonids. There is enormous seasonal variability in weather conditions shifts from hot, dry summers, reduced flows and high temperatures to wet winters with cool water temperatures, and high flow events that are physically challenging to withstand. In addition, there is tremendous interannual variability in precipitation with most years being either incredibly wet or incredibly dry, few come in as "normal." Under these types of conditions, anadromy allows fish to escape difficult river conditions, while still reaping the benefits of using rivers to spawn and rear juveniles.

Ocean conditions vary as well, depending on currents and larger climatic cycles such as El Nino and La Nina that change the direction of prevailing winds and therefore the patterns of weather, current, and upwelling off of California. Salmon and other organisms depend on the ocean currents to bring cold, nutrient rich water up from the depths, generating huge amounts of phytoplankton that form the basis of the food web. This allows for rapid growth and allows the salmon to store reserves of fat and energy to make the journey inland to spawn. Poor ocean conditions occur when the prevailing winds do not create upwelling; currents slow, and reduce phytoplankton productivity, which in turn limits the available food for salmon. During these times salmon may experience high mortality rates or chose to return to the rivers to spawn early. Poor conditions in both environments often lead to population crashes, which are especially severe in systems degraded by human development.

Spring-run Chinook, now extirpated from the entire San Joaquin watershed, were not sexually mature when they entered fresh water. They entered rivers in the spring when flows were high, allowing them to access higher reaches (perhaps up to Preston Falls before damming) of the watershed than the fall-run fish, creating geographical isolation between the two runs. Once in the upper reaches, spring-run Chinook over-summered in the permanent, cold, deep pools until fall, when they would spawn and then die. Upon emergence, spring-run juveniles stayed in the middle-elevation pools until the yolk sac was absorbed, then moved downstream to the lower river reaches, estuaries, and floodplain habitats for rearing, where they might spend over a year before migrating into the ocean. Chinook juveniles from both runs entered the ocean, typically remaining close to California for 1-5 years to take advantage of the productive feeding grounds created by the upwelling of cold, nutrient-rich water off the coastal shelf.

The Central Valley Steelhead (*Oncorhynchus mykiss*), an anadromous rainbow trout, is highly adaptable and opportunistic, successfully colonizing all suitable and accessible habitats in California. In fact, steelhead make up the southernmost populations of anadromous salmonids in North America. In general steelhead had the most plastic life history variations of any of the salmonids, and a very high rate of straying. At one time there were probably two runs of steelhead in the Tuolumne River: winter steelhead and summer steelhead. Winter steelhead entered freshwater from the ocean when the high flows permitted access to higher elevation habitats for spawning. Summer steelhead entered freshwater as immature fish when spring flows were receding. They migrated upstream to locations where they could spend the summer in cold, deep pools, much like spring-run chinook. They matured over the summer, spawning the next winter or spring. Unlike Chinook, Tuolumne River steelhead were iteroparous, meaning that they had the potential to spawn several times, returning to the ocean and migrating back into the rivers to reproduce again. Juveniles spent one or two years in fresh water, eating invertebrates and avoiding predators. After entering the ocean, they fed on marine invertebrates and other fish, spending 1-4 years in the ocean before returning to fresh water to spawn.

In addition, two species of lamprey, Pacific lamprey (*Lampetra tridentata*) and River lamprey (*Lampetra fluviatilis*) inhabited the Tuolumne River. Adult lampreys preyed on the blood and body fluids of other fishes using a circular sucker mouth, which they use to latch onto fishes and rasp a hole in the fish with a bony tongue covered with sharp, horny plates. Fishes generally survived these attacks; some fishes sustain multiple lamprey scars. The lifecycle of lamprey included an adult predatory phase spent in the ocean, after which they migrated into fresh water in the spring to spawn and die. The larvae are known as ammocoetes, and anchor themselves into the stream substrate where they live for 5-7 years filter-feeding before metamorphosing into predatory adults and migrating to the ocean.

Fish assemblages in California post-human

The characteristics of the Tuolumne River and its fish assemblages are profoundly different today then before Europeans colonized California. Starting in the formerly fishless headwaters and throughout fishless waters in the Sierra Nevada, non-native, hatchery-bred trout were systematically stocked by humans. Further downstream, the development of the Tuolumne River for water and power blocked fish passage above La Grange, while each dam effectively segregated fish populations from one another throughout the watershed and blocked spring Chinook runs from their spawning grounds. In addition, the reservoirs formed behind the major dams are now home to an assortment on non-native warm-water fishes. In the lower reach, levees have nearly eliminated floodplain habitat that was critical for juvenile native fishes.

Overall, the trend of increasing disturbance has resulted in increasing numbers of established alien species, particularly near dams. Dams block rivers and form reservoirs resulting in slower moving water, which can warm considerably if the reservoir is small, but larger reservoirs possess stratified temperatures and can be quite cold in the lower layers. The native fishes that survive these altered river conditions are often further reduced in numbers by introduced predators such as largemouth bass and sunfish, exotic diseases, and competition. Less disturbed streams are more resistant to establishment of invaders, because introduced species often cannot cope with seasonal flow regime, cold temperatures and faster flows.

Rainbow trout assemblage

The rainbow trout assemblage rarely exists in its historical state anywhere in California; it is more appropriate to refer to these former areas as "assemblages with rainbow trout in them." Though local, wild populations of rainbow trout in urban and heavily agricultural areas may be diminished or gone, rainbow trout are more abundant in California and throughout the world than ever before due to intensive hatchery production and widespread introductions by humans.

The range of rainbow trout has been extended in the Tuolumne River and throughout the Sierra Nevada due to stocking. Humans planted fish in the formerly fishless waters in the upper reach of the Tuolumne beginning in the 1800s. For nearly fifty years, the Department of Fish and Game used planes to stock remote backcountry lakes and streams with trout. Currently, the range of rainbow trout and related introduced species includes most of the lakes and streams in the once-fishless Sierra Nevada, as well as the Dana and Lyell forks of the Tuolumne River (Figure 7.5). At middle elevations, ongoing stocking programs have augmented the existing wild populations, though these fish typically last only a few years without restocking due to pressure from anglers, and lower survival rates of hatchery fishes in general. However, cold outflow from the tailwaters of New Don Pedro, La Grange, and O'Shaugnessy dams support rainbow trout and riffle sculpin.

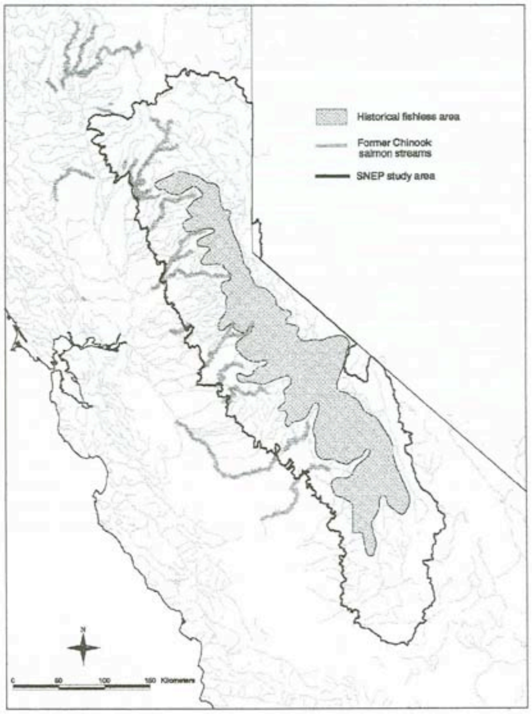

Figure 7.5 Changes in distribution of fishes in central California. Two major changes have occurred in fish distribution as shown in this map. The dark lines indicate major dams that block formerly accessible habitat for steelhead and Chinook salmon. The shaded area at higher elevation indicates the formerly fishless region of the Sierra Nevada now occupied by stocked fishes, predominantly trout. From Moyle 2002.

In addition to the extension of the range of rainbow trout throughout the Tuolumne River, human impact has increased the complexity of assemblages with rainbow trout due to introductions of brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*), both of which prey upon rainbow trout juveniles and compete with them for food and space. There is generally some segregation, but where they coexist, rainbow trout are subordinate and occupy less desirable habitat. Brown trout prefer pools, feeding on bottom invertebrates and fishes, while Rainbow trout stick to undercut banks and riffles, preferring drifting insects at the surface. Brook trout prefer cold water in spring-fed tributaries, and dominate in the smaller higher streams. In addition, brown and brook trouts spawn in fall while rainbow trout spawn in the spring. This means that juvenile brook and brown trout have a competitive advantage over the young-of-the-year rainbows.

In the Tuolumne River, riffle sculpin are still locally abundant, (and can be abundant in the cold tailwaters below dams) but their populations are increasingly isolated by disturbed habitat, and may become locally extinct. They are particularly sensitive to reduced flows and increased temperatures. Sculpin populations can also be reduced by gold dredging practices that destroy riffle habitats and cause high turbidity, and a reduction in gravel. Because they are so sensitive to habitat and water quality degradation, the presence of riffle sculpin is generally a sign of a healthy salmonid habitat.

California roach assemblage and pikeminnow-hardhead-sucker assemblage

In the California roach assemblage, the Sacramento-San Joaquin subspecies of California roach is now a species of special concern, largely replaced by introduced green sunfish (*Lepomis cyanellus)* and largemouth bass, both of which eliminate roach from streams through predation and competition. Though the Sacramento-San Joaquin roach subspecies remains abundant, it has disappeared from some areas. Remaining populations are increasingly isolated and vulnerable, confined to reaches below barriers such as dams and diversions, or relegated to polluted waters containing predatory fishes. Additionally, much of their habitat is located within private lands where land management leads to diminished stream flow, warmer temperatures, and degraded habitat.

Dams and reservoirs have fragmented the pikeminnow-hardhead-sucker assemblage. Native fishes are still present in areas of a more natural flow regime, probably because behavioral adaptations allow them to withstand high flows by finding refuges or using the stream edges to avoid being flushed downstream. In addition, they have hydro-dynamically shaped bodies that can handle faster currents than the deep bodies of the introduced centrarchids which are native to the slow-moving waters of the southeast U.S. Hardhead are still reasonably common, thought they have declined in the Tuolumne River and overall. This is primarily due to habitat loss and predation by introduced fishes, particularly basses. Hardhead can survive in reservoirs, but populations generally grow and then crash in these habitats. When the Don Pedro Reservoir was first built, hardhead became so common that they were considered pests. However subsequent introductions of predators have caused these populations to collapse.

No longer the only top predator in the Central Valley, Sacramento pikeminnows are less common in their native range due to increased turbidity, reservoirs, and the introduction of centrarchid basses. Like the hardhead, their population increased and then crashed in Don Pedro Reservoir as new species became established. Sacramento suckers have fared better than hardhead or Sacramento pikeminnow with the changes in California waterways, though they are also less common in the Tuolumne River.

Deep-bodied fish assemblage

The deep-bodied fish assemblage that once inhabited the lower reach of the Tuolumne River has probably changed the most dramatically since Europeans colonize California. Many exotic species have been introduced here, both intentionally and inadvertently. The thicktail chub is extinct, and the Sacramento perch is extirpated from nearly all of its historical range and has undergone a severe genetic bottleneck.

The main reason for these changes include dams and levees, which altered the historic flow regime and have nearly eliminated floodplain habitat. Today most water in the valley floor flows through human-modified channels. These levees and diversions confined native fishes to ditches and sloughs until they were replaced by introduced species such as white catfish and carp. The tule beds that served as valuable rearing and feeding ground for many species are nearly gone, further reducing populations of many species of native fishes. Some native fishes do occur, such as pikeminnows, suckers and other juvenile cyprinids, but usually in less disturbed areas or as a minor part of the fauna. The entire system is now dominated by alien fishes and invertebrates, including Asian clams (*Corbicula fluminea*) and red swamp crayfish (*Procambarus clarkii*). Alien plants (e.g., *Myriophyllum* spp.) have also flourished and changed the ecosystem. Fish assemblages still occur, but are not stable because species are still being introduced and spreading, the natives are still declining, and habitats continue to be modified by humans.

Hitch can survive in disturbed areas such as channelized streams and turbid waters, because they have the highest temperature tolerance of any native Central Valley fish. However they are declining due to loss of high spring flows required for spawning, predation by non-native fishes, loss of summer rearing and holding habitat, and pollution. Hitch are preyed upon by other fishes, avian predators, raccoons, mink and otter, especially during spawning migrations. In addition, hitch and the closely related Sacramento blackfish may hybridize as a consequence of sharing spawning areas that are now vastly reduced in area, leading to introgression, loss of species adaptability and species purity. Today the most common associates of hitch are introduced species, but they are still commonly found with Sacramento blackfish, Sacramento sucker and Sacramento pikeminnow. Surveys of the Tuolumne River indicated few hitch relative to other fishes, which is typical of hitch populations in other San Joaquin tributaries today.

By 1884, thicktail chub were already scarce and became extinct by the late 1950s, most likely because they could not adapt to the modification of Central Valley lowland habitats. In particular thicktail chub may not have tolerated the downstream effects of hydraulic mining, as well as the constant siltation from sluices, dredge mining, and diversions. Though surveys were done in recent years, thicktail chub have not been found. The loss of tule beds and large shallow lakes for spawning were also problematic, though predation by non-native fishes likely also played a role in the extinction of thicktail chub.

Now federally threatened and a state species of special concern, Sacramento splittail, are largely absent from their most upstream habitats. They now reside primarily in the lower parts of the Sacramento and San Joaquin Rivers and tributaries, and in some Central Valley sloughs. In addition, much of the lowland habitat that they once occupied has been altered so that it is now accessible only in wet years. Splittail now migrate into the San Joaquin River only during these wet years, they might reach as far upstream as Modesto, where presence of adults and juveniles indicate a successful spawning.

Tule perch are extirpated from much of the San Joaquin basin, presumably due to the introduction of centrarchids, thought they are still found in the lower Tuolumne River. Tule perch residing in lakes are commonly associated with bluegill and other alien centrarchids, but in streams they are associated primarily with other native fishes. They are less common in areas dominated by exotic fishes, but this appears to be more a result of poor water quality than competition with non-native fishes.

No longer found in its native range, the Sacramento perch is now a California species of special concern. Sacramento perch are thought to be unable to persist in habitats with other centrarchids, especially black crappie and bluegill. When present, these nonnative species successfully compete for food and space, and prey on perch embryos and larvae. Extirpation of Sacramento perch was caused by introduced species and habitat destruction, especially draining of lakes and sloughs and reduction of native aquatic plant beds.

Anadromous fishes

A number of factors have contributed to the decline Chinook salmon and other anadromous fishes in the Tuolumne River, but the most egregious is the construction dams that block upstream spawning migrations. Steelhead and fall-run chinook still spawn in the Tuolumne River below LaGrange Dam, but the supply of spawning gravels in the river has been reduced because replenishing gravels are unable to move downstream past the dams. The resulting smaller degraded spawning areas can lead to an inadequate amount of available spawning habitat. This can lead to redd superimposition, where later-arriving females dig redds on top of pre-existing redds, causing substantial mortality of the previously-deposited eggs.

Other factors leading to salmonid decline include over-harvesting for the commercial fishery, and the construction of delta water pumps, which can kill fish or make them more susceptible to predation when they get trapped. In addition, loss of floodplain habitat in the Central Valley has led to a decline in juvenile rearing habitat. Changes in stream structure such as loss of vegetation cover and undercut banks, or the proliferation of invasive plants such as water milfoil (*Myriophyllym* spp.) and Brazilian waterweed (*Egeria densa*) expose juvenile salmon to increased predation. Finally, general stream and water quality issues such as pollution, loss of riparian forests leading to increased temperatures, and the reduction of good spawning habitat due to siltation also negatively impact salmon.

The Central Valley fall-run Chinook is considered an ESU (Evolutionary significant unit) by NMFS. They are still the most abundant run of Chinook in the Central Valley, persisting in large numbers in rivers below dams, and are the principal run raised in hatcheries. The abundance of fall-run Chinook before European settlement and into the 19th century is poorly known due to a dearth of records, but salmon were certainly impacted by humans. In addition to being heavily fished, hydraulic mining debris buried major spawning and rearing areas. In addition, construction of levees and the use of rip-rap and removal of trees to contain rivers has simplified bank structure, reduced shade, and limited floodplain access. Levees, in combination with reduced peak river flows, have led to the process of “bank hardening,” contributing to the high mortality rate of juveniles as they pass through the estuary on the way to the ocean. Juveniles fare better during wet years, due to better access to floodplains and increased freshwater habitat. Restoration of floodplain habitat is regarded as critical for juvenile salmon growth and survival.

Escapements (numbers of fish that “escape” predation or fishing and return to fresh water to spawn) vary tremendously over time in the tributaries to the San Joaquin River (Stanislaus, Tuolumne, and Merced Rivers). The exact cause of the variation in abundance in these three rivers is not well understood but the largest returns follow years with high outflows and high smolt survival. Recent data showed that from 2007-2009, returning salmon numbered between 50 and 200 individuals, years with low runs throughout the state.

Box 7.5

Reservoirs

Few California native fishes are adapted to man-made reservoirs, which are characterized by still, deep waters. However introduced fishes, typically centrarchids species popular with anglers and their bait fishes thrive. Deeper reservoirs have cold water at the bottom, and a layer or warmer water nearer the surface, and these layers may rarely mix, though these layers "turn over" seasonally. In these deeper reservoirs, two groups of fishes are usually stocked: warm-water-loving, deep-bodied, relatively sedentary fishes (e.g., bass and bluegill) that inhabit the near-shore regions of the reservoir. Inhabiting the deeper water far from shore are the sleek, fast-swimming fishes that prefer colder water (e.g., kokanee salmon (Oncorhynchus nerka), threadfin shad (Dorosoma petenense), and hatchery rainbow trout). During summer, the cold-water fishes live in deeper water while warm-water fishes are found near the surface. After turnover in late autumn, cold-water fishes come to the surface to feed while warm-water fishes descend to deep-water refuges to wait out the cold months. Reservoirs with these divided fish communities (e.g., New Don Pedro Reservoir) are called "two-tiered fisheries."

Different species of introduced fishes (and natives when they occur) prefer different microhabitats in a reservoir habitat from the inlet stream downstream to the dam itself. Near inlet streams where the current is higher and the substrate is coarser, smallmouth bass predominate, feeding heavily on rock-loving creatures such as crayfish. The deeper, slower mid-section of the reservoir is inhabited primarily by the spotted bass, which uses its sleek body to chase prey fish (e.g., threadfin shad) along the steep walls. Largemouth bass prefer slower-moving waters, and dominate near the dam where the water is still, hiding in rip-rap or aquatic weeds to ambush prey such as bluegills. When present, native fishes such as Sacramento sucker and hardhead are usually most common near the inlet, where the habitat most closely resembles the flowing environment that existed before the reservoir.

The National Marine Fisheries Service has concluded that populations of naturally reproducing steelhead have been experiencing a long-term decline in abundance throughout their range. However, there is evidence that small populations of steelhead persist in some lower San Joaquin River tributaries (e.g., Stanislaus River and the Tuolumne River). Researchers concluded that water development and water management have been the major contributors to the decline in steelhead. Impassible dams have blocked historic habitat, forcing steelhead to spawn and rear in lower river reaches, where water temperatures are often lethal. There is little recent information available on the run timing, life history, and population numbers of steelhead occurring in the San Joaquin basin, but it is likely that a least a small run is in existence. River lamprey is a species of special concern in California. The river lamprey population trends are unknown in the southern portion of its range, but it is likely they have declined in response to degradation of adequate spawning and rearing habitat in lower sections of large rivers. Pacific lamprey has declined throughout its range as well, but in California, the extent and timing of spawning migrations of both river lamprey and Pacific lamprey are not well known.

The Invasive Species

Though countless species have been introduced to the Tuolumne River and other watersheds throughout California, only a few have become well established. The species that are now naturalized throughout the upper, middle, and lower reaches of the Tuolumne and throughout California are generally from Eastern North America and Europe and include members of the Cyprinidae, Ictaluridae, Centrarchidae, Salmonidae, and Atherinopsidae families. These fish are typically highly fecund, predatory and aggressive, and prefer disturbed habitats such as reservoirs. They are generally territorial, and will defend nests, ensuring greater success in development of offspring. Less disturbed areas of the Tuolumne River and other rivers in California still tend to have more native species than invasives, indicating that restoration of natural flow regime and other restoration measures may help ensure that the natives survive well into the future as a part of California's natural heritage.

Living fast (spawning in first year) and dying young (~1-2yr), Mississippi silverside (*Menidia audens*, family Atherinopsidae) are extremely fecund, with females producing 200-2,000 eggs *per day* during the California spawning season running from April-September. Due to this reproductive capacity, silversides are often the most abundant fish in shallow areas of warm water lakes, reservoirs, and estuaries, where they shoal in large numbers. They occupy the same shallow water habitat as juvenile salmon, splittail, and other fishes, which may negatively affect these natives.

The Golden shiner (*Notemingonus crysoleucas*) and the red shiner (*Cyprinella lutrensis*) are cyprinids that became ubiquitous in California in the 1950s when they were established as a legal baitfish. Both are adaptable, omnivorous, highly fecund spawners. Golden shiners are most abundant in slow-moving, turbid environments with muddy bottoms such as low-elevation reservoirs and sloughs, but can also be present in coldwater lakes as long as there are warm, shallow areas for breeding and rearing their young. Red shiners are smaller and shorter-lived than golden shiners, and prefer similar habitats. Both species spawn in slow-flowing water, and eggs will adhere to just about any substrate, such as submerged vegetation, gravel and sand, root wads, woody debris, and even active sunfish nests.

Black Crappie (*Pomoxis nigromaculatus*), and white crappie (family Centrarchidae) were both introduced into California in the early 1900s. Black and white crappies are now well established throughout the state in reservoirs or where there is warm quiet water. Black Crappie are usually associated with abundant aquatic vegetation and sandy or muddy bottoms, and are ecologically similar to the native Sacramento perch; the establishment of black crappie in the Sacramento/San Joaquin delta region in the 1920s occurred at the same time as a decline in Sacramento perch. This was likely due to predation and competition for food, as well as competition for breeding sites.

Bluegill (*Lepomis macrochirus*) and green sunfish (*Lepomis cyanellus*) (family Centrarchidae) were introduced to California over 100 years ago and are now probably the most widely distributed freshwater fish in California, thriving in human-altered habitats. They limit native fishes through competition and predation. Bluegill are extremely adaptable, preferring warm, shallow habitats with aquatic vegetation such as reservoirs but surviving in colder systems. They lurk among plants, feeding on smaller organisms such as aquatic insects, fish and fish eggs, snails, zooplankton, and crayfish. Green sunfish compete with or prey on native species such as the California roach, and minnows, and can prevent the reestablishment of displaced native species. Opportunistic predators, green sunfish feed on a wide spectrum of benthic invertebrates, zooplankton, and small fish. Green sunfish are usually found in small, warm, streams, ponds and lake edges with dense growths of emergent vegetation and brush piles. They are often the sole species in warm isolated pools in disturbed intermittent streams, and will re-colonize dewatered streams quickly when flows resume.

A very popular fish with anglers, largemouth bass (*Micropterus salmoides*, family Centrarchidae) were introduced to California in 1891 and now occur throughout California in warm, quiet water habitats. Like green sunfish, they can survive in intermittent pools and quickly recover once the habitat expands again. Largemouth bass are adaptable predators and feed on a variety of prey including larger invertebrates, amphibians, small mammals, and fish, even sometimes cannibalizing young of their own species. Wherever largemouth bass are present they generally have adverse impacts on native species because they are so large, aggressive and adaptable. In isolated water bodies they are capable of causing native species extirpations.

White catfish (*Ameiurus catus*), black bullhead (*Ameiurus melas*) and brown bullhead (*Ameiurus nebulosus*) are introduced fishes that are now widespread throughout California and the lower reach of the Tuolumne River. White catfish are piscivorous (fish eaters), and are responsible for the decline of some native cyprinids, though they will also feed on smaller organisms, such as amphipods, shrimp, and chironomid larvae. They prefer areas of slow velocity and avoid deep, faster velocity channel waters. They spawn in summer, with both parents caring for eggs and fry. Other introduced catfishes include the black and brown bullheads, which are more omnivorous than white catfish. Bullhead females dig shallow nests and deposit a mass of eggs, which both parents care for until young emerge and are large enough to swim to shallow reaches. Both black and brown bullheads are increasingly more prominent in highly disturbed lowland aquatic environments, and both support small recreational fisheries. They are typically found with other non-native species, such as bluegill, green sunfish, Mississippi silverside, carp, red shiner and others.

Mosquitofish (*Gambusia affinis*) were originally introduced to drainage ditches and diversions to control mosquito populations. They now inhabit a wide array of habitats including brackish sloughs, salt marshes, warm ponds, lakes, disturbed portions of low-elevation streams, and especially warm, turbid pools with aquatic plants. Mosquitofish are omnivorous and opportunistic, feeding on the most abundant prey and are livebearers, which ensures greater success of juvenile fish. Although mosquitofish introduction has been used effectively as a biological control method for mosquito populations, they also have a negative effect on native organisms that also prey on mosquitoes, such as native small fish and fish larvae, amphibians, and endemic invertebrates. Mosquitofish prey on various life stages of these organisms and harass adults, potentially interfering with breeding. Furthermore, mosquitofish can develop resistance to local pesticides, and have a remarkable capability to withstand and even thrive under extreme and fluctuating environmental conditions. There are many more invaders in California than are described here, and it is likely that even more will be introduced in the future.

Undoubtedly, as humans continue to expand in California and use the natural resources, the native fishes will continue to decline given current trajectories and management. However of all California's native fish species, only 11 (mostly salmonids) are important for fisheries today, making conservation of the majority of the native species that are not of economic importance a tough sell. To those who might be convinced that native fishes are important, there are several arguments for conservation of the natives.

First, many of the native fish species are underappreciated as food sources. Large cyprinids and suckers (and even smaller species) were used by Native Americans as a food source, as well as Asian immigrants in the United States. Ocean and fresh water fisheries for large top predators are declining, so fisheries for fishes that are lower on the food chain may provide an important, readily available, inexpensive protein source for people. Second, when fishes decline, it is a sign that the ecosystems they inhabit have deteriorated. Human disturbance is therefore the major reason for native fish declines in California. Healthy aquatic ecosystems are important for humans, providing services such as clean water, flood control, recreation and fisheries. By protecting native fishes we are ensuring that these ecosystem services are available to us as well. Finally, native fishes have inherent value, particularly given the fact that so many of California's native fishes are either endemic or represent the southern range limit. We as humans hope to preserve a healthy planet for ourselves and for the next generation. Native fishes, though they may not have a direct economic benefit, are a part of this legacy. In California in particular we are lucky to have many species that are found nowhere else such as the tule perch and the Sacramento perch. The loss of these species is irreversible, and surely represents a greater loss for humanity.

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Chapter 8: Amphibians of the Tuolumne River Watershed

TEEJAY O'REAR

INTRODUCTION

Like aquatic insects and fishes, the members of the amphibian community change from the Tuolumne River's headwaters to its confluence with the San Joaquin River. Each amphibian has a suite of adaptations finely tuned to the unique environments found in the three main reaches of the river. However, human-caused changes in the environment have turned once beneficial adaptations into liabilities. Consequently, populations of nearly all native amphibians in the Tuolumne River are in decline.

AMPHIBIANS IN THE UNREGULATED TUOLUMNE RIVER

Upstream of Hetch-Hetchy Valley

The plethora of cold high-altitude lakes and connecting creeks in the headwaters of the Tuolumne River creates a harsh environment for amphibians. These small water bodies can sometimes freeze for up to nine months, allowing only those animals able to withstand prolonged periods of near-freezing temperatures to survive. Ice and snow can cover lakes and prevent oxygen production by blocking light that would normally power photosynthesis. Additionally, ice on the surface of lakes prohibits diffusion of atmospheric oxygen into the water. As a result, if the ice remains long enough, the lake may become seriously depleted in oxygen (i.e., hypoxic). While the granitic basins in which the high-elevation lakes sit are nutrient poor and relatively unproductive, they are usually richer compared to the nearby upslope terrestrial environments. Amphibians of the upper Tuolumne River watershed have life histories and physiologies specifically adapted to take advantage of these unique, high-elevation environmental conditions.

The most notable frog of the upper watershed is the Sierra Nevada yellow-legged frog *Rana sierrae* (formerly known as the mountain yellow-legged frog, *Rana muscosa*). This frog has a biphasic lifecycle (Figure 8.1), with tadpoles (phase 1) that feed on algae and frogs (phase 2) that eat insects. Although most common in glacially carved lakes, Sierra Nevada yellow-legged frogs are also found in adjoining streams.

A number of life history and behavioral traits allow Sierra Nevada yellow-legged frog tadpoles to persist in the upper watershed. First, tadpoles are able to survive hypoxic conditions for long periods, thus increasing their chances of surviving through long winters. Second, tadpoles will remain in the warmer depths of lakes in winter and move daily into warm shallows during the summer. These movements allow Sierra Nevada yellow-legged frog tadpoles to maintain high body temperatures that maximize their growth rate. However, the short growing season in the high-country lakes limits how quickly tadpoles can develop. Thus, Sierra Nevada yellow-legged frog tadpoles must hibernate through at least one winter before metamorphosing into frogs.

Sierra Nevada yellow-legged frogs are very aquatic compared with other native frogs. As a result, a large proportion of the frog diet consists of aquatic organisms such as the adult stages of aquatic insects (e.g., mayflies and caddisflies) and tadpoles of other species. Sierra Nevada yellow-legged frogs also serve as food for birds and garter snakes and thus link aquatic and terrestrial food webs. Like tadpoles, frogs hibernate in lakes and streams; however, *unlike* tadpoles, frogs are less tolerant of hypoxia. Because the chance of developing hypoxic conditions decreases with increasing lake depth, frogs are generally restricted to relatively deep lakes.

The Yosemite toad, *Anaxyrus canorus* (formerly *Bufo canorus*), is the other hallmark frog of the high country. While Sierra Nevada yellow-legged frogs dominate perennial streams and lakes, Yosemite toads take advantage of temporary aquatic habitats such as snowmelt ponds and wet meadows. The low productivity in the high-elevation environment sometimes precludes the ability of females to produce eggs each season; consequently, females usually do not breed every year. Conversely, males require less energy for producing sperm and thus generally mate every year. Additionally, males spend more time in ponds by calling to females; as a result, males are much more aquatic than females. However, Yosemite toads spend less time in water than do Sierra Nevada yellow-legged frogs. For instance, while Sierra Nevada yellow-legged frog tadpoles must wait at least a year to metamorphose, Yosemite toad tadpoles can metamorphose in as quickly as five weeks in shallow snowmelt ponds. Instead of wintering in deep lakes like Sierra Nevada yellow-legged frogs, Yosemite toad adults weather the cold season in mammalian burrows.

Hetch-Hetchy Valley to La Grange Dam

The middle reaches of the Tuolumne River have been the realm of a frog closely related to the Sierra Nevada yellow-legged frog: the foothill yellow-legged frog (*Rana boylii)*. Like many other stream-dwelling animals (e.g., salmonids), the foothill yellow-legged frog is finely tuned to the natural flow regime of California rivers. Foothill yellow-legged frogs deposit their eggs in spring on the lee side of cobble-sized rocks in stream reaches that are wide and shallow. This egg-laying site minimizes the possibility of the eggs drying out by rapidly declining river levels or being washed away by high flows. Foothill yellow-legged frogs breed when temperatures warm in spring and high flows from snowmelt runoff are declining. However, prolonged rain that signals a rise in flows can delay reproduction until the river level once again begins to decrease. Foothill yellow-legged frog tadpoles usually metamorphose in three to four months, with the juvenile frogs first hopping onto land at the end of summer or beginning of autumn. Almost immediately, they begin migrating up tributaries to escape the high flushing flows that occur during winter in the larger stream reaches.

The timing of life-history events in the Sierra newt (*Taricha torosa sierra)* is similar to that for foothill yellow-legged frogs. For instance, newts usually migrate from terrestrial hibernation sites to breeding streams in spring; females then attach eggs to drowned wood or rocks in the river. Aquatic larvae generally transform into terrestrial newts in early autumn and subsequently move onto land. Unlike foothill yellow-legged frogs, the skin of Sierra newts contains a poison that is well advertised by the newt's bright orange belly. As a result, Sierra newts have few predators and can frequently be seen cruising about the forest floor during wet periods.

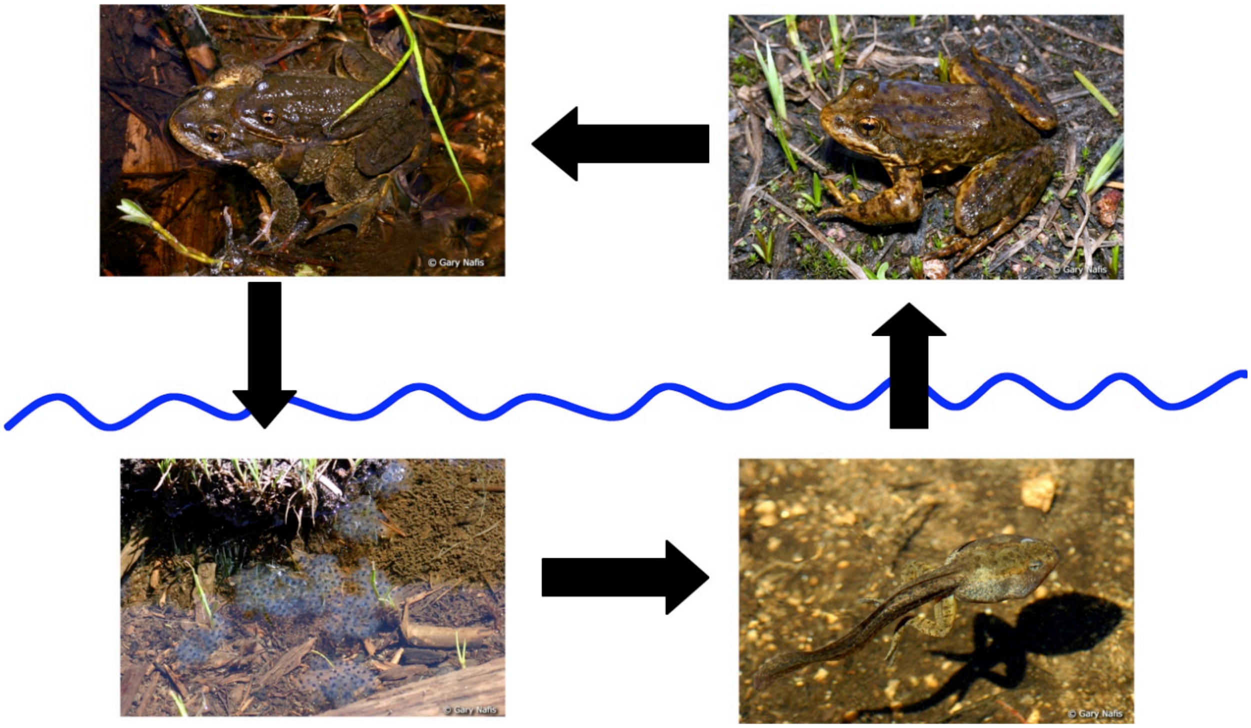

Figure 8.1 Biphasic lifecycle diagram. The Sierra newt and all frogs found in the Tuolumne River and have a biphasic lifecycle, which means that eggs and larval stages (i.e., tadpoles for frogs) are aquatic while recently metamorphosed juveniles and adults are terrestrial. This type of lifecycle allows the Tuolumne River's amphibians to take advantage of both aquatic and terrestrial environments. For instance, Pacific treefrog tadpoles live in temporary ponds that lack fish predators but contain plenty of food in the form of algae. Before ponds dry, the tadpoles metamorphose into terrestrial frogs that then disperse onto land and feed on terrestrial insects. In this way, Pacific treefrogs are able to evade predation during the vulnerable tadpole stage while exploiting transient food sources.

La Grange Dam to the Confluence of the San Joaquin and Tuolumne Rivers

The lower reaches of the Tuolumne River were originally the home of the California red-legged frog (*Rana draytonii)*, the star of Mark Twain's "The Celebrated Jumping Frog of Calaveras County" and the largest frog native to California. Before human modification of the landscape, the lower reaches of the mainstem river were flanked by thick growths of riparian vegetation, seasonally inundated floodplains covered with aquatic plants such as cattails and bulrushes, and numerous low-velocity side channels. California red-legged frogs were well adapted to this slow-flowing, marshy environment. Eggs were laid in late winter or early spring to coincide with cold water temperatures necessary for proper embryonic development. Tadpoles exhibited large tail fins and thick, chunky bodies, which provided the propulsion and maneuverability necessary for moving through the highly vegetated, still-water environment. Like foothill yellow-legged frogs and Yosemite toads, most California red-legged frog tadpoles metamorphosed at the end of their first summer, enabling them to utilize temporary waters for rearing. Adult frogs evaded predators such as herons by being most active at night (the other native frogs are active mainly during the day) and by using dense vegetation for concealment. California red-legged frogs used vibrations transmitted along plant stems to detect small-mammal prey and approaching predators.

AMPHIBIANS IN THE REGULATED TUOLUMNE RIVER

Upstream of Hetch-Hetchy Dam

While many of the high elevation lakes in the Tuolumne River basin appear pristine, their amphibian fauna most definitely is not: Sierra Nevada yellow-legged frogs are absent or severely reduced in the majority of the waters they historically inhabited. Three major factors, of which two are clearly due to humans, have pushed Sierra Nevada yellow-legged frogs to the brink of extinction. These factors have been especially effective at harming this highly aquatic frog because they all depend on water.

The vibrant colors, aggressiveness, tasty flesh, large size, and acrobatics of trout have long infatuated anglers. The settlers that colonized California after the Gold Rush were no different and stocked many trout species throughout the state's waters. The Sierra Nevada's historically fishless waters were attractive for trout planting for two major reasons: small lakes and streams were everywhere, and they were cold. Thus, in addition to "private" plantings by laypeople, fisheries agencies collected and dumped trout into high-mountain lakes and streams with milk jugs and mules, trucks, and eventually airplanes. Although some of the introduced trout were unable to persist due to poor spawning conditions, many established viable populations (most notably, the brook trout *Salvelinus fontinalis)*. Deeper lakes sustained trout for the same reason they were preferred by Sierra Nevada yellow-legged frogs: they did not become hypoxic. Trout are carnivorous and feed selectively on the most energy-rich food source available. In high-elevation waters, the Sierra Nevada yellow-legged frog served as ideal trout food: they were larger than the common aquatic bugs; their long tadpole stage meant they were a year-round food source; and their conspicuous use of shallow, warm waters made them easy prey. Additionally, where Sierra Nevada yellow-legged frog tadpoles were few or absent in trout lakes, the fish would then focus on eating the immature stages of aquatic insects or the tadpoles of other frogs (e.g., Pacific treefrogs). This reduced the amount of food available for Sierra Nevada yellow-legged frogs. As a result, few if any Sierra Nevada yellow-legged frogs or tadpoles are found today in lakes or streams with trout.

In 1998, biologists discovered a new disease-causing pathogen, the chytrid fungus, *Batrachochytrium dendrobatidis*, that killed frogs in rainforests of Central America and Australia. Not long thereafter, chytrid fungus was found worldwide and in many different species of frogs, including Sierra Nevada yellow-legged frogs. The effect of chytrid fungus on Sierra Nevada yellow-legged frogs appeared particularly dramatic, with local extinctions occurring as rapidly as one year after an outbreak of the disease.

A number of factors have made the chytrid fungus an especially potent killer of Sierra Nevada yellow-legged frogs. First, the disease is aquatically transmitted from infected to uninfected individuals; consequently, the more aquatic Sierra Nevada yellow-legged frog has a high chance of contracting the fungus. Second, chytrid fungus infects and is transmitted between both tadpoles and frogs; however, it only kills frogs. Until infected tadpoles metamorphose and die, they can spread the disease to other tadpoles and frogs for years. Third, chytrid fungus spreads more quickly when tadpoles and frogs are close together, which happens often in the warm waters of summer. Fourth, tadpoles are infectious even when hibernating in ice-covered lakes. And fifth, the chytrid fungus spreads most rapidly around 20°C, a temperature commonly reached in the shallows of high-elevation lakes during summer. If warm water temperatures become more common due to climate change, then the effects of chytrid fungus on the Sierra Nevada yellow-legged frog might become even more drastic.

The third contributor to the decline of the Sierra Nevada yellow-legged frog is pesticide drift from San Joaquin Valley agricultural fields. Westerly winds that move across the valley deposit pesticides onto the foothills and mountains of the Sierra Nevada. Some of these pesticides are extremely toxic in water and harm amphibians in many ways. For instance, frogs poisoned with insecticides swim poorly, grow slowly, are relatively unresponsive, and thus are more likely to be eaten by predators. In Yosemite, Pacific treefrogs have been found with high levels of pesticides such as diazinon and DDT. Additionally, many populations of the Sierra Nevada yellow-legged frog have been eliminated in areas downwind of pesticide-sprayed agricultural fields. Thus, pesticides have interacted with introduced trout and chytrid fungus to deliver a three-pronged attack that threatens the existence of this frog.

Similar to Sierra Nevada yellow-legged frogs, numbers of Yosemite toads have drastically declined in recent years. However, the causes for the loss of Yosemite toads are somewhat ambiguous. While pesticides have been indicted as a significant player in the loss of many California amphibian populations, Yosemite toads are one of the few species that seems unaffected by the poisons. Trout predation also does not appear to be a major factor: Yosemite toads mostly breed in temporary waters without fish and exude toxins from glands on their heads that are distasteful to predators. Since Yosemite toads are susceptible to chytrid fungus and the more aquatic males appear to suffer higher mortality rates than females (although not as high as for Sierra Nevada yellow-legged frogs), the disease may be partly responsible for population reductions.

California's climate may have also played a role in the decline of the Yosemite toad. Because breeding ponds are fed by snowmelt, they dry later in years with large snowpacks. In drought years, however, ponds may become dry before tadpoles have a chance to metamorphose. Consequently, alterations in hydrology and more frequent droughts care of climate change may have caused greater losses of tadpoles to desiccation. Additionally, the hatching success of the closely related western toad *Bufo boreas* was significantly reduced when exposed to ultraviolet radiation, presumably due to DNA damage. Coupled with the fact that ultraviolet radiation is more intense as one increases in altitude, then Yosemite toad eggs may suffer similarly to western toad eggs. Finally, cattle grazing in meadows may have exacerbated the other factors by lowering water tables, trampling vegetation and tadpoles, and silting in ponds and streams.

Hetch-Hetchy Dam to La Grange Dam

Amphibians in the middle reaches of the Tuolumne River, like those in the upper basin, have suffered severe population declines. However, foothill yellow-legged frogs and Sierra newts have had their own unique problem: dams. Since both species, especially foothill yellow-legged frogs, are adapted to the natural flow regime, changes in river flows by dams have virtually eliminated amphibians in the mainstem river. Foothill yellow-legged frogs have suffered in two major ways. First, warm weather in late spring no longer equates to predictably declining river levels. Instead, warm weather is now associated with severe fluctuations in flows due to hydropower generation. Thus, without the cue of rain delaying reproduction, eggs laid by foothill yellow-legged frogs are simply scoured by the high daytime flows. Secondly, the eggs washed downstream are essentially lost to the population through stranding, crushing, or deposition in suboptimal habitats (this also holds true for the eggs, larvae, and adults of Sierra newts). Consequently, only free-flowing tributaries to the middle reach of the Tuolumne River, such as the Clavey River, contain viable populations of foothill yellow-legged frogs and Sierra newts.

Box 7.1

The Pacific Treefrog (*Pseudacris regilla)*

All amphibians in the Tuolumne River watershed have declined substantially except for the Pacific treefrog. This frog is not restricted to a single reach of the Tuolumne River but in fact ranges from the headwaters all the way to the confluence with the San Joaquin River. Although it has suffered from pesticide poisoning and predation by trout, a suite of physiological and life-history traits have allowed it to persist where other species have gone extinct. Following is a list of these traits:

- *Relatively high amounts of photolyase, an enzyme that repairs DNA damaged by ultraviolet-B light*
- *Resistance to chytrid fungus*
- *Short time period spent in water, which limits its exposure to pesticides and fish predation*
- *Ability to breed in very temporary waters, including snowmelt ponds, water troughs, bird baths, and toilet tanks*

Figure7.2 Pacific Tree frogs (*Pseudacris regilla*) in amplexus.

La Grange Dam to the Confluence of the San Joaquin and Tuolumne Rivers

While declines in native amphibians have been precipitous in the upper and middle reaches, it could not possibly be worse than downstream of New Don Pedro and La Grange dams: the California red-legged frog is now extinct in the Tuolumne watershed. Many factors, of which some were unique, contributed to the demise of the California red-legged frog. The wholesale draining and diking of marshes and floodplains for agriculture, coupled with the taming of the Tuolumne River with dams and levees, eliminated much of the habitat that California red-legged frogs originally occupied. A large demand for frog legs in San Francisco resulted in the overharvesting and decline of the California red-legged frog (the one native frog big enough to be harvested) throughout much of its range. To mitigate the loss of this food source, the American bullfrog *Rana catesbeiana (*recently renamed *Lithobates catesbeianus*) was introduced in the early 20th Century. The introductions were successful, and today bullfrogs range throughout California, including the Tuolumne River. The bullfrog is a voracious, hardy species that is known to feed on both frogs and tadpoles of other species; additionally, it is ecologically similar to the California red-legged frog. Thus, bullfrogs not only usurped areas that were previously occupied by California red-legged frogs, but they also prevent the possible recolonization of such areas through predation and competition. Like Sierra Nevada yellow-legged frogs, California red-legged frogs were also probably consumed by introduced fishes. Finally, the few California red-legged frogs that inhabited the basin in the latter half of the 20th Century were likely affected by pesticides, since they are almost never present in areas downwind or downstream of pesticide-treated lands throughout the Central Valley.

SUMMARY

Before human-caused changes to the landscape, the Tuolumne River hosted an amphibian fauna well adapted to the different environments found from its headwaters to its mouth. However, water development, agricultural activities, introduction of non-native species, and overharvesting have severely reduced or eliminated almost all native amphibians by exploiting traits that had previously been adaptive. Consequently, the amphibian communities of the Tuolumne River are now depauperate or dominated by the bullfrog. Unfortunately, the many threats that native amphibians face still exist and thus we can expect their populations to decline further.

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Chapter 9: Tuolumne's Natives

SABRA PURDY AND NAOMI MARKS

INTRODUCTION

This chapter illustrates human influence and endeavors in California before gold was discovered in 1848. Native Americans were present in California for an estimated 10,000 years before Spanish, Mexican, Russian, and American colonization and the subsequent major changes in the land use, management, and ecology took place with the arrival of those settlers. Prior to the gold rush, the Tuolumne River watershed was almost exclusively the domain of the Yokut, Me-wuk, Mono, and Paiute tribes. Their landscape management practices (most obviously burning, but including other activities as well), while not readily evident to many of the white settlers that followed, definitively shaped the ecology of the watershed they lived in. The lower reaches of the watershed were part of the Mexican land grants of the early 1800s, but few Euro-American installations existed outside of the coast and became more sparse as one traveled east in the Central Valley. This chapter includes some of the larger early history of California, not just the history of the Tuolumne watershed, because it is critical to understand the social, political, economical, and ecological conditions at the time of the gold rush and its impact upon the native people and the landscape that they both tended and depended on. The influx of Euro-Americans into California and the Tuolumne River watershed irrevocably altered not only the lives of the people living there, but the very function of the landscape itself.

Figure 9.1 Northern California Indians from several tribes as depicted by Russian artist, Ludwig Choris in 1822 from sketches made on a 1816 voyage along the California Coast. Image from Bancroft Library from Calisphere website BANC PIC 1963.002:0365—B.

The Sierra Me-wuk (or Mi-wok as it is sometimes spelled) were comprised of three divisions. The Northern Sierra Me-wuk occupied foothills and mountains of the Mokelumne and

Calaveras River drainages; the Central Sierra Me-wuk claimed the foothill and upland portions of the Stanislaus and Tuolumne watersheds; and the territory of the Southern Sierra Me-wuk embraced the upper reaches of the Merced and Chowchilla Rivers. The Yokut tribe inhabited the lower reaches of the Tuolumne River and various sub-groups within the tribe held territory throughout the San Joaquin Valley to the south.

There is a long history of trade between the Mono, Paiute and Me-wuk people although peace between these groups may have been tenuous at times. A long-established trade route between west-slope foothills and east slope obsidian grounds was accessed from Mono Pass and Tuolumne Meadows via Soda Springs, and Grand Canyon of the Tuolumne. Travelers along this route used Hetch Hetchy Valley to foraging for acorns, plants, and berries, as well as to hunt small game, fish, insects, and other animals.

Horticultural and Landscape Management

Landscape management by indigenous people was ongoing, and caused permanent changes in plant associations, species composition, and in the gene pools and genetic structures of species in a multitude of Sierra Nevada vegetation types. Me-wuk and Paiute land managers used burning, irrigation, pruning, selective harvesting, tilling, transplanting and weeding to manage and cultivate wild plants, with varying degrees of permanent ecological and environmental impact. Fire was undoubtedly the most important land management tool. Burning was employed to clear brush, maintain grasslands and meadows, improve grazing for deer, enhance production of basketry and cordage materials, modify the composition of understory species in forests, and reduce fuel accumulation that might otherwise sustain intense fires.

The results of these land management practices can be classified in three broad realms: 1) Plant dispersal, in which Native Americans deliberately rearranged the distribution of some plant species, resulting in some unusual plant distributions and genetic variations; 2) habitat modification, in which Native Americans expanded and maintained suitable habitat for desired species (e.g. promoting the growth of preferred grazing materials for deer); and 3) modified gene pools, changing the genetic structures of plants through selective harvesting and transplanting. Many intensively used plant species were selected and adapted to small-scale human disturbance and cultivation as a result of hundreds to thousands of years of horticultural management.

The Mission Period

The advent of the Spanish missions in California had profound impacts on the Native Americans and was the beginning of a long period of servitude and diaspora for the tribes. The Indians of the Tuolumne River watershed were generally not part of the Spanish missions, but the influence of the missions on other tribes and the runaway neophytes that joined the interior tribes created an important cultural and social shift, and is thus discussed here in some detail. The early Spanish voyagers began exploring Alta California in 1542, but their exploration was primarily ship-based and limited to coastal regions. At that time, Alta California was little valued, and largely ignored. By the 1760s, there were fifteen Jesuit missions established in Baja California through the Spanish territories in Mexico. In 1767, a series of political maneuverings in Europe resulted in the expulsion of the Jesuits from the Roman Catholic Church in Spain and Portugal. The Jesuits were forcibly removed from their missions in Baja, and the Franciscans, under Father Junipero Serra were given responsibility for the Baja missions in 1768. However, it became clear that tsarist Russia, established in Alaska in the 1730s, had territorial ambitions for the greater Pacific coast and began to establish forts in British Columbia, the southern-most being Fort Ross in Sonoma County. The Spanish government felt that the crown's interests would be better served if the Franciscans concentrated on establishing missions in Alta California, giving the Baja missions to the Dominicans. The orders given to Visitador General José de Gálvez by King Charles III were to "Occupy and fortify San Diego and Monterey for God and the King of Spain." These were the first of 21 missions that the Franciscans established in Alta California.

The idea behind the missions was to claim land for Spain, civilize the natives, and eventually secularize the mission and its holdings once the neophytes were ready to take control and become tax-paying citizens of Spain. This model worked well enough with the more complex societies of Mexico; however, it soon became evident to *Padre* Serra that the more simplistic hunter-gatherer life style of the California natives would not easily lend itself to Catholicism's civilizing influences. Another viewpoint suggests that as these Alta California missions became more successful and wealthy (they controlled 1/6 of the land in the state), the *Padre*s were increasingly loathe to turn over their holdings to the native converts. These coercive religious and labor camps were highly successful in producing wealth for the Spanish Crown and the Franciscans, and they were in no hurry to release control over the vast free labor force they had cultivated.

Mission compounds were set up with an eye towards permanent water, ample wood for building and fires, grazing areas for livestock, and soil to grow crops. Farming was the predominant activity. Livestock were primarily used for hides and tallow. Native Americans joined the missions at first out of curiosity or were enticed in by the pageantry of the mass and the lure of abundant food. However, it quickly became evident that the purpose of the military escort accompanying each *Padre* and mission was as much for the procurement of new converts as it was protection. Many individuals were taken in raids on the interior tribes after most of the coastal tribes had either been converted or eliminated by disease. By the early 1800s the population of neophytes in California's missions reached 20,000.

The Franciscan priests had little good to say about their neophyte converts. *Padre* Pedro Font of Mission San Antonio called them "dirty, not pleasantly formed, and embarrassingly primitive in their mode of dress." The *Padre*s' primary goal was to achieve a large "harvest of souls." The *Padre*s kept careful records of their activities at the mission. By 1832, there were a recorded 87,787 baptisms 24,529 marriages, and 63,789 deaths. Once baptized, however, the neophytes (new converts) were essentially indentured servants who were no longer free to come and go as they pleased and were subjected to harsh treatment and complete acculturation. Crowded, unsanitary conditions led to disease and exceedingly high mortality rates among the mission Indians, particularly among women and girls who were forcibly sequestered until marriage. Children were separated from their parents. Tribal history and knowledge was sharply diminished.

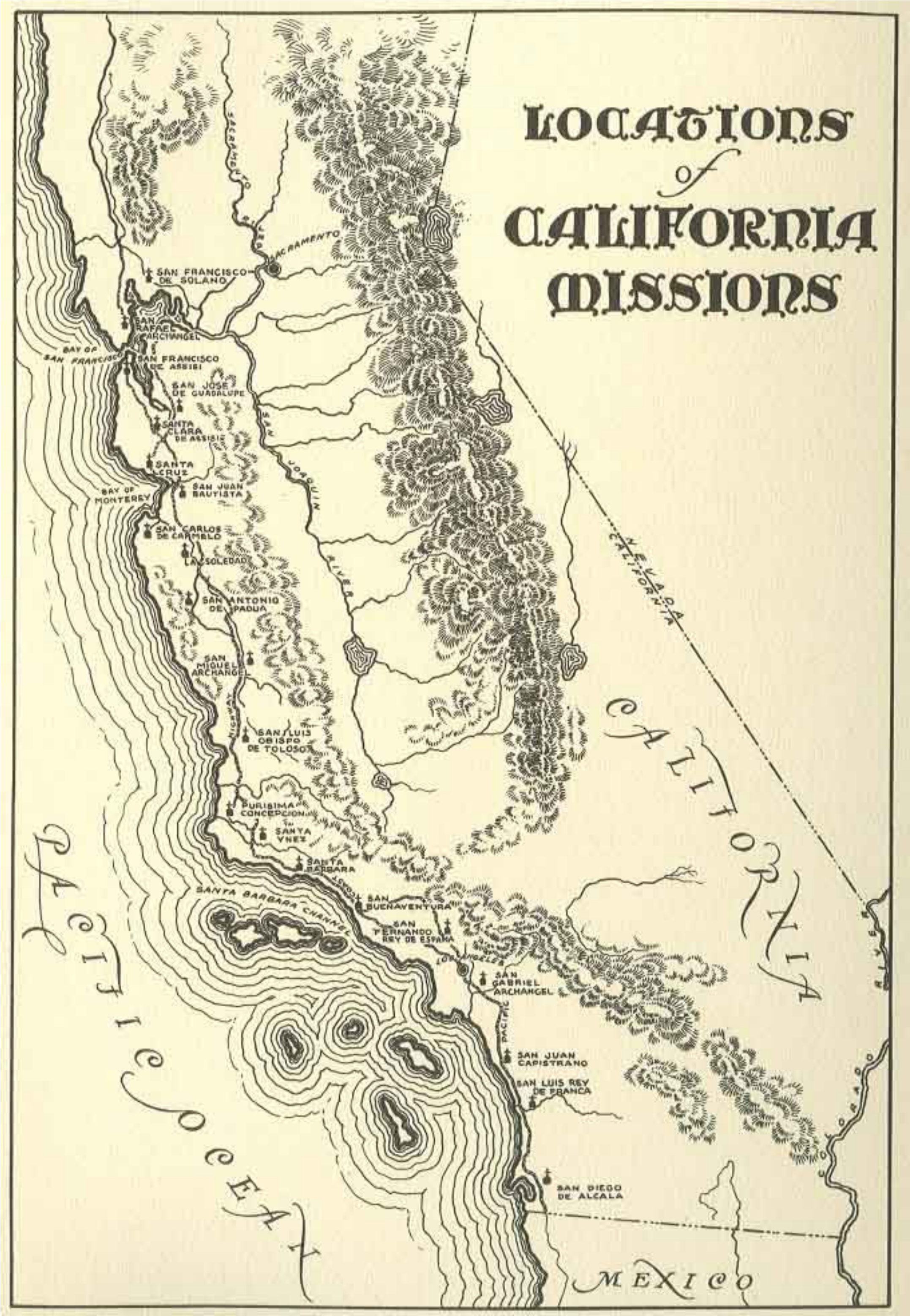

Figure 9.2 Locations of California Missions. From www.sacred-texts.com.

Most mission Indians were in essence slaves, their activities severely curtailed and the punishments for misbehavior or insubordination were severe. Every mission had its whipping post. Runaways were treated brutally. Nevertheless, many neophytes did run away, and typically joined up with the interior tribes outside the mission's direct influence. The interior tribes were well aware of the missions' presence and had already suffered indirectly through waves of a number of novel diseases they had no resistance to including small pox, measles, and malaria that were brutally effective in reducing their population. California's native population was estimated at ~300,000 at the beginning of the colonial period, but by the eve of the gold rush, it had decreased to around 150,000 individuals, a stunning decline in only 79 years. Food had become a major problem for the interior tribes as well. Free ranging Castilian cattle, feral hogs, horses, goats, and other mission livestock decimated native vegetation and food sources in the Central Valley and foothills. In particular, the feral hogs ate acorns, a primary staple for many of the tribes. The native grasslands in the Central Valley were already giving way to introduced annual grasses and game was driven out through competition, over hunting, and changes in the ecosystem structure. This created a desperate situation for the interior tribes.

As the missions expanded and raided for neophytes from farther afield, more and more runaways of different tribes fled the missions (one estimate is that 1/24 neophytes successfully escaped the mission, though many failed and were brought back). Often, they could not return to their historic territories, their tribes dissolved or absorbed by the missions. Instead, they turned to the interior tribes forming new, conglomerate tribes cobbled together from the survivors from many regions. E.D. Castillo writes:

> Many of these returned exiles were faced with difficult tasks of reconstructing their decimated communities in the wake of crippling population declines. Furthermore their tribal lands had become transformed by the introduction of vast herds of horses, cattle, sheep, goats and hogs that destroyed the native flora, the primary source of native diet. Wild game animals were likewise driven off by these new animals. What developed from this new condition was the emergence of guerrilla Indian bands made-up of former fugitive mission Indians and interior tribesmen from villages devastated by official and unofficial Mexican paramilitary attacks and slave hunting raids. Eventually a significant number of these interior groups joined together to form new conglomerate tribes. These innovative and resilient tribes quickly converted the anti-mission activities of their members into systematic efforts to re-assert their sovereignty by widespread and highly organized campaigns against Mexican ranchers and government authority in general.

This created a melding of cultures amongst the interior tribes before they came in direct contact with Euro-Americans, though linguistic and cultural information must have retained its importance, since many of the tribes maintained their languages well into the 20th century. The new interior tribes made use of the knowledge gained by the mission Indians and stole horses which they sold to Canadian and American fur trappers across the Sierras, harassed land grant ranches encroaching into the Central Valley, and took advantage of the missions' large, free ranging herds of cattle in the to supplement the loss of game. The missions were sometimes subjected to raids from these amalgamated tribes, but overall, direct contact with the foothill tribes did not take place until the gold rush.

Mexican Independence

Mexican independence from Spain was initiated in 1810, when Mexican-born Spaniards, Mestizos and Indians launched a revolution against the colonial Spanish government. It lasted 12 years, but Spain was heavily engaged in fighting its own civil war and ultimately the 1821 Treaty of Córdoba gave Mexico independence. With Mexican independence, much of the support for the missions dried up. In 1833, the Mexican Congress passed An Act for the Secularization of the Missions of California which dissolved the official mission system and pushed the colonization of Alta California through the sales of mission holdings to private interests. At this time, the Mexican government also began to issue land grants to encourage settlement in Alta California. Those in favor of dissolving the missions spoke promisingly of freeing the native Americans from mission servitude, voting rights for natives, and ownership of the mission lands, but it became clear in the early years of the Mexican government that those were empty words and the California Indians remained marginalized, unwanted, and unlanded.

The Early Explorers

The eastern side of the Central Valley of California was principally the domain of the Yokut Indians before the 1830s. The first non-indigenous person known to have explored the region between the Stanislaus, Tuolumne, and Merced Rivers was thought to be Spanish Lieutenant Gabriel Moraga. In 1806, he crossed the Coast Range somewhere south-west of Los Banos, and moved north along the San Joaquin River. Along the way he took it upon himself to name the tributary rivers he passed: the Rio Merced, which still bears the same name, the Rio Dolores (later renamed Tuolumne), and the Rio Laquismes (later renamed Stanislaus). He also changed the Rio San Francisco to the Rio San Joaquin, in honor of his father, Joaquin Moraga, who had explored some of the northern San Joaquin valley in 1776. Soon after Moraga, Canadian and American fur trappers came to tap the bountiful beaver pelts along the San Joaquin tributaries. Jedediah Smith (ostensibly the first "American" in California) trapped along the lower Tuolumne from 1825 to 1827 and spoke of a river teeming with salmon, otters, and beavers. In 1846, the treaty ending the Spanish-American war gave possession of California to the United States. Part of the terms of the treaty was that the land grants given by the Mexican government to stimulate agriculture and ranching be honored. A number of these land grants occurred in the Tuolumne River watershed, most famously, one called "Las Mariposas," originally given to Juan Bautista Alvarado, the former governor of California under Mexico, in 1844. However, Senor Alvarado never occupied it because of fear of marauding Indians. It was sold to John C. Fremont in 1847and became the site of the 1851 Mariposa Indian war.

European and American Immigration

British and American entrepreneurs and ranchers began to take advantage of the relaxed rule under Mexican authorities, in the 1820s and 1830s. These ambitious ranchers demonstrated that it was possible to turn a profit by raising cattle and exporting the hides to the Eastern U.S. and tallow to South America. Beef was primarily a waste product at this point, but the business was so profitable that it precipitated the breakup of the vast Mission land holdings and allowed the spread of ranching nearly as far east as the Mother Lode. Among these early entrepreneurs was one Johann Augustus Sutter (a.k.a. John Sutter) who amassed an enormous holding near Sacramento, which he dubbed New Helvetia in honor of his native Switzerland.

Prosperity increased, and immigration of Americans via covered wagon began in earnest in the 1840s.

In 1846, tensions between the United States and Mexican governments over the annexation of Texas to the Union led to a declaration of war. Word eventually spread to California and a small group of citizens revolted and seized the Mexican military garrison stationed in Sonoma. Word spread throughout the state and the U.S. Army eventually took over Sacramento, San Francisco (then Yerba Buena), and Sacramento and attacked southern California outposts in the Los Angeles area. There was some resistance from local vaqueros banding together, but eventually, California was U.S. controlled. The U.S. was clearly dominant in other areas of the conflict, and Mexico's government was in shambles. In February, 1848, the two countries signed the treaty of Guadalupe Hidalgo, ending the war and ceding California, Arizona, New Mexico, and Texas to U.S. control.

The Gold Rush and its Consequences

On January 24, 1848 James Marshall discovered gold in the millrace of the sawmill he was constructing on the American River at Coloma in support of Sutter's New Helvetia Fort. News spread quickly of the find, and within months prospectors were searching for gold in the drainages of every major river and tributary draining the Sierra. Despite effort to keep the find a secret, by the time the California Star published its first report of the gold discovery on March 15, 1848, many in California were already heading to the gold mines. In all some 300,000 men, women and children flocked to California from the rest of the United States and from abroad that year. That the Mexico missed the opportunity to exploit the Mother Lode is one of the great ironies of history.

With the influx of vast numbers of Euro-American prospectors, conflict with the Native Americans inhabiting the region was inevitable. There was no infrastructure in place to support the thousands of new immigrants to the Sierran foothills. The new population of immigrants competed with existing residents for food and other resources. Native Americans living in the Tuolumne watershed region subsisted on varied diet that included small game, insects, fish, plants and berries. The newly arrived miners decimated game animals in the Sierra foothills and food became scarce for the resident natives. In response, Native Americans became increasingly aggressive towards the encroaching miners.

Miners decreased the quantity of wild game available to Native Americans by disrupting and destroying woodland habitats and by heavily hunting deer and other large game to feed the rapidly growing mining camps littered throughout the foothills. The increases in population also put significant stresses on the traditional foraging areas, and this combined with the overhunting of game animals caused deep reductions in the availability of food. Traditional land management practices were also arrested as miners began to stake claims throughout traditionally managed lands. These changes forced Native Americans into a period of famine, and conflicts with miners escalated as Native Americans began to steal horses and mules for meat. Conditions were incredibly bad for Native Americans at that time and their population, already halved as a result of mission disease, labor, and fighting, was halved again to fewer than 70,000 individuals. Some sources credit the century of colonization in California as the Indian was with the highest number of casualties in the entire United States. Violence against Native Americans was rampant and without political or legal recourse, many died at the hands of fortune seekers. The survivors fled further north and east as additional waves of settlers arrived. The population of the Central Sierra Miwok serves as a sobering example; their population declined from approximately 8,000 before European contact to about 700 by 1910. In this diaspora, much of the cultural and linguistic knowledge of the tribes was lost and the history of that time from the tribes' point of view is sketchy at best.

The Mariposa Indian War

Clashes over limited resources escalated between 1849 and 1850 as the Native population was further pushed out of their historic locales, had more dealings with the settlers, and found that raiding remote outposts and ranches was far more lucrative than the meager living now available in the forest. James Savage was an ambitious easterner who immigrated to California in 1846, losing his wife and child en route to the rigors of the trail. He arrived in California at the height of the Bear Flag Revolt and immediately joined Fremont's battalion. The records indicate that he was a less than exemplary soldier. Fortunately the conflict ended quickly and he was discharged. At that time he traveled inland and took up residence with the Tulareno Indians of the southern Central Valley. He quickly learned the language and customs of the tribes and married the daughters of several tribal leaders to fortify the bonds of kinship and authority within the region. The Indians began calling him "El Rey Huero," (the blond king) until his request that he instead be called "El Rey Tulareno," (king of the Tularenos). Having thus assumed authority over his new tribe, he led the tribe in various battles and skirmishes with neighboring tribes, and the victories gained there further cemented his influence and authority over the region's tribes. When gold was discovered in Tuolumne County in 1848, he immediately organized a group of approximately 500 Indians to work claims on Woods Crossing on the Tuolumne River, as well as running several trading posts. He accumulated considerable wealth in this manner.

In 1849, Savage opened a new trading post on the Merced River just 25 miles west of Yosemite Valley, a move which angered the Yosemite Indians. This was an amalgamated tribe that had vacated Yosemite Valley for some time after the murderous malaria outbreak that decimated Central Valley and foothills tribes in 1833. Survivors fled to the eastern Sierra to take refuge with the Mono Indians. Under Chief Tenaya (also spelled Teneiya) this merged tribal entity consisted of Yosemite Me-wuks, Monos, and Paiutes returned to Yosemite Valley. Savage's trading post on the Merced was viewed as a hostile incursion into their land, and Savage's tribal influence was limited to the more southern Westslope groups, rather than this coalition of eastern Sierra Paiute and Me-wuks who called themselves Ahwanheechee. The Ahwanheechee divided themselves into two parts and the word "Yosemite" is the white interpretation of the word "Uzumati," which denoted the larger of the two Ahwanheechee groups.

In May of 1850, the Ahwanheechee attacked Savage's Merced River trading post, but the attack was repulsed by Savage and his native employees. They tracked the Ahwanheechee towards Yosemite Valley, but turned back for fear of an ambush. Savage then abandoned the Merced trading post and opened another on Mariposa Creek near Agua Fria. By the fall of 1850, there was generalized unrest amongst the natives throughout the foothills. One of Savage's wives informed him that there was a plan afoot to rid the foothills of the white intruders. Savage realized his limited influence over the natives of the area and decided a show of force was in order to convince the local natives of the folly of trying to battle the whites. He took the leader of the Tularenos, Chief Juarez, to San Francisco where he could observe the ships, cannons, soldiers, and sheer numbers of whites that filled the city. Juarez remained heavily drunk for the duration of the trip which included October 29, 1850, the day California was admitted to the Union. He and Savage argued violently and blows were exchanged, humiliating Chief Juarez and further alienating him from Savage. Upon returning to the foothills, Savage once again attempted to dissuade the tribes from an open war with the whites. He asked Juarez to recount what he had seen in San Francisco. Juarez replied that he did not think the whites of San Francisco would come to the aid of the gold digging whites if the Indians made war upon them. He felt that the whites of many tribes lacked the unity to come to the aid of the miners. Their ships and cannons could not come inland, and therefore, it was not only safe, but prudent to make war against the miners. The leader of the Chowchillas, Chief Jose Rey, agreed with Chief Juarez, and they pledged their warriors to the fight. Savage realized that he could not dissuade the natives from their fight and went back to his Mariposa trading post to organize a contingent of men to protect it.

By December of 1850, the Governor of California, Peter Burnett, called upon United States Indian Agent, Col. Adam Johnston to investigate and settle the dispute between the miners and the natives. Johnston joined Savage at the Mariposa trading post and soon after, nearly all of the Native Americans living in the area disappeared; something both Savage and Johnston took to be an ill omen. Again Savage tried to intervene with the native plan, and taking Johnston and 16 men with them, they tracked the missing Indians and their leader, Chief Baptiste, to a hilltop 30 miles east of the Mariposa trading post. Again Savage tried to induce the natives to return to their villages and his service rather than make war against the whites. Chief Baptiste replied that mining was a tough way to make a living and that they could better satisfy their needs by stealing from the whites. He also told Savage that he and his men had already robbed Savage's Fresno River trading post, killing three men. War had begun.

Savage and his party returned to Mariposa Creek and the news of the native attack on the Fresno trading post was confirmed. Col. Johnston organized a force of thirty-five volunteers to go to the Fresno and assess the situation and bury the dead. Upon reaching the Fresno trading post, Johnston found it had been thoroughly raided and what could not be carried off had been burned. He described is as a "a horrid scene of savage cruelty."

The Sherriff of Mariposa County, James Burney, organized a force of seventy-five men to hunt down the Native Americans. They found a group of approximately four hundred encamped near present-day Oakhurst. It was before dawn and most of the camp was asleep, but the Sherriff's force was discovered and the battle began. While the native forces greatly outnumbered the Sherriff's posse, their weaponry was a hodgepodge mix of bow and arrows and old guns. The better armed Sherriff Burney and his men were able to take over the natives position, driving them into the rocks above the camp. Eventually Burney and his men drove them from the rocks as well, and then made their withdrawal. The casualties for the whites were few. Six men were injured of which two died. The natives lost an estimated forty men.

After this skirmish, Burney and Johnston redoubled their efforts to persuade the state and federal government to intervene in this Indian war. New governor, John McDougal, felt strongly that there should be a military solution to the Indian problem and by February of 1851 had authorized a force of 200 men to exact surrender from the rebellious natives. McDougal was certain that the federal government would happily support such an expedition, but the trio of United States Indian Commissioners sent to examine the problem and issue a policy statement, reported that the governor was "belligerent" about Indian affairs and still hoped a peaceful solution could be found. Upon hearing that a force of 200 men had already been authorized and that the federal government was expected to compensate, the three Indian Commissioners quickly set out for Mariposa to see what could be done.

Meanwhile, Savage and Sherriff Burney had gathered a militia of 164 men to continue the campaign against the natives. Burney split the force into two groups to cover more ground and left the northern contingency under the control of a man named John Boling with Savage as a scout. Together with approximately 100 men, Savage and Boling discovered a group of some five hundred natives of the Chowchillas, Chookchancies, Nootchu, Honahchee, Potoencie, Kahwah, and Yosemite tribes under chiefs Jose Rey and Jose Juarez of the Chowchillas. The white militia attacked at dawn and set fire to the native's shelters. Under the cover of the smoke, most of the natives escaped and the militia had no casualties, though an early retreat was called when the fire turned towards the militia's bivouac. The militia deemed it a victory.

The state-authorized "Mariposa Battalion" was mustered the 13th of February 1851 with "the duty of subduing such Indian tribes as could not otherwise be induced to make treaties." The battalion was thereby under the command of the federal Indian Commissioners, and all officers were to report to the commissioners. The commissioners began to make contact with the tribes to try to convince them to sign treaties. Historian David Smith writes:

> The first treaty council was held on 9 March. As a result, sub-tribal groups of the Mercedes and the Potawachtas became the first to agree to the government's terms. The most significant treaty, that which involved the greatest number of Indians, was signed on 29 March. The treaty guaranteed substantial aid in establishing agrarian communities, reservation land located in the fertile San Joaquin Valley, and hunting and gathering rights in their traditional homelands. A total of sixteen tribes and sub-tribes signed the treaty including the Pohonochees, the Nookchoos, and some sub-tribes of the Chowchillas. The treaty also gave the Yosemites and other Indians the option of being associated with the program offered by the treaty upon their arrival at the reservation. On 16 March, Company A had its first skirmish with Indians at Fine Gold Gulch, and although the action allegedly incited those natives involved to turn themselves in, the progress of removing the Indians from their homelands had slowed. Impatient, Major Savage sought orders from the governor hoping to end the stalemate between the Indians and the battalion, but before he received a reply, the commissioners gave him permission to initiate an extensive campaign against native tribes which had yet to sign a treaty. On 20 March, the Mariposa Battalion left camp to begin a campaign against the Chowchillas, Nootchus, and Yosemites. Fighting foul weather, Major Savage marched with B and C Companies to the Wawona

> area where they established a base camp for their operation. Captain Kuykendall was sent south with Company A to round up the Chowchillas who had refused to come to the reservation. On the morning of 24 March, B and C Companies advanced upon a Nootchus village in the Wawona area. The natives, having no other option available to them, surrendered at once, and Major Savage began to arrange their transport to the reservation. He also sent a few Indian runners to other villages in the region and to Chief Tenieya of the Yosemites, explaining the offer guaranteed by the treaty.

Chief Tenieya arrived at the battalion's camp at Wawona to discuss the treaty and had little choice but to agree to its terms on the spot. The remainder of Tenieya's tribe was supposed to arrive shortly, but after several days of fruitless waiting, Major Savage decided to search out the missing natives himself. With Chief Teneiya and his people in tow, Savage pushed on to the northeast, soon encountering a small band of mostly women and children. When asked where the remainder of his tribe was, Chief Teneiya replied that they had fled to the east side of the Sierras to take refuge once again with the Mono Lake groups. Savage did not believe this to be true and the group continued east, eventually arriving in Yosemite Valley. This was ostensibly the first sighting of Yosemite Valley by whites and the battalion, impressed by the sheer walls of granite towering over them took a vote and named it after the natives who resided there, the "Yosemite." Their search for more natives in the valley proved futile and the group returned to Wawona. Major Savage left Captain Boling with the Indians and took most of the men on ahead to resupply. On the night of April 1st, Chief Tenieya and 250 Yosemites slipped away. At the same time, the other battalion companies were playing cat and mouse with the remaining Chowchillas down in the Fresno and San Joaquin River drainages. The company managed to capture three young native men that turned out to be Tenieya's sons. One of Tenieya's sons was sent to him to tell of the capture and explain the terms for peace. The other two made an escape attempt and one was killed. Members of the battalion pursued Chief Tenieya through what is now known as Tenaya Canyon, and he too was eventually captured. When he was brought to the body of his son, he purportedly wept, tried to escape, and begged to be shot. Captain Boling evidently empathized with the stricken Chief, but nonetheless kept him a prisoner. After Chief Tenieya's capture, the final action of the Mariposa Battalion was to round up one last village of Yosemites near Tenaya Canyon. The disbandment of the battalion came none too soon for many of its members since they were in need of food, clothing, tobacco, and other supplies that were hard to come by.

By the end of the Mariposa Indian War, the Indian agents sent by the federal government negotiated eighteen treaties with approximately five hundred Native American leaders to provide some 8.5 million acres of reservation lands for the tribes. However, the state of California was violently opposed to the treaties, calling them a "great evil." The state lobbied the federal Congress and which in turn refused to ratify these treaties. The land given to the Indians was thought to be too valuable to squander as such, and in combination with the hostile state government, all promises conferred to the natives at the end of the Mariposa War came to naught. The state government of California preferred a martial solution and in 1853, the state of California issued an "extermination order" on all California natives. In 1856, the governor placed a bounty of $0.25 per scalp on native heads. By 1860, the bounty was upped to $5. The situation remained very bad for the Me-wuk for the remainder of the century. There were whites who were sympathetic to the plight of the native Californians, but nearly all favored assimilation over independent tribal sovereign states. The thought was that integration was the only way out of the poverty and mistreatment that most Indians faced in the century after the Gold Rush. Children were taken from Indian homes to be educated at boarding schools or raised with white families. State laws were unbelievable prejudiced against the tribes and rights were severely curtailed.

The large reservation on the San Joaquin never materialized the unratified federal treaties disappeared for over 50 years. The combination of federal and state jurisdiction in dealing with Native American land issues, the lack of consistency in the terms of the treaties, the lack of ratification, and the difficulties incurred by senseless inheritance laws combined to further reduce the amount of land in tribal possession. The government essentially treated the small remaining Indian reservation lands as homesteads, and in many cases, the parcels eventually fell into non-native hands. In 1910, the federal government purchased the Tuolumne Rancheria, a 289 acre parcel near the town of Tuolumne expected to support the remaining Me-wuks in the area. It was not until 1924 that Native Americans were given U.S. citizenship, and because states managed voting rights, there remained systemic racism and repression in official dealings with natives. Pervasive poverty, lack of access to education, despair, rampant alcoholism, and loss of culture, the frequent outcome of the U.S. Indian wars, deeply impacted the tribes of California long after the bounty on native scalps was lifted. Currently, the Tuolumne Band of Me-wuks operates a casino on their land that has greatly improved the lives of tribal members, including housing and health care. The devastation wrought on indigenous Californians was tantamount to genocide. The almost complete annihilation of California's native tribes, often just a footnote in historical annals, must be recognized and remembered.

SUMMARY

For the 10,000 years leading up to the mid nineteenth century, land in the California foothills, and Central Valley had been under constant, horticultural and land management by Native Americans. With the influx of invading settlers, first Spanish Missionaries and later assorted entrepreneurs and gold seekers, indigenous life was dramatically and irreversibly disrupted. Drastic changes in land management practices, major alterations to watercourses, and intensive logging led to significant impacts on Sierran ecology. The loss of Native American management on the landscape coupled with major negative impacts from gold seekers wreaked havoc on the local environment. Today, biodiversity is significantly lower and the structure of the forest has shifted profoundly. In particular the loss of fire as an annual management tool resulted in huge brush and ladder fuel accumulation throughout the Sierra Nevada, which has created the catastrophic fuel load conditions we continue to struggle with today. The damage to tribal cultural knowledge, the almost complete eradication of the tribes themselves, and the diaspora that took place within the tribes in the last two hundred years represent one of the most devastating stories in the sad history of native people in the United States.

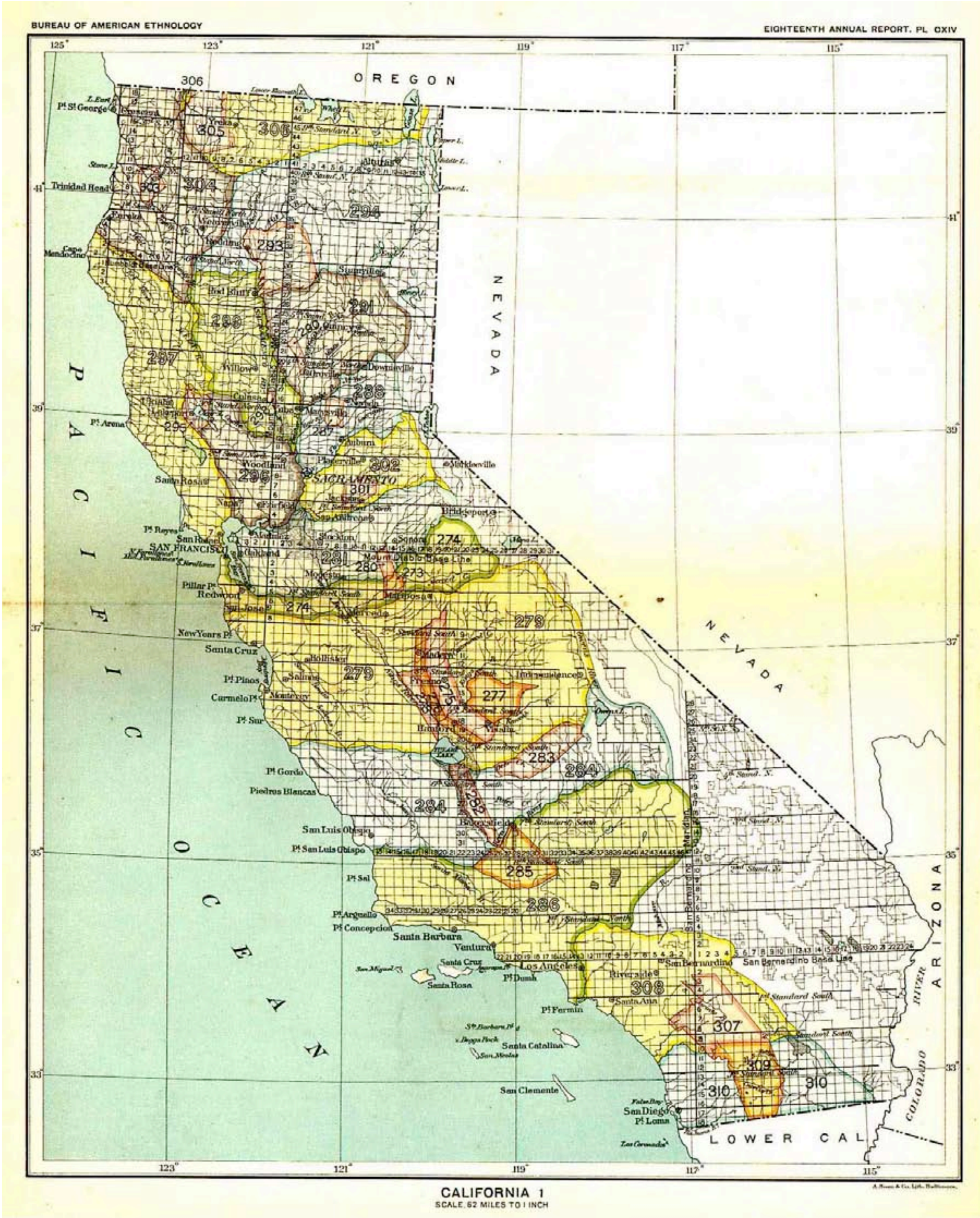

Figure 9.3 Map of California Indian Tribe land cessions resulting from the 18 unratified treaties negotiated by the federal government. Native Americans lost their land, but were not provided with alternative territories and federal support promised in the treaties. The areas marked 223 and 224 represent the land cession negotiated in March of 1851 ending the Mariposa Indian War and ceding most of the land between the Merced and Tuolumne Rivers. Other treaties nearby such as 279 and 277 removed even greater swaths of land from native territories. Map from Library of Congress Public Domain.

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Chapter 10: The Gold Rush

NAOMI MARKS AND SABRA PURDY

INTRODUCTION

The history of gold in the Tuolumne watershed is really the history of gold in California. As the third largest producer of gold in the state, Tuolumne County, and the Tuolumne River were huge contributors to the gold rush economy and to the establishment of California as one of the largest economies in the world. The story of gold in the Tuolumne watershed, and the immediate and lingering consequences of its discovery and extraction will be detailed in the following chapter.

California was a sleepy province in 1848. Most activity took place around the Franciscan missions dotting the coastline with large Mexican Land Grant holdings in the Central Valley. Nevertheless, with the discovery of gold in 1848, fortune seekers from the ends of the earth converged on California and engaged in an orgy of gold gathering that ranks as the greatest mining rush of all time. The term argonaut refers to those engaged in a dangerous but potentially rewarding adventure, and there is no better moniker for the immigrants who streamed into California from the East Coast of America, Europe, Central and South America, Mexico, China, and Australia. The flood of people and resources into the fledgling state, in concert with the vast wealth that could be culled from the Sierra foothills and streambeds, conspired to produce the greatest economic expansions in history.

Gold was first discovered in the Tuolumne watershed in the early part of the summer of 1848, mere months after James Marshall's initial find on the American River. A party of prospectors led by Rev. James Woods discovered placer gold in abundance along the banks of a tributary to Tuolumne River, which the miners subsequently called Woods Creek. The earliest deposits in the Tuolumne watershed, located at Woods Crossing, were so rich that early prospectors recovered 30-50 oz per day just by prying nuggets from exposed streambed with their pocketknives. The population of Tuolumne County grew rapidly as news of the gold spread. The major mining camps at Sonora, Columbia, and Jacksonville (distinct from the Jackson currently on Hwy 49) were all also founded in mid-1848 and early 1849. Other sites included Peppermint Gulch, Mount Brow, Jackass Gulch, Springfield, and Yankee Hill. The county produced an estimated $600,000,000 worth of gold earning it the title of the Queen of the Southern Mines.

The Boom

In 1849 San Francisco remained a tent city amid scattered wooden buildings that sat on bluffs overlooking the bay and harbor. But by summer of 1849, the harbor had begun to look like that of a big city. More than five hundred vessels were left to rot in the bay that summer. The fleet of ghost ships included many good ships robbed of their crews by the irresistible pull of gold, although these were later joined by a number of hulks that had barely made it to California and were not worth sailing away. The abandoned ships rotting at anchor served as a reminder of the magnitude of the migration spurned by the desire for gold (Figure 10.1).

Figure 10.1 Abandoned ships in San Francisco Harbor near the start of the gold rush.

Immigration to the Sierra foothills in the late 1840s and 1850s caused a tremendous demand for infrastructure, tools, food, and agricultural products. The impact of the mining boom on the economy of California and the development of the state cannot be overstated. The population explosion in the diggings created a huge demand for goods and services where previously there had been an economic void. The demands of this large population were backed up by the tremendous buying power of gold. The result was stimulation of the most intense expansion of commerce the American West had ever witnessed. It set in motion a chain reaction that spread from the mines, to storekeepers, to transport of goods by packers, wagon freighters and ships on bay and river, to wholesalers, to importers from depots as near as Oregon and as distant as England, to producers in California fields and forests, in industry wherever it could flourish, and to all sorts of supporting activities including drover, slaughterer, banker, usurer, investor, speculator, realtor, insurer, restaurateur, and launderer. The consequences of this economic expansion could be felt around the world.

While an occasional miner struck it truly rich, most just barely made do, and of course many did not. In contrast, quite a number of the California fortunes, including those of Stanford, Huntington, and Hopkins, were begun in gold rush merchandising. Food demands initially stimulated production of beef, but as time went on miners demands for flour stimulated wheat production. By the 1890s California was the largest exporter of wheat in the world. Farmers also began to plant potatoes, turnips, onions, melons, grapes, berries, and fruit trees. The gold rush undoubtedly stimulated the growth and diversification of agricultural production in the state. The growth of industrial production was similarly spurred by the gold rush. In short order ironworks sprung up in San Francisco and Oakland. Tanneries, textile mills, lumber mills, and facilities for building wagons, barrels and all sorts of tools, were quickly established to meet the needs of the new population. The development of newspapers, banks, churches, synagogues, theatres and entertainment venues, public transportation (including paddlewheel ferries and stagecoaches), medical facilities, hotels, saloons and gambling parlors all owe a debt to the California miners.

Foreign Miners Tax

Between 1848 and 1857 as many as 300,000 people and about a million animals immigrated to the gold country. California had been sparsely populated by an assortment of Mexican, European, and American farmers and trades people prior to the acquisition of California by the United States in 1846. Foreign miners were initially welcomed to California, however, the European-American miners came to resent them as time progressed, the pickings became slimmer, and most of the land was claimed. The placer workings were crowded, with as many as 700 men working the gravel bars on a small stretch of river near Jacksonville alone. Xenophobic miners sought to relieve the crowding and believed that "foreigners" were finding gold that "American" miners deserved.

Figure 10.2 Photo of Chinese miner prospecting in 1852, either near Jacksonville in Tuolumne County or Mongolian Flat on the American River. Note the caption on the photo "The Heathen *Chinee* Prospecting." FN-04470. From http://www.calisphere.universityofcalifornia.edu/

In April 1850, the state legislature levied a tax on Non-American born miners that required a payment of twenty dollars each month at a time when most miners were making approximately six dollars a month. It applied to all individuals not of American birth, and was even levied against Mexicans who had resided in California prior to the cessation of the state in 1846. The tax was aimed at excluding experienced Mexican miners and was strongly resisted by French, Mexican, Chilean and German miners as well as from merchants who faced considerable loss in business as a direct result of the tax. The effect was the immediate depopulation of many of the mining camps, especially in the Southern Mother Lode and Tuolumne County, which had large population of Mexican prospectors. Foreigners were also forced to surrender their firearms, a particularly galling indignity considering the general lawlessness of the time. Sonora (heavily populated by Mexicans and named after the Mexican State) and Columbia lost almost 80% of their population overnight. Many of the excluded miners gave up gold mining for good; still others retreated to less conspicuous diggings to hide out. After much protest the tax was lowered to $4 per month, and eventually repealed in March of 1851.

Extraction Methods for Placer Mining

Most of the earliest argonauts were not professional miners, and their equipment reflected their predominantly agricultural backgrounds. These included picks, shovels, crowbars, and Bowie knives; specifically designed picks and trenching tools for mining began to be designed and imported in early 1850s.

Mining technology progressed rapidly from very simple to increasingly elaborate as more experienced miners flooded into the region and brought the knowledge of more advanced techniques. Placer gold-washing techniques had been brought to the New World by the Spanish, and had been in use in Mexico for nearly 300 years. The miner’s pan used in the gold rush was likely an imitation of the Spanish “batea,” a wooden bowl used for panning. Early miners likely employed available equipment such as frying pans and baskets woven by Native Americans, but adopted the familiar sheet metal pans as they became available in the summer of 1848.

Gold-Washing Techniques

Gold panning rapidly gave way to more sophisticated techniques, the first of which were the rocker and cradle, so called because of their resemblance to baby cradles. The cradle was typically about 4.5 feet long, made of pine, with three sides and a bottom. Gravel was poured into a hopper attached to the top, and then was washed with water while the cradle was rocked back and forth to force the gravel through the cradle. On the bottom of the rocker would be three cleats an inch wide upon which the gold would be caught up as the gravel was washed. The finest material passing through was then washed again in a gold pan to recover as much of the gold as possible. The primary advantage over panning techniques is that they allowed miners to wash much larger quantities of dirt and recover gold more efficiently. Rockers and pans required significant quantities of water, and when insufficient quantities were present, simpler winnowing methods were employed.

Water was a scarce commodity in Columbia and miners were compelled to carry buckets of gold bearing dirt to a water source to in order to wash it. This led to a lucrative business in diverting water to the “dry diggings” (see below). Subsequent diversion and fluming of local creeks eventually made gold washing and hydraulic mines less problematic.

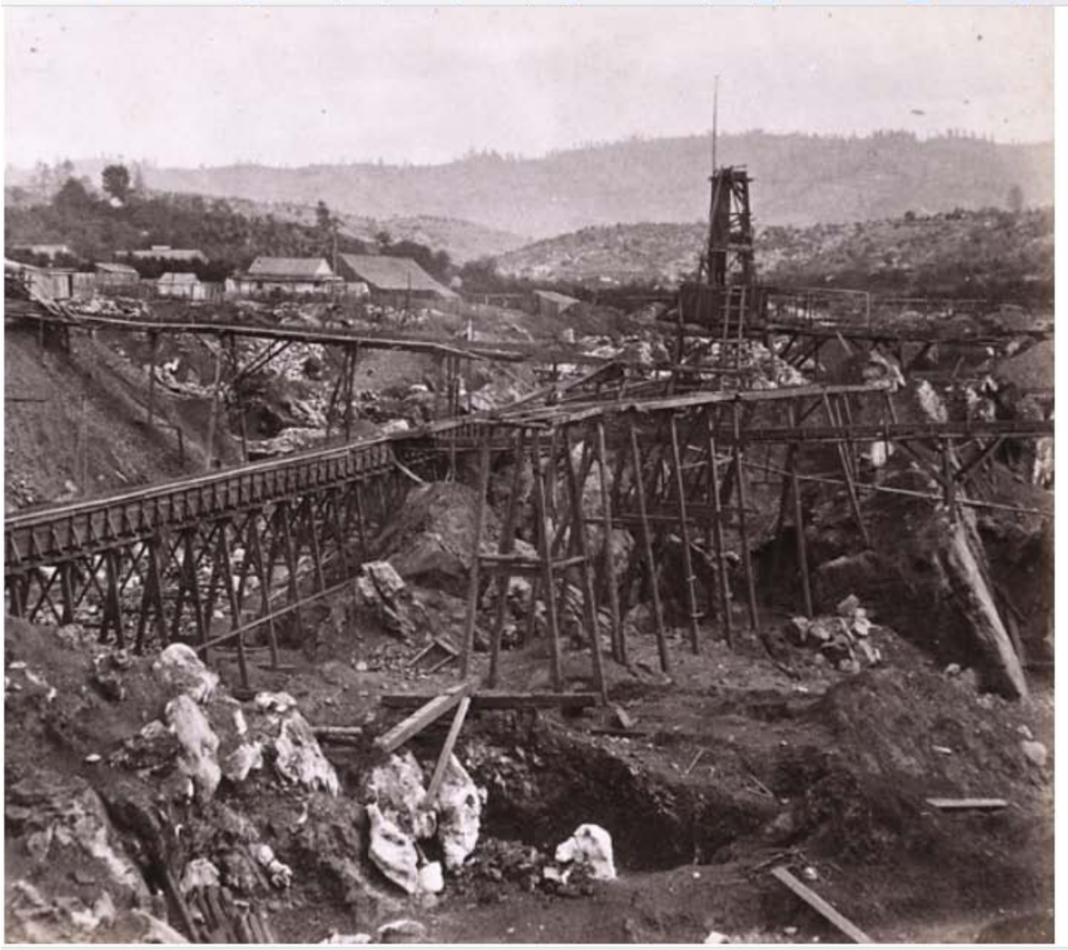

Figure 10.3 Placer Mining in Columbia Gulch. Originally a dry diggings, expansion of mining in Columbia required massive infrastructure to divert water from the upper reaches of the Stanislaus and Tuolumne watersheds to process placer gold. The exposed limestone is still visible today. LH0988, album 2 in box B001772 ark:/13030/kt567nc381From http://www.calisphere.universityofcalifornia.edu/

The Long Tom evolved from the rocker, and was basically a longer riffle box, which used more water and was worked by several miners. The long tom usually washed 4 to 5 times the amount of gravel as a regular rocker. By the early 1850s, both the long tom and rocker gave way to the sluice box as the most widely used method of gold washing among Euro-American miners. The sluice box required much more water, but was far more powerful than previous methods. It was essentially a long series of wooden troughs with riffles that fit together and allowed very thorough washing of the auriferous gravel. Sluice boxes were seldom used before 1850 because their considerable washing power was not needed to achieve respectable gold recovery. The sluice box required significant hydraulic head, which meant the dawn of water diversions, particularly for dry diggings. It became the washing method of choice for mass mining operations where the availability of water made hydraulic mining possible. Water was supplied to sluice boxes by short ditches from upstream diversions that required considerable engineering and manpower to construct (Figure 10.3).

Box 3.2.1

Mercury

As the rush of 1849 progressed and more people flocked to Tuolumne County, the richest placers had been claimed and miners were forced to work lower-grade deposits that required more refined mining technology. The use of "quicksilver" or mercury to enhance gold recovery expanded after 1849. An estimated 26,000,000 pounds of mercury was used in mining in California's gold rush. Mercury was used to enhance recovery by amalgamating with the gold that was then more likely to catch on troughs (riffles) within the sluices. After scraping the amalgam into a buckskin bag, excess mercury was squeezed out and the remainder was heated in a retort to boil off the quicksilver, leaving a gold sponge that could be melted into bars or ingots. While miners of the gold rush did not understand the long-term problems associated with mercury use, they did quickly learn to avoid breathing the mercury fumes. Loss of mercury during gold processing was estimated to be 10 to 30 percent per season, resulting in highly contaminated sediments at mine sites and downstream, especially in sluices and drainage tunnels. Figure 10.4 shows transport and fate pathways for mercury and contaminated sediments associated with gold extraction. The use of mercury in the Tuolumne watershed has created environmental impairments that persist to this day. The demand for merucury in the Sierran mines created its own mining boom in the mercury-rich Coast Range. Drainage and tailings from these mines leached considerable amounts of mercury into the San Francisco estuary. In addition, much of the mercury used in Sierran gold extraction is still trapped in river sediments, but an estimated 10,000 tons of mercury made its way downstream into the San Francisco estuary and bay from all of the Sierran Rivers. There are currently fish-consumption advisories throughout the bay and delta and also in a number of northern and Sierran Rivers because of the human and wildlife health hazards associated with mercury poisoning. While most of the mercury work in the Sierra has been in the more northerly watersheds, there has doubtlessly been some impact from mercury in the Tuolumne River watershed.

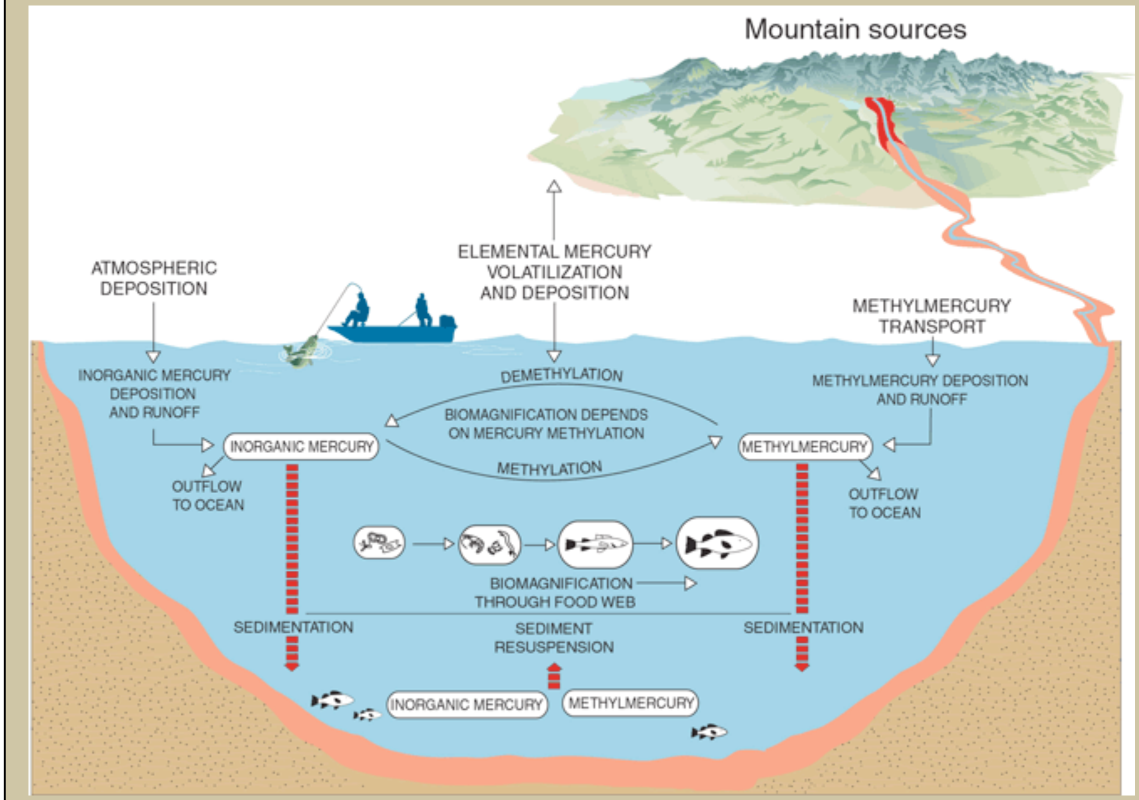

Figure 10.4 Environmental pathways of mercury from pubs.usgs.gov

River mining

By the early 1850s, the gold rush miners realized that gold accumulated in the lowest portions of streambed gravels, and as a result began to divert river flows so that streambeds could be mined to bedrock. Diversions could be achieved with flumes and embankments: water wheels were often used to power the de-watering operations (Figure 4). Water level was critical for this type of mining, so in summer miners worked deeper parts of the streambed and the bedrock bottom, while in winter they worked higher benches and bars. Chinese immigrants were especially vulnerable to the xenophobia and racism of the Euro-American miners, and were frequently run off more profitable claims. River mining operations employed many Chinese workers, and often Chinese companies would take-over failed or abandoned Euro-American efforts.

Figure 10.5 Placer Mining on the Tuolumne River, probably near the site of the current Don Pedro Dam. Note the multiple channels, water wheels, and diversions and the complete lack of any riparian life. This certainly resulted in complete extirpation of all fishes in this reach and impaired water quality and habitat downstream. From http://www.calisphere.universityofcalifornia.edu/.

Ambitious engineering feats were often rendered useless by washouts of diversions and infrastructure in high spring flows. One early attempt to recover gold from the riverbed was begun by the Jacksonville Damming Company, which organized in 1850 to divert the Tuolumne in the Woods Creek area. The company began by constructing a stone dam and then proceeded to dig a 2380-foot long canal, thereby allowing for the mining of the bedrock underneath the riverbed. Construction and dewatering efforts extended over a number of dry seasons, each season ultimately hampered by high flow and unseasonable weather. Although they moved a substantial amount of rock their success was dramatically constrained by the primitive nature of the engineering and the serendipity of fluvial flow. It is a testament to their tenacity that dam and canal were eventually completed and the riverbed was, with much hardship and toil, successfully mined (Figure 10.5).

Hydraulic mining/hydraulicking

Early miners concentrated on the placers of bars and streambeds along present-day fluvial channels, but as these became exhausted, their attention turned to Tertiary channels often located several hundred feet above the present day streams. To work these ancient riverbeds, the overlying soil and sediment had to be removed, and the most efficient method of removing this overburden material was with water. Miners created hydraulic head by damming rivers and streams, and then used flumes and canvas hoses to feed nozzles aimed at the gravel deposits. The nozzles were called “monitors” and each design had distinctive trademark names like the Hydraulic Chief, Little Giant, Hydraulic Giant, the Dictator, and Craig’s Globe Monitor. Powerful jets of water from these hydraulic appliances blasted away overburden material and washed the auriferous gravels into sluices. The amount of material mobilized by hydraulic mining was almost inconceivably massive, and as a result of the relative ease of hydraulic mining, gravels of diminishing ore grade became increasingly economic to mine. Once the gold was extracted, immense quantities of sediment were then returned to the existing river and stream channels.

The immense quantities of sediment produced by hydraulic mining created an array of environmental problems. Smaller streams were choked with sediment and lacked the flow to carry away the debris accumulated in their beds, which impaired stream wildlife. A number of mines were closed because they lacked an adequate means to dispose of the tailings. This material inundated downstream users, choking dams, causing severe flooding and negatively impacting irrigation efforts by farmers in the Central Valley. Hydraulic monitors displaced 1.5 billion cubic yards of soil and rocks from the Sierra hillsides. Columbia in particular still bears the evidence of extensive hydraulic mining. Approximately 230 million cubic yards of sediment were displaced from the Mokelumne-Tuolumne area during the hydraulic mining period. This sediment choked streams, and caused massive mudflows, flooding, and devastation when torrential rains mobilized the streambeds where the debris had been perched (Figure 10. 5).

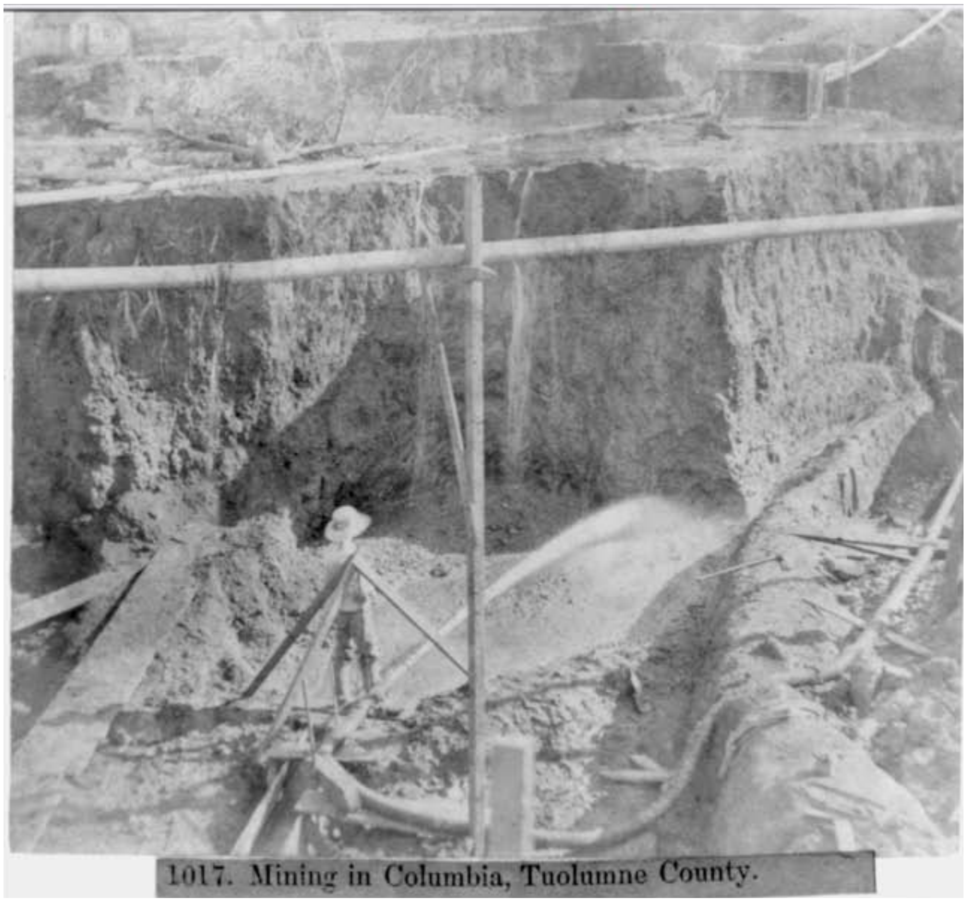

Figure 10.6 Hydraulic mining in the town of Columbia. Thousands of tons of sediment were washed from such operations into local streams and rivers, wreaking environmental havoc and property damage downstream.

Much of the hydrualicking in the Tuolumne Watershed was near Columbia and Sonora, although hydrualicking also occurred at Patricksville on the Tuolumne River. Although hydraulic mining was employed far less along the Tuolumne than farther north (i.e. Feather, Yuba, and Bear Rivers), it was still actively practiced along the Tuolumne, Stanislaus, and their tributaries. The New Don Pedro Reservoir has inundated many of the sites of former hydraulic mining operations, and much of the sediment from the hydraulic operations is trapped behind the dam.

Few individuals could gather sufficient capital for mining operations on this magnitude. Although a single man could direct the massively violent jet of water issuing from an 8 inch wide monitor nozzle, it took dozens more to construct the canals and work the sluice boxes to process the immense amounts of gravel dislodged by the monitors. Stock companies were formed comprising tens of to hundreds of men to provide the necessary labor and capital for such operations.

The hydraulic hoses were capable of knocking a man off his feet 200 feet away, and blasted water at 100 mile an hour force against the rocks, using millions of gallons of water a day. The runoff polluted streams; the gravel and thick mud carpeted farmlands and overflowed streambeds. Hydraulicking around Columbia lowered the ground level by at least 10 feet and left massive pits and exposed boulders. The massive influx of disrupted sediments meant that even levees could not protect towns from disastrous flooding. The inundation by the monitors devegetated farms, destroyed hundreds of mining camps, and deforested many square miles of lush timberlands. It is difficult to overstate the damage caused by hydraulic mining. In the great floods of 1862, mud, sand, and gravel washed from the hills inundated unprotected farmlands, and farmers began to raise their voices in protest. Hydraulicking continued through a second mining boom of the late 1860s and 1870s, and it was not until 1884 that hydraulic mining was banned. In January of 1884, Judge Lorenzo Sawyer handed down a decision in Woodruff v. North Bloomfield Gravel Mining Company that effectively curbed all hydraulic operations in the state, although some clandestine operations continued until at least 1888 (Figure 10.7). Despite the Sawyer decision, the California Debris Commission, an entity designed to mitigate the effects of hydraulic mining, has received more than 1000 applications to resume hydraulic mining for gold in the Sierra foothills since the commission was formed in the late 1880s. Sediments mobilized during the gold rush continue to cause siltation issues and impede navigation in the San Francisco Bay Delta to this day.

Figure 10.7 Malakoff Diggings in Nevada County near the town of North Bloomfield. Multiple monitors remove vast amounts of sediment from the hillsides and mobilize it into the south fork of the Yuba River causing major problems downstream. This operation was the impetus for the Sawyer decision that banned hydraulic mining in 1882. Runoff from the diggings continues to impact the Yuba River. From http://www.calisphere.universityofcalifornia.edu/

Diversions

Many of the prospecting sites were rich in gold, but had no streams nearby for processing the diggings. Gold could be processed during the heavy winter rains, however, and resourceful miners constructed elaborate systems to catch and recycle rainwater. These rainwater-based systems were inadequate for year round mining and this led to the first large-scale diversions to bring water in from many miles upslope.

One early project was initiated by the Tuolumne County Water Company, which, in 1852 completed a large canal to Montezuma Flats (north of Table mountain) that provided a “stream” 2.5’ wide by 2’ deep. Later, the Tuolumne Hydraulic Association built a canal that tapped the North Fork of the Tuolumne 25 miles east of Sonora at 5000 ft. (not far from the town of Sugar Pine) and carried water to Montezuma Flats (9 miles west of Sonora). There was a timber and stone dam at the head of the race and it likely dewatered the entire river in the summer, since the builders feared that the N. fork was inadequate to the miners’ needs year round. At that time, a survey party was sent to look into the feasibility of diverting water from the middle fork to the north fork. Another diversion, completed in 1855, brought water from the South Fork of the Tuolumne to Big Oak Flat.

Pollution and Sanitation

The argonauts rushed to the California goldfields in remarkable numbers, and the infrastructure to support them was woefully insufficient. Towns were cobbled together quickly with little regard for sensible city planning or public works. Impacts to water quality (e.g. pollution/sanitation) were significant, and problems of water and sanitation were appalling. Sickness was a constant companion to the mining life. In one year cholera killed 1500 in Sacramento alone, nearly 16% of the population of the city, and almost half of the attending physicians succumbed to the disease. An estimated 30 percent of the original 49ers died of disease, accident, or violence. Uncounted Native Americans and other non-Anglos were casualties of poor sanitation, succumbing to cholera, pneumonia, dysentery, venereal disease, and malaria, to name a few.

Mining technology was not limited to gold extraction techniques, and in time hard rock miners trained their considerable ingenuity on the problem of human waste and sanitation in the mines. The use of abandoned rooms, drifts, and other out-of-the-way places for human waste was commonplace and obviously problematic. An "underground privy car" was to provide for underground latrines, and this, in turn led to the invention of the “honey bucket” for removal of wastewater from underground workings, yet another California innovation.

Dredge Mining

Placer mining did not end with the demise of hydraulic mining. By the turn of the century, the bucket line gold dredge had made its appearance on the mining scene. Early dredges could dig 40 to 50 feet deep into the gravel of a river channel, and gradually their digging capacity was extended to more than 100 feet, at a rate of 175,000 yards per month. Dredge spoils were dumped into an elaborate screening and washing works mounted on the dredge itself, and the gold was collected as an amalgam with mercury and saved for eventual retorting. Coarse material discharged from the dredges was carried by conveyer belt to the aft of the dredge and deposited it into immense, symmetrical piles on top of fine material that had passed through the screens from a previous dredge position. Quality dredging extended along stream channels and onto the adjacent floodplains on either side of existing channels in the lower reaches of the river. Many acres of prime farmland were consumed in dredging operations and buried beneath immense piles of gravel. The environmental degradation that occurred as a result of dredging was profound and can still be seen along many Sierra Foothill streams and into the Central

Valley around La Grange and Snelling. Some of the dredged gravel has been reclaimed in recent years as important sources of sand and gravel aggregates.

Box 10.2
Lode Mining
Hard rock/vein (a.k.a. orogenic gold deposits)

Miners had long noticed the association between quartz and gold. As the placer fields were played out, they turned to locating the "mother lode" i.e. the quartz vein sources of rich placers. Early quartz vein mining commenced in 1850s following discoveries in Mariposa and Calaveras counties, although hard rock mining was somewhat limited by the available technologies. Experienced Mexican miners introduced circular rock grinding mills called arrastras to crush broken ore. These were useful in exploiting small, high-grade lodes of Pocket and Mother Lode belts. A lack of capital and expertise, however, delayed development of the sophisticated techniques necessary to fully exploit the major lode mines until 1890s.

The Rawhide mine, situated northwest of the original site of Jamestown just north of Table Mountain, was first fully capitalized in 1888 and placed under aggressive development. In the first year of intensive development it yielded 3900 oz. The Rawhide Mine drew the interest into other lode mines, and Tuolumne County entered into a Golden Age of Lode Mining that lasted until 1915. Total production of lode gold in Tuolumne County reached 2.7 million ounces. Hard rock mining was essentially shut down during WWI, and mines remained closed until the Great Depression, when an increase in the government legislated price of gold from $20.67 to $35.00 per ounce drove miners to resume their efforts at placer claims and small-scale lode mining operations. The mines were closed once more in 1942 during WWII when Federal order L208 prohibited all non-essential industries. Mining did not become economically viable again until the price of gold was deregulated in 1970. In the 1970s, the Pocket Belt mines began to be exploited again and operations on a large scale open-pit mine commenced at the Jamestown Mine, which continues to operate to this day.

One example of a successful lode-mining venture in the Tuolumne watershed was the Jacksonville – Eagle-Shawmut Mine. The mine was located in a portion of the mother lode belt that extends southeast of Jacksonville to Moccasin Creek. Jacksonville in Tuolumne County was founded in 1848, as a locale of extremely rich placer deposits. Lode mining began here in the late 1850s and occurred mainly between 1897 and 1942, in deposits that formed at or near the contact between serpentine and slate, schist and interlayered greenstone. Mine workings reached depths as great as 3000 feet. The buildings and workings of the Eagle-Shawmut mine were removed prior to inundation by the new Don Pedro Reservoir. It is not clear what the environmental impact of inundating the ore processing facilities might be, but presumably they add to the mercury load in New Don Pedro Reservoir and in the lower reaches of the Tuolumne River.

In 1859 the placers were largely exhausted and agriculture became the dominant industry near La Grange bar. However, with new advances in dredge technology, there was resurgence in placer mining. Dredging at La Grange began in earnest in 1900 in a field that extends westward from town of La Grange along the Tuolumne River. The dredged area is nine miles long and ½ mile wide. La Grange dredging operations included a dredging field two miles to the south on a Pleistocene river that was dredged for 1.5miles and ¼ mile wide, as well as surface diggings to the north. Both gold and minor platinum were recovered at La Grange. The environmental consequences of dredging include the destruction of streambed and bank topography, a profound degradation of water quality during dredging operations, the loss of mercury and other contaminants to the remaining sediment during processing, and the destruction of adjacent habitats for flora and fauna. The scars from dredging near LaGrange remain visible to this day.

In the 1930s a new type of gold dredge was developed that began to recover gold from stream placers that had been long abandoned. These new dredges were small, and capable of working in narrow and shallow creek bottoms that regular bucket line dredges could not work allowing access to smaller streams higher in the watershed. Many were constructed out of used equipment and scrap metal, and stacked washed gravel tailings in trails behind them in a pattern that resembled the residue of an insect; as a result they became known as “doodlebugs.” In the late 1930s doodlebugs operated on the Tuolumne below Moccasin and ran 24 hours a day, seven days per week. Doodlebug dredges operated up until the 1950s, and can still be seen in rusting heaps in the Delta backwaters.

SUMMARY

Tuolumne County has the third largest total recorded gold production of California counties, and placer mining dominated the local economy from 1850 to 1870, producing 7.5 million oz of gold, including some very large nuggets. The Tuolumne watershed ranks among the richest placer fields in the world, by way of example, over 2.6 million ounces were produced from the one square mile Columbia basin alone. The environmental impacts from hydraulic mining, dredging, lode mining, and ore processing continue today. Mining scars remain visible along the Tuolumne and its tributaries. More subtle impacts from acid mine drainage and ore processing require ongoing monitoring and remediation of trace metals, arsenic, iron, and mercury at various locations within the watershed. The impact to the native tribes living in the area is incalculable and very nearly led to their complete extermination.

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Chapter 11: Boom and Bust: The Economy and the Environment

SABRA PURDY

INTRODUCTION

When ownership of California changed hands from Mexico to the United States in 1848, there were a mere 14,000 Euro-Americans living in the state. Economic activity centered on the mission holdings along the coast and was just beginning to spread inland through large land grants for ranching by the Mexican government. The economy of the state was centered on a hide and tallow trade, and most crops were for subsistence. Gold discovery by James Marshall on the American River in 1848 resulted in an immediate influx of people to the state—reaching 100,000 in 1850 and 250,000 by 1852. This presented a huge demand for goods and services in the virtually uninhabited interior of California, with effectively no supporting infrastructure. The miners needed food, clothing, building materials, and tools. The hardships of a supply and demand economy in a land of scarcity were predictable. There was too much money and too little of everything else and inflation was rampant. The mining boom created the conditions for spectacular economic growth, particularly if you were not a miner. This chapter focuses on the evolution and individual economic trajectories in the Tuolumne River watershed. First logging and agriculture, in the wake of the gold rush, and later tourism and recreation with the formation of Yosemite National Park and the decline of the more extractive industries.

The Merchant Class

James Marshall was building a saw mill on the American River at Coloma when he stumbled upon gold. He worked for Johann Sutter, a Swiss native who had received a sizable land grant from the Mexican Government and was in the process of building himself a modest agricultural empire (New Helvetia, current day Sacramento) at the time of gold discovery. Reportedly, Sutter was not well pleased at the news of gold discovery, though he stood uniquely poised to make a fortune from the incoming wave of prospectors. His holdings were vast, he owned the closest outpost to the new gold fields, and he had thousands of head of livestock. However, Sutter was a poor business man and was given to drink and easily swindled. The influx of fortune hunters into California were a hard bunch, opportunistic, not overly honest, and looking to make money. Sutter was an easy target and eventually lost his little empire and left California destitute.

Others recognized the obvious implications of hordes of people descending on unsettled land and went into the business of supply. Sam Brannan in particular was credited as being the “king of the wheeling dealing entrepreneurs” of the gold rush. While Sutter was trying to keep the news of gold discovery a secret, Brannan took the news to San Francisco, and proclaimed it in the streets, igniting gold fever across the globe. He then turned around and shrewdly began to buy up key supplies. He would, for example, purchase all of the shovels in San Francisco, then once he had cornered the market, he would turn around and sell them for wildly exorbitant prices. He made a vast fortune with this method time and time again. Other notable names that launched their fortune in gold rush merchandising included Levi Strauss, Leland Stanford, John Studebaker, and Henry Wells and William Fargo—all recognizable names 150 years later.

LOGGING

The Mining Days

Logging development followed fast on the heels of the gold rush as the demand for lumber in the mining camps grew. At first, the miners needed lumber for housing and firewood, but soon, huge amounts of lumber were in demand as the basic infrastructure for mining became more complex. As the rockers, sluices, and major races (some as many as 25 miles long) became the standard mining methods, the demand for lumber and price per board foot skyrocketed. Initially, nearby lumber was used to supply camps, but as the population and demand grew, local trees were quickly depleted and more focused logging operations went into effect, ranging further afield and requiring greater infrastructure. Ponderosa pine at the lower elevations was used first, but as supplies dwindled, the cutting moved higher in elevation, and shifted to sugar pine, and red and white firs. There was such intense demand for lumber in the mining camps and developing towns that many found it more profitable to be lumbermen than miners and numerous operations were established.

At the outset, these were single operator or small operations, but as demand for wood grew, so did the companies, rapidly industrializing to match the mining industry and burgeoning population in the foothills. By 1856, there were some 24 mills operating 34 saws in Tuolumne County. Fourteen of these mills were steam-driven, and the remainder used water power, which enabled the mill operator to sell the water to thirsty dry diggings downstream for an added profit. These mills manufactured some 15 million board feet annually, employing around 250 for a wage of $50-$100 per month. The price per thousand board feet was approximately $30 in 1856. Mining infrastructure required approximately two thirds of the lumber produced, while the remainder was used for other purposes such as building, fencing, and firewood. At the start of the gold rush, the foothills were covered in park-like groves of old growth yellow pine, sugar pine, cedar, oak and spruce, a result of the intensive management by the Native Americans, and a resource of almost incalculable value to lumbermen. The forest that took the place of those original timber stands was considerably altered in both composition and structure.

Timber and the Railroads

After a number of frustrated attempts, Congress passed the Homestead Act in 1862. This made nearly a trillion acres of land available to homesteaders in the untamed west during the height of the civil war. Fast on its heels came the Pacific Railroad Act of 1862. This act set aside lands from the public domain that would have been available to homesteaders, and gave it to the railroad companies to encourage growth and development in the west and to thwart the confederacy. By 1870, a full ten percent of the continental United States had been granted to the railroad companies, with few stipulations, and even less enforcement. Railroad grants covered all of the odd numbered sections that were not already in private hands, which created the checkerboard pattern of ownership still in existence throughout the west. A pattern of ownership that has made management of public lands incredibly difficult and has played an enormous role in shaping US Forest Service timber and land management policies. The lands provided to the railroads extended for 20 miles on each side of the right of way, with an additional 10 miles on each side provided to make up for inholdings of private land (Figure 11.1). The Oregon and California railroad grant was made in 1866. The final amount of land granted was 3,728,000 acres in a 60 mile swath from the Oregon border along the west side of the Sierras.

Figure 11.1 Map of the railroad land grant right of ways in California IN 1875. From www.landgrant.org/graphics/calif-1875.jpg

The advent of the railroads, including the completion of the trans-continental railroad in 1869, created a huge demand for lumber. Not only for the laying of track, but it was now possible to ship Sierran lumber all over the west to timber-poor areas such as Salt Lake City, Utah, the booming mining towns in Arizona, and the growing cities of California's Central Valley and San Francisco, as well as southern California. The more northerly areas of the Sierra, with their lower elevation, less rugged topography, and closer proximity to the trans-Sierra railroad, received most of the focus of the lumber industry at the time. After the boom times of the gold rush, lumbering in Tuolumne County slowed down. The challenging terrain and massive exploitation that had occurred during the gold rush made it more difficult to log efficiently in the remaining stands. Poor regeneration after the intensive cutting, devastating fires, and rampant overgrazing by livestock reduced the available timber considerably. Lumber production in Tuolumne Country dropped by almost two-thirds. In 1880, lumber output was approximately 5,400,000 board feet, with just six mills in operation in the county. Logging continued at this comparatively low rate until the turn of the century, when depletion elsewhere, as well as advances in technology made it profitable to exploit the untapped stands of high quality timber, and a lumbering industry once again became a keystone of the Tuolumne County economy.

There was virtually no regulation of timber until the 1890s. The California Forestry Board was established in 1885; it was authorized only to "investigate, collect, and disseminate information about forestry." In an early report from 1886, the newly formed board estimated that the massive unregulated cutting had "consumed and destroyed" one third of the standing timber in the Sierra Nevada. Soon after, however, the political climate in California became inhospitable to such oversight and the California Forestry Board was disbanded in 1893. When it was reinstated in the early 1900s, it was predominantly as a fire fighting agency, which it continues to be to this day. At the federal level, the Forest Reserves were set aside in the 1890s. Under the leadership of Gifford Pinchot, whose belief in utilitarian conservation for commercial purposes gained the ear of President Theodore Roosevelt, the Forest Reserves were transferred from the Department of the Interior to the Department of Agriculture. The USDA Forest Service was established in 1905, and Stanislaus National Forest was designated. Currently, 70% of Tuolumne County's 2,229 square miles are publicly owned, almost entirely by the federal government.

In keeping with Gifford Pinchot's ideals of a working landscape, timber production and grazing continued to be major land management activities on the National Forest. The legacy of the checkerboard patterns of land ownership necessitated a high level of cooperation with the railroad companies, who held much of the landscape, and who had morphed far beyond railroading to large-scale timber extraction. Many of these companies or their subsidiaries hold this land today. For example, Sierra Pacific Industries is the largest single private land holder in California. In 1903, the Standard Lumber Co. built the Sugar Pine Railway in order to more efficiently log its own holdings, but it was soon extended into the neighboring National Forest lands. In order to justify the considerable costs of extending the railroad, the Forest Service had to guarantee the lumber company large timber sales.

Figure 11.2 Railroad Logging in the Cherry Creek watershed part of the Yoseimite-Sugar Pine Logging Operation. Photo from the Sierra Nevada Logging Museum. http://snlm.wordpress.com/logging-history/

Smaller tracts were impractical to log via railroad and were left virtually untouched until the post World War II boom in logging and the tremendous road-building activities undertaken by the Forest Service in the 1950s and 1960s. Following the heavy federal investments in the logging industry including thousands of miles of roads and heavily subsidized timber sales, Tuolumne County had among the highest timber production of the central and southern Sierra counties. Logging was especially prevalent in the years after World War II until the 1980s, and was the dominant economic driver for the county. It became even further entrenched as a part of the economy by the policy of using timber receipts to fund public schools, which had major implications for scaling back or altering timber harvest plans to be less environmentally destructive. The distribution of land ownership, the demands of the market, and industrialization of resource extraction had major influences on the evolution of National Forest policies and management. This persisted for a century despite the evidence of major environmental problems associated with timber harvest practices. The agency had become acculturated to the workings of the timber industry, and the industry itself became an ingrained part of the social and economic fabric on the landscape. The legacy of that relationship and the government subsidies that built the industry up are still in place. There have been substantial decreases in timber cutting activities since the late 1980s, due in part to the advent of more stringent endangered species legislation enforcement, but also due to market changes within the industry. Current production is around 23,570 board feet per year down from a peak of 179,623 board feet in 1986.

Environmental Costs

The economic realities of logging by rail, and a generalized lack of concern about ecological conditions, resulted in millions of acres of clear cuts throughout the Sierra Nevada. This wrought intense environmental destruction. There were tremendous impacts from deforestation in the basins where intensive logging took place. The rugged topography of the west slope with its steep slopes, and erodible soils behaved in a predictable fashion when deforested. It moved. Massive erosion, sedimentation, and altered stream flow patterns resulted from the denuded landscape and put tons of sediment into the streams and rivers. In some cases, the streams themselves were used to transport logs. The use of “splash dams” became a popular way to move a large amount of logs downstream. A temporary dam would be built until a large number of logs could be floated on the reservoir. The dam would then be knocked down and the torrent of water would carry the logs to a downstream mill. This practice was incredibly destructive to the stream banks, as well as anything that happened to be living in the river. The streambed was first dewatered, and then inundated, killing fish, desiccating spawning sites, and then a sudden flood filled with heavy logs was unleashed. So much property damage was caused by this method of conveyance that complaints and lawsuits halted its use. Another logging related impact to streams came from the saw mills. Many of the early sawmills were water powered with the water then being diverted to the downstream mines, leaving very little in the streams, which doubtlessly had a negative impact on the aquatic communities. Furthermore, the sawmills generated a tremendous amount of sawdust, a combustible hazard that they were eager to get rid of. Often, the mills would dispose of the excess sawdust by pitching it into the river, which essentially suffocated the entire aquatic community and acidified the water.

Figure 11.3 Rangers on the Stanislaus National Forest around the turn of the century. From http://www.fs.fed.us/r5/stanislaus/heritage/voices/voices41.shtml

The prevalence of clear cutting had significant negative effects on forest structure and diversity. The targeted clearcutting of mature ponderosa pines and sugar pines resulted in large swaths of land that had no seed trees available for reforestation. Consequently, the community that followed was predominantly brush and non-commercial trees. Cedar and white fir (both capable of germinating in the shade) dominate where ponderosa and sugar pine were once the prevailing species in the landscape. This change in species composition can be seen throughout the forest to this day. Not only did the community structure of the forest change, but the loss of so many healthy, reproductive trees must certainly have drastically altered the gene pool of the remaining trees. Vulnerability to drought and fire both increased significantly with the new canopy and community structure. Much of the forest is now dominated by brush and unthinned, stunted trees that are far too close together and have created such a massive fuel load that cataclysmic fire is a reality on nearly an annual basis.

There has been a demonstrated increase in the severity and frequency of catastrophic fires associated with fire suppression, forest management, timber harvest practices, and climate warming. Meanwhile, the urban/wildland interface in Tuolumne County has become increasingly diffuse. There has been a tremendous expansion of decentralized growth over the past 30 years and in many areas, the forest holds a large amount of private residences with little defensible space. The resources spent on protecting these properties from the increasingly frequent large conflagrations are staggering. It has been recognized that the fuel loads in most of the forested lands are dangerously high. There are few entities better equipped to perform thinning operations than the logging companies with their skilled workforce, equipment, and infrastructure. However, thinning operations are expensive to conduct and generally target the less economically valuable types and sizes of timber (i.e. brush and crowded stands of stunted trees). Few timber companies are willing to bid on such sales, because the economic benefit is negligible. Therefore, the Forest Service finds it necessary to include commercially valuable trees in the sale in order to compel the timber companies to perform the thinning operations.

Figure 11.4 Clear cut and fire in the Sierra Nevada. www.dailyrepublican.com/clearcut.jpg

A further result of the poor management and excessive harvest over the last century and a half is evidenced by the widespread use of herbicides of both private and national forest timber lands. Herbicides are used in an attempt to speed up succession and encourage only the commercially valuable timber species to grow (i.e. ponderosa pine and sugar pine). The most commonly used herbicides are hexazinone, glyphosate, clopyralid, and triclopyr, though 108 different types have been approved for forestry use in California. In Tuolumne County in 2001, Sierra Pacific Industries applied 1,505 gallons of liquid herbicide and 4,712 pounds of solid herbicide, generally in pellet or powder form. These measurements refer to the weights of the active ingredients only; therefore many other chemicals are also applied to the ground whose impacts are not known. The USFS uses the four main herbicides on their land, with glyphosate being the predominant type. However, herbicide use on private timber holdings is unregulated and disclosure of type and amount is not required in timber harvest plans. Thus, an unknown amount of chemical defoliants, most of them water soluble, are being put into the watershed annually, with little study of its impacts and little recourse for management on private lands.

Common criticisms and concerns include lack of monitoring, lack of testing to see effects, exposure to wildlife, loss of forage for wildlife, improper applications, lack of a buffer to aquatic features, impacts to the aquatic system, feminization of amphibians, impacts to rare plants as well as the overall integrity of the plant community, and impacts to human health (particularly amongst the Native American community, who often use public lands for gleaning). Aerial applications are the predominant method, and broadcast herbicides over thousands of acres. This is of particular concern due to the indiscriminate destruction of nearly all of the native plant species within the targeted area. Rather surprisingly, given the valid criticisms and lack of any real necessity for herbicides on forest lands, herbicide use appears to be on the increase. From 2001 to 2002, reported herbicide applications in Tuolumne County increased by 52%.

The post-WWII boom in road building on the National Forest has created a major environmental impact to forested ecosystems. The Stanislaus National Forest contains nearly 3,000 miles of roads, with the vast majority (93%) being gravel or unimproved dirt. There is an estimated road density of 3.3 miles of open road per square mile of land in the Stanislaus, which is a staggeringly high density from an environmental perspective. Roads increase wildlife mortality, cause habitat and wildlife disturbance, fragment habitat and migration pathways, impact sensitive habitats, and create negative edge effects. Roads are also the single greatest contributor to the establishment and spread of noxious invasive weeds (particularly associated with fire fighting operations). In addition to direct negative impacts to wildlife and habitat, roads are a source of chronic stream sedimentation from cuts, fills, and improperly installed culverts. The Stanislaus National Forest contains an estimated 257 miles of unclassified (i.e. roads not approved by the USFS) roads. These are generally spur roads for timber projects or made by OHV (off highway vehicle) use. It is estimated that these unclassified roads are the single greatest source of sediment in the watershed.

Ranching and Agriculture

The eastern side of the Central Valley of California was principally the domain of the Yukot Indians before the 1830s. The first non-indigenous person known to have explored the region between the Stanislaus, Tuolumne, and Merced Rivers was thought to be Spanish Lieutenant Gabriel Moraga. In 1806, he crossed the Coast Range somewhere south-west of Los Banos, and moved north along the San Joaquin River. Along the way he took it upon himself to name the tributary rivers he passed: the Rio Merced, which still bears the same name, the Rio Dolores (later renamed Tuolumne), and the Rio Laquismes (later renamed Stanislaus). He also changed the Rio San Francisco to the Rio San Joaquin, in honor of his father, Joaquin Moraga, who had explored some of the northern San Joaquin valley in 1776. Soon after Moraga, Canadian and American fur trappers came to tap the bountiful beaver pelts along the San Joaquin tributaries. Jedediah Smith (ostensibly the first "American" in California) trapped along the lower Tuolumne from 1825 to 1827 and spoke of a river teeming with salmon, otters, and beavers. In 1846, the treaty ending the Spanish-American war gave possession of California to the United States. Part of the terms of the treaty was that the land grants given by the Mexican government to stimulate agriculture and ranching be honored. A number of these land grants occurred in the Tuolumne River watershed, most famously, one called "Las Mariposas," originally given to Juan Bautista Alvarado, the former governor of California under Mexico, in 1844. However, Senor Alvarado never occupied it because of fear of marauding Indians. It was sold to John C. Fremont in 1847and became the site of the 1851 Mariposa Indian war.

At this time, there were a number of ranches nestled along the coast range, and there were thousands of Castillian long-horn cattle and wild horses roaming the Central Valley. These had their origins with the Spanish missions, and were often "liberated," along with horses when *neophyte* Native American converts fled the oppressive conditions of mission servitude. The Spanish cattle were typically used for hides and tallow rather than beef, and it was not until the gold rush and the massive influx of people to the foothill region that the beef industry began in earnest. The agricultural potential of the Central Valley was recognized early on, and Stanislaus County became the dominant producer of wheat in the state by the 1860s. The climate was excellent for grain cultivation with the Mediterranean wet winters and dry summers, and agriculture began to boom. The gold rush had slowed in the upper watershed by this time, and a new economic driver was required to fuel growth. More fields were put into production and the Civil War raging in the traditional wheat-growing regions of the eastern U.S., followed by the Franco-Prussian war in Europe, created a huge demand for wheat, and California became the prime grain producer in the country. The ranching industry declined in the Central Valley as agriculture grew. A particularly devastating blow to the Stanislaus County ranching industry was the enactment of “no fence” laws in 1870. These laws stated that ranchers were responsible for fencing their cattle in, rather than farmers bearing the responsibility of erecting fences around their crops to keep cattle out. Few could afford the massive costs of fencing the amount of rangeland it took to keep cattle going, and many ranchers went out of business, while others moved further up into the foothills and made use of the short but productive growing season in the alpine meadows.

As the wheat business boomed, the Central Valley spawned a number of farming innovations. The vast tracts of land in grain production required industrialized farming equipment. Larger, more efficient mowers, reapers and headers were invented, and in the 1860s gang plows were introduced, by which wheat growers could plow several furrows at once. In 1876, the Centennial Harvester was invented to mechanize harvesting. Early Stanislaus County historian, L.C. Branch, wrote this of his first encounter with the Centennial Harvester in an endless sea of wheat.

> At last our eyes caught sight of queer looking object in the distance, and curiosity as well as a desire to see something besides wheat, led us toward it. We were astonished at the sight, and looked long in wonder and amazement at a combined header and thresher. Twenty-four horses were pushing this immense machine over the ground and as it passed along dropped sacks filled with wheat. The horses were six abreast – twelve each side the tongue – and the swath cut was, we judge, thirty feet wide. The grain heads in the meantime, instead of passing into the header wagon, went directly into the separator and the grain was sacked and thrown off. It was worth a long journey to see this wonderful machine with its twenty-four horses trained like circus animals, and all moving at the command of the man ‘at the wheel’ who guides the header by a tiller attached to a wheel at the end of the tongue which acts as a rudder for this ‘agricultural ship.’ While watching its operations the writer wondered if on his next trip that way, he would not also see the gristmill attached and the machine throwing off sacks of flour!

Figure 11.5 Artist’s rendering of the centennial harvester.
http://californiaantiquetractors.com/_mgxroot/page_10773.html

California possessed the soil, the climate, and the space for industrialized farming, the only missing component was reliable summer-time irrigation water. It was recognized that California’s climate was not conducive to summer farming, a talk of large-scale irrigation projects began. The decade of the 1860s saw severe drought as well as the massive floods of 1861 and 1862. The popularity of state-subsidized irrigation waxed and waned with the water year. In 1871, the editor of the *Stanislaus County News*, John Dillard Spencer wrote, "*We have the climate; we have the soil of a first class country; but, for the want of that water which runs to waste at our very doors, and which a little sagacity and industry could make pour itself over our rich earth, we are living in a comparative desert, and are becoming notorious for our poverty.*"

For decades following, the notion of public irrigation districts vs. privately held water diversions caused emphatic debate. The profitable business of diverting water and selling it for mining purposes created a precedent of private holdings supplying riparian water to downstream users. One of the earliest attempts to create a public irrigation district was the dam at La Grange. It was originally built in 1852 by San Francisco financiers to aid in hydraulic mining. It was sturdy enough to withstand the floods of 1861-62 and as mining waned and agriculture boomed, it was acquired by M.A. Wheaton who envisioned the dam feeding some 200 miles of irrigation canals down to the San Joaquin. However, the cost for this venture was prohibitive, and Wheaton sought some $300,000 in subsidies from Stanislaus County. Many opposed the substantial government support of a private company, and the deal was never made. The deliberation around public vs. private water supply was passionately debated. Some thought that the water should be held in trust for all users, rather than only those with riparian water rights, based on the amount of land in production. Those who held water rights feared their condemnation if public irrigation districts had precedence over them. There were numerous pieces of legislation that were enacted, suits and counter-suits were filed, the state Supreme Court was consulted and heard, a duel was fought, and in 1887, the Wright Act passed through the state legislature.

The Wright Act allowed the formation and bonding of irrigation districts for the purpose of building dams, filling reservoirs, and allocating water to users. However, the Act got off to a shaky start with newly formed irrigation districts encountering difficulty selling their bonds, acquiring water, and distributing it to users. The anti-irrigation contingent blocked all activities related to assessing lands, collecting taxes, and completing irrigation projects, while filing suit after suit challenging the constitutionality of the Wright Act. They managed to take control of the irrigation district board and halt all progress towards irrigation, meanwhile the depression of 1894 continued to hamper the agricultural economy. It was not until 1902 that the Modesto Irrigation district finally formed and began the work of delivering crop water to farmers and major irrigation projects claimed much of the water in the Tuolumne River. Today, diversions for urban and agricultural uses total an average of 60% of river's flow, with as much as 90% being utilized in the driest years.

The Park, Recreation, and the Environment

While the intensive resource use of the mining, logging, and agriculture boom shaped the course of development in the lower and middle Tuolumne watershed, it cannot be forgotten that the headwaters of the Tuolumne are located in Yosemite National Park. In the 1850s and 1860s, a number of early conservationists projected the results of the prevailing manifest destiny attitude of the times, and urged the protection of California's scenic wonders by holding them in the public trust. The giant Sequoias had been ravaged by the logging industry, sheep grazed like locusts in the alpine meadows, damaging soil and plants, and the rivers ran with mud from mining, logging, and grazing activities. In 1864, the General Land Commission set aside a chunk of 56 square miles that included Yosemite Valley and the Mariposa Grove of Sequoias to protect them from commercial interests and logging. The language of the Yosemite grant stipulated that the reserved should be managed by the state of California to provide a place of scenic beauty that was safe from the development of individual interests.

Frederick Law Olmstead (the park's first chairman of the Board of Commissioners) wrote a fascinating treatise on the need for the human spirit to have access to places of scenic beauty to rejuvenate the soul and stimulate the mind as a basis for setting aside public lands. The rich had easy access to such places by dint of having money, but those of more modest means had the same needs, and it was the duty of the state to provide access to these places for the benefit of all. Despite the mission of protecting the park from commercial interests, enterprising individuals quickly realized the economic opportunities associated with a major tourist draw. Hotels, tour guides, pack outfits, etc. sprang up surrounding the entrance to the park, and a spectacular number of toll roads were established to collect fees from any direction one might want to approach the park from. The state managed Yosemite until 1880, at which time it became a national park and was transferred to federal control. In 1886 all private trails and roads within the area were purchased by the government and made available to the public at no cost. Later, the government would realize the monetary benefits of running a toll road, and today, Tioga Pass is the only toll road running over the Sierras.

In the early days of the park, drought and increasing agricultural activities in the lower elevations sent livestock grazers higher into the Sierras in search of forage. Summer grazing in the high country became a mainstay of the livestock business. The headwaters of the Tuolumne happened to fall in one of the largest contiguous meadow systems in the Sierra Nevada, and were duly targeted by grazers. John Muir first came to the Sierra as a sheepherder, and soon pronounced his charges to be "hoofed locusts." He advocated for the conservation and protection of the Sierra Nevada until he died. Wild grazers such as bighorn sheep and deer were doubtlessly pushed out by domestic livestock and their diseases took a major toll as well. Sheep grazing was generally overseen by Basque shepherds and there was great complaint over the effects of the sheep on the land and soil, though the anti-foreigner and anti-sheep sentiments prevalent at the time must also be taken into account. Cattle grazing continues throughout much of the non-park pasture land in the Sierras to this day and has had massive deleterious effects on the ecosystems of the Sierras.

By the late 1800s, it was determined that the park was not to support grazing and the U.S. Cavalry was sent in to rout the shepherds and their stock from the alpine meadows, a process that took quite awhile due to the roughness of the terrain and multitude of clever places one could hide a flock of sheep from a group on horseback. The Cavalry was empowered to patrol the park and protect it from poachers, stockmen, fires, mining, and other threats. Outside the park, grazing continued at a disastrously unsustainable level. Stock numbers were far higher than the land could support with heavy damage to soil, aquatic systems, and forage. In 1934, the Taylor Grazing Act was enacted. It was intended to "stop injury to the public grazing lands by preventing overgrazing and soil deterioration; to provide for their orderly use, improvement, and development, and to stabilize the livestock industry dependent on the public range." The current system of range management has changed relatively little since then, grazing permits are essentially privatized in all but name, and they are heavily subsidized by the federal government.

The Sierra Club

Despite the good intentions behind the formation of the park, commercial interests abounded. On an 1889 trip to Yosemite, John Muir and his compatriot, Robert Underwood Johnson, editor of *Century Magazine*, were appalled to find fenced pasture, plowed hayfields, and rampant development in the Valley. In 1892, the Sierra Club formed with John Muir as president. The original purpose of the Sierra Club was to build a constituency of citizens who appreciated the natural beauty and scenic value of the undeveloped Sierras. When became serious about damming Hetch Hetchy to provide San Francisco with a permanent supply of water (see chapter 12), the Sierra Club directed their attention towards the prevention of constructing a dam in a national park. Ultimately, they failed in that case, but the environmental ethic that was awakened by that environmental battle galvanized generations of Sierra Club members and changed the face of modern environmentalism. Their tireless efforts, admiration, and concern for Yosemite and the enviroment produced a legacy of protected land that we enjoy today. The Sierra Club became one of the most enduring and effective environmental groups in the United States and have been pivotal in many environmental battles since their inception. There has been a fascinating evolution of environmental ethics over the past century that can trace its lineage directly to John Muir and the early members of the Sierra Club.

Figure11. 6 John Muir.

Tourism

While Yosemite continued to grow in popularity and accessibility in the early 20th century, many of the surrounding towns were in decline from the end of the mining boom years in the 19th century. Yosemite's tourists were big business for the surrounding towns, but Sonora, Columbia and the other small towns in the region were bypassed by highway 120 with few being lured in. Timber harvest continued, but at a lower rate and the Great Depression hit hard because there was little demand for lumber at that time. The population of the old gold towns in the county was declining. In Columbia, many abandoned buildings had become public nuisances, and the population of the town had decreased from a peak of 6,000 people to about 500. The gold rush had always been viewed with romanticized nostalgia, even as early as the 1880s when many of the original "forty-niners" were still alive. B.F. Alley wrote an extensive document in 1882 collecting the stories, history, and recollections of the early gold rush days that shows the remarkable hold on the imagination that era possessed. In the 1920s, the idea took hold that the gold rush era should be preserved and Columbia should become part of the newly burgeoning state parks system. A serious effort for State Park-hood was undertaken in 1934, but was defeated in the legislature. Efforts continued, and in 1945, the Columbia State Historic Park was created by the California legislature. Columbia now operates as a fully functional ghost town with kitschy tourist shops where one can buy gold pans and union suits. Many people still live and work in the town and the park created a major tourist draw to the region.

Sonora, while less derelict in the 1930s than Columbia, also capitalized on the allure of the lawless gold rush times, painted ladies, and rich history. The historic downtown contains abundant bed and breakfast establishments and an impressive number of antique shops. More recently, numerous vineyards have been developed in the area adding to the tourist industry appeal. In the mid-1970s, whitewater rafting became a major draw to the county.

Rafting and Wild and Scenic

The Stanislaus, Tuolumne, and Merced Rivers each possessed popular white water runs and a number of companies were established to capitalize on the growing recreation industry. However, the construction of New Melones Dam on the Stanislaus River completed in 1978, drowned the Stanislaus River run and was a rallying point for the rafting companies, conservationists and others concerned that the proposed dams on the Tuolumne would be approved and another world class white water river would be lost, not to mention the environmental degradation associated with the dams. The Tuolumne River already had 90% of the water in the system tied up for power generation, meaning that additional dams would not really be necessary for hydropower. The Tuolumne River Trust, a non-profit environmental group, compiled the first recorded cost-benefit analysis of dam construction vs. environmental, scenic, and recreation values and built a convincing case for not building the proposed dams. At the time, California was governed by Pete Wilson, a Repulican who politically could not oppose the dam for environmental reasons, but changed his mind about the dam once the economic case was presented. The Tuolumne River Trust analysis changed the way the environmental movement approached conservation and created a new model to challenge extractive resource proposals. Once the proposed dams were defeated in the early 80s, the conservation community worked for further protection of the river and its resources by proposing wild and scenic legislation which was ultimately passed by congress in 1984, protecting 29 miles of the Tuolumne River from future development. However, the Wild and Scenic designation did not extend to the Clavey River, which is truly an exemplary candidate. Conservation groups continue to try to pass Wild and Scenic legislation for the Clavey to this day.

Conclusions

The economic development of Tuolumne County began with the gold rush in the 1840s and continued with a series of boom and bust economic endeavors including timber, agriculture, and tourism. The need for goods and services in an area with no infrastructure launched the timber and agriculture booms fast on the heels of the gold rush. Each has followed its own economic trajectory and gone from small, individual efforts, to massive, industrialized undertakings. Today, Tuolumne County relies predominantly on a service-based industry capitalizing on the abundant recreational opportunities afforded by its ample public lands and waters, the rich history of the gold rush exemplified by Columbia State Historic Park, access to Yosemite National Park, and considerable scenic value. Increasingly, the population has trended towards retirees from the Bay Area. Unemployment remains a problem for the county and the need for more lucrative jobs than the service industry provides is evident in county politics and commerce. The future directions for the economy in the Tuolumne River watershed are unclear, but considerable growth is anticipated in the decades to come. Opportunities seemingly arise from the ashes of the booms and busts of earlier commerce in Tuolumne County entrepreneurs. As the county's demographics continue to shift and expand, there will be yet another evolution of economic drivers, entrepreneurial endeavor, and opportunism. It is as it has always been. Perhaps it's in the water.

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Chapter 12: The Power of Water: Harnessing the Tuolumne River

SARAH NULL, ANNE SENTER, GERHARD EPKE, AND SABRA PURDY

INTRODUCTION

This chapter introduces the water and power projects that have been developed in the Tuolumne River watershed. It is divided into three sections, covering water resource management and development, controversies and potential water use changes in the Tuolumne River watershed, and comparison with other Sierra Nevada watersheds. The first section chronicles how water resource development has fundamentally altered the flow regime of the Tuolumne River, affecting the hydrology and geomorphology. It also outlines the multiple water uses from the river, such as urban water supply, irrigation, instream water supplies for environmental protection, hydropower generation, flood control, and recreational benefits. These uses change in different reaches of the Tuolumne River and sometimes compete for the same water resources. The second section describes current and past controversies involving the Tuolumne River, illustrating how water resource management in California is dynamic - changing with societal values, economic pressure, and technology. The final section of this chapter compares water resource management in the Tuolumne River with that of other Sierra Nevada rivers to show that basic water uses remain the same for other watersheds, although management of the Tuolumne River is relatively simple compared with watersheds such as the American, Yuba, or Bear Rivers located in the northern Sierra Nevada.

Water and Power Development and Infrastructure

Water development in the Tuolumne River watershed began in the 1800's. The city of San Francisco, the Modesto Irrigation District (MID) and the Turlock Irrigation District (TID) all own pre-1914 water rights to appropriate water from the Tuolumne River. The rights of the two irrigation districts are older, and therefore senior, to those belonging to San Francisco. TID, MID, and San Francisco own the

Box 12. 1
Water and Power Measurements

Acre foot (af) *is 325,851 gallons, or the volume of water necessary to flood one acre of land under one foot of water. An acre foot of water typically provides water for a family of 4-5 people for one year.*

Kilowatt *- One kilowatt (kW) is 1,000 watts. A kilowatt hour (kWh) is one kilowatt of energy that is used for one hour. For example, a 100 watt light bulb that is on for one hour uses 0.1 kWh of electricity. If the 100 watt light bulb is on for one hour each day for a month, it will use 3 kWh of electricity (100/1000 kilowatts * 30 hours). Energy delivered by energy utilities is often charged by kWh. One household typically uses approximately 900 kWh per month, although usage changes by region and season depending on factors such as air conditioning.*

Megawatt *- A megawatt (MW) equals 1,000,000 watts. Megawatts are typically used by utility districts for measuring larger amounts of electrical energy.*

large water rights, although additional appropriative and riparian water rights belong to other entities within the watershed.

Today, total water storage on the Tuolumne River is 2,686,000 acre feet (af) for the San Francisco Public Utilities District (SFPUC), TID, and MID, although the Tuolumne River has a mean annual flow of approximately 1,800,000 af. This means the Tuolumne River has a larger capacity for water storage relative to the average volume of water that runs off from its watershed. The watershed ranges in elevation from less than 1,000 ft to over 13,000, with capacity to generate approximately 560 megawatts (MW) of hydropower. This section first presents water projects built by the irrigation districts, and then discusses San Francisco's Hetch Hetchy System.

IRRIGATION DISTRICT PROJECTS (TID AND MID)

La Grange Dam

A dam has existed at La Grange since the 1850s. The first dam was small and used to divert water for mining, although it was strong enough to survive large floods of 1861-62. The dam undoubtedly blocked fish passage, altering the ecology of the Tuolumne River. Due to these early developments, poor records exist of the natural flow of the river prior to alterations by humans, called unimpaired flow.

In 1893, a larger dam was built at La Grange as a partnership between TID and MID. TID is the oldest irrigation district in California, followed by MID, both established in 1887. Farmers needed more water to support their crops during the hot, dry summer months of the Central Valley. The new dam was a 125 ft stone masonry run-of-river dam, and was the first large dam on the Tuolumne River. A run-of-river dam is a dam that simply ponds water behind it, but does not allow control of outflow from the

Box 12.2
Water Rights

Appropriative Water Rights *- Most water rights in the Tuolumne River watershed are appropriative water rights. Appropriative water rights are allocated based on time, so the earliest claims receive the highest priority, and more recent claims receive lower priorities. With appropriative rights, water can be diverted to land that is not located near rivers, and water can even be transferred to other watersheds. Water can be stored or sold, but must be put to a beneficial use, such as for irrigation, or the right is lost. Appropriative water rights in California are divided between rights that were initiated before December, 1914, and rights that were issued after 1914. Pre-1914 water rights do not require permits, are limited to the amount of water diverted in 1914, and nearly always receive full allotments of water.*

Riparian Water Rights *– These water rights can be used for properties that are neighboring a stream or river. Water cannot be stored or transferred outside the watershed. Permits are not needed for riparian water rights.*

Federally Reserved Water Rights *– Rights that apply to federal land are federally reserved water rights. For the Tuolumne River, these rights are used within Yosemite National Park, and can only be used for purposes of federal land. (San Francisco Public Utilities Commission leases land from the National Park Service for its reservoirs within the park.)*

dam. When it was built, the Tuolumne River was already incised below the surrounding floodplain (irrigable lands) and so a high dam was needed for water to flow by gravity into irrigation canals of the water districts. La Grange Dam still exists today.

Don Pedro Dam

The original Don Pedro Dam was built in 1915 by TID and MID because farmers needed more irrigation water in summer months, and because the districts were concerned that if they did not use their water, the city of San Francisco would take it (Figure 12. 1). The original Don Pedro Dam was a concrete gravity dam and was completed in 1923. Reservoir capacity was 290,400 af, with a 15 kilowatt (kW) power plant (it was upgraded to 30 kW by 1926). TID and MID worked together to build the reservoir and associated power plant despite disagreements they had about how to fight San Francisco's water grab.

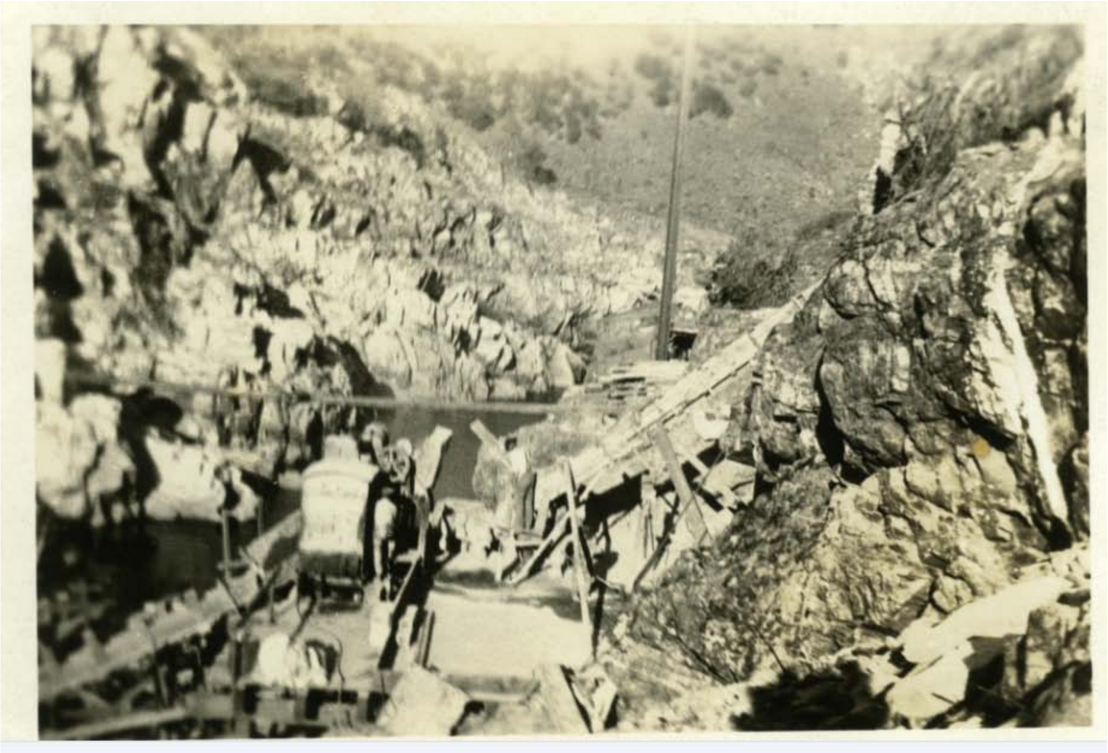


Figure 12.1 Early construction on Old Don Pedro Dam circa 1922. One construction worker appears to build one of the wooden chutes used to convey concrete. Another man is visible by the large machine which is probably a cement mixer. The Old Don Pedro Dam was designed and constructed on the Tuolumne River, northeast of Turlock, California. The project began in 1921 and was completed in 1923. Almost 300,000 cubic yards of concrete was used to build the dam and spillway. From http://www.calisphere.universityofcalifornia.edu/. California State University, Stanislaus. University Library. Special Collections

New Don Pedro Dam

In 1971, a larger earthen dam was built to replace the original Don Pedro Dam (the first dam is now submerged in the reservoir). It was renamed New Don Pedro Dam, has a storage capacity of 2,030,000 af, and was financed jointly by TID, MID, the San Francisco Public Utilities Commission (SFPUC), US Army Corps of Engineers (USACE), and California Department of Water Resources (CDWR). A powerplant at the base of New Don Pedro dam produces 203 megawatts (MW) of hydropower with four generators, which is approximately 0.3% of California's overall electricity supply and 1.5% of California's hydropower capacity. New Don Pedro is a multi-purpose reservoir, operated for agricultural and urban water supply, flood control, hydropower, and recreation.

CITY OF SAN FRANCISCO PROJECTS (THE HETCH HETCHY SYSTEM)

Damming Hetch Hetchy Valley

In 1880 the population of San Francisco exceeded 200,000, and was quickly growing. The city was in need of a permanent and reliable water source for drinking water and power generation. In 1882, San Francisco's water engineers began to look east to the Sierra Nevada for a permanent source of water to fill the city's needs. Many sites were considered including diverting water from Lake Tahoe, but in 1890, San Francisco Mayor James Phelan proposed to dam the Tuolumne River at Hetch Hetchy. The site was perfect; it had sufficient water, a large watershed with high elevation snow-fed headwaters, and a steep elevation drop below for power generation. It was the ideal solution to the city's water (and power) needs. However, Hetch Hetchy Valley was located inside the boundaries of the nation's newly created wilderness preserve that would later be known as Yosemite National Park.

In 1906, following the San Francisco earthquake, the shortcomings of San Francisco's water supply became obvious. At that time, a small private water company, Spring Valley Water Works, delivered San Francisco's water. A shortage of water contributed to fires burning uncontrolled after the earthquake. While city water planners had already targeted Hetch Hetchy Valley high in the Tuolumne watershed as the potential site of a large dam for San Francisco's water supply, the fires acted as a catalyst for the public to realize the city's water supply shortage.

San Francisco's proposal to dam Hetch Hetchy Valley was met with considerable opposition. For the first time in American history, a significant national voice for preservation and defense of natural resources was heard. John Muir formed the Sierra Club and spearheaded the battle to stop the valley from being dammed. In The Yosemite, he wrote, "Dam Hetch Hetchy! As well dam for water-tanks the people's cathedrals and churches, for no holier temple has ever been consecrated by the heart of man." With the Sierra Club, Muir wrote articles and editorials in newspapers, handed out pamphlets, and wrote thousands of letters to Congress asking for the protection of Hetch Hetchy. It should be noted that the Sierra Club did not envision a pristine wilderness; rather they saw the park as a place where recreational tourism brought people into the wilderness. There would inevitably be some development (and a certain amount of financial gain for the concessionaires that provided services to the tourists), but the Sierra Club did not see that as anathema to their preservationist goals. John Wesley Powell testified that his U.S. Geological Survey would not support plans to submerge Hetch Hetchy Valley for water supply. Central Valley farmers also opposed the dam, fearing their water would be taken even though they had senior water rights.

On the other side of the controversy, leading the water developers and city planners were San Francisco mayor James Phelan, Secretary of the Interior James Garfield, and chief forester for the U.S. Forest Service Gifford Pinchot. Pinchot used a utilitarian mentality, seeing benefits from multiple uses of public land to argue the need for damming Hetch Hetchy Valley. "The delight of the few men and women who would yearly go into the Hetch Hetchy Valley should not outweigh the conservation policy, [which is] to take every part of the land and its resources and put it to that use in which it will serve the most people." At that time, traveling to Yosemite took weeks, and therefore was limited to only a handful of fairly wealthy travelers.

The battle for Hetch Hetchy ground on for years through several administrations. The conservationists became frustrated. There were numerous site options for the dam outside the park, including upgrading the Spring Valley Water Company, which would have been considerably cheaper than the Hetch Hetchy project. However, Muir recognized San Francisco's need for water and offered Lake Eleanor as an acceptable dam site that the Sierra Club would not protest. Lake Eleanor would likely have sufficed the city's needs, but in their 1908 application to the Department of Interior, the city filed for both Lake Eleanor and Hetch Hetchy. Muir said in disgust, "Nothing dollarable is safe, however guarded. Thus the Yosemite Park, the beauty glory of California and the Nation, Nature's own mountain wonderland, has been attacked by spoilers ever since it was established, and this strife I suppose, must go on as part of the eternal battle between right and wrong."

San Francisco voters approved construction of a dam in Hetch Hetchy Valley by an 86% majority vote in 1908. However, because Hetch Hetchy Valley was inside Yosemite National Park, a special act had to be passed by Congress enabling a private reservoir to be built in a national park. The Taft administration suspended San Francisco's vote, but the political maneuvering continued and finally in 1913 Congress passed the Raker Act under the new administration of Woodrow Wilson. The Raker Act granted the city of San Francisco the water and damming rights to Hetch Hetchy and Lake Eleanor. In 1914 John Muir died. The fight for Hetch Hetchy Valley had taken a major toll on his health and friends noted he had become despondent with the loss.

Box 12. 3
Raker Act

The Hetch Hetchy Act, or Raker Act as it is more commonly known, was passed by Congress in 1913 allowing the city and county of San Francisco to build privately-owned dams within Yosemite National Park for the water and power supply of the San Francisco Bay Area. The act specifically granted San Francisco the right to build O'Shaughnessy and Eleanor Dams, and stipulated that San Francisco must provide public electricity to the city, and that water and power could not be resold for a profit.

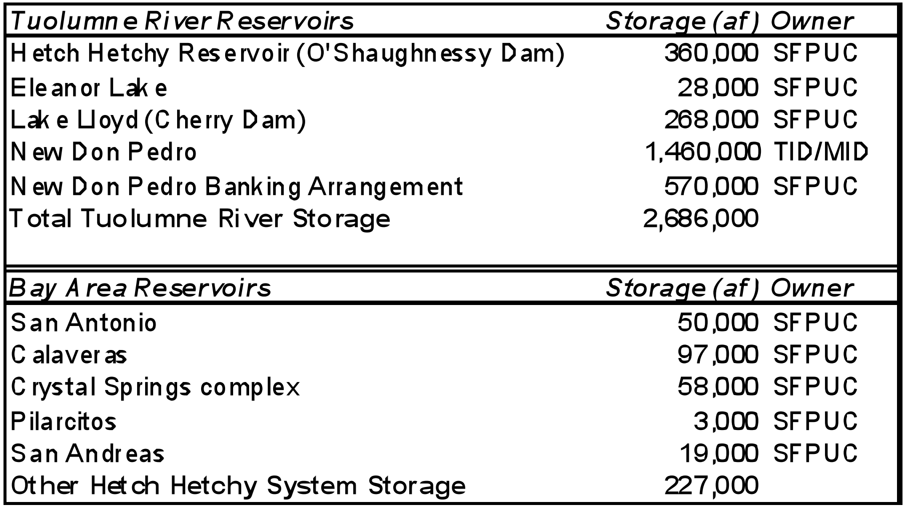
Claims that the city of San Francisco violated the Raker Act by failing to provide public power as specified began in 1923 and continue today. The city uses PG&E's transmission lines to carry power to the city. Prior to 1945, the city sold power to PG&E, who then sold it back to the public at an inflated price. Two world wars during that period increased power demands and caused Raker Act requirements to be ignored or postponed by Washington. In 1945, San Francisco was designated as the official retailer of Hetch Hetchy power. This change in wording changes little in practice. Technically San Francisco distributes the power from Hetch Hetchy, but only on paper by paying PG&E a substantial "wheeling fee' for use of their transmission system. This is perhaps a legally gray area masked by clever accounting. The San Francisco Bay Guardian Newspaper claims that San Francisco is still in violation of the Raker Act for failing to provide public power to the city.

The Hetch Hetchy System

O'Shaughnessy Dam (Hetch Hetchy Reservoir), Cherry Dam, Eleanor Dam, and numerous Bay Area reservoirs (San Antonio, Calaveras, Upper and Lower Crystal Springs, Pilarcitos, and San Andreas

Reservoirs) and connecting pipelines make up the Hetch Hetchy Water System operated by the SFPUC. In addition to these reservoirs, the SFPUC is allowed 570,000 af of water storage in New Don Pedro Reservoir under a water banking arrangement. Total surface storage in the Hetch Hetchy System is 1,453,000 af (Table 12.1), with 1,226,000 af of that storage on the Tuolumne River. The majority of the Tuolumne River water is transferred to San Francisco and Bay Area cities for water supplies, providing an example of a large out-of-basin water transfer. The Hetch Hetchy System supplies water to 77% of the urban and industrial uses of the city and county of San Francisco, as well as parts of San Mateo, Santa Clara, and Alameda counties. In total, approximately 2.4 million urban users are supplied with water from the Hetch Hetchy System. Three powerhouses (Kirkwood, Holm, and Moccasin) on the upper Tuolumne River have a maximum capacity of 403 MW, and provide an average 2 million kWh per year of hydropower. This is a clean source of energy for residents of San Francisco and an important source of revenue for the SFPUC.

Table 12.1 Hetch Hetchy System reservoir storage capacities



Tuolumne River Reservoirs	*Storage (af)*	*Owner*
Hetch Hetchy Reservoir (O'Shaughnessy Dam)	360,000	SFPUC
Eleanor Lake	28,000	SFPUC
Lake Lloyd (Cherry Dam)	268,000	SFPUC
New Don Pedro	1,460,000	TID/MID
New Don Pedro Banking Arrangement	570,000	SFPUC
Total Tuolumne River Storage	2,686,000	
Bay Area Reservoirs	*Storage (af)*	*Owner*
San Antonio	50,000	SFPUC
Calaveras	97,000	SFPUC
Crystal Springs complex	58,000	SFPUC
Pilarcitos	3,000	SFPUC
San Andreas	19,000	SFPUC
Other Hetch Hetchy System Storage	227,000	

O'Shaughnessy Dam (Hetch Hetchy Reservoir)

O'Shaughnessy Dam, which impounds Hetch Hetchy Reservoir, was completed in 1923, raised in 1938, and has been in use for the past eighty years. It is owned by the SFPUC, and has a storage capacity of 360,360 af. The dam is a 430 ft concrete gravity arch, with a multipurpose reservoir. Its current uses include water storage, hydropower generation, and to a lesser extent flood reduction, although primary flood control benefits are provided downstream at New Don Pedro Reservoir. Hetch Hetchy Reservoir is not used for recreation (swimming and boating are prohibited to maintain water quality), although recreation around the reservoir is allowed, such as fishing from shore, hiking, and viewing wildlife.

Typically, filtration of water supplies is an integral step in the multiple drinking water treatment processes used to meet water quality and public health standards. However, water from O'Shaughnessy Dam has filtration avoidance status, meaning O'Shaughnessy Dam impounds extremely high quality water from a protected watershed that meets federal water quality standards. Only minimal water treatment is currently necessary, such as addition of lime for corrosion control and chlorine or chloramine as a disinfectant. The watershed above O'Shaughnessy Dam is pristine, lying within Yosemite National Park. O'Shaughnessy Dam is the only reservoir in the Hetch Hetchy System to have filtration avoidance. Even nearby Lake Lloyd (Cherry Dam) and Eleanor Lake, which are less than ten miles from O'Shaughnessy Dam, do not qualify for filtration avoidance. Filtration avoidance status is exceptionally rare in large municipal supply systems, and has been grandfathered in for Hetch Hetchy Reservoir water. It makes the water impounded behind O'Shaughnessy Dam economically more valuable than water from other reservoirs in the system.

Cherry Dam (Lake Lloyd) and Eleanor Dam (Eleanor Lake)

Cherry and Eleanor Dams also belong to the SFPUC and are a part of San Francisco's Hetch Hetchy water system. Eleanor Dam was built in 1918, and Cherry Dam was built in 1955. These reservoirs are connected via the Eleanor Diversion Tunnel; therefore, these reservoirs have interconnected operations, and are discussed jointly here (Figure 12.2). Adequate water supply storage is usually provided by O'Shaughnessy Dam, enabling Cherry and Eleanor to be operated primarily for hydropower at Holm Powerhouse. Water from O'Shaughnessy, Cherry, and Eleanor Reservoirs merges into the mainstem Tuolumne River or is diverted into the Hetch Hetchy Aqueduct for delivery to San Francisco and other Bay Area cities. These operations are discussed more thoroughly in the water management section of this chapter.

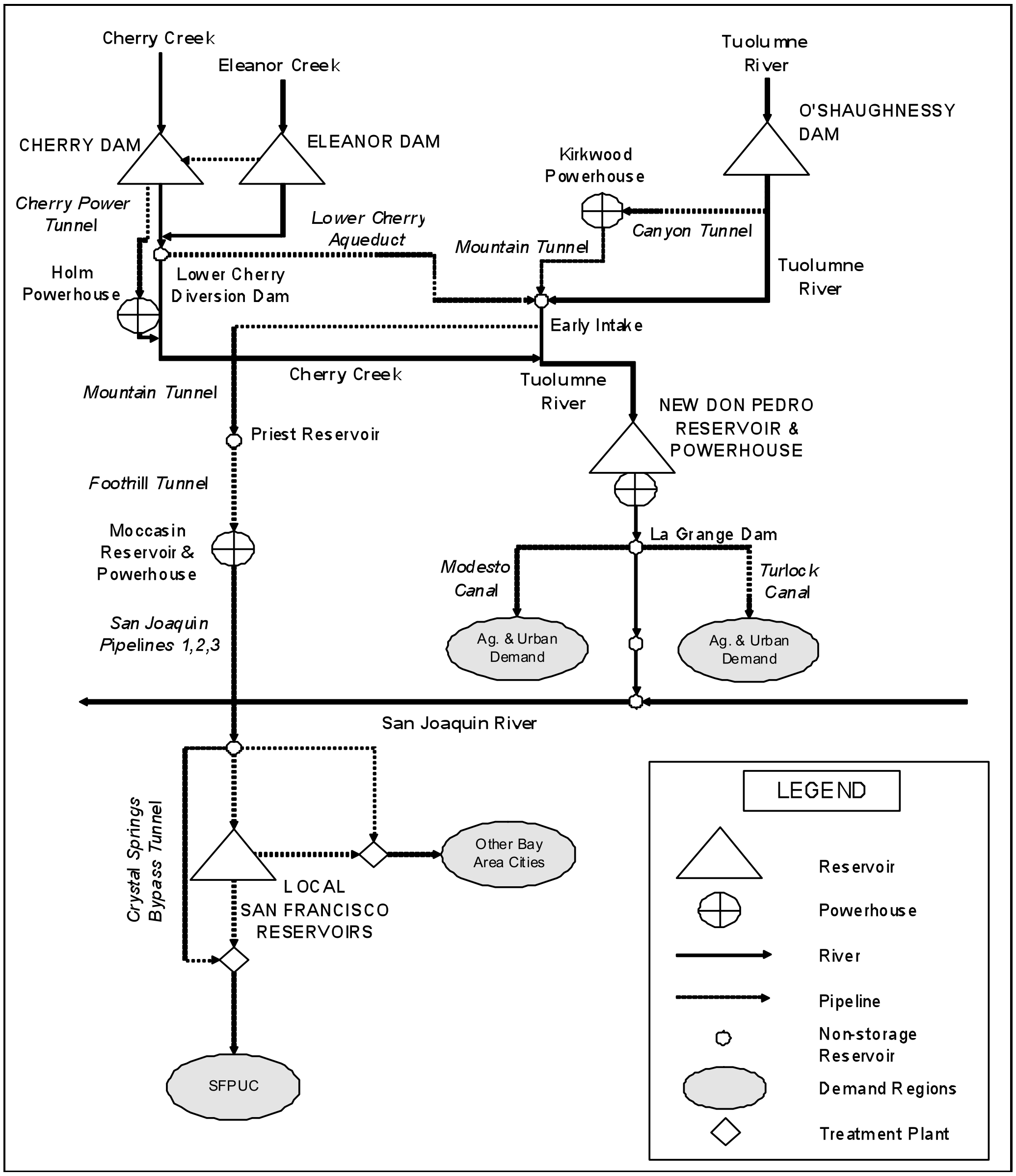


Figure 12.2 Schematic of Tuolumne River water and power infrastructure

The Effects of Dams on the Landscape

Dams profoundly change the hydrology and geomorphology of rivers both upstream and downstream of reservoirs. Common changes to river flow regime by dams are decreased magnitude of winter and spring peak flows, increased summer low flows, shifts in the timing and variability of discharge, and decreases in total downstream flow due to diversions and consumptive water use. Figure 11 shows measured and estimated unimpaired flow in the Tuolumne River below La Grange Dam, illustrating the differences to the flow regime that occurred by constructing the multiple upstream dams.

Reduced water and sediment supply downstream of dams incises, or erodes the river channel downward, disconnecting it from the surrounding floodplain. This disrupts and narrows the riparian corridor, limiting seedling recruitment, armoring the river channel, and generally degrading habitat. Finally, water quality in reservoirs and below dams is often impaired, impeding migration of aquatic organisms and providing suboptimal habitat conditions for native species. This section discusses the impacts of dams on the surrounding landscape, beginning with high elevation dams and ending with low elevation dams.

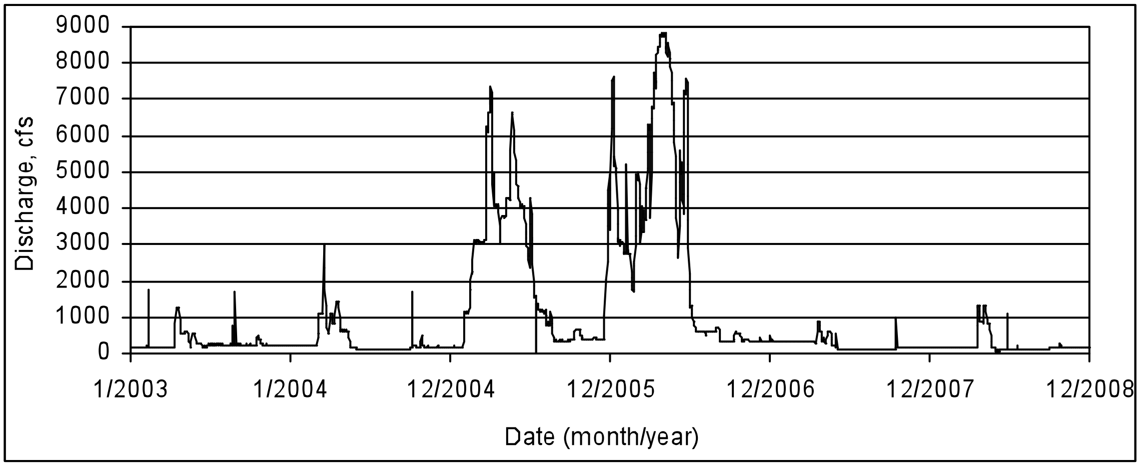


Figure 11.3 Tuolumne River flow below La Grange Dam (2003 - 2008) (CDEC)

High Elevation Reservoirs

Sedimentation in a reservoir is a common problem from dams. Sediment is carried downstream by rivers. Higher flow velocities can carry larger sized sediments as both suspended sediment and bed load, which is rolled along the bottom, or bed, of the river. When a river joins a reservoir, the velocity slows, and most sediment is deposited into the reservoir. This occurs at the upstream end of reservoirs (sediment is not physically stopped by the dam itself). Sedimentation is a problem because it reduces capacity and because downstream reaches no longer receive sediment.

High elevation reservoirs in the Tuolumne watershed, such as Hetch Hetchy Reservoir, are unique since the surrounding landscape is predominantly solid granite bedrock so sedimentation is negligible. Rates of sedimentation in alpine Sierra Nevada lakes typically vary based on size of the lake, but are generally quite low. The smallest lakes can receive 2 ft of sediment per 1000 yrs, whereas larger natural lakes such as Tenaya Lake may receive 6 in per 1000 yrs. Hetch Hetchy Reservoir probably also receives no more than 6 in of sediment per 1000 yrs. Furthermore, because of the resistant granite underlying the area, channel incision from the reservoir occurs on a geologic timescale rather than human timescale (decades or centuries).

Hetch Hetchy Reservoir also has very low organic pollution. Dams typically increase nutrient retention in the reservoir, but there is little pollution above the reservoir because the upper watershed is almost entirely within Yosemite National Park, meaning grazing is not allowed. Also the snow-fed water in the Tuolumne River is cold, and there are relatively few aquatic organisms in the river. Cherry and Eleanor Creeks both have grazing allotments in their headwaters, probably resulting in more organic pollution and higher sediment loads.

Downstream of O'Shaughnessy, Cherry, and Eleanor Dams, the most obvious ecological and geomorphic effects are changes in flow regime from dam operations (Chapter 4). The change in hydrology is such that today there are increased low flows, decreased peak flows, later onset of snowmelt discharge, and capture of a portion of snowmelt in reservoirs resulting in an abrupt decrease in the snowmelt pulse downstream. Summer flows would have been much lower without regulation from upstream dams. However, more importantly from a geomorphic point of view, is the decreased peak flows. It is well established that river systems and dependent organisms require periodic flooding to maintain adequate habitat conditions. Flooding is the catalyst for most of the geomorphic work of the river, maintaining the structure of the river, turning gravels, flushing silt, and creating stable floodplains and terraces needed for riparian vegetation. Overall, conditions are more homogenous throughout the year, and some of the dynamic nature of the Tuolumne River has been lost. Efforts are underway to re-introduce small-scale flooding below O'Shaughnessy Dam.

Low Elevation Reservoirs

New Don Pedro Reservoir causes a different set of problems associated with dams because it is lower in the watershed. As the Tuolumne River flows through the foothills, it accumulates water and sediment from tributaries until it reaches New Don Pedro, where sediment is released into the reservoir. This reduces water storage capacity through time, but also greatly reduces the sediment supply in the river reaches below New Don Pedro Dam.

A full suite of river management problems exists on the Tuolumne below its lowest dam, La Grange Dam. Here, irrigation and municipal water diversions have reduced flow while dams have reduced sediment supply. The lack of peak flows, combined with trapping of sediment behind the reservoir, result in less dynamic systems, where the river erodes, or incises downward, disconnecting it from its floodplain. Additionally, human development and urbanization of the floodplain have tightly constrained maximum dam releases, so downstream flows are kept below 9,000 cubic feet per second (cfs) to prevent flooding. These low flows, combined with dredge mining for gold and gravel have resulted in degradation of the riparian corridor.

WATER RESOURCE USE AND MANAGEMENT

Upper Tuolumne River

Much of the upper Tuolumne watershed is located within Yosemite National Park, which is managed primarily for wilderness, resource protection, and preservation. The Tuolumne River is also designated a Wild and Scenic River from its headwaters (the Lyell and Dana Forks of the Tuolumne River) to the upstream end of Hetch Hetchy Reservoir to protect the wild, scenic, and recreational characteristics of the upper Tuolumne River. Recreation is an important use of the upper Tuolumne

River. Although whitewater boating is not allowed in the reach above Hetch Hetchy Reservoir, camping, hiking, and fishing are common activities throughout the Tuolumne high country, and hiking the Grand Canyon of the Tuolumne River is a popular route within Yosemite National Park.

The snowpack at upper elevations of the watershed also serves as water storage through the winter. Thus, the entire upper Tuolumne River watershed could be considered one large snowpack reservoir for downstream water uses. Spring snowmelt occurs relatively slowly (compared to floods from rain storms) and can therefore be captured in reservoirs during late spring when the region is entering the warm, dry phase of its Mediterranean climate. If precipitation over the Sierra Nevada were rainfall instead of snowfall, much of it would flow to the ocean as floods. Decades ago, this water was called waste, now it is referred to as 'undeveloped water'. The possibility of more precipitation as rainfall rather than snowfall from climate warming is a future challenge for water resource managers.

Middle Tuolumne River (including Hetch Hetchy Reservoir)

Water management becomes more complicated in the middle Tuolumne River reach, from Hetch Hetchy Reservoir to New Don Pedro Reservoir. As mentioned in the O'Shaughnessy Dam section of this chapter, the water impounded behind O'Shaughnessy Dam is primarily used for municipal water supplies to San Francisco and Bay Area communities, with hydropower as a side benefit. Because the water behind O'Shaughnessy Dam has the filtration avoidance status discussed above, swimming and boating are prohibited in Hetch Hetchy Reservoir, so recreation is not a direct use of this reservoir. Flood protection is a secondary benefit of O'Shaughnessy Dam. While flood storage space is not mandatory, operators often keep space in the reservoir during winter to generate hydropower (hydropower cannot be produced from uncontrolled releases). Capturing water from flood events behind O'Shaughnessy Dam reduces their magnitude downstream. Estimates suggest that without O'Shaughnessy Dam, flood protection for the lower Tuolumne River would be reduced from the current 1 in 50 year level to 1 in 40 year level (more on this below). During wet years with large snowpacks, a percentage of the flood storage space required at New Don Pedro Dam can be transferred up to O'Shaughnessy Dam.

Box 12.4
National Wild and Scenic Rivers System

The National Wild and Scenic Rivers System was created by Congress in 1968 to preserve rivers with outstanding natural, cultural, and recreational values in a free-flowing condition for the enjoyment of present and future generations. Rivers are classified as wild, scenic, or recreational, depending on their existing level of development. Wild and Scenic River designation is meant to balance established policies of building dams, hydropower facilities, and dredging rivers with protecting natural and cultural values of free-flowing rivers. The designation does not protect them from development or preclude existing private property rights. There is generally a ¼ mile buffer on each bank of the designated section that is also protected.

As indicated in Figure 12.22, part of the water released from O'Shaughnessy Dam is diverted into the Canyon Tunnel, where it generates hydropower at Kirkwood Power Plant, and some water is released into the Tuolumne River. Twelve miles downstream at Early Intake, a non-storage reservoir, water from O'Shaughnessy Dam via Canyon Tunnel, water from Eleanor and Cherry Dams via the

Mountain Tunnel, and water from the Tuolumne River below O'Shaughnessy Dam merge. Here, some water is diverted into the Hetch Hetchy Aqueduct to San Francisco, and some water is released into the Tuolumne River.

The 35 miles downstream of O'Shaughnessy Dam (the first six mi are in Yosemite National Park) have also been designated as a Wild and Scenic River, and minimum instream flows of 50-125 cfs are required below O'Shaughnessy Dam. This reach is one of the most popular whitewater boating runs in California, and releases of approximately 1,000 cfs are scheduled for rafting every day except Sunday from March through September.

Given the competing uses between diverting water for urban water supplies, hydropower generation, minimum instream flows, and recreational releases, decisions are negotiated so that water is allocated to the different water demands. Since TID and MID have senior water rights their allotments, which are diverted downstream, must be met before water is diverted to San Francisco. Typically, instream flows and recreational releases vary by water year so that more water is delivered to these uses in wetter years. After minimum instream flows have been released into the Tuolumne River, priority is given to urban water supplies, and as much water is diverted as is possible until the Hetch Hetchy Aqueduct is at capacity (465 cfs). Hydropower can be generated from upper powerplants before water is diverted into the Hetch Hetchy Aqueduct. Environmental and recreational releases are also used to fulfill the downstream water rights of TID and MID and to generate power downstream at the New Don Pedro Hydropower Plant, which are discussed next.

Lower Tuolumne River (including New Don Pedro Dam)

Water management remains complicated in the lower Tuolumne River reach. The water in New Don Pedro Reservoir is used for urban and agricultural water supplies, flood protection, hydropower generation, and minimum instream flows for the lower Tuolumne River. New Don Pedro Reservoir is a popular recreation lake, where visitors enjoy, swimming, boating, fishing, camping, and water sports such as water skiing and wakeboarding. The Don Pedro Recreation Agency oversees recreational elements and opportunities of the reservoir (and is funded by TID, MID, and the city and county of San Francisco).

New Don Pedro Dam provides flood protection for communities and property owners along the lower Tuolumne River. Despite the large storage capacity of the reservoir, operators aim to keep releases from New Don Pedro below 9,000 cfs because homes, agriculture, and property improvements have encroached on the floodplain, severely constraining the river channel. Higher flows are avoided when possible to limit downstream flood damage to levees and property owners. The U.S. Army Corps of Engineers (USACE) requires 340,000 af of flood storage in New Don Pedro during winter and spring runoff seasons. This protects against a 50 year flood (probability of a flood event that occurs approximately once every 50 years). Flows have exceeded the 9,000 cfs target infrequently (1964, 1986, 1997) (Figure 12.4). In 1997, flows in the Tuolumne River below New Don Pedro Dam reached nearly 60,000 cfs, causing widespread flooding and damage downstream of the dam.

Although once a natural occurrence, flooding of the channel now damages downstream levees and property. Encroachment on the floodplain is an ongoing problem with costly consequences. Agricultural and range lands are giving way to more housing developments along the lower Tuolumne River, which drastically increase the costs and danger of floods. In 1997, many Sierra Nevada rivers flooded, and total costs from that storm exceeded $2,000,000,000. On the Tuolumne River, flood protection is in direct competition with water storage, and generally water supply takes precedent. In fact, the federal government offered to pay $5,000,000 to buy additional flood control storage in New Don Pedro in the 1960's, but local interests preferred to dedicate that space for irrigation water and hydropower. The 1997 flood has been quickly forgotten and new housing developments continue to be built in the floodplain, with hope that levees, dykes, and dams will render them immune to flooding. Reservoir operators are tasked with striking a delicate balance between crippling droughts and devastating floods.

Figure 12.4 New Don Pedro Spillway during January, 1997 flood when flow reached 60,000 cfs (from Jay Lund's dam website)

Aside from the 570,000 af of storage owned by SFPUC in New Don Pedro Reservoir (discussed in the Hetch Hetchy System section of this chapter), water is used for urban and agricultural water deliveries to TID and MID, generating hydropower in the process at the New Don Pedro Power Plant. Water is released from New Don Pedro Dam, where up to 203 MW of hydropower is generated at New Don Pedro Power Plant, and then flows into the lower Tuolumne River. La Grange Reservoir, a non-storage reservoir, is approximately two miles downstream where water is diverted into the TID canal to Turlock Lake or to the MID canal to Modesto Lake. Annual average deliveries of 575,000 and 310,000 af are delivered to TID and MID, respectively. These supplies are mostly used for agriculture, and top crops for the region include milk, almonds, chickens, grapes, walnuts, cattle, tomatoes, and peaches. The districts also provide municipal water to Central Valley cities, such as Modesto, Turlock, Merced, Manteca, and Madera.

Environmental minimum instream flows (MIF) are required to protect native fisheries and aquatic ecosystems downstream of New Don Pedro Dam as part of the Federal Energy Regulatory Commission's (FERC) hydropower license. MIFs vary by month and water year type (wet, normal, or dry years), and range from approximately 50 – 300 cfs. Under the 1995 FERC Settlement Agreement and Lower Tuolumne River Corridor Restoration Plan, the lower Tuolumne River is being restored for Chinook salmon, riparian habitat, instream river conditions, and to increase the flood capacity of the lower Tuolumne River channel. Chinook salmon populations have plummeted following the dam building era in the western U.S., and widespread efforts are underway to restore populations in the San Joaquin River and all its major tributaries. Many groups worked together for the 1995 FERC settlement agreement such as TID, MID, SFPUC, state agencies like Dept. of Fish and Game (CDFG), and numerous environmental groups like the Tuolumne River Trust, National Resource Conservation District, and Friends of the Tuolumne. Current efforts include improving flow, adding gravel below dams, increasing floodplain area, restoring channels damaged by gravel mining, and conservation easements to provide a continuous floodplain corridor from New Don Pedro to the confluence with the San Joaquin River.

Controversies

Ongoing controversies within the Tuolumne watershed include efforts to both dam the Clavey River and to protect it as a Wild and Scenic River, attempts to increase San Francisco's 'rental fee' for Hetch Hetchy Valley, and efforts to remove O'Shaughnessy Dam to restore Hetch Hetchy Valley. This section emphasizes that although water projects are built for long time periods (decades to centuries), they are still altered, reflecting economic costs, societal values, population increases, technology, and increasingly climate change.

CLAVEY RIVER

Early Development

The Clavey River is a tributary to the Tuolumne River, and is one of just three remaining free-flowing streams in the Sierra Nevada. The watershed encompasses 157 mi^2, with its headwaters at an elevation of 9,200 ft in the subalpine forests and exposed granite of the Emigrant Wilderness in Stanislaus National Forest. It is oriented north-south with a deeply carved mainstem canyon and is situated within the larger east-west oriented Tuolumne River watershed. Located to the northwest of Yosemite National Park, montane forests blanket the majority of the watershed. The Clavey River is home to 70 miles of streams before it reaches its confluence with the Tuolumne River at 1,200 ft elevation.

Ranchers, homesteaders, miners, and loggers have diverted Clavey River flows in small quantities for more than 100 years. In the early 1900's three large diversion projects were proposed. In 1905, the Tuolumne Electric Company proposed a 33 ft high dam that would divert Clavey River flows from low in the watershed to a powerhouse on the Tuolumne that would generate electricity for mining operations. Although the dam was not built, Clavey River flows were diverted to the powerhouse from 1908-1911. Flooding on the Tuolumne in 1911 damaged the powerhouse and the flume carrying water from the Clavey River. Once limited repairs were made, operations continued without Clavey River water until 1916, when competition shut the powerhouse for good. The dam permit for the Clavey River was never granted, and in 1923 the Forest Service terminated the Tuolumne River powerhouse permit.

The Tuolumne Electric Company was industrious throughout the watershed in the early 1900's. In 1906, one year after the initial application to dam the lower Clavey River, the company applied for a permit to build a hydropower dam at the upper end of the watershed at Bell Meadows, situated high in the watershed and accessible from Mono Road (now Highway 108). The perennial Bell Creek supports an extensive meadow system with large stands of quaking aspens and a self-supporting rainbow trout fishery. Sometime after 1850, settlers established a summertime dairy farm at the meadow.

Overgrazing by cattle and sheep was the norm for decades as the meadow degraded (by the 1980s, Bell Creek's channel had incised into the meadow as much as eight ft). Forest Service personnel tasked with weighing the benefits of a reservoir to that of the dairy, meadow, and trout fishery (in keeping with the Forest Service' mandate of natural resources being utilized for the greatest good for the greatest number of people) strongly opposed the dam. Despite this, the dam was approved.

However, the great San Francisco earthquake of 1906 not only devastated much of the city of San Francisco, it also dealt a fatal blow to the plans for a dam at Bell Meadows. A number of principle owners of the Tuolumne Electric Company lived in San Francisco and had bigger problems to deal with, thus work on the dam was not started promptly. In 1908 the Forest Service rescinded the permit for this site along with power sites along 16 other western rivers in a federal effort to prevent private speculators from monopolizing potential hydropower sites.

Potential Wild and Scenic Designation

Decades later another dam was proposed for the Clavey River. In 1968, TID and MID proposed to build a hydropower dam 20 miles upstream of its confluence with the Tuolumne River. Designs for the dam proceeded slowly, and meanwhile the Clavey River was identified as a *potential* Wild and Scenic River in 1982, in part because it was one of the last large watershed corridors in California with few developments from its high alpine ecosystem to the foothills. A related 1972 designation as a Wild Trout Stream by CDFG was designed to limit trout stocking in order to preserve the last existing self-sustaining trout fishery in the Sierra Nevada.

Other local hydropower developments were in the works as well. In 1983, FERC issued a preliminary permit to the MID, TID, and city and county of San Francisco to explore the construction of up to three hydroelectric dams on the Tuolumne River. One proposed dam, the Clavey-Wards Ferry Dam, would have affected seven miles of the lower Clavey River and 27 miles of the Tuolumne River, although the existing hydropower infrastructure on the river already captured 90% of the existing water for power generation. In response to this permit, Environmental Defense completed one of the first cost-benefit analyses of a major public-works project to include direct quantification of lost ecosystem services against benefits of the project. They identified the loss of whitewater rafting on the Tuolumne River and damage to the self-sustaining rainbow trout fishery of the Clavey River as two major negative environmental impacts, and calculated the cost associated with the loss of these recreational opportunities at $26 million per year (in 1984 dollars). In addition, they proposed that the Tuolumne River be designated as a Wild and Scenic River, which would preclude any further development. The report provided an out for politicians who had previously supported the dam schemes and received a great deal of attention at the federal level. They did not have to side with environmentalists over water and power; they could now provide a solid economic argument against the dams. By September 1984, much of the mainstem Tuolumne River from Tuolumne Meadows in Yosemite National Park to the impoundment at Don Pedro Reservoir was designated a Wild and Scenic River. However, the Clavey River did not receive Wild and Scenic status.

A preliminary application for the Clavey River Dam Project was filed with FERC in 1986 by the TID and a new entity, the Tuolumne Utility District (TUD). Opposition to the application was immediate and vociferous, but others welcomed the prospect of increased renewable energy resources. Two groups, the Clavey River Preservation Coalition and the Tuolumne River Preservation Trust led the opposition. Fierce public opinion battles raged throughout the Sierra Nevada and California. Ultimately, FERC denied the dam license in 1994, after FERC determined that the construction of a dam was not feasible. Additionally, the Clavey River was determined as “eligible but unsuitable” for Wild and Scenic River designation. Appeals to this determination were denied in 1990 and again in 1991. Finally, in 1996 the Forest Service agreed that the Clavey was suitable for Wild and Scenic designation. Since that ruling, the Forest Service has managed the watershed as if it has been designated as Wild and Scenic. In 1998, a recommendation for designation of the Clavey River as Wild and Scenic was sent to Congress, but as of 2009, they have not approved the recommendation. Today, the river remains vulnerable to additional dam proposals until federally protected.

Cost to San Francisco of Leasing Hetch Hetchy Valley

As part of the Raker Act, San Francisco is required to pay the Department of the Interior a "rental fee" for the use of Hetch Hetchy Valley. The payments began in 1918 at $15,000 annually, increasing to $20,000 per year in 1928, and $30,000 per year in 1938. There have been no increases in rent since then. In the early 1990's a rent increase was proposed, and again in 2004 President Bush proposed increasing rent to $8 million per year, money that would remain in Yosemite National Park. Outraged Senators Diane Feinstein and Barbara Boxer immediately fought the rental fee increase, claiming it was a "raid on the city's coffers".

To date there has been no increase in rental fees, and currently San Francisco still pays $30,000 annually for the land below Hetch Hetchy Reservoir. The city rents nearly 2,000 acres at approximately $0.07 per acre per year. Hetch Hetchy Valley has cost San Francisco $30,000 per year for more than 70 years, probably the only rent that has not increased in the nation during this time period.

Efforts to Restore Hetch Hetchy Valley

O'Shaughnessy Dam was controversial at the time it was proposed and built in the early 1900s. Some people, including John Muir, questioned whether a reservoir for San Francisco belonged in a national park 200 miles from the city. Today the idea of removing O'Shaughnessy Dam to restore Hetch Hetchy Valley has been revisited, although the debate has changed and is more complex than in the early 1900s. Yosemite National Park is now one of the most loved and visited parks in the United States, with roads providing easy access for the 3.5 million people that visit the park annually. San Francisco is a major urban center in California, with 2.4 million residents requiring reliable water supply. The Tuolumne River now has significant storage capacity with construction of New Don Pedro Reservoir and other upper elevation reservoirs. In a basin with considerable water storage, more storage does not mean more water. For restoration to be considered, it must be determined that the Hetch Hetchy System can supply enough water without O'Shaughnessy Dam, or that alternative sources exist. Also feasible hydropower replacement options must be identified.

There are valid arguments for both keeping and removing O'Shaughnessy Dam. The arguments for keeping O'Shaughnessy Dam in use are primarily economic. Hydropower is generated from O'Shaughnessy Dam releases. Loss of filtration avoidance from removing the dam would necessitate additional water treatment facilities, incurring considerable costs to the Hetch Hetchy System, and thus to water users. Furthermore, the existence of O'Shaughnessy Dam provides security in the water supply to operators of the Hetch Hetchy System and its customers, whether real or imagined. Finally, some environmentalists believe that O'Shaughnessy Dam is a poor candidate for limited environmental restoration funds because there is relatively little ecological improvement to be gained from removal of this dam. Its removal would benefit no threatened or endangered species, and would make only minor improvements to the ecological connectivity of the Tuolumne River system. The land under the reservoir could be restored, but this is a small land area to justify removal on environmental grounds.

The arguments for removing O'Shaughnessy Dam are also economic and deal primarily with increasing open space in Yosemite National Park for tourism and recreation, as well as removing the dam for aesthetic or ethical reasons. Yosemite National Park is one of the most heavily visited national parks in the nation. Within the park, Yosemite Valley is grossly impacted. Restoring Hetch Hetchy Valley could open a valley nearly identical to Yosemite Valley in terms of beauty, and approximately half the size to wildlife and the public (Figure **12.**12.5). Revenue from tourism could offset some or all of the lost revenues from removal of O'Shaughnessy Dam. However, SFPUC would lose revenue from removal of O'Shaughnessy Dam, though the federal government and concessionaires would benefit from increased tourism to Hetch Hetchy Valley. Still, this problem can be thought of as weighing two scarce resources, water and space, in Yosemite National Park. There are also ethical questions regarding the existence of O'Shaughnessy Dam. It has been argued by John Muir and others that a reservoir for San Francisco residents simply does not belong in Yosemite National Park, land that in theory belongs to all Americans. Indeed, using Gifford Pinchot's rationale for benefiting the greatest number of Americans for the longest time, it may no longer serve the best interests to use Hetch Hetchy Valley as a private water supply for San Francisco and other Bay Area communities.

Figure 12.5 Hetch Hetchy Valley (USGS, 1906)

Throughout the past century, there has been substantial controversy between water developers and conservationists regarding O'Shaughnessy Dam. Most of the literature pertaining to the controversy about damming Hetch Hetchy Valley pre-dates 1920. John Muir's writings are, without question, the most famous. For many, Muir's writings alone give Hetch Hetchy Valley the feeling of a majestic and awe-inspiring place. Excellent summaries of the debate to dam Hetch Hetchy Valley are posted on the Sierra Club webpage and the Library of Congress conservation crossroads webpage[1].

After O'Shaughnessy Dam's completion in 1923, the idea of Hetch Hetchy Valley without a reservoir was largely forgotten. In 1987, Donald P. Hodel, then Secretary of the Interior under Ronald Reagan,

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[1] Library of Congress website: http://memory.loc.gov/ammem/ndlpedu/lessons/97/conser1/lesson2.html

1913 NY Times Editorials opposing Damming of Hetch Hetchy:
http://www.sierraclub.org/ca/hetchhetchy/ny_times_1913_editorials.html

renewed interest in Hetch Hetchy Valley by suggesting that restoration of Hetch Hetchy Valley might be possible. The U.S. Bureau of Reclamation produced a report for the National Park Service on possible water replacement scenarios to enable dam removal. Soon after, the Department of Energy issued a report discrediting those proposed replacement scenarios.

The past decade has seen a growing interest in restoring Hetch Hetchy Valley. In 2004, Sarah Null's master's thesis from U.C. Davis[2] analyzed the feasibility of removing O'Shaughnessy Dam for water supply, and determined the dam could be removed with little water scarcity to downstream urban and agricultural water users if an inter-tie connects New Don Pedro with the Hetch Hetchy Aqueduct. Physically, the Hetch Hetchy Aqueduct crosses New Don Pedro Reservoir. As stated above, the Hetch Hetchy System owns storage space in New Don Pedro Reservoir; however, there currently is no way to route this water to Bay Area users except by releasing it through the Tuolumne River to the San Joaquin River, pumping from the Sacramento-San Joaquin Delta, then routing it to either the South Bay Aqueduct or the Pacheco Tunnel via the California Aqueduct. This hypothetical New Don Pedro-Hetch Hetchy Aqueduct inter-tie increases flexibility in the conveyance system and ensures higher quality water to Bay Area customers than water pumped from the Delta.

This option is physically simple, but operationally, legally, and politically difficult as TID, MID, and SFPUC would need to combine their operations without sacrificing water reliability to their customers. In the past 75 years, there have been only four agreements between the SFPUC and the irrigation districts concerning water rights, O'Shaughnessy Dam operations, flood control, cost-sharing for Don Pedro Reservoir, a water-banking and credit-exchange agreement for Don Pedro, and sharing of FERC operation requirements at Don Pedro. These entities tend to limit contact with each other, and current operations are simple enough that they can largely avoid interacting; however, that may not be the case in the future.

Also in 2004, Environmental Defense released a report[3] with essentially the same conclusions as the U.C. Davis study. The Environmental Defense report also outlined power replacement opportunities for the lost hydropower generation from removing O'Shaughnessy Dam. Hydropower generation can continue at Holm, Moccasin, and New Don Pedro Power Plants, but is largely eliminated at Kirkwood without the reservoir.

A handful of non-profit organizations support finding water and power alternatives to O'Shaughnessy Dam, investigating policy concerns relating to possible removal of the reservoir, and ultimately restoring Hetch Hetchy Valley. The most prominent group is Restore Hetch Hetchy[4]. Policy analysts, engineers, environmental activists, and legal advisors from this organization have been researching and promoting the possibility of removing O'Shaughnessy Dam. They have met with politicians, the public, and Hetch Hetchy System managers to discuss alternatives to the dam. Sierra Club and Environmental Defense also have publicly endorsed restoration of Hetch Hetchy Valley or studies to evaluate restoration potential of the valley.

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[2] Null, S., 2003. Re-Assembling Hetch Hetchy: Water Supply Implications of Removing O'Shaughnessy Dam. Master's Thesis, U.C. Davis, California.

[3] See <u>Paradise Regained</u> in the further reading section at the end of this chapter.

[4] http://www.hetchhetchy.org/

In 2005, Tom Philp from the Sacramento Bee Newspaper received a Pulitzer Prize for writing a series of editorials discussing the possibility of removing O'Shaughnessy Dam. This brought additional media attention to the idea of restoring Hetch Hetchy Valley. Governor Schwarzenegger then asked the California Department of Water Resources (CDWR) to analyze existing studies on removing O'Shaughnessy Dam to see whether the idea was feasible. In 2006, they released their conclusions. Existing research is scientifically sound, but restoration would be expensive (they estimated a $3-10 billion price tag). At present, controversy remains. Senator Feinstein is staunchly opposed to the idea, calling O'Shaughnessy Dam a 'birthright' for the city of San Francisco.

There is a good deal of irony that San Francisco, one of the nations 'greenest' cities, continues to transfer water from Yosemite National Park. Even Los Angeles has made arrangements to limit water supplies from Mono Lake to preserve its fragile and unique ecosystem and to mitigate for drying Owens Lake (both located in California east of the Sierra Nevada). A century after John Muir famously fought to preserve Hetch Hetchy Valley for the public trust, the debate has once again been raised and is gaining momentum.

Potential Restoration of Hetch Hetchy Valley

If O'Shaughnessy Dam were to be removed, restoration efforts would likely be intensive since Hetch Hetchy Valley is in Yosemite National Park. Restoration could include removal of the concrete face of the dam, which would be more thorough but also entails disturbing a restoration site. Or the reservoir could be drained but the dam left in place as a historical monument, with restoration focusing on the valley behind it. For either option the lower 118 ft of the dam, the portion that was excavated into bedrock, would most likely be left to avoid creating a cataract and causing downstream impacts. Sedimentation has been negligible in the reservoir behind O'Shaughnessy Dam because the granite bedrock in the surrounding area provides little loose sediment. Thus, were O'Shaughnessy Dam to be removed, no dredging or removal of silt would be necessary. It is assumed the Tuolumne River would return to its natural channel without human assistance. During 1977, a critically dry year, the river was in its original channel in the upper four miles of Hetch Hetchy Valley that were exposed from low reservoir levels. Reservoir draw down could occur within one year or over a period of five years with slower draw down allowing more intensive restoration management and dispersal of native seeds over newly exposed land. Herbaceous vegetation could return to Hetch Hetchy Valley within a year or two. Woody shrubs and tree saplings could follow over the next decade. Thus, it would not take long for Hetch Hetchy Valley to become a pleasant recreation site. Very large trees could take 50-100 years. National Park Studies predict that within 150 years, the "entire valley would appear much as it did before construction" of O'Shaughnessy Dam. The bathtub ring left by the reservoir would be noticeable long into the future. The bathtub ring occurs from the absence of lichen, as well as the bleaching of natural water stains from submersion of the granite walls. Lichen could grow within 75-120 years. The staining of the granite from moisture would not return on a human timescale.

The Tuolumne River and other Sierra Nevada Watersheds

The level of development, water uses, and future challenges for the Tuolumne River are largely similar to other watersheds in California and the western U.S., although the Tuolumne River may serve as a fairly simple example. Regardless, the primary water uses of urban and agricultural water supply, hydropower, flood control, recreation, and environmental protection represent the major water uses. Also water resource management and operations reflect current societal needs and opinions, economic constraints, and technology improvements, which change through time. California is often at the forefront of water management due to an arid climate, hydrologic variability and uncertainty, competing water demands for urban, agricultural, and environmental supplies, recreation, flood protection, water quality concerns, power needs, and ecosystem services provided by rivers. Development and water resource statistics for select Sierra Nevada watersheds are discussed in the following paragraphs to provide a basis for comparing the Tuolumne River with other Sierra Nevada rivers, and to show the complexity in which some Sierra Nevada watersheds are managed. Watersheds such as the Feather, Yuba and American have many small reservoirs instead of few large reservoirs, as occurs in the Tuolumne basin (Table 12.2). Partly because of this, the Yuba and American River watersheds generate more hydropower because multiple reservoirs in series repeatedly generate hydropower as water flows down the watershed. Water storage is abundant in the Tuolumne River, primarily from 2,030,000 af New Don Pedro Reservoir, although there are less dams than other basins. The next paragraphs highlight the American River watershed as an example of a watershed with a high level of water resource development as well as complex operations and management.

Table 12.2. Water resource benefits by watershed from north to south

Watershed	Total Online Capacity (MW)	Hydropower Facilities	FERC Relicenses (next 40 yrs)	Total Water Storage Capacity (af)	Number of Dams (>1,000 af)	Wild and Scenic Rivers (mi)	Rafting or Recreation	Area (mi^2)
Feather	1,635	23	7	5,405,836	25	78	x	3,634
Yuba	424	12	4	1,430,098	22	--	x	1,202
Bear	257	15	1	181,600	5	--	--	282
American	1,221	19	5	1,796,540	24	62	x	1,862
Cosumnes	0	0	0	41,346	1	--	x	535
Mokelumne	374	7	2	851,249	13	--	x	578
Calaveras	2	1	1	319,421	2	--	--	362
Stanislaus	1,010	12	7	2,841,550	12	--	x	904
Tuolumne	**558**	**6**	**1**	**2,717,511**	**9**	**83**	**x**	**1,533**
Merced	108	3	2	1,041,766	2	122	x	1,037
San Joaquin	1,278	17	5	1,269,577	12	--	--	1,666
Kings	1,715	6	4	1,245,255	6	81	x	1,544
Kaweah	26	4	2	142,686	1	--	x	560
Tule	10	3	3	82,693	1	--	--	392
Kern	84	4	5	568,310	1	94	x	2,310

As discussed throughout this chapter, there are three large water agencies on the Tuolumne River watershed, the SFPUC, TID, and MID. In contrast, major water developments in the American River watershed include Sacramento Municipal Utilities District's (SMUD) Upper American River Project, the Central Valley Project's American River Diversion (operated by USBR), PG&E's Chili Bar Project, and Placer County Water Agency's Middle Fork American River Project. These projects provide urban and industrial water supplies, irrigation water, hydroelectricity, flood control, environmental protection and enhancement (including water quality improvements), and diverse recreational uses. The upper Bear River watershed is sometimes included with the American River because it is linked by a network of canals that transfer water from the Bear to the American watershed. These canals date from the Gold Rush era and are still in use today.

The forks of the American River are also one of the most important commercial whitewater recreation resources in California. In 2007, a new settlement agreement was signed that provides environmental minimum instream flows, fish screens to prevent entrainment of native fish, and reliable flows for whitewater boaters below Chili Bar Dam on the South Fork American River. The agreement is meant to benefit fish, aquatic ecosystems, anglers, boaters, and reservoir recreationists, although the groups still find themselves at odds with each other over flow ramping, or the rate at which flows increase and decrease. This settlement agreement was signed by SMUD, PG&E, US Forest Service, State Water Resources Control Board, CDFG, US Fish and Wildlife Service, and the California Hydropower Reform Coalition (which represents river advocacy groups such as California Sport Fishing Protection Alliance, Friends of the River, and American Whitewater). The complexity of this single agreement reflects the level of negotiations required to manage water resources in the American River watershed. Many additional projects have dams that are up for FERC relicensing in the next decade, allowing opportunities for environmental and recreational changes to existing operations.

Like the Tuolumne River, development and resource management has changed through time in the American watershed. Water rights for CVP's proposed 2,000,000 af Auburn Dam at the confluence of the Middle and North forks of the American River were recently lost after they had not been used for over 40 years. Dam construction was authorized in 1965, but delayed due to skyrocketing costs, concerns it was not seismically safe, and environmental concerns. The dam was proposed primarily to improve flood protection in the lower American River, with increased water supply a secondary benefit. However, new water yield from Auburn Dam was estimated at only 50,000 – 75,000 af (because that is the volume water that is not already captured in other dams). Water storage is not water.

Changing Attitudes throughout the Nation

The 1920's and 30's marked the age of the dam building in California and the western US. The dam building era was defined by an aggressive policy of seeking water on a grander scale than was ever seen before. Construction of massive water storage and conveyance systems collected and moved approximately 60% of the state's surface water supply. Two of the largest projects include the federally-funded Central Valley Project and the state-funded State Water Project. Ironically, as San Francisco passed bonds to pay for a private water supply, the federal and state governments were paying for water resource development in other watersheds of the Sierra Nevada. Other private water supply systems were constructed though, including the Los Angeles Aqueduct for the Owens and Mono Valleys; and East Bay Municipal Utilities District's Mokelumne Aqueduct. Development of California's water resources helped transform it into a world agricultural and economic juggernaut. The dam building era largely ended in the 1970's because the best sites have been taken, the cost of new dams became prohibitively expensive, and because the unforeseen environmental costs of building dams has been extensive and costly.

Although John Muir and the Sierra Club lost their early environmental battle over Hetch Hetchy, the loss resonated with the public. It galvanized an entire movement that called to task the previously unquestioned rights of manifest destiny and dominion of the natural world for the benefit of man. It was widely recognized that water resource development should not occur in national parks again. Later efforts to dam the Colorado River in Grand Canyon National Park and the Green River in Dinosaur National Monument were defeated, largely because of the national movement created by the loss of Hetch Hetchy Valley. A new sensibility of conserving natural values was catalyzed in that experience, and its influences extend beyond park boundaries. A robust environmental movement took hold in California and the nation.

As the movement gained momentum, it eventually paved the way for an environmental legal framework. Important legislation from the environmental movement includes the Wild and Scenic Rivers Act of 1968, the Clean Water Quality Act of 1972, and the Endangered Species Act of 1973. The dam building era came with tough and largely unforeseen environmental lessons. When dams were originally proposed, they were justified with economic benefits, such as 'reclaimed' agricultural land, flood protection, and hydropower generation. These are all worthwhile causes, and have helped to make California the 5th largest economy in the world. However, the environmental costs were never included (and were often poorly understood). With development of water, fish populations plummeted (for which fish hatcheries are imperfect substitutes), invasive species dominate many river systems, downstream river reaches do not receive sediment (causing erosion and disappearance of beaches in coastal systems), agricultural soil productivity decreased from the lack of natural flooding, and numerous other effects outlined in this book. Increasingly, valuation of natural systems is estimated to equitably compare proposed developments with environmental and recreational losses. Furthermore, there is a growing awareness that the sum of ecological connectivity is greater than its individual parts, although it hard to quantify. Restoration projects have been extensive, and costly, and most have achieved only marginal success. It is difficult to change water project operations, although FERC relicensing of non-federal hydropower facilities provides one such formal opportunity.

SUMMARY

Water and power development in the Tuolumne River has a long and contentious history. Water supplies for irrigation began well over a century ago. The controversy surrounding damming Hetch Hetchy Valley for the city of San Francisco was a national debate 100 years ago, and John Muir's writings and attitudes in part marked the beginning of the environmental movement. Beginning in the 1920's, water was diverted from high in the Tuolumne River watershed and transferred 200 miles to San Francisco and other Bay Area communities. At the time O'Shaughnessy Dam was completed, only Los Angeles' Mono and Owens Lake diversions were similar in scope to San Francisco's Hetch Hetchy System. Over the past century, additional dams have been built for water supply, hydropower, and flood protection. With construction of these dams, the need for Hetch Hetchy Reservoir has again been questioned, and numerous studies have found that the dam could be removed with little change in water supply. Restoring Hetch Hetchy Valley is being revisited with new science studies, and newspapers articles on both coasts of the US calling for removal of O'Shaughnessy Dam.

Efforts exist to both dam the Clavey River and protect it as a Wild and Scenic River. Until it receives designation is a Wild and Scenic River, it is open to the threat of new dams. With water use development, there is less water to sustain aquatic ecosystems, and migratory fish can no longer access habitat above La Grange Dam. In 1984, 83 mi of the Tuolumne River was designated a Wild and Scenic River to protect unique wild and recreational resources. Restoration is underway in the lower Tuolumne River. FERC relicensing has outlined environmental protections for the lower Tuolumne River to enhance native salmon populations, although populations have not yet increased substantially.

Water resource development in the Tuolumne River mirrors other California watersheds. Primary water uses are urban, agricultural, and environmental water supplies, hydropower generation, flood control, and recreation. In California, water management is dynamic and will undoubtedly change in coming decades. Climate warming may cause fundamental changes to the hydrology of the Tuolumne River, including more precipitation as rainfall instead of snowfall, earlier snowmelt at higher elevations changing runoff timing, and changes to the mean annual flow of the river, although scientists are not yet sure whether the region may have increased or decreased flows. The uncertainty regarding climate warming ensures that water management must continue to evolve to meet the demands of a growing population while maintaining agriculture and protecting aquatic ecosystems.

Acronyms
af – acre feet
cfs – cubic feet per second
CDFG – California Department of Fish and Game
CVP – Central Valley Project
FERC – Federal Energy Regulatory Commission
kW – kilowatt
kWh – kilowatt hour
MID – Modesto Irrigation District
MIF – Minimum Instream Flows
MW - Megawatt
PG&E – Pacific Gas and Electric
SFPUC – San Francisco Public Utilities Commission
SMUD – Sacramento Municipal Utilities District
TID – Turlock Irrigation District
TUD – Tuolumne Utility District
USBR – U.S. Bureau of Reclamation

Further Reading:

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Chapter 13: An Uncertain Future

JEFFREY MOUNT

INTRODUCTION

The preceding pages have explored two key concepts. The first is that there are broad linkages in watersheds. That is, that landscapes are connected, exchanging water, energy, animals and people, and that no landscape, whether it be a high mountain meadow, foothill town or floodplain forest is fully isolated from the rest. The second concept is that these landscapes are dynamic at a range of scales. Geologic, climatic, evolutionary, and socio-economic forces impose constant change, such that the watershed of the past is different from the watershed of today, and the watershed of tomorrow will be different from both. This book has used the Tuolumne River and its watershed as a case study.

It is relatively easy to describe historic change in the Tuolumne watershed and to assert that the future will be different. It is altogether much more complicated to predict, with precision, the nature and pace of that change. Predictions of future conditions in the watershed are fraught with uncertainty. There are the model uncertainties that plague climate change predictions; the uncertainty over human responses to that change and their efforts to mitigate and adapt to it; the difficulty in predicting the timing and spread of invasive species and their impacts on native communities; the uncertainty over economic and population growth; the stochastic nature of natural disasters such as fires, floods, and droughts; and the great uncertainties over our understanding of how all these interact.

With all these uncertainties, it would seem futile to predict the future of the watershed. Yet that is precisely what good planning and management requires. Too often, management of a watershed's resources or natural hazards is based on past conditions, rather than on anticipated future conditions. Take flood management in the Tuolumne as an example. The flood reserve set aside in New Don Pedro Reservoir to protect the town of Modesto (inadequate in the flood of 1997) is based principally on a statistical analysis of historic flows before 1960. This makes one basic, erroneous assumption: the hydrology of the past is the hydrology of the future. A large body of science now points to an on-going shift in climate, with large and more frequent floods. Despite this, there have been no adjustments in how New Don Pedro is operated, either for floods or for water supply. Indeed, it takes an act of Congress to change operations, since it is a federally-authorized dam. Yet we know that change is happening and seem incapable of adjusting.

Acknowledging the great uncertainties about predicting the future, we offer here a brief description of how the watershed will likely change over the course of the next few centuries. Although lacking in breadth and depth, the list is intended to highlight some anticipated management challenges in the future.

Climate Change

As discussed in Chapter 4, the Tuolumne River and its watershed are undergoing constant changes in climate. From the seasonal May-November drought, to medium-term fluctuations associated with El Nino and the Pacific Decadal Oscillation, "average" as some metric for yearly conditions is an almost meaningless statistic. Indeed, "average" is the exception, rather than the rule in Mediterranean climates. What is critical for the future of this watershed is whether long-term change is taking place. That is, instead of varying wildly about some average condition, there is a shift in the mean of those conditions. This has the fancy term of *hydrologic non-stationarity* and is the subject of much debate and analysis.

In science, consensus is a rare commodity. This is a good thing because knowledge and understanding are advanced when orthodoxies are constantly challenged. This is certainly the case when it comes to global climate change. A small minority of scientists will deny that climate is changing. However, there are numerous, disparate lines of empirical evidence from around the world that paint an internally consistent picture: the planet is warming. An overwhelming majority, but appropriately not all, of the scientific community is convinced that human activities are accelerating this warming through the production of greenhouse gases. The size of this majority, reflected in the extraordinary reports of UNESCO's International Programme on Climate Change (IPCC), indicates that this is as close to scientific consensus as you are likely to ever get. This majority may have gotten it wrong, but for the purposes of this chapter, it is assumed that they have gotten it right, or at least pretty close to right.

Warm and Wet, or Warm and Dry?

Determining the future of climate change in the Tuolumne watershed can only be done with sophisticated, complex computer models. There are multiple Global Circulation Models (GCMs) that are used to predict the global-scale response to greenhouse gas increases. Each model has an array of assumptions about future trends in greenhouse gas emissions, along with feedbacks between the ocean, atmosphere and the terrestrial surface. Because of the great demands on computing power, the resolution of these models is not particularly high, tending to lump large areas the size of many watersheds into a single cell with one temperature and one climate. To deal with this, climate modelers will hand off the results of their GCMs to higher-resolution models that can incorporate the all-important changes in topography that drive local climates. Known as down-scaling, this hand-off imposes additional uncertainties on the models.

Although climate models are improving at an accelerating pace, these nested uncertainties and differences in approach insure a wide range of future predictions of climate change. Figure 13.1 depicts a recent summary of these results, illustrating this range. Known colloquially as "spaghetti diagrams," these models suggest a bewildering array of possibilities. However, when analyzed closely, there is a central tendency of these models for the Sierra Nevada and much of the west. Warming is the most consistent feature, indicating a roughly 3-5^{o}C increase in annual average temperature by the end of the 21st Century. This result is consistent with, and continues a trend of a 1^{o}-2^{o}C of warming over the last half century.

While the models are pointing consistently to warming, there is less certainty about precipitation patterns. Some models point to an increase in precipitation, others a decrease, many, no change. This stems, in part, from uncertainties over the magnitude of warming, since this dictates the path of future storm tracts as they enter California. The latest models (as of 2009), however, do appear to be trending toward a decrease in overall precipitation for the Sierra Nevada and the Tuolumne watershed.

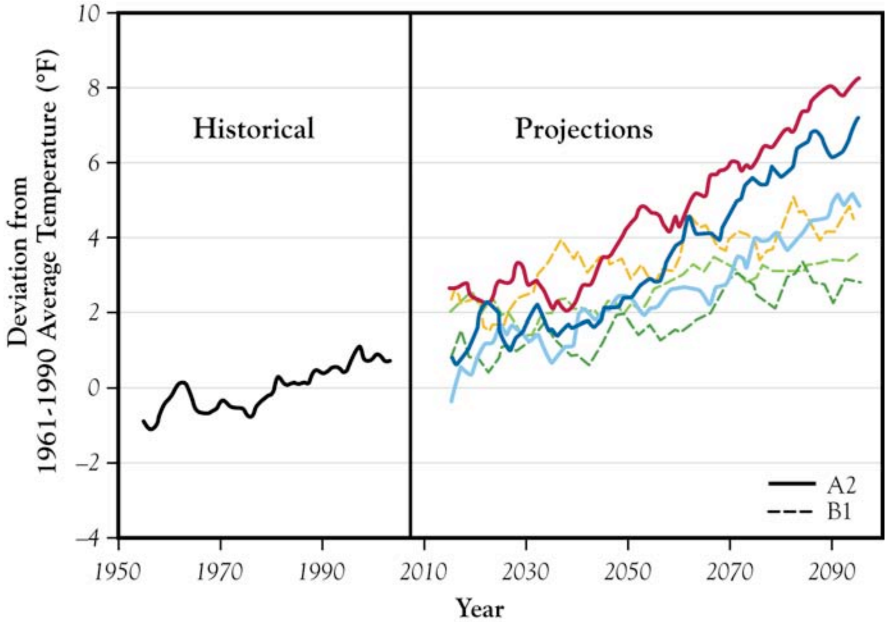

Figure 13.1 Historical and projected annual average temperatures for California based on various model ensembles. Thick lines represent 6-year running averages of recorded and modeled temperatures. The solid lines are for the A2 projections for carbon emissions (pessimistic). The dashed lines are for the B1 projections for emissions (optimistic). From Moser, S., G. Franco, S. Pittiglio, W. Chou, and D. Cayan, 2009. *The Future is Now: An Update on Climate Change Science Impacts and Response Options for California*. California Energy Commission Report: CEC-500-2008-071, 99 p.

Changes in Runoff

The impact of warming on a watershed comes, in large measure, from its impact on the hydrologic cycle. By increasing the growing season and average temperatures, warming increases the amount of water that plants export into the atmosphere through evapotranspiration. This, coupled with direct evaporation decreases the amount of water that comes out of a watershed as runoff. More importantly, in montane-Mediterranean watersheds like the Tuolumne, you get a large change in the snowpack. The cooling of warm, moist Pacific air as it rises over the Sierra is the source of prodigious snowpacks that are the state's great reservoir every (almost) spring. At around 5000 ft. in elevation, roughly half of the precipitation that falls on the Sierra falls as snow. With increase in elevation, this percentage goes much higher. Warming, by increasing winter temperatures, will cause a rise in the elevation of the rain/snow line. This translates to a greater percentage of precipitation falling as rain, rather than snow. This, in turn, translates to more water leaving the watershed in winter, rather than in the spring, and a decrease in the amount of water stored in the snowpack. This process is, in part, responsible for the increase in winter flood intensity seen in the last 50 years and projected to increase in the future.

In addition to more rain and less snow, the increase in temperatures changes the dynamics of snowmelt. As discussed in Chapters 3 and 4, during the spring a combination of increasing length of day and increases in temperature cause the snowpack to melt. Increasing temperatures, particularly when applied to thinner snowpacks, will lead to a shift in timing of the spring snowmelt pulse. There is a well-documented on-going shift in snowmelt timing throughout the west over the past 50 years, coincident with warming. Simply put, spring is coming one to four weeks earlier than it did in the early 1900's and the projections are for it to be earlier still in the future.

To illustrate the magnitude of potential changes in hydrology of the Tuolumne and other basins, results of modeling efforts conducted jointly between the UC Davis Center for Watershed Sciences and the Stockholm Environment Institute are presented in Figure 13.2a and b. Using a rainfall-runoff model, changes in amount and timing of runoff are simulated for increases of 2, 4, and 6^{o}C in average annual temperature. These models simply warm up the weather from the period 1981-2000 and thus do not incorporate any changes in total amount of precipitation.

Watershed	Annual Average Flow (taf)						
	Basecase	T2	% Change	T4	% Change	T6	% Change
Feather	4682	4580	2	4434	5	4268	9
Yuba	2448	2400	2	2344	4	2275	7
Bear	399	385	4	372	7	361	10
American	2883	2795	3	2701	6	2609	10
Cosumnes	489	463	5	440	10	420	14
Mokelumne	794	767	3	745	6	719	9
Calaveras	268	259	3	251	6	244	9
Stanislaus	1265	1235	2	1201	5	1163	8
Tuolumne	1982	1946	2	1908	4	1868	6
Merced	1093	1060	3	1032	6	1003	8
San Joaquin	1860	1836	1	1812	3	1784	4
Kings	1717	1698	1	1678	2	1655	4
Kaweah	475	457	4	439	8	421	12
Tule	162	154	5	146	9	138	14
Kern	751	719	4	689	8	659	12

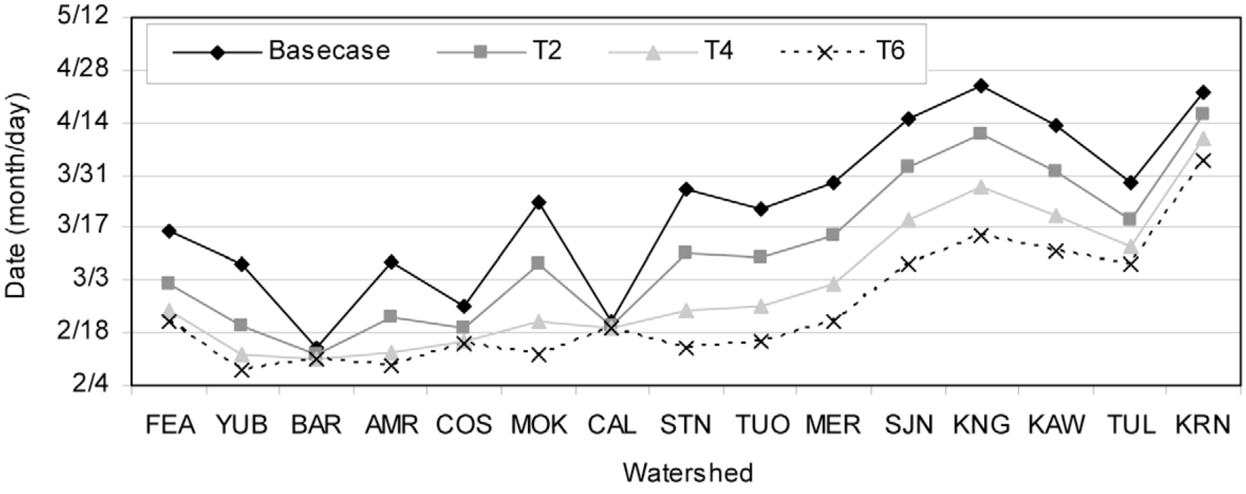

Figure 13.2. A) Potential impacts of climate on runoff in the Sierra Nevada. A) Simulations of changes in runoff from basecase conditions (average from 1982-2001) with 2, 4 and 6° C. B) Average annual centroid timing by watershed and climate warming scenario. From: Null, S., J. Viers and J. Mount, 2010. Hydrologic response and watershed sensitivity to climate warming in California's Sierra Nevada. PLoS ONE 5(4): e9932. doi:10.1371/journal.pone.0009932

The results of the modeling effort illustrate the potential for significant future changes in the watershed's hydrology. Figure 13.2b summarizes the shifts in the timing of the center of mass of runoff from the watershed. Center of mass, or *centroid timing*, simply refers to the date in which half of the year's total runoff passes out of the watershed. Increases in rain vs snow, coupled with an earlier spring snowmelt contribute to this shift. Figure 13.2a demonstrates an additional impact of warming on total amount of water that the watershed yields. The longer growing season and warmer temperatures send an increasing proportion of the annual precipitation into the atmosphere, rather than the river.

In sum, it appears as though climate change in the Tuolumne watershed will lead to more winter runoff and less spring-summer flows, with an overall net decrease in total water yield from the watershed. However, the critical question to be answered is "how much and when"? Although modeling and understanding of future climate have improved significantly over the past decade, this question is not yet answerable with any precision. Instead, and for the purposes of this brief and incomplete review of future conditions of the watershed, two scenarios are offered (Table 13.1, see Appendix). The first assumes a modest amount of warming over the course of the next century, coupled with no change in precipitation. This scenario presumes that greenhouse gases will be significantly reduced and that our existing water resource infrastructure will be able to adapt to this change while minimizing ecosystem impacts. The second scenario presumes that there will be limited greenhouse gas mitigation and that California will warm dramatically. Additionally, this second scenario assumes that weather patterns will shift, and the Sierra will receive less precipitation, outpacing the ability of our existing infrastructure to adapt and ushering in substantial ecological changes.

Aquatic Ecosystems

All aspects of natural and human ecology of the watershed are linked to the hydrologic cycle, but none more so than the aquatic ecosystems. Chapters 6,7 and 8 lay out the remarkable complexity of these ecosystems and how human activities have changed them. Most notable is how the life history strategies of aquatic organisms, as well as the plants and animals of the riparian corridor, are tied to seasonal and interannual changes in flow timing and magnitude. Climate change, with its warming and changes in rain/snow mix, may have significant impacts on these communities by changing four key interrelated flow variables: annual runoff, winter flood peaks, spring snowmelt timing and magnitude, and late season baseflow.

Providing there are no changes in precipitation amounts in the watershed, increases in average temperature will, as discussed above, lead to a decline in annual runoff. This change is unlikely to manifest itself as a decline in total runoff every year, but rather as a shift toward an increase in frequency of dry years. The consequences of this change for aquatic ecosystems will depend, in large measure, on how water resource and hydropower systems are operated (discussed below). The largest impact may well be associated with attempts to restore the natural functions of the Tuolumne River below La Grange Dam. Currently, the 2.0 maf capacity of New Don Pedro reservoir is capable of capturing and controlling all of the runoff from the basin in an "average" year. If long-term average runoff shifts to a lower value, the number of years where the reservoir fails to fill will increase. Modeling studies have shown that under the warm-dry scenario used here, New Don Pedro Reservoir will fail to fill in all but the wettest year, creating continuous water scarcity. The impact of this on the lower Tuolumne has yet to be evaluated with any rigor. However, increases in air temperature translate to increases in water temperature, reducing the quality of habitat for salmon and steelhead and improving conditions for the non-native fishes that prey on natives. This scenario suggests increasing demand for more cold water releases from New Don Pedro Reservoir. Given the reductions in available water, this will presumably exacerbate the current contest between environmental flows and the irrigation needs of the 300,000 acres of farms currently served by the Tuolumne River. Under the warm-dry conditions, it is likely that the cold water pool behind New Don Pedro that is used to regulate temperatures would be unavailable in dry years.

Above New Don Pedro Reservoir, the life cycles of most aquatic and riparian organisms, including fish, insects, amphibians and trees will be directly affected by the change in temperature and the rain/snow mix. To illustrate the scope of this problem, Figure 13.3, depicts the hydrologic change associated with 2, 4, and 6°C warming of the watershed on weekly flow volumes, measured as inflow to New Don Pedro. As above, this is based on preliminary modeling efforts conducted by UC Davis and the Stockholm Environment Institute and assumes no change in total amount of precipitation. The impact of this warming suggests a significant change in the hydrology of the watershed, with larger flows in the winter, reduced springtime snowmelt flows, and earlier snowmelt timing. In the extreme case—6°C of warming—the spring snowmelt pulse disappears from the watershed.

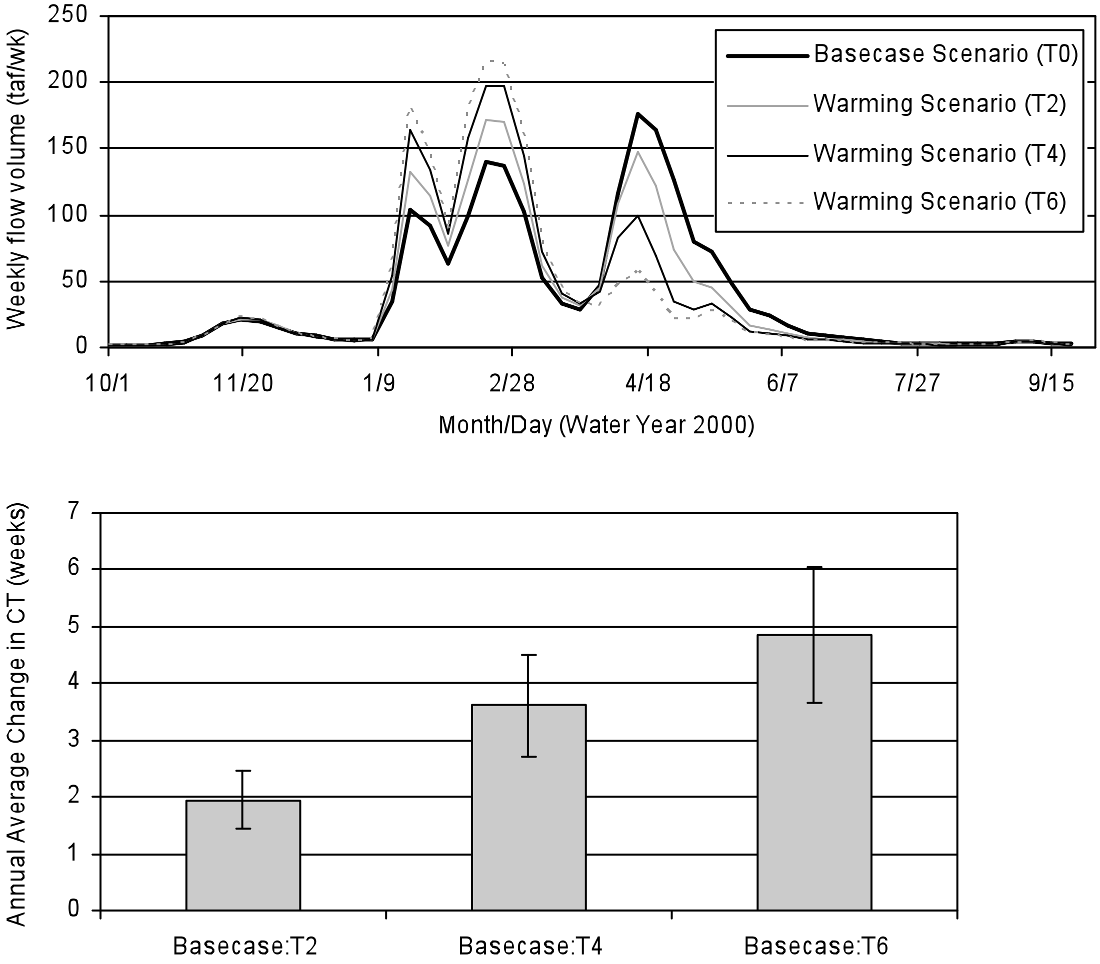

Figure 4.3: Changes in flows based on modeling of unimpaired Tuolumne under warming. A) Change in timing and magnitude of flow, with an example of water year 2000 (a normal year). B) Changes in centroid timing (center of mass of runoff) from basecase due to warming. Data from UC Davis Center for Watershed Sciences.

Biologists are just beginning to assess how these changes in timing and magnitude are likely to affect aquatic plant and animal communities. The uncertainties are large. We do not know whether organisms will simply adapt to these changes by either shifting the timing of spawning, seed release, etc., to earlier, more suitable periods, or by shifting locations within the watershed to elevations and hydrologic conditions that meet their life history needs. For example, many of the amphibians found in the watershed appear to be able to adjust the timing of egg laying, allowing them to adapt to these changes. Aquatic insect production may take advantage of the warmer temperatures and increase, enhancing overall productivity to the benefit of species. Temperature-sensitive fish may, where possible, simply move up in elevation to suitable habitats. This latter adaptation highlights the importance of the middle portions of the watershed, where the tributaries join the mainstem river. The large, unregulated tributaries—the Clavey River, the South and Middle Forks—may turn out to be crucial cold water refugia for temperature-sensitive native species under climate change. However, New Don Pedro Dam prevents access from the lower reaches.

Alternatively, change may not work in favor of most native species, particularly if a more aggressive warming scenario is realized. The largest impact of warming will be on the spring snowmelt recession. In Mediterranean-montane climates such as the Sierras, extreme variability is the norm, with one general exception. The rise and gradual fall in flow that occurs every spring (almost) is the most stable and predictable hydrologic event in the Sierra. The winter, with its cold temperatures and large flow fluctuations, and the late summer, with its low flows and warm temperatures, are more stressful to aquatic communities. It should be no surprise that life history strategies in Sierra aquatic communities are linked so tightly to the snowmelt period, with its abundant, reliable cold water and gradual change in conditions. As shown in figure 13.3, this is the period that is most starkly affected by warming.

The glacially-scarred landscape of the upper watershed faces its own challenges under climate change. The alpine and sub-alpine streams, meadows and lakes, have, like much of the watershed, a complex mixture of native and non-native species. Native fishes were historically absent from the upper basin, unable to colonize it after the retreat of the Pleistocene glaciers. The fishes that are there now were all planted, with the more prominent lake dwellers brought from the eastern U.S. or Europe. The native and non-native biota of the upper watershed, including several highly-specialized amphibians, are adapted to long, harsh winters and short, cool summers. Warming, depending on its magnitude, has the potential to significantly impact these aquatic communities.

One of the issues facing aquatic and terrestrial communities in the upper watershed under warming is the lack of a place to go. While the plant and animals of the middle watershed may be able to move upslope in response to warming, there is limited available space for this in the uppermost watershed. For this reason, some species—native and non-native—well known from the upper watershed may undergo local, climate-forced extinctions.

Terrestrial Ecosystems

Changes in the aquatic ecosystems of the Tuolumne River will be mirrored by, and linked with, changes in terrestrial plant and animal communities. The increase in temperature and shift to increasing winter rainfall at the expense of spring snowmelt changes one of the most important components of the hydrologic cycle: evapotranspiration. As noted above, the longer growing season and higher temperatures increase the amount of water that plants are able to transmit from the soil into the atmosphere. This increase, coupled with declining snowpack and, in the most aggressive warming case, decreases in precipitation, will lead to decreases in soil moisture. The impact of this will be broad on the plant communities.

Currently, the vegetation of the Tuolumne watershed is arranged in a relatively orderly pattern governed principally by elevation (see chapter 5 for a full description). As you rise in altitude in the basin you have shorter growing seasons, higher precipitation, and higher soil moisture. Exceptions to this orderly transition are created by differences in orientation--dry on south facing slopes, wet on north facing slopes—and soil types. Vegetation bands track this soil moisture. At the edges of the bands, plants are often stressed by too much or too little soil moisture, sub-optimal growing conditions, or direct competition from adjoining bands.

Over the past few decades, researchers have been closely monitoring forests of the Sierra Nevada and the surrounding mountains. Several trends have emerged that suggest significant change is in store. First, tree ring analyses suggest that growth rates of trees over the past 50 years have been at rates unseen in the last 1000, suggesting rapid and significant climate change is underway. Second, forest plots in Yosemite National Park and other parts of the Sierra indicate that there has been a significant increase in the mortality rate of trees at a range of elevations. Tree death is due to two principal, typically related factors: drought stress and insect infestations. This mortality rate is exacerbated by no significant change in survivorship of new recruits. In essence, trees are dying faster than they can be naturally replaced. Finally, exacerbated by human management of the forest, fire intensity has increased, enhancing tree mortality rates in some regions (Figure 13.4). The current levels of fuel loading due to fire suppression have already created conditions where fire frequency and intensity are consistently higher than they were historically, but further warming will create conditions even more favorable to large, catastrophic crown fires. While many of the Sierran forest species are fire adapted, these high intensity, larger area fires have a much higher environmental and economic cost.

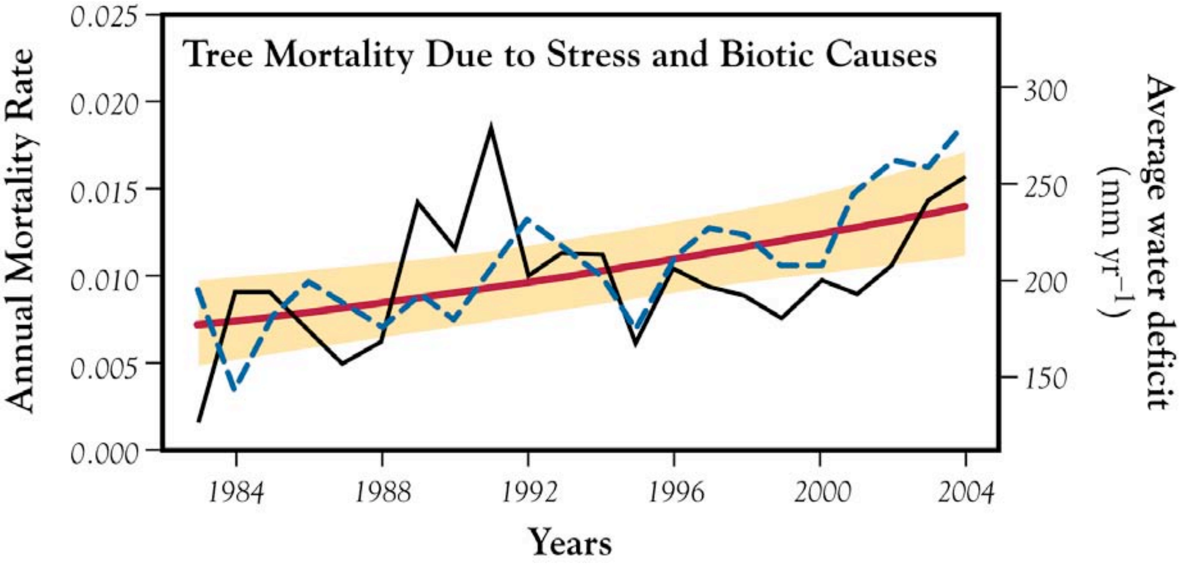

Figure 13.4. Mean annual tree mortality rates from 1983 to 2004 due to water stress and biotic causes for 21 permanent forest plots in the Sierra Nevada, California. The thin solid line represents the annual mortality rate averaged among plots, with the thick solid line showing the expected mortality rate (± 2 SE, shaded area) from significant ($P < 0.05$) models of the annual trend. Mean annual mortality rate for stress and biotic causes increased at 3% per year. Average water deficit (dashed line), an index of drought, predicted changes in the stress and biotic mortality rate. Modified from van Mantgem, P and N. Stephenson, 2007. Apprent climatically induced increase of tree mortality rates in a temperate forest. Ecology Letters, v 10: p. 909-916.

Although it is difficult to separate the climate change signal in evolving Sierran forests from that associated with current management practices, the result is unmistakable. Vegetation bands are moving upslope as temperatures rises and soils become drier. The long-term trend is for the alpine and mountain meadow portions of the watershed to shrink as montane forests take advantage of the warmer temperatures. In the middle portions of the watershed, the drought-tolerant (and fire-prone) chaparral communities will expand their range upslope, taking advantage of the retreat of the forests. This change will not be steady and equal everywhere. In large measure, it will depend upon the frequency and intensity of fires and droughts, which will hasten vegetation change.

Animal communities that are tied to these vegetation bands will, where possible, move upslope with them, with those dependent upon the highest elevations of the watershed at greatest risk of extirpation. An issue of concern is the preservation of migration corridors. Many of the large mammals of the Sierra migrate great distances over the course of a year. They utilize specific habitats for these seasonal migrations, which may be at risk from climate change.

Humans and the Watershed

The future of the Tuolumne River watershed under climate change depends, in large measure, on how human populations manage, occupy, visit and exploit it. As has been pointed out throughout this book, humans and their activities in the watershed are fully integrated into the ecology and hydrology, making this a linked human-natural system. Even the most remote portions of the Yosemite Wilderness have been affected by human activity, most significantly since the gold rush.

The land use issues that will face the watershed in the future are too many to cover in this brief summary. Instead, a short list is provided here of issues that will be affected by climate change. These include agriculture, urbanization and water supply in the lower watershed, development of private lands, and hydropower and water supply operations in the middle watershed, and management of fire and ecotourism in the upper watershed. While traditional sources of economic activity, such as mining, logging, and grazing, will continue into the future, they are unlikely to grow significantly over the course of the next century and are not included here.

The Lower Watershed: Farming, Urban Growth, Water Supply

The alluvial fan that makes up the lower Tuolumne watershed faces two significant challenges under climate change. At the top of this is sustaining agricultural production at its current level. Water that is stored behind New Don Pedro reservoir is reserved principally for two irrigation districts: the Turlock Irrigation District and the Modesto Irrigation District. These two districts irrigate roughly 300,000 acres of farmland. Although warming has the potential to increase agricultural production on these farms due to an extended growing season, this may be offset by increased water scarcity as climate warms.

Recent work at UC Davis that looks at how to adapt to these changes helps bracket this problem. Using an economic optimization model, researchers evaluated the best way to adapt to changes in inflow to New Don Pedro Reservoir under the two climate scenarios discussed here (Figure 13.5). The potentially good news for farming interests is that the very large capacity of New Don Pedro Reservoir allows for considerable flexibility to meet climate change. Assuming that the more benign change in climate occurs—warming only, with no change in precipitation—the impacts on agriculture can be reduced by flexible operations of the dam in conjunction with good groundwater management and crop choices. However, the more aggressive warming scenario—warming plus reduction in precipitation—produces a wholly different result. On average, the reservoir would only fill half way under this scenario, leading to permanent water scarcity costs and substantial dislocations within the agricultural community. Most germane to the argument over whether we need more dams as a hedge

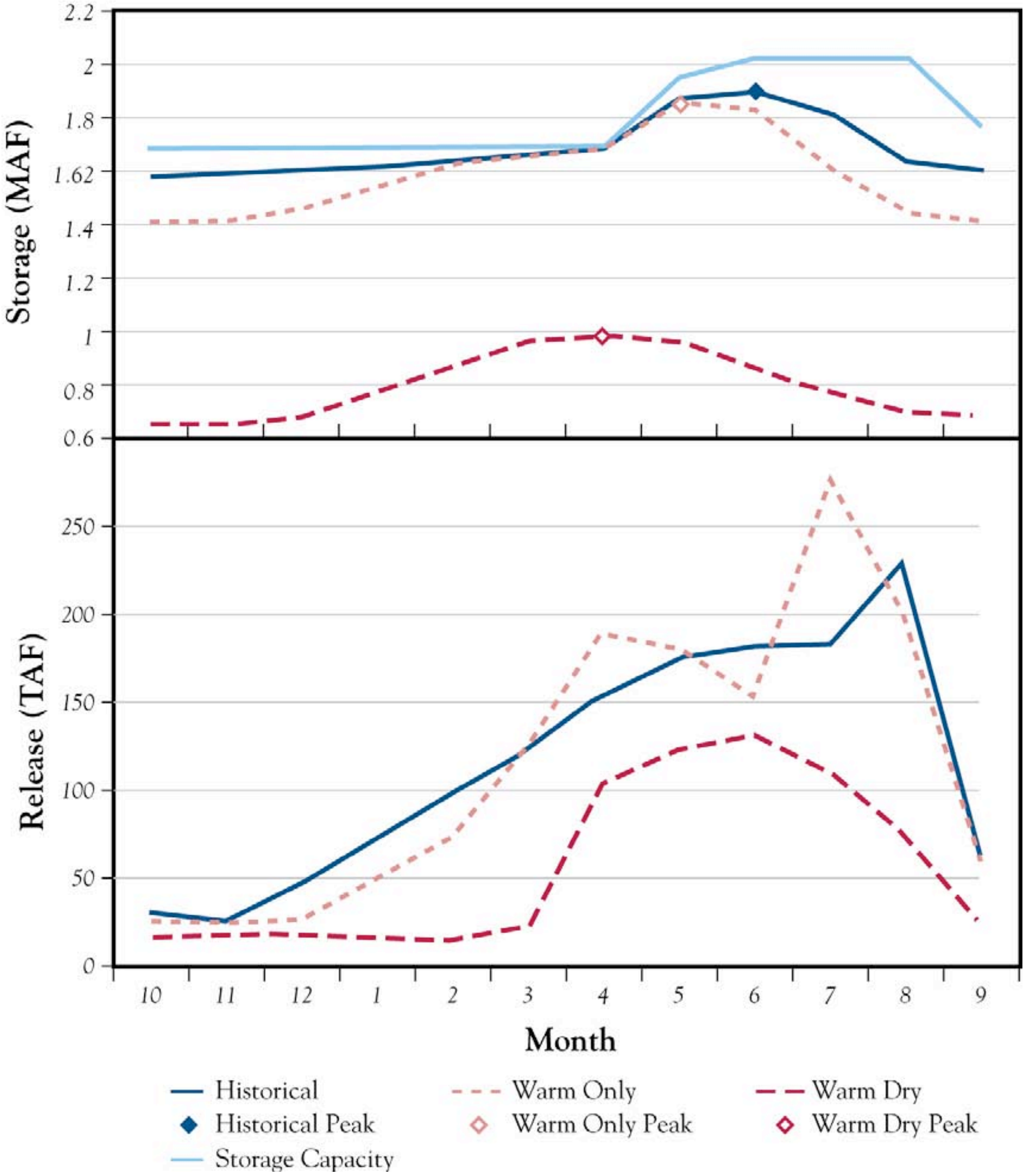

Figure 13.5 Modelled Average Monthly Storage (A) and Average Monthly Releases (B) in thousand acre-feet (TAF) at New Don Pedro Reservoir under two climate scenarios: warm only and warm-dry. The warm-only results do not account for decreased inflows due to increased evapotranspiration losses and should be viewed as a conservative maximum. The modeled releases are based on an economic optimization model that seeks to optimize economic benefit with constraints. This is the cause, in part, of divergence under warm-only from historic release patterns. Storage capacity changes over the course of a year due to flood reserve requirements. Modified from Connell , C, 2009. ***Bring the Heat, but Hope for Rain: Adapting to Climate Warming for California*****. University of California, Davis MS thesis. 46 p.**

against climate change is the fact that under this scenario, more storage would not do any good. Simply put, more storage does not equal more water because you will not be able to fill it often enough to make economic sense.

The second major challenge will be managing urban growth on the Tuolumne River alluvial fan. Up until the recession beginning in 2008, growth in and around Modesto and other nearby towns was some of the highest in California. Pressures for this kind of growth will come again as the economy of California recovers. Urban growth in the lower watershed involves the conversion of farmland. For this reason, growth is unlikely to produce an increase in demand for water above current agricultural demands. Rather, the greater threat will be continued urban growth on the Tuolumne River floodplain. As the floods of 1997 demonstrated, Modesto has done a very poor job of floodplain management, placing homes and vital water supply infrastructure on the active floodplain of the river. Although chastened somewhat by the floods of 1997 that caused extensive damage, the flood memory half-life has passed in this region and there are numerous proposals to repeat and compound the mistakes of the past. Given the projections for potential increases in winter flood magnitude and frequency, Modesto and other floodplain towns are likely to be flooded more often in the future, with escalating costs to property and loss of life. The current reliance on New Don Pedro as the principal source of flood management for this region (rather than the more cost-effective land use planning approach) insures that the urban interests will be pitted against the agricultural interests in the future. Flood managers want an empty reservoir to catch floods; farmers want a full reservoir to improve water supply. Add to this, future demands for environmental flow releases to support lower Tuolumne ecosystem restoration efforts and the future becomes clear. There will be a lot of squabbling over how to operate New Don Pedro under climate change.

The Middle Watershed: Private Lands and Hetch Hetchy

The middle portions of the Tuolumne watershed have a complex mix of public and private land ownership. For example, roughly one quarter of Tuolumne County is privately owned, with the bulk of that private land in the lower elevations within the foothills, but a considerable amount of diffuse development increasing the urban/wildland interface. The activities on this private land historically included logging, mining and grazing, with extensive conversion of some oak woodland and chaparral to grasslands. Today, these three traditional economic activities are shrinking. Like foothill regions throughout the Sierra, these activities are giving way to conversion to rural-residential developments, otherwise known as "ranchettes" for their small size and occasional horse or cow pets and hobby farms. The second significant conversion of foothill lands in the Sierras is the proliferation of vineyards. This has been less of an impact on the Tuolumne watershed than those to the north, but this pressure is already visible and will continue in the future, another demand on a thoroughly allocated water supply.

The current recession has significantly reduced the rates of land conversion to rural-residential developments. However, economic and population projections all point toward an inevitable surge in demand for these developments in the future. How this plays out depends in large measure on how local and state planning entities respond to this pressure. If current growth trends resume the rates seen in the 1990s, it is reasonable to assume that the population of the middle watershed will double by 2040 with most growth taking place close to existing foothill towns.

Land conversion and population growth in the middle watershed will run head-long into climate change. The increase in temperature and the decline in soil moisture that will hasten the drying out of the foothills will leave less water available to support these developments. For the larger developments, there will be the inevitable efforts to tap into foothill tributary streams as a water source (they have already been successful in this regard in the watershed). For the typical ranchettes, water will come from wells. Both surface diversions and wells will be used to support conversion to vineyards. This increased demand will inevitably amplify the declines in baseflow to the mainstem associated with warming. If the more aggressive warming-drying scenario plays out, there is the likelihood of seasonal dewatering of some of the smaller tributaries and the inevitable fights over water use and water rights.

Added to the contest for available water will be the growing problem of managing fire in the urban-wildland interface (chapters 5 and 11). Fire frequency in the watershed today is driven by climate, with dry years producing the most frequent and intense fires. Recent observations indicate that the drier the spring, the higher the likelihood of severe fires. Fuel reduction programs, defensible spaces and concentrated rural-residential developments, can mitigate this to some degree, but the actions of fire will be a major issue in the future.

The pressures to develop the middle watershed are constrained by Federal ownership of the land. The upper portions of the middle watershed lie mostly within Stanislaus National Forest or Yosemite National Park. Unless there is a significant change in national policy, these are unlikely to be developed in the foreseeable future. In the national forest and park lands of subalpine portions of the watershed, two climate change-related issues will dominate attention: fire management and Hetch Hetchy.

The management of the nation’s national forests for multiple beneficial uses has produced a political stalemate. As discussed in Chapters 5 and 11 and above, fire suppression in these forests have produced high fuel loads. Coupled with warming and drying, and the accelerated death of trees due to drought stress and insects, this mix virtually insures a continuation of the current trend of increased intensity and frequency of fires. Efforts to develop a regional and national policy for fuel load reductions have yet to be successful, with little sign that there are likely to be significant breakthroughs in the future. Management of this issue and the associated transformation of forest plant and animal communities, will occupy the Forest Service and the Park Service into the indefinite future.

Hetch Hetchy under climate change is also an issue that will remain for the indefinite future. Despite grass-roots efforts to promote removal of O’Shaughnessy Dam and restoration of Hetch Hetchy Valley, there is little evidence of significant political traction (Chapter 12). Much as David Broward swore that he would outlive Glen Canyon Dam on the Colorado River, it appears unlikely that the opponents of O’Shaughnessy Dam will live long enough to see it come down. Rather, the most pressing controversies will revolve around operation of the Hetch Hetchy water supply system by the San Francisco Public Utilities Commission (SFPUC).

Given changes in temperature and the rain/snow mix, the Hetch Hetchy water supply system will be impacted to some degree. Recent modeling work by one of the authors of this book (S. Null) has shed some light on the worst case scenario and its impacts on operations. A warm-dry climate significantly reduces the amount of water stored in the Hetch Hetchy system. For example, the modeling suggests that annual average storage in the Hetch Hetchy system would drop to 180 thousand acre-feet, reaching its capacity (360 TAF) less than half the water years and completely draining itself to “dead pool” (meaning not able to operate) in more than three quarters of every year. For the people of the San Francisco Bay Area, this is a significant dent in their water supply system, driving water costs up considerably. It also translates to significant declines in hydropower revenues that help offset some of the costs of water supply. For the middle Tuolumne watershed, this has the potential to impact both recreation and aquatic ecosystems on the mainstem of the river. For recreation impacts, the focus has to be on the two world-famous whitewater runs: Cherry Creek and Merals' Pool to Ward's Ferry. Summertime rafting and kayaking on these reaches is entirely dependent upon the kindness of SFPUC and its storage rules. As SFPUC's ability to fill its reservoirs declines, their ability to deliver whitewater flows from their hydropower/water transfer operations will certainly decline. There will always be recreational boating on Cherry Creek and the Tuolumne River, but it is likely, much like the shift in snowmelt timing, to shift more toward the spring. The second impact will stem from early-season exhaustion of reservoir capacity, increasing periods of low flow conditions. In addition, depending upon the magnitude of climate warming, there will also be a reduction in available cold water storage in the reservoirs. The reduction in flows, warmer temperatures, and cranky rafters will be a management headache for SFPUC as they try to adapt to climate change in the future.

The Upper Watershed: Yosemite National Park

Finally, climate warming, regardless of the worse or better case scenarios, will bring change to the upper watershed of the Tuolumne River. Change in aquatic and terrestrial plant and animal communities—outlined above—are inexorable and inevitable. The extensive, roadless tracts of land in the upper watershed, provides a wilderness experience with spectacular scenery and solitude to more than a million visitors every year. At issue is whether climate change will diminish this experience.

The Park Service will have to grapple with the upward shift in vegetation bands of the upper watershed. The change in alpine/sub-alpine boundary will inevitably alter the mix of native species and the experiences of those who come to enjoy the Pleistocene landscapes. At lower elevations, fire and fuel loads will be the other great challenge for the Park Service, with the same issues of vegetation change through drought stress and disease that will affect the middle watershed. To date, there is no comprehensive plan for how to accommodate this change and to preserve, conserve or restore key plant and animal communities.

Finally, the attributes that draw people to the upper watershed—solitude, wilderness, scenic beauty—are likely to be there indefinitely, regardless of the magnitude of change. It will just be different, while retaining many of the features that drew John Muir to the high country to tend his sheep and fall in love with the Range of Light.

Table 13.1: Better case versus worse case scenarios of impacts of warming.

Hydrologic Change	**Moderate warming, no change in precipitation**	**Significant warming, decrease in precipitation**
Winter Flows	Continuation of trend of last 50 years of increase in magnitude	Amplification of current trends; increase in frequency of flooding, drought
Spring Snowmelt	1-2 week earlier snowmelt pulse; modest reduction in magnitude	Loss of snowpack reduces or eliminates spring snowmelt pulse, lower yearly base flows from dams
Late Summer Baseflow	1-2 week longer period of lowflow conditions late in the year, 1-2°C increase in average water temperatures in summer	Low flow conditions from May through October, 4°C+ increase in average water summer temperatures
Aquatic Ecosystems		
Lower Watershed	Increase in productivity and improved flow regulation supports higher salmon populations; increase in early spring flooding improves aquatic and riparian habitat	Loss of cold water pool in New Don Pedro due to reduced inflows; extirpation of salmon due to warm temperatures and low flows below dam
Middle Watershed	Increase in productivity; some communities shift upstream to refugia in unregulated tributaries	High temperatures and low flows favor invasion by non-native fishes, reducing native biodiversity
Upper Watershed	High altitude meadows, lakes and streams managed as refugia for cold water native species	Warming leads to loss of wet meadow habitats for amphibians and reptiles; increase in productivity of lakes and streams leads to loss of native biodiversity
Terrestrial Ecosystems		
Lower Watershed	Increased flooding improves riparian and floodplain habitat	Reduced inflows leads to decline in outflows and riparian habitat
Middle Watershed	Fire and fuels management promote gradual upslope shift in vegetation bands based on temperature increases; reduced conifer incursion in meadows	Catastrophic fires and declines in precipitation lead to dramatic expansion of chaparral communities
Upper Watershed	Wilderness areas continue to support mix of subalpine forests and meadows in transition	Wilderness areas lose meadows during upslope expansion of montane forests; increased disease and drought stress
Human Uses		
Lower Watershed	Continued farming of floodplain, progressive floodplain management reduces impacts of increased winter flows	Significant reduction in farming due to reduced flows; continued urban encroachment on floodplain; increased flood damages
Middle Watershed	Limited expansion of urban areas, fuels reduction and land use planning reduces fire risk	Increased water scarcity, increase in fire damages, reduced recreational flows
Upper Watershed	Continuation of current trends in ecotourism, recreation	Decline in ecotourism, recreation due to loss of alpine biomes and degradation of subalpine forests

Further Reading:

General:

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