ONE

Introduction to the Sierra Nevada

Abstract. Physical, geographic, and ecological features and cultural aspects of the Sierra Nevada are described as an introduction to the Sierra Nevada, John Muir's "range of light." The range extends about 700 km north to south and reaches an elevation of 4,421 m. Pleistocene glaciations, last retreating between 10,000 and 25,000 years ago, sculpted valleys and high- elevation lake basins. Native Americans lived on the flanks of the Sierra and utilized its rich ecological diversity. Beginning with the influx of Europeans sparked by the discovery of gold, the natural resources in the high-elevation Sierra have been exploited for mining, grazing, water supply, and hydroelectric power. The Sierra Club, founded in 1892, has played a key role in fostering recreational uses and conservation of the region. Subsequent legislative actions have led to the establishment and expansion of national parks and national forests throughout the Sierra.

Key Words. physical features, geographic features, ecological features, natural resources, conservation, Native Americans

THE SIERRA NEVADA OF CALIFORNIA extends about 700 km (40°15′N to 35°N), with a width of 100 km to 130 km, and reaches an elevation along its crest at Mount Whitney of 4,421 m (figures 1 and 2). To one group of Native Americans it was known as "rock placed on rock." A Franciscan missionary called it "una gran sierra nevada"—a great snow-covered range. To John Muir, the Sierra Nevada was the "range of light." Scenes of the region are widely known from the iconic photographs by Ansel Adams (e.g., *Moon and Half Dome*, 1960; *Clearing Winter Storm*, 1940; *Winter Sunrise*, 1944), his collected works (e.g., Adams 1979), and the Sierra Club photo-essay,

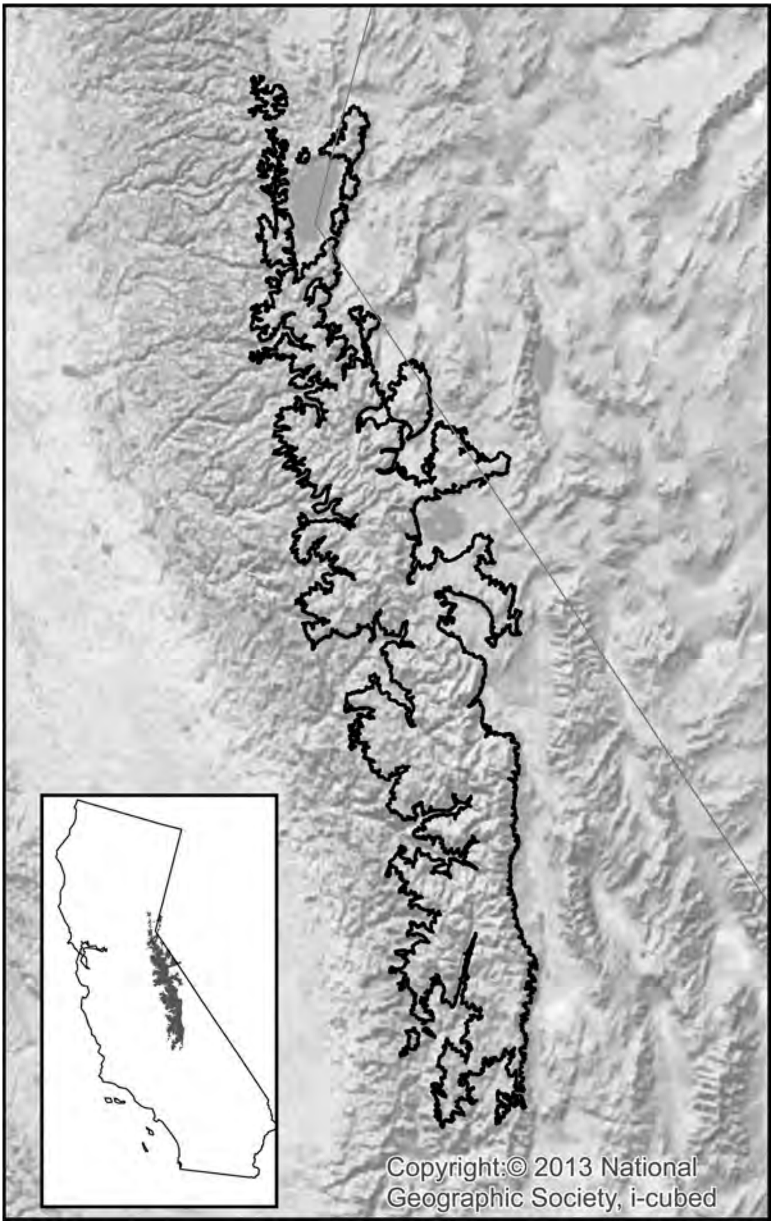

FIGURE 1. Sierra Nevada location and topography. Environmental Systems Research Institute (ESRI) base map is shaded relief using National Geographic Style (www.esri.com/en-us/arcgis/products/data-location-services/data/basemaps-imagery#image7). Solid black line is 2,300 m contour.

FIGURE 2. High-elevation Sierra landscapes and lakes. Photograph by S. Sadro.

Gentle Wilderness (Kaufman 1964). Indeed, the Sierra Nevada is all of these and more, as its cultural history and scientific discoveries have revealed.

This book provides a synthesis of our current understanding of the hydrology, watershed biogeochemistry, and limnology of high-elevation lakes and their watersheds and the impacts of environmental changes on these aspects. For our analysis, we define "high elevation" as lakes above about 2,300 m. We combine three decades of measurements from specific watersheds with regional surveys, experimental results, and paleoecological data. Acidification, eutrophication, invasive species, and climate change are environmental issues addressed in multiple facets. As an introduction we begin with a description of the physical, geographic, and ecological features and cultural aspects of the Sierra Nevada.

PHYSICAL FEATURES

The Sierra Nevada has evolved over the past 500 million years (Hill 1975) and is composed largely of igneous and metamorphic rocks of diverse composition and age. By about 70 million years ago (Mya), the granitic rocks forming the Sierra batholith were in place. From 80 Mya to 40 Mya much of the metamorphosed rock deposited in the Paleozoic and Mesozoic eras was removed by erosion. During the mid- to late Tertiary period basic volcanic material buried much of the northern Sierra, and volcanism has continued.

The traditional view suggests that increased tectonic activity in the past 3 million to 5 million years is responsible for the current elevation. However, some recent studies provide evidence that the Sierra Nevada was close to its current elevation 40 Mya to 50 Mya and may have been the edge of a pre-Eocene continental plateau (Mulch, Graham, and Chamberlain 2006; Mulch et al. 2008; Crowley, Koch, and Davis 2008). Pleistocene glaciations occurred several times over the past 3 million years, last retreating between 10,000 and 25,000 years ago and leaving sculpted valleys and high-elevation lake basins.

The sloping western side of the Sierra contrasts with the steep escarpment on the eastern flank and reflects the broad genesis of the range as a tilted faulted block that continues to uplift. The elevation of the Sierra crest and the height of peaks tend to increase from Desolation Wilderness in the north to the region around Mount Whitney in the south, where thirteen peaks reach above 4,200 m (Storer, Usinger, and Lukas 2004). The high-elevation Great Western Divide in Sequoia National Park separates the Kern River from the Kings and Kaweah watersheds. Steep-sided and deep valleys dissect the eastern and western sides of the range, with Yosemite Valley and the Kings and Kern Canyons being the most spectacular.

Sierra soils derived primarily from granites tend to be slightly acidic (pH 5–6.5), with limited capacity to retain moisture compared to soils formed from volcanic and metamorphic rocks (Melack and Stoddard 1991). Soils derived from volcanic and metavolcanic rocks are finer textured and have more iron- and magnesium-rich minerals and calcic feldspars than soils derived from granites. High-elevation soils (most commonly inceptisols) experience cold temperature regimes, with mean annual temperatures ranging from 0°C to 8°C.

Warm, dry summers and cool, wet winters are characteristic of the Sierra Nevada. Typically, most precipitation occurs in winter as snow, with only occasional summer rain. Statewide, California has high year-to-year variability in precipitation (Dettinger, Redmond, and Cayan 2004). Prevailing westerly winds entering California are strongly influenced by the position of the North Pacific high-pressure cell (Iacobellis et al. 2016). During summer, the high-pressure system is largest and strongest, and its descending air suppresses rainfall. As the high pressure weakens and shifts to the southeast in the winter, precipitation-bearing storms enter California from the Pacific. Features called atmospheric rivers, bands of air with large amounts of moisture from the tropical or subtropical Pacific Ocean, are responsible for the majority of the winter rain and snow falling in the Sierra Nevada (Dettinger et al. 2011). During summer, infrequent convective storms, sometimes associated with the North American monsoon, can occur.

Climatic variation associated with the El Niño/Southern Oscillation (ENSO) is strong in the Sierra Nevada. During El Niño events heavy snowfall often occurs, but about one-third of El Niño winters are dry. In contrast, during the La Niña phase, precipitation is usually below average (Redmond and Koch 1991). Large differences in orographically influenced precipitation occur between the western and eastern sides of the Sierra Nevada (Pandey, Cayan, and Georgakakos 1999). Analyses of the regional and temporal differences in precipitation and their consequences are considered in subsequent chapters. Two of the best records of meteorological measurements for the high-elevation Sierra Nevada are from our studies in the Tokopah basin, in Sequoia National Park, and at Mammoth Mountain. These data are utilized in our examination of hydrological and limnological aspects of Sierra lakes and watersheds in later chapters.

ECOLOGICAL ASPECTS

The natural history of the flora and fauna of the Sierra is described by Whitney (1979), Storer, Usinger, and Lukas (2004), Smith (1976), and the High Sierra hiking guides (e.g., Felzer 1981; Selters 1980).

Vegetation in the Sierra Nevada is controlled by a combination of temperature, precipitation, and soils, and there are three broad vegetation zones (Rundel, Parsons, and Gordon 1977; Majors and Taylor 1977). The elevational ranges of these zones rise from north to south and are higher east compared to west of the crest. All three zones are characterized by deep winter snow and infrequent summer rain. The upper montane zone occurs at elevations of approximately 2,100 to 2,700 m and is often characterized by nearly pure stands of red fir and lodgepole pine. Jeffrey pine and western juniper are also found in this zone, particularly on drier slopes. The growing season is 12 to 16 weeks, with 40 to 70 frost-free days annually. The subalpine zone extends from approximately 2,700 to 3,100 m and is relatively sparsely forested. Dominant tree species include whitebark pine, foxtail pine (southern Sierra), mountain hemlock (central and northern Sierra), lodgepole pine, and western white pine. The growing season is 6 to 9 weeks, and frosts can occur during all summer months. The alpine zone occurs at the highest elevations (> 3,100 m), and harsh climatic conditions prevent tree establishment. Vegetation is sparse and is composed of short-statured shrubs that grow in the limited areas containing soil. The growing season is short, and temperatures are cool even during summer. The tree line occurs at between 3,200 and 3,400 m, and above about 3,200 m vegetation is largely only alpine meadows, often growing near lakes.

A variety of fungi, lichens, ferns, and mosses are scattered through the high-elevation Sierra, including the giant lenticus (*Nelentinus ponderosus*) living on decaying conifers; the brown tile-lichen (*Lecidea atrobrunnea*), which imparts a gray cast to the granite; and fragile fern (*Cystopteris fragilis*) and star moss (*Syntrichia ruralis*). Plants such as sky pilot (*Polemonium eximium*) occur above 3,500 m. Other plants living at high elevations include western wallflower (*Erysimum capitatum*), alpine gold (*Hulsea algida*), lupine (*Lupinus* spp.), asters (*Aster* spp.), daisies (*Erigeron* spp.), mountain sorrel (*Oxyria digyna*), alpine columbine (*Aquilegia pubescens*), Sierra shooting star (*Dodecatheon jeffreyi*), and alpine phlox (*Phlox* spp.). Common shrubs include white heather (*Cassiope mertensiana*), red mountain heather (*Phyllodoce breweri*), alpine laurel (*Kalmia polifolia*), wax currant (*Ribes cereum*), alpine gooseberry (*Ribes montigenum*), and mountain ash (*Sorbus californica*).

At upper elevations common mammals include pika (*Ochotona princeps*), yellow-bellied marmot (*Marmota flaviventris*), Belding ground squirrel (*Spermophilus beldingi*), heather vole (*Phenacomys intermedius*), alpine chipmunk (*Tamias alpinus*), and occasional black bear (*Ursus americanus*) and coyote (*Canis latrans*). Predators include long-tailed and short-tailed weasels (*Mustela frenata* and *M. erminea*), marten and fisher (*Martes americana* and *Martes pennanti*), gray fox (*Urocyon cinereoargenteus*), and the threatened Sierra Nevada red fox (*Vulpes vulpes necator*). Grizzly bears (*Ursus arctos*) have been extirpated from the region. California bighorn sheep (*Ovis canadensis*) are now endangered. Reptiles are limited to the western terrestrial garter snake and the Sierra garter snake (*Thamnophis elegans* and *T. couchii*). Rattlesnakes (usually *Crotalus oreganus*) seldom venture above 2,300 m, but rare sightings have been reported on south-facing slopes at 3,000 m. Amphibians include the Mount Lyell salamander (*Hydromantes platycephalus*), the endangered Yosemite toad (*Bufo canorus*), Pacific treefrog (*Hyla regilla*), and the endangered mountain yellow-legged frog (*Rana muscosa*, *Rana sierrae*). Examples of birds commonly observed in the High Sierra include the mountain chickadee (*Poecile gambeli*), red-tailed hawk (*Buteo jamaicensis*), yellow-rumped warbler (*Dendroica coronate*), rock wren (*Salpinctes obsoletus*), white-throated swift (*Aeronautes saxatalis*), common raven (*Corvus corax*), water ouzel (*Cinclus mexicanus*), gray-crowned rosy finch (*Leucosticte tephrocotis*), Clark's nutcracker (*Nucifraga columbiana*), American robin (*Turdus migratorius*), mountain blue bird (*Sialia currucoides*), hermit thrush (*Catharus guttatus*), and dark-eyed junco (*Junco hyemalis*).

CULTURAL HISTORY

Not much is known about Native Americans who lived in the Sierra Nevada before the arrival of Europeans. The northern, central, and southern Sierra Miwoks occupied the foothills and mountains along the central western Sierra, with populations of each estimated to be from approximately 2,000 to 2,700 (Levy 1978). As was typical of other Native Americans living in the Sierra, the Miwok hunted black and grizzly bear, deer, smaller mammals, and game birds and fished and harvested a variety of plant products. They traded for salt and obsidian with the Washoe and Paiute living in the Great Basin. The Monache (also called the western Mono) were composed of six tribal groups along the western Sierra, and they also crossed the Sierra for trading (Spier 1978). In the southern Sierra along the Kern River, the Tubatulabal lived much as their neighbors to the north (Smith 1978). On the eastern flanks of the Sierra, the Owens Valley and northern Paiute and the Washoe made a living (Liljeblad and Fowler 1986; Fowler and Liljeblad 1986; D'Azevedo 1986). The Owens Valley Paiute occupied semipermanent camps with artificial irrigation of native plants and numbered between 1,000 and 2,000 before white settlement. Obsidian fragments are found throughout the lower elevations of the east side of the Sierra Nevada, even though obsidian outcrops in only a few locations. The northern Paiute ranged from Mono Lake into southern Oregon, and the Washoe lived around Lake Tahoe and numbered about 1,500. Trading and some intermarriage appear to have occurred along and across the Sierra among at least some of these groups. Smallpox, scarlet fever, measles, and violence caused by European settlers led to large population declines and the cultural demise of the Native Americans by the mid- to late 1800s in much of the Sierra Nevada.

The first Europeans to traverse the Sierra included the trapper Jedediah Smith in 1827, Joseph Walker in 1833, and John C. Frémont in the mid-1840s (Farquahar 1965). The discovery of gold, the so-called Mother Lode, on the Sierra's western slopes in 1848 precipitated the first mass migration to California, and by the mid-1860s the nonindigenous population increased sharply to about 223,000. With support from the California State Legislature, the so-called Whitney Survey began in 1860 and reached into remote recesses of the Sierra. Over subsequent decades the population of California continued to increase and by the 2010 census had reached slightly more than 38 million, with about 70% living in coastal counties and over 90% in urban areas (Alagona et al. 2016).

HISTORY OF NATURAL RESOURCE USE AND CONSERVATION

Beginning with the influx of Europeans sparked by the discovery of gold in California, the natural resources in the high-elevation Sierra Nevada have been exploited for mining, grazing, water supply, and hydroelectric power. Fish were introduced to provide food for miners and more recently to support sportfishing (Christenson 1977; Knapp 1996). Starting during the Civil War to supply wool, sheepherding in Sierra meadows increased through the late nineteenth century. Grazing by sheep, called "hoofed locusts" by John Muir, and the fires set by the ranchers caused substantial damage to the vegetation and soil. Human alteration had occurred earlier with burning by Native American peoples to maintain meadows and remove understory growth to enhance hunting and travel (Gruell 2001). A well-referenced historical account of the European exploration and utilization of the Sierra Nevada is provided by Farquhar (1965). Natural resource values and management issues in the Sierra Nevada forests and surroundings are treated extensively by the Sierra Nevada Ecosystems Project (1996) report.

Placer gravels on the western slope contain gold, and the hydraulic mining that was used to expose these gravels deformed the stream channels and led to downstream movement of vast amounts of debris. Tons of mercury used during the gold rush to amalgamate gold have created a legacy of aquatic food web contamination in the Sacramento–San Joaquin Bay-Delta (Singer et al. 2013). Quartz veins in metamorphic bands also contained gold, and these deposits led to further mining activities, as did discovery of deposits of silver, especially the Comstock Lode near Lake Tahoe, and of copper, lead, zinc, chromium, and tungsten (Sharp 1976). For example, the Copper Mountain Mining Company was active beginning in the 1890s in the remote Deadman and Cloud Canyons in the Triple Divide Area that became part of Sequoia National Park in 1926 (Selters 1980). Though mining in the Mineral King area of the southern Sierra started in the 1870s, it was not sufficiently productive and largely ended by the 1880s (Felzer 1981).

Starting in 1868, John Muir, a Scottish sheepherder, began his wandering and writings about the Sierra. The Sierra Club was founded by John Muir in 1892 and has played a key role in fostering recreational uses and conservation of the region. In 1864 the U.S. Congress ceded Yosemite Valley to the State of California as a park; striking photographs by Carleton Watkins taken in the 1800s played a key role in the establishment of the park (Green 2018). Subsequent legislative actions have led to the establishment and expansion of national parks and national forests and, more recently, wilderness designations within them. Currently, about 1.5 million hectares of the Sierra lie within national parks and national forests. Hence most human activities are now recreational hiking, camping, and fishing, and lakes and streams are an important focus of these activities. Between 4 million and 5 million people visit the area each year.

In popular culture, the Sierra Nevada has been used as the backdrop for many Hollywood films beginning with the silent era and continuing to the present day. Prominent locations include the Alabama Hills and Whitney Portal near Lone Pine and the Lake Tahoe and Truckee area (Lone Pine Film History Museum, Truckee-Donner Historical Society). Interestingly, one of our main study sites, Pear Lake, was prominently featured in the 2003 blockbuster film *Hulk*, directed by Ang Lee.

While several dams have created or modified lakes at high elevations (e.g., Sabrina, South, Edison), most large and moderate-sized reservoirs are located at lower elevations on the western slopes of the Sierra Nevada. These reservoirs are operated for water supply, irrigation, and consumption, as well as for flood control, recreation, and generation of electricity. The California Water Plan (Department of Water Resources 2009) provides an overview of the network of major reservoirs and water conveyance systems throughout California. For example, planning to import water from the Tuolumne River followed the 1906 earthquake in San Francisco, and Hetch Hetchy Valley, located within Yosemite National Park, was identified as a potential dam site. Despite opposition from John Muir and the Sierra Club, O'Shaughnessy Dam, creating Hetch Hetchy Reservoir, was completed in 1923, after Congress passed the Raker Act in 1913 (Hundley 2001).

Though remote from most direct damage, the watersheds and lakes of the high-elevation Sierra are susceptible to purposeful or accidental introductions of alien species, atmospheric transport of contaminants, and regional climate changes, as explored in subsequent chapters.

TWO

Introduction to High-Elevation Lakes and Watersheds of the Sierra Nevada

Abstract. The Sierra Nevada is a region with thousands of high-elevation lakes and ponds. The abundance of Sierra lakes is highest in the central part of the range and tapers at both the northern and southern ends in conjunction with changes in elevation, precipitation, and underlying geology. Although lakes distributed throughout the Sierra have been sampled to different degrees, the most extensive, intensive, and longest record comes from Emerald Lake and its watershed in Sequoia National Park. Complementary measurements are available for three watersheds located on the eastern side (Ruby, Crystal, Spuller), one at the northern end (Lost), and three on the southwestern side (Pear, Topaz, and the upper Marble Fork of the Kaweah River). Each of these lakes and watersheds is briefly described.

Key Words. Emerald Lake, Ruby Lake, Crystal Lake, Spuller Lake, Pear Lake, Topaz Lake, Lost Lake

LAKES OF THE SIERRA NEVADA

The Sierra Nevada is a lake-rich region, with iconic Lake Tahoe and scenic and saline Mono Lake (reviewed in Melack and Schladow 2016; Patten et al. 1987; Melack et al. 2017), in addition to thousands of other high-elevation lakes as well as ponds. The number of lakes and ponds within the glacier-carved high-elevation basins of the Sierra Nevada is remarkable; there are at least 12,000 water bodies located above an elevation of 2,280 m along the length of the range. To determine the abundance and distribution of lakes throughout the Sierra Nevada, we created a comprehensive data set by combining information from multiple data sources. California Department of Fish and Wildlife (CDFW) data were augmented with data collected from Yosemite National Park, Sequoia and Kings Canyon National Parks, and surveys by Roland Knapp (Sierra Nevada Aquatic Research Laboratory, University of California, Santa Barbara). We used digital elevation models (1 arc-second, ~30 m) from the National Elevation Database (www.usgs.gov/core-science-systems/national-geospatial-program/national-map) to determine the elevation of each lake and the average slope for a 250 m band around the lakes. Land cover within the 250 m band was determined using the landscape classifications in the National Land Cover Database (2001, www.mrlc.gov; 1 arc-second resolution).

The distribution of lakes in the Sierra Nevada is largely a result of glacial activity. Sierra lakes are most abundant in the central part of the range and taper in number at both the northern and southern ends in conjunction with changes in elevation, precipitation, and underlying geology (figures 3 and 4). The longitudinal distribution of lakes is skewed toward the east, with abundances peaking just west of the Sierra crest. This east-west distribution is related to elevation, which is typically higher near the eastern crest, where glacial scouring and deposition occurred more frequently at higher elevations, causing an increase in lake abundance at around 3,300 m. Glaciation did not extend to the uppermost elevations (Moore and Mack 2008; Moore and Moring 2013).

The majority of high-elevation water bodies are small; nearly three-fourths of them might be considered ponds based on their surface area (< 0.5 ha) (figure 5). At least a third of these ponds are classified as ephemeral in the CDFW database, holding water only through spring snowmelt and the first part of summer in most years. The 3,151 water bodies with areas > 0.5 ha might be considered lakes, and all are perennial (figure 6). Of these, nineteen are reservoirs, which comprise seven of the ten largest water bodies. Unlike the large drowned river valley reservoirs found within the western foothills of the Sierra, these high-elevation reservoirs are more often natural lakes whose outlets have been dammed to increase storage capacity.

While ponds dominate the Sierra in terms of abundance, they collectively account for less than 7% of the cumulative surface area. Ponds are surprisingly regular in size; median surface area and interquartile range, which characterizes dispersion between the 25th and 75th quartiles, are both 0.1 ha. In contrast, median lake area, excluding reservoirs, is in the 1.8 ha ± 3.3 ha interquartile range. The higher dispersion is due to the abundance of relatively small lakes. The reservoirs in our study were similarly skewed; they had