Chapter 6.1—Watershed and Stream Ecosystems

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Summary

Water and aquatic ecosystems in the synthesis area have high social, cultural, and ecological values. National forests in the synthesis area are a major source of water supply, hydropower, and recreational activity for much of California. Recent research has provided more information on water and nutrient budgets; these data are fundamental to understanding the interaction of terrestrial and aquatic ecosystems, current forest conditions, and response to stressors. Rapid changes in climate pose a threat to water resources, as warming has produced a shift toward more precipitation falling as rain than snow, which reduces snowpack water storage, causes earlier runoff, increases the frequency of major floods through rain-on-snow events, and diminishes late-season flows and the stability of headwater habitats. Because climate change is expected to increase impacts from storms and wildfires, flooding and sediment movement may increase, which could in turn reduce channel stability and habitat quality. Hydrologic response to climate change is expected to be different for the northern, central, and southern Sierra Nevada. Recent research has noted that natural disturbances such as fires and floods and associated erosion can be important for maintaining stream functions and biodiversity; however, systems that are already degraded or have limited connectivity for aquatic life may be vulnerable to losses following disturbances. Significant increases in sedimentation rates may negatively affect sensitive aquatic organisms and reservoirs. Therefore, efforts to promote a fire regime that results in fewer uncharacteristically large and severe wildfires can help maintain resilience of aquatic systems.

Forest restoration treatments may promote resilience to drought, wildfire, insects, and disease, and they could increase water available to soils, groundwater, and streams owing to reduced transpiration and increased snowpack. However, forest treatments that are not designed primarily to increase water yield may not remove sufficient trees to result in an easily measured and sustained increase in water. Consequently, evaluations of the water benefits of general restoration treatments will depend on the combination of long-term experimental studies and modeling, which have been initiated in the past decade. Aquatic systems that have not

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been degraded by historical land management may demonstrate relatively greater declines in water quality because of warming and deposition of nitrogen, so it is important to include them in a long-term monitoring network. It is also important to have data on physical, chemical, and biological indicators of water quality and quantity to detect both change and the causes of change. Stream invertebrates are good indicators of small-stream conditions where many forest management activities take place. Additional management strategies to promote resilience of aquatic ecosystems to stressors include restoration of natural processes, including fire regimes, flow regimes, hyporheic exchange, lateral channel migration, and habitat connectivity.

Introduction

All life depends on an adequate supply of water. The national forests play an important role in water protection, stemming from the Organic Administration Act of 1897, which asserted that one of the primary reasons for establishing forest reserves was to "secure favorable conditions of water flows." How much and where water occurs is a direct function of climate and weather patterns. Soils, topography, and vegetation affect how water is partitioned in the landscape, and these factors, along with human activities, air quality, and ecosystem disturbances, affect the quality of water. Measurements of physical, chemical, and biological characteristics serve to characterize the condition or health of water resources and aquatic ecosystems. Monitoring environmental attributes at different scales or doing research, especially with designed experiments, can help to gain knowledge about effects of land use practices. The Adaptive Management Plan, Appendix E, in the Sierra Nevada Framework (USDA FS 2001, 2004) described the need for status and trends monitoring and research; it also identified priority questions and knowledge gaps that required new information to improve Forest Service management of water resources and aquatic ecosystems. Since that time, most Forest Service efforts toward aquatic resources in the Sierra Nevada have been directed to studies of amphibians, grazing practices, and invertebrates. More recent attention has been given to meadow restoration. A long-term watershed research project in the Sierra Nevada was established by the Pacific Southwest Research Station in 2000 at the Kings River Experimental Watersheds (KREW), which includes a portion of the Teakettle Experimental Forest. This research site has attracted National Science Foundation funding for the establishment of the Southern Sierra Critical Zone Observatory (Lin et al. 2011),[4] which is starting to provide new information on hydrology and geosciences in the Sierra Nevada. Older watershed research sites

[4] Southern Sierra Critical Zone Observatory, http://criticalzone.org/sierra.

with long investments exist at University of California's Blodgett Forest Research Station and Sagehen Experimental Forest (see fig. 1 in chapter 1.5).

This chapter begins with a review of values and services associated with aquatic ecosystems. It then considers climate change and wildfire before turning to recent science on water quantity, water quality, and macroinvertebrates as indicators of water quality. This chapter concludes with a discussion of management strategies to promote resilience of aquatic ecosystems. A challenge for the future is to better integrate water and aquatic ecosystems into forest planning, which typically has focused on tree structure and composition, fire, and a few wildlife species in the synthesis region (e.g., North 2012, North et al. 2009).

Values and Services of Aquatic Ecosystems

> Water, in all its forms, is indeed the crowning glory of the Sierra. Whether in motion or at rest, the waters of the Sierra are a constant joy to the beholder. …Above all, they are the Sierra's greatest contribution to human welfare.
>
> —*History of the Sierra Nevada*, F.P. Farquhar (1965: 1)

National forests supply 45 percent of California's water, and most of the state's surface water originates in the Sierra Nevada. In the Pacific Southwest Region, one of the most valuable ecosystem services that national forests provide is an adequate supply of good water for aquatic ecosystems and human needs. California's economy is highly dependent on agriculture, and much of the country relies on fresh fruits and vegetables produced in California. Water is therefore pivotal to California's economy and the Nation's food supply. Furthermore, human recreation is highly influenced by the presence of water bodies.

Streams, riparian areas, and wet meadows support a wide range of social, cultural, and ecological values, including plant and wildlife diversity, water quality, water quantity, cultural values, aesthetic values, sport fishing, and tourism. Native American cultural resources are often concentrated along perennial streams owing to availability of water and culturally important plants, travel corridors, and other patterns that facilitated settlement (Jackson 1988). Activities such as timber harvest, recreation, and livestock grazing (see chapter 9.5, "Managing Forest Products for Community Benefit") can affect the condition of riparian and meadow areas. Such areas can sustain a diverse array of ecosystem services and ameliorate effects of climate change (see also chapter 6.3, "Wet Meadows").

The value of riparian ecosystems (termed aquatic-terrestrial ecotones in the international literature) has been discussed extensively (Holland et al. 1991, Malanson 1993, Petts 1990, Pinay et al. 1990). Historically, riparian ecosystems were valued for their economic uses: transportation corridors, water supply and electricity, construction materials and waste disposal, agriculture and livestock, and settlement. The more recently recognized economic, social, and biological values of riparian ecosystems are listed below. Luce et al. (2012) identified valued functions of riparian plant communities for native fishes: provision of shade for thermal modification of stream temperature, inputs of large wood for in-stream habitat complexity, organic matter inputs to aquatic food webs, and provision of streamside habitat and stabilization of streambanks.

Values of riparian ecosystems from the referenced literature

Economic:

- Reduce downstream flooding
- Recharge aquifers
- Surface water supply in arid regions
- Support secondary productivity, e.g., for fisheries
- High yields of timber

Social:

- Recycle nutrients
- Store heavy metals and toxins
- Filter of diffuse pollution from uplands
- Accumulate organic matter as a sink for carbon dioxide
- Intermediate storage for sediments
- Natural heritage
- Recreation
- Aesthetics
- Natural laboratories for teaching and research

Biological:

- Special habitat for some endangered or threatened species
- Habitat for aquatic species

Riparian areas are unique environments because of their position in the landscape; they are both ecotones between the terrestrial and aquatic zones, and corridors across regions (Malanson 1993). The term ecotone was first used in 1905 by Clements; with the development of the discipline of landscape ecology, there was a renewed interest in the ecotone concept in Europe around 1990, and it was explored by the Man and Biosphere program (Holland et al. 1991, Naiman and Decamps 1990). An ecotone was then defined as "a zone of transition between adjacent ecological systems, having a set of characteristics uniquely defined by space and time scales and by the strength of interactions between adjacent ecological systems" (Naiman and Decamps 1990: 3).

Resilience and Degradation in Stream Ecosystems

Ecological resilience has been defined as the amount of disturbance an ecosystem can absorb without crossing a threshold to a different stable state, where a different range of variation of ecological processes and structures reigns (Gunderson 2000) (see also chapter 1.1). This general idea is also reflected in the concept of dynamic equilibrium, which Heede (1980) described as the capacity of streams to adjust to perturbations within a few years. These concepts depend on the timeframe being considered and the range of variation in processes and structures. For example, understanding thresholds of erosion beyond which long-term sustainability is jeopardized requires extensive monitoring and understanding of reference conditions and natural variability. Developing site-specific restoration and management strategies therefore requires consideration of the evolutionary history of particular sites (Miller et al. 2001).

Some scientists have challenged the concept of dynamic equilibrium by arguing that many fluvial systems are inherently unstable (Lave 2009). Fluvial systems in Mediterranean climates in particular have been characterized as highly variable and ever-changing (Kondolf et al. 2012). Reflecting this view, scientists in recent years have challenged efforts that emphasize promoting channel stability, and they cautioned that management and restoration approaches are often overprotective in seeking to avoid disturbances and erosion. They pointed out that channel instability may have desirable consequences; for example, erosion and deposition following major disturbances, such as wildfires, can be important for maintaining stream functions and biodiversity (Bisson et al. 2003). Florsheim et al. (2008) outlined the various benefits of streambank erosion for maintaining aquatic habitat diversity and reiterated that total elimination of bank erosion should not be a goal when restoring rivers.

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Climate Change Effects on Watersheds and Stream Ecosystems

Effects on Hydrology

Anticipating that a changing climate in California will substantially affect water resources and aquatic ecosystems, strategies for assessing the impacts of altered stream flows need to be developed. Changes in the Sierra Nevada, the primary source area of water in the state, are of particular concern. Warming has produced a shift toward more precipitation falling as rain than snow, and this reduces snowpack water storage, causes earlier runoff, increases the frequency of major floods through rain-on-snow events, and diminishes late-season flows and the stability of headwater habitats that are important for maintaining watershed hydrological and ecological function (fig. 1). The California Department of Water Resources (DWR 2006) identified some other potential effects of climate change in California on water resources, including changes in vegetation, increased incidence of wildfires, increased water temperatures, and changes in human water demand.

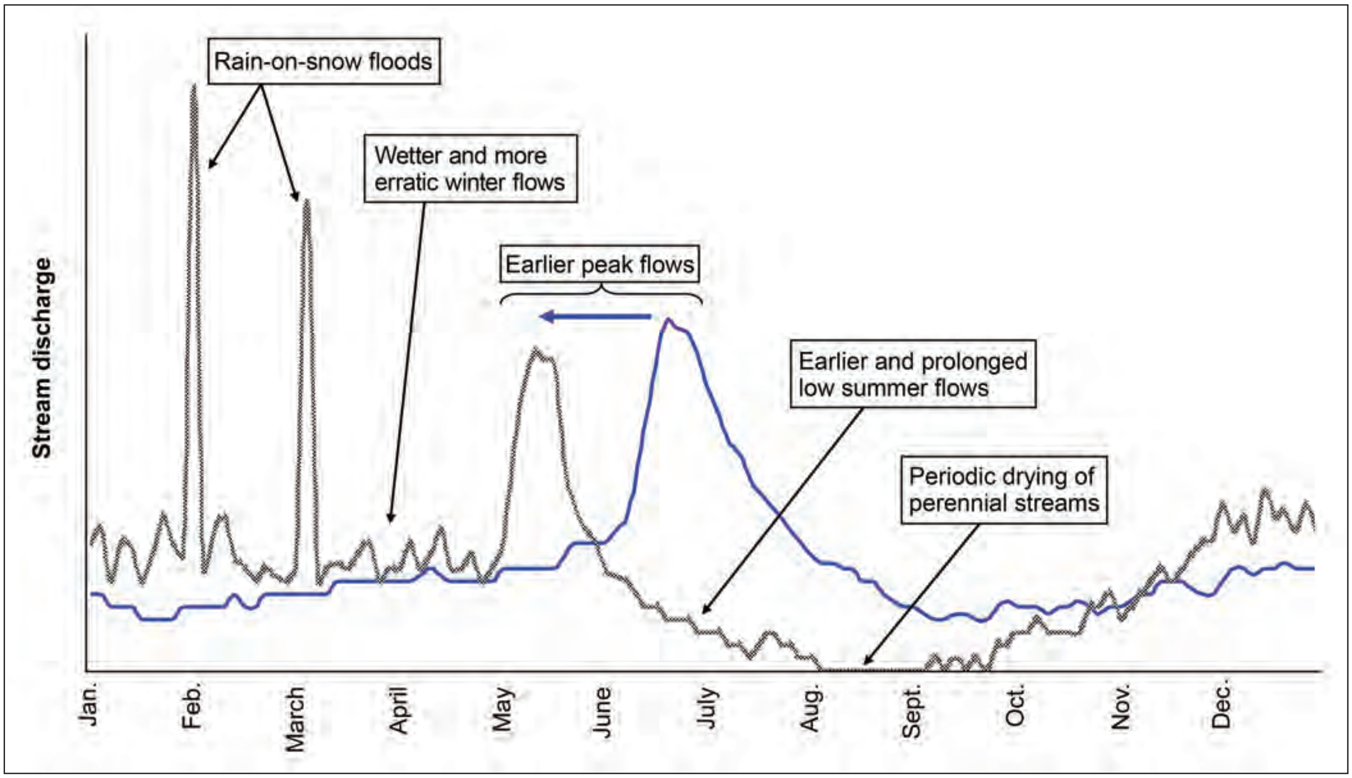

Figure 1—Conceptualization of the climate-driven changes (gray line) to the natural hydrograph (blue line) of a Sierra Nevada stream.

The water resources of the Western United States depend heavily on snowpack to store part of the winter precipitation into the drier summer months. A well-documented shift toward earlier runoff in recent decades has been attributed to more precipitation falling as rain instead of snow and earlier snowmelt (Knowles et al. 2006). The starting date of snowmelt is earlier now by about 15 days, based on data from 1960 to 2000 (fig. 2). A decline in the mountain snowpack of western North America has also been documented (Barnett et al. 2008, Mote et al. 2005). The California Department of Water Resources report (DWR 2006) showed how hydrologic patterns by river basin have already changed in California during the past 100 years. There is a slight decreasing trend in precipitation in central and southern California and increased variability in precipitation. There is also a difference between changes in northern and southern California. For example, the total annual water year runoff has been increasing for the Sacramento River basins (northern

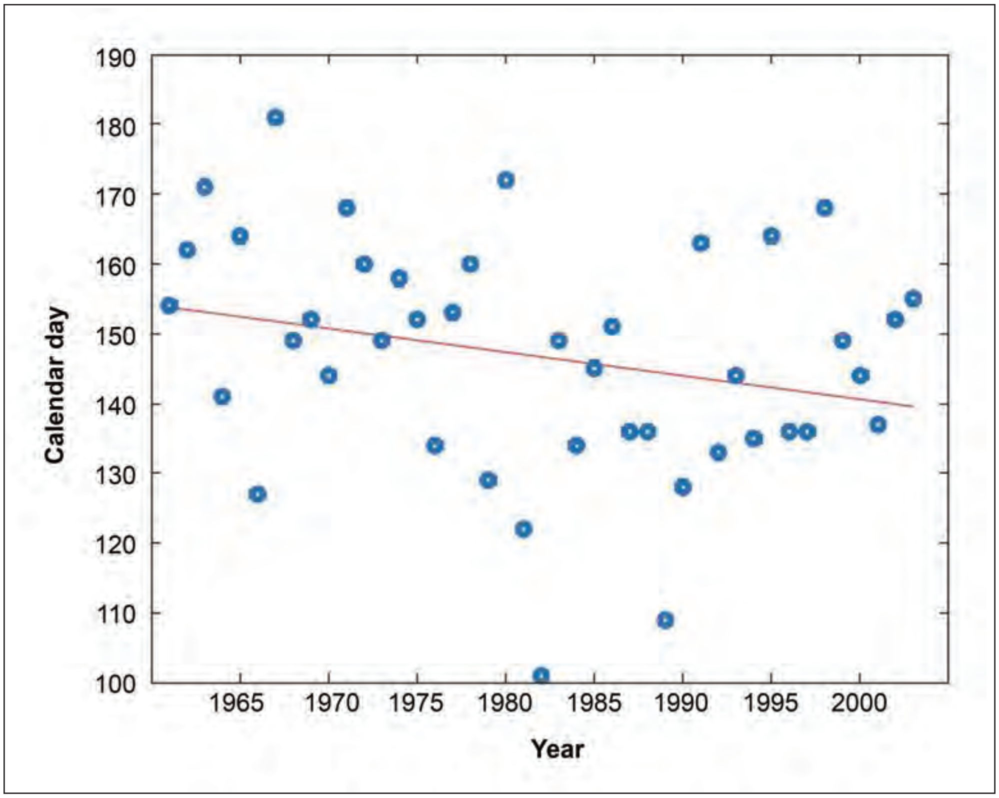

Figure 2—Trend in the timing of snowmelt discharge based on the day of maximum daily discharge, Kern River, California. Figure is from Peterson et al. 2008.

and central Sierra Nevada) and decreasing for the San Joaquin River basins (central and southern Sierra Nevada). However, both areas experienced decreases in spring runoff; runoff from April through July declined by 9 percent for the Sacramento River basins and declined by 7 percent for the San Joaquin River basins.

Snowpack provides 20 percent of California's total runoff and 35 percent of its usable surface water. Climate modeling predicts a loss of snowpack for the mountains in California (table 1), with a greater effect in the northern Sierra Nevada, where the mountains are lower in elevation than in the southern Sierra (Knowles and Cayan 2002). A change in surface water quantity of this magnitude will affect aquatic ecosystems and human uses.

Table 1—Temperature increase and effect on Sierra Nevada snowpack

Temperature increase	Loss of snowpack	Predicted year of effect
°C	*Percent*	
0.6	5	2030
1.6	33	2060
2.1	50 (43 in south and 66 in north)	2090

Source: Knowles 2002.

In the past 10 years, many publications and modeling efforts have focused on predicting climate change effects on critical ecological variables, including air temperature, amount and timing of precipitation and stream discharge, and soil moisture (Dettinger 2005, Hayhoe et al. 2004, Jeton et al. 1996, Knowles et al. 2006, Maurer 2007, Stewart et al. 2004, Vicuna et al. 2008). Some of these findings for the synthesis area are briefly discussed to highlight their importance for watershed and aquatic ecosystem condition.

Global climate models use a grid that is too coarse to adequately depict the complex structure of temperature and precipitation in California, especially within the rugged terrain of the synthesis area. A statistical technique allows coarse data to be "downscaled" to a finer level of detail, and a grid scale of 12 km (7 mi) was available by 2006 (Cayan et al. 2006). More recent work is downscaling data to even finer grids that allow predictions on possible changes to other attributes, such as stream discharge, water quality, and erosion. For example, Ficklin et al. (2012) developed and applied a hydroclimatological stream temperature model within the Soil and Water Assessment Tool (SWAT) to mountain areas of the Western United States. These scientists are also working on projections of (1) future hydrologic flow components for the major river basins of the Sierra Nevada using an ensemble of general circulation models, and (2) the effects of climate change on water quality (stream temperature, dissolved oxygen concentration, and sediment concentration) in the Sierra Nevada. The U.S. Geological Survey in Sacramento has an ongoing study of the effects of climate on snowmelt and water availability in the southern Sierra Nevada (Tuolumne, Merced, San Joaquin, King, and Kaweah River basins). These new downscaling efforts and predictions at the river-basin scale and for smaller watersheds will be useful to forest managers in considering climate change effects on water resources.

Null et al. (2010) used WEAP21 (Stockholm Environment Institute's Water Evaluation and Planning System), a weekly one-dimensional rainfall-runoff model, to compare the hydrologic responses of 15 watersheds on the west slope of the Sierra Nevada to air temperature increases of 2, 4, and 6 °C while keeping other climatic variables unchanged. Predicted changes in mean annual flow were largely driven by area and increased evapotranspiration from climate warming, while snowfall and snowmelt timing resulted in runoff timing changes. Predicted changes in low flow duration were a function of deep soil moisture capacity and infiltration. Null et al. (2010) found that vulnerabilities varied from north-to-south within the Sierra Nevada. Northern watersheds were sensitive to decreased mean annual flow owing to their extensive use for water storage; central watersheds were sensitive to length of low-flow conditions owing to their large areas of mountain meadows;

south-central watersheds were sensitive to changes in runoff timing owing to their importance for hydropower; and the southernmost watershed, the Kern, appeared to be the most resilient (table 2). For the 15 watersheds included in the study, total water storage is approximately 24 590 mcm[5] for all dams greater than 1.2 mcm, and total online hydropower capacity is approximately 8,751 MW. Null et al. (2010) state that their results are broadly consistent with other climate forecasts (Brekke at al. 2004, Lettenmaier and Gan 1990, Miller et al. 2003).

Bales et al. (2006) identified three pressing hydrologic information needs for the western mountains of the United States given climate change, population growth, and land use change:

- To better understand the processes controlling the partitioning of energy and water fluxes within and out from these systems.
- To better understand feedbacks between hydrological fluxes and biogeochemical and ecological processes.
- To enhance our physical and empirical understanding with integrated measurement strategies and information systems.

[5] Million cubic meters. 1 mcm = 810.7 acre feet or the volume of water necessary to cover 1 acre to a depth of 1 foot (also equivalent to 325,851 U.S. gallons).

Table 2—Modeled mean annual flow by watershed and air temperature increase

	Annual average flow (MCM)			Percent decrease from basecase	
Watershed	**Basecase**	**2 °C increase**	**6 °C increase**	**2 °C increase**	**6 °C increase**
Feather	5776	5649	5264	2.2	8.8
Yuba	3020	2960	2806	2.0	7.1
Bear	492	475	445	3.6	9.6
American	3556	3448	3218	3.1	9.5
Cosumnes	603	571	518	5.2	14.0
Mokelumne	979	946	887	3.4	9.4
Calaveras	330	319	301	3.3	8.9
Stanislaus	1561	1523	1435	2.4	8.1
Tuolumne	2445	2401	2304	1.8	5.8
Merced	1348	1308	1237	3.0	8.2
San Joaquin	2294	2265	2201	1.3	4.1
Kings	2117	2094	2041	1.1	3.6
Kaweah	586	564	519	3.8	11.5
Tule	199	190	171	4.6	14.3
Kern	926	887	813	4.2	12.2

Source: Null et al. 2010.
MCM = million cubic meters.

The KREW research (see box 6.1-5 on page 290) can help one to understand climate change effects for the southern Sierra Nevada, because five of the KREW streams are located in the rain-snow interface zone and five are in the snow-dominated zone. The current functioning of the lower elevation streams provides valuable insight into what can be expected for higher elevation streams with a 2 °C air temperature shift (Bales et al. 2011a, Hunsaker et al. 2012). New information is also being developed on these topics with field instrumentation and data analyses by the Sierra Nevada Adaptive Management Project (SNAMP) and the Southern Sierra Critical Zone Observatory (SSCZO).

Using data from four eddy covariance towers, Goulden et al. (2012) reported a large decline in evapotranspiration (ET) between 2015 and 2700 m that is associated with development of winter dormancy in trees. This elevation range marks the transition from a mixed rain-and-snow precipitation regime to one dominated by snow (Hunsaker et al. 2012). During 3 years of observations, the ET at 2015 m ranged from 70 to 80 cm/yr (Bales et al. [2011a] estimated 96 cm/yr at this location), whereas it was only 35 to 50 cm/yr at the 2700 m elevation. Goulden et al. (2012) interpreted their results as suggesting that winter transpiration could increase because of climate change, thus decreasing the amount of water available for streams.

Because climate change is expected to increase the incidence of severe wildfire, high-intensity storms, and rain-on-snow events, the threat of post-wildfire debris flows is expected to increase and become more widespread.

Effects on Channel Processes

Because climate change is expected to increase rainfall and storm intensity (Moody and Martin 2009) and the occurrence of uncharacteristically severe wildfire (Miller et al. 2009), flooding and sediment movement may increase owing to the incidence of rain-on-snow events or post-wildfire floods, which could in turn reduce channel stability and habitat quality. Negative impacts of climate change may be especially pronounced in high-elevation, currently snow-dominated systems that shift toward more winter rainfall (Battin et al. 2007). Herbst and Cooper (2010) suggested that increased rain-on-snow floods might pose a particular threat to streams that are already degraded (see “Effects of floods” on page 300). Riebe et al. (2001) concluded that outside of glacial transition periods, climate change is unlikely to substantially affect watershed-scale erosion rates in the Sierra Nevada; however, they cautioned that climate change could alter sediment storage in floodplains, terraces, and colluvial hollows, which would affect short-term sediment delivery and channel stability. In reviewing effects of climate change on streams in the mountains of Idaho, Goode et al. (2012) contended that sediment yield could increase tenfold compared to recent historical levels owing to increases in postfire debris flows. Because climate change is expected to increase the incidence of severe wildfire, high-intensity storms, and rain-on-snow events, the threat of post-wildfire debris flows is expected to increase and become more widespread (Cannon and DeGraff 2009). If postfire landforms persist beyond the wildfire recurrence interval, successive wildfires will have an important cumulative impact on watershed morphology (Moody and Martin 2001).

Debris flows—

Intense storms, in many cases following wildfires, can trigger debris flows.[6] Most debris-flow activity occurs within about 2 years following a fire, because revegetation tends to quickly stabilize hillslopes. Substantial hazards from flash flooding, however, could remain for many years after a fire (Cannon and Michael 2011). In studies of postfire debris-flow processes throughout the Western United States, the great majority of fire-related debris flows initiate through a process of progressive bulking of storm runoff with sediment eroded both from hillslopes and from channels, rather than from infiltration-triggered landsliding. Statistical-empirical models have been developed to estimate the probability and volume of debris flows that may be produced from burned drainage basins as a function of different measures of fire severity and extent, gradient, and soil physical properties in the basin (Cannon and Michael 2011). The probability model was developed using data from 388 basins in 15 recently burned areas of the Western United States, and the volume model was developed from 55 debris-flow-producing basins burned by eight different fires where the volume could be attributed to a single storm. This modeling work used a 30-minute-duration, 10-year-recurrence rainstorm of 0.73 in (18.5 mm) to trigger an event. Intense rainfall events, rain-on-snow storms, and rapid snowmelt are all associated with debris flow occurrence in the Sierra Nevada. Cannon et al. (2008) summarized research on runoff and sedimentation events from recently burned watersheds and found that a 30-minute peak rainfall intensity greater than 10 mm/h resulted in significant increases in runoff, and intensities greater than 20 mm/h resulted in significant sediment movement. The association between wildfire, debris flow, and floods is well established in the southern Sierra Nevada (DeGraff et al. 2011), and the modeling work by Cannon and Michael (2011) enables risk potential and volume of sediment from wildfires to be estimated for comparison to sediment from management activities.

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[6] Land and rock slides are another geomorphic disturbance that can deliver sediment to stream networks in the synthesis area. However, compared to some mountain ranges, such as the European Alps or the Himalayas, the Sierra Nevada generates relatively infrequent massive rock slides. In the southern Sierra Nevada, nine slides have been documented from prehistoric times to 1997, ranging in size from 23 000 m^3 to 11 million m^3 (Harp et al. 2008). Such slides have had severe impacts on people, communities, and infrastructure and can create dams in steep river canyons.

Large debris flows down channels may be among the most persistent effects of wildfires (Benda et al. 2003, Goode et al. 2012, Moody and Martin 2001). Debris flows are a major concern in southern California and the Intermountain Region, and those flows tend to be larger than flows in more humid climates such as the Pacific Northwest (Santi and Morandi 2012). The wetter western slopes of the Sierra Nevada have experienced debris flows associated with landslides following high rates of rainfall, rapid snowmelt, or rain-on-snow events (DeGraff 1994). In addition, there have been instances of post-wildfire debris flows from burned watersheds upslope from El Portal, California, near Yosemite National Park (Cannon and DeGraff 2009). In the southern Sierra Nevada, monsoonal storms on July 12, 2008, produced intense rainfall that triggered large debris flows in the southern Sierra Nevada (fig. 3) (DeGraff et al. 2011). One flow traveled down the north and south forks of Oak Creek through the town of Independence on the east side of the Sierra Nevada; it resulted in substantial damage to homes, a Forest Service campground,

Jerome V. De Graff

Figure 3—Damage to residences along Oak Creek following the postfire debris flow incident of July 12, 2008, on the Inyo National Forest.

and other infrastructure. The other flow traveled down Erskine Creek through the town of Lake Isabella, California, and into the Kern River on the southern end of the Sierra Nevada. The Inyo Complex fire had burned 30 percent of the Oak Creek watershed at high or moderate severity in 2007, and the Piute Fire had burned 15 percent of the Erskine Creek watershed at high or moderate severity, but the two events shared relatively intense rainfall (16 to 30 mm/hour) (DeGraff et al. 2011). These incidents demonstrate that postfire debris flows are a significant concern in the southern and eastern parts of the Sierra Nevada, which experience high-intensity rainstorms. Further research would be needed to evaluate risks within the synthesis area, given high amounts of variability in these watershed processes. A comparison of rainfall regimes by Moody and Martin (2009) showed that the region that includes the Sierra Nevada experiences less intense rainfall than the mountains of Arizona, but more intense rainfall than in the Great Basin. However, they found very high variability within the Pacific region and poor correlation between post-wildfire sediment yields and rainfall intensity (measured as the average 2-year event over 30-minute periods).

Effects on Aquatic Ecosystems

Projected effects of climate change on aquatic ecosystems include hydrologic effects discussed above (especially lower summer baseflows, earlier runoff, and higher summer water temperatures), as well as biological effects, such as increased isolation of native aquatic species and spread of invasive species (Viers and Rheinheimer 2011).

Impacts on trout—

The projected impacts of climate change on trout and salmon species are a particular concern because of the vulnerability of those species to increased stream temperatures (Moyle et al. 2011). Although the middle of the Sierra Nevada includes a large area that was historically fishless, the northern and southern Sierra Nevada support several endemic strains of native trout (fig. 4). Several varieties of redband or rainbow trout (*Oncorhynchus mykiss*) evolved in the Sacramento-San Joaquin drainages of the Sierra Nevada, while varieties of cutthroat trout (*Oncorhynchus clarkii*) evolved within the interior east-side drainages of the Lahontan basin (Behnke 2002). Because of stocking with nonnative trout species, translocations of trout outside of their native streams, and impacts to habitats, most of these native trout have become confined to relatively small streams, leaving them vulnerable to the effects of climate change and wildfire (see box 6.1-1). Wenger et al. (2011) forecasted significant declines in trout habitat and associated socioeconomic consequences across the interior Western United States over the next 60 years.

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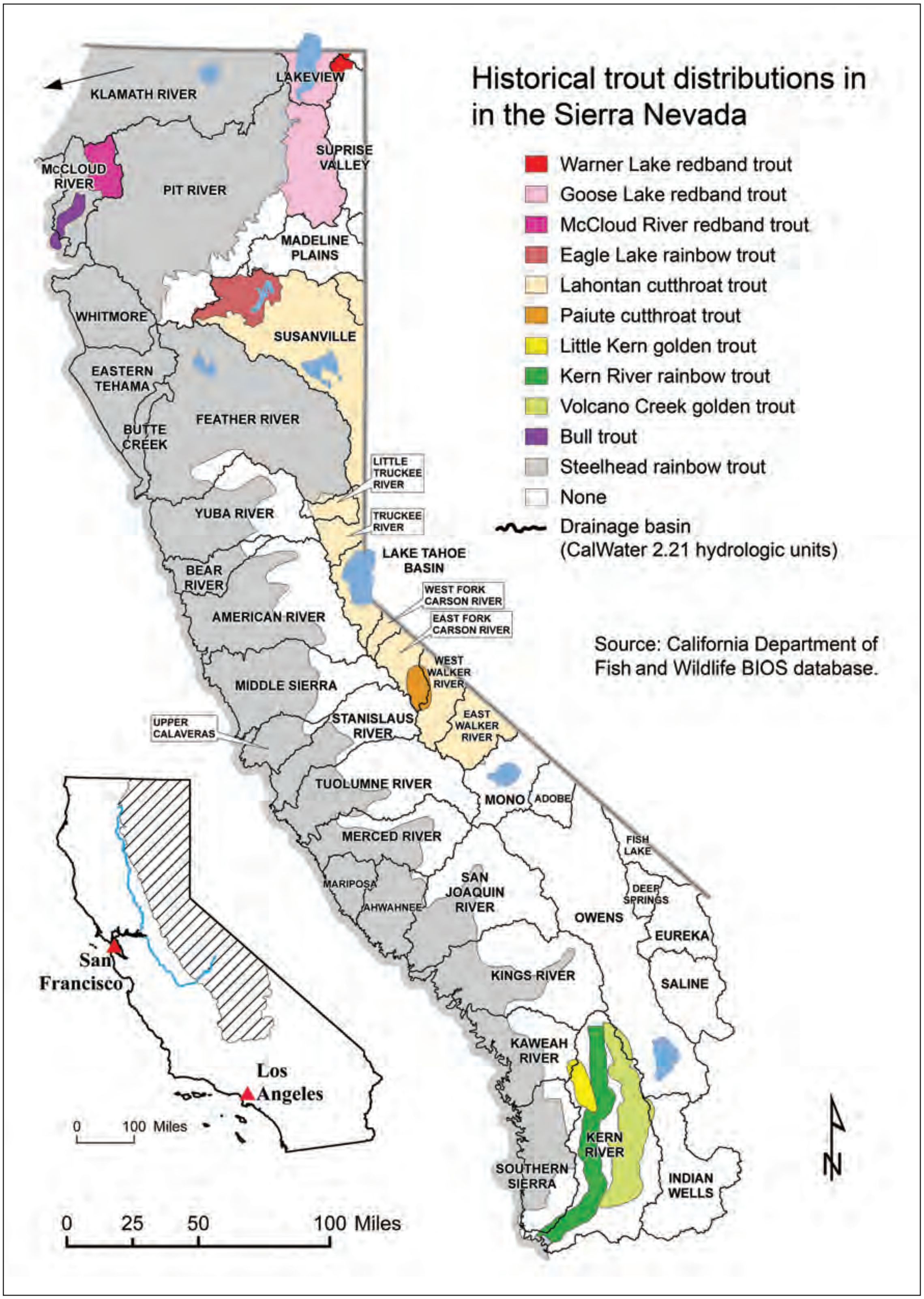

Figure 4—Historical distribution of native trout within the synthesis area. Map by Ross Gerrard.

Post-wildfire floods that reorganize channel habitats can have significant impacts on fish populations, including extirpation of isolated native trout populations in headwater streams in the Southwest (Brown et al. 2001). A study by Isaak et al. (2010) in Idaho demonstrated that severe wildfires followed by channel-reorganizing floods can increase rates of stream warming over long periods. These events can cause streams to warm by removing vegetation and widening channels; those effects may offset the potential of such events to lower temperatures by increasing base flow (a potential short-term effect resulting from reduced transpiration in the watershed) (Sugihara et al. 2006), or by increasing heat exchange with colder groundwater (Dunham et al. 2007). In contrast, native fish populations that inhabit relatively intact stream networks in the Northwest and the northern Rocky Mountains have demonstrated resilience following wildfires (Gresswell 1999, Neville et al. 2009). However, the responses of aquatic systems to wildfire and climate change observed in other regions may not transfer well across the synthesis area because of variations in climate, topography, extent of nonnative competitors, and connectivity of aquatic populations.

Box 6.1-1

Reports on Threats From Climate Change and Wildfire on Aquatic Species

Trout Unlimited has generated a series of reports under its Conservation Success Index program (Williams et al. 2007) that characterize risks for native salmonids from changes in climate and fire regime within their ranges.

More recently, researchers at the University of California–Davis prepared a white paper report on the effects of future climates on freshwater fishes (Moyle et al. 2012).

In addition to the recently published study of postfire debris flows by DeGraff et al. (2011), the Forest Service has conducted monitoring of impacts to aquatic ecosystems following recent fires, including the Moonlight Fire (2007), Cub Fire (2008), and Lion Fire (2011). These observational efforts should afford opportunities to evaluate resilience of streams in the synthesis area to wildfires of different severities.

Tom Whitaker

Figure 5—Intense rain events or rain-on-snow events can increase suspended sediment and turbidity in streams, as shown at one of the flumes in the Kings River Experimental Watersheds, Sierra National Forest.

Effects on Biological Indicators of Water Quality

Understanding particular effects of climate change on the biology of mountain streams would be valuable, because many management agencies use biological criteria to measure trends of ecological health, water quality, and the integrity of ecosystem function. In particular, streams in relatively undisturbed watersheds serve as references to evaluate condition. Against a background of climate-driven alteration to the ecology of streams across the Sierra Nevada, the biological integrity of reference streams may decline. Biological diversity in confined headwater and alpine streams may be especially sensitive to shifting hydrologic patterns. Even though all streams and lakes are affected by climate change, the reference habitats may have more to lose than disturbed streams that have already been affected by localized sources of pollution and other forms of degradation. If reference streams lose a higher proportion of aquatic life to warming and hydrologic disruption, then the "signal," or difference relative to disturbed test sites, would be decreased. The reference condition for streams is typically developed based on many sites sampled over many years, so if these streams slowly degrade, the range of variability or "noise" in the cumulative reference condition will increase. The net effect of a declining reference condition is that it will be harder to detect degradation by nonclimate factors. Establishment of current conditions and quantification of climate-induced drift would help to monitor conditions within the Sierra Nevada and to recalibrate standards as climate conditions change.

Box 6.1-2

Stream Monitoring Network for Climate Change

In 2010, the Management Indicator Species Program of the Pacific Southwest Region funded the establishment of a stream observatory network, designed by David Herbst of the Sierra Nevada Aquatic Research Laboratory, to detect the ecological impacts of climate-induced changes in hydrologic balance and temperature of Sierra Nevada streams and to provide a historical context for recovery of degraded ecological values. The network includes 12 sites (6 in the southern Sierra Nevada and 6 in the northern Sierra Nevada) that serve as undisturbed reference sites for streams that are expected to have high and low risk for climate-induced loss of snow cover and hydrologic stability, in combination with high and low resistance to climate change. This network also sets up a natural experiment within which differing hypothesized risks based on forecasted climate conditions and hydrographic susceptibility can be contrasted. The sites are broadly representative of Sierra Nevada streams across a range of elevations from 1220 to 3660 m (4,000 to 12,000 ft). Meas-urements at these sites include stream invertebrates, algae periphyton, water chemistry, geomorphic characteristics, stage height, riparian cover, and water and air temperature. Benthic invertebrate samples from this network partition into two community groupings—those sites north of Yosemite National Park and those south of the park. A possible difference is that southern Sierra Nevada streams have less groundwater recharge based on a comparison of their chemistry with that of northern streams, and they are thus more susceptible to low flows and drying, and support less biological invertebrate diversity. Southern Sierra Nevada streams with greater upstream length may be less prone to drying and therefore have a higher level of diversity.

Water Resources

This section includes a discussion of ecosystem processes and issues that are important to water quantity and quality. Stream benthic macroinvertebrates (BMIs) are included here as important biological indicators of water quality.

Water Quantity

Streamflow response to a change in forest density is strongly related to climate, species composition, and the percentage change in vegetation density. Troendle et al. (2010) provided a review of the many studies on this topic and made the following observation (Troendle et al. 2010: 126–127): "The data from 95 watershed experiments conducted in the United States show that, on average, annual runoff increases by nearly 2.5 mm for each 1 percent of watershed area harvested (Stednick 1996). Because runoff is quite variable from year to year, the general conclusion is that approximately 20 percent of the basal area of the vegetation must be removed before a statistically significant change in annual runoff can be detected (Bosch and Hewlett 1982, Hibbert 1967, Stednick 1996)." Because most of these paired watershed experiments imposed a partial or complete clearcutting of the mature trees, our current understanding of the hydrologic impacts of thinning and prescribed fire comes from inference supported by some plot and process studies.

Forest treatments that remove less than 20 percent of tree basal area may result in a change in flow, although it likely will not be detectable.

Many fuels management treatments or forest restoration efforts remove less than 20 percent of the basal area of trees; although this may result in a change in flow, it likely will not be detectable, especially in dry years. With best management practices (BMPs), which should not cause overland flow from skid trails or soil compaction, there should be little or no detectable effect on peak discharges. Any change will be short-lived because of vegetation regrowth, except in cold snow zones (Rocky Mountain region). Prescribed fire by itself is less likely to influence water yield than mechanical treatments because of the smaller reduction in basal area and lack of ground disturbance by heavy machinery (Troendle et al. 2010).

During the past decade, a better understanding of hydrologic processes has developed for the southern Sierra Nevada. Hunsaker et al. (2012) characterized the climate and hydrologic patterns for eight headwater catchments, including both the rain-snow transition zone and the snow-dominated zone of the southern Sierra Nevada. A water-balance instrument cluster at these rain-snow catchments enabled an estimate of total annual evapotranspiration at 76 cm in 2009, a value higher than previous estimates for the Sierra Nevada (Bales et al. 2011a). Water loss rates from soil were estimated to be 0.5 to 1.0 cm d^{-1} during the winter and snowmelt seasons. Soon there will be data on the effect of both prescribed fire and mechanical removal of vegetation on streamflow (see box 6.1-5).

Engle et al. (2008) provided the only new experimental data on streamflow response to prescribed fire in the Sierra Nevada. The Tharps Creek watershed (13 ha) was burned after having no fire for at least 120 years; the preburn surface fuel load was 210 Mg ha^{-1} and fuels were reduced by 85 percent as a result of the fire. After fire, runoff coefficients increased by 7 percent in dry years and 35 percent in wet years. (The runoff coefficient is the relationship between the amount of runoff to the amount of precipitation; the value is large for areas with low infiltration and high runoff.) Mean annual runoff in the 50-ha Log watershed (control) during the dry years was 29 percent of precipitation; mean annual runoff was 56 percent of precipitation when drought years are excluded. Runoff coefficients in the Tharps watershed were consistently lower than in the Log watershed, averaging 51 percent during wet years and 8 percent during dry years. Nine years after the burn, there was no evidence that runoff in the Tharps watershed was returning to prefire levels.

Box 6.1-3

Water Yield Predictions

A recent report based on modeling suggests a somewhat different conclusion from Troendle et al. (2010) about the ability to increase water yield through forest harvesting. Bales et al. (2011b) suggested that reducing forest cover by 40 percent of maximum levels (based on leaf area index) across a watershed could increase water yields by about 9 percent. They estimated that proposed treatments at the Onion Creek Experimental Forest on the Tahoe National Forest could increase water yield by as much as 16 percent and extend snow storage (i.e., delay snowmelt) by days to weeks. They also cited recent studies in the Sierra Nevada that report potential increases in snow accumulation of 14 to 34 percent after forest harvest (see Bales et al. 2011b). However, a well-integrated approach to forest management considers many values in an area rather than focusing on opportunities to maximize any one value such as water yield.

Water Quality

General condition—

Water from the Sierra Nevada accounts for 60 percent of the total dollar value of all natural products or services produced by the entire region—more than forest products, agricultural products, recreational services, or even residential development (SNEP Science Team 1996). A number of indicators can be used to characterize water quality, including chemical indicators (nutrients, conductivity, pH, metals, pathogens, pesticides, and organics), physical indicators (temperature and sediment), biological indicators such as stream invertebrates, and human use criteria (water that is "swimmable, fishable, drinkable"). A general overview of water quality for major Sierra Nevada river basins is based on publicly available data about various indicators—some quantitative and some qualitative (Timmer et al. 2006).

The conditions of waters in the synthesis area may be affected not only by ongoing human activities but also by legacies associated with historical mining, logging, and construction for homes, roads, and railways. Because of enhanced planning, BMPs, and state and federal regulations, impacts from contemporary development activities are typically much less severe than during historical periods. Even though legacy impacts (e.g., mercury contamination from historical mining, high sediment loads from old and poorly constructed roads, or human health hazards from old septic systems) can be substantial in local areas, they are not a focus of this synthesis. Instead, this chapter focuses on water quality issues that tend to be common across the synthesis area and are a focus for monitoring to maintain or improve water quality. Some human health issues with water quality are briefly discussed in chapters 6.3, "Wet Meadows," and 9.3, "Sociocultural Perspectives on Threats, Risks, and Health").

The U.S. Environmental Protection Agency (EPA), state of California, and Forest Service all use macroinvertebrates as a biological indicator of water quality along with measures of stream physical habitat and water chemistry. An ecological condition assessment (2000 through 2006) of California's perennial wadeable streams provided an overview of water quality for forested lands (Ode 2007). This assessment reported that forests had 80 percent of the monitored stream segments in an **unimpaired** condition, compared with agriculture and urban land uses that had more than 80 percent being in the **impaired** and very impaired condition classes. When a forest stream segment was highly impaired, the following stressors were associated the most with that poor condition: total nitrogen (N) (30 percent), chloride (20 percent), total phosphorus (P) (10 percent), lack of habitat complexity (20 percent), and riparian disturbance and streambed stability (10 percent).

National forests are mostly in the headwaters of Sierra Nevada river basins; often the impaired portion of a river or stream is downstream of the forests or associated with reservoirs or other impoundments. As an example, Timmer et al. (2006) reported the following information for the Kings River watershed. The upper North Fork has been listed as impaired for wetland habitat and flow alterations by the EPA and listed as threatened for habitat, fishery, and freshwater by the California State

Amber Olsson

Figure 6—Sediment is removed, weighed, and sampled to quantify and characterize the annual load in a stream. A sediment basin is emptied at the Teakettle Creek, which is used as a control watershed in the Kings River Experimental Watersheds.

Water Resources Control Board. The Main Fork Kings River is listed by the EPA as impaired for flow alterations and threatened for habitat, fishery, and freshwater. Timmer et al. (2006) listed the probable sources for these detrimental impacts as construction, agriculture or nursery operations, and modification of the streambed. At Pine Flat Reservoir, EPA listed the Kings River as impaired for pathogens, habitat, and freshwater and as threatened for swimming, fishing, fish tissue concentrations, and recreation user days. The **threatened** designation means that the water currently supports designated uses, but may become impaired in the future if pollution control actions are not taken. **Impaired** means that a designated water use is not supported. This report also indicates if a water body is affected by a particular metal and if human exposure is a concern. Similar general condition information exists for all major watersheds in the Sierra Nevada (Timmer et al. 2006).

Stream sediment and erosion—

Undisturbed forests are an important source of the clean water that is necessary for ecosystem health as well as urban and agricultural uses. By altering infiltration rates and evapotranspiration rates and disturbing the soil, forest management activities (including road construction, timber harvesting, site preparation, fuels reduction, and prescribed fire) can increase overland flow rates and sediment yields. Sediment yields are dependent on many factors: climate, topography, soil type, vegetation, historical land use, and the dominant erosion processes (Stednick 2000). Robichaud et al. (2010) provided a review of fuels management effects on erosion. Reported sediment yields from undisturbed forests in the Western United States are 0.007 Mg ha^{-1} (0.003 t ac^{-1}), but values up to 25 Mg ha^{-1} (11 t ac^{-1}) have been reported (Stednick 2000). Hunsaker and Neary (2012) reported an average of 16 ± 21 kg ha^{-1} (0.016 ± 0.021 Mg ha^{-1}) over 7 years of measurement at the undisturbed Teakettle Experimental Forest in the headwaters of the Kings River (Mg = 10^6 grams or 1 metric tonne). Breazeale (1972) reported mean annual sediment rates of 260 Mg km^{-2} (110 t mi^{-2}) for the North Fork of the Kings River, and Dunne and Reid (1985) reported 100 Mg km^{-2} (43 t mi^{-2}) for the Teakettle Experimental Forest.

Research to better understand cumulative watershed effects in the Sierra Nevada has focused on sediment data from roads, timber harvests, and wildfires. On the Eldorado National Forest, MacDonald et al. (2004) found the median sediment production rate from roads was 0.2 kg m^{-2}, nearly an order of magnitude higher than any of the other sources they evaluated (including skid trails, off-road vehicle trails, prescribed fire, and wildfire). In a more recent study of 200 harvest units on the Eldorado, Lassen, Plumas, and Tahoe National Forests, Litschert and MacDonald (2009) found only 15 rills and four sediment plumes on 14 of the units. Only 7 percent of the units had sediment entering the streamside management zones, and the majority of these involved skid trails. They attributed these relatively limited impacts to the increased use and refinement of BMPs and a shift from clearcuts to thinning and group selection. Litschert and MacDonald (2009) suggested that attention should focus on proper construction and postharvest treatment of skid trails for additional reduction of sediment input to streams (e.g., use of proper water bars, ripping to maximize infiltration where soils are compacted, and adequate surface roughness at water bar outlets).

Any type of land use change that causes soil disturbance or vegetation removal (timber harvest, brush clearing for fuels reduction, fire, and road construction, use, and decommissioning) has the potential to cause erosion and subsequent sediment delivery to water bodies. Historically, roads have been considered the primary source of sediment and a significant problem in many landscapes. The potential in the Sierra Nevada for erosion and sediment effects on water quality and aquatic habitat from forest management and wildfire needs to be evaluated with respect to current knowledge and practices. Coniferous forests across western North America are experiencing widespread mortality as a result of drought, insect outbreaks, and wildfire associated with climate change. In many of these landscapes, wildfires and subsequent storms commonly result in the delivery of large, infrequent pulses of sediment to water bodies. Goode et al. (2012) suggested that sediment yields may be roughly 10 times greater with climate-modulated processes than those observed during the 20^{th} century. Although coarse sediment is important for forming geomorphology and aquatic habitat, an order of magnitude increase may have undesirable impacts to aquatic organisms and reservoir management and life expectancy.

Gucinski et al. (2001) synthesized scientific information on forest roads and noted that the Forest Service has a framework (USDA FS 1999) in place for evaluating benefits, problems, risks, and tradeoffs of roads. On November 9, 2005, the Forest Service published the Final Travel Management Rule (70 Federal Register [Fed. Reg.] 216, November 9, 2005; p. 68264–68291), which required designation of roads and trails for motor vehicle use. Implementing travel management plans to meet this requirement should help reduce sediment from roads. Despite the size of the forest road network, road effects have been examined in only a few places, especially in the Appalachians, Pacific Northwest, and Rocky Mountains. Given the wide variability in road history, age, construction methods, and use patterns in relation to topography, climate, and social setting, the narrow geographical scope of these studies limits their extrapolation to other regions or their usefulness in addressing more subtle effects. In forests along the west side of the Sierra Nevada, major roads were built along broad ridges, with secondary roads leading down into headwater areas. In general, Sierra Nevada roads create less erosion and landslides when compared to roads in western Oregon forests, which usually entered watersheds along narrow stream bottoms and then climbed the adjacent steep, unstable hillslopes to access timber extending from ridge to valley floor. Road placement in the landscape, combined with local geology and climate, resulted in different effects of roads on watershed, vegetation, and disturbance processes in the Western United States (Gucinski et al. 2001). A summary of points discussed by Gucinski et al. (2001) about road erosion effects is included here.

- Although mass erosion rates from roads typically are one to several orders of magnitude higher than from other land uses based on unit area, roads usually occupy a relatively small fraction of the landscape, so their combined effect on erosion may be more comparable to other activities, such as timber harvest.

- Roads interact directly with stream channels in several ways, depending on orientation to streams (parallel, orthogonal) and landscape position (valley bottom, midslope, ridge).
- The geomorphic consequences of these interactions, particularly during storms, are potentially significant for erosion rates, direct and offsite effects on channel morphology, and drainage network structure, but they are complex and often poorly understood.
- Encroachment of forest roads along the mainstem channel or floodplain may be the most direct effect of roads on channel morphology in many watersheds.
- Poorly designed channel crossings of roads and culverts designed to pass only waterflow also may affect the morphology of small tributary streams, as well as limit or eliminate fish passage.
- Indirect effects of roads on channel morphology include the contributions of sediment and altered streamflow that can alter channel width, depth, local gradients, and habitat features (pools, riffles) for aquatic organisms.
- Extensive research has demonstrated that improved design, building, and maintenance of roads can reduce road-related surface erosion at the scale of individual road segments.

Although poorly constructed roads in the Sierra Nevada can cause soil erosion and increase sedimentation to water bodies, their effects have not been studied very much in the synthesis area. Two studies do provide recent information for the Sierra Nevada (see box 6.1-4). Road impacts to water quality and aquatic habitat should be less in the future because very little new road construction is expected and knowledge exists about how to construct and maintain roads to lessen impacts. Larger sources of soil erosion may include increased wildfires (see "Debris flows" on page 275), as well as a lack of road maintenance that results in progressive degradation of road-drainage structures and functions (Furniss et al. 1991). A nationwide, multi-site study by Meadows et al. (2008) found that all-terrain vehicle (ATV) traffic on existing trails can increase runoff and sediment, but that proper trail design and maintenance can reduce those impacts.

Goode et al. (2012) projected that climate change would increase sediment yield in semiarid basins, primarily through changes in temperature and hydrology that promote vegetation disturbance (i.e., wildfire, insect/pathogen outbreak, and drought-related die-off). Although their case study took place in central Idaho, it is relevant for the Sierra Nevada because of similarities in conditions, such as coarse-textured, granitic soils and forests on steep mountain terrain. Istanbulluoglu et al. (2004) demonstrated that the mechanism driving higher long-term sediment yields

Box 6.1-4

Master's Research: Roads and Measured Sediment Loads in the Sierra Nevada

In master's degree theses, Coe (2006) and Stafford (2011) provided data on sediment production and delivery from forest roads in mixed, rain-snow climate regimes in the Sierra Nevada. After studying roads for 3 years on the Eldorado National Forest, Coe (2006) found that sediment production rates from native surface roads (median value of 0.14 kg m^{-2} yr^{-1}) were much greater (12 to 25 times) than those from rocked roads (median value of 0.009 kg m^{-2} yr^{-1}), and that sediment from roads with slopes greater than 7 percent was 75 percent higher than for less steep roads. He also found that the annual amount of sediment delivered from episodic gully erosion below road segments was comparable to the amount of sediment being delivered from the native road surface. For comparison, sediment production from unpaved roads in the Sierra Nevada was approximately 67 percent of reported values for the Idaho batholith and only 4 percent of that for the Pacific Northwest. Fifty-nine percent of the road segments that connected to streams were at stream crossings, whereas 35 percent of the connected segments resulted from road-induced gullies. Sediment traveled less than 42 m below the drainage outlet for 95 percent of the road segments. In-sloped roads drained by relief culverts, longer road segments on steeper slopes, and drainage outlets discharging onto hillslopes with compacted soils were usually associated with road-induced gullies. Coe (2006) concluded that road sediment production can be mitigated by rocking native-surface roads, improving and maintaining drainage from roads, reducing the number of stream crossings, and rocking the approaches to stream crossings.

Stafford (2011) performed a study similar to Coe's within the southern Sierra Nevada. She measured an average sediment production rate of 1.8 kg m^{-2} yr^{-1} for native surface road segments in the rain zone; higher than was measured by Coe. At the rain-and-snow and snow-dominated zones, the average sediment production for native surface road segments is more than an order of magnitude lower (0.13 kg m^{-2} yr^{-1}), which is similar to that measured by Coe (2006) in the same type of precipitation regime. There was no significant difference in sediment production from native and gravel-surfaced road segments in the lower elevation area, but in the higher elevation area, the sediment production was 22 percent less for graveled roads. Surprisingly, Stafford (2011) found no significant difference in sediment production and delivery between road segments in a highly erodible soil type (Holland) and road segment less erodible soil types. She suggested that sediment production from forest roads can be reduced by using more than 30 percent gravel cover on native surface roads, minimizing grading, and improving the construction of water bars.

Road maintenance and decommissioning are generally effective and beneficial for water quality but will not mitigate an increase in sediment yields from increased wildfire frequency.

in smaller catchments (<25 km) is rare, postfire erosional events that are typically two orders of magnitude larger than the long-term average yields of 146 t km^{-2} yr^{-1} (determined from cosmogenic dating). Sediment yields from experimental basins with roads are on the order of 101 t km^{-2} yr^{-1}, whereas yields from individual fire-related events in this region are three orders of magnitude greater (10^4 t km^{-2} yr^{-1}). An experiment (Ketcheson et al. 1999) showed that for 1 to 2 km/km^2 of new road, the amount of sediment yield increased by 7 to 12 t km^{-2} yr^{-1} compared with 2.5 t km^{-2} yr^{-1} for the control basin (more than a doubling during the four study years). Goode et al. (2012) concluded that road maintenance and decommissioning are generally effective and beneficial for water quality but will not mitigate an increase in sediment yields from increased wildfire frequency. They also highlighted the substantial uncertainty about the efficacy of postfire treatments for vegetation and hillslope erosion in forest mountain basins (Robichaud et al. 2000) and the growing body of literature discouraging further interference in natural landscape disturbance processes because the dynamic response to such disturbances may help maintain more diverse ecosystems that are more resilient to changed climates (DellaSala et al. 2004). Therefore, work to reduce the magnitude and frequency of wildfire is likely important to influence total sediment yields from forests in the Sierra Nevada drainage basins.

Box 6.1-5

Current Research—Kings River Experimental Watersheds

The Kings River Experimental Watersheds (KREW) is a watershed-level, integrated ecosystem project for headwater streams in the Sierra Nevada (http://www.fs.fed.us/psw/topics/water/kingsriver). Eight watersheds at two study sites are fully instrumented to monitor ecosystem changes. The KREW project was designed to address several of the information gaps for water resources and aquatic ecosystems included in the Monitoring and Adaptive Management Plan for the Sierra Nevada (Appendix E, Sierra Nevada Forest Plan Amendment [USDA FS 2001, 2004]). A few examples of these questions are:

- What is the effect of fire and fuels reduction treatments (i.e., thinning of trees) on the physical, chemical, and biological conditions of riparian areas and streams?
- Does the use of prescribed fire increase or decrease the rate of soil erosion (long term versus short term) and affect soil health and productivity?
- How adequate and effective are current stream buffers (areas on both sides of a stream with restricted uses) at protecting aquatic ecosystems?

Continued on next page

Box 6.1-5 (continued)

Prior to 2000, when KREW was designed, there was no long-term experimental watershed study in the southern Sierra Nevada to guide future land management activities. KREW has a site in the rain-snow zone and a site in the snow-dominated zone of Sierra Nevada mixed conifer. Data have been gathered for a 9-year pretreatment period (Brown et al. 2008; Hunsaker and Eagan 2003; Hunsaker and Neary 2012; Hunsaker et al. 2007, 2012; Johnson et al. 2011a; Liu et al. 2012). Tree thinning was completed in 2012, some prescribed underburns were completed in 2013, and final burns are planned for 2014. The experimental design will allow partitioning of effects between thin only, underburn only, and the preferred treatment of thin and burn.

This research is evaluating the integrated condition of the streams and their associated watersheds (i.e., physical, chemical, and biological characteristics).

- Physical measurements include upland erosion, turbidity (suspended sediment), stream temperature, streamflow, channel characteristics, and weather conditions.
- Chemical measurements for stream water, shallow soil water, precipitation, and snowmelt include nitrate, ammonium, and phosphate (primary biological nutrients); chloride; sulfate; calcium; magnesium; potassium; sodium; pH; and electrical conductivity.
- Biological measurements include stream invertebrates (like dragonflies and mayflies), algae, and riparian and upland vegetation (herbs, shrubs, and trees). Yosemite toads (*Anaxyrus* [=*Bufo*] *canorus*) are also being studied at the Bull Creek site.

Unique aspects of KREW include the following:

- An integrated design of physical, chemical, and biological components being measured at the same locations and at several spatial scales.
- A control watershed that can provide the "natural range" of variability (no roads or timber harvesting).
- A designed comparison of fuels and vegetation for riparian and upland parts of the watersheds.
- Use of a long-term data set for stream invertebrates to evaluate water quality effects after management treatments at a designed before-after control-impact (BACI) experiment.
- A comparison of adult Yosemite toad movement before and during treatments.
- A comparison of rain-snow and snow-dominated watershed function before and after land disturbances.

Nutrients and chemistry—

Water chemistry is of interest for various reasons: human health, aquatic ecosystem condition, and agricultural and industrial uses downstream of the forests. Although the chemistry of water is usually very good within national forests, it is prudent to monitor some characteristics. The EPA and state of California use chloride, specific conductance, and total N and P as indicators of stress in perennial, wadeable streams (Ode 2007). Additional information on chemistry processes in forests can be found in chapters 5.1 and 8.1. This discussion focuses on nitrogen, which is a necessary nutrient for vegetation, but in high enough amounts can be a substantial stressor on both terrestrial and aquatic ecosystems. Sudduth et al. (2013) reported on the significant role that forests have in reducing concentrations of nitrate in stream water, as compared to watersheds that have been developed for urban use or agriculture. Soil solution and stream water nitrate were positively correlated across 40 undisturbed forest watersheds, with stream water values usually being half of the soil solution concentrations. A similar relationship was seen in 10 disturbed (usually clearcut tree harvest) forest watersheds.

Nitrogen is an important indicator of the overall health of a forest, and knowing its concentration over time in atmospheric deposition, vegetation, soils, and stream water provides a useful assessment tool (see chapter 5.1). Usually, Sierra Nevada stream water has very low N concentrations, almost at detection limits (Engle et al. 2008, Hunsaker et al. 2007). However, atmospheric deposition (as discussed in chapter 8.1) is high and moderately high in the southern and central Sierra Nevada, respectively. Nitrogen leaching from soils to water, which can lead to acid conditions and a fine root biomass loss of 26 percent, are expected at N deposition levels of 17 kg N ha^{-1} yr^{-1} (Fenn et al. 2008). High N deposition, coupled with recent findings of high N content in mineral soils and water flowing through forest floor litter in both the western and eastern Sierra Nevada (Johnson et al. 2010, 2011a, 2011b; Miller et al. 2005), are reasons to have long-term measurements on N partitioning in the forest ecosystem.

A recent study by Argerich et al. (2013) highlighted the importance of long-term, uninterrupted stream chemistry monitoring data. They examined long-term data (greater than 12 years) from seven Forest Service experimental forests to see whether stream N concentrations in undisturbed catchments have changed over long periods and if patterns were consistent across the United States. They found high variability both across the country and within individual sites, which suggests that local factors were important. The analysis did not include data from the synthesis area, but two Western sites were included: H.J. Andrews Experimental Forest in Oregon and Fraser Experimental Forest in Colorado. Stream nitrate and ammonium mostly decreased or showed no trend in Oregon, whereas stream nitrate in Colorado showed an increasing trend and stream ammonium was neutral or decreasing. Nitrogen concentrations in wet deposition at both locations usually showed no trend. As mentioned earlier, N is an important indicator of forest health. Nine years of extensive N data will soon be available from the KREW project in the synthesis area; these data can be compared to the trends for these other western watershed studies. This evaluation of N is especially important where deposition levels are high, as they are in the southern Sierra Nevada (see chapter 8.1).

The long-term (decade-scale) effects of fire on watershed chemical balances relate to changes in vegetative cover and include N fixation and the accumulation of elements in aggrading plant biomass (Johnson et al. 2009). Tree mortality, crown scorch, and stand replacement can affect canopy-related processes that are important in watershed balances of water and nutrients, such as interception of precipitation and cloud water, scavenging of aerosols and gases, and transpiration. The changes in nutrient budgets expected soon after fire (first few years) are a result of many processes, as listed by Engle et al. (2008): wind- and water-driven sediment export, changes in the physical properties of soil, dissolution of ash, shifts in soil water pH, changes in microbial biomass and activity, increased decomposition, and changes in biological demand for water and nutrients.

Johnson et al. (1998) stated that fire and postfire N fixation are more important than atmospheric deposition and leaching for N fluxes in most semiarid forests of the Southwestern United States. Exceptions may occur in areas with high atmospheric inputs of N from local air pollution. They argued that existing literature shows that the nutrient cycling paradigm established for humid forest ecosystems, which emphasizes fluxes into and out of the ecosystem by water, needs modification for semiarid forests. Odum et al. (1994) proposed that a realistic paradigm for natural systems is one in which the system is subjected to regular pulses of N from processes such as fire rather than the concept of steady-state and one-dimensional, vertical nutrient cycling. Nitrogen cycling studies in semiarid forests require a long-term, landscape-scale perspective that encompasses episodic fire and periods of intensive postfire N fixation. Johnson et al. (1998) concluded that the frequency of fire and the occurrence and duration of postfire N fixation are crucial factors that determine the long-term productivity of semiarid forest ecosystems and require more study; datasets comparing N fluxes via fire and water at the same site are very rare.

Fire has both short- and long-term effects on nutrient availability and cycling in forest ecosystems. Because of its low volatilization temperature (200 °C), nearly all N in burned biomass is lost in gaseous form, and N losses are disproportionately large compared to carbon (C) losses. Fire can also result in the loss of other nutrients, including sulfur and phosphorus, by volatilization, though to a lesser extent than for N (Raison et al. 1985, 1990). The mean and median values for N losses during wildfire and prescribed fire are 360 and 280 kg ha^{-1}, respectively, which equal approximately 500 to 12,000 years leaching loss of N from semiarid forests (measured rates 0.1 to 0.6 kg ha^{-1} yr^{-1}). Data exist for the east side of the Sierra Nevada (Little Valley, Nevada) to compare fluxes of N via deposition and leaching versus wildfire (Johnson et al. 1997), and they show that at a 100-year interval, wildfire was the dominant factor in long-term N losses, exceeding leaching losses by more than two orders of magnitude (3 to 6 compared with 0.03 kg ha^{-1} yr^{-1}).

Some combination of restoring natural fire frequency, vegetation conditions, or fuel loading to landscapes is usually the goal of prescription burning and forest restoration, thus it is important to understand how watershed balances respond to fire on time scales that match target fire return intervals (FRIs). Tree ring studies indicate that, from 1700 to 1900, natural FRIs in the region of Sequoia National Park averaged 10 to 20 years (Engle et al. 2008); this is an accepted FRI for mixed-conifer forests in the southern Sierra Nevada.

Engle et al. (2008) provided the only new long-term research on stream chemistry before and after prescribed fire in the Sierra Nevada. Their research is for a 16-year paired catchment study in sequoia/mixed-conifer forest in Sequoia National Park. Seven years of prefire chemistry data were compared to 9 years of postfire chemistry data for two adjacent headwater streams—the intermittent Tharps Creek (13 ha) and the perennial Log Creek (50 ha) in the rain-snow zone of the southern Sierra Nevada. This study provides an excellent opportunity for the comparison of water chemistry data collected before and after thinning and burning treatments at KREW; these two long-term research projects should provide the necessary information for resource managers to understand small-stream response and recovery processes to forest restoration practices in the southern Sierra Nevada. Measurement of ecosystem outputs after fire using gauged streamflow is rare (Engle et al. 2008).

Inorganic N was elevated in stream water for 3 years after fire in the Tharps Creek watershed. Increased export of water, SO_4^{-2}, Cl^-, SiO_2, and base cations continued through the end of the study. This loss was calculated to be less than 1 percent of the N, up to one-third of the calicum (Ca) and magnesium (Mg), and up to three-fourths of the potassium (K) contained in the forest floor prior to combustion. Changes in watershed balances indicated that low-end natural FRIs may prevent complete reaccumulation of several elements between fires. However, this result needs to be considered in the context of the high fuel loads that had built up over 120 years. Unfortunately, we do not have data that relate nutrient losses to more historical or natural fuel loads that would have built up under a historical FRI of 10 to 20 years.

Stephan et al. (2012) compared the effects of wildfire and spring prescribed burning on headwater streams in central Idaho. They found that stream nitrate concentrations were elevated by an order of magnitude for three growing seasons after wildfire and appeared to be related positively to the percent of watershed burned in wildfire. They found no significant effects of the much less severe prescribed burning on aquatic N dynamic. Terrestrial plants and in-stream mosses were found to sequester postfire available inorganic N, which Stephan et al. (2012) interpreted as evidence that the systems were adapted to pulses following fire. For that reason, they concluded that rehabilitation measures for N cycling are not generally required after wildfire, and prescribed burning treatments may need to sometimes result in higher severity to stimulate N cycling.

Spatial variability of nutrients on the landscape—
Understanding soil nutrient hot spots is important for water quality and plant nutrition. "Hotspots" are areas (or patches) that show disproportionately high reaction rates relative to the surrounding soil area (or matrix). In semiarid soils, these patches have long been recognized where "islands of fertility" occur near widely spaced shrubs or patches of vegetation (Johnson et al. 2011b). Schimel and Bennett (2004) highlighted the importance of hot spots as sources of nutrients to plant roots, which are otherwise outcompeted by microbes for nutrients in the rest of the soil matrix. A review of data sets for forests in the eastern Sierra Nevada mountains showed N hot spots in soils, resin lysimeters, and resin capsules; other measured nutrients (extractable P, Mg^{2+}, K^{+}, SO_4^{2-}, and Ca^{2+}) also showed positive skew and outliers, but less so than N (Johnson et al. 2010). A recent study at KREW on the western side of the Sierra Nevada showed that nutrient hot spots occur in mixed-conifer forests for nearly all measured nutrients; these nutrients were measured using soil cores, resin collectors, resin probes, and resin capsules in 6 by 6-m plots (Johnson et al. 2011b).

Recent literature shows that the lack of rooting in the O horizon of semiarid forests (during extreme summer drought) results in a spatial decoupling of the processes of decomposition/nutrient mineralization and vegetation uptake, and a lack of the intense competition for N between roots and decomposers (Johnson et al. 2011b). Because of this vertical decoupling, nutrients released during decomposition in O horizons are not immediately taken up and are solubilized by rain or snowmelt, creating solutions with very high inorganic N and P concentrations, which presumably infiltrate the soil at preferential flow paths and contribute to hot spots and possible leaching to surface water (Miller et al. 2005). Nutrient-enriched O horizon interflow has been quantified in both the eastern (Miller et al. 2005) and western (Johnson et al. 2011b) Sierra Nevada. At KREW, values for ammonium-N ranged from less than 0.1 to 456 µmol L^{-1} (<0.1 to 6.3 mg N L^{-1}), NO_3-N concentrations ranged from less than 0.1 to 622 µmol L^{-1} (<0.1 to 8.8 mg N L^{-1}), and ortho-P concentrations ranged from less than 0.1 to 98 µmol L^{-1} (<0.1 to 3.1 mg P L^{-1}); upper values exceeded those found in soil solutions and stream waters at these sites by ten to a hundredfold (Hunsaker et al. 2007).

Stream benthic macroinvertebrates—

This synthesis examines studies in which the ecology of aquatic invertebrates in streams (fig. 7) has been used to monitor or evaluate management actions, stressors from different kinds of disturbance, and natural processes in stream ecosystems. Informed decisionmaking in the Forest Service or other agencies is founded on reliable science, so the studies reported here emphasize practical applications for management planning and design. The studies cited in this section come exclusively from the Sierra Nevada, have not been covered in previous summaries (such as Erman 1996), and include only those with some invertebrate data component.

Development of biomonitoring tools and bioassessment programs in California—

Use of stream invertebrates as biological indicators has become one of the most common water quality tools of regulatory agencies (Allan 1995, Rosenberg and Resh 1993). Invertebrates are especially useful indicators in small, wadeable streams in the Sierra Nevada, and in headwaters and fishless or intermittent streams. These organisms can be used as sentinels to show how much the ecological integrity of watersheds is changing, and how effective management may be in protecting these natural resource values. Adaptive management requires monitoring tools for tracking the progress of desired outcomes. Bioassessment sampling by California's Surface Water Ambient Monitoring Program (SWAMP) provides extensive new data on community composition and indicators of environmental quality. The database, which is under construction, compiles surveys from portions of the Sierra Nevada, and these will be used to develop quantitative numeric biological objectives for use in water quality monitoring programs of the state of California (Ode and Schiff 2009). The Southwest Association of Freshwater Invertebrate Taxonomists has summarized various regional taxonomic updates and species descriptions from the broader region.[7] Online documents provide lists by state, taxonomy resources, compilation of tolerance values, and functional feeding groups as sources for bioassessment, but those documents cannot currently be compiled just for the Sierra Nevada (although the SWAMP database can). Benthic macroinvertebrates are being used in a probabilistic sampling design for monitoring

[7] Southwest Association of Freshwater Invertebrate Taxonomists, http://www.safit.org.


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Figure 7—Benthic macroinvertebrates are collected from streams with nets, woody material is removed, and organisms are sorted in the field before being preserved and taken back to the laboratory for identification.

of status, trend, and health in response to management activities in the Pacific Southwest Region of the Forest Service.

Hawkins et al. (2000) provided the foundation for developing predictive models (RIVPACS) for assessing stream health in the Sierra Nevada and Klamath Mountains, and those models are now being used in SWAMP to establish biological objectives for streams across California. Results suggest that logged sites had subtle losses of diversity (10 percent) compared to reference areas (<5 percent of the basin logged), with losses related mostly to reduced riparian cover rather than amount of area logged or number of roads (logging intensity and type were not specified in the analysis).

Herbst (2004) provided an overview of stream survey work done in the Sierra Nevada through 2002, including initial steps in identifying reference stream standards, monitoring of grazing and mining practices, and gaps in understanding of stream invertebrate ecology. An eastern Sierra Nevada multimetric index of biotic integrity (IBI) and predictive models (RIVPACS) show how differing methods and analytic tools are robust in giving the same assessments of loss of stream health related to channel modifications or livestock grazing (Herbst and Silldorff 2006).

Natural patterns of variation in stream communities in space and time—Carter and Fend (2001) found that differences in the richness of invertebrates in riffles and pools appear to depend on annual discharge regime and are more pronounced during low discharge years and disappear when flow is higher. This study, which took place on the Merced River in the Yosemite Valley, suggests that differences in erosional and depositional features between riffles and pools diminish when flows increase, so communities become more similar. An implication of this is that it is possible that flow regulation may influence the natural variations in habitat-based diversity and that channelization (eliminating riffle-pool geomorphology) may also produce less diverse assemblages of aquatic life and more limited ecosystem processes (such as nutrient recycling, productivity, organic matter transport, conversion, and decomposition). Beche and Resh (2007) found that traits related to environmental adaptations vary in response to gradients of flow between years, from dry to wet conditions. Traits that provide adaptation to drying (e.g., desiccation resistance, aerial respiration) were more common in drought years, whereas traits permitting survival during high flows (e.g., flat body shape, drift dispersal) were more common in wet years. Prolonged drought or wet conditions result in shifts in trait composition. Despite this relationship, traits among taxa are often sufficiently redundant that taxa can be replaced without losses in trait diversity. Consequently, it may be more difficult to conserve species diversity than trait diversity in the face of a changing climate regime.

Erman (2002) studied the invertebrates of spring and springbrook (outflow) communities over 20 years to describe the biota and physical/chemical properties of Sierra Nevada cold springs. Results showed the individualistic nature of springs even within the same stream basin. Spring invertebrate assemblages differed greatly from one spring to another, as did timing of insect emergence and abundance of species. Invertebrate species richness was greater in deeper, more permanent springs, which were distinguished by high concentrations of dissolved ions, especially calcium. Spring permanence was also determined by direct observations over time, measurement of discharge variability, correlation of discharge with ionic concentration, and water dating. This study demonstrated the high conservation value of spring habitats and the high levels of diversity that can serve as a biodiversity refuge in cold-water environments.

***Fire effects*—**Beche et al. (2005) found minimal effects from prescribed fire on stream invertebrates in a Sierra Nevada study. Prescribed fire altered BMI community composition only within the first weeks postfire, but there were no lasting (1 year) impacts on BMIs. Densities and percentage of sensitive taxa were significantly reduced after an intense wildfire on Angora Creek in the Lake Tahoe basin, but there were no consistent changes in taxonomic richness or diversity (Oliver et al. 2012). Canopy cover and bank stability declined dramatically following the wildfire and substrate also changed substantially, with fine sediment more abundant and cobble less abundant postfire. There were large reductions in relative abundances of shredder and scraper taxa, whereas collector-gatherer abundances increased. Community composition shifted away from prefire configurations, and continued to diverge in the second year following the fire. Scores from a regionally derived IBI were variable, but overall they were much lower in postfire samples and did not show recovery after 2 years. This study demonstrated substantial postfire effects to aquatic ecosystems even in the absence of large flooding or scouring events, and it showed that these effects can be transmitted downstream into unburned reaches. These findings, when compared to those from Beche et al. (2005), suggest that fire effects are strongly related to fire intensity.

***Forest management practices*—**Although stream invertebrates have been adopted as good water quality indicators for the Forest Service, little published information exists regarding effects of mechanical forest management practices (road building and maintenance, tree thinning and commercial harvesting, tractor piling of slash and burning) on stream invertebrates in the Sierra Nevada. A few publications exist on prescribed fire effects on stream invertebrates (see previous discussion). The usefulness of stream invertebrates for monitoring aquatic ecosystem condition and associated information gaps were recognized in the Adaptive Management Plan, Appendix E, of the Sierra Nevada Framework (USDA FS 2001, 2004), and one new research experiment exists (see box 6.1-5 on page 290). McGurk and Fong (1995) found that there was reduced diversity and increased dominance by common taxa in stream invertebrate communities in the Sierra Nevada where equivalent roaded area (ERA, a metric of cumulative land disturbance associated with timber harvest and roads) exceeded 5 percent of a watershed.

***Flow regulation and impoundments*—**Aquatic organisms have evolved life history strategies to take advantage of high flood predictability and associated seasonal processes. The timing of the spring snowmelt recession and the shape of the recession hydrograph contribute to reproductive cues for many riparian and aquatic species, such as cottonwoods, willows, mayflies, amphibians, and salmonids. Yarnell et al. (2010) developed a conceptual model about snowmelt recession that provides some testable hypotheses about regulated flows in streams and climate change effects on the hydrograph. As flows gradually decrease through spring, the hydrograph passes through windows of biological opportunity at magnitudes that support habitat (i.e., availability) in sufficient condition (i.e., suitability) for species persistence. Shifts in the timing of the recession or changes to the shape of the recession hydrograph that preclude suitable habitat during a particular species' window of reproduction can lead to a lack of success. Shifts in the timing of the recession may push periods of reproduction out of phase with the availability of suitable habitat. Shifts in the rate of the recession affect both abiotic and biotic conditions, creating the largest observed changes to the stream ecosystem. The effects of climate warming on aquatic ecosystems in Mediterranean-montane climates will be profound, with shifts in each of the three primary components of the recession (magnitude, timing, and rate of change). Shifts in the timing at the start of the recession and decreases in the magnitude of the flow, coupled with a shorter duration resulting from a relatively small increase in the rate of change, will alter in-stream and riparian species compositions, forcing cold-water aquatic species to inhabit higher elevations, and leading to a higher abundance of nonnative species. Shifts in the spring recession as a result of flow regulation can create similar patterns. On the basis of this conceptual model, the authors found that managed hydrographs with a flashy, short-duration spring snowmelt recession overlying a steady base flow can create channel conditions reflective of the two observed extremes in discharge, flood and base flow. Aquatic and riparian species will be reflective of the homogeneous channel conditions and lack diversity. Rehn (2008) used a reference stream dataset to establish a multimetric IBI for Sierra Nevada west-slope streams to evaluate the effects of hydropower releases on BMIs. Degradation of the invertebrate community (quantified through comparison with upstream sites) was found within 3 km of dams and was mostly related to flow regulation and constancy below dams (i.e., loss of natural flow regime). Rehn's findings support the conceptual model and hypotheses in Yarnell et al. (2010).

***Effects of floods*—**Herbst and Cooper (2010) evaluated conditions before and after the 1997 New Year's Day floods for 14 small, headwater streams in the eastern Sierra Nevada. The streams showed loss of bank stability and riparian cover resulting from scour. Densities of BMIs in previously disturbed habitats increased, with increases mainly consisting of small opportunistic species (rapid-growing colonizers) feeding on fine particulate organic matter. These results show a shift to common taxa with generalized food habits. Undisturbed reference streams changed little from 1996 to 1997, suggesting that these more diverse and stable communities persist even in the face of short-term extreme flows, and are important biodiversity refugia for downstream habitats where flooding may be more severe. These results highlight the importance of protecting the integrity of less disturbed headwater stream habitats.

Introduced invasive species—A paired watershed study of fishless streams with adjacent trout-stocked streams in Yosemite National Park showed that trout reduce native grazers and permit more dense growth of algae on stream rocks (Herbst et al. 2008b). This study showed losses of 20 percent of BMI taxa richness, mostly as losses of endemics and native montane species, in the presence of trout. The higher algae cover in streams with nonnative trout corresponds to more collector-gatherers and fewer predators and grazers. Conserving biodiversity and restoring natural food webs likely depends on removal of introduced trout.

Conserving biodiversity and restoring natural food webs likely depends on removal of introduced trout.

The New Zealand mud snail (NZMS) has caused significant disruptions in stream food chains across many trout streams of the Western United States. Herbst et al. (2008a) suggest that specific conductance levels may control which streams NZMS can colonize. In streams with specific conductance below 50 µS, snails do not survive, and at levels below 200 µS, their growth and survival are inhibited. Invasive herbivores like NZMS can have strong top-down and bottom-up influences on invaded ecosystems, but these impacts can be extremely variable across time and space.

Information gaps—The Sierra Nevada Ecosystem Project (SNEP) provided a summary on the status of invertebrates, highlighting high endemism (among caddisflies and stoneflies in particular) and dependence of diversity on habitat quality, but it provided little information on ecological structure, function, and ecosystem processes in streams (Erman 1996). The distribution and abundance of aquatic invertebrates in the Sierra is still mostly unknown. Many studies are localized at research areas (see fig. 1 in chapter 1.5), such as the Sierra Nevada Aquatic Research Laboratory (SNARL) on Convict Creek, Sagehen Creek Experimental Forest, the Blodgett Forest Research Station, and KREW, or where restoration project monitoring has occurred. Recent sampling done under the California SWAMP provides more survey data, but important geographic gaps remain. High elevations, intermittent streams, springs, remote regions, and whole catchments remain poorly characterized (most surveys represent only 100- to 200-m reaches within larger basins). Data from some studies show an emerging pattern of north-south distinctions in biogeography.

Researchers still do not know a lot about the biodiversity of aquatic invertebrates in the Sierra Nevada. Erman (1996) reported that species-level information was lacking for many taxa and that inventories or lists were incomplete; this statement remains true. She reported approximately 400 taxa from streams and lakes, approximately 20 percent of which were endemic to the Sierra Nevada (see box 6.1-6 for an update). Further genetics research is likely to reveal unknown biodiversity. For example, studies of the Cascades stonefly (*Doroneuria baumanni*), which is the most common large predatory insect in the high Sierra Nevada, show genetic variation in isolated Sierra Nevada and Great Basin populations (Schultheis et al. 2012).

Box 6.1-6

Ongoing Aquatic Macroinvertebrates Research in Eastern Sierra Nevada Streams

About 400 surveys in streams of the eastern Sierra Nevada have contributed to a database developed at the Sierra Nevada Aquatic Research Laboratory (SNARL) with more than 500 distinct taxa from about 200 stream surveys (see http://vesr.ucnrs.org/pages/Herbst_Research.html for more on this database). More comprehensive listings of taxa from high-elevation streams in the western Sierra Nevada, and at species-level resolution (many are only at the genus level currently), will likely place this total closer to 1,000 species or more. Reference specimen collection cataloguing is underway at SNARL for hundreds of surveys in the Sierra Nevada and Great Basin.

Strategies to Promote Resilience of Water and Aquatic Ecosystems

Because fuels reduction activities are expected to reduce the risk of wildfires, they can be considered as an opportunity to maintain or improve water quality because wildfires can have significant impacts through increased sediment loads and phosphorus concentrations and debris flows.

Recent science indicates that watershed management should be guided by an understanding of disturbance regimes that recognizes the nonequilibrium nature of ecosystems (Bisson et al. 2003, Rieman et al. 2010, Wallington et al. 2005, Welsh 2011, and chapter 1.2, “Integrative Approaches: Promoting Socioecological Resilience”).

Promoting Favorable Waterflows

Given changing climate conditions, maintaining or improving water quantity and quality in low-order streams through fuels reduction activities (mechanical thinning and prescribed fire) can be considered as a management opportunity rather than a constraint. For water quality, this approach requires a balancing of short-term, low-intensity effects against high-intensity effects from more extreme events. For example, potential for extreme wildfires is increasing with climate change. Because fuels reduction activities are expected to reduce the risk of wildfires, they can be considered as an opportunity to maintain or improve water quality because wildfires can have significant impacts through increased sediment loads and phosphorus concentrations and debris flows. Also, with warming temperatures, trees are expected to decrease soil moisture and increase evapotranspiration, thus leaving less water for movement to streams; mechanical thinning of trees and low-intensity underburning of vegetation would reduce evapotranspiration and help maintain soil and stream water amounts. The strategic orientation of PSW-GTR-220 (North et al. 2009) and PSW-GTR-237 (North 2013), which focuses on restoring heterogeneity and landscape-scale ecological processes, can be extended to aquatic ecosystems. The incorporation of key hydrologic and nutrient processes as treatment objectives facilitates a more holistic forest restoration effort.

Because N concentrations are a good indicator of forest health (both productivity and stress), it would be beneficial to have a few locations where N is measured periodically in wet and dry atmospheric deposition, mineral soil, and soil and stream waters. Such measurements are most likely to be done at research locations (fig. 1 in chapter 1.5), and they could continue through collaborative activities between research and forest management (examples include studies such as those reviewed in Argerich et al. [2013], Sudduth et al. [2013], and ongoing at KREW [see box 6.1-5]).

The scientific literature indicates that increased wildfire impacts in the future are a concern in terms of soil erosion, sedimentation, and impacts to water resources (Goode et al. 2012). To mitigate potential impacts to water bodies, it is important to evaluate overall watershed potential for erosion and sedimentation resulting from wildfires, as well as fuels reduction activities; timber harvest; and road construction, use, improvement, and decommissioning. Some research exists and can be augmented with monitoring data from future forest management projects.

Addressing roads—

Although the ability to measure or predict the hydrologic consequence of building or modifying a specific road network might be limited, general principles and models are available to decrease the negative effects of roads. These principles can be useful during upgrading or decommissioning of roads to meet various objectives. A list of principles provided by Gucinski et al. (2001) includes the following:

- Locate roads to minimize effects by conducting careful geologic examination of all proposed road locations.
- Design roads to minimize interception, concentration, and diversion potential, including measures to reintroduce intercepted water back into slow (subsurface) pathways by using outsloping and drainage structures rather than attempting to concentrate and move water directly to channels.

- Evaluate and eliminate diversion potential at stream crossings.
- Design road-stream crossings to pass not just water but also woody debris, sediment, and fish.

Assessing water quality using stream macroinvertebrates—
Much work remains to be done to characterize the health of Sierra Nevada streams using stream invertebrates. Mapping invertebrate distributions would provide a basic understanding of biodiversity patterns, hot spots, and biogeographic regionalization of aquatic invertebrate fauna. Future planning efforts will benefit when forestwide analyses and multiforest syntheses can be done on stream invertebrate data and stream physical properties data (Stream Condition Inventory) that already exist for the synthesis area.

Spatial analysis of watersheds, from headwaters to major river systems, would provide information on how the ecological health of interconnected stream systems changes as a function of land use disturbances, habitat fragmentation, and reservoirs/dams. Combining data from SWAMP, the regionwide Management Indicator Species Program, the Forest Service Pacific Southwest Research Station and other organizations like SNARL could yield valuable information to improve assessments of cumulative watershed affects. Furthermore, distribution data on fish and amphibians could be combined with the accumulating data on aquatic invertebrates to assist in identifying areas of high biological value (richness, endemism, index of biological integrity) for conservation management to provide a means for identifying and protecting reference areas of biological integrity. Knowledge about forest stream condition (as shown by Ode 2007) can improve substantially if invertebrate monitoring occurs at selected management projects that have not yet proceeded to an implementation phase. It is possible to use bioassessment tools to gather data using a before-after control-impact (BACI) statistical design to evaluate project outcomes in terms of aquatic invertebrate indicators of desired ecological improvements. These case histories could provide a foundation for adaptive management (monitoring informs decisions on how to proceed with actions) and advance restoration as a prescriptive science (what works and where and how long it takes) (see box 6.1-5 about KREW). Opportunities exist at the Sierra Nevada Adaptive Management Project, the Dinkey Collaborative Forest Landscape Restoration Project on the Sierra National Forest, and for similar projects where planned management affords an opportunity to learn more about prescribed fire, selective logging practices, or fuels reduction in protecting aquatic ecosystems within the context of forest ecosystem health.

Promoting Resilience of Aquatic Ecosystems

Landscape-scale consideration of tradeoffs in managing forests for wildfires— Although wildfire can have negative or neutral impacts on fish, wildfire-related disturbances can also help to maintain diverse and productive habitats (Rieman et al. 2003). Many of the processes associated with wildfire disturbance have potential to benefit aquatic habitats, including contributions of nutrients, wood, and coarse substrate; reorganization of in-channel habitat structure; increases in streamflow; and increases in temperature, light, and in-stream food production (in systems that are below optimum growth levels) (Gresswell 1999). The overall impact of a wildfire on aquatic organisms depends on the specific context of that event; however, scientists have come to a general conclusion that fishes in large habitat networks are more likely to benefit even after relatively severe wildfires, whereas fishes in small, isolated systems are more vulnerable to losses (Rieman et al. 2010). A recent synthesis of short-term effects of wildfire on amphibians yielded similar conclusions, specifically that (1) wildfire can provide important benefits for amphibian diversity overall; (2) wildfire can pose threats to small, isolated, or stressed populations, particularly in the Southwest; and (3) negative effects on populations or individuals are greater in fire-suppressed forests, and high-severity burns cause greater negative effects on populations or individuals (Hossack and Pilliod 2011). In addition, some research suggests that native fishes may be better adapted to fire-associated disturbances than nonnative competitors. This relationship, combined with the potential for wildfire to extirpate or greatly reduce nonnative trout species, suggests that wildfires, even uncharacteristically severe ones, could provide important opportunities to enhance native species.

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Forests may be treated to reduce the threat of uncharacteristically severe wildfire or to emulate some of the desired effects of natural disturbances, consistent with the principle of disturbance-based management (see chapter 1.2). Burton (2005) and Rieman et al. (2003) emphasized the need to carefully weigh the costs and benefits of treatments, because road networks and stream crossings that may be used to implement the treatments have potential to perpetuate impacts to streams and aquatic populations. Collectively, these studies recommend spatially explicit analysis of risks for aquatic species in the synthesis area.

Stream and riparian restoration to promote resilience to climate change— Restoration of stream and riparian ecosystems is a core strategy for enhancing ecological resilience to postfire impacts and climate change (see chapter 1.1), because of the important roles of streams in providing linear habitat connectivity, laterally connecting aquatic and terrestrial ecosystems, and creating thermal refugia for cold water species such as salmonids (Seavy et al. 2009).

***Promoting connectivity*—**Increasing longitudinally connected networks from mainstem rivers to headwater tributaries has been recommended to help native trout species cope with the threat of wildfire under projected climate change (Haak and Williams 2012). However, because many remaining native fish populations have been purposefully isolated from nonnative invaders, efforts to reconnect isolated populations could leave populations exposed to potential invaders (Fausch et al. 2009). For that reason, Williams et al. (2009) observed that a shift away from an isolation strategy would require increasing efforts to reduce nonnative fishes.

***Ameliorating high temperatures*—**An analysis by Wenger et al. (2011) suggested that proactive trout conservation strategies in the face of climate change should include ameliorating high temperatures along with reducing interactions with non-native species. Stream restoration has potential to ameliorate increases in stream temperatures, reductions in base flows, and other projected effects of climate change. Restoration efforts can promote vegetation growth and channel narrowing that reduce solar exposure, and they can also promote channel complexity and associated hyporheic exchange (where surface water mixes with shallow groundwater) by developing riffles, secondary channels, and floodplain sediments (Hester and Gooseff 2010, Kondolf 2012, Poole and Berman 2001). As an example of this strategy, researchers are investigating how wet meadow restoration could increase summer discharge and reduce water temperatures to help sustain California golden trout (*Oncorhynchus mykiss aguabonita*) (see chapter 6.3).

Restoring flow regimes on regulated rivers—

Management of reservoirs and regulated rivers was not a focus of this synthesis, although these systems are clearly important as a source of ecosystem services in terms of recreation opportunities, flood control, water supply, and power generation (Null et al. 2010). Recent research demonstrates that the cross-cutting theme of disturbance-based management relates strategies for river management to conservation of endemic species. A recent study examined time series data for the foothill yellow-legged frog (*Rana boylii*) and California red-legged frogs (*R. draytonii*); the findings suggest that flow management that emulates natural flow regimes is likely to promote resilience of populations of these native frogs (Kupferberg et al. 2012). Dams generally reduce overall heterogeneity in flow regime, while also permitting unnaturally rapid changes in flow, such as sharp decreases in flow following spring runoff (Kupferberg et al. 2012, Moyle and Mount 2007). Climate change may also alter hydrologic regimes in ways that are similarly detrimental to these aquatic species by reducing snowpacks, inducing earlier and more rapid snowmelt in the spring, and by extending periods of low flow in the summer and fall (Null et al. 2010). Those changes may harm species that are adapted to gradual spring recession flows (Yarnell et al. 2010), and also reduce whitewater boating opportunities. Kupferberg et al. (2012) reported a negative association between hydrologic modification, as suggested by dam height, and persistence of foothill yellow-legged frog populations. In regulated rivers, a management strategy to protect native riverine species is to emulate natural flow patterns, especially by limiting rapid fluctuations in water levels; this strategy could benefit the species directly, by helping them avoid mortality, and perhaps indirectly, by promoting changes in channel morphology and in-stream habitat (Yarnell et al. 2012). Another component of a management strategy to benefit these species could be meadow restoration efforts, to the extent that they can extend base flows longer into the summer (see chapter 6.3).

Restoring fluvial processes—
Researchers have emphasized the fundamental importance of restoring fluvial processes in dynamic stream systems (e.g., by removing levees or other artificial structures) as a strategy to restore fluvial form and aquatic habitats (Kondolf 2012, Kondolf et al. 2012). This approach shares close parallels with the idea of restoring fire as an ecological process, and as such, its success will depend on careful articulation of goals and understanding of the ecological and social context of the system. In particular, the more passive approach of setting aside a "zone of liberty," where natural riverine processes of deposition and erosion can occur freely, is more likely to succeed in relatively large and powerful streams or rivers (Kondolf 2012).

Researchers have emphasized the fundamental importance of restoring fluvial processes in dynamic stream systems as a strategy to restore fluvial form and aquatic habitats.

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