RICHARD KATTELMANN
University of California Sierra Nevada
Aquatic Research Laboratory
Mammoth Lakes, California

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Hydrology and Water Resources

ABSTRACT

Water is a critical component of the resource issues and conflicts of the Sierra Nevada. Almost every environmental dispute in the range involves water as principal or secondary concern. Most human activities have some potential to influence the quantity, distribution, or quality of water.

Rivers of the Sierra Nevada appear to have shown remarkable resiliency in recovering from the gold mining era; however, so few channels were left untouched by historic disturbances that reference streams in a completely natural state may not exist for comparison. Water management structures developed concurrently with hydraulic mining and have since come to dominate the flows of water from the Sierra Nevada. Few river systems in the range have natural flow regimes over much of their length. In most river basins, this active management of the water itself affects the annual water balance, temporal distribution, flood hydrology, minimum flows, and water quality much more than any human disturbance of the landscape. Ironically, the primary benefits to society of water from the Sierra Nevada cause the primary impacts. By trying to serve the so-called highest beneficial uses, domestic water supply and production of food and power, we have caused the greatest impacts.

Watershed disturbance in the form of mining, road building, logging, grazing, fire, residential development, and other uses has altered vegetation and soil properties in particular areas. Where these disturbances have altered a large fraction of a watershed, including areas near stream channels, flows of water and sediment may be changed significantly. Nevertheless, major changes in hydrologic processes resulting from watershed disturbance have been noticed in only a few streams. More extensive changes are suspected, but they have not been detected because of the minimal monitoring network that is in place. Proposed programs for reducing the amounts of fuels in forests have potential for significant aquatic impacts; however, catastrophic wildfire carries far greater risks of grave damage to aquatic systems.

INTRODUCTION

> 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.
>
> Farquhar 1965, 1

Water is central to the resource issues and conflicts of the Sierra Nevada. Changes in water availability, stream-flow quantity and timing, flooding, quality of surface and ground water, aquatic and riparian habitat, soil erosion, and sedimentation have occurred throughout the range as results of land disturbance and resource management (Kattelmann and Dozier 1991). However, the magnitude of such changes, their relative importance, and the ability of natural and human communities to adapt to or recover from alterations in hydrologic processes in the Sierra Nevada are largely unknown. Concern about degradation of water quality is widespread in public reaction to past and proposed resource management activities. Californians need to know whether their primary water source, the Sierra Nevada, is functioning well in general and what problems need attention.

The Sierra Nevada generates about 25 km^3 (20 million acre-feet [AF]) of runoff each year out of a total for California of about 88 km^3 (71 million AF) or about 28% (Kahrl 1978; California Department of Water Resources 1994). This runoff accounts for an even larger proportion of the developed water resources and is critical to the state's economy. The rivers of the Sierra Nevada supply most water used by California's cities, agriculture, industry, and hydroelectric facilities. The storage and conveyance systems developed to utilize the water resources of the Sierra Nevada are perhaps the most

Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources, 1996.

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extensive hydrotechnical network in the world. Major water supply systems have tapped the Tuolumne River for San Francisco, the Mokelumne River for Alameda and Contra Costa Counties, eastern Sierra streams for Los Angeles, and the Feather River for the San Joaquin valley and other parts of southern California. Irrigated agriculture throughout California consumes more than the annual runoff of the Sierra Nevada and accounts for more than 90% of consumptive use in the state (U.S. Geological Survey 1984; California Department of Water Resources 1994). More than 150 powerhouses on Sierra Nevada rivers produce about 24 million megawatt-hours of electricity per year (see Stewart 1996). Operations of most of the water projects are quite sensitive to fluctuations in climate over periods of a few years. Sierra Nevada rivers support extensive aquatic and riparian communities and maintain the Sacramento–San Joaquin Delta estuary ecosystems (see Jennings 1996; Moyle 1996; Moyle and Randall 1966; Moyle et al. 1996; Erman 1996).

Perhaps the most common perception of water from the Sierra Nevada is no perception at all, merely benign ignorance. For many, water is something that appears at the kitchen faucet, showerhead, garden hose, or is a choice among bottled beverages. Water rarely makes the general news except in times of serious shortage or excess. Agricultural and urban communities of the Central Valley that are dependent on water from Sierra Nevada rivers probably have the greatest direct interest in water issues, but they are chiefly concerned about the amount delivered and how fisheries policies might affect those deliveries. Most residents of the Sierra Nevada are probably knowledgeable and concerned about local water supplies and ground water but are not known to harbor any common misperceptions about the local resource, just a shared hope that there always will be enough water available. People in cities benefiting from water supplies exported from the Sierra Nevada are concerned about quantity and quality of water at the tap, but many are unsure about the source of their water. Visitors to the Sierra Nevada are usually concerned about the aesthetic qualities of water that they see. Environmentally conscious segments of the public may believe the water resources of the Sierra Nevada are substantially degraded. Serious water problems in parts of the Sierra Nevada and throughout the country may be extrapolated and perceived as occurring throughout the Sierra Nevada. For example, if poor logging practices in the Pacific Northwest are initiating landslides and ruining fish habitat, then some people may assume the same things are happening within the Sierra Nevada. Water issues highlighted in popular books (e.g., Reisner 1986; Postel 1992; Doppelt et al. 1993; Palmer 1994) are often assumed to apply to the Sierra Nevada but may not be of similar severity.

Water flowing from the Sierra Nevada has far-reaching effects. On the western slope, runoff naturally flowed through the Central Valley of California and San Francisco Bay to the Pacific Ocean or, in the south, contributed to Tulare and Buena Vista Lakes. On the eastern slope, streams flowed toward the terminal lakes of the western Great Basin. In all cases, the waters of the Sierra Nevada enriched the lands through which they flowed. In the past century, the fluid wealth of the mountains has been extended well beyond natural hydrographic boundaries through engineering projects to distant agricultural and urban areas. Electricity generated from falling water in the Sierra Nevada and distributed through the western power grid affects distant communities. Crops grown with and containing water precipitated over the Sierra Nevada are sold around the world. The recreational and aesthetic qualities of Sierran rivers and lakes attract visitors from throughout the United States and the world. Artwork portraying water in the Sierra Nevada is found around the globe; for example, a watercolor mural in traditional Chinese style of waterfalls in Yosemite Valley hangs in the Taipei airport as an example of Chinese scenery.

Water has played a critical role in Euro-American affairs in the Sierra Nevada since the discovery of gold in a channel leading to a water-powered sawmill in 1848. Water was essential to large-scale gold mining and processing. Water development for mining led to one of the nation's earliest major decisions in environmental law (that halted hydraulic mining) and to our intricate network of hydrotechnical structures that transfer water from the Sierra Nevada to farms, cities, and powerhouses. Conflicts over water from the Sierra Nevada are likely to be a continuing part of the California scene. Water is simply too valuable to society and all forms of life to be anything but a high priority for resource policies and management. Water eventually emerges in almost all environmental disputes, even when the debate starts on some other distinct issue. All parties to the dispute can usually agree that water is an influence on or is influenced by the original issue. Water is tied to all other issues considered by SNEP, with some links more obvious than others, but it is literally an integral component of the ecosystem approach.

GENERAL STATE OF KNOWLEDGE

Despite the importance of water to California, there have been remarkably few integrative studies of water resources in the state or the Sierra Nevada. State agencies have issued reports about statewide water matters for more than a century (e.g., Hall 1881; Conservation Commission 1913; California Department of Public Works 1923). The first California Water Plan was released by the Department of Water Resources in 1957. Originally a description of proposed water projects, updates to the California Water Plan have evolved into a more thorough evaluation of water supply, demand, and management (e.g., California Department of Water Resources 1994). Comprehensive descriptions of water in the state appear in books by Harding (1960), Seckler (1971), and the Governor's Office of Planning and Research (Kahrl 1978). The history of water development in California is treated by Hundley (1992). The condition of California's rivers is assessed by the California State Lands Commission (1993). Possible scenarios of the future of water resources in California have been developed by the California Department of Water Resources (1994) and the Pacific Institute (Gleick et al. 1995). Although all these books deal with the Sierra Nevada as a critical part of the California waterscape, and books devoted to the Sierra Nevada (e.g., Peattie 1947; Lee 1962; Johnston 1970; Webster 1972; Bowen 1972; Palmer 1988) at least mention water resources, a thorough treatment of water in the Sierra Nevada has yet to be written. Thousands of articles, chapters, and reports address the various aspects of hydrology and water resources in the Sierra Nevada, but there has been little synthesis of this vast work. The isolated, topical work provides a wealth of information about specific details but does not inform society about the context of that work at the scale of the mountain range or even of a river basin. In addition, there are serious gaps in the collection of information about Sierra Nevada waters. Although knowledge is far from complete for most aspects of the water-resource situation, the most troubling gap is the virtual absence of experimental research on hydrologic impacts of land management activities. Because of this near lack of local research, we usually had to infer the likely consequences of disturbance from studies done outside the Sierra Nevada. In addition, the state does not have a thorough description of each river basin that would be adequate for environmental assessments. Comprehensive lists of environmental problems in each river basin do not exist. There is no consistent method for characterizing watersheds. Absence of consistent criteria for evaluating ecological conditions along streams or in watersheds inhibits assessment of management consequences or need for restoration (California State Lands Commission 1993).

OVERALL APPROACH AND SOURCES

This assessment was primarily a literature review augmented with the author's experiences throughout the Sierra Nevada over the past two decades and a few weeks of specific field checking during the SNEP period. The libraries of the University of California and the Water Resources Center Archives at Berkeley, in particular, were critical to the effort. Offices of the national forests in the Sierra Nevada also provided a wealth of documents. Other materials were provided by dozens of agencies and individuals. Newspapers were essential sources of current information. Interviews with agency personnel and private parties augmented the written word. The primary challenges were to compile and synthesize the diversity of material. The quantity and quality of information gathered varied widely between river basins throughout the range. Important sources were undoubtedly overlooked because of ignorance of their existence and inability to actually locate all known sources. One of the critical assumptions of this assessment was that the reported material was indeed reliable. Multiple sources of information that were consistent provided greater confidence in most material. Information was organized by resource, by impact, and geographically by river basin. Use of natural hydrologic areas was a central tenet of this effort. Consideration of nested catchments from headwaters to large river basins provides a logical hierarchy that makes physical and ecological sense. Watersheds are becoming a more common unit of analysis and planning. The California Resources Agency is organizing many of its programs on a watershed basis and has adopted a watershed delineation scheme called Calwater. This system was used in this study and by other parts of SNEP. River basins and major streams of the study area are identified in figures 30.1–30.3.

Attributes of Water

There are several attributes of water and streams that are impacted by management activities. The physical attributes are briefly described in the following paragraphs (see Moyle 1996; Moyle and Randall 1996; Erman 1996; Moyle et al. 1996; Jennings 1996 for biological impacts). The present study did not perform any systematic analyses of these attributes. Such analyses (within the constraints of readily available data) would not provide clear indications of the health of the hydrologic system of the Sierra Nevada. Instead, synthesis of existing analyses originally performed for various other purposes provided the basis of this assessment.

Stream flow (or stream discharge) is the most fundamental aspect of watershed hydrology. Stream flow will usually be addressed in this assessment just as a concept: volume of water passing by a point on a stream over some period of time. Fortunately, this concept is also measured at hundreds of sites within the SNEP study area. However, the number of sites with data useful to this study is much more limited, numbering in the dozens. Most stream-flow measuring stations are located in association with some water management project rather than for scientific study. Therefore, most information is available on highly regulated streams that suggest little about hydrologic response to changes in the landscape other than the direct manipulation of water in the channel. Gauges on unregulated (often called unimpaired) streams often have short or incomplete records or are sited in locations inappropriate for any particular after-the-fact study. The number of such gauges in the Sierra Nevada has decreased with time as costs have risen. Stream gauging stations are operated by the U.S. Geological Survey, utilities, irrigation districts, and a few other public agencies. Many of the records are published as daily values in annual volumes by the U.S. Geological Survey (USGS). Most of these records are now available on CD-

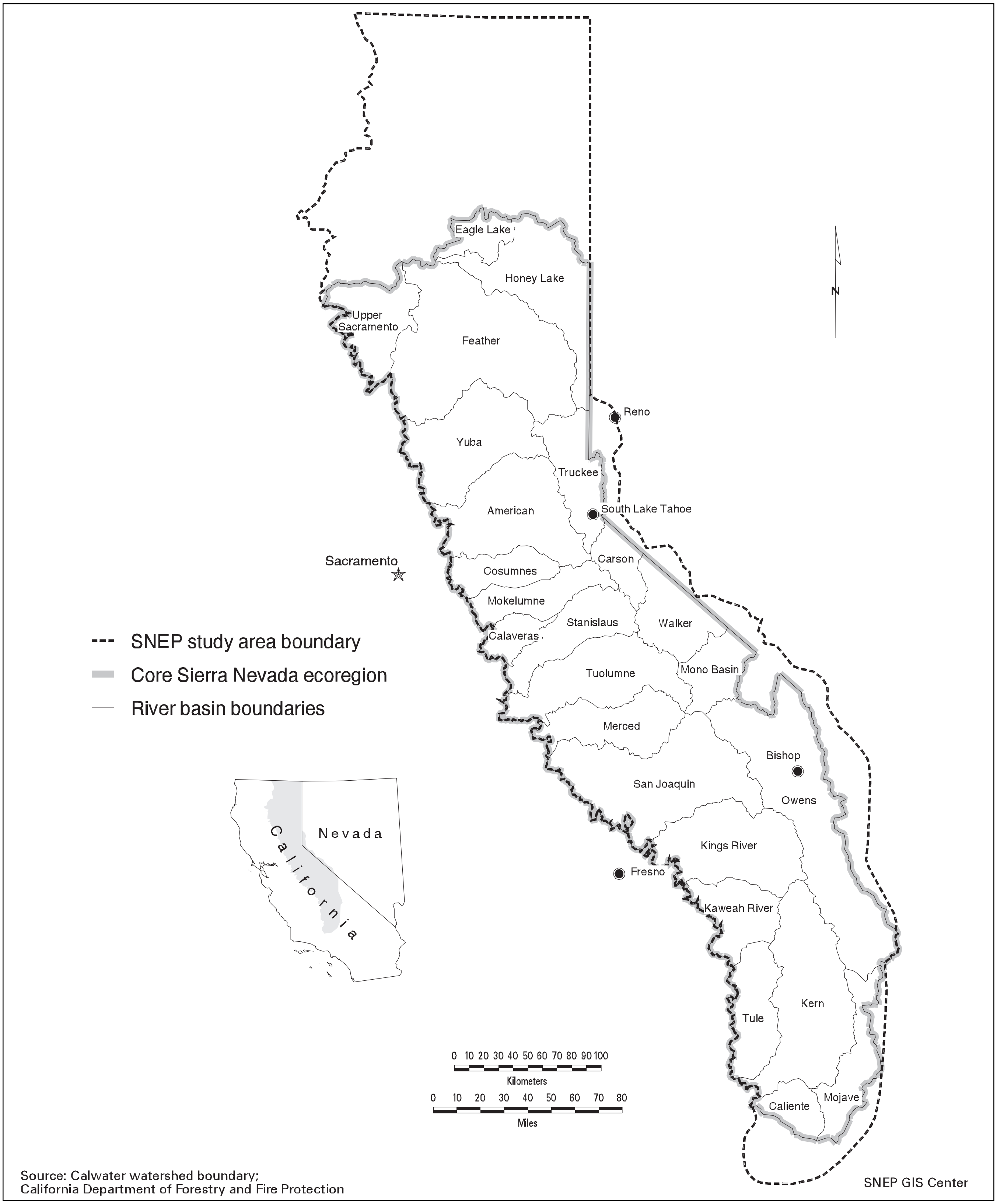


FIGURE 30.1

Major river basins of the SNEP core study area.

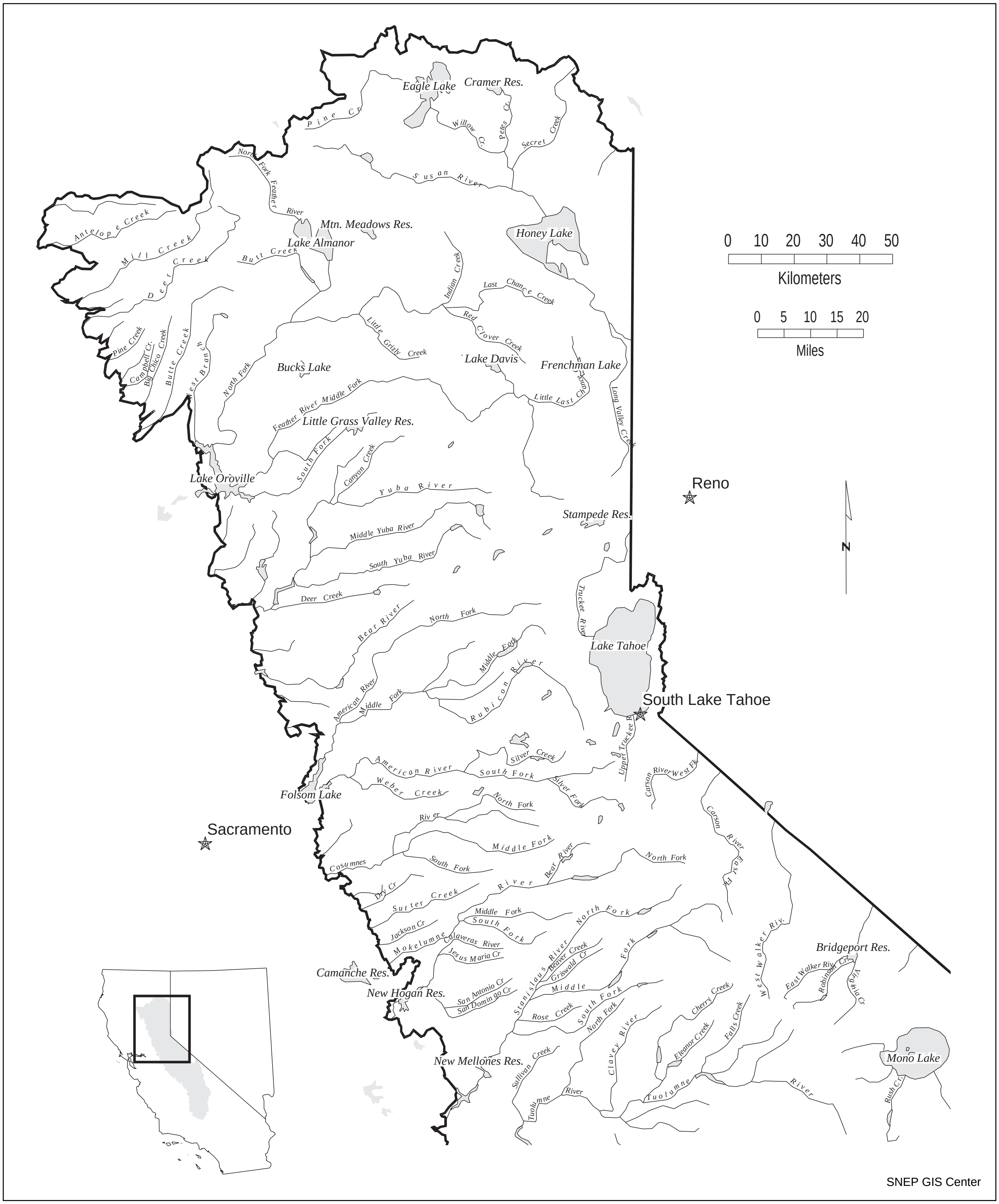


FIGURE 30.2

Principal rivers and streams of the northern half of the SNEP core study area.

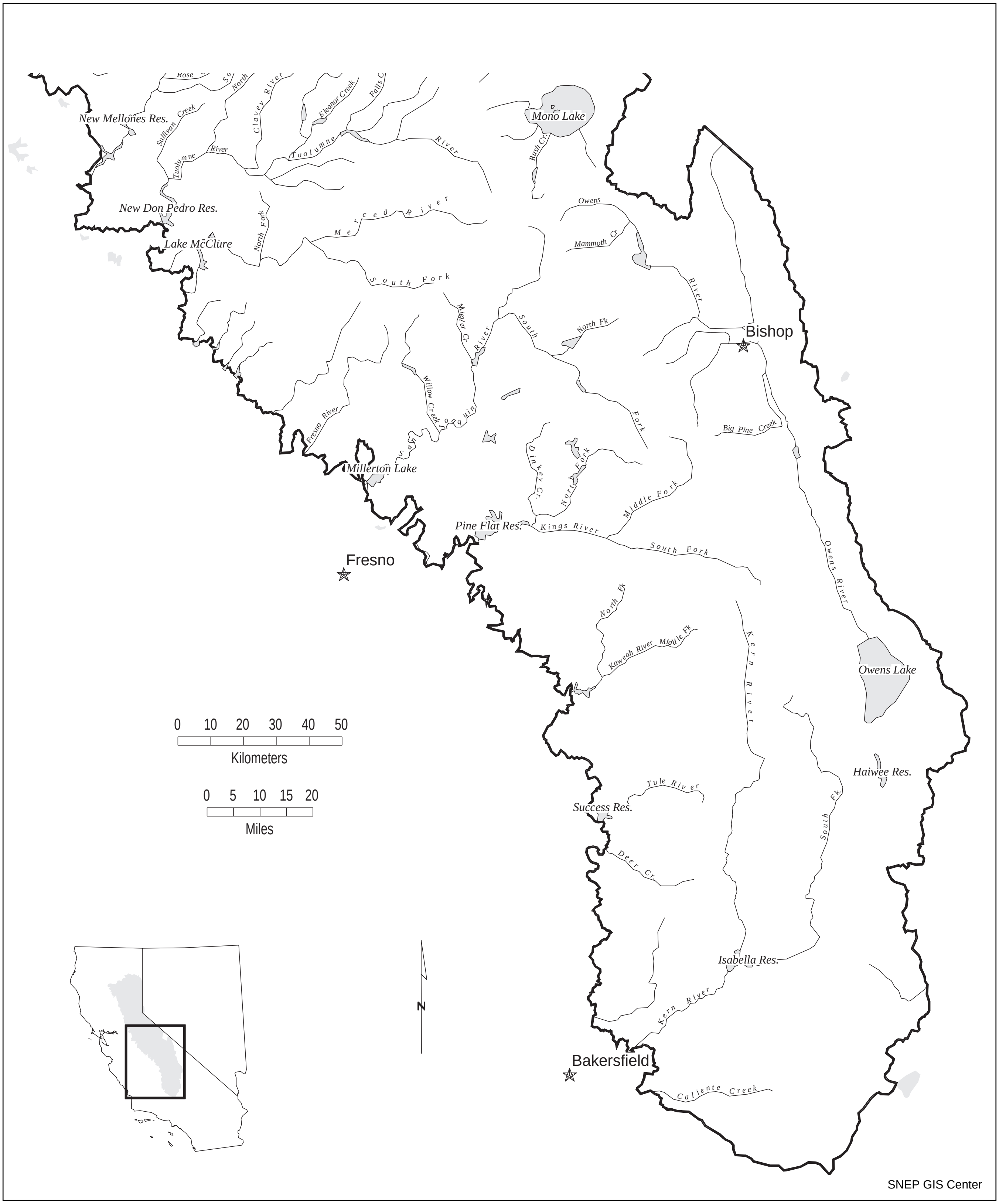


FIGURE 30.3

Principal rivers and streams of the southern half of the SNEP core study area.

ROM from private firms and the USGS. The usual characteristics of stream flow that are studied are the annual volume, distribution over time (i.e., annual hydrograph), maximum flows, and minimum flows. Measurement of flows in natural channels is not a trivial exercise, and errors can exceed 10% to 20% of the measured value (Herschy 1985). Natural variability in all aspects of stream flow can be quite high.

Sediment is the other main constituent of the fluid flowing in streams that we casually call water. Changes in sediment removal, transport, and deposition affect the general nature of stream channels and riparian areas and their biota, as well as affecting human uses of water. Mineral particles eroded from the land surface and transported mostly by flowing water gradually (or sometimes suddenly) move downslope from the mountains. These particles of various sizes are either suspended in the water or bounce along the channel as bedload. Both types of sediment move episodically as the capacity of streams to transport sediment varies with flow velocity. Sediment can be stored in a channel for years (or even centuries) before conditions are right to dislodge and transport it. Individual particles have a discontinuous journey downstream, with intermittent advances of varying lengths interrupted by temporary storage of varying duration. Suspended sediment is sampled at few stations throughout the Sierra Nevada and is a marginal measure of total sediment load. Bedload moving past a point is not routinely measured anywhere in the Sierra Nevada, but it has been measured in special studies (e.g., Andrews and Erman 1986). Repeated surveys of the bottom topography of natural and artificial lakes and calculation of the change in volume over the time interval is the best means of estimating total sediment transport (Dunne and Leopold 1978). However, this technique integrates sediment production from a large area and duration and, therefore, is difficult to associate with particular land-use activities. It is also very expensive.

Most other materials that are found in flowing water constitute the dissolved load of streams. A variety of ions occur naturally in streams, although the waters of the Sierra Nevada tend to have relatively low amounts of dissolved constituents compared with other rivers of the world (e.g., California State Water Resources Control Board 1992a). The chemical quality of streams is routinely measured at only a few gauging stations in the Sierra Nevada. There is also a biotic component of streams, ranging from viruses and bacteria to invertebrates and fish (see Moyle 1996; Moyle et al. 1996; Erman 1996).

Water temperature is another important attribute of streams, particularly with respect to suitable conditions for aquatic life. Some creatures can tolerate only relatively narrow ranges in temperature at different stages in their life cycles. The amount of dissolved oxygen also varies with temperature, decreasing as temperature increases. As with other water quality parameters, temperature is measured at only a few river gauging stations. Stream temperature varies primarily with stream discharge, original temperature of water inputs, exposure to sunlight, geothermal conditions, and temperature of reservoir releases.

Attributes of ground water that are of primary interest and are subject to change are the amount and quality of water in storage. Ground-water conditions in the Sierra Nevada are not routinely monitored in the manner of stream flow. Public utilities that pump ground water for water supply monitor their own wells but do not systematically report their results. Most of the publicly available information about ground water in the Sierra Nevada is from a handful of special studies.

Scale

Consideration of the scale of hydrologic impacts is crucial to understanding how water resources are affected by disturbance. A point of reference is necessary. Usually, some particular point along a stream where measurements are made of flow and/or quality parameters provides the geographic context. Impacts upstream of that point may have some measurable effect at the reference site. Activities in the river channel itself are likely to produce the greatest noticeable impacts in the channel at the point of reference. Activities near the channel in areas with occasional hydraulic connection to the channel will also have direct impacts (i.e., change in water or sediment yield) in the channel under consideration. Such areas may be surface-runoff contributing zones (sometimes called variable source areas) that yield water as sheet flow or near-surface pipe-flow in response to rainfall. At greater distances from main channels or ephemeral tributaries, water resulting from rainfall or snowmelt moves slowly downslope through soil or subsoil. Alteration of hillslope properties at locations distant from the stream channel simply has less opportunity to make a difference at the downslope and downstream point of reference. To restate the typical effect of geographic location on hydrologic impacts, a given disturbance matters less on a ridgetop than adjacent to a channel.

Cumulative Effects

One must also consider the combined or cumulative effects of activities on attributes of water at a point of reference. Altering the local water balance of a small fraction of a watershed or even adding a small quantity of pollutant to a stream usually will not result in any detectable change at some distant downstream point of reference. However, altering many small fractions of the watershed or adding the small quantity of pollutant at many places along the stream will cause a detectable change downstream. Even though each individual impact is insignificant with respect to the whole watershed, their cumulative effects may be dire. An instructive example of cumulative watershed effects occurs in the Lake Tahoe Basin, an easily visualized hydrologic unit in which the lake is the item of reference. Construction of roads, houses, casinos, parking lots, ski runs, septic systems, and so on initially affected only the immediate area of the particular development.

However, at some time, perhaps in the 1960s, there were so many individual disturbances that the nutrient balance of the lake was profoundly changed and algal production increased, with a consequent decrease in lake clarity (e.g., Goldman 1974 and 1990). Similarly, while a small diversion from a stream for irrigation might not be detectable at a downstream point, hundreds of small diversions can totally dry up a stream. Ground-water overdraft is typically the cumulative result of hundreds of small extractions. Therefore, when considering the potential impact of some activity on water resources, one must examine the intensity of the impact, how extensive it is (what fraction of the watershed is affected), the proximity of the activity to a stream channel, what other impacts in the watershed it is adding to, and the degree of recovery from past impacts. These questions of scale are implicitly addressed throughout this chapter.

HISTORY OF IMPACTS ON WATER RESOURCES

Examination of past impacts to streams and rivers helps us understand their current condition. Impacts of Native Americans on the hydrologic system appear to have been minor, largely because of the comparatively small population in the mountains and limited technology. Their deliberate use of fire as a vegetation-management tool would have been the primary agent in altering local hydrology. To the extent that intentional fires removed vegetation, evapotranspiration was reduced, water yields were increased, and surface erosion was increased. The geographical extent, intensity, and frequency of such fires cannot be quantified. Therefore, about all we can say concerning the hydrologic consequences of this activity is that there were some. Areas near to population centers were probably impacted to a greater degree than remote areas. Little is known about water development by Native Americans. Perhaps the best documented projects occurred on Bishop and Big Pine Creeks. Starting perhaps 1,000 years ago, the Paiute built dams and large irrigation canals to irrigate areas exceeding 5 km^2 (2 mi^2) in the bottomlands of the Owens Valley to enhance the growth of native vegetation (Steward 1934; Lawton et al. 1976). More modest water impoundments and diversions were built in the Tahoe basin by the Washoe (Lindstrom 1994).

The discovery of gold in 1848 had swift and dramatic consequences for streams and rivers of the Sierra Nevada. Streams were dammed, diverted, dewatered, excavated, polluted, and filled with debris from enormous hydraulic mines. Removal of trees over large areas for flumes, mine timbers, buildings, and fuel resulted in soil loss, augmentation of downstream sedimentation, and major changes in vegetative cover. Gold mining also led to many innovations in water institutions and engineering. Miners established the principle of priority in determining water rights just as in mining claims. The resultant doctrine of prior appropriation has far-reaching effects in the allocation of water resources throughout the western United States. Acquisition of water for hydraulic mines developed engineering technology and physical works that have had lasting impacts on California's water distribution system. Generation of power for mines and mills led to one of the world's most extensive hydroelectric networks.

Initially, miners worked as individuals on small claims with simple implements. Shallow gravels were excavated and washed with water in pans, rockers, long toms, and other crude devices (Silva 1986). Virtually all streams on the central western slope of the Sierra Nevada were prospected (Averill 1946; Clark 1970). Although the depth of disturbance was limited, these excavations destabilized channel beds and banks and devastated riparian vegetation over a vast area. As the surface gravels were exhausted, more intensive methods required cooperation and consolidation of the miners. Flumes were constructed to carry the summer flows of streams so that beds could be blasted and excavated. Small dams were built so that several hours of discharge could be stored and released suddenly to disaggregate the gravels hydraulically and carry away lower-density sediments in a practice known as booming or gouging. Diversions and flumes were also built to supply water to off-channel claims for separating gold and for ground sluicing where diverted water was used to erode ancient stream deposits (Averill 1946). Natural channels were often totally dewatered to supply maximum flow in an artificial waterway (Pagenhart 1969).

The erosive power of water was marshaled to great effectiveness by containing water within pipes and hoses under high pressure and then directing it at hillslopes composed of gold-bearing gravels (Stanley 1965; May 1970). As an example of the power and water use of hydraulic techniques, flumes and pipes with 120 m (400 ft) of head could deliver about 3.8 million liters (1 million gal) of water per hour through a 25 cm (10 in) nozzle at a speed of about 200 kph (120 mph) (Logan 1948). Sediment-laden runoff from the eroded hillslopes was directed into long sluice boxes, often in tunnels, to extract the gold and then discharged into the nearest creek.

At the peak of hydraulic mining, there were more than four hundred hydraulic mines in operation (Wagner 1970). Hydraulic mining was most prevalent from the Feather River to the North Fork American River (Gilbert 1917; Averill 1946). The largest quantities of material were found in the South Yuba, lower Yuba, Bear River, and North Fork American River (Gilbert 1917; James 1994). Collapse of the English Dam on the Middle Fork of the Yuba (Ellis 1939; McPhee 1993) in June 1883 released almost 18 million m^3 (15,000 AF) of water suddenly and cleaned out much of the stored mining debris in that channel (James 1994). Several of the individual pits excavated more than 75 million m^3 (60,000 AF) of material and flushed it downstream (Gilbert 1917; Senter 1987; McPhee 1993). Channels immediately downstream of the hydraulic pits were usually overwhelmed by the enormous sediment loads and stored the sediments until high-flow events flushed some of the material downstream. Surveys of the 1870s showed accumulations of 30 to 60 m (100 to 200 ft) depth in tributaries to the Bear River (Pettee in Whitney 1880, cited by James 1994). Debris was redeposited throughout the channels, but often formed tailings dams at confluences where channel gradients lessened (James 1994). Temporary reservoirs formed behind these debris accumulations, which occasionally failed catastrophically, releasing large volumes of sediment, perhaps as hyperconcentrated flows. In the early years of hydraulic mining, the upper gravels of the Tertiary river channels were attacked first. After 1870, the lower gravels, which were more strongly cemented than those above, were mined by more powerful methods that moved even more of the landscape (Lindgren 1911). This second phase of hydraulic mining produced coarser sediments and greater quantities of debris than the first period (James 1988).

As sediments moved downstream, valley rivers aggraded dramatically, and coarse sediments were deposited on farms and fields. Thousands of acres of farmland became inoperable under annual deposits of unnaturally coarse sediments (Hundley 1992). As the farmers of the Central Valley gained economic and political power, they were able to successfully challenge the mining interests (Kelley 1959). In 1884, after eighteen months of deliberation in the case of Woodruff v. North Bloomfield, Judge Lorenzo Sawyer of the Ninth U.S. Circuit Court in San Francisco issued an injunction against further discharge of mining debris. This decision held that release of mining waste inevitably damaged the property of others and destroyed the navigability of the Sacramento and Feather Rivers, violating both common and statutory law and interfering with commerce (Hundley 1992).

After hydraulic mining was halted, some of the debris created earlier continued to move through the rivers, largely in pulses during peak flows. Debris that was not entrained during the phase of active stream incision continues to erode into channels and perpetuates the enhanced sediment delivery of the affected streams (James 1988). Many of the small debris dams intended to stabilize mining sediment failed and released the stored material. Large competent dams have effectively stopped transport of upstream sediment to the lower reaches of the main rivers. Even after a century, exposed surfaces in the pits continue to erode through mass failures, gullying, rainsplash, and rill erosion and produce substantially elevated sediment concentrations downstream of the old mine sites (i.e., Senter 1987).

The total volume of mining debris delivered to the Central Valley has been estimated at about 1.1 billion m^3 (900,000 AF) from five rivers, with the Yuba contributing about 40% of that quantity (Gilbert 1917; Mount 1995). Gilbert (1917) also estimated that mining sediment was produced at rates about ten times greater than natural sediment yield from the Sierra Nevada, although these estimates of background rates were highly uncertain.

Mercury used in ore processing is another legacy of the mining era remaining in stream channels. The amount of mercury used in gold extraction in the Sierra Nevada and largely lost to soils and streams has been estimated at 3.4 million kg (7.6 million lb) (Central Valley Regional Water Quality Control Board 1987). Much of this mercury has moved downstream, and some of it may have contaminated mudflats of San Francisco Bay. Large amounts of mercury are still found in stream sediments throughout the Gold Country and are also trapped in reservoir sediments (Slotten et al. 1995). The cyanide process for extracting gold from powdered rock was introduced about 1896 (Clark 1970; Shoup 1988). The degree of water pollution resulting from its use and the earlier chlorination process is unknown.

Underground mining, also called hard-rock, quartz, or lode mining, began shortly after the discovery of gold in streambeds, with the Argonaut mine near Jackson opening in 1850. The Sixteen to One mine in the Yuba River Basin persisted as the main gold mine in California until 1965 and was reopened a few years ago. Hundreds of quartz mines were operated throughout the Mother Lode of the western slope (Jenkins 1948; Clark 1970). The main mining districts of the eastern Sierra Nevada were at West Walker River, Bodie, Green Creek, Virginia Creek, Lundy Canyon, Tioga Pass, Mammoth Creek, Pine Creek, Bishop Creek, and Independence Creek (De Decker 1966; Clark 1970). Both lode and placer deposits were mined in the Kern River drainage beginning in 1851 (Troxel and Morton 1962). Disposal of tailings, mine water, and ore-processing effluent were the main impacts of the underground mines on streams. Although perhaps significant locally, these impacts were minor compared with those of the surface operations.

Dredging was an important source of gold and a major impact on the lower reaches of the main rivers where the Sierra Nevada meets the Central Valley. Large-scale river dredging began in 1897 along the Yuba near Marysville (Logan 1948) and lasted until 1967 (Clark 1970). The largest dredging operations were at Hammonton on the lower Yuba and near Folsom on the lower American. Dredging was also practiced on Butte Creek, Honcut Creek, the lower Feather, the Bear near Lincoln, the Cosumnes at Michigan Bar, the Calaveras at Jenny Lind, the Mokelumne at Camanche, the Tuolumne at La Grange, and the Merced at Snelling (Aubury 1910; Clark 1970). Between 1900 and 1910, dredge capacity increased from about 20,000 m^3 (25,000 yd^3) to 200,000 m^3 (250,000 yd^3) per month (Aubury 1910). Reclamation and revegetation of dredge spoils were concerns as early as 1910 (Aubury 1910).

The development of mining towns put great pressure on local resources, which probably had consequent impact on local streams. Towns sprang up quickly when new strikes were rumored and were successively rebuilt after surprisingly frequent fires. Some towns like Elizabethville in Martis Valley and Summit City near Cisco grew to several thousand people before suddenly collapsing. Development of trails, roads, railroads, and agriculture to support the towns converted forests to bare and compacted soil, which was susceptible to erosion. Overgrazing for food production further altered plant cover and degraded riparian zones. Harvesting of fish and mammals for food and loss of habitat decimated wildlife populations and altered ecological processes (Hinkle and Hinkle 1949; Strong 1984). Demand for wood for shelter and fuel quickly depleted the forests closest to the new towns and then progressively expanded the circle of destruction. Lumber was also needed for underground mine supports, railroad ties, and flumes. In a few cases such as Bodie, lumber and fuel wood were imported from considerable distances. Forests of the Tahoe basin were cut extensively to supply wood for the Comstock silver mines near Virginia City. The Bonanza mines alone consumed 28,000 m^3 (12 million board feet) of lumber and 145,000 m^3 (40,000 cords) of fuel wood per year. An extensive network of skid trails, haul roads, railroads, tug boats, and flumes efficiently removed the forests of much of the Tahoe basin. An estimated 600 million board feet of lumber were buried in the Comstock mines (Hinkle and Hinkle 1949; Strong 1984). More than twenty sawmills in the Middle and South Forks of the American River produced lumber for buildings and replacement flumes for those destroyed by annual floods (Lardner and Brock 1924, cited by James 1994).

The first known miner's ditch was a V-shaped flume about 3 km (2 mi) long built at Coyote Hill near Nevada City in March 1850 (Pagenhart 1969). Later that year, a 14 km (9 mi) long ditch was built by the Rock Creek Water Company, which recovered its investment in just six weeks from the sale of water (Wagner 1970). Natural lakes in the upper Yuba basin were augmented and regulated with crude dams as early as 1850 (Pagenhart 1969). Acquisition and delivery of water to mines became a huge industry that was probably more profitable than mining. If ditches were important to the mining of surficial placer gold, they became critical to the hydraulic mining industry. Large companies built vast networks of reservoirs and waterways acquired through purchase, filing on abandoned claims, court challenges to water rights, and real and implied violence (Hundley 1992).

The levels of investment, labor, and engineering skill devoted to the miners' ditches were impressive. The main supply ditches were 2.4–4.6 m (8–15 ft) wide at the top, 1.2–1.8 m (4–6 ft) wide at the bottom and at least 1 m (3 ft) deep (Wagner 1970). Water was conveyed across valleys and rock outcrops in wooden flumes or iron pipes mounted on trestles (Logan 1948). By 1857, $13.5 million had been invested in mine water systems, with $3 million of that total in Calaveras and Tuolumne Counties (Langley 1862, cited by Shoup 1988). In the 1860s, more than 8,500 km (5,300 mi) of main canals and about 1,280 km (800 mi) of branch ditches had been constructed (Browne 1868; Logan 1948; McPhee 1993). By 1884, the total length of ditches, flumes, and pipelines built for mining purposes reached 12,800 km (8,000 mi) (Wagner 1970). (This figure was probably for all of California.) The South Yuba Canal Company maintained 720 km (450 mi) of waterways at its peak, and the Auburn and Bear River Canal operation included 460 km (290 mi) of ditches. The dam at Meadow Lake constructed by the South Yuba Canal Company in 1858 was 12 m (42 ft) tall and 350 m (1,150 ft) long (Hinkle and Hinkle 1949). By 1880, the California Water Company had twenty-one reservoirs and 400 km (250 mi) of flumes and ditches between the Middle Fork and the South Fork of the American River. At the peak of hydraulic mining activity, there were more than 1,600 km (1,000 mi) of ditches in Nevada County (Kahrl 1978). By the 1870s, artificial reservoirs in the Sierra Nevada stored more than 185 million m^3 (150,000 AF) of water (Pisani 1984). The Eureka Lake and Yuba Canal Company operated four high-elevation reservoirs to supply water to mines near North San Juan, 100 km (65 mi) away (Wagner 1970). In the same region, the North Bloomfield Gravel Company used 55 million m^3 (45,000 AF) of water annually at up to 110,000 liters (30,000 gal) per minute (McPhee 1993) or 227,000 m^3 (184 AF) per day and had reservoir storage capacity of 28 million m^3 (23,000 AF) (Pisani 1984). The company's Bowman Dam was 22 m (72 ft) tall in 1876 and was raised another 7 m (23 ft) to increase storage as the mine's water demand increased. The Cherokee mine in Butte County used up to 150,000 m^3 (123 AF) of water per day (Hundley 1992). Abandoned ditches have become naturally revegetated but can still affect runoff processes today (Pagenhart 1969). Occasional failure of both maintained and abandoned ditches can cause local debris flows and gully erosion.

Water Development

Water was also sold for domestic use and for water power for lumber and stamp mills, air compressors, and Pelton-wheel electric generators after 1890. Increasing scarcity of wood for fuel led to the use of high-pressure water for mechanical power. By the mid-1880s, most of the large hard-rock mines were using water power instead of steam power. The first known use of electrical generation for operation of mining and milling equipment in California occurred in El Dorado County in February 1890 (Logan 1948). After hydraulic mining was halted in 1884, many of the canals were acquired by irrigation districts and later by power companies. The Nevada Irrigation District still relies on reservoirs and canals built for mines in Nevada County. The Pacific Gas and Electric Company eventually took over 520 separate ditch enterprises and their water rights and facilities. By the 1890s, the log-and-brush and earth-filled dams of the miners were replaced by more substantial concrete structures (Pisani 1984). Irrigated agriculture in the foothills occupied about 36 km^2 (14 mi^2) around Auburn and Placerville in 1880 (Pisani 1984) and grew substantially in the following decades (see Momsen 1996).

The vast network of artificial channels built for mining allowed the hydroelectric industry to take off as soon as water-powered generating technology became available. A dam on the American River at Folsom begun in 1866 that was originally intended for hydromechanical power later provided water for the first transmission of hydroelectricity out of the

Sierra Nevada. This project at Folsom began supplying power for an electric railroad in Sacramento in 1895 (Fowler 1923). After its first dam failed in 1892, a hydroelectric power plant on the South Yuba was completed in 1896 and supplied electricity for the Grass Valley and Nevada City area (Pacific Gas and Electric Company 1911). In the next two decades, dozens of hydroelectric facilities were completed throughout the Sierra Nevada: Knight's Ferry-Stanislaus, 1895; Electra-Mokelumne, 1897; Kern 1897; Newcastle-Bear, 1898; Colgate-Yuba, 1899; Farad-Truckee, 1899; Phoenix-Stanislaus, 1901; American, 1903; De Sabla-Butte 1903; Bishop Creek No. 4, 1905; San Joaquin No. 3, 1906; Kittredge-Merced, 1906; La Grange-Tuolumne, 1907; Big Creek No. 1, 1913; Kaweah No. 3, 1913 (Pacific Gas and Electric Company 1911; Fowler 1923; Coleman 1952). Independent companies were quickly merged and integrated, and multiunit projects were developed by the two companies that emerged from the consolidation battles, Pacific Gas and Electric and Southern California Edison. The Crane Valley project involving Bass Lake and Willow Creek was developed between 1900 and 1920. On the North Fork of the Feather, Pacific Gas and Electric was filling Lake Almanor and Bucks Lake by 1928 (Coleman 1952). The Big Creek project, started in 1911 by the Pacific Power and Light Corporation, was completed by Southern California Edison in 1929 and included three large reservoirs, eight tunnels, and five powerhouses (Redinger 1949).

In addition to the dozens of hydroelectric projects taking advantage of the mining waterways, three immense municipal-supply projects began as mining faded out. A scheme to develop Lake Tahoe as a water supply for San Francisco was proposed even earlier, in 1866, but failed to find support (Strong 1984). The city of San Francisco itself began prospecting for water in the Sierra Nevada as early as 1886 (Kahrl 1978). The city remained focused on the Tuolumne River with a dam at Hetch Hetchy Valley despite other feasible alternatives (Freeman 1912; Jones 1965). Largely because the project was in a national park, the proposal generated enormous controversy; however, the city prevailed with congressional approval of the Raker Act in 1913. Hydroelectric generation on a subsidiary portion of the project began in 1918, but water deliveries to San Francisco did not begin until 1934. The Owens Valley project of the city of Los Angeles was constructed more rapidly. After the general concept arose in the 1890s, construction bonds were approved in 1907 and work began in 1908. The project was operational in 1913, when Owens Valley water reached the San Fernando Valley. An extension into the Mono basin was built between 1934 and 1940. A second aqueduct was completed in 1970, enabling greater export of surface water and pumped ground water. The controversies created by the Owens Valley diversions have been described by dozens of authors (i.e., Chalfant 1922; Nadeau 1950; Kahrl 1978; Hoffman 1981; Kahrl 1982; Reisner 1986; Walton 1992; Davis 1993; Sauder 1994). By comparison, political conflict was almost absent in the Mokelumne project of the East Bay Municipal Utility District. Work began in 1923, and Pardee Reservoir began filling in 1929, with water deliveries to Alameda and Contra Costa Counties that same year (Harding 1960). These systems deliver large volumes of water to distant communities with a large net production of electricity. Hydroelectric power production has been a key source of revenue in the financing of water projects in the Sierra Nevada.

The federal government's involvement with water in the Sierra Nevada began with the Newlands Reclamation Act of 1902, which authorized the Truckee-Carson Project. Preexisting dams that raised the level of Lake Tahoe were reconstructed to provide 1.8 m (6 ft) of controllable storage. The newly created Bureau of Reclamation assumed operation of the Tahoe dam in 1913 for irrigation of lands near Fallon, Nevada. The interstate and tribal conflicts created by this project have maintained a steady stream of litigation for eight decades (Jackson and Pisani 1973; Jones 1991; Chisholm 1994). Early in the twentieth century, the state government began considering large-scale water development (Kahrl 1993). A report by the Conservation Commission (1913) devoted half of its 500 pages to water resources. The first comprehensive plan for water development in California was prepared by R. B. Marshall in 1919. A few years later, the California Department of Public Works (1923) released the first statewide hydrographic survey, which examined 1,270 potential reservoir sites and recommended dams at 260 of them. That report led to another comprehensive development plan (Bailey 1927). After California voters approved the concept in 1933 as a state project, California was unable to sell the bonds required for financing. The U.S. Congress stepped in, federalized the proposal, and authorized the Bureau of Reclamation to begin construction of the Central Valley Project in 1935 (Harding 1960; Kelley 1989). Most of the project's water originates outside the Sierra Nevada in the upper Sacramento and Trinity Rivers. The main pieces of the Central Valley Project in the Sierra Nevada, the Friant, Folsom, and New Melones Dams, took decades to complete.

After World War II, other big water projects got under way in the Sierra Nevada, with major dams constructed on the San Joaquin, Kern, Kings, and American before 1960. The big-dam era continued at full speed through the sixties, with projects completed on the San Joaquin, Kaweah, Bear, Mokelumne, Calaveras, American, Merced, Tuolumne, and Yuba Rivers (Kahrl 1978; California Department of Water Resources 1994). The Feather River Project (later named the State Water Project) was approved by the California legislature in 1959 and by the voters in 1960. The centerpiece of the project, Oroville Dam, was completed in 1967.

Although mining in stream channels and water development have been the overwhelming impacts on hydrologic processes in the Sierra Nevada, other human activities in the past 150 years have also altered the hydrology and streams of the range. Unfortunately, there is relatively little information about the extent of these various impacts. We are left, therefore, to a few broad inferences and generalizations.

Grazing

Grazing was perhaps the most ubiquitous impact, as cattle and sheep were driven virtually everywhere in the Sierra Nevada that forage was available (see Menke et al. 1996; Kinney 1996). Anecdotal accounts describe vast herds and severe overgrazing (Sudworth 1900; Leiberg 1902). Overgrazing has been blamed for accelerated erosion beginning in the late 1800s and massive gullying of meadows in the decades that followed (Wagoner 1886; Hughes 1934). Widespread deterioration of meadows led to efforts by the U.S. Forest Service to reduce the degradation (Kraebel and Pillsbury 1934). However, continuing presence of large herds did not allow riparian vegetation to recover enough to reduce erosion of stream banks.

Timber Harvesting

Timber harvesting in the nineteenth century certainly impacted local streams but perhaps mainly because of its typical location: near streams. We can assume that riparian and near-channel forests were targeted during the mining era because they grew on gold-bearing stream deposits and wood was needed where most of the activity was: along streams. Rivers were also used for log transport. As early loggers got farther away from streams, their impacts presumably diminished. Because transportation of the logs was difficult, large amounts of slash were apparently left in the woods. Such material could reduce erosion. In addition, loggers of the 1800s simply lacked the heavy equipment that can grossly disturb hillsides. The advent of railroads had two major impacts on Sierra Nevada forests. Railroad construction consumed vast quantities of lumber for ties, trestles, and snowsheds, and the steam engines burned wood. Railroad logging caused a change in harvesting practices: economics favored removal of almost all trees near the tracks instead of taking individual trees selected for wood quality and relative ease of transportation. Where railway networks allowed large fractions of a watershed to be harvested, local yields of water and sediment could be expected to have increased. Because the degree of ground disturbance from these early logging operations is unknown, their hydrologic effects are difficult to infer. However, because early harvests did not involve road construction and persistent ground skidding to centralized landings, they may be assumed to have had lower impacts than those following World War II.

Wildfire

Fire suppression policies that began early in this century may have caused extensive and persistent changes in the water balance of the forest zone. If forest density significantly increased beyond that generally maintained under a pre-1850 fire regime, then we may assume that evapotranspiration has been maximized in the absence of harvesting. Therefore, the presumably denser forests resulting from fire suppression may have reduced water yields in many basins of the western slope. Quantifying such a reduction is not possible without knowing something about the water relations of forests before the gold rush. Regionally, changes probably do not amount to more than a few centimeters (inches) of areal water depth at most. However, the local effects of denser stands in some instances could be sufficient to reduce the flow of springs and headwater creeks. The thick ground cover resulting from the lack of fires has probably decreased surface erosion as well.

Roads

Following the Second World War, timber production increased markedly, as did construction of forest roads necessary to serve emerging techniques of log removal. The road-building boom of the 1950s through the 1970s was the greatest disturbance of the Sierra Nevada landscape since the gold rush. Initially, forest roads were just built, rather than properly engineered to minimize the risk of mass failure and surface erosion. Stream crossings were particular problems when fords or cull-logs covered with dirt were the preferred means of crossing water. Inadequate road drainage and undersized culverts were common causes of road failure and sediment production. With time, road engineering improved, but total mileage increased as well. At the extreme, up to a tenth of the land area of some catchments became road surface, with a large number of stream crossings.

Point-Source Water Pollution

The first known water pollution by industry other than mining in the Sierra Nevada involved the sawmills near Truckee. Mill waste was disposed of in the nearest de facto sewer, the Truckee River. The large loads of sawdust filled pools in the river, clogged the gravels, and probably removed oxygen from the water, killing fish in the river. Acts of both the California and Nevada legislatures in 1890 and continued enforcement by the California Fish Commission were required to halt the pollution (Pisani 1977). Construction of a pulp and paper mill at Floriston in 1899 added chemical pollutants to the Truckee. This pollution continued until the mill closed for economic reasons in the 1930s (Pisani 1977). Growth of communities in the Sierra Nevada led to water quality problems relating to solid waste and sewage disposal. All known problems were local and relatively minor. Technology for centralized sewage treatment has been both improved and widely deployed throughout the range. Bacteriological water quality around the mining camps may have been poor, as inferred by common intestinal ailments of Euro-American miners that spared the boiled-tea-drinking Chinese laborers (Johnson 1971).

SURFACE WATER QUANTITY

The Sierra Nevada annually yields a large but variable amount of water. Continuous stream-flow records began to be maintained in the mountains less than one hundred years ago and are of short duration with respect to longer-term natural variability. Based on this recent historical record, the Sierra Nevada generates about 25 km^3 (20 million AF) of runoff each year, on average, out of a total for California of about 88 km^3 (71 million AF). Stream flow in the Sierra Nevada is generated by seasonal rainfall and snowmelt. About half of average annual precipitation occurs during winter, about a third in autumn, about 15% in spring, and generally less than 2% in summer (Smith 1982). About 50% of annual precipitation falls as snow at 1,700 m (5,600 ft) at a latitude of 39° N (Kahrl 1978). Stream flow generated below 1,500 m (4,900 ft) is usually directly associated with storms, while stream flow above 2,500 m (8,200 ft) is primarily a product of spring snowmelt. Between these approximate bounds, stream flow is generated both by warmer storms and by melt of snow cover in spring. Of course, the major rivers collect inputs throughout their elevation range with a mix of events. Cayan and Riddle (1993) calculated the seasonal distribution of runoff of six Sierra Nevada rivers (table 30.1), which illustrates that snowmelt runoff becomes more important and midwinter rainfall runoff becomes less important with increasing elevation. In the American River Basin, less than half of annual runoff occurs from April through July in the lower two-thirds of the basin. In small catchments of the American adjoining the Sierra Nevada crest, more than two-thirds of annual runoff occurs during this period (Elliott et al. 1978).

Disposition of Precipitation

Overall, about half the precipitation in the major river basins of the west slope of the Sierra Nevada becomes stream flow (table 30.2) (Kattelmann et al. 1983). Stream flow, both in absolute magnitude and as a proportion of precipitation, increases with elevation. In the American River Basin, streamflow data from twenty-five subbasins (Armstrong and Stidd 1967) indicate an increase in stream flow of about 3 cm per 100 m (3.6 in per 1,000 ft) gain in elevation. Also, in the American River Basin, runoff efficiency increases from about 30% in the foothills to more than 80% near the crest (Elliott et al. 1978). In four small catchments in the Kings River Basin at 1,900 to 2,500 m (6,300 to 8,100 ft), about half the precipitation became stream flow on average. However, there was considerable variation among the nine years of record, depending on total precipitation. Runoff efficiency in the four years with more than 120 cm (47 in) of stream flow ranged from 63% to 75%, while in the five years when stream flow was less than 30 cm (12 in), runoff efficiencies ranged from 21% to 33% (Kattelmann 1989a). A stream gauge on the North Fork of the Kings River at 2,480 m (8,130 ft) is the highest long-term station on the western slope of the Sierra Nevada. This basin of 100 km^2 (39 mi^2) extends above 3,700 m (12,100 ft). The average annual stream flow of 74 cm (29 in) is 70% to 80% of the estimated annual precipitation. About 85% of the annual flow in this basin occurs from April to July (Kattelmann and Berg 1987). In a 1 km^2 (250 acre) research basin in Sequoia National Park at 2,800–3,400 m (9,200–11,100 ft), 75% to 90% of the annual precipitation became stream flow (Kattelmann and Elder 1991). The high-elevation portion of the Sierra Nevada, which covers approximately 3% of California and produces an average of 90 cm (35 in) of annual runoff, contributes about 13% of the state's annual stream flow (Colman 1955). This contribution amounts to an even higher proportion of the state's developed water supply because of its persistence into summer.

TABLE 30.1

Seasonal distribution of stream flow in selected rivers (from Cayan and Riddle 1993).

River Basin	Mean Elevation (m)	Percentage of Mean Annual Stream Flow			
		Aug–Oct	Nov–Jan	Feb–Apr	May–Jul
Cosumnes	1,120	1	21	59	18
American	1,430	2	19	46	33
Stanislaus	1,770	3	13	38	46
San Joaquin	2,290	6	9	29	56
East Carson	2,490	7	11	24	58
Merced	2,740	4	5	21	70

TABLE 30.2

Approximate disposition of precipitation in major rivers (from Kattelmann et al. 1983).

River (Gauging Station)	Precipitation (cm)	Stream Flow (cm)	Losses (cm)
Feather (Lake Oroville)	120	60	60
Yuba (Smartville)	160	100	60
American (Folsom Lake)	135	65	70
Cosumnes (Michigan Bar)	105	35	70
Mokelumne (Pardee Reservoir)	120	65	55
Stanislaus (Melones Reservoir)	115	75	40
Tuolumne (Lake Don Pedro)	110	55	55
Merced (Exchequer Reservoir)	115	45	70
San Joaquin (Millerton Lake)	110	50	60
Kings (Pine Flat Reservoir)	95	50	45
Area weighted average	120	60	60

Snow

Snow plays a dominant role in the overall hydrology of the Sierra Nevada. Storage of frozen precipitation in winter as snow cover and its subsequent release during the spring snowmelt period controls the seasonal distribution of flow in most major rivers. Snow cover is measured at about 400 index locations (300 manually measured snow courses and 100 telemetered snow sensors) in the Sierra Nevada that are used for river forecasting. Basinwide means of April 1 water equivalence for snow courses above 2,500 m (8,200 ft) suggest that peak snowpack water equivalence for the high Sierra Nevada averages 75 to 85 cm (30 to 33 in), decreases from north to south, and is lower on the east side of the crest than on the west side (Kattelmann and Berg 1987). Snow courses between 1,800 m and 2,500 m (5,900 and 8,200 ft) have an average peak water equivalence of about 60 cm (24 in).

Flow Variability

Flow in Sierra Nevada rivers is highly variable in time, both within and between years. Peak flows can be up to five orders of magnitude greater than minimum flows. Annual volumes can be twenty times greater in very wet years than in very dry years. Some smaller streams cease flowing during prolonged dry periods.

Floods

High water levels are an integral feature of Sierra Nevada rivers and have a variety of effects on aquatic biota as well as channel morphology (Erman et al. 1988). Peak flows in the Sierra Nevada result from snowmelt, warm winter storms, summer and early-autumn convective storms, and outbursts from storage (Kattelmann 1990). In rivers with headwaters in the snowpack zone, snowmelt floods occur each spring as periods of sustained high flow, long duration, and large volume. However, they rarely produce the highest instantaneous peaks. The magnitude of a snowmelt flood depends on the spatial distribution of both snow and energy input to the snowpack. The largest volumes occur when all or almost all the basin is contributing high rates of snowmelt runoff. In basins spanning hundreds of meters of elevation with varied aspects, such situations are rare. Snow usually disappears from south-facing slopes and low elevations long before melt rates peak on north aspects and high elevations. Large snowmelt floods occurred in many river basins of the Sierra Nevada during 1906, 1938, 1952, 1969, and 1983. In all cases, snow deposition was more than twice average amounts and persisted into April and May even at low elevations. In basins of less than 100 km^2 (39 mi^2) within the snow zone, maximum specific discharges during snowmelt have ranged from 0.2 to 0.8 m^3 per second per km^2 (18 to 73 $ft^3/s/mi^2$) on the western slope and 0.1 to 0.2 $m^3/s/km^2$ (9 to 18 $ft^3/s/mi^2$) on the eastern slope.

Midwinter rainfall on snow cover has produced all the highest flows in major Sierra Nevada rivers during this century (Kattelmann et al. 1991). The most important factor in rain-on-snow floods is probably their large contributing area. During these warm storms, most of a basin receives rain instead of snow, generating short-term runoff from a much larger proportion of the basin than during cold storms. However, even during the warmest storms, snowpacks above 2,500 m (8,200 ft) rarely melt much because temperatures are close to 0°C (32°F). If snow cover extends to low elevations prior to a warm storm, there can be a substantial snowmelt contribution from those areas. In basins that are largely above 2,000 m (6,600 ft), the highest peaks also tend to be caused by rain-on-snow events. For example, in the Merced River in Yosemite National Park, the four highest floods were caused by rain on snow and were 1.5 to 1.8 times greater than the maximum snowmelt peak of record in 1983. In the past sixty years, six large-magnitude floods (peak flows greater than twice the mean annual flood) have occurred in almost all rivers draining the snow zone: December 1937, November 1950, December 1955, February 1963, December 1964, and February 1986. Specific discharges of these largest floods ranged from 0.2 to 4 $m^3/s/km^2$ (18 to 360 $ft^3/s/mi^2$). The largest flood in California history occurred in January 1862. Following hundreds of millimeters (tens of inches) of antecedent rainfall and snowfall down to the floor of the Central Valley, 250 to 400 mm (10 to 16 in) of rain fell in Sacramento (and undoubtedly higher amounts in the Sierra Nevada) between January 9 and 12. High-water marks on the American River near Folsom were 3.5 m (11 ft) above those observed in 1907, the third highest flood measured on the American. In the eastern Sierra Nevada, Owens Lake rose 3 to 4 m (10 to 13 ft) during that winter.

When subtropical air masses move into the Sierra Nevada in summer and early autumn, sufficient moisture is available to generate extreme rainfall. Intense convective storms occurring over a period of three or four days can generate local flooding. These convective storms can generate the greatest floods in some alpine basins that are high enough to avoid midwinter rain-on-snow events. For example, the four highest floods of Bear Creek (gauged near Lake Thomas A. Edison) were generated by summer rainfall. The peak discharge was more than twice that of the largest snowmelt flood in this basin of 136 km^2 (52 mi^2) with a mean elevation of about 2,850 m (9,300 ft). The greatest recorded floods in several east-side streams occurred in late September 1982 when 150 to 200 mm (6 to 8 in) of rain fell in two days.

In limited areas, the greatest floods occur during a sudden outburst from storage because of avalanche-induced displacement of lake water or failure of a natural or man-made dam or aqueduct. Peak flows generated by such mechanisms can be several times greater than those produced by meteorological events.

Droughts

At the other extreme, stream flow in Sierra Nevada rivers can become quite low during intense and/or extended droughts. For example, during 1977 when average snow water equivalence in early April was only 25% of the long-term mean, stream flow as a proportion of average annual flow ranged from 0.08 to 0.26. Basins with most of their area at low elevations generally had the lowest proportions of average volumes. Dry periods may last for several years. From 1928 through 1937, runoff was below average in each year. The past two decades have included record droughts for one year (1977), two years (1976–77), three years (1990–92), and six years (1987–92). The recent six-year drought was similar to the 1929–34 dry period. Total stream flow averaged across many rivers was about half of average in each case (California Department of Water Resources 1994). Other indications of past climate suggest that severe droughts in the Sierra have persisted for periods from decades to more than two centuries (Graumlich 1993; Stine 1994, 1996; Millar 1996; Woolfenden 1996). The presence of tree stumps well below modern lake levels in Lake Tahoe and Lake Tenaya and elsewhere provides strong evidence for very arid conditions in the past (Stine 1994). The period 1937 through 1986 was an anomalously wet period in a 1,000-year-long reconstruction of precipitation from dendrochronological evidence (Graumlich 1993). However, our water resources infrastructure and institutions were largely developed during this period. Inferences about the climate of the past 100,000 years (e.g., Broecker 1995) suggest that great variability in temperature has been common and the temperature of the last 10,000 years was anomalously stable. Any resumption of such a variable climate would be challenging to California's water resource system and society in general. Dramatic shifts in climate could alter the distribution of vegetation over decades to centuries and could interact with a changed precipitation regime to alter runoff generation (Beniston 1994; Melack et al. in press).

Trends

In both extremes of wet and dry conditions, there do not appear to be any strong trends in water becoming more or less available in the recent past. Concern was raised a few years ago that the proportion of annual runoff occurring in the months of April through July in the Sacramento, Feather, Yuba, and American Rivers had declined since about 1910 (Roos 1987). However, this trend appears to be a result of increased runoff for the remainder of the year and no change in absolute amounts during spring (Wahl 1991; Aguado et al. 1992). On the western slope of the Sierra Nevada, there have been no obvious trends in flood magnitude or frequency over the historical period. In rivers of the eastern slope, clusters of events at both extremes have been evident in recent years (Kattelmann 1992). Five of the largest eight to eleven snowmelt floods (in terms of volume) since the 1920s occurred from 1978 to 1986. Five of the smallest thirteen or fourteen snowmelt floods since the 1920s occurred from 1987 to 1991. Instantaneous peak flows have a similar distribution. For example, in Rock Creek, four of the ten largest annual floods and three of the six smallest annual floods occurred during the 1980s. These events support theories of some climatologists that extreme events are becoming more common in the western United States (Granger 1979; Michaelson et al. 1987). Variability in flow remains a defining characteristic of Sierra Nevada rivers.

Even the limited variability in precipitation and runoff that occurred in this century caused water managers to attempt to augment supplies through deliberate weather modification. Soon after the theoretical basis for cloud seeding to increase precipitation was established, the world's first operational program began in the eastern Sierra Nevada in 1948. Within the next few years, cloud seeding programs were started in the San Joaquin, Kings, Mokelumne, and Feather Rivers (Henderson 1995). A dozen programs were active in the Sierra Nevada in 1994 and 1995. Despite dozens of studies, the effectiveness of cloud seeding remains uncertain. Conventional wisdom suggests that a well-designed cloud seeding program may yield up to 6% additional stream flow (American Meteorological Society 1992). Hundreds of papers have been written on environmental effects of cloud seeding (e.g., Berg and Smith 1980; Parsons Engineering Science 1995), but major impacts have not been found, perhaps because of the uncertainty in the amount of precipitation augmentation. The amounts of the primary seeding agent, silver iodide, released in a typical year (7–18 kg [15–40 lb]) over a large river basin are several orders of magnitude less than quantities naturally present in soil.

SURFACE WATER QUALITY

The Sierra Nevada is generally regarded as producing surface water of excellent quality, meaning the water is suitable for almost any use and contains lower amounts of contaminants than specified in state and federal standards. Most of the runoff would be suitable for human consumption except for the risk of pathogens. Very little of the water of the Sierra Nevada can be considered highly polluted (i.e., contaminated with materials having potential adverse effects at concentrations above natural background). Areas of lower water quality correspond to those areas with greater human activities and access. Headwater streams are particularly sensitive to pollution because of low flow conditions and nutrient limitations. The relatively few point sources of pollution throughout the range are mostly associated with inactive mines, dumps, and towns. Many contaminants that enter Sierra Nevada streams can be considered non-point-source pollutants because they are generated over large areas. Livestock waste is an example of non-point-source pollution. Sediment is the most pervasive pollutant because its production may be increased above natural background levels by almost any human activity that disturbs the soil or reduces vegetation cover. Sediment augmented above natural levels usually impairs some beneficial uses of streams. Erosion and sediment are discussed separately in another section of this chapter. Ground-water quality is discussed in the section about ground water. Water temperature is treated in Kondolf et al. 1996.

Human activities in the watershed have the potential to alter nutrient cycling. A classic study in New England provided some of the first measurements of changes in nutrient budgets as a result of complete killing (but not removal) of trees in a small catchment (Likens et al. 1970). This study at Hubbard Brook found that loss of nitrates in stream flow increased by forty times in the first year following devegetation, and export of other nutrients increased several times. Studies in Oregon (Fredriksen 1971; Brown et al. 1973) suggested that typical harvesting procedures that impact less than half of a watershed with deep soils will not significantly contaminate small streams or risk serious declines in soil productivity (Brown 1980). However, frequent harvesting of large portions of catchments with shallow soils and low cation exchange capacity can result in substantial nutrient losses from soils to streams. Elevated concentrations of nitrates and phosphates may be expected in catchments with agriculture, fish farms, and residences. Most of the work on nutrient cycling in the Sierra Nevada has been done in the Lake Tahoe area (e.g., Coats et al. 1976; Coats and Goldman 1993). In one catchment in the Tahoe basin, biological processes effectively prevented release of nitrogen in nitrate form in surface water or ground water (Brown et al. 1990). These authors cautioned that creation of impervious surfaces allows nitrates to bypass potential sinks. Human activities that decrease residence time of water in soils have potential to increase nitrate export. Nitrate concentrations sampled in seventy-seven streams of the eastern Sierra Nevada were less than 1 mg/l in all cases and usually less than 0.1 mg/l, demonstrating that there is usually little export of nitrates in streams (Skau and Brown 1990).

Point-Source Pollutants

There are very few known localized sources of water pollution in the classic outfall-into-the-stream sense in the Sierra Nevada because of the virtual absence of industries that process chemicals and continuing abatement of the few existing sources. Point-source pollution has also been reduced very effectively under the Clean Water Act of 1972 and subsequent amendments. Municipal and industrial discharges are controlled through National Pollutant Discharge Elimination System permits. Most pollution of that general nature is associated with active and abandoned mines and is discussed in the section on mining. Industrial-type pollutants may also be found in the vicinity of many cities and towns and abandoned lumber mills. However, serious problems of this nature are not known to exist (Central Valley Regional Water Pollution Control Board 1957; Central Valley Regional Water Quality Control Board 1991; Lahontan Regional Water Quality Control Board 1993). Over the entire western slope, there are only ten "municipal and industrial discharger groups": Chester, Quincy, Paradise, Portola, Nevada City, Auburn, Placerville, Jackson, Sonora, and Bass Lake (Central Valley Regional Water Quality Control Board 1991). Water quality was considered impaired in streams receiving wastewater from Nevada City, Grass Valley, Placerville, Jackson, and the Columbia-Sonora area (Central Valley Regional Water Quality Control Board 1991).

Sewage

Most communities with a centralized population in the Sierra Nevada have common sewage collection and treatment systems. Discharges from treatment facilities are regulated by the regional water quality control board; however, short-term failures are a persistent difficulty. Disposal of treated wastewaters on land instead of directly into streams is encouraged where practicable (Central Valley Regional Water Quality Control Board 1991). An experiment in Tuolumne County demonstrated several problems with spraying treated effluent on hillsides: the soil became overloaded with nutrients, salts, and water, and algal growth effectively sealed the soil surface, minimizing infiltration (California Division of Forestry 1972). Effluent from a sewage treatment plant in the Lake Tahoe Basin was sprayed over a 40 ha (100 acre) area from 1960 to 1965. Even five years after application ceased, substantial amounts of nitrates were entering a creek downgradient from the site. A stand of Jeffrey pine at the site was also killed by the persistent high level of soil moisture (Perkins et al. 1975).

A significant fraction of the residences in the Sierra Nevada are too dispersed to allow connection to community sewage facilities and rely on individual septic systems (Duane 1996a). Septic systems in Nevada County have led to significant bacteriological contamination in streams below unsewered subdivisions (California Department of Water Resources 1974). Septic tank and leach field systems on individual lots provide a good example of cumulative watershed effects. The soils of a particular catchment have sufficient capacity to treat a particular quantity of sewage under a particular set of conditions. When the soil system is overloaded, some fraction of the waste or its derivatives is discharged to streams. Each residential septic system contributes only a small fraction of the total, but the community as a whole has polluted the catchment. Recreational developments such as ski areas and campgrounds also generate significant quantities of sewage and may have their own treatment facilities if geographically isolated. In the 1950s, Yosemite Valley was the most significant wastewater source in the upper-elevation parts of the San Joaquin River Basin (Central Valley Regional Water Pollution Control Board 1957).

Urban storm water runoff can add a variety of contaminants directly to streams. Pet waste can be a significant source of fecal coliform bacteria in some areas. Street runoff in the Lake Tahoe Basin is beginning to be routed into publicly owned lots to allow for some pollutant removal.

Even in the backcountry, inadequate disposal of human waste from dispersed recreationists has contaminated enough of the streams in remote areas of the Sierra Nevada to make consumption of any untreated water somewhat risky. Although the level of risk is unknown, pathogens including coliform bacteria, campylobacter, and Giardia have been found in many areas throughout the range (Hermann and McGregor 1973; Suk et al. 1986). In a survey of seventy-eight backcountry locations with varying levels of recreational use, Giardia cysts were found in 44% of water samples collected downstream of heavily used areas and 17% of samples from areas of relatively low use (Suk et al. 1987). Giardia cysts have also been detected in fecal matter of cattle grazing in backcountry areas (Suk et al. 1985). Recreational pack stock contribute to nutrient and bacterial pollution. Heavily used trails (e.g., Mt. Whitney) have had sufficient problems with human waste to warrant the installation of backcountry toilets. Low-level release of nutrients from wilderness campers have stimulated increased plant growth on lake bottoms (Taylor and Erman 1979).

Non-Point-Source Pollution

When non-point-source pollution gained widespread recognition as a critical water quality problem in the 1970s, administrative and regulatory approaches were lacking. Eventually, Congress (in the Clean Water Act of 1977 and Water Quality Act of 1987) and the Environmental Protection Agency adopted the concept of best management practices (BMP). This general concept can be stated as doing the best one can to minimize water pollution and meet water quality standards while still conducting the intended activities. Different approaches to developing and applying BMPs have been tried in different states. Ideally, BMPs should reflect the most cost-effective approach to minimizing water pollution in a specific area using practical technology (Dissmeyer 1993; Brown and Binkley 1994). Determining what is most effective and efficient in a particular region should be an iterative process of applying a practice, monitoring its effectiveness, evaluating the cost and impact, modifying the practice in its next application, and so on. Unfortunately, monitoring has been limited, so there is often little basis for improving techniques. However, the learning and refinement process has led to continual improvements in BMPs on national forests in California and on all lands in the Lake Tahoe Basin (U.S. Forest Service 1992; Tahoe Regional Planning Agency 1988). A recent review of forest management impacts on water quality concluded that the use of BMPs in forest operations was generally effective in avoiding significant water quality problems (Brown and Binkley 1994) . However, this report cautioned that proper implementation of BMPs was essential to minimizing non-point-source pollution and that ephemeral channels were often overlooked in the application of BMPs. Additionally, further development work is necessary for BMPs with respect to grazing, maintenance of slope stability, and avoiding losses of nitrates from soils (Brown and Binkley 1994). Much can be done to protect water quality simply by avoiding activities in sensitive areas, such as riparian zones, areas susceptible to mass movement, and areas where soils may become saturated and produce overland flow (Megahan and King 1985). The Tahoe Keys development in a former marsh on the upper Truckee River is an outstanding example of a major failure to respect such areas.

Forest Chemicals

Following the example of agriculture, forest management incorporated the use of fertilizers, pesticides, and herbicides in its operations during the 1960s and 1970s. As concerns about the environmental hazards of such chemicals have grown, their use appears to have decreased (Norris et al. 1991). Even at its peak, the use of silvicultural chemicals was tiny compared with that of agricultural chemicals. On the average, less than 1% of commercial forest land in the United States received any chemical treatment in a year (Newton and Norgren 1977). By contrast, most agricultural land receives multiple treatments every year.

Chemicals have been used in forest management for a variety of purposes (see Helms and Tappeiner 1996). Herbicides limit competition from other species so as to enhance opportunities for conifer regeneration and growth. Herbicide use has declined markedly since the early 1980s, when legal decisions in the Pacific Northwest limited their use and Region 5 of the U.S. Forest Service halted aerial applications of herbicides. However, chemical use now seems to be increasing again under new regulations. The use of insecticides has varied widely between years, depending on insect outbreaks (Norris et al. 1991). Fungicides and soil fumigants can control certain diseases and have been used mostly in tree nurseries. Rodenticides limit damage from gophers and other rodents, and animal repellents have been used to reduce damage to trees from porcupines and rodents. Fertilizers are used to enhance productivity by selectively compensating for nutrient deficiencies (Allen 1987). Fire retardants are the only class of forest chemicals that do not have a parallel in agriculture. They are used at margins of wildfires to slow the rate of fire spread.

Because pesticides, by definition, are toxic to some organisms, they pose hazards to some components of ecosystems. They have long been regarded as a particular threat to water quality and aquatic life (Brown 1980). Their use assumes that managers have decided that the pest that is the object of control efforts really should be eliminated or reduced in number. Therefore, the ecological risk associated with pesticides involves the consequences of that decision and the impacts on nontarget species. In general, the hazard to nontarget organisms depends on the exposure to significant doses and the toxicity of the chemical (Brown 1980). However, some groups of organisms, such as butterflies, are at risk from exposure to certain chemicals (see Shapiro 1996). Toxicological studies of forest chemicals in common use are reviewed by Norris et al. (1991).

Pesticides have the greatest potential to contaminate streams by direct (presumably unintentional) application and wind-borne drift into water courses. Toxicants used in fisheries management are applied intentionally to streams but may have a variety of unintended consequences (see Erman 1996). Spraying by ground crews is much more effective at placing all the pesticide where desired. The greatest potential for pesticides to appear in runoff exists when substantial precipitation occurs soon after the pesticide is applied. Opportunities for a chemical to reach a stream via overland flow depend on the distance from the stream to the closest point of chemical application, infiltration properties of soil and litter, the rate of flow toward the stream, and adsorptive characteristics of soil and organic matter (Brown 1980). Chemicals that reach streams may be removed through volatilization, adsorption on sediments, adsorption by aquatic biota, degradation by chemical, photochemical, or biological processes, and simple dilution with downstream movement (Norris et al. 1991).

Current practice generally limits insecticide and fungicide use to well-defined problems over relatively limited areas, such as insect-outbreak zones and nurseries. By contrast, herbicides can have rather broad application in forestry, and there is public concern about the potential for indiscriminate use. The Record of Decision on the California Region Final Environmental Impact Statement for Vegetation Management and Reforestation (U.S. Forest Service 1988) contains language prohibiting the use of hexazinone and similar herbicides "when they are expected to enter ground water or surface water, such as when soils are very sandy or have low clay or organic matter contents." A letter of October 30, 1990, to forest supervisors from the regional forester suggested that a margin of safety be established so that expected dose levels should be 100 times less than the dose level for which no adverse effects have been detected by laboratory studies. The standard that the Central Valley Regional Water Quality Control Board has established follows EPA practice as 200 parts per billion (ppb) for hexazinone (Stanislaus National Forest 1993). Monitoring for hexazinone in streams has been conducted on the Eldorado National Forest and Sierra National Forest after fall applications between 1991 and 1993. On the Eldorado, fifteen samples out of ninety contained hexazinone ranging from 1 to 19 ppb. No hexazinone has been detected and reported yet on the Sierra National Forest (Stanislaus National Forest 1993). However, a news media account suggested that hexazinone had killed riparian vegetation downstream of an application area on the Sierra National Forest in 1993.

Glyphosphate and triclopyr are two other herbicides that are being used more widely in the Sierra Nevada. Herbicide monitoring programs (Frazier and Carlson 1991) on three national forests in the Sierra Nevada in 1992 and 1993 found trace amounts of the two chemicals in only 3 of more than 120 samples, and those samples testing positive were suspected of being contaminated (Stanislaus National Forest 1993). In studies throughout the United States, chronic entry of herbicides into streams has not been observed (Norris et al. 1991). Artificial alteration of vegetation composition and cover has some potential for alteration of nutrient cycling. We are not aware of research concerning this issue at an operational scale. Pesticides are also widely used in residential areas in the Sierra Nevada and could cause localized contamination.

Fire retardants are applied during crisis situations without the opportunity for careful planning or management. Therefore, their impacts must be considered well before the time they are actually deployed. When aerial application of fire retardants was first used, the main active ingredient was sodium-calcium borate. After a few years, this material was noticed to have a tendency to sterilize the soil and restrict growth of new vegetation following the fire. In recent years, ammonium phosphate and ammonium sulfate have become the primary retardants in active use. Nitrogen in several forms is released as a breakdown product of these chemicals. Nonionized ammonia (NH_3) is the only reaction product that is highly toxic to fish. A series of experiments relating to environmental impacts of ammonium fire retardants found that the compounds had little adverse effect on soil fertility, contributed a short-duration pulse of ammonia to streams, and moderately elevated levels of nitrates in receiving waters (Norris et al. 1978). The quantity of nutrients released by burning is likely to overwhelm any signal of those resulting from retardant application.

Forest chemicals may have a variety of unintended indirect effects on ecosystems by performing more or less as intended but in the wrong places. Insecticides may kill aquatic insects and reduce food supplies for fish. Herbicides can kill aquatic plants and disrupt the food chain at higher levels. Herbicides can also kill riparian vegetation, thereby reducing cover and shade benefits for fish and possibly increasing sediment yields. Death of riparian vegetation can add much organic debris to streams over a relatively short time and possibly deplete dissolved oxygen as it decomposes and also reduce the longer-term supply of organic matter until vegetation is reestablished on the banks. Fertilizers can contribute to eutrophication if the receiving waters are nutrient limited. To restate the obvious, minimizing the adverse impacts of forest chemicals on aquatic ecosystems requires that the chemicals be kept away from the streams and riparian zones.

Atmospheric Deposition

During the 1980s, concerns about the potential effects of atmospherically derived pollutants on aquatic ecosystems (Roth et al. 1985; Schindler 1988) focused attention on high-elevation lakes of the Sierra Nevada (Tonnessen 1984; Melack et al. 1985). The California Air Resources Board initiated a comprehensive study of the sensitivity of a small alpine lake basin in Sequoia National Park as part of a statewide acid-deposition program (Tonnessen 1991). This study explored the hydrochemical processes and biotic responses of this high-elevation system to possible shifts in precipitation chemistry (e.g., Williams and Melack 1991; Kratz et al. 1994). Hydrology and water chemistry of six other high-elevation lakes have been monitored over the past few years (Melack et al. 1993), and deposition has been monitored at several sites (Melack et al. 1995). These studies indicate that the loading rates of hydrogen, sulfate, nitrate, and ammonia are relatively low in the Sierra Nevada compared with rates in other parts of the country. However, snowpack processes can produce a distinct ionic pulse in the early part of the snowmelt season that temporarily lowers the pH of streams and lakes in high-elevation catchments with little buffering capacity (e.g., Williams and Melack 1991). Such surface waters may be at risk of acidification if air pollution and acidic deposition increase (see Cahill et al. 1996). A comprehensive state-of-knowledge review of aquatic impacts of acidic deposition by the University of California at Santa Barbara and the California Air Resources Board should be completed in 1996.

Monitoring

Obtaining adequate knowledge of water quality conditions throughout the Sierra Nevada on a continual basis is challenging at best. Frequent and long-term sampling from dozens to hundreds of sites is necessary to respond to sudden events, detect long-term trends, enforce regulations on discharges, improve the effectiveness of best management practices, and assess overall status. Sampling methodologies and analytical techniques are now fairly well developed (Stednick 1991; MacDonald et al. 1991). Bioassessment techniques using aquatic invertebrates as an integrative index or screening tool of water quality conditions is gaining widespread acceptance (U.S. Environmental Protection Agency 1989). However, broad strategies and philosophies for deciding what parameters to measure in what locations for what purpose have yet to be refined. Interpretation of water quality data to provide a sound basis for management or regulatory actions remains problematic (Ward et al. 1986). Most agencies and individuals concerned with water issues probably find the scarcity of monitoring data frustrating and inadequate to meet their needs. Additions to the present monitoring network will require implementation of creative mechanisms to provide substantial funding. No single agency can accomplish all the necessary monitoring independently. Interagency coordination is needed to maximize efficiency from available funds.

Evaluations of Water Quality in Streams

Assessments of water quality are made by the Department of Water Resources, the Central Valley and Lahontan Regional Water Quality Control Boards, the Environmental Protection Agency, the U.S. Geological Survey, the U.S. Forest Service, reservoir operators and proponents, and various other agencies. Every other year, the State Water Resources Control Board compiles water quality data from the regional water quality control boards and presents its findings to the Environmental Protection Agency under section 305(b) of the federal Clean Water Act. The 1992 Water Quality Assessment listed twenty-one streams draining the west slope of the Sierra Nevada as having serious quality problems. The principal problems in more than half these cases were degradation of fisheries habitat and inadequate flow. Mine drainage was noted in four cases, and sedimentation was recognized as a problem in tributaries of the Feather River and Little Butte Creek. Recreational impacts were mentioned as an additive problem in some cases (California State Water Resources Control Board 1992a). More rigorous criteria were used on the eastern slope, where almost all streams had some impairment of water quality, usually from water diversion or overgrazing. A subset of those streams (Blackwood Creek, Bryant Creek, Carson River, Heavenly Valley Creek, Monitor Creek, and Ward Creek) had more serious problems where violations of water quality objectives had occurred either from sedimentation or mine drainage. A list of thirty streams throughout the Sierra Nevada with various kinds of toxic contamination appeared in a companion report (California State Water Resources Control Board 1992b). Unfortunately, this listing does not rank the problems in terms of severity, and some problems on the list are known to be much more significant than others. What is worse, there is no information available for the majority of streams in the Sierra Nevada.

The Central Valley Basin plan summarizes water quality in Sierra Nevada streams above 300 m (1,000 ft) as “excellent” in terms of mineral content (Central Valley Regional Water Quality Control Board 1991). In general, concentrations increased from east to west (downslope and downstream). The Chowchilla and Fresno Rivers had the highest levels of total dissolved solids among western-slope rivers, but those amounts were still much lower than for streams in the Central Valley. A major assessment of water quality in the Sacramento River Basin was started by the U.S. Geological Survey in 1994 and will continue through 1998.

An evaluation of water quality in ten rivers in the central Sierra Nevada was carried out from 1975 to 1987 (California Department of Water Resources 1989). Nine of the rivers had very low levels of total dissolved solids (less than 150 mg/l—adequate for most industrial applications and well below a state criteria for drinking water of 500 mg/l). The tenth river in the survey, the East Walker, occasionally had high levels of total dissolved solids (up to 800 mg/l). High-elevation lakes in the Sierra Nevada as a group had the lowest ionic concentrations of any region sampled in the United States (Landers et al. 1987).

Several studies have focused on the Truckee River. Because of the high public value of the clarity of Lake Tahoe, water quality in the Lake Tahoe Basin is more thoroughly monitored than that in any other river basin in the Sierra Nevada. Water quality in most of the tributaries to the lake would be considered fine if not for the high sensitivity of the lake to nutrient additions. Downstream of Lake Tahoe, the Truckee River has largely recovered from the intense insults to water quality of the 1870s to 1930s (log transportation on artificial floods, sawdust dumping from lumber mills, and chemical waste from a pulp and paper mill) (Pisani 1977). Today, the principal problem in the Truckee River above Reno is elevated temperature resulting from water storage in Martis Creek, Prosser, Boca, and Stampede Reservoirs (Bender 1994). Total dissolved solids have been in the 6 to 210 mg/l range. Naturally occurring uranium is found in Sagehen Creek, and iron is high in a few places within the Truckee River system (Bender 1994). Water quality problems have been identified on Leviathan/Bryant Creeks (bacteria, nutrients), Little Truckee (nutrients), and Trout Creek (total dissolved solids, suspended sediments) (California State Water Resources Control Board 1984).

Although the surface waters of the Sierra Nevada are no longer pristine in terms of quality or other attributes, most streams could rank as excellent or outstanding compared with conventional standards or water elsewhere in the state, nation, or world. However, water quality in the Sierra Nevada, as elsewhere, is intimately connected to water quantity. Reduction in natural flows because of diversions is perhaps the most widespread water quality problem. Water remaining in the stream must support the same habitat needs and dilute whatever material and heat loads that arrive downstream of the points of diversion. For these reasons, what is usually considered a quantity problem is also a problem of quality. Additionally, there are persistent problems in different river basins. In the Lake Tahoe Basin, nutrient loads that would be considered small anywhere else are accelerating eutrophication of the lake. Within many parts of the Feather River Basin, unstable stream banks resulting from long-term overgrazing and roads are producing sediment yields at the basin scale that are up to four times greater than natural yields. Throughout much of the Sierra Nevada, a few problem mines continue to leach heavy metals into streams, and mercury remains in the beds of many streams from a century ago. Isolated problems such as poorly designed and located septic systems and roads impact local portions of streams and should be correctable by moderate investments for improved water quality.

EROSION AND SEDIMENTATION

Soil erosion, mass wasting, channel erosion, and sedimentation are natural processes that alter the landscape and streams. They are important disturbance mechanisms in terrestrial and aquatic ecosystems. These geomorphic processes are critical in nutrient cycling, transport of organic matter, and creation of fresh surfaces for colonization (Naiman et al. 1992). The rates at which they occur are highly variable across the landscape and over time. These processes operate most intensely in association with major rainstorms and so can be considered episodic in nature. Nevertheless, streams tend to adjust their form to accommodate the long-term sediment supply. Processes that detach and transport particles of soil and rock downslope and downstream can be lumped together as erosion. Sedimentation occurs when these particles come to rest in transitory or long-term storage.

Aquatic Effects

Alteration of stream sediments can seriously impact populations of fish and other aquatic organisms. Aquatic ecosystems have developed in response to a particular regime of water and sediment flows and channel conditions. When conditions change, such as when annual floods cease because of a dam or the proportion of silt-size sediments increases because of a road built next to the stream, some organisms will benefit and some will suffer. Trout and other salmonids require streambed deposits of gravel-size particles in which to prepare nests (redds) for their eggs where there is substantial flow of water and dissolved oxygen. Until the fry emerge after two to six months, the redds are vulnerable to scour and deposition of other sediments that could block flow of water through the redd (Lisle 1989). When sediment inputs to a stream exceed the transport capacity of the channel, fine sediments (clays, silts, and sands) tend to accumulate on the bed surface (Lisle and Hilton 1992). Fine sediments have been found to fill substantial fractions of pools in streams on the Sierra National Forest that were known to have high sediment yields, such as Miami Creek (Hagberg 1993). These fine sediments often smother invertebrates, reduce permeability of streambed gravels and fish-egg nests (redds), impede emergence of fish fry, and cause poor health or mortality of fry at emergence because of reduced levels of dissolved oxygen (Burns 1970). Sedimentation also adversely impacts invertebrate habitat (Erman 1995). In many streams in the Sierra Nevada, suitable gravels for spawning are found only in isolated pockets and lower-gradient reaches (Kondolf et al. 1991; Barta et al. 1994). The limited extent of such areas increases their importance for fisheries maintenance. Fortunately, scour and deposition processes are highly variable within and between streams, so that some spawning areas are almost always available (Lisle 1989). Sediment transport processes in streams of the Sierra Nevada have been the subject of few studies (e.g., Andrews and Erman 1986), and even basic information is scarce. Much of the sediment in mountain streams consists of large particles known as bedload. In fourteen streams of the eastern Sierra Nevada, the proportion of bedload varied between 0% and 65% of the total sediment load (Skau et al. 1980).

Natural Sediment Yields

Natural surface erosion is generally regarded as small in the Sierra Nevada because of high infiltration capacity of the soils, predominance of snowmelt as a water input to soils, rarity of overland flow, predominance of subsurface flow, and relatively continuous vegetation cover. The sources and pathways of sediments supplied to stream channels are not completely understood. The channel system itself is an obvious candidate as a source for most of the sediment (King 1993). During persistent rainfall and peak snowmelt, the network of very small channels becomes rather extensive, mobilizing sediment from a large fraction of a watershed. Such sediment probably does not move very far but may be made available for transport by a high-magnitude runoff event. The sequence of events of different magnitudes can determine the net sediment transport over long time periods (Beven 1981). In the Sierra Nevada, the greatest potential for overland flow to occur appears to be below the snow zone in woodland-grassland communities between 300 and 900 m (1,000 and 3,000 ft) (Helley 1966). The maximum rates of sediment production have been observed in this same altitude range (Janda 1966). The woodland zone also was the primary sediment source in part of the American River Basin with annual erosion of about 150 m^3/km^2 (0.3 AF/mi^2) (Soil Conservation Service 1979).

Accelerated Erosion

Human activities often disrupt the natural geomorphic processes and accelerate erosion or destabilize hill slopes. Modeling erosion in the Camp and Clear Creek Basins suggests that disturbance, especially roads, can increase erosion many times above natural rates (McGurk et al. 1996). When soil loss and sediment transport occur at unusually high rates in response to some human disturbance, erosion and sedimentation become issues of concern. Accelerated soil loss is primarily a problem in terms of losing productivity for growing vegetation (Poff 1996). Excessive sedimentation can damage terrestrial plants and aquatic organisms. High levels of sediment deposition can also reduce the utility of facilities for water storage and diversion and hydroelectric production. At the extreme, hydraulic mining for gold on the west slope of the Sierra Nevada intentionally eroded entire hillsides. The resulting sedimentation in downstream river channels left deposits tens of meters thick. Sediment yield in the Yuba River was up to twenty-five times greater than natural rates (Gilbert 1917) and led to a legal decision effectively halting hydraulic mining. Activities that purposefully move soil, such as construction of roads and structures, have the greatest potential for increasing erosion. Activities that reduce vegetative cover and root strength can also increase erosion rates. Activities in and near stream channels have the greatest potential for altering sediment delivery and storage as well as channel form. For example, destruction of riparian vegetation can lead to massive streambank erosion, or dams can trap sediment from upstream while causing channel incision or narrowing downstream.

Processes involving movement of large units of soil or rock rather than individual particles are collectively known as mass wasting. Landslide activity is a typical mass failure in which a portion of a slope fails all at once. Movement may be catastrophic in seconds or progressive over years. Mass wasting may be important in providing a material supply to channels slowly through soil creep or suddenly when a debris flow reaches a stream, but it is not regarded as a major erosive agent in most of the Sierra Nevada (Seidelman et al. 1986). Mass movement typically occurs when most of the pores in the material become filled with water. The positive pressure of the pore water and its added mass may exceed the strength of the material, and failure of part of the slope may occur. Unusually high rates of water input to previously wet soils can lead to large numbers of landslides in the Sierra Nevada (De Graff et al. 1984). Disturbance of slopes accelerates the natural occurrence of landslides (Sidle et al. 1985). Excavations across slopes for roads intercept water flowing downslope through the soil and increase pore water pressure at the exposed seepage face. In granitic portions of the Sierra Nevada, ground-water flow is often at a maximum at the interface between the porous coarse-grained soils and underlying relatively impermeable bedrock (De Graff 1985). Exposure of this layer can bring large quantities of water to the surface (Seidelman et al. 1986). Such excavations also reduce the mechanical support for adjacent parts of the slope. Tree roots are often important in maintaining the integrity of a slope. Minimum strength occurs about ten years after fire or timber harvesting when roots from young trees have not yet compensated for the progressive loss of old roots (Ziemer 1981). Most opportunities to minimize mass wasting as a consequence of road construction and forest harvesting involve commonsense approaches to avoiding accumulation of subsurface water on steep slopes (Sidle 1980; McCashion and Rice 1983).

In years of high precipitation with large individual storms, the number, extent, and size of mass movements increase well above those of years with modest precipitation. Landslides were particularly active during the wet years of 1982 and 1983. In both those years, springs and seeps appeared in places they had not been noticed before, including many road cuts and fills. More than $2 million in damage occurred to roads on national forests in the Sierra Nevada during 1982, and additional damage estimated at more than $1 million occurred in 1983 (De Graff 1987). A landslide in the American River canyon blocked U.S. 50 for April, May, and June of 1983. Sustained high levels of soil moisture and ground water occurred throughout the winter and spring of each year. Additional water input from rainfall, combined rainfall and snowmelt, and snowmelt alone triggered the unusual number of failures (Bergman 1987; De Graff 1987). However, there seems to be relatively little interaction between high flows and initiation of landslides within the inner gorges of Sierra Nevada streams (Seidelman et al. 1986). Landslides can also be initiated by earthquakes (Harp et al. 1984) and summer thunderstorms (Glancy 1969). An extraordinarily intense storm occurred in the headwaters of the South Fork of the American River on June 18, 1982 (Kuehn 1987). About 100 mm (4 in) of rain fell in 30 minutes and produced a peak flow of about 200 $m^3/s/km^2$ (19,000 $ft^3/s/mi^2$). These values of precipitation intensity and specific runoff are records for the Sierra Nevada and well above values assumed to be the maximum possible in the range (Kuehn 1987). The event also caused a large debris torrent in a small basin that had been burned the previous year.

Roads

Roads are considered the principal cause of accelerated erosion in forests throughout the western United States (California Division of Soil Conservation 1971a; California Division of Forestry 1972; Reid and Dunne 1984; McCashion and Rice 1983; Furniss et al. 1991; Harr and Nichols 1993). Roads destroy all vegetation and surface organic matter, minimize infiltration and maximize overland flow, oversteepen adjacent cut-and-fill slopes to compensate for the flat roadbed, and intercept subsurface flow, directing more water across the compacted surface (Megahan 1992). Stream crossings by roads are particularly effective at increasing sediment yields because of their direct impact on the channel. Stream banks are excavated for bridges and filled for culverts. Failure of inadequately designed and constructed culverts adds large amounts of sediment to streams. Increases in fine sediment and decreases in fish populations were associated with the number of culverts and roads near streams on the Medicine Bow National Forest in Wyoming (Eaglin and Hubert 1993). A classic study in the granitic batholith of Idaho found that sediment yields relative to an undisturbed forest increased by 60% as a result of logging and by 220 times (22,000%) from road construction (Megahan and Kidd 1972). A compilation of studies in the Oregon Coast Range showed that the quantity of mass movements associated with roads was 30 to 300 times greater than in undisturbed forest and was more than 10 times greater than that associated with large clear-cuts (Sidle et al. 1985). Large highway projects also produce significant amounts of sediment, with fill slopes often providing the most easily transported material (Howell et al. 1979). During major storms, highways are often damaged and provide much sediment to streams. For example, during February 1986, four serious debris flows in the Truckee River canyon closed Interstate 80, and sixty-three road failures occurred along 55 km (35 miles) of the Feather River Highway 70 (McCauley 1986; Keller and King 1986).

Land Development

Construction activities also have the potential to increase erosion rates (California Division of Soil Conservation 1971a). Residential construction around Lake Tahoe has been a major contributing factor in accelerating erosion and increasing nutrient inputs to the lake (Tahoe Regional Planning Agency 1988). In Nevada County, even by 1970, more than 35% of the length of streams in the county had been damaged by siltation and stream-bank erosion resulting from subdivision development (Gerstung 1970). Only a few examples of major erosion are well documented. For example, erosion from a single storm on freshly cleared land for a new subdivision in Plumas County killed 80% of the aquatic life in Big Grizzly Creek (California Division of Soil Conservation 1971b). Sediment from a failure of a channelization project for a new golf course largely filled Hunter's Reservoir on Mill Creek (California Division of Soil Conservation 1971b).

Logging

Timber harvesting itself seems to have relatively little effect on soil erosion compared with the construction of roads used for log removal (see McGurk et al. 1996; Poff 1996). Although soil disturbance associated with cutting trees and skidding logs exposes mineral soil to raindrop splash as well as to rill development where soils are compacted, in practice, comparatively little soil leaves harvested areas. The California Division of Forestry (1972) has asserted that "timber harvesting, when done carefully with provisions made for future crops, has little adverse effect upon soil erosion, sedimentation, or water quality." During his evaluation of sedimentation from hydraulic mining, Gilbert (1917) noted that erosional effects of timber harvesting were minor compared to other, nonmining effects such as overgrazing and roads. Several factors appear to mitigate potential adverse effects of harvesting: only small and discontinuous areas are compacted to an appreciable extent; infiltration capacity is generally maintained over large areas; a lot of slash is left behind; and some type of vegetation usually reoccupies the cutover land quickly. Another important factor to date has been the concentration of harvests in the most productive sites and most accessible areas, which tend to be on relatively gentle slopes. As harvesting moves to less desirable and steeper ground, risk of erosion and mass failure will increase. Avoidance of lands sensitive to disturbance, such as slopes greater than 60%, streams with soil-covered inner gorges, riparian areas, meadows, and known landslides, will minimize erosion associated with timber harvest (Seidelman et al. 1986).

Despite mitigating factors that can reduce logging-related erosion, some harvest units lose large amounts of soil. Such areas appear to be a minority, although their local effects can be quite significant. The degree of soil compaction seems to be a controlling influence on subsequent erosion (Adams and Froehlich 1981). Severe sedimentation in the West Fork of the Chowchilla was noted after upstream areas were virtually denuded of vegetation to supply fuel for a smelter at the Mariposa Mine about 1900 (Helley 1966). The headwaters of Last Chance Creek on the Plumas National Forest had erosion rates from 150 to more than 300 m^3/km^2 (0.15 to 0.66 AF/mi^2) during a severe thunderstorm following a salvage sale in the Clark Fire area (Cawley 1991). A series of studies of northern California streams, including some in the Sierra Nevada, found significantly greater amounts of fine sediments and altered benthic invertebrate communities downstream of logged slopes (Erman et al. 1977; Newbold et al. 1980; Erman and Mahoney 1983; Mahoney and Erman 1984). Some effects of logging on streams were persistent for more than a decade (Erman and Mahoney 1983; O'Connor 1986; Fong 1991). A study of erosion rates from small plots recently started by Robert Powers of the Redding office of the Pacific Southwest Research Station of the U.S. Forest Service should improve our understanding of erosion processes and rates in the Sierra Nevada.

Christmas tree plantations have been found to have very high rates of erosion (Soil Conservation Service 1979). Management for Christmas trees typically attempts to minimize other ground cover that would compete for water and, therefore, makes the plantations more vulnerable to erosion.

Measured Sediment Yields

Compared to other parts of California and the United States, the Sierra Nevada overall has relatively low sediment yields (Brown and Thorp 1947). A map of soil erodibility for California shows the absence of "very severe" ratings throughout the Sierra Nevada except for areas of western Plumas and eastern Butte Counties and in part of Yuba County, whereas such ratings are common in the Coast Range (California Division of Soil Conservation 1971a). General estimates shown on another statewide map show that the Sierra Nevada has the lowest sediment yield in California (generally less than 100 $m^3/km^2/yr$ [0.2 $AF/mi^2/yr$]) (California Division of Forestry 1972). Sediment transport measurements in a variety of streams in the eastern Sierra Nevada were generally less than 10 m^3/km^2 (0.02 AF/mi^2), but there were exceptions of up to 450 m^3/km^2 (0.9 AF/mi^2) (Skau and Brown 1990). An estimate of annual sediment yield for the San Joaquin Basin above the San Joaquin valley based on a comprehensive geological investigation was about 38 m^3/km^2 (0.08 AF/mi^2) (Janda 1966). For comparison, an average value for the entire United States is 76 m^3/km^2 (0.16 AF/mi^2) (Schumm 1963). The Colorado River Basin produces about 300 $m^3/km^2/yr$ (0.6 $AF/mi^2/yr$) and the Columbia River yields about 30 $m^3/km^2/yr$ (0.06 $AF/mi^2/yr$) (Holeman 1968). A compilation of sediment studies from forested regions provided an average rate of about 30 $m^3/km^2/yr$ (0.06 $AF/mi^2/yr$) from forest land in the United States excluding the Pacific Coast Ranges (Patric et al. 1984). A Soil Conservation Service report classified sediment yields below 150 m^3/km^2 as "low" with respect to nationwide rates (Terrell and Perfetti 1989).

The best means of determining sediment yields over long time periods is with repeated bathimetric surveys of reservoirs (Dunne and Leopold 1978; Hewlett 1982; Rausch and Heinemann 1984). Comparison of the bottom topography after a span of a few years allows calculation of the change in volume of sediment over the time interval (Rausch and Heinemann 1984; Jobson 1985; Mahmood 1987). Most of the information for the Sierra Nevada came from a Soil Conservation Service study in the 1940s (Brown and Thorp 1947). This same data set has been republished many times (e.g., Dendy and Champion 1978; U.S. Army Corps of Engineers 1990; Kondolf and Matthews 1993), but there have been few additions to it. Until 1975, the Committee on Sedimentation of the Water Resources Council compiled data for reservoir surveys throughout the United States (Dendy and Champion 1978). Records of suspended sediment at water quality monitoring stations reported by the U.S. Geological Survey were also examined but did not prove to be useful. Almost all stations are downstream of dams, and uncertainty resulting from the assumptions required to estimate annual totals would mask any trends over time.

Estimates of average annual sediment yields in the Sierra Nevada were compiled from all available sources (tables 30.3 and 30.4). These values provide order-of-magnitude approximations of sediment yield. The numbers should be considered uncertain and may contain some serious errors resulting from the original measurements, assumption of inappropriate densities if reported as mass rather than volume, and conversion from some unusual units. The period of measurement varies greatly between basins, resulting in different sediment delivery regimes depending on the inclusion of floods. Some of the values in tables 30.3 and 30.4 were based on total basin area above the reservoir or measurement site, and others were based only on the sediment contributing area not regulated by upstream reservoirs and lakes. Tables 30.3 and 30.4 illustrate that sediment yields vary considerably between river basins but that the generalizations mentioned above seem appropriate. Most reported values are less than 100 $m^3/km^2/yr$ (0.2 $AF/mi^2/yr$), which is the simple average of table 30.4. This value can be visualized as a tenth of a millimeter in depth over the entire contributing area, which is not how sediment is produced, but the conversion is useful for illustration. The relatively high sediment yields of the Kaweah and Tule are somewhat surprising, especially in the Kaweah Basin, which is largely in Sequoia National Park. However, this short period (1960–67) includes the massive floods of February 1963 and December 1964, which would tend to bias the annual sedimentation rate.

Unfortunately, very few measurements of reservoir sedimentation have been reported in the past two decades. The one-time measurements in isolation do not provide sufficient information or provide much confidence in using the values to infer differences between basins or over time. Comparison of modern sedimentation rates with those summarized by Brown and Thorp (1947) would be very useful in determining whether more intensive land management has altered sediment yields at the basin scale. A highly detailed bathimetric survey of Slab Creek Reservoir (in South Fork American River Basin) in 1993 revealed less than 0.5 m of accumulation on the bed of the reservoir since 1968 but did not estimate the volume of the deposit (Sea Surveyor, Inc. 1993). Crude estimates based on information provided in the report suggest an annual sediment yield less than 10 m^3/km^2 (0.02 AF/mi^2).

TABLE 30.3

Sediment yields from reservoir surveys.

Site	Drainage Area (km^2)	Elevation of Dam (m)	Interval (years)	Annual Sediment Yield (m^3/km^2)	Annual Sediment Yield (AF/mi^2)	Source
Sacramento Tributaries						
Magalia	21	681	18–46	150	0.3	Brown and Thorp 1947
Yuba						
Bullards Bar	1,226	488	19–39	130	0.2	Brown and Thorp 1947
Bear						
Combie	330	488	28–35	360	0.8	Brown and Thorp 1947
American						
Ralston	1,095	362	66–89	80	0.2	EA 1990
Folsom	6,955	146	55–91	250	0.5	California Department of Water Resources 1992 in Kondolf and Matthews 1993
Cosumnes						
Big Canyon	14	232	34–45	30	0.1	Brown and Thorp 1947
Blodgett	8	48	40–45	80	0.2	Brown and Thorp 1947
Calaveras						
Davis	19	34	17–45	120	0.3	Brown and Thorp 1947
Gilmore	13	69	17–45	60	0.1	Brown and Thorp 1947
McCarty	1	350	37–45	140	0.3	Brown and Thorp 1947
Salt Spring Valley	47	357	82–45	100	0.2	Brown and Thorp 1947
Stanislaus						
Copperopolis	5	297	15–45	20	0.03	Brown and Thorp 1947
Lyons	102	1,287	30–46	50	0.1	Brown and Thorp 1947
Mokelumne						
Pardee	980	173	29–43	70	0.2	Brown and Thorp 1947
Pardee	980	173	29–95	150	0.3	EBMUD 1995
Upper Bear	72	1,791	00–46	10	0.2	Brown and Thorp 1947
Schadd's	72	886	40–90?	100	0.2	Euphrat 1992
Tuolumne						
Don Pedro	2,550	186	23–46	100	0.2	Brown and Thorp 1947
La Grange	3,842	92	95–05	40	0.1	Brown and Thorp 1947
Merced						
Exchequer	2,616	216	26–46	80	0.2	Brown and Thorp 1947
San Joaquin						
Crane Valley	135	1,026	01–46	80	0.2	Brown and Thorp 1947
Kerckhoff	3,031	296	20–39	80	0.2	Brown and Thorp 1947
Mammoth Pool	2,550	1,026	59–72	90	0.2	Anderson 1974
Kings						
Hume	62	1,616	09–46	10	0.03	Brown and Thorp 1947
Pine Flat	3,948	296	54–56	90	0.2	Dendy and Champion 1978
Pine Flat	3,948	296	54–56	30	0.1	Anderson 1974
Pine Flat	3,948	296	56–73	80	0.2	Dendy and Champion 1978
Wishon	445	2,000	58–71	10	0.03	Anderson 1974
Kaweah						
Terminus	1,453	212	61–67	360	0.8	Dendy and Champion 1978
Tule						
Success	1,006	190	60–67	400	0.9	Dendy and Champion 1978
Kern						
Isabella	5,309	776	53–56	35	0.1	Dendy and Champion 1978
Isabella	5,309	776	56–68	90	0.2	Dendy and Champion 1978
Walker						
Weber	6,241	1,284	35–39	10	0.02	Dendy and Champion 1978
Weber	6,241	1,284	?	30	0.05	Soil Conservation Service 1984

TABLE 30.4

Sediment yields from suspended sediment records and other estimates.

Site	Drainage Area (km^2)	Annual Sediment Yield (m^3/km^2)	Annual Sediment Yield (AF/mi^2)	Source
Feather				
Oroville	9,244	90	0.2	Jansen 1956
Oroville	9,244	100	0.2	U.S. Army Corps of Engineers 1990
Oroville	9,244	120	0.3	Soil Conservation Service 1989
East Branch North Fork	3,131	270	0.6	Soil Conservation Service 1989
Yuba				
Nonmining		160	0.3	Gilbert 1917
Hydraulic mining		3,300	7	Gilbert 1917
Castle Creek	10	70	0.1	Anderson 1979
Castle Creek (logged)	10	220	0.5	Anderson 1979
American				
Auburn dam site	2,485	130	0.3	U.S. Army Corps of Engineers 1990
Cameron Park		70	0.2	Soil Conservation Service 1985
Onion Creek	4	30	0.06	Dendy and Champion 1978
Cosumnes				
Michigan Bar	1,098	30	0.06	Anderson 1979
Stanislaus				
New Melones	2,314	60	0.1	U.S. Army Corps of Engineers 1990
Merced				
Happy Isles	463	3	0.01	Anderson 1979
Chowchilla				
Buchanan		40	0.1	Helley 1966
San Joaquin				
Kerckhoff		40	0.1	Janda 1966
Kings				
Teakettle	7	10	0.02	Dendy and Champion 1978
Kern				
????	2,613	150	0.3	Anderson 1979
Truckee				
Tahoe Basin	839	30–60	0.05–0.1	Tahoe Regional Planning Agency 1988
Tahoe (in 1850)	839	3	0.01	Tahoe Regional Planning Agency 1988
Upper Truckee	142	21	0.04	Hill and Nolan 1990
General Creek	19	13	0.03	Hill and Nolan 1990
Blackwood Creek	29	65	0.14	Hill and Nolan 1990
Ward Creek	25	63	0.13	Hill and Nolan 1990
Snow Creek	11	3	0.005	Hill and Nolan 1990
Third Creek	16	20	0.04	Hill and Nolan 1990
Trout Creek	95	12	0.03	Hill and Nolan 1990
Squaw Creek	21	12, 93	0.03, 0.2	Woyshner and Hecht 1989
Sagehen	28	2	0.005	Anderson 1979

Recent bathimetric surveys of Pardee Reservoir on the Mokelumne River suggest that the average annual rate of sediment deposition has more than doubled since the last survey in 1943 (150 m^3/km^2 [0.3 AF/mi^2]) (EBMUD 1995). Parts of the Mokelumne River Basin have been extensively roaded and logged in the past few decades, and there has been much concern about apparent increases in sediment yield from some of the erodible soils (e.g., Euphrat 1992). These new results offer evidence of a sedimentation response to large-scale disturbance of a forested basin. Much greater sedimentation rates are apparent in Camanche Reservoir, downstream of Pardee. Additional studies are needed to determine the sources of sediment trapped in Camanche. At rates of deposition suggested by the recent sediment surveys, half the original storage volume of Camanche would be lost in 380 years, and half of the original storage volume of Pardee would be lost in 600 years.

An Example of Disturbance Effects

The North Fork Feather River has perhaps the worst erosion and sediment problem of any large basin in the Sierra Nevada. Conditions were certainly much worse in several drainages during the hydraulic mining era and for following decades until most of the debris was flushed into the lower reaches of the river systems. Nevertheless, sediment production under current conditions in the North Fork Feather River can be considered high compared with natural background rates (Plumas National Forest 1988). A comprehensive evaluation of sediment sources in the basin found that about 90% of the erosion and about 80% of the sediment yield is accelerated (induced by human activities) (Soil Conservation Service 1989). That estimate and the current sediment yield of about 270 m^3/km^2 (0.6 AF/mi^2) imply that under natural conditions, sediment yield would be about 50 m^3/km^2 (0.1 AF/mi^2). The difference is caused mainly by bank erosion where riparian vegetation has been eliminated by overgrazing and erosion from road cut-and-fill slopes (Soil Conservation Service 1989; Clifton 1992, 1994). Mining, logging, and overgrazing before 1900 initiated widespread changes in hydrologic conditions of the land surface and channels. Gullying and channel erosion were noted by the 1930s (Hughes 1934). After about 1940, stream channels widened rapidly with little reestablishment of riparian vegetation along new channel banks. More than 75% of the stream length in the Spanish Creek and Last Chance Creek watersheds was found to be unstable and eroding (Clifton 1992). Bank erosion contributes sediment directly into the streams, which in turn transport it to lower elevations. About one-third of the forest roads are eroding rapidly as well and often contribute sediment directly into streams where roads cross or run parallel (Clifton 1992). By contrast, sheet and rill erosion appear to produce very little (less than 2% of the total) of the sediment in the basin because the nearly continuous vegetation cover protects the soil (Soil Conservation Service 1989). A cooperative effort among local landowners, public agencies, Pacific Gas and Electric Company, and private individuals is attempting to reduce erosion throughout the basin (Wills and Sheehan 1994; Clifton 1994). The Pacific Gas and Electric Company is involved because it operates two small reservoirs in the canyon of the North Fork Feather River as part of its hydroelectric network. Sediment is rapidly filling the reservoirs, interfering with operation of the control gates on the dams and accelerating turbine wear (Harrison 1992). A costly program of dredging and reconstruction of the dams to allow pass-through sluicing of sediment during high flows is being planned in addition to participation in the upstream erosion control program (Pacific Gas and Electric Company 1994). A few other reservoirs in the Sierra Nevada have filled with sediment and had to be dredged. This topic is discussed further in the section on dams and diversions.

GROUND WATER

Ground-water storage is generally limited throughout the Sierra Nevada compared with surface water resources. However, ground water is significant in providing small amounts of high-quality water for widely scattered uses, such as rural residences and businesses, campgrounds, and livestock watering. Without ground water, the pattern of rural development in the Sierra Nevada would be quite different. The geology of the mountain range is not conducive to storage of large quantities of subsurface water. Ground water occurs in four general settings: large alluvial valleys; small deposits of alluvium, colluvium, and glacial till; porous geologic formations; and fractured rocks. The shallow aquifers tend to be highly responsive to recharge and withdrawals. The effects of low precipitation in the recent drought cannot be readily separated from effects of increased pumping on declining water levels in some areas. Tens of thousands of wells tap ground water throughout the Sierra Nevada for local and distant municipal supply, individual residences, and recreational developments. Nearly one-quarter of all homes in the Sierra Nevada are supplied by private, on-site wells (Duane 1996a). More than 8,000 residents of Tuolumne County alone depend on wells for water supply. In 1982, there were about 5,800 wells in Placer County, 6,100 in El Dorado County, 3,400 in Amador County, and 2,200 in Calaveras County (California Department of Water Resources 1983a). Some of these wells were west of the SNEP study area. Contamination appears to be minimal overall (California State Water Resources Control Board 1992a).

Ground-Water Resources

A few ground-water basins in the Sierra Nevada store vast quantities of water, but they have limited recharge compared with some proposed exploitation plans. Honey Lake/Long Valley has a capacity of about 20 billion m^3 (16 million AF) in alluvial and lake sediments up to 230 m (750 ft) thick. The quality is poor in some areas, with high concentrations of boron, fluoride, sulfate, sodium, arsenic, and iron. Sierra Valley stores about 9 billion m^3 (7.5 million AF) of water in sediments up to 370 m (1,200 ft) deep. Hot springs occur in the center and southern part of the valley, and excessive amounts of boron, fluoride, and chloride have been found in some wells. Several schemes have been proposed for mining ground water from both Sierra Valley and Long Valley for export to Reno. Martis Valley contains about 1 billion m^3 (1 million AF) of water, is an important water source for the Truckee area, and has the lowest concentration of total dissolved solids (60–140 mg/l) of any large ground-water basin in the state. By contrast, ground water in the 4 billion m^3 (3.4 million AF) volume Mono basin is highly mineralized. The Owens Valley is the largest ground-water basin partially within the SNEP study area, with a storage capacity of about 47 billion m^3 (38 million AF). Export of ground water from the Owens Valley to southern California began in 1970. This ground-water development led to declines of ground water dependent vegetation (e.g., Groeneveld and Or 1994) and continues (as of 1995) to be the subject of negotiations between Inyo County and the City of Los Angeles. Smaller alluvial valleys include Indian and American Valleys of the Feather River Basin, Tahoe Valley in the upper Truckee River Basin, Slinkard and Bridgeport Valleys of the Walker River Basin, and Long Valley in the Owens River Basin.

Many wells in the Sierra Nevada are located in shallow deposits of glacial till, alluvium, and colluvium. These surficial deposits, which are often only a few tens of meters deep (Page et al. 1984; Akers 1986), are fairly porous and convey water to streams. Deeper deposits are capable of serving the needs of small communities but may be sensitive to recharge conditions. Placer County (1994) has determined that ground water in the foothills is not a reliable source of water for future growth.

Some rocks and other geologic formations, like buried river channels, are relatively porous and transmissive. Hydrogeologic properties of these formations are highly variable, as are well yields. Locating a well is often hit-or-miss, but drillers familiar with an area can usually find sources of water adequate for residential use. Mixed results have been obtained in recent drilling through the complex layers of till, volcanic ash, and basalt found in the Mammoth Lakes area. Some wells have been highly productive, and others have quickly gone dry.

Granitic and metamorphic rocks of the Sierra Nevada are essentially impermeable except where fractured. In some locations, the joint and fracture systems can transmit significant quantities of water. A recent study in the Wawona area of Yosemite National Park investigated fracture systems and the regional movement of deep ground water (Borchers et al. 1993). Most wells in southwestern Nevada County, and presumably in other parts of the foothills with similar geology, are located in areas of fractured rock (Page et al. 1984). Of some 13,000 wells drilled in Placer, El Dorado, Amador, and Calaveras Counties between 1960 and 1982, more than 90% were located in hard rock (California Department of Water Resources 1983). The size and frequency of fractures decline with depth away from the surface, so the more productive wells in Nevada County have been less than 60 m (200 ft) deep. Mean yield in that study area was less than 70 l/min (18 gal/min) (Page et al. 1984), with about half the wells yielding less than 38 l/min (10 gal/min) (California Department of Water Resources 1974). Average well yields determined from drillers' logs were less than 80 l/min (20 gal/min) in both Nevada and Amador Counties (Harland Bartholomew and Associates et al. 1992; California Department of Water Resources 1990a). Wells in Tuolumne County are often more than 90 m (300 ft) deep and are adequate for domestic use. The drought between 1987 and 1992 limited recharge throughout the Sierra Nevada, and yields of many wells declined through the period. There is insufficient information available to determine whether the proliferation of wells throughout the foothills in the past decade has had a pronounced effect on preexisting wells.

Pumping of water for industrial uses has lowered water tables in western Tuolumne County (comments by Tuolumne Utility District in DEIS on Yosemite Estates). Ground-water pumping can also impact local stream flow. Interactions between ground water and streams are very complex in some areas of the Sierra Nevada where glacial till is interlayered with volcanic mudflows and ash and is dissected by old stream courses and faults (Kondolf and Vorster 1992). Drilling of supplemental water-supply wells for Mammoth Lakes raised concerns that pumping could further reduce flows in Mammoth Creek, which is already diverted as the principal water source for the town (Kattelmann and Dawson 1994).

In a small lake basin in the alpine zone of Sequoia National Park, water released from short-term subsurface storage accounted for less than 15% of the annual stream-flow volume, but it controlled the chemistry of stream and lake water for more than two-thirds of the year (Kattelmann 1989b).

Springs are an important water source for small demands that require minimal development. Because springs are often fed by shallow aquifers, they are more susceptible to contamination than deep sources and often require protection of their contributing areas. Dense vegetation resulting from decades of fire suppression may maximize transpiration losses from hill slopes above springs, thereby reducing spring flow. Developing springs as a water source usually alters or even eliminates riparian and aquatic habitat in the immediate area. Springs are one of the most threatened habitats in the Sierra Nevada (see Erman 1996). Springs as well as pumped water are commercially developed for packaging as mineral water. Bottled water operations are present in the northern and southern Owens Valley.

Ground-Water Quality

The mineral content of ground water is generally much higher than that of surface water. The long residence time of water in the ground allows it to dissolve minerals and accumulate ions. Nevertheless, total dissolved solids in ground water in the Sierra Nevada are usually not an impediment for use. Deeper ground water in parts of the Honey Lake/Long Valley Basin and the Mono basin and below Mammoth Lakes contain substantial concentrations of various ions. Concentrations of naturally occurring iron are sometimes too high for domestic uses (Thornton 1992; Placer County 1994). Some wells in Kern Valley have very high levels of fluoride. Shallow ground water may be contaminated with nutrients from septic and sewage disposal systems, livestock, and chemicals applied to farms and gardens. Nutrients found in ground water in the Lake Tahoe Basin were relatively low in an absolute sense, but they still contributed to enrichment of the lake waters (Loeb and Goldman 1979). Water quality problems of the larger ground-water basins in the Sierra Nevada identified in the biennial state water quality assessment included drinking water impairment from heavy metals, fuel leaks, volatile organic compounds, naturally occurring radioactivity, pesticides, and wastewater (California State Water Resources Control Board 1992a). Some wells in the foothills of the southern west slope of the Sierra Nevada have been found to contain concentrations of uranium, radon, and radium above state health standards (California Department of Water Resources 1990b). Water in certain hot springs has high levels of natural radioisotopes. High levels of radionuclides have also been found in wells of the Lake Tahoe Basin (California Department of Water Resources 1994).

The leaking underground storage tank problem has probably introduced fuels to ground water in isolated spots throughout the Sierra Nevada. Gasoline contamination has been documented in Bishop, Mammoth Lakes, Bridgeport, and Placer County. Tetrachloroethylene, a solvent used in dry cleaning, was found in two municipal wells in East Sonora. The wells were removed from service, and an expensive extension to surface water supply was installed. Old landfills are another potential source of contamination.

MINING

Historically, mining had the most intense impact on rivers of the Sierra Nevada. As discussed in the history section, hydraulic mining for gold until 1884 truly wreaked havoc throughout the Gold Country. Affected streams and hill slopes have been recovering ever since. In most cases, the degree of recovery is remarkable. Much of the region appears to have healed over the past century. In terms of their more obvious hydrologic and biologic characteristics, the streams have improved dramatically compared to photographs and descriptions of the nineteenth century. Stream channels are now largely free of mining sediment, although large deposits remain as terraces (James 1988). Riparian vegetation has become reestablished. Aquatic biota have returned to the streams, at least partially. Some fish species that would be expected are not present in rivers heavily impacted by mining (Gard 1994). We can assume that the present form of the ecosystems is simplified compared to the pre–gold rush situation, but we really do not know what the west slope of the Sierra Nevada might have looked like had gold not existed in the range. Unfortunately, the Gold Country was so heavily mined that "natural" streams are not available for comparison. Portions of streams that were lightly impacted could be compared to those that were heavily impacted, but doubt would remain about what constitutes "natural" conditions. The water projects initiated during the mining period and other associated land uses have further modified the hydrologic system.

Legacy of Hydraulic Mining

After the 1884 Sawyer decision and the 1893 Caminetti Act, hydraulic mining continued on only a sporadic basis where the debris could be kept on-site. Mines in three old hydraulic pits in the Yuba River Basin were active in the late 1960s: near French Corral, Birchville, and North Columbia (Yeend 1974). A few such mines continue operation today. When the original mines closed, there was no attempt at site reclamation, and the mines were simply abandoned. A variety of dams were constructed in attempts to prevent further movement of mining debris downstream (Rollins 1931). Only the larger, better-engineered structures did not fail. Dams such as Combie on the Bear, Englebright on the Yuba, and North Fork on the American have restrained vast amounts of mining debris from washing downstream to the Sacramento valley. An attempt to destroy a debris dam on Slate Creek with explosives was made in the 1960s by miners desiring another opportunity to recover gold. The initial bombing failed, but the structure is damaged and loses sediment during floods (Kondolf and Matthews 1993). Also along Slate Creek, a wooden wall retaining a large volume of mining debris appeared ready to fail in 1994. The hydraulic mine pits are slowly becoming revegetated, but they continue to release unnaturally high volumes of sediment as their walls continue to collapse until a stable slope angle is attained (Senter 1987). The unnaturally high sediment loads continue to affect aquatic biota (Marchetti 1994). A large open-pit gold mine that was operated at Jamestown until 1994 offers the first major opportunity for modern reclamation technology to be applied to a recently closed mine in the Sierra Nevada. The pit may also be used as a garbage dump. Current mineral potentials are discussed in Diggles et al. 1996.

Dredging

Massive riverbed dredging operations at the lower margins of the foothills persisted until 1967 (Clark 1970). The spoil piles may remain as a peculiar landscape feature for centuries. Some of the tailings in the Feather River were used in construction of the Oroville Dam, and other uses of the material and the land may be found. Small-scale suction dredging continues in many streams of the Gold Country. This activity has become widespread wherever there is easy access to the streams (McCleneghan and Johnson 1983). Powerful vacuums mounted on rafts remove stream gravels from the bed for separation of any gold particles, and the waste slurry is returned to the river, where the plume of sediment stratifies in the flowing stream. Turbidity obviously increases, and the structure of the bed is rearranged. The morphology of small tributaries can be dramatically altered by suction dredging (Harvey 1986; Harvey et al. 1995). Where stream banks are illegally excavated, the potential for damage is much greater. A study of effects of suction dredging on benthic macroinvertebrates showed local declines in abundances and species richness, but biota rapidly recolonized the disturbed sites after dredging stopped (Harvey 1986). Although dredging seems to have relatively little impact on adult fish, eggs and yolk-sac fry and amphibians within the gravel are usually killed by dredging (Johnston 1994). Dredging also has the potential to reintroduce mercury stored in sediments contaminated by early mining (Harvey et al. 1995; Slotten et al. 1995).

Underground Mining

Hard-rock mining often releases hazardous materials to ground water and streams. The nature and impacts of some of the typical mine effluents are reviewed by Nelson et al. (1991). Excavation of hard-rock mines exposes tunnel walls and tailings to water and oxygen and vastly increases the reactive surface area of minerals, allowing chemical reactions to occur at much faster rates than if undisturbed. If the mines or their waste piles contain sulfide minerals, oxidation in the flowing water can release sulfuric acid and metals into the drainage water. Exposure as a result of mining also allows reaction products to be leached from tailings piles or abandoned mines. Contaminated water can be flushed into streams in sudden pulses during storm runoff or slowly during base flow. In some cases, these products are highly toxic, and the runoff is acidic. The downstream extent of impacts along streams seems to depend on interactions between source concentrations, hydrologic characteristics of the mine or waste rock, storm characteristics, chemical behavior of the particular constituents, bacterial influences, presence of other substances as complexing agents, and dilution potential of the receiving waters. Fortunately, the mineralogy and geochemistry of most mines in the Sierra Nevada have resulted in relatively few serious surface-water problems (Montoya and Pan 1992). However, exceptions such as the Leviathan, Walker, and Penn mines have seriously degraded downstream areas. The substrate of a housing development built on tailings of the Central Eureka mine near Sutter Creek contains arsenic levels about seventy-five times greater than average values for soils in California. Discharge from mine dewatering and from rejuvenation of closed mines probably released toxic materials into nearby streams. Abandoned pits often fill with water and attract waterfowl and other wildlife. If the water contains toxic materials, these substances can enter the food chain.

Water Quality Impacts

An inventory of mines causing water quality problems has been developed by the Central Valley Regional Water Quality Control Board (1975). Mines in the Sierra Nevada included on that list appear in table 30.5. All except two are underground mines. The list is evenly split between gold mines and mines for other minerals, chiefly copper.

A more recent survey by the Central Valley Regional Water Quality Control Board (Montoya and Pan 1992) limited to the Sacramento valley investigated thirty-nine inactive mines from Butte Creek to the American River. Water quality of the drainage from these mines and waste piles was highly variable between mines and over time. For example, copper concentrations below the Spenceville mine on Dry Creek southwest of Grass Valley were up to eight times higher than EPA standards in the first hours of a rainfall-runoff event and then decreased with time. Such sudden spikes in concentrations may be harmful to aquatic life but are rarely captured in water quality sampling. Many of the adits of the different mines were dry when visited and were not releasing contaminants. Most of the mines studied in the Yuba River Basin were releasing high levels of arsenic because the gold in this region is associated with arsenopyrite minerals. Otherwise, mine runoff in this area was typically clear and was not acidic. Gold mines in the Bear River Basin were similar to those in the Yuba, but copper mines had acidic discharge with high levels of copper, zinc, cadmium, and other metals. Mines in the lower American River Basin near Folsom Lake were dry and did not appear to have serious water quality problems. The study demonstrated that surface-water quality problems associated with mines are highly site specific. Insufficient ground-water monitoring has been done in the vicinity of mines in the Sierra Nevada to identify potential problems.

The amount of mercury used in gold extraction in the Sierra Nevada and largely lost to soils and streams has been estimated at 3.4 million kg (7.6 million lb) (Central Valley Regional Water Quality Control Board 1987). Mercury is known to exist in streams below gold-ore processing sites; however, the bioavailability of mercury in the Sierra Nevada is not well understood. A survey found elevated concentrations of mercury in the upper tributaries of the Yuba, Bear, Middle Fork Feather, and North Fork Cosumnes Rivers

TABLE 30.5

Mines cited by the Central Valley Regional Water Quality Control Board (1975) as degrading local water quality.

Mine	Receiving Stream
Cherokee	Sawmill Ravine / Dry Creek / Butte Creek
Mineral Slide	Little Butte Creek / Butte Creek
China Gulch	Lights Creek / Wolf Creek / North Fork Feather River
Engel	Lights Creek / Wolf Creek / North Fork Feather River
Iron Dyke	Taylor Creek / Indian Creek / Wolf Creek / North Fork Feather River
Walker	Little Grizzly Creek / Indian Creek / Wolf Creek / North Fork Feather River
Kenton	Kanska Creek / Middle Yuba River
Malakoff Diggings	Humbug Creek / North Fork Yuba River
Plumbago	Buckeye Ravine / Middle Yuba River
Sixteen to One	Kanska Creek / Middle Yuba River
Dairy Farm	Camp Far West Reservoir / Bear River
Lava Cap–Banner	Little Clipper Creek / Greenhorn Creek / Rollins Reservoir / Bear River
Alhambra Shumway	Rock Creek / South Fork American River
Copper Hill	Cosumnes River
Newton	Copper Creek / Sutter Creek / Dry Creek / Mokelumne River
Argonaut	Jackson Creek / Dry Creek /Mokelumne River
Penn	Mokelumne River
Empire	Copper Creek / Black Creek / Tulloch Reservoir / Stanislaus River
Keystone	Penny Creek / Sawmill Creek / Black Creek / Tulloch Reservoir / Stanislaus River

(Slotten et al. 1995). The heavy metal is readily trapped in reservoir sediments, and lower concentrations have been measured below reservoirs than above (Slotten et al. 1995). Mercury concentrations exceeded 0.5 mg/kg in sediment samples obtained from Camp Far West Reservoir, Lake Wildwood, Lake Amador, and Moccasin Reservoir (Central Valley Regional Water Quality Control Board 1987). Certain bacteria can convert metallic mercury to a methylated form that can be incorporated in tissue. Mercury tends to accumulate in the food chain. Although the opportunity for bacterial mercury methylation is minimized in cold, swift streams, the process can occur in the calm waters of reservoirs (Slotten et al. 1995). However, the reservoirs do not appear to be net exporters of bioavailable mercury. Instead, they seem to be sinks for both bioavailable and inorganic mercury (Slotten et al. 1995). Tissue samples of fish caught in the Yuba River contained more than 1 mg/kg, and samples exceeding 0.5 mg/kg were found in fish caught in Pardee, Don Pedro, and McClure Reservoirs (Central Valley Regional Water Quality Control Board 1987). A National Academy of Sciences report suggests that mercury amounts in tissue exceeding 0.5 mg/kg may be injurious to animals.

The Penn mine near the lower Mokelumne River has been considered one of the worst abandoned-mine problems in the Sierra Nevada. The mine was opened in 1861 and operated continuously until 1919 and then sporadically until the 1950s. Copper and zinc were the primary products of the mine (Heyl et al. 1948). More than 16,000 m (55,000 ft) of tunnels and the associated spoil provide the opportunity for percolating ground water to become acidic and leach zinc, copper, and cadmium from the mine. Flushing of some of the mine shafts in 1937 killed fish for 100 km (60 mi) downstream. A series of retention ponds were constructed and other attempts were made to restrict movement of the contaminants into the river in the 1980s, but they have had limited effectiveness (California State Lands Commission 1993). Until 1929, water draining from the mine into the Mokelumne River was diluted by the large volume of discharge. However, after the construction of Pardee Dam by the East Bay Municipal Utility District and export of up to one-third of the annual volume of the river upstream of the mine, concentrations of contaminants in the Mokelumne increased (Slotten et al. 1994). The dam for Camanche Reservoir just downstream of the mine was completed in 1964. Toxic materials leached from the mine are stored in sediments trapped by the dam. The potential for resuspension of the metals is minimal as long as water levels are kept relatively high (Slotten et al. 1994). In December 1993, the Environmental Protection Agency ordered the East Bay Municipal Utility District to control pollution from the mine. However, the utility contends that it is not responsible for the mine, which was last operated by the federal government during the Korean War.

The Leviathan mine provides another example of a water quality problem resulting from an abandoned operation. A copper and sulfur mine on Leviathan Creek in the Carson River Basin near Monitor Pass was started by the Anaconda Copper Company in 1953. Overburden was dumped in the stream channel, causing the water to percolate through the material. Below the stream blockage, the water is highly acidic and polluted with toxic materials. The stream was sterile below the mine during the 1950s. In 1969, an isolated population of rainbow trout still existed in the unpolluted portion of Leviathan Creek above the mine. Below the mine, fish and macroinvertebrates were absent from 18 km (11 mi) of stream affected by the mine drainage. The effects of the pollution even extend for 3 km (2 mi) in the East Fork of the Carson River below the confluence with the contaminated creek (Davis 1969; Hammermeister and Walmsley 1985). Attempts at revegetating the spoils began in the 1970s (Everett et al. 1980).

Reclamation

California's Surface Mining and Reclamation Act of 1975 and amendments should prevent future disasters (Pomby 1987), but remediation of past problems requires massive investments. Even ascertaining the location of abandoned mines remains problematic (Desmarais 1977). Sealing of much of the Walker mine, a notorious problem in Plumas County, in 1987 significantly lowered copper concentrations in receiving waters and allowed partial recolonization of formerly sterile reaches by macroinvertebrates (Bastin et al. 1992). There is also a major question of liability in cleanup efforts. Current law holds those attempting remediation to be liable for any damage caused by their activities or, presumably, failure of the project to solve the problem. Therefore, under the cloud of legal liability, little action is undertaken by private or public agencies (California State Lands Commission 1993). Scores of small mines have been established under the terms of the antiquated 1872 Mining Act. In many cases, the properties are sources of sediment and toxic chemicals. Reform of portions of the Mining Act could finally alleviate some major land and water management problems associated with mining. Conversely, legislation has been introduced in California to weaken the state's regulations regarding reclamation of mined land.

Future Prospects

Changes in mineral economics and technology and new discoveries may lead to new mines. Reactivation of a large underground gold mine near Grass Valley has been proposed. Water pumped out of that mine would probably require thorough treatment before it could be discharged. In the eastern Sierra Nevada, the tungsten mine in Mt. Morgan on Pine Creek has been maintained on a standby basis awaiting an increase in the price of the metal. Reactivation of gold mines at Bodie and Independence Creek have been explored in recent years. A disseminated gold deposit in Long Valley near Mammoth Lakes has been identified through exploratory drilling in

1989–94. About one part per million of the ore is gold, which could be recovered through massive excavation and cyanide heap-leach processing.

Aggregate Mining

Sand and gravel are the most economically important nonfuel minerals mined in California. The $560 million value of sand and gravel produced in California in 1992 far surpassed the combined total value of all metallic minerals mined in the state (McWilliams and Goldman 1994). More aggregate is used per capita in California than in any other state, and the State Department of Transportation is the largest single consumer (California State Lands Commission 1993). Because aggregates are fundamental to most types of modern construction, they are used in almost every building and roadway project. The widespread demand and high transport costs of sand and gravel make aggregate production a highly dispersed mining activity (Poulin et al. 1994). Each 40 km (25 mi) of transport doubles the cost as delivered (California State Lands Commission 1993), so sources near the construction site are highly desirable. Materials excavated from stream deposits tend to be durable and have relatively few impurities and, therefore, are favored over hill slope deposits (Bull and Scott 1974).

Excavation within stream channels will obviously have direct effects on the fluvial system (Sandecki 1989; Kondolf and Matthews 1993). Removal of part of the streambed alters the hydraulic characteristics of the channel and interrupts the natural transport of bedload through the stream. The most immediate consequence is degradation of the bed both upstream and downstream. Creation of a hole in the streambed makes the channel locally steeper and thereby increases the shear stress on the bed. Erosion of the bed will propagate upstream as additional sections become steeper and erode progressively (Collins and Dunne 1990). The initial pit also serves as a bedload trap and relieves the stream of part of its load. The flowing water will then have greater availability to erode the bed in the downstream direction (Kondolf and Matthews 1993). The downcutting reduces the proportion of smaller sediments and can produce a bed composed of cobbles and boulders. Some stream reaches can lose their deposits of gravels that are suitable for fish spawning. The deeper channel can lower the local water table and kill riparian vegetation as the former floodplain dries out. Loss of the vegetation in turn makes the banks more susceptible to erosion. Incision of the channel limits the opportunity for overbank flooding to deposit sediments on the floodplain. These combined effects can result in dramatic changes in the overall form and structure of the channel and dependent aquatic and riparian habitat (Collins and Dunne 1990; Kondolf and Matthews 1993). Human structures in the channel such as bridges, culverts, pipelines, and revetments may be damaged by the geomorphic changes.

Gravel is also mined from streams by skimming a shallow layer off of gravel bars. Depending on the flow regime, distribution of particle sizes, and opportunities for establishment of riparian vegetation, a variety of complex channel and vegetation responses may occur (Kondolf and Matthews 1993). Mining of terrace deposits and abandoned channels can be problematic if the channel shifts enough to reoccupy the excavated areas. A swiftly flowing stream can be converted into a series of giant ponds if the floodplain and terraces are extensively excavated and then captured by the stream. Part of the lower Merced River suffered such a conversion in 1986 with serious impacts on a salmon population (California State Lands Commission 1993). Abandoned gravel pits and quarries well above the stream channel can also act as major sources of sediment input to streams (California Division of Soil Conservation 1971a).

The number and location of in-stream gravel operations in the Sierra Nevada is unknown, but large mines have been identified on the East Branch of the North Fork of the Feather, Middle Feather, North Yuba, Yuba near Camp Far West Reservoir, Bear, lower American, and Calaveras below New Hogan Dam (California State Lands Commission 1993). A major gravel mine operating on Blackwood Creek in the Tahoe basin increased sediment yield from the watershed about fourfold (Todd 1990). Smaller operations are assumed to be widespread throughout the Sierra Nevada. Reservoir deltas appear to be an environmentally benign source of aggregate, and removal would extend reservoir capacity. The delta of the Combie Reservoir on the Bear River has been mined for sand and gravel since 1946 (Dupras and Chevreaux 1984). Mining has occurred on the delta of Rollins Reservoir upstream from Combie (James 1988). Gold was recovered from sand and gravel operations during the construction of Friant Dam on the San Joaquin River in 1940–42 (Clark 1970).

Geothermal Resources

Geothermal energy is another subsurface resource that has potential adverse impacts on water resources when developed. Heat can be extracted from portions of the earth's crust that are unusually warm and close to the surface by pumping out hot water and using its heat to vaporize another fluid that drives turbines, which generate electricity. During the 1970s, many parts of the Sierra Nevada were explored for geothermal potential. Monache Meadows on the Kern Plateau was proposed for large-scale development. Geothermal energy in the Sierra Nevada has been developed most extensively in Long Valley near Mammoth Lakes. The large complex of geothermal power plants, located at Casa Diablo near the junction of Highways 395 and 203, had a capacity of more than 30 megawatts in 1991. The power plants operate as a completely closed system, reinjecting the water after some of its heat has been removed. After several years of operation, changes in nearby hot springs have been observed, and effects are suspected but not proven at springs feeding a fish hatchery downgradient. Additional geothermal development is being considered near Casa Diablo, Mono Craters, and Bridgeport Valley in Mono County.

DAMS AND DIVERSIONS

Impounding and diverting of streams are the principal impacts on the hydrologic system of the Sierra Nevada. While other resource management activities cause environmental alterations that, in turn, may affect stream flow, water management activities avoid the intermediate steps and intentionally and directly alter the hydrologic regime. The thoroughness of the hydraulic engineering in the Sierra Nevada that has been developed over a century and a half is probably underestimated by most water users in California. However, one simple fact stands out: no rivers reach the valley floor unaltered. Only three Sierra Nevada rivers greater than 65 km (40 mi) long flow freely without a major dam or diversion: Clavey, Middle Fork Cosumnes, and South Fork Merced Rivers (figures 30.2–30.4). Selected segments of the North Fork American, Middle Fork Feather, Kern, Kings, Merced, and Tuolumne Rivers receive some protection from additional dams under the National Wild and Scenic River System (Palmer 1993). Few streams get very far from their source before meeting some kind of structure. In the Mono Lake and Owens River Basins, about 730 km (460 mi) out of 850 km (530 mi) of streams are affected by water diversions (Inyo National Forest 1987). In California's Mediterranean climate, water is most available in winter and spring. Dams are built to reduce the peak flows of winter, provide irrigation water during the growing season, provide domestic and industrial water on a semiconstant basis, allow optimum hydroelectric generation, and secure some interannual storage for protection against drought. With so many uses of water, attempts to manage it are found throughout the Sierra Nevada.

Structures

The total number of water management structures in the Sierra Nevada is unknown but must be in the thousands. The storage capacity of all dams in the range is about 28 billion m^3 (23 million AF), which is about the average annual stream flow produced in the range. The dozen largest reservoirs (each with capacity greater than 500 million m^3 [400,000 AF]) account for about three-fourths of the rangewide storage capacity. The smallest dams in the Sierra Nevada are those built for minor domestic water supply on small creeks and may impound only a few cubic meters of water. Somewhat larger dams have augmented natural lakes and were often built for fisheries management purposes. Most of these dams were constructed before World War II, but a few continued to be built up to the 1960s. Their main purpose was to store water for releases in late summer to maintain some stream flow for fish survival. About thirty such dams were built on the Eldorado National Forest (1980).

Dams are constructed in a great range of sizes for various purposes. Dams of a few meters' height are found throughout the Sierra Nevada to improve hydraulic conditions for tunnel intakes diverting water for municipal supply or irrigation or toward powerhouses. Such dams or weirs are not intended to have any effect on the seasonal pattern of stream flow. Dozens of small dams for small-scale hydroelectric production were proposed throughout the Sierra Nevada under the favorable climate created by the Public Utility Regulatory Policy Act of 1978 (California Energy Commission 1981). Many of these projects were ill conceived and were based on unrealistically high projections of future energy prices. Only a small proportion of those proposed were ever built. Several existing and proposed hydroelectric projects are being reconsidered by their owners or proponents because of currently low prices for electricity. The larger diversion dams can store stream flow accumulated over a few days. Dams intended to redistribute water over time have storage capacities equivalent to the stream flow of at least several weeks. A few of the megaprojects can hold more water than is produced in an average year. These massive structures account for most of the storage in an entire river basin. For example, the New Melones Reservoir has 84% of the total storage capacity in the Stanislaus River Basin, while the next largest forty dams in the basin represent only the remaining 16% (Kondolf and Matthews 1993). The dam at Lake Tahoe controls only 1.8 m (6 ft) of storage, but the vast area of the lake makes its storage volume the ninth largest in the Sierra Nevada. The big dams in the Sierra Nevada cause many of the same problems as other large dams in the western United States (e.g., Hagan and Roberts 1973). These dams prevent the further migration of anadromous fish and completely change the water and sediment regimes downstream. The combined effects of all the large dams on rivers tributary to the Sacramento River have significantly modified the annual hydrograph of the largest river in the state (Shelton 1994).

The other critical structures in water management are the conduits and canals for transferring water between rivers or to powerhouses or users. The vast network of artificial waterways redistributes water over short and long distances. A water molecule can take a very circuitous journey from the mountainside to the valley through several pieces of the plumbing system. Many of the old ditches and canals originally constructed during the mining era and that still supply water for hydroelectric generation, municipal use, or irrigation have become a secondary channel system. They both collect water from and discharge water to soils and slopes. In a 160 km (100 mi) long canal network in El Dorado County, about half of the initial water plus any gains en route are lost to seepage (Soil Conservation Service 1984). Water-supply agencies have sought to increase the efficiency of their antique delivery systems by reducing seepage from the old ditches. Replacement of the open ditches with pipes avoids

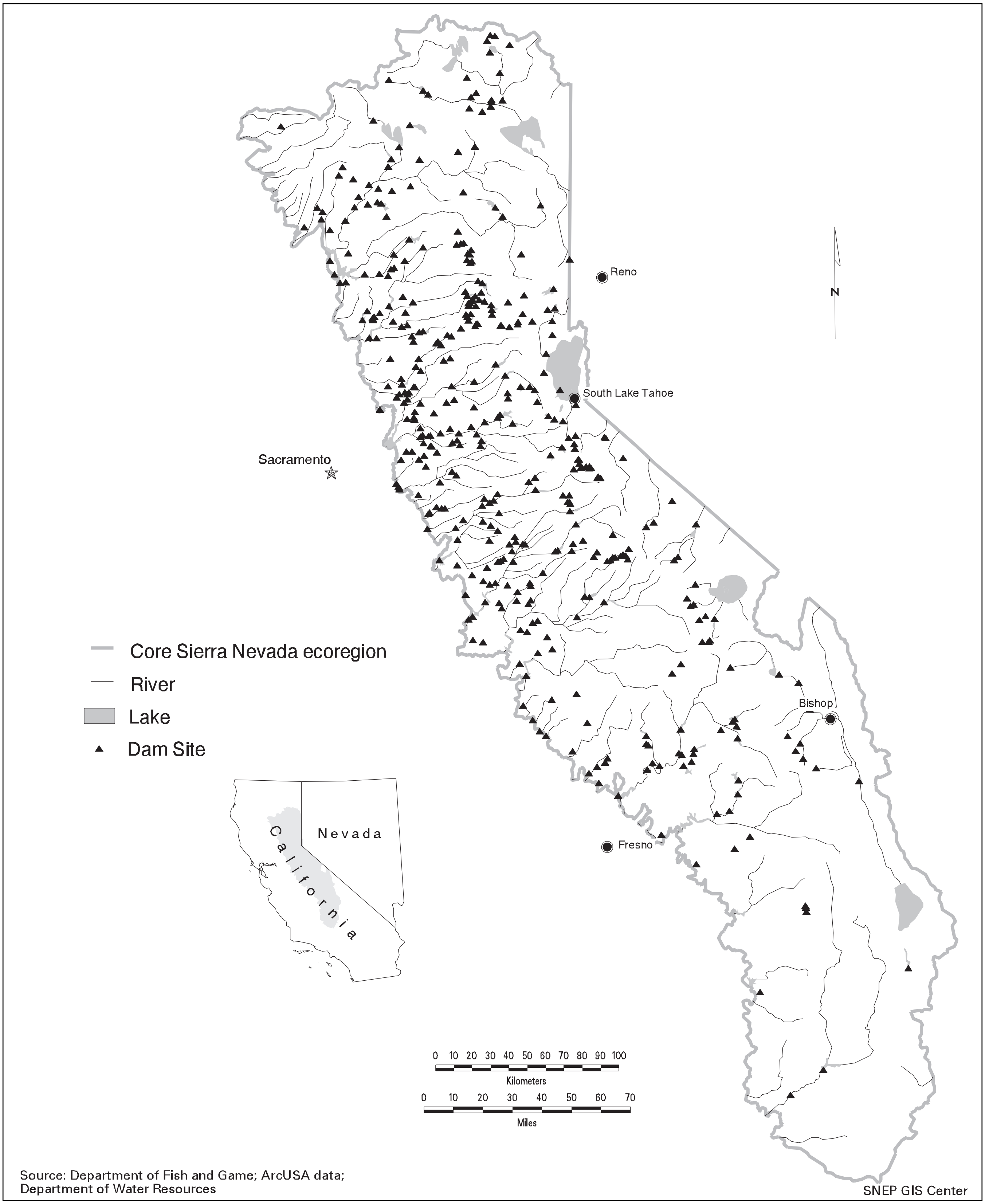


FIGURE 30.4

Larger dams that are regulated by the California Division of Dam Safety are found on almost all major streams of the Sierra Nevada.

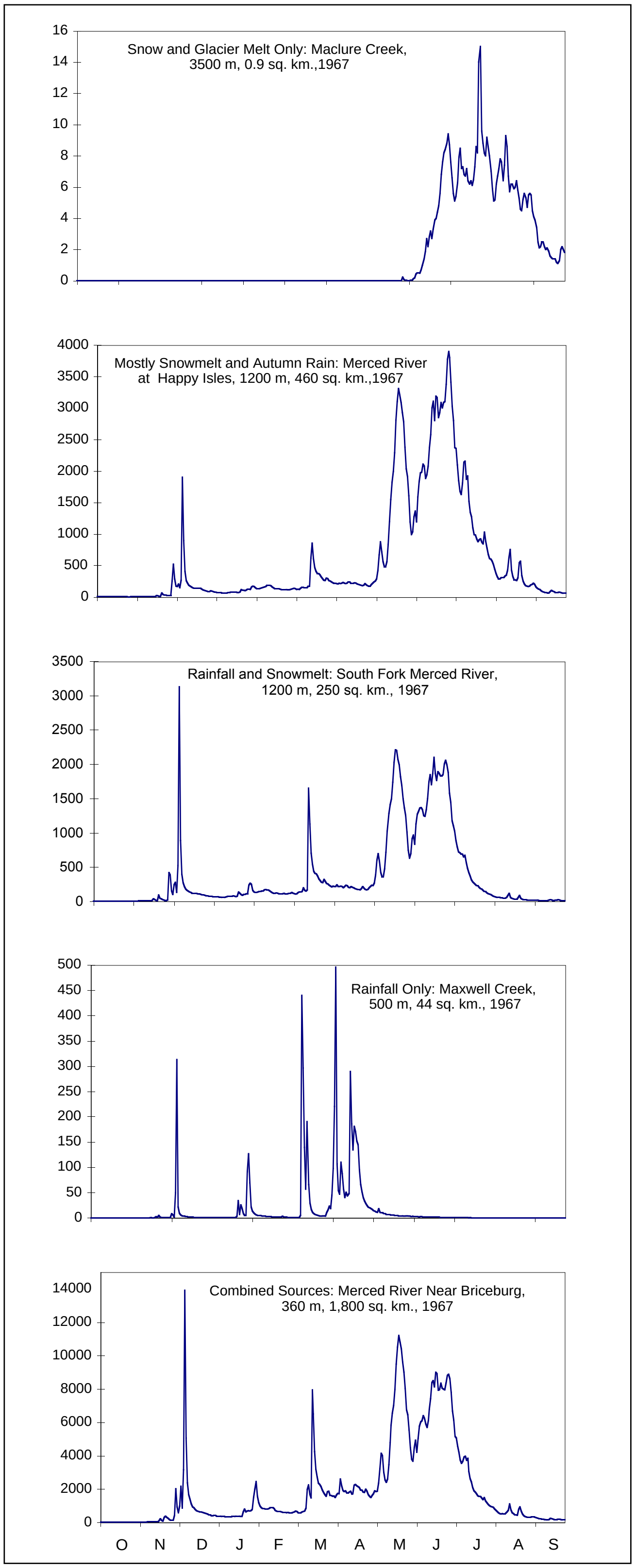


FIGURE 30.5

Watersheds with different elevation ranges and sources of runoff have different patterns of stream flow over a water year (October to September).

contamination of the enclosed water and provides greater operational flexibility. However, a finding by the staff of the State Water Resources Control Board held that improvements effectively constitute a new diversion that the ditch owner does not hold rights to. Leakage currently provides water for improvement of wildlife habitat and other uses. A decision is pending on this case involving the Crawford Ditch of the El Dorado Irrigation District (Borcalli and Associates 1993). Occasional failures of these (and more modern) canals result in serious erosion or debris flows. Four flume failures occurred along the Tule River just between 1962 and 1965. In 1992, the Cleveland fire in the South Fork of the American River Basin destroyed a large portion of the El Dorado Canal, which supplies about a third of the total water to the El Dorado Irrigation District. In November 1994, a fallen oak blocked the Tiger Creek Canal, diverting water to the slope below and eroding hundreds of cubic meters of soil.

Environmental Consequences

The construction, existence, and operation of dams and diversions have a variety of environmental effects. Inundation of a section of stream is the most basic impact. A river is transformed into a lake. The continuity of riverine and riparian habitat is interrupted. To creatures that migrate along such corridors, this fragmentation has consequences ranging from altering behavior of individuals to devastating populations. Dams have the potential to alters downstream flows by orders of magnitude and, at the extreme, can simply turn off the water and dry up a channel. Changing the natural transport of water and sediment fundamentally alters conditions for aquatic and riparian species. Changing stream flow also has dramatic impacts on chemical and thermal attributes of downstream water. The abundance of impoundments in the Sierra Nevada is impressive when one realizes that virtually all flat water at the lower elevations of the west slope is manmade. The terrain is simply not conducive to the formation of natural lakes below about 1,500 m (5,000 ft).

An obvious impact of water management is alteration of the natural hydrograph (temporal pattern of stream flow). For example, during the snowmelt season, the daily cycle of runoff and recession may be transformed into a constant flow. A series of hydrographs from streams in and near Yosemite National Park illustrate natural stream flow patterns generated under various watershed and climatic conditions at different elevations (figure 30.5). Dams are built to change those patterns (figure 30.6). Diversions not associated with large impoundments change the volume without much effect on timing (figure 30.7). Large projects usually alter both volume and timing (figure 30.8).

High Flows

The most obvious alterations in formerly natural hydrographs are decreases in peak flows. The size of an impoundment and

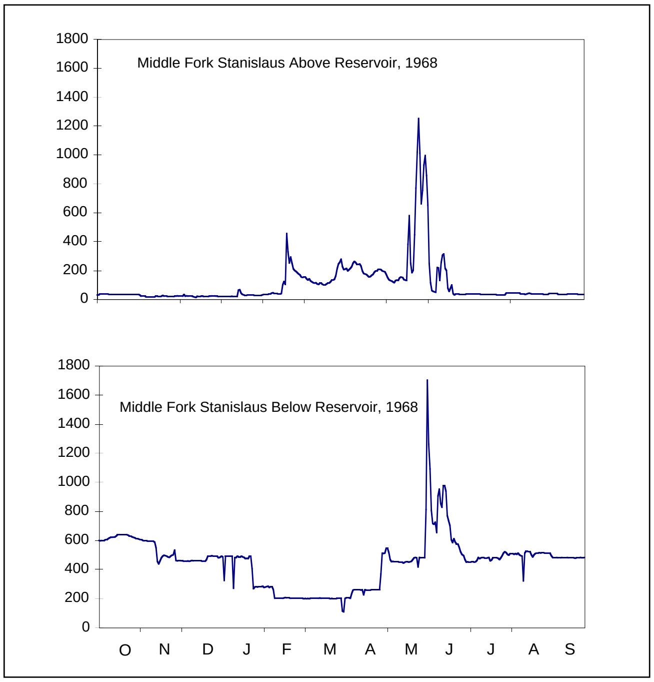


FIGURE 30.6

Storage reservoirs without diversions can greatly modify the natural hydrograph without reducing the annual volume.

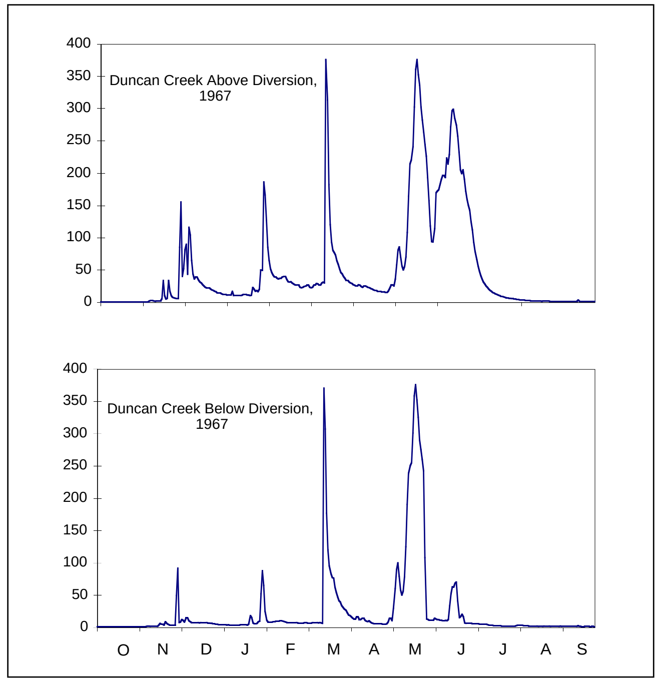


FIGURE 30.7

Diversions at small dams with minimal storage reduce the volume of stream flow without eliminating the natural pattern of fluctuations.

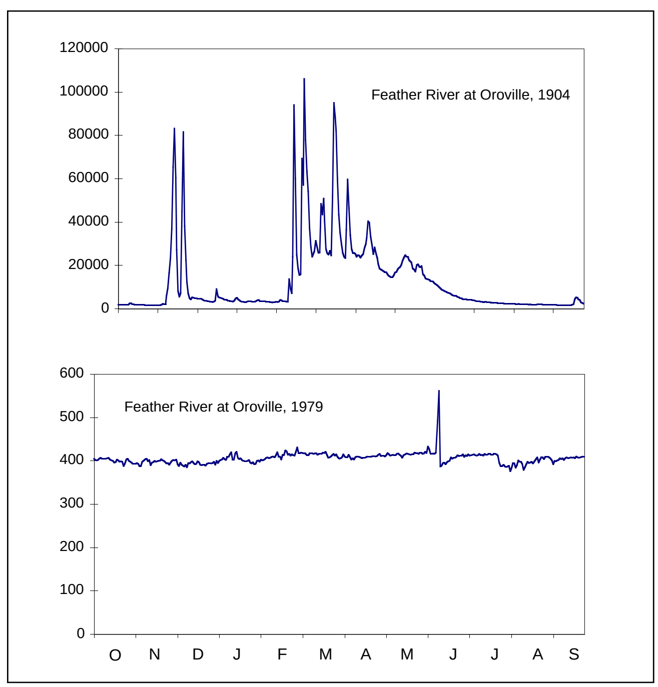
its flood reservation (management rules to keep a portion of the reservoir unfilled depending on the risk of floods at different times of the year) determine its ability to capture floodwaters and release them at a controlled rate. Small structures must pass the bulk of a flood without much influence. Large reservoirs can absorb large inflows by increasing the amount of water stored. Peak flows below some major reservoirs are reduced to essentially nothing as the dams perform their flood control functions. In a simplistic sense, all dams have a threshold for flood control. They can eliminate floods immediately downstream up to the point at which their storage capacity is exceeded. After they are filled, they exert no further control on stream flow. Of course, few reservoirs are operated in a static mode except small recreational impoundments such as Hume Lake. Most large reservoirs in the Sierra Nevada are multipurpose facilities whose releases are carefully controlled depending on inflows that are forecast, consequences of releases downstream, irrigation and power demands, and probability of additional precipitation.

Low Flows

Reservoir management also determines the releases under nonflood conditions. In the most severe cases, no water is allowed to flow in the natural channel; the entire natural flow is diverted elsewhere. Many streams in the Sierra Nevada, as in the classic example of inflows to Mono Lake, were completely dewatered below the points of diversion. In other

FIGURE 30.8

The largest reservoirs and associated diversions completely change the availability of water downstream. Note the extreme difference in scale (thousands of cubic meters per second in 1904 versus a constant 11 m^3/sec in 1979) after the Oroville Dam was completed.



cases, low flows are augmented, and the streams run at unnaturally high (and often constant) levels throughout the year. Below some hydroelectric powerhouses, discharges related to power demands can fluctuate wildly over a few hours. Afterbays allow regulation of the water released to the river.

Reservoir releases that partially resemble a natural hydrograph probably have the least adverse impact on downstream ecological processes. The minimum (and relatively constant) flow requirements on many water projects may serve to keep fish alive, but they are quite different from the flow regime that the aquatic community evolved with. Greater consideration of downstream ecological needs could be incorporated in the operations of many reservoirs without incurring major costs. The opportunities for alterations in release scheduling and their potential benefits and costs need to be explored on a project-by-project basis.

Changes in the flow regime also impact water quality. When stream flow is diminished substantially, there is less volume available to dilute contaminants entering downstream. In 1994, the U.S. Supreme Court decided that states had the authority under the Clean Water Act to regulate reservoir releases in the context of managing water quality. In some cases, reservoirs can improve riverine quality by allowing contaminants adsorbed on particles to settle out of the water column. However, this same process may be converting some reservoir beds into storage deposits of heavy metals (Slotten et al. 1994, 1995).

Water Temperature

Temperatures of streams below dams are affected by the volume and temperature of reservoir releases. If little water is released from a dam in summer, streams can become unnaturally hot because the radiant energy of sunlight on the channel is absorbed by a smaller volume of water than under natural flow conditions. Dams may be designed to release water from different depths in the lake. Reservoirs become thermally stratified like most natural lakes. In summer, stored water tends to be warmer near the surface, so releases from upper levels will result in higher temperatures than releases near the base.

Evaporation

The reservoirs behind the dams also export water to the atmosphere. Lakes lose water by evaporation roughly in proportion to their surface area. Creation of large expanses of open water by damming a river can significantly increase the opportunities for water losses from a watershed. Up to a meter of annual evaporation can be expected from reservoirs in most of the Sierra Nevada (Harding 1935; Longacre and Blaney 1962; Myrup et al. 1979).

Sediment Storage and Transport

Reservoirs dramatically change the sediment transport regime of a river. Virtually all bedload and most suspended load is deposited when a river enters the still water of a reservoir. The coarser fraction of the sediments forms a delta at the upper end. Deposits tend to be progressively finer toward the dam. When the water level is lowered, the streams cut through the deposits and relocate materials closer to the dam. Under some conditions, this channel incision can progress upstream (Galay 1983). With the extensive water development in most river basins of the Sierra Nevada, changes in sediment delivery should be considered throughout the basin. Each dam in the network affects the channel below it. With the presence of many dams upstream, contributing areas for sediment are often much smaller than contributing areas for water (in the absence of exports out of the basin).

Most of the geomorphic adjustments to dams occur downstream. These channel changes occur in response to shifts in sediment delivery and flow regimes, especially peak flows. Whatever water is released has significantly less sediment than when it entered the reservoir. Unless releases are minimal, the sediment-free discharge has the capacity to entrain and transport particles from the bed and banks of the downstream channel. Progressive lowering or degradation of the riverbed may occur after dam completion. Typical consequences of degradation include lowering of ground-water levels and consequent loss of riparian vegetation, reduction in overbank flooding and deposition of sediments and nutrients, bank erosion and loss of land, exposure of bridge foundations, and abandonment of diversion intakes (Galay 1983). The severity of channel incision depends on the size distribution of particles in the bed, characteristics of the channel, how the reservoir is operated and the sequence of flood events following construction (Williams and Wolman 1984). Downcutting seems to be greatest in rivers with fine-grained bed materials and where flood peaks are not greatly reduced by the dam. However, larger dams usually reduce flood peaks substantially and thereby limit the rate of degradation (Milhous 1982). Where channel incision occurs below dams, the finer particles are removed, and the larger cobbles and boulders are left behind. As the bed becomes coarser or "armored," it is more resistant to erosion and interferes with salmonid spawning. Also, downcutting decreases the channel gradient slightly, and degradation becomes somewhat self-limiting. The bed of the Yuba River below Englebright Dam has become armored with large cobbles and boulders but is still susceptible to incision during the largest floods (Kondolf and Matthews 1993). Conversely, flood control is so effective below both Pardee and Camanche Dams that channel degradation has not occurred and the gravels are immobile (BioSystems Analysis 1990, cited by Kondolf and Matthews 1993). Unfortunately, we lack any information about the condition of channels before placer mining and dam construction. Therefore, we are unable to make definitive statements about what constitutes natural channel conditions in most of the Sierra Nevada, although channels were unlikely to have been as armored as many are currently.

Where streambeds are not armored with large materials and are not actively degrading, fine sediments can interfere with fish spawning. Salmonids require gravels with sufficient pore space to allow interstitial flow to bring oxygen to eggs. Fine particles may be deposited between the gravels and limit the flow of water. Higher discharges are necessary on occasion to cleanse the gravels. Control of high flows by dams eliminates the opportunity to flush the fine sediments out of the spawning gravels. Many studies have been conducted in the past decade to define how much water is needed for this flushing function, and many rules-of-thumb have been suggested. However, variability in fluvial processes among streams illustrates the need to actually observe flows that begin to entrain particles of a particular size rather than depend on generalized procedures to estimate flow releases necessary to remove fine sediments from spawning gravels (Kondolf et al. 1987).

Limiting the size and frequency of floods below dams has also altered conditions for riparian vegetation. As total discharge and scouring flows decrease, riparian vegetation is able to become established in the former active channel (Williams and Wolman 1984). Roots stabilize the bank materials, and the plants slow overbank flows, which allows deposition of additional sediment. Gradually, the channel becomes narrower, and large trees occupy former parts of the channel. If allowed to become well established, mature riparian vegetation can resist significant flows. Confining the stream to a narrower channel can increase hydraulic forces on the bed and lead to incision and loss of riparian vegetation. To some degree, dams mimic the effects of long-term droughts on vegetation-channel interactions (Mount 1995). Depending on characteristics of the channel and plants, establishment of riparian vegetation can be enhanced by either higher or lower summer flows than occurred before dam construction. Encroachment of vegetation into river channels has been noted below Tulloch, Don Pedro, La Grange, and McClure Reservoirs (Pelzman 1973). Augmentation of flows at the receiving end of trans-basin diversion has widened channels and has pushed back riparian vegetation, as in the case of the upper Owens River.

Although larger dams seem to have sufficient space to store sediment for hundreds of years, at least at rates determined in the 1940s, smaller structures can become overwhelmed with sediment in just a few years. Unusually large floods can completely fill smaller diversion works, as occurred at Log Cabin Dam on Oregon Creek and Hour House Dam on the Middle Yuba in 1986 (Kondolf and Matthews 1993). Assuming that the dam is to remain in operation, the accumulated sediment must be removed. How that removal is accomplished can have an assortment of impacts. Dredging, trucking, and disposal of the sediments in a stable location has been a costly approach to the problem. Ralston Afterbay on the Middle Fork American River has had sediment removed on six occasions between its completion in 1966 and 1986 (Georgetown Ranger District 1992). The average annual rate of filling of about 80 m^3/km^2 (0.2 AF/mi^2) is not excessive compared with that of other basins, but the Ralston Afterbay has a capacity of only 3.4 million m^3 (2,782 AF) with 530 km^2 (205 mi^2) of unregulated contributing area above it (EA Engineering, Science, and Technology 1990). Location of suitable sites for long-term storage of removed sediments within a short distance from the reservoir has been difficult (Georgetown Ranger District 1992). The small forebays on Southern California Edison's Bishop Creek system have also required dredging of accumulated sediments. Estimates of the costs of dredging and transportation depend on access and distance to a disposal site and have ranged from \$26/m^3 (\$20/yd^3) (EA Engineering, Science, and Technology 1990) to about \$3,500/ m^3 (\$2,700/yd^3) (Kondolf and Matthews 1993).

Another option for removal of accumulated sediments is sluicing. Opening sluice gates or an outlet tunnel allows water levels to fall and sediment to be resuspended and flushed out with the water. This action creates a sudden pulse of sediment downstream. Problems have arisen when sluicing has been conducted during summer months, at times when flows are inadequate to disperse the redeposited sediment. Sluicing of Forbestown Reservoir on the South Fork Feather River in 1986 left a thin layer of sand over the entire channel well downstream of the dam. Another example was Democrat Dam on the Kern River in 1986. In the years following sluicing, high flows did not occur, and sand remained within the channel until scouring flows occurred in 1992 (Kondolf and Matthews 1993). Accidental releases of sediment occurred on the Middle Yuba River from Hour House Reservoir in 1986 and from Poe Dam on the North Fork of the Feather River in 1988. More than \$1 million was spent excavating sand out of the channel below Hour House Dam, but a flood during the early stages of the North Fork Feather cleanup conveniently flushed all the excess sediments out of the channel (Ramey and Beck 1990; Kondolf and Matthews 1993).

When sediment is flushed out of reservoirs at low flows, it will be redeposited close to the dam; however, when it is introduced at higher flows, it will usually be carried downstream and dispersed. Engineering approaches to letting sediments pass through dams during high flows are being considered at several sites. The Pacific Gas and Electric Company (1994) is designing pass-through systems to retrofit two of its dams on the North Fork Feather River. Sediment is rapidly filling the reservoirs, complicating operation of the dams, and accelerating turbine wear (Harrison 1992). Such pass-through systems could allow reservoir operations to interfere less with natural sediment transport and could have geomorphic benefits with regard to channel degradation below dams (Kondolf and Matthews 1993).

Failure

Catastrophic failure of impoundments is always a concern of those living below dams. Sudden releases of water also have great potential for dramatic environmental change. During the gold-mining era, dam failures were fairly common, both because of design flaws and because of intentional releases to rearrange gold-bearing sediments in the practice known as booming. Early debris dams were also intentionally destroyed to allow fresh access to impounded gravels and to create new storage space. Unintentional collapse of the English Dam on the Middle Fork of the Yuba (Ellis 1939; McPhee 1993) in June 1883 released almost 18 million m^3 (15,000 AF) of water suddenly and cleaned out much of the stored mining debris in that channel (James 1994). Excessive water releases from an upstream dam washed out a small dam on Bishop Creek in June 1909. Following failure of the Saint Francis Dam in the Ventura River Basin in 1929, the Division of Dam Safety of the Department of Water Resources has regulated larger dams and inspected them at least annually. Dams that are either more than 7.6 m (25 ft) tall and store more than 62,000 m^3 (50 AF) or, alternatively, more than 1.8 m (6 ft) tall regardless of capacity or impound more than 19,000 m^3 (15 AF) regardless of height are regulated by the Department of Water Resources (1988). Modern dams have little risk of failure; however, failures are not unknown. The best-known dam collapse in the Sierra Nevada in recent decades was that of the Hell Hole Dam on the Rubicon in December 1964 (Scott and Gravlee 1968). Failure of the North Lake Dam during a storm in September 1982 produced the largest flood of record on Bishop Creek and severely damaged one of the powerhouses. During the massive floods of February 1986, the coffer dam at the Auburn Dam site failed when diversion tunnels became clogged and the dam was overtopped. Structural failure of a penstock during high-pressure testing at the Helms Creek pumped storage facility in 1982 resulted in massive scouring of Lost Canyon (Chan and Wong 1989). Even partial failures, such as the gate damage on Folsom Dam in July 1995, can result in large releases of water and prolonged difficulties in project operation.

Eventually, some larger dams will become filled with sediment and no longer worth operating. The Federal Energy Regulatory Commission now has the authority to take dams out of service when they come up for relicensing. We have no real experience with what to do about a dam filled with sediment. Early debris dams on the Yuba and Bear Rivers just failed or were intentionally destroyed, and the sediments eventually moved downstream or became semistable terraces. However, that option probably won't be acceptable in the future. Plans are being made to decommission a dam on the Elwha River in Olympic National Park in Washington. Initial estimates suggest that removal of the dam could cost \$60–80 million and sediment removal could cost \$150–300 million. If estimates of reservoir sedimentation rates made during the 1940s turn out to be conservative, society will have a long time to think about what to do with the dams of the Sierra Nevada.

ROADS

Roads provide the most intensive modification of land surface properties relevant to the hydrology of common land-management practices. All vegetation is removed and prevented from reestablishment. Dirt-surfaced roads are compacted to a near-impervious state, and sealed and paved roads are completely impervious. Runoff from the surface is collected and discharged as potentially erosive flows at points below the road. Roads that are cut into slopes intercept subsurface water flow and bring it to the surface. Fill materials cover additional portions of the slope and often contribute to sediment yields slowly over time or catastrophically if they become saturated from subsurface water entry and then fail. Erosion from the actual roadbed of unpaved roads may be significant as well (Garland 1993; Adams 1993). Unauthorized use during wet surface conditions adds to the erosion of the road. A principal side effect of an extensive road network is the access that is provided to allow additional alterations. Few adverse impacts occur in the absence of roads. Avoidance of new road construction can minimize other potential impacts in currently unroaded areas.

Stream Crossings

The most serious impacts of roads occur where roads are in close proximity to streams or wetlands. Stream crossings by ford, culvert, or bridge have direct effects on the channel and local sediment regime. Although virtually any stream crossing will have some impact on the channel, careful engineering, construction, and maintenance can limit the severity. The basic problem just comes down to disturbing the bed, banks, floodplain, and terraces. Because the crossing is coincident with the channel, there is little opportunity to buffer the inadequacies of design or construction. Also, roadside ditches near the crossing drain directly into the stream, often contributing sediment to the stream. In past decades, very little attention was paid to stream crossings, and the cheapest alternative was usually chosen. Often, that choice was merely pushing a stack of cull logs into the channel and covering them with dirt. Installation of culverts sized only for summer flow, with anticipated reconstruction, was often a more cost-effective choice than a properly engineered crossing. Fortunately, engineering and construction practices have improved dramatically since crossings have become widely accepted as a potential problem (Furniss et al. 1991).

Forest Road Network

As with other disturbances, the proportion of a catchment that roads occupy greatly influences their net downstream impact. Sediment yield associated with roads has even been claimed to increase exponentially with their density in a watershed (California Division of Soil Conservation 1971a). Within national forests of the Sierra Nevada, gross road densities range from 0.6 km/km^2 (1.0 mi/mi^2) on the Inyo to 2.3 km/km^2 (3.6 mi/mi^2) on the Eldorado (U.S. Forest Service 1995a). There are approximately 28,000 km (18,000 mi) of roads on national forests of the Sierra Nevada. Construction of new forest roads has declined markedly in recent years, and reconstruction and obliteration have varied among years (table 30.6).

Sediment Production

A variety of studies have examined sediment production and mass movement occurrence from forest roads. As usual, there is little information from the Sierra Nevada. Studies of road impacts in northwestern California (e.g., Burns 1972; McCashion and Rice 1983), Oregon (e.g., Beschta 1978), Washington (e.g., Reid and Dunne 1984), Idaho (e.g., Megahan and Kidd 1972), and elsewhere have demonstrated increases in local erosion rates hundreds of times greater than natural rates as well as severalfold increases in sediment yield at the catchment scale. Sediment yield from roads is usually greatest in the first year following construction. Road construction and some timber harvesting in the 10 km^2 (4 mi^2) Castle Creek Basin near Donner Summit resulted in a fivefold increase in suspended sediment during the first year. Sediment yields decreased to twice the preconstruction levels during the second year (Rice and Wallis 1962; Anderson 1979). In a rapidly urbanizing part of the Lake Tahoe Basin, roadways were found to generate about half of the total sediment (California Division of Soil Conservation 1969). The presence of roads can increase the frequency of slope failures compared with the rate for undisturbed forest by up to hundreds of times (Sidle et al. 1985). Road location seems to be the most important single factor because it determines the opportunity of most other controlling influences to contribute to failure (Furniss et al. 1991; Rice and Lewis 1991). Road placement in topographic hollows caused ground-water flow to be impeded, leading to several major failures along a principal road in the Tahoe National Forest (McKean 1987). In the past, there was little rational planning or design for inslope versus outslope road surfaces and associated drainage works as a means of minimizing erosion.

Landslides and surface erosion can often be traced to haphazard road design, location, and construction (McCashion and Rice 1983). Forest roads constructed as part of a carefully planned system usually disturb much less ground, produce less sediment, and have lower construction and maintenance costs (Brown 1980). Road stability is often jeopardized by infrequent maintenance. A looming problem for the Forest Service is how to maintain some 28,000 km (18,000 mi) of roads in the Sierra Nevada with budgets inadequate even at present. Declining budgets have decreased maintenance activities overall and placed roads in lower maintenance categories than specified in the original design (Clifton 1992). If maintenance is not improved, quality of both transportation and streams will suffer. Lack of maintenance is often used as an excuse for failures resulting from poor design or construction (Seidelman et al. 1986). The road network must be acknowledged as both an investment and a liability for the long term.

TABLE 30.6

Kilometers of road activities in national forests in the Sierra Nevada by fiscal year (U.S. Forest Service, Region 5, Engineering Section).

Activity	1990	1991	1992	1993	1994
Construction	113	83	75	53	11
Reconstruction	620	326	323	453	307
Obliteration	NA	136	86	111	180

Rehabilitation

Casual examination of Watershed Improvement Needs Inventories on many of the national forests of the Sierra Nevada illustrated that fixing road problems is an overwhelming priority. The same engineering and construction skills needed to build roads can be used to repair, relocate, and obliterate roads that cause excessive water quality problems. Modern concepts of road location and design that are currently used to build new roads with minimal problems (Larse 1971) can be applied to reducing the adverse effects of existing roads (Clifton 1992). Reshaping road cuts, pulling back side-cast material, ripping compacted surfaces, and removing stream crossings were successfully employed in a watershed in northwestern Washington (Harr and Nichols 1993). The decommissioned roads survived with little damage two major storms that caused widespread failures of active roads. Sources of funding must be identified to maintain and stabilize the road network; otherwise, forests will be left with an analog to toxic waste dumps that get increasingly difficult to treat and cause additional impacts with the passage of time. Public education is also necessary to build acceptance for closing roads that damage public resources. Closure of unsurfaced roads during the wet season can also help to reduce erosion.

Streets and Highways

Although unsurfaced forest and rural roads have received most of the attention, urban streets and major highways can also create severe problems of slope instability and water quality (Scheidt 1967; Parizek 1971). Beyond sharing most of the impacts associated with forest roads, paved roads of higher standard have additional effects. Primarily, they are simply wider and affect more area per unit of length. A four-lane highway can occupy a substantial fraction of a small catchment. Their impervious surface can create overland flow over large areas where it was nonexistent before construction. They are designed for more traffic at higher speeds and so tend to be forced through the landscape, minimizing curvature and changes in grade instead of following the topography more closely. In partial compensation for the greater hill-slope alteration, highways are better engineered than lightly used roads. Large investments are made in adequate drainage structures, slope reinforcement, and revegetation. Nevertheless, mitigation for the sheer size and location of the highway projects is difficult at best. Major highways are immediately adjacent to portions of the Feather, North Yuba, South Yuba, Truckee, South Fork American, Merced, Walker, Kaweah, Tule, and Kern Rivers. Within cities and towns, the storm water drainage system for the entire road grid is often inadequate during large storms because communities tend to develop in a piecemeal fashion, rather than having a complete road and drainage network planned from the start. Contaminants from tire wear, fluid leaks, pet waste, and exhaust that accumulate on the roadway are washed off into the nearest waterway. Oils used for road dust abatement can also be problematic. For example, contamination of Ponderosa Reservoir on the South Fork Feather River with polychlorinated biphenyls (PCBs) was traced to the use of transformer oil on forest roads (Plumas National Forest 1988).

Deicing Agents

Chemicals used to remove snow and ice from roadways in winter can affect local water quality and roadside vegetation (Hawkins and Judd 1972; Scharf and Srago 1975; Goldman and Malyj 1990). During a heavy winter (1982/83), rock salt (sodium chloride) was applied to Interstate 80 near Donner Summit in an average quantity of about 45 metric tons per km (80 tons per mi) of roadway (Berg and Bergman 1984). Stream samples obtained about 0.5 km (0.3 mi) downstream from the last highway crossing of the channel contained up to 100 times more chloride and 10 times more sodium than water obtained just upstream from the highway (Berg and Bergman 1984).

FIRES, FIRE SUPPRESSION, AND POSTFIRE TREATMENTS

Catastrophic fire can produce some of the most intensive and extensive changes in watershed conditions of any disturbance. Within areas of intense fire, most vegetation is killed and stops transpiring, allowing soil moisture levels to remain high. Organic matter in the litter layer is volatilized and often forms a layer within the soil that reduces infiltration of water into the soil (see Poff 1996). Riparian zones that would not be harvested under current forest practices are often partially burned in intense fires. The combined effect of these changes is to increase total water yield and overland flow. As the proportion of overland flow increases, streams receive more water in less time than under prefire conditions, and peak flows may be increased. If a nearly continuous water-repellent (hydrophobic) layer is a few centimeters below the surface, the soil above that layer may become saturated and form shallow debris flows. With bare soil, increased overland flow, and lack of vegetation and litter, soil particles are more easily detached and transported. As with other impacts, the proportion of a catchment that is modified by fire and the location of the burned area with respect to the channel largely determine the effects on streams. A stream draining a watershed burned over 90% of its area will show much greater effects than a stream emanating from a similar watershed in which only the upper slopes and ridgetops were burned. Fire intensity is often highly variable over the landscape, and patches of unburned or lightly burned vegetation (especially near streams) can reduce the adverse effects of upslope areas that were intensely burned.

Water Yield

Fires affect water yield primarily by killing vegetation. Interception loss is decreased because of the loss of leaves, low vegetation, and litter. Transpiration is virtually eliminated wherever fire is intense. A daily cycle in stream flow reflecting transpiration demand during daylight hours in a catchment in Washington came to an abrupt halt following a catastrophic fire (Helvey 1980). Annual runoff in this completely burned watershed increased by 10–47 cm during the first seven years after the fire. Water yields in a small catchment in British Columbia that was burned over about 60% of its area increased by 25% on average for four years following the fire (Cheng 1980). Dramatic increases in flow of a small spring and a creek in the Sierra Nevada were observed following burning of riparian vegetation (Biswell 1989). A detailed modeling study for Pacific Northwest forests has suggested that a reduction in leaf area or basal area of about 50% is necessary before annual water-yield increases exceed about 50 mm (2 in) (Potts et al. 1989). Snow accumulation and melt rates might be expected to increase from opening a forest canopy by fire, and such effects have been observed in Washington and British Columbia (Helvey 1980; Cheng 1980) but not in Idaho (Megahan 1983).

Peak Flows

Peak flows can be expected to increase following significant fires because of higher soil moisture resulting from reduction of transpiration, decreased infiltration, and higher rates of snowmelt. Infiltration is usually the most important influence, and it is decreased in two ways. Removal of vegetation and the litter layer exposes bare mineral soil to raindrop impacts, which can physically force the soil particles closer together and disperse soil aggregates into surface pores, thereby reducing the infiltration capacity. Fires also vaporize organic compounds in the litter layer, some of which move into the soil until the vapor condenses and forms a layer that is water repellent, or hydrophobic (De Bano 1981). These layers tend to be more coherent in coarse-textured soils (e.g., decomposed granitics), under very hot fires, and where a thick litter layer and/or organic horizon was present (De Bano 1981; Poff 1989b). The continuity of such layers, which may be a function of fire intensity and litter distribution, determines their overall impact on hill-slope water movement. Additionally, larger macropores from roots and animals allow some water movement through the hydrophobic layers (Booker et al. 1993). Although the water-repellent layers tend to break down within a year or two, those formed in soils that are somewhat hydrophobic even without burning may be more persistent (Poff 1989b). Under some conditions, a hydrophobic layer forms on the surface of the soil and acts as a binder and sealant, maximizing overland flow while minimizing erosion (see Poff 1996). As usual, there is a lack of measured hydrologic response to fire in the Sierra Nevada. A variety of studies elsewhere in the western United States have demonstrated dramatic increases in peak flows following wildfire (Tiedemann et al. 1979).

Sediment Yield

In general, sediment yields increase markedly after fires, particularly if riparian vegetation was burned. Most of the sediment response seems to be from the channels themselves. In the absence of streamside vegetation, soil particles move into the channels from dry ravel erosion, and the banks become less stable. Increases in total discharge and peak flows result in channel erosion. Debris torrents may scour streams if extreme climatic events follow the fire (Helvey 1980; Kuehn 1987). If the fire is particularly hot, woody debris that helped stabilize the channel may be destroyed. Erosion from the general land surface usually increases, but it may not always be as important a delivery mechanism as has been assumed (Booker et al. 1993). Erosion from plots in brushland near North Fork in the San Joaquin River Basin increased by 200 to 400 times after repeated burning (Lowdermilk and Rowe 1934). In Dog Valley in the eastern Sierra Nevada near Reno, a single storm produced about 600 m^3/km^2 (1.3 AF/mi^2) of sediment from a burned catchment while an adjacent unburned area yielded only a trace of sediment (Copeland 1965). Under extraordinary rainfall, gully erosion, sheet erosion, and a debris torrent removed more than 19,000 m^3 (15 AF) of material from a burned catchment of about 0.8 km^2 (0.3 mi^2) in the headwaters of the South Fork of the American River in 1982 (Kuehn 1987).

Nutrient Yield

Fires provide an opportunity for nutrients that have been stored in vegetation and soils to move into streams. Materials that are not volatilized and lost to the atmosphere are left in ash on and near the soil surface in forms that are readily mobile. A variety of studies throughout the West have demonstrated that concentrations of nitrates and other ions in streams usually increase dramatically after fires (Tiedemann et al. 1979). However, the background concentrations of these constituents in streams draining healthy forests are typically so low that the relative increases following fires appear to be huge even though the absolute amounts often remain almost negligible or at least below water quality standards. Nevertheless, there is potential for a nutrient flush to dramatically increase algae in streams, which can have additional consequences. There is also the potential for large nutrient losses associated with physical erosion of soil particles that often carry nutrients with them (Tiedemann et al. 1979). A study of the chemistry of Sagehen Creek north of Truckee following the Donner Burn in 1960 did not detect any change in the ionic composition of the stream relating to the fire, which did not burn the riparian zone (Johnson and Needham 1966). The inevitable fires in urban intermix zones have the potential to release a variety of chemicals and combustion products into the aquatic environment. Reconstruction can keep soils bare and disturbed for years.

Aquatic Effects

Studies of the aquatic effects of a fire on the Plumas National Forest demonstrate how both physical and biological features of the stream change over time (Roby 1989; Roby and Azuma 1995). The lower two-thirds of this catchment, including riparian vegetation, was thoroughly burned. Initially, the channel widened in response to presumed higher flows of water and sediment. However, as vegetation became established and the watershed recovered, the cross sections of the channel returned to their prefire areas within six years of the burn. Partial recovery of the invertebrate community seemed to have occurred relatively quickly. No differences in community similarity were noted between burned and unburned reaches one year after the fire, and density and taxa richness were comparable within three years. However, significant (though declining) differences in a species-diversity index between the burned and unburned reaches remained throughout eleven years of monitoring (Roby and Azuma 1995).

Fire Suppression

Fire suppression during this century has created forests with greater density of vegetation than in the past (Chang 1996; Skinner and Chang 1996; Weatherspoon 1996). This forest structure has current and potential hydrologic consequences.

The present situation may decrease yields of water and sediment somewhat compared to a natural fire regime (if impacts of other activities, such as residential development and road construction, are ignored). Although these changes cannot be quantified, transpiration from the dense forests should be at or near maximum, and a more open forest structure resulting from more frequent fire could be assumed to use less water. The dense vegetation also increases the opportunity for intense conflagrations (Chang 1996; McKelvey et al. 1996; Skinner and Chang 1996) that could produce major increases in water and sediment yields. There is a basic contrast between moderately higher stream flow and sedimentation on a semiconstant basis with relatively frequent low-intensity fires and the other extreme of lower stream flow with less sediment for now with the looming possibility of damaging floods and sediment loads from less-than-perfect fire suppression.

Actual on-the-ground fire-fighting activities, as opposed to the general policy of fire suppression mentioned above, also have impacts on water resources (California Division of Forestry 1972). In general, the net effect of such actions is probably less than doing nothing, given current fuel loads. The principal impacts of the past, which presumably are rare under current practices, involved operation of heavy equipment in streams and riparian zones and down the fall line of slopes. In some large fires, an extensive network of fire breaks may be bulldozed and require rehabilitation. Aerial application of retardants can also have adverse aquatic impacts (Norris and Webb 1989).

Postburn Activities

Following fires, there is usually a strong desire by landowners, agencies, and the public to react quickly. Hastily constructed fire lines often require obliteration or drainage; otherwise, allowing natural recovery processes to function may often be the best policy (Beschta et al. 1995). For example, natural regrowth on north-facing slopes virtually stopped erosion within three years of a fire in Idaho that initially produced more than 1,000 m^3/km^2 (2.3 AF/mi^2) of sediment (Megahan and Molitor 1975). Unfortunately, the state of the art in postfire rehabilitation remains poorly developed. Despite vigorous implementation of various actions over vast areas of the western United States, there has been minimal monitoring of the effectiveness of those actions. We therefore have very little collective experience or documentation of what works and what doesn't work. There are a lot of different treatments recommended in rehabilitation handbooks, but there is little apparent basis for the recommendations measured as success or failure in years following the prescription. There is active debate among fire specialists, soil scientists, hydrologists, and ecologists about some very basic issues. For example, rye grass seeding has been encouraged for years as a means of getting some vegetation cover in place as quickly as possible. Despite evidence compiled over thirty years that it inhibits establishment of native vegetation, results in less total cover after a couple of years than in nonseeded areas, and may even enhance net soil loss or have other adverse effects (Krammes and Hill 1963; Booker et al. 1993; Roby and Azuma 1995), many people seem to view it as a panacea. Contour felling of logs and straw-bale check dams to trap sediment are other widely accepted practices that may be less effective than generally assumed. These techniques appear to meet certain objectives in some situations (e.g., De Graff 1982), but their indiscriminate use is ineffective at best and may be counterproductive. One of the lessons of the catastrophic fire in Oakland in 1991 was that we simply didn't know what erosion control measures would be appropriate.

In the past decade, salvage logging of dead and dying trees has become quite controversial, with some people feeling it is just an excuse to cut trees while others feel it is the only thing maintaining their business. Postfire salvage operations influence aquatic recovery in a variety of ways. Perhaps most important in the present economic climate, salvage sales have potential to generate revenue for watershed rehabilitation, which unfortunately seems to be underutilized. Culverts are often replaced with larger structures in anticipation of larger flows; the soil disturbance from reconstruction is much less than what would occur if the road were to fail. The replacements are probably better designed than the original and should be more stable in the long term. Some roads may be decommissioned. Logging slash can be used to provide some physical protection for soils. Cutting shallow-rooted trees avoids the displacement of their root masses if they were to be blown over. On the negative side, logging operations disturb soils when the soil is particularly sensitive to compaction and erosion in the absence of cover and organic matter. Significant ground disturbance during a salvage sale of the Clark Burn in the Last Chance Creek watershed of Plumas County led to severe erosion during a thunderstorm (Cawley 1991). Where strong hydrophobic layers have developed, such disturbance might be valuable in promoting infiltration (Poff 1989b). However, on slopes subject to deeper mass failure, hydrophobic layers may be desirable as a means of limiting accumulation of water in the soil. If postfire treatments of salvage logging and site preparation prevent rapid reestablishment of low vegetation, resulting erosion can be greater than that directly produced by the fire. Timing of major storms relative to the amount of bare soil is a dominant influence. A fire in the Tuolumne River Basin in 1973 was not immediately followed by any major erosion-producing events (Frazier 1984). However, widespread ground disturbance associated with salvage operations prolonged susceptibility of soils to erosion. Eventually, substantial rain-on-snow events provided the energy for serious rill, gully, and bank erosion, which resulted in significant soil losses (Frazier 1984).

The principal objectives of postfire rehabilitation work should be to avoid making things worse; repair potential problems from fire-fighting activities (e.g., bulldozed fire breaks); enhance establishment of native vegetation to provide soil cover, organic matter, stream-bank stability, and shade as quickly as possible; attempt to stabilize channels by nonstructural means; minimize removal of large woody debris from streams; minimize adverse effects from the existing road network; schedule operations to minimize exposure of bare soil; and allow natural processes to heal the landscape.

Fuels Reduction

A major program of fuels reduction could increase gross water yields, peak flows, and sediment yields, depending on how extensively particular treatments are applied. As part of the investment in such a program, a team of soil scientists, hydrologists, and aquatic ecologists must actively participate to minimize the adverse effects on soil productivity and the aquatic environment. Although we have created forests that carry a high risk of damage to aquatic resources, pursuit of quick fixes in an atmosphere of crisis carries substantial risks as well (Beschta et al. 1995).

TIMBER HARVESTING

Harvesting of trees, especially in large clear-cut blocks, is commonly perceived as a major impact on the hydrology of river basins. Although timber removal has dramatic effects on the water balance of the immediate site, consequences at the catchment scale are not so obvious. As with many of the land management activities discussed in this chapter, the proportion of the catchment that is treated and the proximity of the treatment to water courses are critical in determining the impacts on water quantity, timing, and quality. In addition, associated activities such as road construction, yarding, slash treatment, and site preparation usually have much greater impacts than just the cutting of the trees. Hydrologic effects of selection harvests are generally considered to be less problematic than those of clear-cutting because the remaining trees remove soil moisture and provide some protection to the soil surface (Anderson et al. 1976). Harvest effects must also be considered with respect to time. Fortunately, trees and other plants quickly reoccupy most harvested areas, reestablishing protection from raindrop impact, uptake of soil moisture, deposition of organic matter to the soil, and support of soil masses by roots. Slopes are most vulnerable to surface erosion and generation of excess water immediately after harvest or site preparation, but they have minimal root strength about a decade after harvest (Ziemer 1981).

Water Yield

Harvesting timber has the potential to increase annual water yields via several mechanisms. Removal of all trees removes the possibility of any interception losses over the former area of the canopy. However, evaporative loss from rain and snow detained in tree canopies may be a relatively small component of the water balance of forests in the Sierra Nevada and has been estimated at about 30 mm (1.2 in) per year (Kattelmann et al. 1983). Removing trees also terminates transpiration in rough proportion to the extent of removal and the ability of remaining plants to use the water. The depth and moisture storage capacity of forest soils largely control the amount of reduction in evapotranspiration from harvesting (Zinke 1987). When trees are harvested at the base of a slope near a stream, a large fraction of the soil water formerly used by those trees will enter the stream. If trees are cut near the top of a slope, residual trees below the area harvested may use much of the "excess" water not transpired in the harvest unit, and relatively little of this water may reach the stream. More than one hundred studies of stream-flow response to forest harvesting have been conducted around the world. These studies have been reviewed by many authors (e.g., Anderson et al. 1976; Bosch and Hewlett 1982; Ponce 1983; Kattelmann 1987; Reid 1993; Marvin 1995, 1996). In almost all cases, stream flow increases as basal area (and evapotranspiration) declines. As vegetation regrows on the site, evapotranspiration increases and stream flow declines correspondingly (e.g., Troendle and King 1985). Intensive timber harvesting under the usual constraints of national forest management could increase stream flow in most Sierra Nevada rivers by 1%–1.5% (6–9 mm [0.24–0.35 in]) (Kattelmann et al. 1983; Rector and MacDonald 1987).

Peak Flows

Although most work to date has been done on changes in the seasonal water balance, short-term changes with respect to storm response and flood augmentation are also important. Timber harvesting can affect peak flows through two principal mechanisms: maintenance of high soil moisture in the absence of evapotranspiration and higher rates of snowmelt during rain events. In a simplistic sense, less rainfall is required before runoff is produced if trees are not using stored soil moisture than if trees occupy the site. Creation of openings in the forest alters energy exchange and snow storage. During warm storms, most snowmelt occurs through turbulent exchange processes (condensation and convection), which are more effective at higher wind speeds. The greater wind speeds in forest clearings compared with dense forests increase the rate of snowmelt in the clearings relative to that under tree cover (Harr 1981; Berris and Harr 1987). Considerably more snow is found in forest openings than under forest canopies because wind deposition of snow is favored in openings and much of the canopy-intercepted snow drips off as liquid water and enters the soil. In the intermittent snowpack zone, this difference in deposition can result in an absence of snow under trees while several centimeters of snow water equivalence is available in openings to add water to storm runoff.

Potential effects of land management on flood generation are most pronounced during small and moderate storm events and in small catchments (Hewlett 1982). During rare, intense storms, the differences in soil moisture storage or snow available for melt are almost incidental compared to tens of centimeters of rainfall (Ziemer 1981). At the river basin scale, flood peaks in the main river depend on synchronization of flood peaks from tributaries, which could be affected by drastic changes in land cover either positively or negatively.

Sediment Yield

Mass movements can be enhanced by timber harvesting by maintaining higher levels of soil moisture in the absence of evapotranspiration and loss of the reinforcement of the soil mass provided by roots (Sidle et al. 1985). On the average, the structural integrity of hill slopes is at a minimum about nine years after harvest, when the decay of old roots is not yet compensated for by the growth of new roots (Ziemer 1981). Roads tend to cause far more problems with respect to mass movement than does timber harvesting, and documentation of logging as a direct cause of mass failure in the Sierra Nevada has not been found.

Brushland Management

Conversion of brush fields to grass could increase stream flow and probably sediment yields at lower elevations (Anderson and Gleason 1960; Turner 1991). A proposal to manage about 130 km^2 (50 mi^2) of chaparral in the lower Feather River Basin with prescribed burning and some conversion to grass estimated that annual stream flow would increase by more than 3 million m^3 (2,500 AF) (California Department of Water Resources 1983b). Risks of increased erosion from such a program (e.g., Pitt et al. 1978) would need to be balanced against those from catastrophic fire. Conversion of brush fields to coniferous forest at higher elevations could delay snowmelt (Anderson 1963).

Observed Impacts

From a mechanistic point of view, forest harvesting in the past couple of decades has had limited opportunity to cause major changes in stream-flow volume, peak discharges, or sediment yield. In most river basins, the fraction of the basin area harvested per decade does not seem sufficient to cause major hydrologic responses. Nevertheless, peak flows in the South Fork Tule River appear to have increased in recent decades coincident with extensive road building and logging (see Marvin 1996). The level of harvesting since World War II has probably increased water yield somewhat in smaller catchments, but any increase may have been partially compensated for by increases in total vegetation density resulting from effective fire suppression over the same period. Unfortunately, neither influence can be quantified with any confidence. Similarly, we lack the appropriate data to observe whether modest changes have actually occurred. Except in the Tule River case (see Marvin 1996), no changes in the stream-flow record that clearly exceed natural variability have been noticed. With respect to sediment yield, data are not currently available to show any change over the past few decades at larger scales except in the Mokelumne River, where sediment yield has increased dramatically (EBMUD 1995). Appropriate baseline data in reservoir surveys could be used to determine if sediment yields have increased as a cumulative result of all types of land disturbance. Carefully performed follow-up surveys are needed to find out if land-management activities have made a significant difference.

At the smaller watershed scale, there is at least some observational evidence to suggest that land management affects the hydrology of small streams in the Sierra Nevada. Again, the impacts are the result of all activities associated with harvesting, such as road construction, skidding, and site preparation. Landslides that begin at roads and that are the only occurrences of mass movement in a catchment can be attributed to management activities. Similarly, when the only pools in a channel reach that are filled with silt are those immediately below clear-cuts that included the riparian zone, we can infer some cause and effect. However, even when impacts are overwhelming at the local scale, they are quickly masked downstream because few other contributing catchments were treated in the same way. A few studies in the Sierra Nevada have indicated impacts at the small watershed scale. Suspended sediment increased in the 10 km^2 (4 mi^2) Castle Creek Basin near Donner Summit during the first year following road construction and timber harvesting (Rice and Wallis 1962). Sediment captured in weir ponds below a catchment 1.2 km^2 (0.5 mi^2) in area on the Sequoia National Forest increased severalfold after road construction and harvesting (McCammon 1977). Stream reaches in twenty-four small streams in the Sierra Nevada and Klamath Mountains had significantly higher indices of stored sediment than corresponding control reaches (Mahoney and Erman 1984). Water yields from Berry Creek (20 km^2 [7.5 mi^2]) near Yuba Pass seemed to have increased substantially following harvests on less than half the basin (Kattelmann 1982). Peak flows may have increased in part of the Mokelumne River Basin as a result of extensive harvesting (Euphrat 1992). Unfortunately, long-term paired-catchment studies have never been performed in the Sierra Nevada, so we are left attempting to infer impacts from experiments elsewhere.

Aquatic Effects

Studies that began in the 1970s on several streams in the northern Sierra Nevada and Klamath Mountains demonstrated that communities of aquatic invertebrates changed significantly in response to upstream logging (Erman et al. 1977; Newbold et al. 1980; Erman and Mahoney 1983; O'Connor 1986; Fong 1991). Some of the aquatic effects have persisted for two decades (Fong 1991). The aquatic communities are particularly sensitive to logging-related disturbance within 30 m of the channel (Erman and Mahoney 1983) and perhaps within 100 m (McGurk and Fong 1995). In a recent study of forest management effects on aquatic habitat in the Sierra Nevada, data were collected on channel characteristics, aquatic habitat, fish abundance and health, aquatic invertebrate abundance, large woody debris, water chemistry, and management history in twenty-eight different basins in the Sierra Nevada (Hawkins et al. 1994). In general, natural variability in the measured attributes masked effects of management activity. Response of aquatic organisms to disturbance in the watersheds tended to be small compared with response to natural factors. Observed increases in nutrient loading and temperature appeared to enhance abundance of some taxa without any noticeable adverse impacts on others. Most of the communities in the observed streams appeared to be limited by food resources. The study noted, "We cannot at this time either measure or predict with any degree of reliability or confidence the cumulative effects most types of land use practices will have on natural ecosystems" (Hawkins et al. 1994, 1).

GRAZING

Grazing of domestic livestock has probably affected more area in the Sierra Nevada than any other management practice (Menke et al. 1996). Over the past century and a half, cattle and sheep have been virtually everywhere in the mountain range that provides forage. The near-ubiquitous presence of grazing animals has left few reference sites that we can be certain were never used by livestock. The best approximations to ungrazed conditions are those areas that have been rested for a few decades. Even Sequoia National Park was grazed until 1930 (Dilsaver and Tweed 1990). The absence of reference sites leaves us uncertain about what an ungrazed stream looks like and how it functions. This uncertainty is not merely an academic concern. Major questions of grazing management depend on our confidence in our understanding of how natural systems function without human-induced perturbations. For example, we can hypothesize that overgrazing on the Kern Plateau in the 1800s contributed to the widespread arroyo development and conversion of wet meadows to dry terraces. There are several lines of evidence that support that hypothesis. However, we would have more confidence if one of the early shepherds had invested a couple of summers in fencing off an entire watershed and preventing entry just to satisfy the curiosity of future generations. This problem of uncertainty exists to some degree with all impacts, but there are many areas that were not mined, dammed, logged, roaded, or urbanized. There just are not many that were not grazed.

In 1924, Aldo Leopold wrote, "Grazing is the prime factor in destroying watershed values," in reference to an overgrazed site in Arizona. Since then, debate has continued about the validity of similar statements applied to watersheds throughout the West. The impacts of grazing that relate to hydrology depend primarily on the behavior of the animals: feeding, drinking, producing waste, and traveling. If the animals remain in one place too long and consume much more than about half the available forage, vegetative recovery may be impaired and an excessive amount of bare soil may be exposed to erosive rainfall (Fleischner 1994; Committee on Rangeland Classification 1994). Although the amount of consumption that constitutes "overgrazing" depends on vegetation and site characteristics (Menke et al. 1996), half of the initial forage is a useful, though admittedly crude, rule of thumb (California Division of Forestry 1972). When insufficient vegetation remains after grazing, raindrop impact can change surface conditions and consequently reduce infiltration and increase erosion (Ellison 1945). Soil can become compacted by the repeated pressure of moving animals, especially if the soil is wet. The combination of soil exposure and compaction can decrease infiltration and increase surface runoff. If infiltration capacity is severely limited on a large fraction of a catchment, the extra runoff can quickly enter streams and generate higher peak flows (e.g., Davis 1977).

Surface and Channel Erosion

Exposure of mineral soil and enhanced overland flow also accelerate erosion. A variety of studies around the West have found dramatic increases in sheet erosion and gullying in overgrazed sites compared with ungrazed areas (Fleischner 1994). Severe gully erosion in the uplands of the North Fork Feather River has been caused by decades of overgrazing (Soil Conservation Service 1989). Nevertheless, the worst erosion problems associated with grazing typically occur near streams. Cattle tend to congregate in riparian areas for obvious reasons: abundant food, water, shade, and lower temperatures. Consequently, riparian vegetation is overgrazed, banks are trampled and eroded back, and bed deposits are disturbed. All this activity adds significant amounts of sediment directly to the stream. Dislocation of sediments in the streambed by moving animals augments suspended sediment. Degradation of riparian vegetation permits bank erosion to accelerate under the more frequent peak flows that are caused by the decrease in infiltration capacity. About half of the channels in the Meiss allotment in the Upper Truckee River watershed were identified as being in fair or poor condition as a result of overgrazing (Lake Tahoe Basin Management Unit 1993). Changes in channel morphology have been related to overgrazing in headwater streams tributary to the Carson River (Overton et al. 1994). Elimination of riparian vegetation by overgrazing in the broad alluvial valleys of the North Fork Feather River has led to rapid channel widening and massive sediment loads (Hughes 1934; Soil Conservation Service 1989). In other areas, such as meadows of the Kern Plateau and San Joaquin River Basin, downcutting has followed overgrazing (e.g., Hagberg 1995). Development of these deep arroyos has lowered the local ground-water table and transformed wet meadows into dry terraces supporting sagebrush. The possibly compensatory effects of less bank storage and less transpiration by vegetation determine whether low flows in summer are decreased or increased by the downcutting. A recent study of channel characteristics between pairs of currently grazed areas on national forests and long-rested areas in national parks in the Sierra Nevada found significant differences in bank angle, unstable banks, bed particle size, and pool frequency (U.S. Forest Service 1995b). Significant differences in undercut and unstable banks were also observed between grazed areas and adjacent fenced exclosures with a few years of rest.

Water Temperature

Removal of riparian vegetation and channel widening by grazing expose the stream to much more sunlight. Therefore, stream temperatures in summer may be several degrees higher than if shade remained. In winter, the absence of riparian vegetation may allow wind scour of snow in exposed creeks in high-elevation meadows. With less snow serving as insulation, ice formation may be greater than in creeks with vegetation capable of trapping more snow, which provides insulation itself. These artificial changes in temperature impact aquatic organisms that rely on a more natural temperature regime.

Water Pollution

Congregation of cattle in and around streams provides a direct pathway for nutrients and pathogens to degrade water quality (Springer and Gifford 1980; Kunkle 1970). High nutrient loads promote the growth of aquatic algae, which can virtually clog streams at low flow. An example of proliferation of aquatic plants apparently augmented by cattle is found in the Owens River above the Benton Crossing road. High levels of coliform and other bacteria have been found in streams heavily used by livestock (Lake Tahoe Basin Management Unit 1993; Central Valley Regional Water Quality Control Board 1995). Cattle grazing in backcountry areas provides a source of Giardia cysts (Suk et al. 1985).

Associated Impacts

There are a variety of ancillary effects of grazing. Road construction to provide access to range improvements has similar impacts to those of roads in general, depending on the location and design. Springs are extensively developed for stock watering, at the expense of native biota. Irrigated pasture consumes immense quantities of water for a low-value product (Romm et al. 1988).

Improved Practices

Improved grazing practices as applied to the Sierra Nevada have the potential for limiting many of the possible adverse impacts (Albin-Smith and Raguse 1984). Major changes in grazing practices in some parts of the eastern Sierra Nevada have recently occurred. A study is currently under way monitoring the response of macroinvertebrates and fish to riparian fencing and rest-rotation management (Herbst and Knapp 1995a, 1995b). Degraded channels in the Meiss allotment at the south end of the Lake Tahoe Basin led to a decision by the Forest Service to rest the allotment for five to fifteen years until stream-bank vegetation has recovered (Lake Tahoe Basin Management Unit 1993). However, this decision was overturned on appeal by the regional forester in 1995.

URBAN, SUBURBAN, AND EXURBAN DEVELOPMENT

The population of the Sierra Nevada foothills is expected to increase rapidly in the next few decades (see Duane 1996a). Conversion of forests and woodlands to residential and commercial land uses has several serious hydrologic effects on local streams (Lull and Sopper 1969). Such conversions dramatically alter the disposition of rainfall or snowmelt on the landscape by reducing infiltration capacity of the surface to zero or near zero. Land that was formerly well vegetated and rarely, if ever, produced overland flow is converted to an impervious zone where virtually all precipitation becomes immediate runoff. The extent of such changes and the ability of adjacent land to absorb the additional runoff determines the response of streams. Gutters, ditches, drains, channels, culverts, and storm sewers are intended and designed to convey runoff as rapidly as possible to streams. The combination of greater volume of runoff, faster generation of runoff, and greater channel efficiency moves more water downstream faster than under natural conditions. This convergence of large volumes of water in short periods of time produces frequent floods downstream from even modest rainfall (Leopold 1968). The more frequent floods lead to channel enlargement by erosional processes (Dunne and Leopold 1978; Booth 1990). Unfortunately, stream gauging stations have not been placed in strategic locations to actually record changes in stream-flow regimes in response to development in the Sierra Nevada.

Impervious Surfaces

The proportion of impervious area created by residential construction is a rapidly decreasing function of lot size. Small urban lots can be effectively sealed over three-quarters of their surface area, while lots of 0.4 ha (1 acre) might be impervious on only 10%–15% of the area. So-called low-density residential lots can be 20%–30% impervious surface (California Division of Soil Conservation 1971b). Larger parcels would have much smaller proportions rendered impermeable by construction. Although impervious area is a small fraction of dispersed "ranchette" development, the amount and intensity of conversion of natural vegetation to other uses, such as orchards, vineyards, pasture, ostrich ranches, and Christmas tree farms, will determine the hydrologic impacts. The area occupied by roads is closely associated with the density of structures. In addition, the quality of road location and construction will influence the potential for adverse effects. Poorly designed roads for subdivisions are a principal source of sediment in Nevada County (Gerstung 1970).

Channelization

Channelization (forcing streams into engineered waterways) has been practiced in the Sierra Nevada since the first miners' ditches for water supply were constructed and rivers were confined in wooden flumes while their gravels were excavated. During the mining era and subsequent development of water resources for hydropower, municipal, and agricultural uses, streams were put into artificial channels to get the water to another place where it was wanted. Around roads and towns, the usual objective of channelization is to get water away from a place where it is not wanted. Creeks of all types and sizes have been relocated, smoothed, and straightened to get water away from roads and homes as quickly as possible. These ditches, canals, and storm sewers enhance the flood-producing effects of general land conversion by routing the extra runoff away from the town or road much more quickly than under natural conditions. Peak flows are augmented downstream, but that is typically beyond the concern of the local channelization project. Flooding in Roseville during January 1995 was a classic example of this phenomenon. Failure of artificial drainageways and streets to perform as expected can also cause damage within the community attempting to control the runoff, as occurred in Cameron Park in 1982 and 1983 (Soil Conservation Service 1985). At higher elevations, runoff rates from snowmelt may also be accelerated where infiltration is limited in significant fractions of a watershed (Buttle and Xu 1988).

Vegetation Removal

Other hydrologic impacts of conversion to residential and commercial land uses include reduction of interception and transpiration functions of trees and other vegetation via their removal. All plants intercept and store some proportion of the precipitation received. Water retained in the canopy eventually evaporates. Continuous vegetation cover can reduce the amount of water reaching the ground substantially, depending on storm amounts and frequency. Removing the vegetation largely eliminates this function. Whatever replaces the plants usually has some interception capacity. However, roofs, latticework, and other structures do not transpire. So, vegetation conversion eliminates the active removal of soil moisture and its transfer to the atmosphere. Soil moisture would remain higher in the absence of transpiration if soil moisture recharge could take place through whatever covers the soil instead of vegetation. Where impervious areas are constructed, recharge of shallow and deep ground water is minimized. If the total area of limited infiltration is a significant fraction of a catchment, ground-water levels will decline. Stream flow during nonstorm periods that was formerly generated by seepage from ground water will also decline. Ground-water pumping for domestic and irrigation supply can exacerbate the problems of restricted recharge. In some cases, irrigation return flows may augment summer stream flow.

Water Pollution

The changes in runoff are closely related to declines in water quality associated with urban development. Enhanced runoff washes various contaminants off roofs, streets, parking lots, gutters, horse corrals, and golf courses and into streams. Diminished base flow increases the concentration of residual pollution entering after the floods. Urban pollutants include soil particles, nutrients, heavy metals, toxic organic chemicals such as pesticides, oil and grease, fertilizers, oxygen-demanding materials such as yard waste, and bacteria and other pathogens (Terrene Institute 1994). The diversity of sources makes control difficult, but best management practices are being developed and applied to control urban runoff. Development of riparian areas limits opportunities for filtering, uptake, and assimilation of contaminants. The combined effects of changes in runoff regime, water quality, and channel structure resulting from urbanization have profound effects on aquatic life. Eliminating infiltration on as little as a tenth of the catchment area led to declines in population of fish and amphibians near Seattle (Booth and Reinelt 1993).

Accelerated Erosion

Removal of vegetation, grading, and exposure of bare ground allows erosion to increase dramatically, especially during construction. Freshly cleared land for a new subdivision in Plumas County produced enough sediment in a single intense storm to kill 80% of the aquatic life in Big Grizzly Creek (California Division of Soil Conservation 1971b). In Nevada County, more than a third of the total length of streams has been damaged by siltation and stream-bank erosion resulting from subdivision development (Gerstung 1970). Erosion rates in the Middle Creek watershed near Shasta City increased more than twentyfold following urban development (Soil Conservation Service 1993). Residential construction around Lake Tahoe has been a major contributing factor in accelerating erosion and increasing nutrient inputs to the lake (Tahoe Regional Planning Agency 1988).

Sewage

Effluents from wastewater treatment facilities and leachates from dispersed septic systems add nutrients to ground water and streams. Breakdowns and spills from sewage facilities can introduce pathogens to receiving waters. Leaks from sewer lines have been recognized as an important source of nutrients in the Lake Tahoe Basin (Tahoe Regional Planning Agency 1988). Wastes from domestic animals and pets can also contaminate streams. Organic wastes can deplete dissolved oxygen in streams as well. Water quality was considered impaired in streams receiving wastewater from Nevada City, Grass Valley, Placerville, Jackson, and the Columbia-Sonora area (Central Valley Regional Water Quality Control Board 1991). Small sewage treatment plants serving recreational developments often suffer from inadequate financing, technology, and management (Duane 1996a). A facility at California Hot Springs alternately released excessive amounts of barely treated sewage or chlorine for several years. Giant Forest Village in Sequoia National Park was largely closed during the winter of 1994/95 because of poor performance of the wastewater treatment facility. Disposal of solid waste also has the potential to contaminate ground water and streams. Older landfills were probably not carefully located or designed and may be producing hazardous leachates. Location of new landfill sites is so difficult that Tuolumne County is planning to export its garbage to Lockwood, Nevada.

Water Supply

Supplying water for new development is problematic in many parts of the Sierra Nevada, which is ironic given the high runoff production of the mountain range. Coping with the seasonal distribution of runoff usually involves construction of storage reservoirs when large numbers of users are involved. Beyond the seasonal availability, most of the difficulties are legal and financial rather than physical. Surface waters are already overappropriated in many watersheds. Newcomers may find that all the local water is already claimed. Also, there seems to be a widespread belief that water should be supplied free or for a minimal charge—that somebody else (i.e., "the Government") should subsidize water supplies. Communities are often in favor of augmenting their water supplies for new development until they find that they are expected to share the cost. The Calaveras County Water District has financed its water development through the sale of hydroelectricity. Tuolumne County is faced with large costs and potentially high water rates from its redevelopment of the Lyons Reservoir system, acquired from the Pacific Gas and Electric Company.

The California Department of Water Resources (1990a) identified several generic problems facing rural water supply in the Sierra Nevada, which remain pertinent today:

- Rapid growth and development will burden existing water supplies and sewage treatment.
- Ground-water sources are not reliable in terms of quantity and quality.
- Water distribution systems are inefficient.
- Communities located on ridges are gravitationally disadvantaged.
- The best locations for impoundments have already been exploited by others.
- The revenue base is not sufficient to support water facilities at low rates per customer.
- Local funding sources are limited.
- Developing new water projects is economically and environmentally costly.
- Construction of new conveyance systems is expensive because of dispersed users and terrain.

Water companies and water-supply service districts in the Sierra Nevada vary in size from a few dozen customers to tens of thousands (Department of Water Resources 1983a; Harland Bartholomew et al. 1992). The nature of their sources, delivery and treatment systems, and demands are highly variable as well (e.g., Thornton 1992; Borcalli and Associates 1993). There are more than 160 separate water purveyors in Placer County alone (Placer County 1994). Water demands for individual households in the foothills have been estimated at 600–1,200 m^3/yr (0.5–1 AF/yr) (Page et al. 1984; Harland Bartholomew et al. 1992). Supplying new customers with existing water supplies may place current consumers at risk of shortfall during dry periods. Legislation was passed in California in 1995 (SB 901) to limit the ability of cities and counties to allow new developments unless local water purveyors certify that adequate water supplies exist for both present and expected residents. Sources of water for large proposed developments in the foothills, such as Yosemite Estates near Sonora, Las Mariposas near Mariposa, and Promontory near Placerville, are uncertain. Excessive water withdrawals from local streams can threaten recreational fisheries that form part of the economic base supporting the communities seeking the extra water for more development (Kattelmann and Dawson 1994). Development of additional water supplies is likely to become increasingly costly in both financial and environmental terms.

The projected demand for additional water in the foothills in the next few decades is staggering (see Duane 1996a). The Georgetown Divide Public Utilities District expects a 50% increase in water use in the next thirty years, and the El Dorado Irrigation District anticipates demand to double in the same period (Borcalli and Associates 1993). In Amador County, domestic water use was forecast to rise by between 2.6 times and 3.6 times between 1983 and 2020, depending on which population projections were used (Department of Water Resources 1990a). Tuolumne County expects to add 14,000 people in the next twenty years, who will need about 8.6 million m^3 (7,000 AF) of water each year to support them. The largest expected increase has been postulated for the service area of the Nevada Irrigation District, where annual domestic use could go from about 15 million m^3 (12,000 AF) to about 40 million m^3 (33,000 AF) between 1992 and 2010 (Harland Bartholomew et al. 1992). Nevada County is in perhaps the best position to meet the expected demands. The Nevada Irrigation District currently has rights to more water than is used and has a vast base of agricultural use that is expected to decline. Calaveras County also appears to have a relatively secure water supply. Some streams that have been dewatered below diversions may receive some flow for instream needs as older contracts expire and are reviewed. Other regions must find new sources of water and presumably will want to build new storage facilities or acquire existing hydroelectric projects.

SKI AREAS

As the major industrial/commercial development in the higher-elevation parts of the Sierra Nevada, ski areas have generated public concern about impacts of the resorts on water resources. Because of their extensive marketing campaigns and their location along the major access roads of the range, one could get the impression that there are ski areas all over the Sierra Nevada. However, the twenty-five alpine resorts occupy a tiny fraction of the land area in the mountain range. Only a few of the larger resorts, such as Squaw Valley, Alpine Meadows, Heavenly Valley, and Kirkwood, occupy a major proportion of the immediate watershed they are situated in. Most of the more significant impacts of ski resort development are associated with base facilities, roads, and parking lots. Such facilities are usually located in a valley bottom and impact streams and wetlands. For example, the parking lot of Boreal Ridge converted a large subalpine meadow into an expanse of impermeable asphalt and channelized Castle Creek. Because of the need for flat ground at the base of ski areas, many streams have been rerouted or even put underground. Access roads are often located in riparian zones. Runoff from roads and parking lots is usually polluted. The base facilities, lodging, and recreational residences generate substantial amounts of wastewater, which has usually required a local sewage treatment plant. Sewage system failures occasionally occur under harsh winter conditions. Most of the impacts of small urban areas can be applied to resort development. Ensuring an adequate water supply for all uses (residential, commercial, snow making, landscaping, erosion control plantings, and golf courses) for a major resort community can be problematic even in prolific source areas of snowmelt runoff (Kattelmann and Dawson 1994).

Vegetation Conversion

Impacts related to the ski slopes themselves begin with tree removal for runs and lift access. Such clearing constitutes a permanent conversion of vegetation type, as opposed to forest harvesting, which implies hydrologic recovery. When runs are cleared, deep-rooted trees are replaced with shallow-rooted grasses, greatly reducing evapotranspiration and increasing soil moisture storage. Because ski runs are typically oriented down the fall line, there is little opportunity for trees downslope to use the extra soil water in transit. Type conversion on ski runs can generate at least 7–15 cm (3–6 in) per unit area harvested of additional stream flow (Hornbeck and Stuart 1976; Huntley 1992). In some situations, subsurface drainage pipes and new surface channels may need to be installed to accommodate the additional water and avoid saturated conditions that could lead to mass movement. In some areas, there is extensive excavation and shaping of the natural terrain. Maintenance of sufficient ground coverage for adequate erosion control may require artificial irrigation and fertilizers in summer. Excessive use of fertilizers can contribute to high nitrate levels in local ground water (Goldman et al. 1984). Erosion from ski areas seems to be fairly well controlled and largely in compliance with rules from the regional water quality control boards, especially in the Lahontan Region. General construction always has the potential for accelerating erosion, but best management practices for minimizing soil loss at ski areas are becoming fairly thorough (i.e., Calaveras Ranger District 1991). In general, ski areas can afford to invest in erosion control and slope stability techniques that are not possible outside of major engineering projects. Somewhat analogous to abandoned mines, abandoned ski areas have potential for severe erosion problems, as occurred at Pla-Vada, where high sediment loads from gullies on the ski slopes damaged fish habitat in the nearby South Yuba River (California Division of Soil Conservation 1971a).

Snow Compaction

Grooming operations, avalanche control, and skiing compact the snow and move some of it downhill. A study of effects of compacted snow near Donner Summit found that snow water equivalence on the narrow ski runs was up to 50% greater than that on adjacent uncompacted slopes and that ski runs remained snow covered for up to two weeks longer than adjacent uncompacted slopes (Kattelmann 1985). Chemicals, such as ammonium nitrate, sodium chloride, and calcium chloride, have been used at a few ski areas to prepare race courses and improve skiing conditions in spring and summer. In general, only small areas are treated with relatively small quantities of chemicals. Degradation of water quality is a concern and has been reported in Europe.

Artificial Snow

Snow making has become widespread among the ski areas of the Sierra Nevada because skier demand seems to be greatest in November and December, when natural snow cover may be marginal. Artificial snow is produced by mixing water and air under high pressure through a nozzle. The sudden expansion cools the water and forms ice particles, which provide a reasonably good skiing surface and base for natural snow. Typical depths of applied water range from 20 to 50 cm (8–20 in), so the area covered is the main determinant of the total volume of water used. Most of the water used is returned to the stream it was originally withdrawn from, but delayed by 5 to 8 months. Evaporative losses of 2%–5% occur at the nozzle, and sublimation losses from artificial snow on the ground (and not covered by natural snow) range from 10 to 50 mm depending on how long the snow is exposed (Eisel et al. 1988; Huntley 1992). If water diversions for snow making will seriously deplete stream flows during the low-flow part of the year, off-channel storage capturing one season's snowmelt runoff to artificially initiate the following season's snow cover, such as is practiced at Mammoth Mountain, may be warranted.

Prospects for Expansion

Despite seemingly flat skier demand and the failure of about a quarter of the nation's smaller ski areas in the past decade, future prospects appear good enough to the ski industry to add additional capacity (see Duane 1996b). For example, revenues at Northstar-at-Tahoe and Sierra-at-Tahoe grew by 4% in the first quarter of 1995. Major expansion occurred at Sugar Bowl in 1994 and is planned at Kirkwood. Squaw Valley has proposed construction of a new base complex and has plans for year-round skiing. An entirely new ski area has been approved by the Forest Service in the Mammoth Lakes area, but $50 million in financing for construction may be difficult to obtain. Various large-scale development schemes have been proposed in the Royal Gorge/Devil's Peak region near Soda Springs.

INTERPRETATIONS

Historic and Current Conditions

The most significant impacts to the hydrologic system of the Sierra Nevada started almost immediately with the boom in Euro-American entry into the mountains during the gold rush. The effects of riverbed and hydraulic mining were devastating to the rivers of the western slope. Substantial recovery of the obvious features of channel morphology and riparian vegetation provides the appearance of natural rivers, but the aquatic and riparian ecosystems may remain quite simplified compared to the pre-1848 conditions. However, we will never know. As mining subsided, water development quickly took its place as an overwhelming, though less intensively destructive, impact. Although the severity of overgrazing may have peaked between about 1890 and 1930, continued grazing pressure has prevented thorough recovery of many degraded streams, and some (e.g., North Fork Feather River) continue to deteriorate. Early logging probably denuded larger expanses of the Sierra Nevada but may have applied less intense hydrologic disturbance to the soil than the road-building and tractor-skidding era that began after World War II. The various impacts of residential development have accelerated in the past decade. Impacts of fire and the legacy of fire suppression have yet to play out.

Water resources of the Sierra Nevada are highly controlled for various social purposes. That management causes the greatest current impacts to other social and ecological uses. The degree of alteration of natural stream flows generally increases in the downstream direction where the water passes through or is withdrawn by successive projects. However, the amount of unregulated flow from hydrologically intact tributaries also increases downstream, helping to "dilute" the effects of river engineering, at least until the big dams on the main rivers are reached. The dilution effect is also important in ameliorating changes in land use, which are most obvious close to their point of occurrence. The addition of water from relatively unimpacted watersheds helps offset the adverse cumulative impacts of assorted disturbances. Downstream of points of diversion, streams may lack the capacity to transport natural and accelerated sediment yields. Overall, water quality remains high compared with other rivers of the United States, but many problems exist locally. Alterations in the flow regime may be the most widespread degradation of water quality.

The primary trends related to water resource conditions at the scale of the entire mountain range have been recovery from gold mining and increasing regulation of stream flow via water developments. Both trends have diminished through time after the main geomorphic adjustments to mining debris and early dams occurred and the optimum dam sites and water rights were acquired and developed. Impacts from forest road building may have peaked as most of the potential road network would seem to be in place (see McGurk and Davis 1996); however, the high road density in some catchments ensures continued sediment yields at high rates. Impacts from residential road building and associated activities seem to keep increasing as the development of the foothills continues. An important question for planners is how to meet growing water demand while minimizing the environmental impacts of additional water development.

Some Implications

The overwhelming impacts on the water-resource system of the Sierra Nevada are those that directly modify the flow regime and the channel. Landscape impacts are secondary in those river basins of the Sierra Nevada with substantial water development. Even among land-use activities, those adjacent to or near a channel have far greater impacts than activities distant from water. Improvement of land-management practices and restoration should focus on issues closest to the streams if amelioration of aquatic impacts is a primary goal. Similarly, stream health will not suffer so much if disturbances are positioned well away from streams. Throughout this discussion of stream health, there is a presumption that fully functional aquatic ecosystems are inherently valuable and that attributes of streams beneficial to aquatic life (natural flow regime, low sediment transport, stable channel, good chemical quality, etc.) are also beneficial to the human uses of water. Aquatic ecosystems in headwater catchments are at greatest risk of damage from land disturbance. Combined effects of water engineering and land management may be particularly harmful to some aquatic communities.

Time Significance

Although there is no absolute urgency in changing the way society treats streams, the sooner damaging practices are improved or avoided, the sooner streams will benefit. Taking care of existing problems sooner rather than later and avoiding new mistakes will reduce the total impact (e.g., less sediment into stream pools or reservoirs) and may cost far less in the long run. Lake Tahoe is the best example of a system that needs urgent attention to slow the rate of deterioration of a particular resource or value (i.e., lake clarity). At Lake Tahoe, human activities have clearly altered a critical component of the ecosystem (nutrient cycling), and because the lake is extraordinarily sensitive in that regard, ecological responses are obvious and rapid. Although there are few real parallels to the Tahoe situation in terms of urgency, there are many other important problems to address. For example, reducing streambank erosion in the North Fork Feather River is clearly an important goal. As long as comprehensive action is delayed, productive alluvial land will continue to be lost, streams will continue to carry high sediment loads, and downstream reservoirs will continue to fill with sediment at unnaturally high rates. The most urgent problems are those where continued degradation could be irreversible or extremely expensive to mitigate if allowed to persist.

Perceptions

The adverse impacts of water management are probably overlooked by the public at large because of the obvious, personal benefits of that management. Perception of water-related impacts from residential development in the foothills is probably mixed depending on whether the individual has lived in a foothill community for decades, is a newcomer, relies on continued growth for personal income, or does not live in the area. Water-related problems associated with land management may be perceived by some people as more serious than they really are because of the visual impacts and media attention. The degree of destruction and subsequent recovery from placer and hydraulic mining are not widely recognized.

Gaps

Obviously, the operational difficulties lie in site-specific details. The assessment in this chapter is a very broad treatment of an entire mountain range. The problems are in particular streams. Every watershed has a story that is critical to its own stream. Management is conducted at that scale. The broad generalizations made here only provide the regional context for individual catchments and streams. The absence of information on recent sediment yields and limited stream-flow records from unregulated streams prevent any quantitative conclusions about how much land management has altered yields of water and sediments in the Sierra Nevada. Impacts on aquatic biota are also difficult to quantify because of scarce baseline data (see Erman 1996; Moyle 1996; Moyle and Randall 1996; Moyle et al. 1996).

Ecosystem Sustainability and Management

The physical recovery of streams from the gold mining era demonstrates the resiliency of rivers. Although recovery is probably to a more simplified state, with some lingering attributes of the original disturbance, this recovery illustrates an inherent long-term sustainability of the fluvial and aquatic systems, even in response to catastrophic impacts. On land, vegetation seems to reclaim favorable sites (i.e., riparian areas, north-facing slopes) very quickly after fire or logging. Drier sites and areas with special problems may require active intervention to reestablish ground cover in the short term or the avoidance of such sites in the first place. Recovery of other ecosystem properties and processes following disturbance requires much more time and possibly some management if we are impatient with nature's schedule. Ecosystem management must avoid impeding natural recovery processes after a fire or other disturbance, incorporate such processes in planning management programs, and augment them when necessary to accelerate ecological change in a desired direction, especially on difficult sites.

Remaining Questions

Among many important questions about hydrologic impacts of land management, three stand out:

1. How much has sediment yield been altered by human activities?
2. How much has the stream-flow regime (annual water yield, peak flows, low flows) been altered?

3. How do changes in water quantity and quality relate to declines in aquatic biota?

Reservoir sediment surveys on a 10- to 20-year cycle could be very informative about the first unknown. Establishment of a long-term network of stream gauges in strategic locations, such as actively managed headwater catchments, could be very informative about the magnitude of changes in hydrologic processes resulting from changes in land use. The present network informs us about water management and needs to be supplemented to inform us about land management. An aquatic research program, such as that suggested by Naiman et al. (1995), would help address many of the gaps in knowledge regarding streams of the Sierra Nevada.

CONCLUSIONS

From a hydrologic perspective, the Sierra Nevada seems to be functioning adequately as the preeminent water source for California society, agriculture, and industry. However, the hydrotechnical structures that facilitate exploitation of streams for social uses create the greatest impacts to those very uses as well as to aquatic ecosystems. This highly managed water system has created artificial patterns of stream flow in the lower reaches of most rivers and their principal tributaries. There are not many opportunities for further development of water resources in the mountain range, given existing infrastructure and water rights. Financing additions to community water supplies without subsidies from hydroelectric generation will be difficult at best. Existing ground-water development near foothill communities limits the availability of subsurface water as a dependable supply for future growth. The managed flows and physical barriers to movement of water, sediment, and biota have substantially altered aquatic and riparian ecosystems to something other than natural.

Compared with the intentional alteration of stream flow through water management, hydrologic side effects of changes in land use are difficult to measure but are still believed to be significant. Major changes in water and sediment regimes have not been observed in the main rivers and their larger tributaries as a result of shifts in land use. There may be a signal, but it is not obvious or well quantified. Hydrologic changes resulting from land management are most likely to be found in headwater areas, where a large fraction of the catchment has been affected. Diversion of water from a stream will limit transport of excess sediment loads and thereby compound the impacts of land disturbance. Roads are believed to have increased sediment yields substantially, but the inferred changes have not been measured in the Sierra Nevada. Overgrazing has probably altered channel conditions extensively, but the scarcity of ungrazed reference sites limits researchers' ability to quantify impacts. Rapid expansion of foothill communities has theoretically altered runoff and erosion processes enough to cause noticeable impacts in downstream channels, but quantitative and documentary evidence outside the Tahoe basin is lacking. Conversion of forestlands to roads associated with timber harvesting may have increased annual water yields and peak flows somewhat at the small watershed scale. However, decades of successful fire suppression may have increased evapotranspiration relative to a pre-1850 fire regime and partially compensated for the flow increases attributed to roads and harvests. The offsetting magnitudes of either impact cannot be quantified at this time. The legacy of fire suppression creates substantial risks of serious hydrologic impacts from potential conflagrations.

Overall, chemical water quality remains high, but water cannot be considered pristine. Because of widespread biological contamination, surface waters throughout the range cannot be assumed to be drinkable. A few local problems are very serious: Lake Tahoe, some abandoned mines, and some communities. Quality of receiving waters from the larger cities in the foothills has been degraded. These aquatic systems are not as sensitive to nutrient loading as Lake Tahoe. Excessive sediment production is the most widespread non-point-source problem, but its extent and severity are unknown. Studies in other areas suggest that roads are the overwhelming source of sediments that end up in wildland streams. Disturbance in and near stream channels generates the vast majority of sediment transported by the streams. Existing information about sediment yields in Sierra Nevada rivers is largely obsolete, and new reservoir sediment surveys are necessary to determine whether changing land use has accelerated sedimentation in the past few decades. Because of the importance of flowing water in diluting and dispersing pollution, alteration of stream flow by storage and diversion may be the fundamental water quality problem in the Sierra Nevada.

MANAGEMENT IMPLICATIONS

The ecological health of a stream is affected by all activities in its watershed. Those activities that directly control the flow regime or occur within the riparian zone usually have the greatest potential impacts. Changes in reservoir management practices may offer the best hope for improving aquatic ecosystems where they are known to be influenced by artificial flow regimes. In general terms, some shifts back toward a natural hydrograph, such as seasonally fluctuating flows, occasional flushing flows, maintenance of adequate low flows, or whatever is appropriate to a particular situation, will be beneficial to the local biota. Simply maintaining constant minimum flows is rarely sufficient. Stream habitat conditions and aquatic biota have developed in response to a highly variable natural flow regime. Restoring some aspects of that variability in managed streams should have ecological benefits in most cases. In some cases, changes in reservoir releases to benefit downstream organisms and water quality may have few adverse impacts on economics of the project. In other cases, there may be substantial costs, which may not be justified for the intended benefits. The tradeoffs between in-stream impacts and operational impacts must be carefully evaluated in the context of each water project, the watershed it is located in, and the ultimate downstream uses. There could be continued realignments in water rights as a result of application of the public trust doctrine, hydropower relicensing requirements, and regulation of reservoir releases by the regional water quality control boards for water quality management. The State Water Resources Control Board could ease legal and administrative matters by improving their water-rights database. An efficient, geographically referenced database for water rights could allow examination of in-stream flow conditions in a cumulative context for each stream and river system. Designation of additional wild and scenic rivers could help maintain ecological values of selected segments.

Major reconstruction of smaller dams to allow sediment pass-through under high-flow conditions could help restore some semblance of a natural sediment regime to many streams. Such work is a serious challenge in hydraulic engineering and reservoir management, but it would be an important contribution of technology to restoring natural processes in the managed rivers of the Sierra Nevada. Provision for flushing flows is particularly important where land disturbance may have augmented natural sedimentation and regulated flows encourage sediment deposition.

Recent actions by the State of California and the U.S. Forest Service to use watersheds as a geographic basis for planning and management are encouraging. As local agencies and citizens begin to incorporate a watershed basis into their own activities, overall conservation of aquatic resources should greatly improve. Continued public education about basic watershed concepts can only help. Application of watershed analysis methodologies developed in the Pacific Northwest (e.g., Montgomery et al. 1995) to the Sierra Nevada would be a worthwhile step toward improved management of wildlands at the landscape scale (see Berg et al. 1996). Watershed analysis can provide managers with better information about resource capabilities, existing problems, and sensitive areas before plans are made and projects are proposed. This analysis develops a logical foundation for decision making.

Reform of the 1872 Mining Act and greater application of California's Surface Mining and Reclamation Act to smaller claims could improve many isolated problems associated with mining and prevent future adverse impacts. Laws relating to liability that prevent rehabilitation of abandoned mines need to be modified, and funding must be generated to clean up problem mines. Mining of sand and gravel in streams of the Sierra Nevada should be directed toward reservoir deltas, despite the increase in transportation cost. Public agencies should set an example by using reservoir sediments as a source of aggregate whenever possible and avoiding chemical use in surface waters. The Department of Fish and Game (which administers streambed alteration agreements) might be able to negotiate agreements between reservoir operators and aggregate miners and users.

Modern information on sediment yields is needed to determine whether sedimentation has increased as a result of land-management activities. The California Department of Water Resources' Division of Dam Safety, the U.S. Geological Survey, and the U.S. Natural Resources Conservation Service might be the appropriate agencies to cooperatively administer a program of routine reservoir sediment surveys.

More efficient means of monitoring hydrologic impacts from land-management activities need to be explored at the operational field level and at the institutional level. Existing programs do not seem to provide the information necessary to evaluate how stream-flow regimes or water quality attributes are changing as a result of changes in land use. Current monitoring is also not adequate to determine whether restoration activities, including postfire treatments, are effective and appropriate. Maintenance and improvement of the snow survey, snow sensor, and climate station network is essential to management of water resources and detection of climate trends. Basic data collection programs to generate stream-flow, water quality, and climate information need to have long-term support to be worthwhile.

Now that the forest road network is largely complete, more attention should be focused on maintenance, relocation, upgrading, and decommissioning of roads by the engineering staffs of the national forests. Resource staffs have already identified many of the specific problems in the road network that need attention. Road construction budgets have been high in the past, and adequate funding is necessary to maintain, improve, and reduce the existing road system to minimize its aquatic impacts.

As foothill communities continue to grow, conversion from individual septic systems (and individual wells, in some cases) to community systems will be necessary to avoid cumulative impacts on local water quality. Construction of treatment facilities and collector systems is extremely expensive, especially where houses are far apart. The issue of who pays for such improvements is problematic. The community systems would not be necessary if not for the growth in potential pollution sources. At the same time, a community system is necessary because the capacity of the soil and ground-water system to treat household sewage is at or near its limit. Except for the service area of the Nevada Irrigation District, Calaveras County Water District, and a few others, foothill communities will need to develop major new sources of water or drastically reduce existing demand if they wish to continue their growth. Unless hydroelectric generating capacity is added when developing new sources of supply, project financing and end-user water rates may be serious constraints on new projects. Purchase of existing facilities (now largely owned by the Pacific Gas and Electric Company) by small communities and water agencies may be an increasing trend in attempts to augment community water supplies.

With all changes in land use and other disturbances, proximity to streams is a critical influence on the aquatic impacts of the activity. Simply minimizing disturbance of vegetation and soils near streams and conscientious application of best management practices for erosion control have the potential for reducing sediment problems. This locational emphasis is especially important with respect to grazing. Overgrazed riparian areas need substantial rest to adequately recover from past problems. Allowing such recovery means minimizing the presence of livestock and other disturbances in riparian zones on a continuing basis.

Management of forest fuels to reduce the risk of catastrophic fire must include thorough consideration of aquatic impacts and mitigation measures. If a major program of fuels treatment is started, a dedicated team of soil scientists, hydrologists, and aquatic ecologists should be involved in the planning and execution of such a program on local administrative units. A team of specialists, on either a zone or regional level, is also needed to monitor and evaluate the long-term effects of postfire treatments. Their experience could develop a rational set of best management practices for dealing with burned landscapes.

Prevention of further degradation and correction of existing water-related problems is expensive, as the Lake Tahoe experience has demonstrated. Rehabilitation of forest roads and restoration of degraded streams will require substantial investment. The forests of the Sierra Nevada contain three resources of substantial economic value to society: water, timber, and recreational opportunities. Some of their value in the marketplace could be returned to their sources and used to improve the conditions favorable to their production. Because the benefits of water from the Sierra Nevada contribute to so many aspects of California's economy, creative means of reinvesting a portion of those benefits into the watersheds need to be explored.

ACKNOWLEDGMENTS

Most members and associates of the SNEP team contributed to this chapter through comments, discussions, suggestions, contacts, reviews of drafts, and material in their own chapters. In particular, I wish to thank Peter Moyle, Don Erman, Bruce McGurk, Neil Berg, Jeff Dozier, Susan Ustin, Larry Costick, Debbie Elliott-Fisk, Rowan Rowntree, Bill Stewart, Jeff Romm, Roger Poff, Mike Diggles, Hap Dunning, Matt Kondolf, Roland Knapp, Doug Leisz, and Connie Millar for their help and insights. Karen Gabriel, Lian Duan, Steve Beckwitt, Paul Randall, and Russ Jones provided much analytical assistance with geographic information. Jen Lucas, Erin Fleming, Mike Oliver, Cindy Seaman, and Sue Enos kept the project going with their behind-the-scenes logistics. Mignon Moskowitz, Virginia Rich, and Zipporah Collins greatly improved the readability of the manuscript. Sarah Marvin and Maureen Davis obtained data that I was unable to access.

Beyond the greater SNEP team, hydrologists and other resource professionals on all the national forests of the Sierra Nevada were very helpful in providing suggestions, information, and access to their files. Ken Roby, Jim Frazier, Luci McKee, Terry Kaplan-Henry, and Bob Gecy were particularly helpful in this regard. Many other people involved with water issues in the Sierra Nevada provided information and assistance. The following list includes only a sample of those who were most helpful: Jane Baxter, Clay Brandow, Bob Curry, Gayle Dana, Gary Freeman, George Ice, Donna Lindquist, Brett Matzke, Sally Miller, John Munn, Robert Nuzum, Randall Osterhuber, Doug Powell, Terry Russi, Tom Suk, Darrell Wong, and Sue Yee.

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