Hydrologic Aspects of the Sierra Nevada Ecosystem Project

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Abstract

A comprehensive assessment of environmental conditions in the Sierra Nevada of California included a detailed examination of human impacts on the hydrology of the mountain range. Gold mining during the 19th century had the most intense effects on rivers of the western slope because of the widespread excavation of channels, riparian areas, and adjacent hillslopes. Since the gold mining era, land disturbance has been comparatively modest. However, an extensive network of forest roads has converted up to ten per cent of some catchments to unvegetated, compacted surfaces. The potential for impacts on aquatic systems is greatest where these roads are located in riparian areas. Water management activities directly modify the flow regime of the rivers of the Sierra Nevada much more than other resource developments across the landscape.

Introduction

The Sierra Nevada Ecosystem Project was an evaluation of environmental conditions in the entire Sierra Nevada mountain range. It was requested by the United States Congress in 1992 in response to widespread concern about continuing degradation of the region. The basic goal of the project was to assess the status of the entire set of ecosystems in the Sierra Nevada, including their social, economic, and ecological conditions. This information should provide an improved basis for managing the natural resources of the Sierra Nevada in a sustainable manner. The project provides an example of a current approach to assessing environmental conditions throughout a large mountain range. Details about the topics outlined in this article may be found in several chapters of the final report of the Sierra Nevada Ecosystem Project (e.g., Kattelmann 1996; Kattelmann and Embury 1996, Kondolf et al. 1996; McGurk and Davis 1996; Moyle 1996).

This assessment of the health of the hydrologic system of the Sierra Nevada examined indicators of problems in water quantity and quality as well as activities that have potential to alter hydrologic processes. The network of monitoring sites for streamflow and water quality is too limited to infer changes directly from the systematic record. Stations that have been installed in areas with known problems, such as Lake Tahoe, were useful for evaluation of local conditions. Stream gauges downstream of reservoirs and diversions were indicative of the degree of intentional modification of flow patterns. The amount of information available varied greatly within and between river basins. The issue of scale was prominent throughout this project. Our task was an evaluation of conditions for an entire mountain range, but people's impressions and monitoring data are usually applicable to only small areas. Ultimately, we found it necessary to report different aspects of the evaluations at nested scales of small catchments, river basins, and the complete Sierra Nevada.

Water is central to almost all resource issues and conflicts in the Sierra Nevada. Changes in water availability, streamflow timing and amounts, quality of surface and groundwater, aquatic and riparian habitats, flooding, soil erosion, and sedimentation have occurred throughout the range as results of resource management and land disturbance (e.g., 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. The water resources' evaluation of the Sierra Nevada Ecosystem Project attempted to determine the overall status of the primary water source of California and what problems require attention.

The Sierra Nevada generates about 25km^3 of runoff each year out of a total for California of about 88km^3. This runoff from the Sierra Nevada 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 utilise the water resources of the Sierra Nevada are perhaps the most extensive hydrotechnical network in the world. Major water supply systems have tapped several rivers to meet the urban needs of several large cities in California. Irrigated agriculture throughout California consumes more than the annual runoff of the Sierra Nevada and accounts for more than 90 per cent of consumptive use in the state. More than 150 power houses on Sierra Nevada rivers produce about 24 million megawatt-hours of electricity annually. Sierra Nevada rivers support extensive aquatic and riparian communities and maintain the Sacramento-San Joaquin Delta and San Francisco Bay ecosystems.

Historical Impacts

The Sierra Nevada Ecosystem Project attempted to analyse historical effects as a means of understanding how the current situation developed. Although Native Americans had a few small-scale irrigation projects in the eastern Sierra Nevada, and their vegetation management practices may have modified the hydrologic regime near some villages on the western slope, human impacts on the hydrology of the Sierra Nevada were minor until the Gold Rush that began in 1849. Within just a few years, thousands of miners invaded the Sierra Nevada and rapidly tore apart the streams and riparian corridors of the western slope in pursuit of gold among the gravels of current and ancient rivers. Streams were dammed, diverted, de-watered, polluted, excavated, and filled with debris from upslope and upstream mines. Harvesting of trees along the water courses and adjacent hillsides for flumes, mine timbers, buildings, and fuel and simply to provide access to gold-bearing alluvium resulted in major changes in vegetation cover, rapid soil loss, and sediment deposition downstream.

The intensity of devastation increased dramatically when the erosive power of water was harnessed for hydraulic mining between 1860 and 1884. At the peak of hydraulic mining, there were more than 400 hydraulic mines in operation in the Sierra Nevada (Logan 1948). Sediment-laden runoff from the eroded hillsides was directed into long sluice boxes to extract the gold and then discharged into the nearest creek. Stream channels immediately downstream of the hydraulic pits were overwhelmed by the enormous sediment loads and aggraded by tens of metres in some cases. During higher flow events, some of the material was transported downstream and was eventually deposited in the Sacramento Valley and San Francisco Bay. As lowland farmers gained economic and political power, they were able to successfully challenge the mining interests in court and won an injunction in 1884 that effectively ended hydraulic mining (Kelley 1959). After this legal decision, mining sediments have continued to be flushed out downstream at declining rates (James 1994). Before dams began to contain these sediments, the total volume of mining debris transported out of the Sierra Nevada was estimated at about 1.1 billion cubic metres or about ten times greater than natural sediment yield (Gilbert 1917).

The development of towns, trails, roads, railroads, and agriculture to support the mines had further indirect impacts on the watersheds and streams of the western slope. Overgrazing was probably the most widespread impact on the Sierra Nevada landscape associated with mining and the growth of California. Accelerated erosion and gullying of meadows as a consequence of overgrazing began to be noticed in the late 1880s, and attempts at control were underway by the 1930s (e.g., Kraebel and Pillsbury 1934).

Capturing and diverting water for the mines became a huge industry that was probably more profitable than mining. In the 1860s, more than 8,500km of main canals and about 1,300km of branch ditches were constructed (Logan 1948). After hydraulic mining was halted in 1884, many of the canals were acquired by irrigation districts and later by power companies. 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. Between 1895 and 1920, dozens of hydroelectric facilities were completed throughout the Sierra Nevada. In addition to these hydroelectric projects, three immense municipal supply projects began as mining faded out. By 1935, waters from the Sierra Nevada were enabling the rapid growth of Los Angeles, San Francisco, and the Oakland-Berkeley area. Additional water projects, large and small, have increased the degree of control over the streams of the Sierra Nevada in each succeeding decade.

Combined Effects of Resource Development

In many rivers, current impacts are superimposed on the legacy of 19^{th} century hydraulic mining and overgrazing. Although the apparent degree of recovery from severe disturbance is remarkable in many cases, the aquatic and riparian ecosystems are believed to be greatly simplified compared to what might have been without the massive anthropogenic disturbance of the 1800s. In places where the source of the disturbance has not been removed (e.g., a road or persistent grazing), natural recovery is impaired or prevented. Present-day water problems usually result from a combination of impacts. In a particular catchment, conversion of vegetation, creation of impervious surfaces, overgrazing of the riparian area, gravel mining, and a water storage project will have cumulative impacts on streamflow and its constituents. Although direct water management is the overwhelming human influence on the hydrologic regime of most river basins in the Sierra Nevada, other activities affect water quantity and quality, at least locally. With most of the forest and alpine zones of the Sierra Nevada in public ownership, timber harvesting, grazing, mining, and associated roads are the primary land uses with potential to alter hydrologic processes. In the privately-owned foothills, conversion of woodlands, chapparal, and grasslands to pasture, agriculture, and towns has the potential to change water and sediment yields. The proximity to a channel, intensity of disturbance, and areal extent of the activity determine the hydrologic effects. Although some land-use practices greatly alter the water balance or erosion rates of the local area affected, such impacts are generally not extensive in most parts of the Sierra Nevada. The typically large proportion of a catchment that is not impacted by a particular practice usually compensates for or masks out the change in water or sediment yields.

Management of water resources through dams and diversions is the principal modern impact on aquatic systems of the Sierra Nevada. While other resource development activities alter the environment in ways that may subsequently affect streamflow, water management practices avoid the intermediate steps and directly alter the hydrologic regime of the stream itself. The hydrotechnical structures that facilitate exploitation of streams for social uses create the greatest impacts on those very uses as well as on aquatic ecosystems. The highly managed water system has created artificial patterns of streamflow in the lower reaches of most rivers and their principal tributaries. The engineered control of streams in the Sierra Nevada is remarkably thorough: none of the major rivers reach the Central Valley unaltered. Few streams flow very far from their source before being influenced by some kind of hydraulic structure. There are relatively few opportunities for further development of water resources in the mountain range given existing infrastructure and water rights. The storage capacity of all dams in the range is about 28 billion cubic metres, with about three quarters of that total in a dozen large reservoirs. These largest projects can hold more water than is generated in an average year. Dams of all sizes have a variety of biological and geomorphic effects (e.g., Ligon et al. 1995). Blockage of fish migration and alteration of sediment transport are two of the most problematic effects in the Sierra Nevada. Fragmentation of riverine and riparian habitats has altered the distribution of particular species and changed ecological relationships between species. Below dams, the most obvious change in formerly natural hydrographs are decreases in floods. Peak flows below some major reservoirs are reduced to essentially nothing as the dams perform their flood control functions. The absence of occasional large flows interferes with natural processes that require disturbance of stream sediments or riparian vegetation. Low flows may be changed by orders of magnitude where streams are alternately dewatered to divert water into a canal or penstock or flooded with releases from storage during the dry season. Many projects have minimum flow requirements to keep fish alive, but these generally-constant flows are quite different from the fluctuating flow regime that the aquatic community evolved with. Changes in reservoir management practices may offer the best hope for improving aquatic ecosystems where they are known to be impacted by artificial flow regimes. In general terms, almost any shifts back towards a natural hydrograph, such as seasonally fluctuating flows or occasional flushing flows, will be beneficial to the local biota. Greater consideration of downstream ecological needs could be incorporated into the operations of many reservoirs without incurring major costs. Opportunities for alterations into release scheduling and their potential benefits and costs need to be explored on a project-by-project basis.

Of current land management practices, roads provide the most intensive modification of land surface properties relevant to hydrology. There are approximately 28,000km of roads through the national forests of the Sierra Nevada. Major highways occupy hundreds of kilometres of riparian corridors along portions of several principal rivers in the range. The road network is believed to be the largest source of accelerated sediment yield in the range. A principal side effect of an extensive road system is that access is provided to allow other alterations. Few adverse impacts, other than overgrazing, were found in the absence of roads. Avoidance of new road construction can minimise other potential impacts in currently unroaded areas. Harvesting timber has the potential to increase annual water yields, peak flows, and sediment production. However, operational constraints limit the area disturbed. Intensive timber management under the usual restrictions of Forest Service management could increase streamflow in most Sierra Nevada rivers by one to two per cent (6 to 10 mm) (Kattelmann et al. 1983; Marvin 1996). 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 (Marvin 1996). Grazing of domestic livestock has probably affected more area in the Sierra Nevada than any other management practice. The near-ubiquitous presence of grazing animals has left few reference sites that we can be certain were never used by livestock. This problem of uncertainty exists to some degree with all impacts, but there are many areas that were not mined, dammed, logged, invaded by roads, or urbanised. There just are not many that were not grazed.

Compared to the intentional alteration of streamflow through water management, hydrologic side effects of changes in land use are difficult to detect. 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. Rapid expansion of foothill towns has theoretically altered runoff and erosion processes enough to cause noticeable impacts in downstream channels, but quantitative and documentary evidence outside of the Lake Tahoe basin is lacking. Conversion of forest lands to roads associated with timber harvesting may have increased annual water yields and peak flows somewhat on the small catchment scale. However, decades of successful suppression of forest fires 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 effect cannot be quantified yet. Excessive fuel loads, accumulated as a result of fire suppression, create substantial risks of hydrologic impacts from potentially severe wildfires.

Across the entire Sierra Nevada, chemical water quality remains very high, but cannot be considered pristine. Some local water-quality problems, such as those at Lake Tahoe, in particular abandoned mines, and in some towns, are very serious. The quality of receiving waters from the larger cities in the foothills has been degraded. Excessive sediment production is the most widespread nonpoint-source problem, but its extent and severity are largely unknown. Disturbances in and near stream channels generate the vast majority of sediment transported by the streams. Estimates of average annual sediment yields in the Sierra Nevada were compiled from all available sources, with emphasis on those derived from repeated bathimetric surveys of reservoirs. The values provide order-of-magnitude approximations of sediment yield. Most reported values are less than 100 $m^3km^{-2}yr^{-1}$. Unfortunately, very few measurements of reservoir sedimentation have been reported in the past two decades, so there is little information about possible sediment responses to recent changes in land use. One intriguing set of measurements recently became available on the Mokelumne River, where repeated surveys suggest that the rate of sediment deposition in Pardee Reservoir has more than doubled since 1943 (East Bay Municipal Utility District 1995). Parts of the Mokelumne River basin have been subject to extensive road construction and logging in the past few decades, and concern about possible increases in erosion led to the new reservoir survey. Sediment production in the North Fork Feather River basin has also been considered to be much higher than natural background rates. A comprehensive evaluation of sediment sources in the basin found that about 80 per cent of the sediment yield in the basin is induced by human activities (U.S. Soil Conservation Service 1989). Most of this accelerated erosion is caused by bank erosion in which riparian vegetation has been eliminated by overgrazing and erosion from road cut and fill slopes. The excessive sediment yield in this river has interfered with the operation of hydroelectric facilities downstream and led to a large-scale cooperative effort aimed at stabilising the stream channels and roads throughout the basin. Elsewhere, 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 streamflow by storage and diversion may be the fundamental water quality problem in the Sierra Nevada.

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