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Camp and Clear Creeks, El Dorado County: Predicted Sediment Production from Forest Management and Residential Development

ABSTRACT

As part of the Sierra Nevada Ecosystem Project case study, we assessed the relative sediment production of fifty years of land use (1940–91) in the Camp Creek and Clear Creek Basins, two catchments in the Cosumnes River Basin. The Camp Creek Basin encompasses 8,245 ha (20,821 acres), ranges in elevation from 975 to 2,316 m (3,200 to 7,600 ft), and is managed by the Eldorado National Forest. The Clear Creek Basin encompasses 3,068 ha (7,580 acres), ranges in elevation from 512 to 1,250 m (1,680 to 4,100 ft), and has been extensively developed with low-density housing. We used the Water Yield and Sediment Model (WATSED) to predict the relative sediment production rates and volumes associated with forest management and residential development in these two basins. Although the best available data were used in this study, the predicted sediment rates should be used with caution.

Camp Creek: Predicted peak sediment production from roads was 4 mT/ha•yr (1.8 T/acre•yr). Two estimates of sediment production from logging were made. At the low rate (based on limited local data), peaks in sediment production for three periods of activity were 0.2 mT/ha•yr (0.09 T/acre•yr) or less. At the high rate (an order of magnitude greater than the low rate), peaks were less than 2 mT/ha•yr (0.9 T/acre•yr). Fires affected 256 ha (633 acres), and minimal quantities of sediment were predicted. At the low erosion rate for logging, relative sediment production for roads and logging was predicted at 98% and 1%, respectively; at the high erosion rate, 90% and 9%.

Clear Creek: Peak sediment production from roads was 2.6 mT/ha•yr (1.2 T/acre•yr). To account for the effects of residential development, sediment yield predictions were made for the area attributed to unsurfaced driveways. Peak sediment production from driveways was 0.4 mT/ha•yr (0.2 T/acre•yr). A fire affected 85 ha (210 acres) in 1972, and a minimal quantity of sediment was predicted. Predicted sediment from roads was 83% of the total, and 16% of the total was from housing.

Predicted mean annual erosion rates due to both disturbance regimes range from 29 to 119 times the assumed natural rate of erosion during the sixty-two-year period. For residential development, the average ratio of mean annual erosion to the natural rate of erosion was 53:1, and for logging the mean ratio was 87:1. Mean total sediment production rates per hectare for Clear Creek were between 53% and 67% the magnitude of the Camp Creek Basin's rates over the period of analysis.

A second normalization procedure was devised to measure sediment from housing and logging by the area of road built to support the land use, rather than by hectare of land involved in the land use. The residential rate was 11 mT/yr per hectare of road (5 T/yr per acre of road), more than twice the rate of 5 mT/yr per hectare of road (2 T/yr per acre of road) for logging. Logging and residential development have different relative scales of impact depending on whether sediment production is normalized by road area or by land area.

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.

INTRODUCTION

Accelerated (management-induced) erosion and sediment production are often the greatest effects of logging, road building, and residential development in forested areas (Hewlett 1982; Anderson et al. 1976). These potential threats to land and water resources can be exacerbated in regions of the Sierra Nevada where erodible, decomposing granitic rock may comprise the bulk of the soil parent material. The few available data from the Sierra Nevada suggest that sediment yield may increase significantly after logging (McCammon 1977). The potential for accelerated erosion and sedimentation is consistently identified by the public in reviews of environmental assessments and appeals of proposed timber sales. A recent overview of hydrology and water resources in the Sierra Nevada, prepared for the Sierra Nevada Ecosystem Project (SNEP), identified sediment yield as one of two preeminent hydrologic issues needing resolution for the Sierra Nevada (Kattelmann 1996). Sediment prediction systems from elsewhere, such as the Idaho Batholith (Megahan and Kidd 1972) and northern California (Lewis and Rice 1989), need to be modified prior to use in the Sierra Nevada because of differences between these areas in physiography, geomorphologic processes, and soils and in the distribution, timing, and type of precipitation.

As part of an analysis of conditions in the Sierra Nevada, members of the SNEP selected two small basins, Camp Creek and Clear Creek near Placerville on the west slope of the central Sierra Nevada, for detailed hydrologic and other analyses. The basins were selected because they are typical of much of the Sierra in their history and land-use patterns. This chapter is a companion to a case study of land-use changes and their hydrologic effects in these basins (McGurk and Davis 1996). The Camp and Clear Creek catchments contain examples of two common land uses in the Sierra Nevada, logging (Camp Creek) and residential development (Clear Creek). The goal of this analysis was to estimate with a simulation model accelerated sediment production from fifty years of land-use change in these basins and to compare the levels.

Few data exist on natural or accelerated sediment production in the Sierra Nevada. Some information on sediment accumulation in large, low-elevation reservoirs is available (Kattelmann 1996), but these data are not directly applicable to higher-elevation, managed landscapes. Reservoir sedimentation may also combine natural and induced hillslope erosion and in-channel sediment production. Soil erosion studies often do not address movement of the eroded soil downslope; the actual delivery of sediment between point of detachment and entry (if at all) into a stream channel has generally not been addressed in the Sierra Nevada.

Management activities that bare the soil surface or accelerate mass movement can lead to increased erosion. Depending on the distance of the hillslope activities from the channel and on barriers between the activity and the stream, eroded sediment may be delivered to the channel. Models attempt to simulate these processes either with "lumped" coefficients that aggregate several processes together or with more physically based models that simulate the mechanics of each geomorphologic process. Physically based models require extensive physical data and typically operate over short time intervals, such as an individual rainstorm.

With high-resolution digital elevation data and detailed soils data, numerical models such as TOPMODEL predict surface and channel flow that lead to particle detachment (Moore et al. 1988). Neither the high-resolution digital elevation nor the soils data were available for the Camp and Clear Creek Basins, so a distributed-parameter, numerical model could not be used. The Water Erosion Prediction Project model (WEPP) was also rejected because of input data requirements (e.g., thirty-three coefficients for vegetation, fifteen values per soil horizon, etc.) and the lack of a completed module for forest land (Agricultural Research Service 1994).

Because of the paucity of local data, the need to model long time periods and large basins, and the SNEP stipulation to use available technologies and information, the Water Yield and Sediment Model (WATSED) was selected. WATSED, an empirically based accounting model that is described in a later section, is currently used on several national forests in Montana (U.S. Forest Service 1991). Our analysis estimated the amount of sediment reaching channels but did not estimate potential in-channel sources of sediment or routing within the channel.

STUDY SITE DESCRIPTION AND HISTORICAL LAND USE

The Cosumnes River Basin, located on the west slope of the central Sierra Nevada (figure 53.1), has been modified by settlers for at least 150 years by logging, fire, mining, grazing, and diversion of water for agricultural use. Using aerial photographs taken between 1940 and 1991, McGurk and Davis (1996) quantified the land-use changes for the Camp and Clear Creek Basins, located in the middle- to upper-elevation range of the Cosumnes River watershed.

Study Site

The Camp Creek Basin is about 20 km (12 mi) east of Placerville. The basin has a west aspect and is a tributary to the North Fork of the Cosumnes River. The upper 8,246 ha (20,821 acres) of the Camp Creek Basin were selected for analysis by the SNEP Hydrology Team. The lower portion of the basin is in steep terrain and has not been extensively logged or roaded and was therefore excluded from the analysis. The analysis area in the middle and upper portions of the Camp Creek Basin ranges in elevation from 975 to 2,316 m (3,200 to

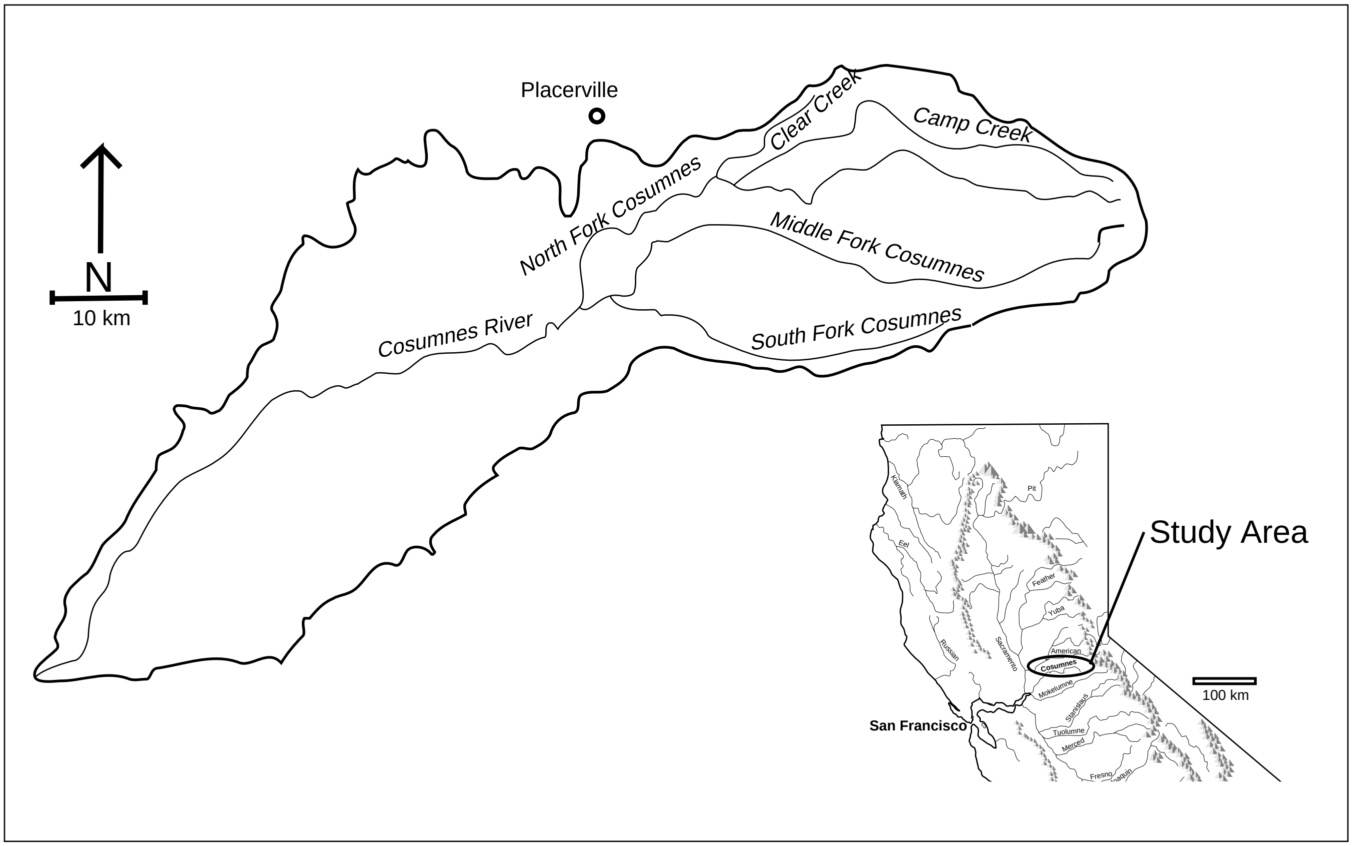


FIGURE 53.1

Location of study area, Placerville, and Clear and Camp Creeks in the Cosumnes River Basin, California.

7,600 ft) and is managed by the Eldorado National Forest (ENF). The main Camp Creek channel ranges from a moderately deep canyon (160 m [400 ft]) to a shallow canyon. The upper reaches are the shallowest, with many forks ending in open meadows.

The Clear Creek Basin is located 14 km (9 mi) east of Placerville. This basin encompasses 3,068 ha (7,580 acres) and is directly west of the Camp Creek Basin. The Clear Creek Basin is predominantly private land and ranges from 512 to 1,250 m (1,680 to 4,100 ft) in elevation; it has a southwest aspect (McGurk and Davis 1996).

Both basins are composed primarily of loam soils that have high infiltration rates (e.g., McCarthy, Josephine, and Cohasset series), although the Clear Creek Basin has some clay soils (Mitchell and Silverman n.d.; Rogers 1974). Soils in the Camp Creek Basin range from 66 to 178 cm (26 to 70 in) in depth and average 88 cm (35 in). The Clear Creek Basin's soils range from 45 to 131 cm (18 to 52 in) in depth and average 103 cm (41 in). Because of the depth and texture of the soils, surface runoff is likely to occur only on compacted zones such as roads.

Geologic parent materials in both basins are dominated by volcanic lahars, although approximately 20% of the soils were formed in materials weathered from granitic rock. Bedrock channel sections are more evident in the middle portion of Camp Creek than the upper portion, where alluvial (volcanic and granitic) components are common (Fiore 1992). About 55% of the soil in the Camp Creek Basin has a high to very-high erosion hazard, and 75% of the soil in the Clear Creek Basin has a high to very-high erosion hazard. Slopes range from 9% to 41% and average 24% in the Clear Creek Basin and range from 15% to 43% and average 31% in the Camp Creek Basin (McGurk and Davis 1996). For Camp Creek, the steepest slopes are part of an inner gorge along the main stem or the mid-basin tributaries (Swanson et al. 1993). Grass, shrubs, and forest areas are found in the Clear Creek Basin, but the Camp Creek Basin is almost entirely mixed conifer forest.

Historical Land Use

In the Camp Creek Basin, logging and road building are the two major land uses. Selective logging (a technique in which small clumps or individual trees are removed from large areas) was performed almost exclusively until the mid-1980s. Over 527 ha (1,303 acres, or 6.4%) were clear-cut between 1984 and 1989, and extensive salvage operations (a form of selective logging) also occurred between 1988 and 1991. The road network expanded by 250% to nearly 100 ha (250 acres) between 1966 and 1986, but little additional road construction occurred after 1986. Fires occurred in 1969, 1973, and 1988 and affected 266 ha (657 acres) (McGurk and Davis 1996).

In the Clear Creek Basin, home and road building are the two primary land uses. In 1940, little area was occupied by either structures (1 ha [2 acres]) or roadways (8 ha [20 acres]), but both uses doubled in area by 1952. Area occupied by homes quadrupled by 1966, more than doubled again by 1976, and nearly tripled again by 1986 to 45 ha (111 acres). By 1991, the area in homes had increased to 59 ha (146 acres). Roaded area increased by 50% between 1952 and 1966 and nearly doubled to 47 ha (116 acres) by 1976. After a small increase to 50 ha (124 acres) in 1986, only minor growth in roaded area occurred. A fire in 1972 affected 85 ha (210 acres) (McGurk and Davis 1996).

Grazing and other land uses, including dispersed recreation (e.g., off-highway vehicle [OHV] use), occur in both basins. The lack of quantifiable information on these activities precluded incorporation of their effects on sediment production.

TABLE 53.1

Summary of annual precipitation and soil loss from erosion plots on selected soils from the Camp and Clear Creek Basins (after Huntington and Singer 1982).

Soil Series	Year	Slope (%)	Aspect	Annual Precipitation (mm)	Soil Loss (mT/ha•yr)
McCarthy	1977–78	20	North	1,588	46.9
McCarthy	1978–79	20	North	Snow	0.2
McCarthy	1979–80	20	North	1,801	72.1
McCarthy	1980–81	20	North	607	35.7
McCarthy	1981–82	20	North	2,073	50.3
					Mean = 41.0
McCarthy	1977–78	27	South	1,588	77.7
McCarthy	1978–79	27	South	Snow	4.5
McCarthy	1979–80	27	South	1,801	107.4
McCarthy	1980–81	27	South	607	29.9
McCarthy	1981–82	27	South	2,073	75.3
					Mean = 59.0
McCarthy	1979–80	9	East	1,801	34.6
McCarthy	1980–81	9	East	607	7.4
McCarthy	1981–82	9	East	2,073	16.2
					Mean = 19.4
Auburn	1974–75	8	—	625	4.0
Auburn	1975–76	8	—	389	0.1
Auburn	1976–77	8	—	312	0.1
Auburn	1977–78	8	—	1,090	5.4
Auburn	1978–79	8	—	754	7.6
Auburn	1979–80	8	—	800	7.9
Auburn	1980–81	8	—	378	1.3
Auburn	1981–82	8	—	1,331	18.0
					Mean = 5.6
Argonaut	1977–78	14	—	996	2.9
Argonaut	1978–79	14	—	726	10.3
Argonaut	1979–80	14	—	772	26.5
Argonaut	1980–81	14	—	386	5.8
Argonaut	1981–82	14	—	1,265	90.3
					Mean = 27.2
					Grand mean = 30.4

SEDIMENT STUDIES

Two primary concerns associated with erosion are the potential loss of soil productivity and the degradation of stream water quality (Poff 1996). Undisturbed upland forests, where mineral soil is fully carpeted by litter and humus, have low natural erosion rates and deliver little or no sediment to streams (Anderson et al. 1976). In this undisturbed situation, sediment in the channel often originates from within the stream zone, often as a result of soil creep, mass failure, or debris torrents. Alternatively, ground-disturbing activities such as logging and road building may become the major sediment sources.

No erosion, sediment transport, or sediment deposition data were available from plots within these two basins. Soil maps and erosion hazard potential maps exist for both basins and are discussed later in the chapter. In addition, results from research or administrative studies in nearby areas were available.

Erosion Plot Studies

Runoff and erosion data from several soils common in the Camp and Clear Creek Basins are available in unpublished studies. From 1976 through 1982, sheet and rill erosion were monitored under natural precipitation conditions at standard erosion plots for soil series that together make up 40% of the soil in the Camp Creek Basin (table 53.1—sediment yield is decribed in metric tons per hectare per year [mT/ha•yr]) (Huntington and Singer 1982). In addition, measurements of runoff and erosion during simulated rainfall were made for soil series comprising 60% of the soil in the Camp Creek Basin (tables 53.2 and 53.3) (Huntington et al. 1979; Baker et al. 1994).

Of these three data sets, the long-term information from the standard erosion plots most closely represents the type of data required by WATSED as first-year values after timber harvest (table 53.1). These values were derived under conditions of natural precipitation, with each plot weeded and raked every two weeks between precipitation events to retain a bare-ground condition. Because of the weeding and raking, the erosion rates from this study certainly represent upper limits for erosion rates from logging and site preparation. Annual soil loss rates are quite variable within each soil series. Although some of the variability may be attributable to variation in precipitation and slope, the range in soil loss rates is typically large, even within a single slope class (table 53.1). Based on the relative ranking of the loss rates in table 53.2, we calculated the relative ratios of soil loss for Holland, Josephine, Aiken, and Windy soils compared with the soil loss for the McCarthy soil. Nearly 55% of the basins are composed of McCarthy and Josephine soils, which have similar erosional characteristics.

Simulated rainfall intensities in the Baker et al. (1994) study were potentially greater than naturally possible (table 53.3). In their study, simulated rainfall was initially applied to dry ground for one hour at a rate of 5.3 cm/hr (2.1 in/hr). The 50-yr 15-min natural rainfall intensity for the study sites equated to approximately 5.3 cm/hr. The duration of the simulated rainfall was therefore four times the duration of the 50-yr rainfall for that rainfall intensity. Long-term soil losses as great as those listed in table 53.3 are impossible to sustain. However, the data from the studies using simulated rainfall were considered to be upper bounds for erosion in this study.

Road and Trail Erosion

Between 1990 and 1993, the ENF monitored erosion downslope of OHV trails and roads at a site in the American River Basin, immediately north of the Cosumnes River Basin (U.S. Forest Service 1995). Silt fences trapped sediment transported off the road or trail surface at three adjacent sites that covered a range of hillslope angles. The roads and trails were designed to conform to current standards for road and trail design. Soil parent material at these sites is metasedimentary rock, a rock type that is not as common and is somewhat more erodible than most of the soils in the Camp or Clear Creek Basins. Sediment yield rates shown in table 53.4 are based on the assumption that the sediment was produced under natural precipitation regimes by concentrated surface runoff. Except for the high-slope category, these soil loss rates are similar to those measured by Huntington and Singer (1982) (table 53.1). Disturbance conditions between the two studies differed in that compaction of the soil surface was incorporated into the OHV study only. The Huntington and Singer (1982) site more nearly matches typical disturbances in logging operations, and the OHV results specifically address road and trail erosion. Differences in parent material between the OHV study site and the Camp and Clear Creek Basins add uncertainty to the applicability of the OHV study results.

TABLE 53.2

Soil loss rate under simulated rainfall and relative erodibility of five forest soils found in Camp and Clear Creek Basins (after Huntington et al. 1979).

Soil Series	Soil in Basins (%)	Soil Loss Rate (mT/ha)	Relative Erodibility
Windy (Typic Xerumbrept)	2.6	3.5	0.63
Aiken (Xeric Haplohumult)	1.6	4.8	0.87
Josephine (Typic Haploxerult)	17.5	5.4	0.97
McCarthy (Umbric Vitrandept)	36.7	5.5	1.00
Holland (Ultic Haploxeralf)	0.7	7.0	1.25

TABLE 53.3

Extrapolated annual soil loss from sixty minutes of simulated rainfall on soils found in Camp and Clear Creek Basins (after Baker et al. 1994).

Soil Series	Soil Loss (mT/ha·yr)	Slope (%)	Aspect	Condition
Aiken/Sites 1a	289.8	24	South	Logged, cleared
Aiken/Sites 1b	68.2	25	South	Logged, cleared
Aiken/Sites 2a	933.0	21	North	Logged, cleared
Aiken/Sites 3a	51.1	22	South	Logged, cleared
Aiken/Sites 3b	717.4	21	South	Logged, cleared
	Mean = 411.9			
McCarthy 1a	315.5	21	West	Logged, ripped
McCarthy 1b	537.2	26	West	Logged, ripped
McCarthy 2a	66.7	24	West	Logged, ripped
McCarthy 2b	865.6	27	West	Logged, ripped
McCarthy 3a	437.8	15	South	Logged, ripped
McCarthy 3b	478.3	14	South	Logged, ripped
	Mean = 450.0			

Watershed Improvement Needs (WIN)

As used on the ENF, the WIN inventory identifies disturbance types (e.g., sheet, rill, channel, or gully erosion, mass wasting, soil compaction) and disturbance sources. Besides induced sources of disturbance (e.g., animal grazing, off-highway vehicles, silvicultural methods, roads, hydrologic diversions), natural mass wasting is listed as a potential disturbance source. Analysis of over forty WIN reports compiled in 1991 for the Camp Creek Basin identified four locations where mass wasting was found. In three of the four cases, roads were associated with the disturbance. WIN reports from 1993 for the upper Camp Creek Basin identified road-related mass wasting as a disturbance cause in two of nineteen reports. In both surveys, roads and silvicultural activities were the most common causes of sediment entering the channels.

Pfankuch Channel Ratings

Pfankuch stream channel ratings (Pfankuch 1978) were assessed during stream surveys conducted on Camp Creek by the ENF (U.S. Forest Service 1993). Pfankuch's channel ratings include a category on the amount of mass wasting on each channel reach and are a second source of information on mass wasting in the Camp Creek Basin. As used on the ENF, existing or potential mass wasting is classed as

excellent: no evidence of past or potential for future mass wasting into channels

good: infrequent and/or very small, mostly healed over, low future potential

fair: moderate frequency and size, with some raw spots eroded during high flows

poor: frequent or large, causing sediment nearly yearlong or imminent danger of same

TABLE 56.4

Sediment yields from off-highway-vehicle roads on the Eldorado National Forest (after U.S. Forest Service 1995).

Slope (%)	Sediment Yield (mT/ha•yr)
0–15	18
16–22	45
23–30	89
>30	135

Of the 200 sites that were assessed, approximately 75% of the mass wasting ratings in the Camp Creek Basin study area were in the "excellent" category, and fewer than 2% were in the "fair" or "poor" categories (U.S. Forest Service 1993). Taken together, the WIN and Pfankuch data suggest that although localized mass movement can occur naturally, especially on steeply sloping inner gorge landtypes, mass wasting is otherwise a minor natural source of sediment. For this reason, mass wasting estimates were not included in the modeling.

MODEL DESCRIPTION AND IMPLEMENTATION

Because of data availability, basin size, and the long study interval, we decided to model sediment production in the Camp and Clear Creek Basins with the WATSED accounting model (figure 53.2). WATSED is used by the Lolo and Kootenai National Forests and others in the Northern Region (U.S. Forest Service 1991). WATSED has comprehensive documentation and experienced users available for assistance and is designed to address the cumulative effects of multiple management activities over time in forested landscapes. WATSED models both water and sediment yield (figure 53.2), but the WATSED water component was not used in this analysis. A more detailed analysis was performed (McGurk and Davis 1996) using the U.S. Geological Survey's Modular Modeling System (MMS) (Leavesley et al. 1992).

Eleven independent data files (or databases) are required by WATSED (figure 53.2). Eight coefficient files describe physical characteristics of the basin, and the manual specifies that these files be calibrated to fit the conditions of the area using local data. The remaining three data files are supplied by the users and incorporate areal information and management history data for the analysis watershed(s).

WATSED requires information on natural and accelerated erosion rates. Unfortunately, field data for the central Sierra Nevada are not common, so we adapted the few locally available data sources to the study area. We used the erosion information and physical data from Camp and Clear Creek Basins to complete WATSED's databases as follows.

Landtypes

Each basin is segmented into landtypes delineated on the basis of morphology, parent material, soils, and vegetation type. Physical information for each landtype is incorporated into the Land Systems Inventory (LSI), and disturbances (entered into the Activities database) are located by landtype.

In a companion hydrologic analysis of these basins, McGurk and Davis (1996) used the MMS to examine hydrologic changes due to changing land use. This model uses many of the same landscape parameters and divides the basin into polygons called Hydrologic Response Units (HRU). We decided to equate HRUs with landtypes. There are fifty-six landtypes designated for the Clear Creek Basin and fifty-eight landtypes identified for the Camp Creek Basin. Landtype areas range from 8 to 184 ha (21 to 455 acres) and average 55 ha (135 acres) in the Clear Creek Basin and range from 28 to 375 ha (68 to 926 acres) and average 145 ha (359 acres) in the Camp Creek Basin.

Land Systems Inventory (LSI)

The LSI is the primary data source for the model. It contains information on natural sediment yield, surface and mass erosion hazards, average slope, soil depth, and sediment delivery ratios for each landtype. In addition, the LSI links the landtypes with other databases (e.g., Surface Erosion Curves).

Natural Rate of Erosion

The term natural erosion refers to the erosion that occurs without anthropogenic disturbances such as roads. Natural rates of erosion vary widely, dependent on geologic parent material, slope, climate, soil, and vegetative cover. Heede (1984) cites 0–0.013 mT/ha•yr (0–0.006 T/acre•yr) as the range of natural erosion for small drainages in Arizona with climate and slope characteristics similar to those of our study basins. Euphrat (1992) cites a rate of 0.07 mT/ha•yr (0.03 T/acre•yr) for the Mokelumne River Basin. Dunne and Leopold (1978) report a rate of 0.004 mT/ha•yr (0.002 T/acre•yr) for an undisturbed forest in North Carolina. Kattelmann (1996) referenced a 1972 California Division of Forestry report that lists a Sierran value of 0.014 mT/ha•yr (0.006 T/acre•yr). Based on these literature values and the types of soils in the Camp and Clear Creek Basins, a mean rate of 0.02 mT/ha•yr (0.009 T/acre•yr) was used in this study for comparison of natural versus accelerated sediment production.

Surface Erosion Hazards

The ENF has incorporated soil and slope data, as well as other factors, into an Erosion Hazard Rating (EHR) system. Percentages of the different categories (very high, high, moderate, and low hazard) by landtype were obtained from the ENF geographic information system, and landtypes were assigned a category based on the dominant percentage (figure 53.3). WATSED adjusts the basic surface erosion curves to reflect slope and natural erodibility. In this case, landtypes with low

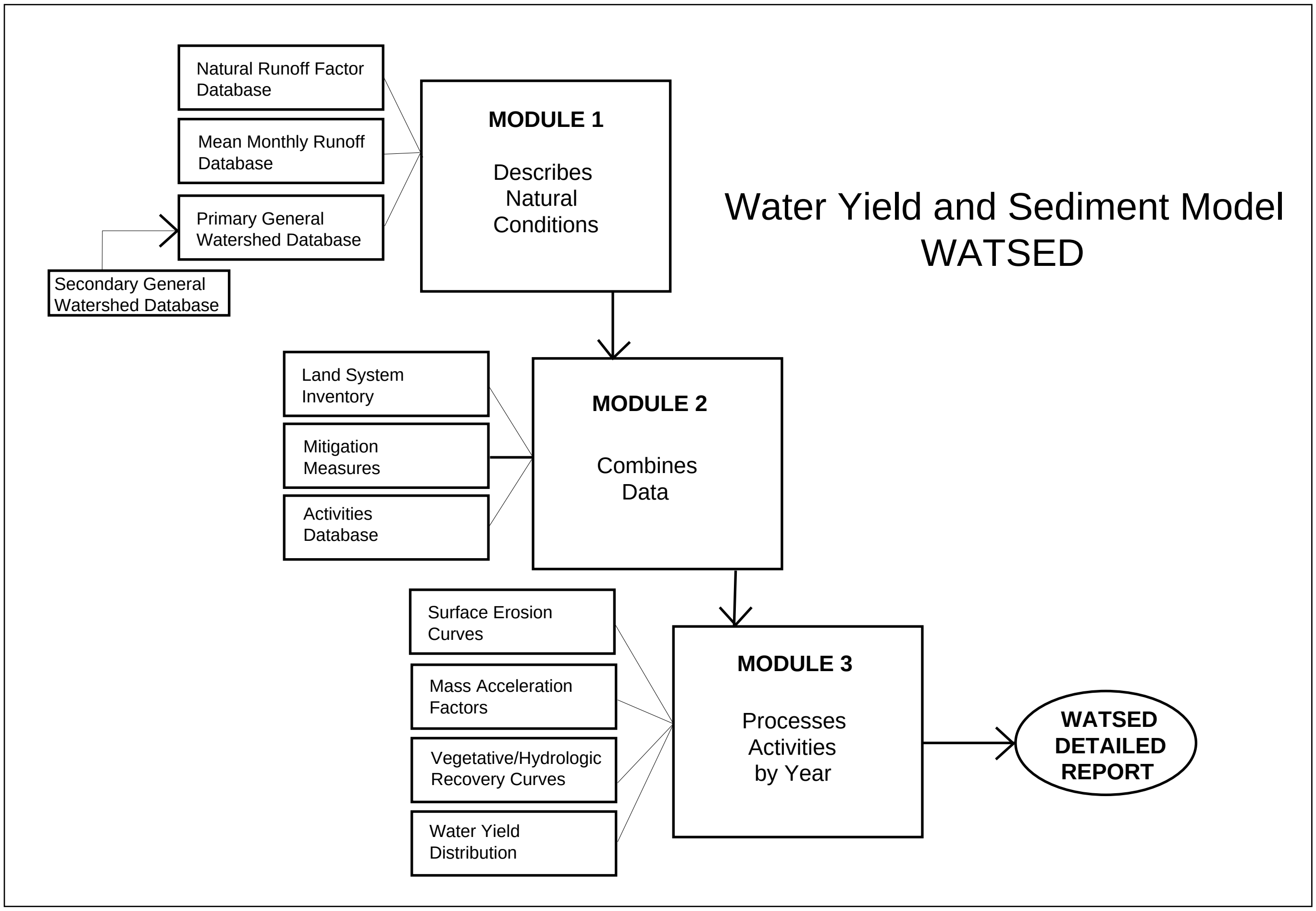


FIGURE 53.2

Schematic of Water Yield and Sediment Model used to predict sediment yields from Camp and Clear Creek Basins (after U.S. Forest Service 1991).

erosion hazard ratings were assigned a correction factor of 25%. This means that only 25% of the potential sediment from a disturbance in a landtype with a low erosion hazard would be generated. Moderate erosion hazard landtypes were assigned a correction factor of 50%, high-hazard landtypes 75%, and very high hazard landtypes 100%. These adjustment values were used for all disturbance types.

Landform Type and Sediment Delivery Ratios

WATSED incorporates hillslope position and presence or absence of ephemeral and first-order drainages by establishing landform types and assigning sediment delivery ratios to each. Using the landform types described in the WATSED manual as a guide, seven landform types were defined for the Camp and Clear Creek Basins (figure 53.3 and table 53.5). Delivery ratios incorporated advice from soils experts at the ENF and at the California Department of Forestry and Fire Protection. Based on analysis of topographic maps, a landform was assigned to each landtype, and the appropriate sediment delivery ratio for each landtype was entered into the LSI.

Primary and Secondary General Watershed Databases

Information for the entire analysis watershed(s) is entered into the Primary database. Water Resources Council code, name, total acres, natural sediment yield, and precipitation and runoff values for Camp and Clear Creek Basins were entered into their respective databases. Area and precipitation for each landtype were entered into the Secondary database.

Surface Erosion Curves

WATSED estimates sediment from each activity over time by applying the area of the disturbance to the appropriate erosion curve. Curves from the WATSED manual (U.S. Forest Service 1991) for roads, logging, and fire were modified to reflect local conditions.

The road curve (figure 53.4), based on observations in Idaho of roads on granitic parent material, predicts that the peak amount of sediment occurs during the year following road construction. Sediment is reduced to 27% of the original value

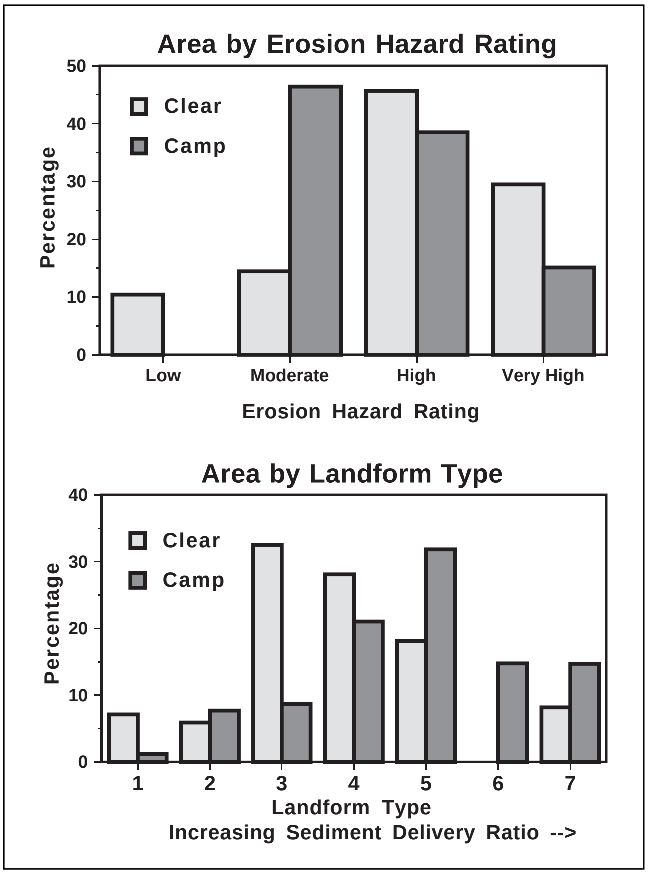


FIGURE 53.3

Distribution of area by soil erosion hazard rating and landform type in the Clear and Camp Creek Basins.

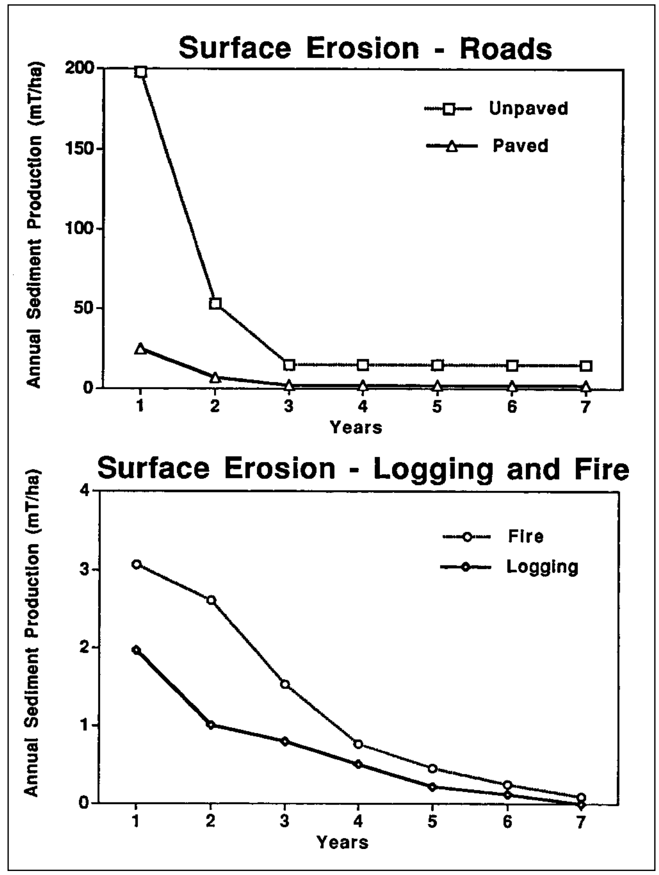


FIGURE 53.4

Surface erosion curves for roads, logging, and fire that were used for sediment predictions in Clear and Camp Creek Basins (modified from U.S. Forest Service 1991).

in the second year and falls to a base level of 7% in the third year and thereafter. For forest roads in Montana, WATSED uses a first-year sediment production value of 237 mT/ha•yr (105 T/acre•yr), but the manual recommends that this value be adjusted based on local data. Erosion data by slope class from the OHV study on the ENF were plotted, and a curve was fit to the data. The maximum average landtype slope was

TABLE 53.5

Definitions of landform types and the sediment delivery ratio values that were assigned to each landtype (after U.S. Forest Service 1991).

Landform Type (#)	Sediment Delivery Ratio (%)
Ridgetop (1)	2
Undissected slopes not adjoining a channel (2)	7
Dissected slopes not adjoining a channel (3)	10
Undissected slopes adjoining a channel (4)	15
Dissected slopes adjoining a channel (5)	20
Very dissected slopes adjoining a channel (6)	25
Inner gorge (7)	75

43%, and the erosion value for this slope was 198 mT/ha•yr (88 T/acre•yr). This value is appropriately higher than the erosion values on more gentle slopes (table 53.1) and lower than the values associated with intense simulated rainfall (tables 53.2 and 53.3). The 198 mT/ha•yr value became the initial value in the surface erosion curve for unpaved roads (figure 53.4), and the subsequent years were estimated based on the percentage changes in the WATSED road curve.

Unlike the watersheds on the national forests where WATSED was developed, the Camp and Clear Creek Basins include paved roads. We developed a new road curve to predict sediment yield generated from the paved roads. Paved roads in these basins are either 6.7 or 7.3 m (22 or 24 ft) wide, according to ENF records. We assumed the paved roads also include an additional 2.4 m (8 ft) of unpaved shoulder and ditch, for a total width of 9.1 or 9.7 m (30 or 32 ft). Although approximately one-quarter of the total surface is unpaved, we selected a paved to unpaved ratio of 1:8 for sediment yield because shoulders and ditches associated with paved roads are not disturbed as often as those associated with unpaved roads. Based on this ratio, 25 mT/ha•yr (11 T/acre•yr) became the initial value in the surface erosion curve for paved roads, 7 mT/ha•yr (3 T/acre•yr) the second-year value, and 2 mT/ha•yr (0.9 T/acre•yr) the value for the third and subsequent years (figure 53.4).

The dominant disturbances in the Clear Creek Basin are roads and residential development. McGurk and Davis (1996) assumed that each residential unit was composed of 762 m^2 (2,500 ft^2) of impervious roof area and an equal amount of driveway and paths. Though sediment may be produced during the construction phase, no information exists on sediment production from house construction for this basin. Most houses are built during the summer season, so erosion during construction may be negligible. Roofs do not generate sediment, and it was assumed that the homeowners maintain ground cover across the rest of their properties. Based on personal inspection, most driveways in Clear Creek subdivisions are unpaved. To account for sediment yield generated from residential development, driveways were represented as roads that are 4.9 m (16 ft) wide.

Surface erosion curves for fire and logging were also established. A survey of the literature yielded relative sediment production factors from logging and roads (table 53.6). The ratios range from 0.005 to 0.11, and a value of 0.01 was initially selected as most appropriate based on soils and climate. This factor was applied to the established erosion value for roads to yield a first-year erosion value for logging of 1.98 mT/ha•yr (0.88 T/acre•yr). This value is between ten and thirty times less than the bare soil loss values for McCarthy soil in table 53.1. To establish a potential upper bound on erosion from logging, a second WATSED prediction was made using a value of 19.8 mT/ha•yr (8.8 T/acre•yr), approximately equal to the lowest McCarthy soil loss values in table 53.1 and an order of magnitude greater than the ratio-based value. Values for subsequent years were then generated using the percentage change values specified in the WATSED manual.

The ratio of the fire value to the Idaho road value used by WATSED was 1.56%, and use of this factor yields a sediment production rate of 3.07 mT/ha•yr (1.37 T/acre•yr) for wildfire in both the Camp and Clear Creek Basins (figure 53.4). This rate was within the bounds established using Sierra data, and Anderson et al. (1976) reported a 45-fold increase over the natural rate of erosion after fire in northern California. Haig (1938) reported a twofold to 239-fold increase over the natural rate after fire in the pine region of the Sierra Nevada. Wells et al. (1979) found that a pine area in Arizona produced 30 mT/ha•yr (13 T/acre•yr) for the first several years after an intense fire. Rates for subsequent years were generated using the percentage values specified in the WATSED manual (figure 53.4).

Mitigation

WATSED accounts for mitigation measures aimed at reducing the amount of eroded material delivered to the stream channel. Mitigation is treated as a linear reduction of sediment from surface or mass erosion for each management action. The WATSED manual provides standard mitigation values for several management activities. We applied our own mitigation measures to logging activities to reflect improved management practices over time. Mitigation values were as follows: for logging in 1966, 1%; logging in 1976, 10%; logging between 1984 and 1986, 25%; and logging between 1987 and 1991, 40%. For example, for logging in 1976 there was a 10% reduction in the amount of sediment estimated by the logging surface erosion curve.

TABLE 53.6

Relative sediment production factors from tractor logging and road building.

Source	Location	Sediment Production (mT/ha•yr) Logging	Roads	Ratio of Logging to Roads
Megahan 1975	Idaho	0.2	24	0.008
Fredriksen 1970	Oregon	1.1[a]	28	0.04
U.S. Forest Service 1991	Montana	1.2	237	0.005
Binkley and Brown 1993	Georgia	0.4	3.6	0.11

[a]Skyline yarding.

Activities Database

Disturbances in the basins are represented by the Activities database. Land-use information (disturbances) developed by McGurk and Davis (1996) for use with the MMS hydrologic model (Leavesley et al. 1992) was modified for use in WATSED.

For MMS, disturbances were given a "photo date," that is, the date (year) of the aerial photograph in which they first appeared. Thus, disturbances were clustered on a small number of years, separated roughly by a decade. Our goal with WATSED was to predict annual sediment yield, so we needed disturbance information that was not clustered.

The actual dates for fires and logging were known through ENF records. We had no information on the actual year of construction for roads or driveways in the basins, so dates were assigned to roads and driveways based on their photo date. These disturbances were distributed, roughly equally, every other year, back into the photo interval in which they first appeared. For example, roads with the photo date of 1976 were distributed equally across the years 1968, 1970, 1972, 1974, and 1976.

Each disturbance (e.g., road segment, clear-cut, fire) was described appropriately by date, activity type code, location by landtype, area, logging method, crown removal percentage, road length and width, and mitigation method applied. Although WATSED can account for the varying effects of high- and low-intensity fires and tractor, cable, and aerial logging, all fires were assumed to be high-intensity and all logging was assumed to be tractor logging. ENF records show that very little cable logging has been done in Camp Creek.

SEDIMENT PREDICTION RESULTS AND DISCUSSION

A sixty-two-year period, 1940 to 2002, was analyzed with the model. The year 2002 was selected to examine the sediment produced during the ten-year period following the last activities in 1991. The model's detailed output was summarized to provide a year-by-year sediment output from roads, houses, logging, and fire (figures 53.5 and 53.6). The sawtooth pattern that is evident in both figures is because road building was spread out at two-year intervals during the photo period. Mean production rates per decade are also presented to further smooth the sediment production rates (figure 53.7).

Annual Sediment Outputs

Roads

Construction of roads produced the largest amount of sediment in both the Camp and Clear Creek Basins (figures 53.5 and 53.6). Camp Creek has over 100 ha (250 acres) of road surface, and Clear Creek has about 50 ha (124 acres) of road surface. Camp Creek (8,246 ha [20,821 acres]) is almost three times the size of Clear Creek (3,068 ha [7,580 acres]), but the Clear Creek Basin has a higher road density (1.7%) than the Camp Creek Basin (1.2%). The Camp Creek Basin has 55 km (34 mi) of paved road because of the presence of Iron Mountain Road, about 4.3 times the paved roads in the Clear Creek Basin. Camp Creek has 256 km (159 mi) of roads overall compared with Clear Creek's 114 km (71 mi) of roads.

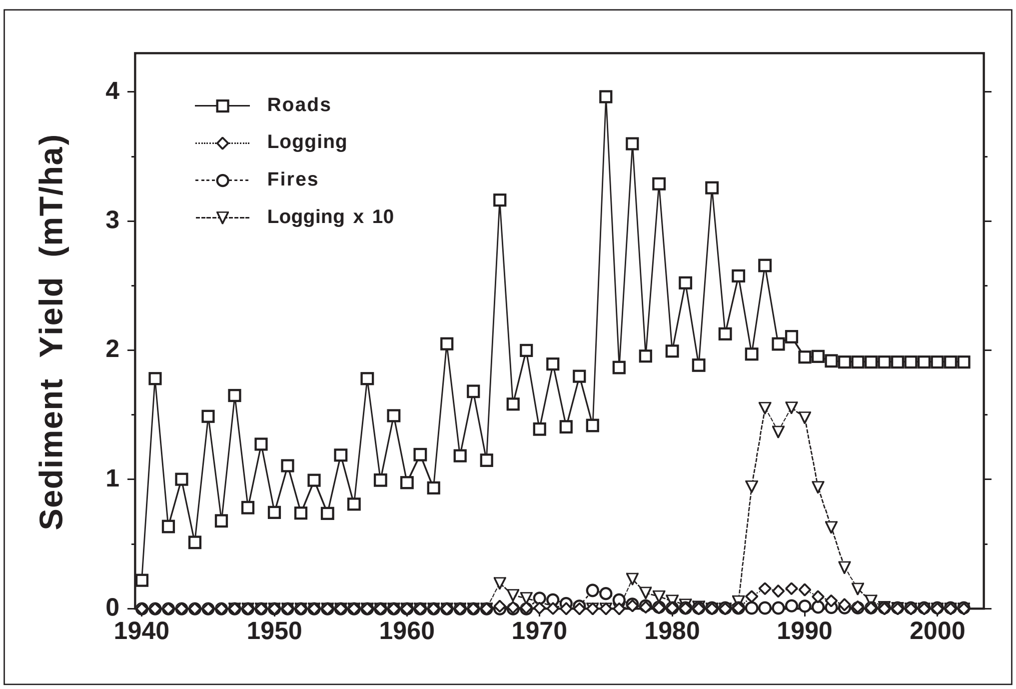
Sediment from roads was generated during the entire sixty-two-year history of the basins, and the peaks vary widely in their magnitude. Camp Creek sediment peaks range from 1 to 4 mT/ha•yr (0.4 to 1.8 T/acre•yr). The decade mean rate for Camp Creek climbs over the analysis interval to nearly 2.5 mT/ha•yr (1.1 T/acre•yr). Clear Creek sediment peaks range from 0.6 to 2.6 mT/ha•yr (0.3 to 1.2 T/acre•yr). The decade mean rate for Clear Creek reaches 1.5 mT/ha•yr (0.7 T/acre•yr) in the 1971–80 period and declines to 1.3 mT/ha•yr (0.6 T/acre•yr) by the end of the analysis period. Over the sixty-two-year period, roads in Camp Creek produced 883,665 mT (803,340 T) of sediment, and the Clear Creek roads produced 168,537 mT (153,217 T) of sediment. The Camp Creek sediment volume is over 5.2 times the Clear Creek volume because the annual rate is higher and the watershed is 2.7 times larger.

Housing

As a proxy for houses in the Clear Creek Basin, sediment was also produced from 29 ha (72 acres) of driveway. Rates exceeded 0.1 mT/ha•yr (0.04 T/acre•yr) after 1959, and peaks sometimes exceeded 0.4 mT/ha•yr (0.2 T/acre•yr) between 1979 and 1991. Over the sixty-two-year analysis period, 33,263 mT (30,239 T) of sediment was produced from driveways. Driveways accounted for 16% of the sediment from the Clear Creek Basin.

FIGURE 53.5

Sediment yields over time from roads, logging, and fire in the Camp Creek Basin.



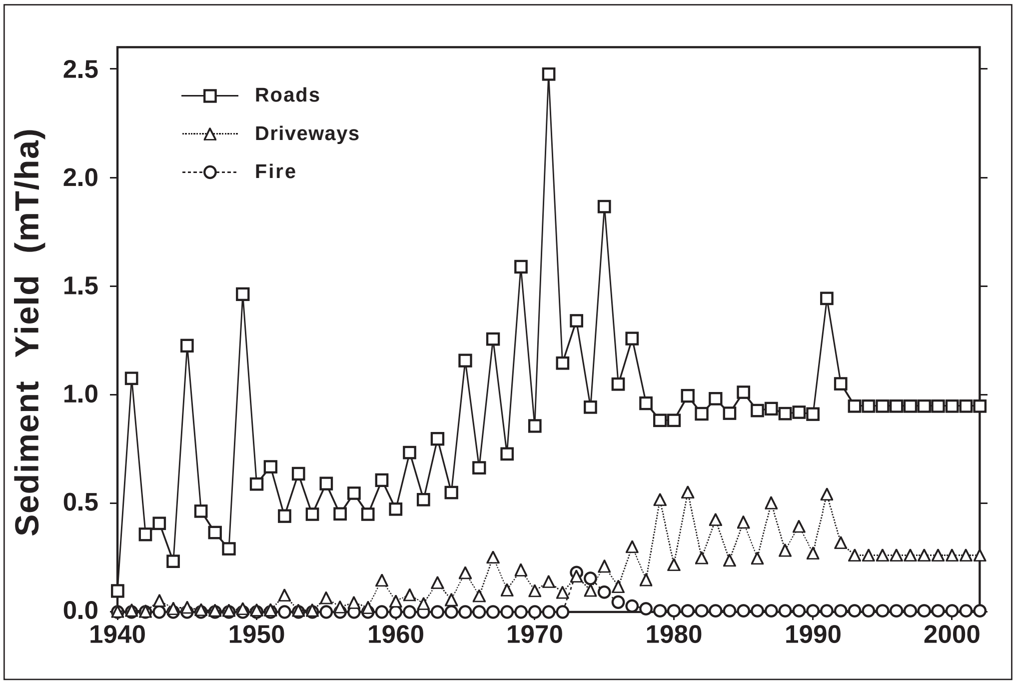


FIGURE 53.6

Sediment yields over time from roads, driveways, and fire in the Clear Creek Basin.

Logging

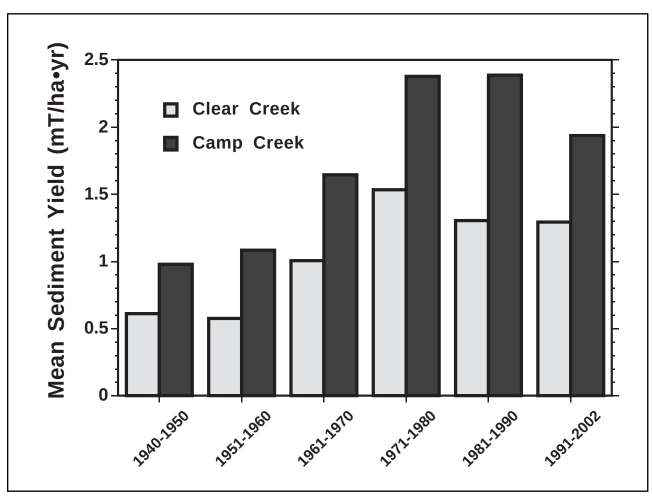
Clear-cut logging in Camp Creek occurred in 1966, in 1976, and between 1984 and 1989. Salvage logging that could be allocated to specific areas occurred between 1988 and 1991. Sediment was generated from logging in Camp Creek between 1967 and 1972, between 1977 and 1982, and between 1985 and 1997. Curves for two erosion rates for logging are presented, but for the low rate, only the last of the three time periods is visible in figure 53.5. All three periods are visible for the high erosion rate. Both the 1967 and 1977 periods produced 0.02 mT/ha•yr (0.01 T/acre•yr) or less in any year at the low rate, and the values for the high rate are larger by a factor of ten. The 1989 value of 0.2 mT/ha•yr (0.09 T/acre•yr) was the peak (1.6 mT/ha•yr [0.7 T/acre•yr] for the high-rate curve), and the values declined to zero by 1997. The total sediment yield from logging was 8,316 mT (7,560 T) between 1967 and 1997 for the low erosion rate and 83,161 mT (75,602 T) for the high erosion rate.

An analysis was performed to determine if more of the highly erodible sites were logged in the later time intervals. This issue pertains to an old nostrum that suggests that the "best sites" would be cut before the "poorer sites." We plotted, by decade, the hectares of roads built (to support logging) in each of the four erosion hazard classes. No shift toward the high or very-high classes was evident. In all but the earliest interval, the largest area of roads was built in the medium hazard zone. In all but the 1970 decade, which had none, two or fewer hectares of roads were built in the very-high class.

About 108 million board feet of timber have been removed from Camp Creek by selective logging between 1952 and 1991 (McGurk and Davis 1996). Because we were unable to allocate most of the selective logging by landtype, we were unable to develop erosion information for selective logging for the entire study interval. However, we have included in our predictions all of the roads built in support of selective logging. In that roads are consistently identified as the primary sediment producer compared with logging (Fredriksen 1970; Binkley and Brown 1993), we feel that the lack of sediment

FIGURE 53.7

Average annual sediment yield from 1940 to 2002, by decade, from roads, driveways, logging, and fire in the Clear and Camp Creek Basins.



projections from selective logging itself is not a critical omission.

Although roads produce most of the sediment in both basins, the relative role of logging in Camp Creek is worth noting. At the low erosion rate (1.98 mT/ha•yr [0.88 T/acre•yr]), sediment from logging is about 1% of the total during the sixty-two-year analysis period. At the high erosion rate (19.8 mT/ha•yr [8.8 T/acre•yr]), the contribution from logging rises to 8.5%. We believe this range encompasses the actual value for logging in the Sierra Nevada, but more information is needed on logging-related erosion and the effectiveness of mitigation.

Fire

The fire curve on the Camp Creek plot is visible in 1970 and 1974 in response to fires in 1969 and 1973, and a small fire in 1988 is undetectable (figure 53.5). The estimated annual sediment production reaches 0.1 mT/ha•yr (0.04 T/acre•yr) in 1974. Sediment from that fire declined after 1974 to less than 0.006 mT/ha•yr (0.003 T/acre•yr) from 1979 to 1988. A fire in 1988 caused a small rise, and the rate was less than 0.01 mT/ha•yr (0.004 T/acre•yr). The total sediment yield from land affected by fire was 6,654 mT (6,049 T) between 1970 and 2002.

Clear Creek was affected by fire in 1972, but the 1973 level was only 0.2 mT/ha•yr (0.08 T/acre•yr). After a six-year decline (controlled by the fire erosion curve, figure 53.4), sediment production remains below 0.01 mT/ha•yr (0.004 T/acre•yr) for the rest of the analysis period. The total sediment yield for land affected by fire was 1,994 mT (1,813 T) between 1973 and 2002.

Mean Sediment Yield

To smooth the sawtooth pattern and to combine the yield from all activities in figures 53.5 and 53.6, total mean annual rates were calculated for six intervals between 1940 and 2002 (figure 53.7). The bars in figure 53.7 are the mean of the values for approximately ten-year intervals. The means include sediment for roads, driveways, logging, and fire for each basin. Compared with the midpoint of the range of assumed natural erosion (0.02 mT/ha•yr [0.009 T/acre•yr]), the accelerated rates of erosion are 29 to 119 times the natural rate. For the Clear Creek Basin, the average ratio of mean annual erosion to the natural rate of erosion was 53:1, and for logging the mean ratio was 87:1. Past research at a location in Idaho found that erosion from roads alone can be as much as 750 times above the natural rate (Megahan and Kidd 1972).

Sediment production from the Camp and Clear Creek Basins increased uniformly for the first forty years as roads were built in both basins. Sediment production remained high in the 1981–90 decade in Camp Creek because of logging, but it declined in Clear Creek as fewer new roads were built. Sediment production in the Camp Creek Basin declined in the last decade as yields from logging declined. Clear Creek sediment production levels peaked in the 1971–80 interval and then declined as road building almost stopped. Mean annual rates per decade increased by a factor of about 2.5 for the Clear Creek Basin and by a factor of just under two for the Camp Creek Basin during the sixty-two years of analysis.

An objective of this project was the comparison of sediment production from residential development versus forest management. Roads are included as part of both activities, and their sediment yield is large compared with the yield from housing and logging. By normalizing for road area, another view of the relative effects of housing and logging can be obtained.

In Clear Creek, 50 ha (124 acres) of roads were built over the fifty-year period, and 33,263 mT (30,239 T) of sediment resulted from driveways appurtenant to the houses. For each hectare of road, 665 mT (605 T) of sediment from housing was predicted during the sixty-two-year period, or 11 mT/yr per hectare of road (4.9 T/yr per acre of road).

Over the study period in Camp Creek 68 ha (168 acres) of roads were built in landtypes where logging occurred, and 8,316 mT of sediment was predicted from logged areas. Per hectare of road built to support logging, 5 mT/yr per hectare of road (2 T/yr per acre of road) of sediment resulted. The residential rate is more than twice the logging rate, because sediment yield from logging is of short duration compared with the permanent effect of driveways, coupled with the higher road density in the Clear Creek (1.7%) versus Camp Creek (1.2%) Basins.

Prediction Accuracy

The state-of-the-art in large-scale, long-term sediment modeling does not permit prediction of precise amounts of sediment. Models such as WATSED allow comparisons of the relative differences between various disturbances and disturbed and undisturbed conditions. They are accurate enough for planning and to support management decisions. We recognize, however, that the results from an analysis such as this are very sensitive to the erosion values selected from the literature to represent the processes that were analyzed. The analysis reported here must be viewed from this perspective. Because of the lack of basin data, no attempt was made to validate that model's prediction. Although absolute values (e.g., mT/ha•yr of sediment) are reported, the confidence interval around these estimated values is unknown.

WATSED has many strengths because of its flexibility, but it also has limitations. Users can incorporate new erosion curves to meet their needs, and the magnitude and shape are set by the user. Polygon size is variable and can be quite small if information is available. The model is limited to yearly average values, however, so variability in the climatic regime is ignored. We did not use the hydrologic portion of the model, so we cannot comment on the accuracy of its predicted changes in water yield.

CONCLUSIONS

A sixty-two-year period was analyzed with a sediment accounting model (WATSED), which included the 1940–91 period of changing land use plus a ten-year post-disturbance recovery period. The primary disturbances in Camp Creek are road building, logging, and fire. The primary disturbances in Clear Creek are road building, residential development, and fire. The natural sediment production rate for this area is thought to be 0.02 mT/ha•yr (0.009 T/acre•yr).

Roads produced the bulk of the sediment in both basins. As of 1991, Clear Creek had about 50 ha (124 acres) of roads, and Camp Creek had over 100 ha (250 acres) of roads. Mean annual sediment production increased in both basins from 1940 through the 1971–80 interval and declined thereafter in Clear Creek. Mean annual sediment production in the Camp Creek Basin stayed constant between the fourth and fifth decades because of logging between 1984 and 1991. Between 1987 and 1991, road construction was insignificant in both basins.

In Clear Creek, roads and then homes were built, and sediment yield was predicted to increase because of areas allocated to roads and unsurfaced driveways. About 29 ha (72 acres) of driveways were assumed to complement the 50 ha (124 acres) of roads, but only 16% of the total predicted sediment from the basin was due to driveways. The combined effect of roads and driveways accounted for 99% of the predicted sediment.

Logging occurred on Camp Creek only, and clear-cut logging became common after 1984. Selective logging has been practiced in the basin since prior to 1940, but selective logging was not analyzed in this study except for salvage logging between 1988 and 1991. Because roads were built in support of the selective logging, the major source of sediment from selective logging is included. The predicted sediment levels after 1984 were 0.2 mT/ha•yr (0.09 T/acre•yr) or less for the low rate of erosion. At the high rate of erosion from logging, peak sediment production level was 1.6 mT/ha•yr (0.7 T/acre•yr). The literature generally supports the lower value.

Fire affected both Camp Creek (256 ha) and Clear Creek (85 ha), but only minimal sediment was produced because the erosion rate is relatively small and the model assumes that erosion due to fire stops after seven years. The peak sediment production rates from fire were 0.1 and 0.2 mT/ha•yr (0.04 and 0.08 T/acre•yr) in the two basins, respectively.

Predicted mean annual erosion rates due to disturbance are 29 to 119 times the assumed natural rate of erosion during the sixty-two-year period. This increase is due to the nearly 700-fold difference between the long-term erosion rate from roads and the natural rate. Mean total sediment production rates per hectare for Clear Creek were between 53% and 67% the magnitude of the Camp Creek Basin's rates over the period of analysis. Camp Creek is steeper and has more area in zones of higher sediment delivery than Clear Creek (figure 53.3), thereby explaining the higher sediment production rates from a lower density of roads.

The WATSED accounting model, once calibrated with local data, was relatively easy to use and could be applied to other parts of the Sierra. In each case, however, local erosion rates for common soils would be required. By proxy, an evaluation of relative road densities would provide a preliminary evaluation of sediment production from logging and residential development.

A normalization procedure was devised to attribute sediment from logging and housing by the area of road built to support the land use. The residential development rate was 11 mT/yr per hectare of road (5 T/yr per acre of road), more than twice the rate of 5 mT/yr per hectare of road (2 T/yr per acre of road) for logging.

Results and conclusions in this study are based on the best available data, but many assumptions had to be made before the sediment model could be implemented. Local erosion data for post-fire and -logging would improve the accuracy of the sediment predictions. The ten-fold range in erosion rates for logging changes the logging contribution from a negligible (relative to roads) to a rather serious, albeit short-term, quantity of sediment. Because roads produced the bulk of the sediment, additional information on erosion from roads is of the highest priority. Conclusions on relative sediment production levels between land uses may be made, but confidence intervals around predicted rates are unknown.

ACKNOWLEDGMENTS

We thank the individuals who provided data or technical advice during this project. Rosa Nygaard (U.S. Forest Service Regional Office, Northern Region) provided the WATSED program we used. John Casselli (Lolo National Forest) provided considerable technical advice on applying WATSED. Chuck Mitchell, Annette Parsons, Sue Rodman, Anne Boyd, and Christine Christiansen (Eldorado National Forest) provided erosion data and information on local erosional processes. John Munn (California Department of Forestry and Fire Protection) also provided erosion data and technical advice. Thad Edens (PSW Research Station) provided invaluable assistance during the model implementation and data analysis.

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