

## EVALUATING FOREST MANAGEMENT EFFECTS ON EROSION, SEDIMENT, AND RUNOFF: CASPAR CREEK AND NORTHWESTERN CALIFORNIA

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### ABSTRACT

The effects of multiple logging disturbances on peak flows and suspended sediment loads from second-growth redwood watersheds were approximately additive. Downstream increases were no greater than would be expected from the proportion of the area disturbed. Annual sediment load increases of from 123 to 269% were measured in tributary watersheds but were not detected at the main channel gages, implying that sediment was being temporarily stored in the intervening channels.

**KEY WORDS:** automatic sampling, California Forest Practices Act of 1973, clearcut, discriminant analysis, erosion, erosion hazard rating (EHR), evapotranspiration, fish, floods, interception lag time, landslides, peak flows, roads, sedimentation, selective harvest, slope stability, stage-based sampling, storm volume, streamflow, suspended sediment, turbidity-based sampling, transient snowpack, water yield

### INTRODUCTION

The debate about the impact of commercial forest management on fish and the identification of acceptable management practices make robust, well-designed watershed research essential. The climate and geology of northwestern California make it an ideal place to study the erosion, sedimentation, and streamflow effects of forest management. Northwestern California is well-watered with average annual precipitation ranging from a little under 40 inches near the coast to more than 120 inches on some of the higher coastal peaks. In this Mediterranean climate, about 90% of the annual precipitation in the commercial forest zone falls as rain between October and April. However, some of the largest floods have been enhanced by the melting of a transient snow pack. Five large floods have struck the area in the last 50 years. Those floods and the geologic setting produce high erosion and sedimentation rates. The area is characterized by high rates of tectonic uplift, resulting in slopes averaging 45%. The western two thirds of the area is dominated by the highly erodible Cretaceous and Jurassic rocks of the Franciscan Assemblage (Bailey et al. 1964). In the eastern portion, there are many deeply weathered granitic plutons, which are the source of landslides and severe surface erosion. As a consequence of the foregoing factors, rivers of northwestern California have the highest sediment loads in the United States and some are comparable to the sediment-laden rivers of Asia.

A redwood-dominated (*Sequoia sempervirens*) forest begins at the coast and extends inland approximately 30 miles. Associated species include Douglas-fir (*Pseudotsuga*

*menziesii*), Sitka spruce (*Picea sitchensis*), grand fir (*Abies grandis*), and western hemlock (*Tsuga heterophylla*). As the environment becomes dryer and warmer inland, the forest changes to one dominated by Douglas-fir, with lesser amounts of white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), and sugar pine (*Pinus lambertiana*). Logging in northwestern California began in the 1850s in response to the demands of the gold rush. In the coastal redwood zone, forests were clearcut to provide lumber for the cities of the San Francisco Bay area and to clear the land for pasture. Often the latter objective was not met because the sprouting redwoods persisted in spite of repeated burning. Logging the coastal redwood forests has continued since the 1850s, with some areas now having been logged for a third time. Inland, the logging history is quite different. With the exception of isolated areas near mining operations during the gold rush, large-scale commercial logging of the inland softwood conifers did not begin until after World War II. The coastal redwood forests were mostly privately owned, while the inland commercial timber stands were mainly on national forests.

Both inland and on the coast, past logging and mining practices left a legacy that is affecting current management. Logging has most heavily impacted the coastal watersheds. Corduroy roads were built in tributary drainages for skidding logs to main channels. Splash dams were used during the earliest logging to facilitate log drives to the mills. Stream channels were straightened and riparian vegetation removed to reduce the chance of log jams. The remnants of these activities exist today. The shift from log drives to rail transport in many cases only moved the disturbance from the streams to the stream banks since gentle right-of-way grades were needed. These railroad rights of way became main truck haul roads following World War II, when yarding and hauling shifted almost exclusively to tractors and trucks. Main skid trails and landings were commonly located in or adjacent to tributary stream channels.

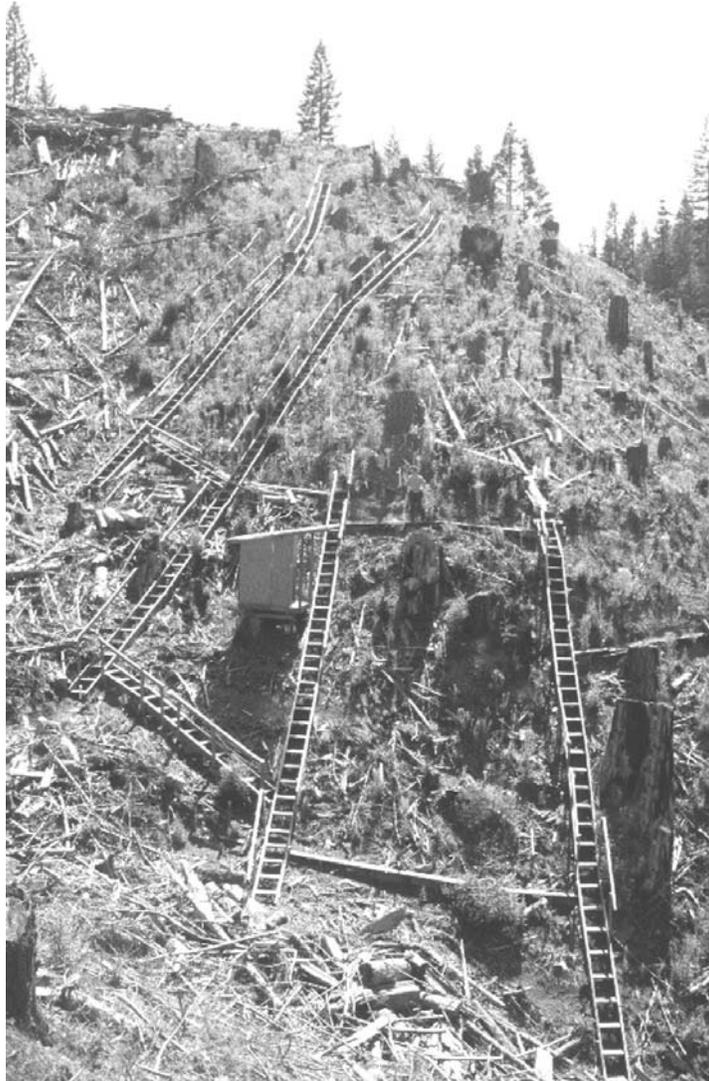
Although there had been forest practice legislation in California since 1945, early regulations dealt mainly with regeneration and fire control (Arvola 1976). The California Forest Practice Act of 1973 marked a dramatic change in the level and focus of forest practice regulation by the State of California. The 1973 regulations addressed a broader range of environmental concerns, and have subsequently been further expanded in response to the California Environmental Quality Act and Section 208 of Public Law 92-500 (1972 amendments to the Federal Water Pollution Control Act). These laws, together with the Endangered Species Act, have become the vehicles by which the general public and various special interests influence forest practices.

## **CASPAR CREEK EXPERIMENTAL WATERSHEDS**

The North Fork and South Fork Caspar Creek watersheds are between 3 and 7 miles from the coast and 7 miles south-south-east of Fort Bragg, California. They are part of the Jackson Demonstration State Forest. Between 1860 and 1906, the watersheds were clearcut and then burned to clear the ground for yarding. Splash dams were constructed and there were extensive modifications to the main stream channels to accommodate log drives.

Watershed experiments, conducted at Caspar Creek by the USDA Forest Service and California Department of Forestry and Fire Protection since 1963, offer an insight into the hydrology of northwestern California and effects that changing forest practices have had on erosion, sediment yield, and streamflow (Figure 1). Approximately 35% of the two

watersheds have slopes <30%. Approximately 7% of the North Fork is steeper than 70%, but <1% of the South Fork is this steep.



**Figure 1.** Process Studies of Soil Moisture, Subsurface Flow, and Pipeflow at Caspar Creek Assist in Understanding Effects of Logging on Streamflow and Erosion

### **The South Fork Study**

The first phase of research at Caspar Creek was a traditional paired-watershed experiment initiated in 1963 when concrete broad-crested weirs with a 120-degree V-notch were installed in the 1047-acre South Fork and the 1179-acre North Fork (Rice, Tilley, and Datzman 1979).

The calibration phase lasted until HY-67 (October 1966 through September 1967). A main haul road was constructed in the South Fork in 1967, with approximately three-fourths of its length within 200 ft of the stream channel. Logging was deferred until the summer of

HY-71 to allow an estimate of the road's effect independent of logging disturbances. Selective logging began at the weir and proceeded up the watershed during two additional seasons. A total of 38.3 million board feet of timber was harvested from the watershed -- 64% of the stand volume. The study was fortunate in that the calibration and postlogging periods each included 30-year peak flows. Consequently, inferences made from the study are not weakened by statistically questionable extrapolations of data in either period.

### ***Peak Streamflow***

The effects of road building and logging on peak flows were evaluated by Ziemer (1981) and Wright et al. (1990). The results agreed with the preponderance of paired watershed studies on the west coast of the US. Ziemer (1981) found statistical differences associated with logging and road building only in peak flows  $<0.01$  cfs  $ac^{-1}$ . Wright et al. (1990) found changes only in peaks  $<0.02$  cfs  $ac^{-1}$ .

### ***Storm Runoff***

Wright et al. (1990) also investigated possible logging effects on the hydrograph lag time and volume of stormflow. Similar to peak flow, significant differences in quick flow volume and total stormflow volume were only found for the class of storms having peaks of  $\leq 0.02$  cfs  $ac^{-1}$  and volumes  $\leq 42,700$   $ft^3$ . Lag time was decreased by approximately 1.5 hours for all three segments of the hydrograph. Therefore, since the total hydrograph was merely shifted forward in time but unchanged in shape, it seems unlikely that this response to logging would have any effect on channel stability or sediment transport.

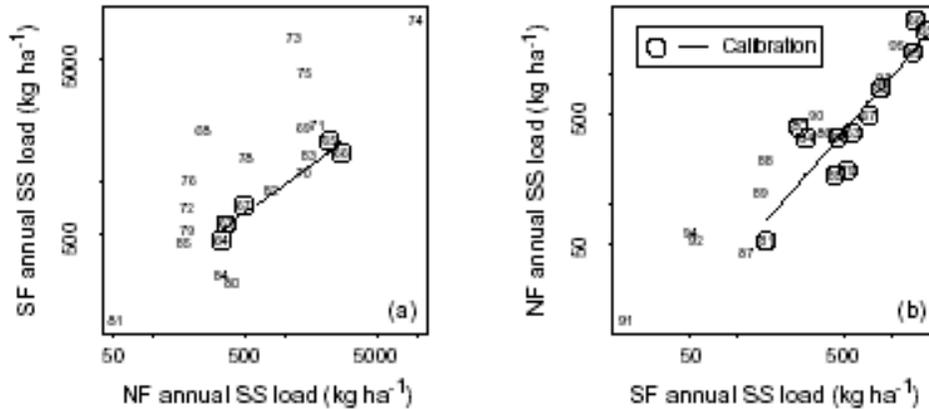
### ***Water Yield and Summer Low Flows***

Keppeler and Ziemer (1990) tracked several aspects of post-logging water yield, especially during the low flow season, from HY-71 to HY-83. Average annual water yield increased 15% or 0.3 AF  $ac^{-1}$ . Most of that increase occurred during the winter rainy season. Summer low flow volume increases averaged 29% (0.04 AF  $ac^{-1}$ ) and the minimum streamflow rate averaged 38% (0.000036 cfs  $ac^{-1}$ ) higher than that predicted by the prelogging relationship with the North Fork. The average length of the part of the low flow period when flow in the South Fork was  $<0.2$  cfs (0.0002 cfs  $ac^{-1}$ ) was shortened by 43 days from 1972 to 1978 -- a 40% reduction. Beginning with 1979, the durations of these low flows returned to the prelogging pattern and the summer minimum flow dropped below prelogging levels (Keppeler 1998). In summary, the authors concluded that, in spite of the benefits measured in their study, a dependence on selective logging for water yield increases was impractical and would be of minimal importance compared to other forest management and production goals.

### ***Sediment Loads***

Although, as mentioned earlier, streamflows before and after logging the South Fork were comparable, the sediment record was clouded by the occurrence of two streamside landslides in 1974. The landslide in the North Fork control watershed was 10 times larger than the landslide in the logged South Fork. As a consequence, the suspended sediment load for the North Fork that year was 4.5 times larger than that predicted from its relationship with flow during all the other years. In view of this anomaly, Rice, Tilley, and Datzman (1979) decided to use the predicted rather than the observed sediment load for 1974 when estimating the effect of logging. Had they not done so, the estimated effect of logging in that year

would have been a *reduction* of  $6.75 \text{ ft}^3 \text{ ac}^{-1}$ . Using the adjustment, the authors estimated that the logging and road construction resulted in an additional  $29 \text{ ft}^3 \text{ ac}^{-1} \text{ yr}^{-1}$  of sediment -- almost a threefold increase above that expected from the watershed in an undisturbed condition (Figure 2a).



**Figure 2.** Comparison of suspended sediment loads after logging (a) South Fork of Caspar Creek and (b) North Fork of Caspar Creek<sup>1</sup>

### ***Erosion***

Road-related erosion was estimated to be  $11,500 \text{ ft}^3 \text{ mi}^{-1}$  (Krammes and Burns 1973). However, they acknowledge being unable to measure all sources of erosion and their estimate is considerably below that of a 1976 study by McCashion and Rice (1983). Rice, Tilley, and Datzman (1979) estimated that sediment related to the road construction exceeded estimated erosion from the road by approximately 35% because of the presumed underestimation of road-related erosion. The discrepancy was attributed mainly to a 25,000- $\text{ft}^3$  failure of the old South Fork splash dam in 1968. The sediment was considered a result of the road because a stream crossing immediately upstream may have caused the failure. Logging-related erosion was estimated on seven plots totaling 94 ac. The estimated rate was  $1150 \text{ ft}^3 \text{ ac}^{-1}$ . That rate was almost 5 times greater than that on 18 similar plots measured elsewhere in northwestern California by the same field crew during the same season.

### ***The North Fork Study***

Cumulative watershed effects had become an important management concern when the second Caspar Creek watershed study was designed. One objective of the study in the North Fork of Caspar Creek was to test for synergistic cumulative effects. To accomplish that goal, 13 additional stream gages were installed on the mainstem and tributary channels of the North Fork. The cumulative effects hypothesis tested was that unit area peak flows or

<sup>1</sup> Numbers represent water year. South Fork was roaded in 1968 and approximately 65% of the timber volume was logged from 1971 to 1973. In the North Fork, roading and logging proceeded concurrently, with 13% of the timber volume removed from 1985 to 1986 and 37% removed from 1989 to 1992. Calibration years for (b) include both pretreatment and post-recovery years from (a).

sediment loads increased as a function of watershed area in addition to the proportion of watershed area treated.

The study also became an evaluation of the effect of Forest Practice Rules that had been revised since the South Fork study. Other than the total proportion of the timber volume removed, the logging of the North Fork had little in common with the logging of the South Fork. The North Fork timber was harvested by clearcutting and 92% of it was cable yarded to landings high on the slopes. All roads were located well away from stream channels. Tractor yarding was limited to the gentle, upper slopes (Figure 3). Streamside buffers, from which 34% of the timber volume was thinned, protected streams that supported aquatic life. Logging began in the upper watershed and proceeded downstream to enhance the chance of detecting cumulative effects.



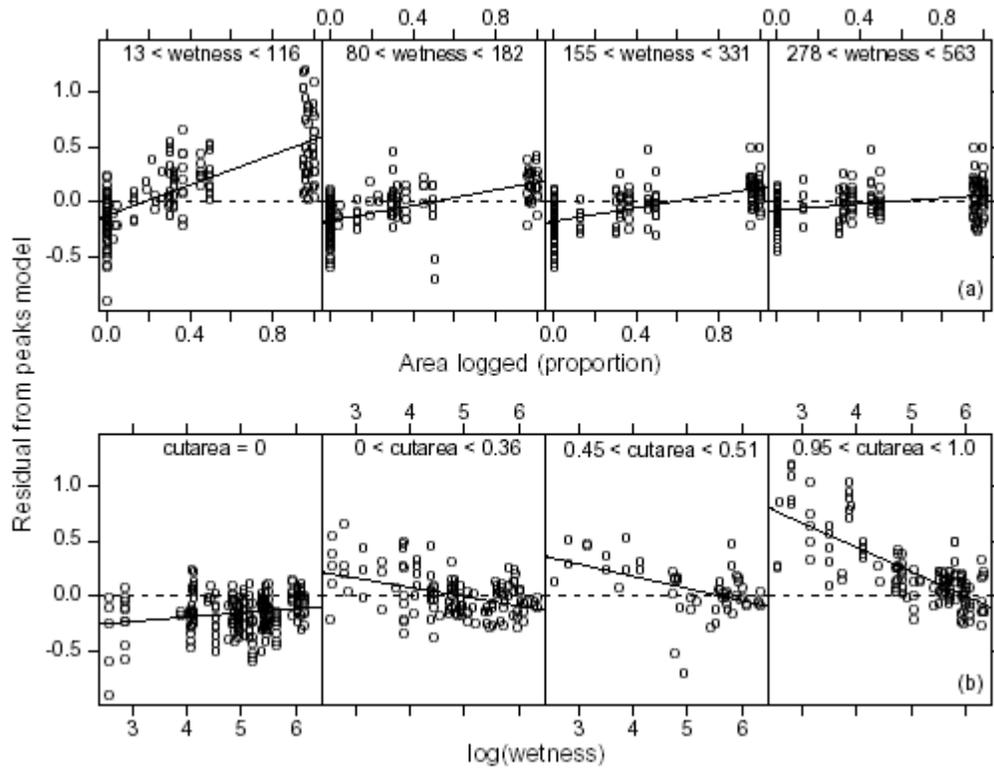
**Figure 3.** Tractor Logging Was Restricted to the Gentle Upper Slopes in North Fork of Caspar Creek

### ***Peak Streamflow***

Similar to the South Fork study, when peak flows at the North Fork weir were regressed against those at the South Fork weir, the post-logging regression was found to not be statistically significantly different from the regression before logging. However, when the test was repeated using two control tributary watersheds within the North Fork, postlogging peak increases were statistically significant (Ziemer 1998). This suggests that the earlier conclusions of no significant change (Ziemer 1981; Wright et al. 1990) may have been the result of a large variance requiring a large change before being detected.

For the cumulative effects analysis, an aggregated regression model was fit simultaneously to all the sub-watershed peaks (Lewis et al. 2001). The peak flow equation

was a function of peaks in the control tributary watersheds, proportion of area logged, the interaction between logged area and antecedent wetness (Figure 4), and time since logging. No variables related to roads, skid trails, fire lines, burning, or herbicide application improved the equation. The estimated average peak flow increases for the 2-year return period storm was 27% for the 100% clearcut tributary watersheds and 9% for the 50% clearcut North Fork. The analysis found an approximately linear recovery rate of 8% per year for the first seven years after logging. The coefficient of the variable testing synergistic cumulative effects was not significant ( $p = 0.21$ ).



**Figure 4.** Residuals from Simple Linear Regressions of Logarithm of Peak Flow in Treatment Watersheds vs Controls<sup>2</sup>

### ***Storm Runoff***

The results of the runoff volume analysis were very similar to those of the peak flow analysis. The largest relative increases were found in the smallest storms and driest antecedent conditions. However, the average increase for runoff volumes greater than 21 ft<sup>3</sup> ac<sup>-1</sup> declined with storm size and then leveled off at an average increase of 30% for clearcuts and 13% in partially clearcut watersheds. The mean percentage increases were still positive even under the wettest conditions of the study -- 27% for clearcuts and 16% for partially clearcut watersheds (Ziemer 1998).

<sup>2</sup> (a) Effect of cutting decreases with increasing wetness.  
 (b) Effect of wetness becomes increasingly negative with more cutting.

The annual storm runoff volume (the sum of the storms measured) increased an average of 60% ( $2.26 \text{ AF ac}^{-1}$ ) in clearcut watersheds and 23% ( $0.87 \text{ AF ac}^{-1}$ ) in partially clearcut watersheds. Based on the complete discharge records at the North Fork weir, the storm runoff volume included in this analysis represents approximately 45% of the total annual runoff volume.

### ***Water Yield and Summer Low Flows***

Similar to the South Fork study, an 8% increase ( $0.2 \text{ AF ac}^{-1}$ ) in annual water yield was found following logging in the North Fork (Keppeler 1998). The minimum summer low flow rate was increased 148%. Unlike in the South Fork, no recovery trend was detected, suggesting that water yield effects will persist longer after clearcutting than when a similar timber volume is removed from a watershed in a selection cut. These differences in water yield recovery are probably related to changes in rainfall interception and evapotranspiration.

### ***Sediment Loads***

Much more so than in the peak flow analysis, sediment load estimates in the North Fork study benefited from improved technology. The North Fork sediment estimates were made from samples taken by automatic pumping samplers using variable probability sampling (Thomas 1985).

Using the South Fork as a control, following logging there was a 28% increase in suspended sediment discharge above that predicted by pre-treatment regression (Figure 2b) and an 8% decrease in total sediment load (suspended plus pond accumulation). Neither of these estimates was statistically significant (Lewis 1998). However, when three unlogged North Fork tributaries were used as controls, the effect of logging was a statistically significant 89% increase in suspended sediment load. Only storm flows were sampled for that estimate, but these storm flows carried approximately 90% of the total suspended sediment load in the North Fork.

In the aggregate analysis, logging was associated with a mean annual increase in suspended sediment load of 212% ( $3.5 \text{ ft}^3 \text{ ac}^{-1} \text{ yr}^{-1}$ ) in clearcut watersheds and 73% ( $3.5 \text{ ft}^3 \text{ ac}^{-1} \text{ yr}^{-1}$ ) in partially clearcut watersheds. The most important explanatory variable in the aggregate analysis was the increased volume of stormflow. With one exception, downstream increases in sediment load were no greater than would be expected by the proportion of the watershed disturbed. However, that may be because the excess sediment produced in tributary watersheds had not yet reached downstream gages.

### ***Erosion***

Road-related erosion in the North Fork was approximately  $5000 \text{ ft}^3 \text{ mi}^{-1}$ , but, because these roads were located away from streams, this erosion did not contribute significantly to sediment loads. Logging-related erosion in the cable-yarded North Fork was approximately  $650 \text{ ft}^3 \text{ ac}^{-1}$ , substantially less than that measured in the tractor-yarded South Fork.

## **EROSION STUDIES**

The study of erosion has some advantages over the study of sediment resulting from forest management activities. Estimating sediment effects usually involves a combined calibration period and treatment period spanning a decade or more. Because of the time and expense, sediment studies are anecdotal -- the watersheds are chosen for study rather than being a random sample of all watersheds. Often even the choice of a control watershed is not

left to chance. Erosion studies, in contrast, can be based on a random sample of the population of interest. They also take less time, even if their execution must wait several years to allow erosion processes to respond to the disturbance before collecting data. The weakness of erosion studies is that usually sediment, not erosion, is the parameter of interest and estimating the delivery of eroded material to a watercourse and its subsequent transport is a very uncertain exercise.

Due to the geology, steep terrain, and climate of the redwood region, mass movement is the dominant erosion process. Sheet erosion was estimated in only one of the studies discussed below. The lack of such estimates stems as much from the difficulty and uncertainty of measuring sheet erosion as from the presumed minor role that sheet erosion plays in total sediment yield. Estimates of rills, gullies, and mass movements are usually based on the volume of the void left by the erosion. Occasionally void volumes are reduced by estimates of local deposition, in which case, the estimates are almost as uncertain as those of sheet erosion.

Erosion hazard ratings (EHR) are often used as a guide for designing appropriate forest practices. California's Forest Practice Rules currently contain an EHR patterned after one used by the USDA Forest Service. As far as we know, its efficacy has never been tested. An earlier version was tested by Datzman (1978) and rejected when it was found to be significantly correlated ( $r^2 = 0.63$ ) only with tractor yarded old-growth logging. Rice and Datzman (1981) used the same data in a regression analysis in an attempt to predict erosion volume from site and operational variables. Their equation, based on slope, aspect, geology, and yarding method was only moderately successful ( $R^2 = 0.43$ ). Mass movements accounted for 55% of the measured erosion, gullies for 37%, and rills for 8%. The study led to two insights: (1) that most (68%) of the erosion was on 4 of the 102 plots; and (2) that operator behavior was responsible for a large part of the variability in erosion. These findings influenced the focus of several subsequent studies.

Concurrently, an inventory of road-related erosion was made of 344 one-mile segments of Forest Service roads (McCashion and Rice 1983; Rice and McCashion 1985; Rice and Lewis 1986). McCashion and Rice concluded that the road *caused* approximately 60% of the measured erosion and that conventional engineering methods or minor relocation of the right-of-way could have avoided only 24% of the total erosion. They found that 95% of the road-related erosion was by mass movements, including bank sloughing. Also, erosion from seasonal roads was approximately 50% greater than that from all-weather secondary roads, even though the rights-of-ways of the latter were 50% wider. Similar to Rice and Datzman (1981), they found their data to be highly skewed. Three mass movement events accounted for 85% of the natural erosion and 33% of all the erosion measured. Two other studies used linear discriminant analysis to identify high-risk sites on forest roads. Rice and McCashion (1985) randomly divided the data into two groups. One of these groups was used to develop an equation separating the stable sites ( $< 1420 \text{ ft}^3 \text{ mi}^{-1}$ ) from the unstable group ( $> 1420 \text{ ft}^3 \text{ mi}^{-1}$ ). It correctly classified 75% of the sites. When tested against the other half of the data, the equation correctly classified 74% of those sites. The sites classified as unstable were responsible for 82% of the total erosion. In a second discriminant analysis, Rice and Lewis (1986) contrasted conditions at 0.2-mi. road segments containing large erosion features with a random sample from all 0.2-mi. segments. It had a similar classification accuracy based on only two variables, slope and geology.

Even before these studies quantified the importance of mass movements in the erosion associated with forest management, problems on national forests fostered research aimed at estimating landslide risk. Discriminant analysis is well suited for such studies since it can produce probabilistic estimates of risk; the task is to identify the portion of the landscape that is at risk. Rice and Pillsbury (1982) studied the English Peak batholith in the Klamath Mountains and produced an equation based on slope, prelogging crown density, drainage area, and distance to a stream. The equation had a classification accuracy of almost 90% with the data used in its development. However, when that equation was tested on two granitic batholiths in Oregon, its classification accuracy was 74% on one and 51% on the other (Rice, Pillsbury, and Schmidt 1985) -- an example of the danger of overfitting developmental data. When the least significant variable was dropped from the equation, the prediction accuracies became 86%, 76%, and 75%, suggesting that the deleted variable, drainage area, was related to some process unique to the English Peak batholith.

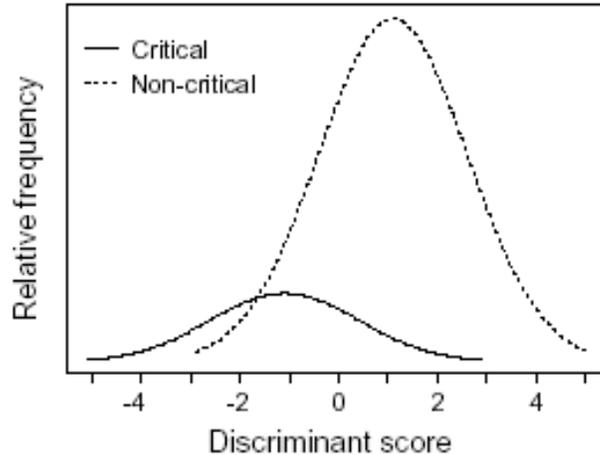
Due to rapid tectonic uplift, topography typical of these coastal mountains consists of a steep "inner gorge" adjacent to streams with gentler terrane above. Slides in the inner gorge are of particular concern since they tend to have high sediment delivery to the streams. Furbish and Rice (1983) sampled 85 clearcut patches on the Six Rivers National Forest. They found that inner gorges, accounting for approximately 30% of the study area, produced 88% of the landslide volume. Outside the inner gorge, 85% of the slide volume was associated with roads. Slides occupied 2.6% of the inner gorge area and 0.14% of the remainder of the study area (Furbish 1981).

In 1985, the findings that a small proportion of large landslides typically yielded a disproportionately large fraction of the total measured erosion led the State of California to provide most of the funding for the Critical Sites Erosion Study (CSES). The CSES sampled population consisted of all areas on private land where harvesting had been completed between November 1978 and October 1979. Access was granted to 75% of the area. It was presumed that the 6-year delay after logging would have allowed enough time for weaknesses in the site or the execution of the harvest to be expressed as excess erosion. The objective was to learn how the sites having large erosion events differed from stable sites. Data were collected on all erosion features displacing more than 350 ft<sup>3</sup> from 2 ac, square plots. Critical plots (> 2700 ft<sup>3</sup> ac<sup>-1</sup>) were found during a reconnaissance of the available harvest areas. Control plots were selected at random. The overall study was divided into two substudies. In one, an interdisciplinary team attempted to learn why the erosion had occurred, based on their appraisal of site conditions and how the harvest or roadwork had been executed (Durgin, Johnston, and Parsons 1989). They developed a numerical index to quantify their evaluations. The other substudy used discriminant analysis to distinguish between critical and control sites (Lewis and Rice 1989). Both sub-studies analyzed roads and harvest areas separately.

Durgin, Johnston, and Parsons (1989) found that, similar to earlier studies, almost all of the erosion measured was produced by 12% of the area studied. They concluded, "Inherent physical factors had the major influence on susceptibility of a road or harvest area to erosion events. On road plots, management factors played an almost equal role to site factors, but on harvest plots, management factors played a decidedly secondary role." They found that roads, covering 4% of the area studied, produced 76% of the erosion. Lewis and Rice (1989) sifted through 56 variables before deciding that the most robust equations for both road and harvest sites were based on only three variables. Extensive testing persuaded

the authors that the addition of other variables “known” to affect slope stability would risk over fitting the developmental data. The chosen equations included: slope, horizontal curvature, and rock strength for harvest areas; and slope, horizontal curvature, and soil hue for road plots. These variables seem to be good surrogates for the forces affecting slope stability. Slope indexes the balance between the downslope component of gravitational force promoting failure and friction at the failure plane resisting it; horizontal curvature represents sites of convergent subsurface flow promoting failure and accumulations of quasi-stable colluvium susceptible to failure; rock strength indexes the resistance to failure; and hue was apparently indexing subsurface water since soils associated with high risk were frequently gleyed soils of low chroma indicating waterlogged conditions. The road equation had an estimated classification accuracy of 78% and the harvest area equation had one of 69%. Lewis and Rice (1990) concluded that these accuracies were high enough to make the functions useful tools for estimating risk and presented a method by which economic and environmental objectives could be balanced objectively.

Rice and Lewis (1991) found that with no site-specific information, the probability of a slope-failure critical harvest site was 0.007 on the northern California coast and 0.001 inland. The probability of a critical road site was 0.022 on the coast and 0.006 inland. As a consequence of scarcity of critical sites, any acceptable risk threshold that correctly identifies a large proportion of critical sites will also misclassify as critical a substantial number of sites that will not fail as the result of management activities (Figure 5). For example, a threshold that correctly identified 90% of critical road sites on the coast would also misclassify 40% of the stable sites. Conversely, a threshold that correctly classified 90% of the stable sites would misclassify 55% of the critical sites. Any site with at least a 1.2% probability of slope failure on the coast, or 0.3% probability inland, would have to be classified as critical, in order to identify 90% of the critical sites. These low risk thresholds seem counterintuitive, but reflect that a wide net must be thrown in order to catch such rare fish. Probably the most effective use of any discriminant function is for screening areas that are steep enough to contain potential mass wasting sites. The sites classified as critical could then be subjected to geotechnical investigation if the expected proportion of ‘false positives’ is unacceptable.



**Figure 5.** Relative Frequency of Critical and Noncritical Sites for Various Risk Ratings (discriminant scores) on Harvest Areas<sup>3</sup>

## MEASUREMENT AND ANALYTICAL CAPABILITIES

### Streamflow

With the nearly universal application of digital computers, traditional methods of recording have largely given way to electronic recording of stage via data loggers. This has eliminated the need to store charts and tape and to digitize or otherwise transfer them to electronic media. Data loggers normally record the gage height sensed by pressure transducers, rather than traditional float or bubble-gage sensors. With these changes, reliability has been improved significantly by eliminating failures associated with mechanical clocks, pens, tapes, pulleys, float switches, etc. Of course that does not eliminate problems associated with sediment in flumes, debris in weirs, and plugging of stilling well intakes; and failures related to transducers, batteries, and wiring. Therefore, it is still important to make frequent site visits to check equipment functioning.

### Suspended Sediment Sampling and Estimation

#### *Manual Sampling*

In most small and medium-size watersheds, including ones that are seasonally dominated by snow, the majority of the annual suspended sediment is usually transported during a few, large streamflow events. Automated data collection is essential to effectively capture such events. Although it is possible to rely solely on manual measurements, important storm flows are infrequent and difficult to predict, and when they do occur, trained personnel may not be available to collect the required information. Infrequent, systematic manual sampling will not provide adequate information to make credible suspended sediment load estimates under these conditions. While manual sampling, for example with DH-48 (F.I.A.S.P. 1958) or D-49 (F.I.A.S.P. 1965) samplers, is necessary to measure the mean and variability of sediment concentration within a stream cross-section, it is generally inadequate for defining the temporal variability. The result is that concentrations for periods of interest

<sup>3</sup> Frequency of non-critical sites has been scaled to be under-represented by a factor of 10.

must be estimated by relying on discharge and sediment rating curves. However, discharge is a very imperfect predictor of sediment concentration (Walling and Webb 1988). While rating curves may be adequate for some rivers and some purposes, their inaccuracy seriously limits their usefulness in detecting changes in sediment transport.

### ***Automated sampling***

The use of data loggers at gaging stations facilitates innovative approaches to suspended sediment sampling because of their programmability and capability of controlling multiple sensors and devices. A number of manufacturers now offer turbidity probes that can be deployed on a continuous basis in streams. Therefore, information about discharge and/or turbidity can be used to control an automatic pumping sampler.

Automatic pumping samplers have some fundamental limitations that are important under some conditions. They collect point samples that are not guaranteed to represent the cross-sectional mean concentration. Their representativeness must be verified by examining the relation between simultaneous pumped and depth-integrated samples. At Caspar Creek, because the channels are small and the suspended material is generally fine, we have found the pumped sample concentrations need little or no correction. In larger channels, especially those with coarser sediments, larger differences can be expected between the pumped and depth-integrated sample concentrations. A more significant problem in streams with very coarse sediment loads, is pumping sampler inefficiency with coarse sand. The problem is exacerbated if the pump must be situated at an elevation much higher than the sampler intake and when water velocity exceeds the sampler intake velocity. At one location where the pump was approximately 13 ft above the intake and where point velocities exceeded  $15 \text{ ft sec}^{-1}$ , we found greater than 90% of the sand coarser than 0.5 mm was escaping the sampler. It is unlikely that correcting to depth-integrated samples can salvage the data in such situations.

Automated sampling programs reduce the cost per sample. However, they are usually designed to sample more frequently than manual programs, hence will typically involve increased total costs for processing samples, in addition to the extra purchase and maintenance costs of automated field equipment. Automated sampling programs also require more technical skills for installation, maintenance, trouble shooting, data processing, and analysis. The superior coverage of storms and the potential for much more accurate load estimates justifies the extra costs for many applications.

### ***Stage-based sampling***

Automated sampling programs often have used a variety of stage-based algorithms for sampling. One stage-based algorithm uses variable probability sampling to increase sampling frequency as a continuous function of stage (Thomas 1985; Thomas 1989). This approach was used at Caspar Creek for 10 years, but was discontinued because it tends to collect too many samples if estimates are needed for each storm. Time-stratified sampling (Thomas and Lewis 1993) is an approach that gives less variable sample sizes for storms. This approach breaks hydrographs into time periods (strata) of varying lengths that depend on the stage height and direction at the start of each stratum. Two or three samples are collected randomly in each stratum. Another approach, flow-stratified sampling, chooses from a set of sampling frequencies corresponding to specific rising and falling flow classes (Thomas and Lewis 1995). Flow-stratified sampling is best suited for estimating seasonal or

annual loads. All of these methods utilize probability sampling, therefore they have the desirable feature that sediment load and its variance can be computed without bias.

### ***Turbidity threshold sampling***

Turbidity-threshold sampling (TTS) bases real-time sampling decisions on turbidity, measured by an instream probe. TTS attempts to collect enough samples to develop a regression from each storm event, so that concentration can be reliably estimated from turbidity for any period with significant sediment transport. The algorithm employed in TTS collects a sample each time a specified turbidity condition, defined by its magnitude and direction, is satisfied. Discharge information is used only to disable sampling when either the turbidity probe or pumping sampler intake are not adequately submerged. Regressions of concentration on turbidity are often linear with small residual variance. Sediment loads from all but the smallest storm events can be accurately estimated from TTS samples. Variance estimation is also possible, but is less reliable than variance estimation from probability sampling designs (Lewis 1996).

### **LESSONS LEARNED FROM NORTHWEST CALIFORNIA**

- Proportional increases in peak flows resulting from both clearcutting and selective logging are greatest for smaller events.
- Increases in peak flows from clearcutting are related to proportion of area logged, watershed wetness, time after logging, and storm size.
- Inability of some studies to detect changes in peak flows after logging may be due to high variance rather than an absence of effect.
- Increases in water yield and summer low flows diminish over time and will probably be of minimal importance compared to other forest management and production goals.
- Suspended sediment loads increased almost three-fold from selective logging and road construction prior to implementation of the 1973 Forest Practice Act.
- Smaller, but statistically significant, increases in sediment were associated with clearcutting and roads under forest practice rules in effect in 1990.
- A few sites contribute most of the erosion and sediment from forest operations.
- Slope angle, horizontal curvature (topographic concavity), rock strength, and soil color can be used to identify sites with a high risk for landsliding.
- Improved monitoring and data analysis technology is available and can greatly benefit watershed studies.

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