FOREST MANAGEMENT EFFECTS ON EROSION, SEDIMENT, AND RUNOFF: LESSONS FROM 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. The failure of previous studies to detect increases in large peak flows following timber harvests may be due to variability in measurements rather than absence of an effect. A few sites are responsible for a large proportion of the erosion resulting from management-related disturbances.
KEY WORDS. Streamflow, runoff, sediment, erosion, logging, roads, monitoring, Caspar Creek

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 produce high erosion and sedimentation rates. The area is characterized by high rates of tectonic uplift, resulting in slopes averaging 45%. As a consequence, rivers of northwestern California have the highest sediment loads in the United States and some are comparable to the sediment-laden rivers of Asia.

Logging in northwestern California began in the 1850's and has continued in the coastal redwood forests since, with some areas now having been logged for a third time. Although there had been forest practice legislation in California since 1945, early regulations dealt mainly with regeneration and fire control. In 1973, regulations were expanded to address a broader range of environmental concerns.

CASPAR CREEK EXPERIMENTAL WATERSHEDS

The North Fork and South Fork Caspar Creek watersheds are between three and seven miles from the Pacific Ocean and seven miles SSE of Fort Bragg, California. They are part of the Jackson Demonstration State Forest. Between 1860 and 1906, the watersheds were clearcut and burned. Splash dams were constructed and the main stream channels extensively modified to accommodate log drives.

Watershed experiments, conducted at Caspar Creek by the U.S. 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.

THE SOUTH FORK STUDY

The first phase of research at Caspar Creek was a traditional paired-watershed experiment initiated in 1963 when weirs were installed in the 1047-acre South Fork and the 1179-acre North Fork (Rice et al. 1979). The calibration phase lasted until 1967 when a main haul road was constructed near the channel of the South Fork. Selective logging began at the weir in 1971 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.

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 U.S. These studies found significant increases only in their smallest discharge classes.

Sediment loads. Logging-related sediment increases in the South Fork were calculated adjusting the record for an anomalously large streamside slide in the North Fork. Using the adjustment, the authors estimated that the logging and road construction resulted in a mean additional $29 \text{ ft}^3 \text{ ac}^{-1} \text{ yr}^{-1}$ of sediment -- almost a three-fold increase above that expected from the watershed in an undisturbed condition.

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 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 upper gentler slopes. Streamside buffers, from which 34% of the timber volume was thinned, protected streams that supported aquatic life.

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, post-logging 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 masking the increase in peak flow.

For the cumulative effects analysis, an aggregated regression model was fit simultaneously to all of the sub-watershed peaks (Lewis 1998). 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, 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

increase for the two-year return period storm was 27% for the 100% clearcut tributary watersheds and 9% for the 50% cut 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 ($p = 0.21$).

Sediment loads. 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, suspended sediment discharge following logging was 28% above that predicted by the pre-treatment regression, but the increase was not 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.

In the aggregate analysis, logging was associated with a mean annual increase in suspended sediment load of 212% (3.5 ft^3 ac^{-1} yr^{-1}) in clearcut watersheds and 73% (3.5 ft^3 ac^{-1} yr^{-1}) in partially clearcut watersheds. The most important explanatory variable in the aggregate analysis was the increased volume of stormflow. The analysis failed to detect synergistic cumulative effects.

EROSION

Rice and Datzman (1981) used a regression analysis in an attempt to predict erosion volume from site and operational variables. Their equation was only moderately successful ($R^2 = 0.43$). The study led to two insights: [1] that most (68%) of the erosion was on four 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.

McCashion and Rice (1983) inventoried road-related erosion on 344 one-mile plots on Forest Service roads. They found that three mass movement events accounted for 85% of the natural erosion and 33% of all the erosion measured. Rice and McCashion (1985) used a linear discriminant analysis to develop an equation separating the stable sites from the unstable ones. It correctly classified 75% of the sites. The sites classified as unstable were responsible for 82% of the total erosion.

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 about 30% of the study area, produced 88% of the landslide volume. Slides occupied 2.6% of the inner gorge area and 0.14% of the remainder of the study area (Furbish 1981).

The findings that a small proportion of large landslides typically yielded a disproportionately large fraction of the total erosion motivated the Critical Sites Erosion Study (CSES) in 1985.

The CSES population consisted of all areas on private land where harvesting had been completed between November 1978 and October 1979. Lewis and Rice (1989) used discriminant analysis to distinguish between critical (> 2700 ft^3 ac^{-1}) and control sites. They concluded that the most robust equations for both road and harvest sites were based on only three variables. The classification accuracies of the road and harvest area equations were 78% and 69%, respectively. Rice and Lewis (1991) found that with no site-specific information, the probability of a 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 non-critical sites.

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. Data loggers normally record the stage height sensed by pressure transducers, rather than traditional float or bubble-gage sensors. Reliability has been improved significantly by eliminating failures associated with mechanical devices. Of course that has not eliminated problems associated with sediment in flumes or 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 the majority of the annual suspended sediment is transported by a few, large flows. Although it is possible to rely solely on manual measurements, important storm flows are infrequent and may be missed. Consequently, sediment concentrations for periods of interest are often estimated by relying on stream discharge and sediment rating curves. However, discharge is a very imperfect predictor of sediment concentration (e.g. Walling and Webb 1988). The inaccuracy of rating curves seriously limits their usefulness in detecting changes in sediment transport.

Automated sampling. Because of their programmability and capability of controlling multiple sensors and devices, the use of data loggers at gaging stations has facilitated innovative approaches to suspended sediment sampling. Therefore, information about discharge and/or turbidity can be used to control an automatic pumping sampler.

Stage-based 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 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.

Turbidity-threshold sampling. Turbidity-threshold sampling (TTS) bases real-time sampling decisions on turbidity, measured by an in-stream 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. Sediment loads from all but the smallest storm events can be accurately estimated from TTS samples.

LESSONS LEARNED

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. Suspended sediment loads increased almost three-fold from selective logging and road construction prior to implementation of the 1973 Forest Practice Act. An 89% increase in sediment was associated with clearcutting and roads under forest practice rules in effect in 1990. A few sites generally contribute most of the erosion and sediment from forest operations. Improved monitoring and data analysis technology is available and can greatly benefit watershed studies.

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